Are We Living in the Middle of an Industrial Revolution?

By Joel Mokyr

I am an economic historian, part economist and part historian. To some, economists are funny. Historians do not appear to be as funny as economists. But at times one can find a good characterization of what historians do. A good metaphor of what economic history is about is contained in a nice anecdote I read not long ago about a tour guide in the Metropolitan Museum of Art, where a group of visitors was shown one of the famous but idealized pictures of George Washington made by Gilbert Stuart. A skeptical member of the group remarked that surely this picture bore but little resemblance to the *real* Washington. "Well," said the guide, "maybe that is not what he looked like *then*, but that surely is what he looks like *now*." This in a nutshell is what historians do: they interpret the past, but when doing so both the questions asked and the way the answers are provided are tainted with a certain measure of "now-ism." That is, they formulate questions that are of interest to them, and as they are children of their own time, their interests are inevitably conditioned by the world they live in. There is nothing wrong with that, as long as we do not force inappropriate mechanical inferences from analogies in the style of "this is the way it was then, so what we can expect now is . . . ."

Each society, then, writes most fondly about historical phenomena with which it is most familiar, and technological progress clearly is dominating our lives as much as it has ever done. The concept of an Industrial Revolution has recently become of great interest to general economists of all persuasions. The New Growth Theory has placed renewed emphasis on the importance of technological change in modern economic growth, and a number of publications have in recent years tried to look at the Industrial Revolution from the point of view of the new growth theory, examining and reexamining the somewhat-questionable time series we have for this period to the point of beating them to death (Brezis and others; Crafts; Greasley and Oxley; Greenwood and Yorukoglu). Rank and file economic historians such as myself who have been laboring in the trenches for decades trying to make some sense out of the historical data we have for the period are rejoicing in our sudden popularity among our fellow economists. It is therefore tempting to look at the events of our

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own time as analogous to those of the British Industrial Revolution since it adds legitimization to the research we were already doing anyway. But the temptation to look at the past to guide us in making predictions and policy recommendations should be resisted. Historical analogies often mislead as much as they instruct and in technological progress, where change is unpredictable, cumulative, and irreversible, the analogies are more dangerous than anywhere.

The British Industrial Revolution

The British Industrial Revolution in its "classical period" was, by and large, a small and localized affair, confined to a few regions in the northwest of England and the Scottish lowlands. As late as 1830, one could travel through the vast part of Britain and never see a factory chimney. The modern sector, as we may call it, employed perhaps 10 percent of the labor force. The largest sectors such as construction, services, agriculture, and most of manufacturing were operating more or less in the same technological paradigm as a century before. By the middle of the century, the small workshop, where the independent artisan labored with his sons and apprentices, was still far more common than the large cotton mill. Consequently, the productivity gains and the increase in real wages and the standard of living occurred late, by the reckoning of some not until the mid-1840s, two generations after the first great breakthroughs occurred (Mokyr 1993).

In our century, everything happens faster. But, adjusting for scale, are the phenomena comparable? For one thing, despite the fact that the British Industrial Revolution in the 18th century was limited to a small part of the economy, it was not limited to a single industry or even a handful. As one author once put it, "It was not the age of cotton, nor the age of steam, nor the age of iron—it was the age of progress." Recent research by Peter Temin confirms this; Temin has shown that in addition to the great industries such as cotton and iron, Britain maintained technological superiority in a vast array of minor industries from the linen and rope industries to the manufacture of toys, belts, buttons, paper, and pins. Many of these advances can be discovered if you just dig deep enough into an obscure literature few venture into.

Consider one simple example: writing. The old, venerable quill pen, despite its virtues, suffered from many defects such as uneven writing and the need to dip frequently into ink. The steel pen, with two slits pierced in the shoulder of the nib, gave the pen both flexibility and the capability to retain ink. It was perfected in the 1820s. By the middle of the century it was universal—it would be speculative but not absurd to suggest that without this modest improvement Anthony Trollope would not have been able to sustain his declared rule of completing 250 words every 15 minutes (Day). Mass production and interchangeable parts, too, made their entrance upon the British scene, American claims of priority notwithstanding. The Portsmouth shipyard in 1801 mass-produced interchangeable wooden gears and pulleys for the British navy using sophisticated control techniques and a highly specialized labor force. Run by two of the most brilliant engineers of the time, Marc Brunel and Henry Maudslay, it was truly Fordism before Ford (Cooper).

There were other technological breakthroughs, many of them in unexpected corners of the economy: during those years the human race broke the tyranny of gravity by flying the first balloons; broke the tyranny of smallpox by introducing the first truly successful vaccination process; broke the tyranny of darkness by bringing the lighting powers of gas to homes and streets; and broke the tyranny of food-spoiling bacteria by the introduction of food canning. There were thus many enclaves of technologically progressive industries, but they remained enclaves.

The current age

In our time—taken roughly to be the years from 1950 to the present—we, too, observe that we are neither the age of the microprocessor, nor the age of antibiotics, nor the age of the advanced plastics, but an age in which progress is like a steady rain, falling in torrents on some places while only drizzling elsewhere, but widespread if not ubiquitous. In its celebrated survey on the world economy published last year, the *Economist* magazine explicitly argued that our age might be compared with the Industrial Revolution because of the pervasiveness of what it called IT, information technology. As a "general purpose" technology, IT shows up almost everywhere in the economy, although, in Solow's well-known quip, everywhere except in the productivity data. Without denigrating the importance of IT, if all we had to show today for our technological achievements were microprocessors and the information storage and communications that go with them, we would not deserve the term. I submit that it is exactly the host of other advances across a huge spectrum that justify more encompassing terms like the Industrial Revolution.

The *number* of major breakthroughs alone, however, is by itself not an adequate criterion to qualify for Industrial Revolution status. What must matter, above all, is the impact that such technological advances have on the economy. The problem is that normally such effects can only be assessed much later. The steam engine, to choose a famous example of a general purpose technology, made its first appearance in 1709 but its impact on the economy before 1830 was not all that enormous, in part because it still needed to be refined and improved, and in part because good alternatives were available. After 1830, with its widespread application to transportation and to manufacturing in areas where water power was unavailable, the steam engine's economic importance increased. Perhaps most crucially, the steam engine led further down the road to the development of other engines and played a major role in the development of thermodynamics. And yet, had there only been the steam engine, the Industrial Revolution would have been just like the 15th century: an era of isolated breakthroughs that eventually petered out.

Judging technological breakthroughs

There are different ways to judge technological breakthroughs; the obvious one and most appealing to economists is the impact on output and productivity. But there are others: I like the notion that pathbreaking inventions allow us to do something previously impossible such as flying or preventing infectious disease. One can judge an era of technological advances by whether it is one of door-opening or gap-filling inventions. It could be argued that if the criterion for an Industrial Revolution is a cluster of such macroinventions, this does qualify our own age as much as the classical British Industrial Revolution, but so does the period roughly between 1860 and 1900 (Mokyr 1991).

It is important to emphasize how different the basic processes of innovation are today from what they were then. For one thing, technology in the 18th century still consisted of largely independently optimized components (Tenner).[1] If you could make a better dye or build a better water mill, you did so. Today most of our technology is constrained by network dependencies. This is not only true for obvious cases like communications, computing, and power supply, but also in the supply of parts and complements such as batteries and film. Standardization is required by consumers expecting it even when they do not need it. This makes innovation far more difficult since compatibility conditions have to be satisfied. Innovation as a coordination game starts in earnest after the Industrial Revolution with the development of railroads and the telegraph in the 1830s. It altered the innovation process in many fundamental ways.

Secondly, research and development in the 18th century were quite different. Firms rarely did any conscious in-house research. Much of it was carried out by brilliant amateurs or professional inventors, some famous like Watt, Roberts, or Bessemer, and many known only to the specialists who study them. The process of productivity growth depended, as it always does, on the thousands of small and anonymous improvements introduced by workmen on the shop floor.

But there is a deeper difference: technological progress in the 18th century was essentially empirical and nonscience based. That is not to say that there were no connections between science and industry during the Industrial Revolution—scholars have devoted their lives to studying those. The technological advances that counted most, however, were not based on a deep understanding of the physical or chemical principles involved; this does not mean that they did not work, of course. It does mean, however, that further progress was often painstakingly slow; it also means that the process of invention was often very inefficient. Simply put, if you know what things work, but you do not know why, you will not know what does *not* work, and you end up going into far more blind alleys than you would have otherwise. It also makes the timing far more difficult to understand; many of the inventions made during the Industrial Revolution could have been made much earlier or much later, it is just a matter of when the right person happened to walk into the right alley. Most important, understanding the underlying scientific principles allows one to adapt techniques to changing circumstances. Cast iron could be turned easily into bar iron following Cort's great invention of 1784, but before the basic principles of iron metallurgy were worked out in the second half of the 19th century, the finely tuned alloys we rely upon now were not available.

Technological progress in our own age is quite different. It may be seriously questioned whether we *fully* understand the natural processes we control, and serendipity still plays a bigger role than we care to acknowledge, but surely we have a much better grip on the underlying principles—indeed in a host of areas from nuclear power to magnetic resonance imaging it is impossible to see how one would have arrived there at all without knowing the science. Needless to say, we still develop and employ techniques for which the underlying principles are not even remotely understood (such as acupuncture) or which may be as bogus as the phlogiston theory on which physics relied before Lavoisier (such as Freudian psychiatry or the prediction of aggregate economic time series), but in the more down-to-earth matters we associate with production technology we are in far better shape than our forefathers were in the 1780s. For that reason, it seems unlikely that the pattern of technological development during our own Industrial Revolution will look even remotely like its predecessors.

Technological change: scale of production

There are a number of other interesting characteristics that need to be addressed if we are to make this comparison meaningful. Consider the microeconomic implications of technological change on the structure of the unit of production. The Industrial Revolution in Britain was not just the time of the "rise of the factory," it was the period in which the firm as a unit of production was born. Before about 1,800 firms, or "houses" as they were usually called, were usually commercial or financial in nature, and actual production normally took place in people's homes.

With very few exceptions, the sharp distinction between the firm and the household in manufacturing did not exist before, say, 1750. Firms might consist of merchants who put work out to domestic producers, or skilled artisans working from their own workshops who sold their goods in markets or little stores. The idea of placing all workers together in a single site became only popular during the Industrial Revolution. The social constructivist view that this was a capitalist plot to squeeze a larger surplus out of the workers notwithstanding, it seems hard to believe that the idea of a factory or "mill" in the terms of the day was not in large part technologically induced. Economies of scale at the plant level become prominent with a centralized power supply, with a decline in transportation costs, and with the appearance of such novelties as gaslighting which makes longer work hours in the short winter days of northern England and Scotland possible (Landes). Modern scholars have added to that an analysis of information costs, the growing need for standardized products and quality control in larger and anonymous markets, the need to retrain workers in an age of rapidly changing technology, and so on.

A *real* Industrial Revolution consists not just of technological innovations but of such innovations that make an impact at the level of industrial organization. They shift cost curves not only by lowering them but by changing the optimal firm scale. The so-called second Industrial Revolution, traditionally dated between 1860 and 1890 or so, reinforced this trend by creating the vast steel and chemical plants and the giant corporations celebrated by Alfred Chandler and his students. At the same time, however, it created universal electric power, which removed at least one source of economies of scale. Our own age, it seems, is on the verge of once more changing the way production takes place. The growing trends of telecommuting and outsourcing seem to suggest that at least in some industries the 200-year-old trend toward the growing concentration of workers under one roof in a rigid time schedule and under strict discipline is about to be reversed. We may be seeing just the beginning of it, and most people still have to show up in the office or on the shop floor at 8:30 in the morning, but each year fewer do. To put it as provocatively as I can, the Industrial Revolution began the separation between home and workplace; our own time may be witnessing the beginning of the movement in reverse.

Technological change: skills, human capital, and distribution of income

Closely related to the micro-issue of production scale is the question of skills, human capital, and the distribution of income. It is often argued that in our own time, skilled labor is more complementary to investment embodying new technology than unskilled labor, and so capital accumulation and technological change favor skilled over unskilled labor. While Marx and the people inspired by him thought that the Industrial Revolution was essentially de-skilling, more recent work by Williamson has turned this argument squarely on its head and claimed that the demand for skills lagged behind the supply before 1850 (Williamson).

Perhaps it should be added that "skills" do not fully capture what early 19th century employers needed: the factory labor needed to be docile, placid, and punctual. Skills may have mattered less for many of the jobs before 1870. In a recent, highly original and imaginative paper entitled

"1974," two economists, Jeremy Greenwood and Mehmet Yorukoglu, pointed out that the sharpening of income distribution inequality in the past two decades mirrors events during the British Industrial Revolution. They hypothesize that rapid technological change favors workers with high skill levels who can better adapt to the early stages of innovative cycles. Later on, when the new technology becomes more user-friendly, the demand for unskilled workers—possibly living abroad—rises.

Without necessarily buying into the details of this theory, we all know about the so-called Kuznets curve which postulates that early on in the process of growth income distribution becomes more unequal, then becomes more equal at a later stage. Whether this phenomenon aptly describes what happened during the British Industrial Revolution is still a matter of serious controversy among specialists (Feinstein). The available data, sad to say, are not as good as the modern statistics indicating a rather obvious trend toward rising inequality in U.S. and UK data for the last quarter century (much less so, incidentally, anywhere else). We therefore do not know precisely what happened to income distribution during the Industrial Revolution; what we *do* know is that the standard of living of the laboring class as measured by real wages shows very little improvement until the mid-1840s. As the income from capital and especially land increased sharply, this may seem as indirect support for a Kuznets curve.

Many may immediately see a parallel here, but again I must warn you against jumping to rash conclusions. Much of the slowness of British real wages to respond to technological change was undoubtedly due to the rapid natural growth of population and the increase of the labor supply in Britain due to migration. While factor mobility—broadly defined as the migration of capital to labor as well as the reverse—in our own days is often regarded as an explanation of the slow increase in real wages, the industrialized West does not experience much natural increase in population. In addition, living standards during the Industrial Revolution were suppressed by some fortuitous events such as harvest failures and wars. Even more disturbing to the comparison is the notion that in fact real wages are mismeasured and that there is a Boskin bias (I prefer to call it a Gordon bias) in the deflator used to calculate it. Nothing like the unprecedented increase in the quality and variety of consumer goods can be observed in Britain during the Industrial Revolution. The working class still spent most of its income on food, drink, and housing. They did buy some cotton clothes and ironwares manufactured by a new technology, but few would doubt that in its first 60 years or so the Industrial Revolution favored investment good prices over consumer good prices.

One interesting debate that always seems to arise during periods of intense technological progress is its effect on labor demand and the possibilities of technological unemployment. Do machines throw people out of work, and if so, is sustained technological change desirable at all? In a recent book named *The End of Work*, noted technophobe and economic troglodyte Jeremy Rifkin maintained that the Luddites were right and that sustained innovation eliminates jobs. Most economists tend to disagree heartily, both on theoretical and empirical grounds. Danny Blanchflower and Simon Burgess, in a recent paper, have concluded flatly that for our own time "job growth and the introduction of new technology appear to be complements rather than substitutes. The Luddites were wrong."

Wrong or not, the debate on what became known as "the Machinery Question" was even more active in the 1820s than it is now, in part due to the famous chapter that Ricardo inserted into his *Principles* in the third edition. In his

A Theory of Economic History, John Hicks showed how such unemployment could occur. Few of us would doubt that one can write a model in which technological progress could reduce the demand for labor. But "could" does not mean "did." There simply is not a grain of evidence for sustained, long-term periods of involuntary unemployment in 19th century Britain. While exact figures are not available, it is telling that hundreds of thousands of people emigrated from a country where there was little or no technological progress (Ireland) to one in which there was a lot. Again, the parallel with the experience of our time is suggestive perhaps, but not much more than that.

Technological change: globalization

One of the more hackneyed debates of our own time involves the effect of technological change on the "g-word," by now so overused as to be practically devoid of any meaning: globalization. If the meaning of globalization is the intensification of international trade and the mobility of labor, capital, and technology, it must be stressed that the first Industrial Revolution was *not* accompanied by a significant increase in worldwide trade relative to total output. The reason for that was largely fortuitous: the critical years of the first Industrial Revolution were accompanied by continuous warfare, including a quarter of a century of what might well be called World War Zero, the prolonged conflict between Britain and France that encompassed the world from the Cape of Good Hope to Cape Cod. Between 1793 and 1815, war disrupted the growth of trade, a point even noted by Ricardo.

In the years following Waterloo, what we call today globalization was inhibited by strongly protectionist policies and even laws that prohibited the export of machinery and the emigration of skilled engineers out of England. All this started to change in the 1830s with the fall in transport and communications costs and the emergence of free trade and internationally integrated factor markets. Indeed, the next 70 years were such that the *Economist* has noted that by some measures, the world in 1914 was more integrated than in the 1990s and that railways, steamships, and the telegraph were far more revolutionary than satellite links, the Internet, and other current wizardry. It then added that "what is different is that globalization in the 19th century was driven mainly by transport costs, whereas now it is being driven by plunging communication costs which make much deeper international integration possible."

That is a neat statement, but I am not totally sure it is accurate. For one thing, the statement ignores the huge improvements in communications in the 19th century due to the telegraph, which for the first time allowed information to travel at a rate faster than people, ignoring only smoke signals and homing pigeons. Postal services, though they had existed before, were reorganized and internationally coordinated in the 19th century. The penny post, invented by Rowland Hill in the 1840s, did an enormous amount for communications—compared with what was before. Its marginal contribution was certainly not less than Netscape's. More important, with the rise of literacy, people discovered *reading* as a means of communications. Newspapers, lending libraries, cheap books, and magazines were all popularized in the 19th century. Hal Varian, who has emphasized the importance of the emergence of reading as an information revolution, ranks this development right beside the Internet in importance.

Moreover, even if the premise to the statement is true, I have yet to be persuaded that these improved communications have a very high direct marginal product. The *Economist* surely is right when it points out that never in history has there been an input the price of which has declined so precipitously. But that observation's relevance is proportional to the marginal product of that input. For the time being, I suspect, better communications and cheaper information have more value in increasing consumer surpluses than in actually increasing traditionally measured output. They allow us to access information quickly and efficiently, but this information was available before, if somewhat less conveniently. An e-mail is on average 300 times faster than an airmail letter, but as editor of a refereed journal which relies heavily on this input I can assure you that it does not really change the job all that much except perhaps by saving a bit on typing and filing costs. To be sure, better communications and information do save resources on a wide array of fronts, from just-in-time inventories to the decline of commuting, but the paperless office has not yet materialized, and anyone who uses the Internet will be hard-pressed to decide whether it saves more time than it gobbles up.

Of course, we have access now to a much larger supply of information, but here we must always keep in mind that the human mind can process at most 50 bytes per second—and most of us probably do not do nearly as well. Few if any persons in our age, I venture, suffer from a lack of information—we all have stacks of unread papers, unanswered e-mail messages, endlessly unopened Internet pages, memos that are still in their brown campus envelopes, videotapes of Public TV programs which we promise ourselves to watch "when there is time." The high priority is no longer in getting the information to us but in selecting and ranking, sorting the duplicative and the false and the irrelevant from the information that we need. Like DNA, most of the information is junk.

As I noted earlier, if the communications revolution is going to have an impact beyond the conveniences of e-mail, on-line reference books, catalog ordering from home, and the wasting of time through Internet surfing, it will be in returning to the home as the location of a lot of production. What the precise effect of such a revolution would be on GDP remains to be seen—I suspect we need to revise how we measure it before we will ever know. Economists have pointed out that, for instance, electronic airline ticketing saves time, but a flight from A to B still takes almost as long as 25 years ago and the journey probably more because of security checks and congested traffic to airports. It matters more only insofar as it substitutes some form of very efficient communication such as videoconferencing for airline travel, and on the margins that may be happening, though academics and researchers still show an affinity to go to conferences and meet each other rather than reading our papers and talks over the Internet.

Modern growth theory

A different argument concerns the question of exogenous versus endogenous growth. Modern growth theory has tended to attribute a much larger portion of economic growth to endogenous factors. The sense of economists is that they prefer models that do not rely on unexplained and exogenous changes, replacing them, as one recent paper has it, "with explanations of historical experience" (Greasley and Oxley; Crafts and Mills). Endogenous growth theory argues that technological progress is really produced by the system, either by people getting better skills and education or by some capital good that brings it about. This view implies, as everyone here surely knows, that the time series properties of industrial output will be quite different than the old exogenous growth models in which economic growth triggered by exogenous technological shocks eventually reverted back to a steady-state rate. In these models the output series does not exhibit persistence to shocks; that is, it does not possess a unit root.

An interesting debate has developed in the pages of the periodical literature on whether the time series of industrial output in Britain between 1780 and 1914 exhibits a unit root, the argument being that trend versus difference stationarity presents a strong test of the kind of process that generates economic growth. The idea is that if the series can be shown to be difference stationary, economic growth will be "endogenous" because a production function of the Romer-type exhibits persistence and does not revert back to its trend.

The econometric argument, thus far, is inconclusive. Nicholas Crafts has argued that at least some part of the growth was exogenous and that trend stationarity cannot be rejected. Others have reexamined their data and concluded the reverse. One problem—revealing my historian's roots—is that too much ink is spilled on devising the right test for persistence and too little, some would say none at all, attention to the underlying data. For a wide range of goods the quantity indices used by all participants in the debate consistently understate the rate of growth and so tend to be biased. It is not clear to me whether such a bias would increase or decrease the likelihood of rejecting the unit root hypothesis, but it does mean that many of the tests have been run on flawed data. While a few products such as cotton and coal are thought to be of more or less uniform quality, improvement in the *quality* and nature of capital goods, from steam engines to cattle to street lights, makes the series compiled by Crafts and others a source of concern. Performing a conclusive unit root test on consistently measured output data is difficult enough, as my colleagues Christiano and Eichenbaum pointed out years ago—doing so with output data which are not and could not be measured in a consistent way strikes me as demanding too much credulity-suspension (Christiano and others; McCallum). To be sure, one can do such analyses on disaggregated series, and here too there is some evidence of persistence. Either way, in this game an ounce of data is better than a pound of econometric technique.

Moreover, exact economic meaning of such persistence is still rather unclear. It means that a sudden technological "shock" due to an invention of sorts will disturb the rate of growth of output forever, which is what one would expect if the production function exhibited increasing returns. But what if technology is itself a Markov process in which present values depend on the past? In that case what looks like output responding forever to a sudden technology shock is nothing but output responding to new knowledge building on itself. The point I am trying to make here is a deeper one than just a technical critique: It is that beneath the changes in technology there are changes in human knowledge not readily observed in time series. That knowledge does not have to be scientific, as I argued it was not. But there was an accumulation of experience, of tricks, of practical engineering knowledge of "what works," "what material is suitable," and "what tool is appropriate here." We know, more or less, how this knowledge was transmitted, diffused, improved upon, and eventually discarded. Very little of it had anything to do with formal schooling, least of all in Britain.

While new growth theorists regard knowledge creation as "endogenous" and thus demanding explanation, I doubt whether just trying to approximate them as human capital, education, schooling, or any of those proxies will do the job. The knowledge we are talking about was largely concentrated in the crania of a few thousand of the most brilliant engineers in the British Isles, men such as Smeaton, Brunel, Watt, Trevithick, Stephenson, and so on. "Exogenous" or not, these men carried the Industrial Revolution in their heads. Can we find a proxy variable to endogenize them? Or should we? How is such knowledge generated, tested, and chosen? How do we map the set of this knowledge onto the domain of useful techniques? The difficulty with building knowledge into the production function is transparent; knowledge cannot be quantified or measured readily, but it is also not subject to any obvious law of diminishing returns. We should remind ourselves of something we of course all knew—the explicit inclusion of useful knowledge as an element in economic growth wreaks havoc on neoclassical theories, be they old or new. The hard truth is that the new growth theory, much like the old growth theory, has tried to write the history of technological progress without paying much attention to the economic history of useful human knowledge. Writing such a history would be far more challenging and difficult than running unit root tests or employing Kalman Filters on cotton output series that have been around for half a century.

We have only the most rudimentary ideas on how knowledge changes and technical knowledge is no exception here. What is more, this is hardly a field in which economists have a comparative advantage. New knowledge is not combined with old knowledge in an obvious way. It does not necessarily add on to old knowledge nor wholly replace it. It is a system in which chance and necessity, luck, and intentionality play a rather complex game, the outcome of which is neither predictable nor wholly understandable. Unlike any other input, knowledge does not even obey the laws of arithmetic. Technical knowledge forms some kind of system that evolves over time, or better yet, coevolves with other forms of knowledge such as science and business administration. Changes in it are in many cases responses to economic stimuli, but they are above all the results of new ideas and inspirations occurring to people involved in production, extensions, and recombinations of things they already knew, somehow different and therefore new.

To say that changes in technological knowledge are "exogenous" does not mean that they rain down on us like manna from heaven and that there is no way we will ever be able to understand them. It only says that in the creation of new technology the exact process that transforms inputs into outputs is far more complex than economic science currently can deal with. Yet we have a variety of attempts to understand it, from Martin Weitzman's idea that any new idea is just a combination of old ideas and so their number will expand at an ever increasing rate, to attempts such as my own to use Darwinian selection models in understanding why certain new techniques were retained and others rejected (Mokyr 1995).

The alternative approach to test for endogenous growth is to hammer on the residual. Thus if endogenous growth is to be confirmed, we need to specify the correct inputs and the Solow residual will disappear. Technology is still important, but it is no longer identified by the unexplained residual, the measure of our ignorance. Instead it is proxied by new capital, learning, measures of R&D input, and other nice measures that economists feel should relate to technological progress. Correctly identifying human capital has been important, but the evidence does not suggest that it bears a one-to-one relation with technology: we need to know *what* is being taught in the schools, how efficient the teaching is, and how students translate what they learn to better production techniques.

Equally important, productivity is often affected by things learned elsewhere. In that regard, neither the British Industrial Revolution nor the last 20 years give us much to hang on. The early

British factory workers were, by all evidence, not better educated or schooled than their forefathers a century or two earlier. Insofar that literacy went up, it seems to have been a consequence rather than a cause. Technical skills were acquired on the job, through apprenticeship and experience. The great inventors of the Industrial Revolution, from Arkwright and Watt down, learned what skills they possessed as apprentices, not something that gets captured by traditional measures of human capital. Indeed, a priori reasoning suggests that heavy investment in training might even be an impediment to sustained technological progress, because the productive sector commits to a particular technique, and then has to "unlearn" it when something else has been devised to replace it. In an age of rapidly changing technology, perhaps the best skill that can be taught is how to learn (and unlearn) quickly, something that macroeconomists seem unusually good at. This, however, is hardly what we mean by standard measures of human capital.

Technological leadership

Finally, I should like to say something about the connection of the Industrial Revolution with the so-called convergence literature. If we go back for a minute to the new growth theory, it is readily realized that it implies in its crudest form a divergence of economic performance. The reason is that Romer models depend on some form of increasing returns, implying that the rich get richer and the poor get richer too, perhaps, but more slowly so. I am not going to discuss the voluminous literature on convergence here, but I should like to point out that for one, Great Britain stands as a grand exception to any such rule. It is one of the best examples enabling us to examine a case of long-term convergence (De Long). During the long reign of Queen Victoria, Britain was the undisputed economic and technological leader of the world, the country where the action was, that other economies observed and studied and envied and tried to emulate. Today, its GDP is slightly below Italy's and soon it will be surpassed by Ireland's at current growth rates. Its leadership is a laughing stock.

I am not sure whether this one observation proves anything, because other early industrializers in Europe such as Belgium and Switzerland have experienced quite different fates. It does serve, in my view, as a good illustration of what I have called "Cardwell's Law," the empirical regularity that technological leadership tends to be hard to sustain and normally ephemeral (Mokyr 1994). Mind you, technological leadership is not the same as GDP or living standards, of course, and in any event a country may be a leader in one product and a follower in others. All the same, the following general observations are true for Britain for the period between 1760 and 1914, and I am leaving it as an exercise to compare this with our own time. First, British technological leadership did not mean that the major breakthroughs were necessarily achieved by Britons. In a dozen important cases, the critical breakthrough was made elsewhere. The British, however, had the capability of adapting, implementing, and then exploiting novel ideas wherever they came from. Great imitators make great inventors, one historian has remarked, and I think there is an important truth in that observation. Second, the new industries developed in Britain during the Industrial Revolution and its aftermath eventually lost their technological dynamism, and while they never became completely ossified, there was just so much you could do to improve cotton spinning machinery or steamships. Third, Britain had considerable difficulty in switching to new industries that became the technological frontier after 1860. That is not to say that they failed altogether, but by 1914 they had lost the edge in chemicals to Germany, in automobiles to the United States, and were a distinctive follower in electrical engineering, mass-produced machinery, and food processing. What went wrong? And are there lessons from it?

The main lesson from this tale is that technological change really is not like any other input. As I keep stressing, it depends a great deal on the formation of knowledge behind it. But it also depends on institutions and political economy. To put it differently, the decision-making institutions in each economy create an environment in which technological progress can either thrive or wither. It may seem trivial to state that society ought to be hospitable to new technology which is a cheap way of increasing economic welfare, but the historical experience indicates that few societies have followed this advice. The amount of resistance against technological progress that we observe through most of history is such that at times one wonders how new technologies emerged at all. To a large extent Britain became a victim of her own success: the industries on which she built her success established certain technological power structures, both among the firms and among labor unions. These power structures set up a variety of political and social barriers after 1880 or so, some of them obvious and some quite subtle and insidious, against innovations. These barriers were not impermeable, and there are instances in which they were breached. All the same, they became an effective obstacle. If Britain lost her technological primacy it is because she continued to produce ships, cotton, engines, fixtures, and machines in old-fashioned ways, and because she was unable until very late to create the kind of formal education in which engineers and skilled workers could be taught not only to do things right but to keep updating such knowledge over their work life.

Let me conclude by reflecting about what we can and cannot learn from such historical analogies. We certainly can identify periods of rapid technological change and realize they belong to a class of historical phenomena. At the same time we should realize that the classical Industrial Revolution was in many ways a *sui generis*. Perhaps that is what future historians will also say about the 1980s and 1990s. They, too, however, are likely to write history in their own image conditional on their own present—and who can say what that will look like? As it says in the Talmud, "Ever since our second Temple was destroyed, the art of prophesy was given to the fools"—surely a wisdom not wasted on a meeting of macroeconomists.

ENDNOTES

[1] See for instance Edward Tenner. There are a few exceptions to this rule: Open field agriculture was clearly a complex system in which individual components such as crop choice could not be optimized independently of the whole. The same is true for the sailing ships, a complex entity in which rigging, masting, hull, and steering all depended on each other and jointly determined the parameters of the vessel.

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