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Thinking About Technology and Institutions

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I. Introduction

Economics, Oscar Wilde is reputed to have said, is so easy that even a parrot could learn it by mindlessly repeating the words "demand and supply." But as all Econ majors know, the seemingly simple diagram can actually lead to some rather hairy problems with counterintuitive solutions. The same is true for other issues in economics. At first glance, it seems obvious that technological progress leads to something we can call "improvement" through enhanced living standards. What could be a more straightforward insight than to argue that human ingenuity supplies us with the ultimate "free lunch," the capability to have at the same time more guns *and* more butter? The 20th century has been a century like no other in human history. In terms of our material welfare—our ability to extend the length and improve the quality of human life and to reduce the many material discomforts that accompany poverty, malnutrition, disease, and uncertainty—the 20th century can boast achievements that exceed those of the total sum of all history before 1900. This simple-minded version of economic growth posits that technological change is the source of prosperity, wisdom, and bliss.

The story here, however, turns out to be more complicated than the freshman courses suggest. For one thing, if technical knowledge is at the source of most modern wealth, why doesn't everyone have it? Knowledge is a pure public good; by giving some away, those who have it do not have less. If the main reason Germany is richer than Zimbabwe is that the Germans know things that Zimbabweans do not, why don't they just teach them? The answer that economists have traditionally given is that Germans are better educated and trained, and are thus more capable to use and absorb the technical knowledge. In the lingo of economics, human capital and technology are complementary. But this argument does not seem to hold up very well either. If human capital was the limiting scarce resource in poor countries, it ought to have a high price there, and we should see German and Japanese engineers traveling to Zimbabwe or Paraguay. Such a flow of human capital can readily be seen in early 19th-century Europe when English and Scottish engineers traveled to the European continent and taught the locals what the British had learned during the first Industrial Revolution.[1] But today this diffusion is not happening. In fact, highly educated engineers and physicians from Asia and Africa settle in the West if they can. If poor countries are so low on human capital, why is there a "brain drain" flowing *out* of these countries? A possible answer is one of complementarities *within* rather than *between* production factors. In other words, trained and skilled people are most productive when they are with other people like them. For example, an Indian computer engineer will be more successful (and thus richer) if he works in Santa Clara or, if he stays in India, in Bangalore, because in Silicon Valley and Bangalore, there are people that he can swap ideas with and learn from. Significant complementarities mean that there could be more than one outcome, or to use the "economese" expression, there could be "multiple equilibria." If the elements that make a nation rich are complementary to one another, the implication is that those that do well will do even better and those that do poorly will do worse and worse, at least in relative terms. For every poverty trap, there is a riches trap. Fairly small differences in initial conditions could lead to historical bifurcations.

The data bear this story out. The basic fact that needs explanation has been whimsically referred to by economists as "twin peaks."[2] It is the observation that the countries of the world seem to be falling into two groups: the rich industrialized countries with high incomes, and the poor countries that are falling further and further behind. Income per head tends to be bimodally distributed. This is, of course, a rough generalization. There are always some countries in between, but the sense is that such countries are either on their way up to join the club of the rich or on their way down to join the bottom-dwellers. But what, really, causes such divergent historical trajectories? Books with titles such as "How the West Grew Rich" or "Why Some Nations are Poor and Others are Rich" keep coming out.[3] Culture, institutions, luck, natural resources, even climate (or distance from the equator) have all been proposed. Our problem, it seems, is not too few, but too many explanations.

II. Institutions versus Technology in Economic Growth

What, then, accounts for this pattern? Basically, economies can grow for three reasons.[4] One is thrift. If they save a lot of their income, they accumulate more capital, meaning that in the future they will have more. With each worker having more equipment and tools to work with, he or she is more productive and the economy grows in per capita terms. The problem with this story is that of diminishing returns. As the economy has more and more capital, each addition contributes less and less, and the payoff for savers declines. Much of the earlier formulation of neoclassical growth theory in the 1950s by Robert Solow and his followers was based on the growth in the capital-labor ratio.

The second mechanism of growth is technology, sometimes referred to as "Schumpeterian Growth." We need to keep in mind that technology is always and everywhere knowledge. It is not the artifact, not the tools, not even the pages of the manual. It is what is in people's minds. Technology is, however, a very special and specific kind of knowledge. In its basic form, technology consists of instructions or recipes on how to make things or supply a service. But these instructions are based on background knowledge of natural phenomena and regularities that can be exploited to yield these instructions. As people learn more about nature and the physical world, they can write better instructions and enjoy better ways to manipulate nature — that is, to produce. We have come to associate such background knowledge as coincident with science, but in reality it is much more. It is a vast set of facts, phenomena, and regularities about the natural world known to us. For example, the discovery of the New World by Europeans added a piece of background knowledge to European societies, namely, that there was a large landmass between them and Asia, and the new navigating instructions were based on this knowledge. It is important to note that the generation of new technology is rarely costless. In modern society, the costs of Research and Development should be factored in as an input into the function that produces new technology. Some economists have gone so far as to view new knowledge as just another input produced by and in the system, subject to more or less the same rules as any other.[5] Historically, however, the costs of technological change have been minuscule compared to its benefits even if we take into account the hidden costs of unsuccessful searches.

Innovation or new knowledge that is useful for productive purposes has some odd characteristics. It does not seem to satisfy most of the attributes that make for commodities that can be traded in markets. The first and most obvious characteristic is that techniques are unquantifiable and do not even satisfy the laws of arithmetic: one invention plus one invention may equal just one invention if the second replaces the first, or they may equal more than two if the two techniques can be combined into a third one. They can be substitutes or complements for existing technology. Thus, inventing the glider plus inventing the internal combustion engine did not just equal those two but combined to produce the airplane. The second characteristic, already alluded to, is that new technology, like all new knowledge, is a public good, and that more people acquiring it does not diminish what is left for others. This means that for first-order efficiency, it should be given away freely. Doing so, however, means that there is no real incentive for would-be inventors to allocate their talents and efforts toward the hard and frustrating work often involved in Research and Development (R & D). To make innovation attractive, someone has to be given the rights to make scarce something that inherently is not. This, in a nutshell, is the dilemma of intellectual property rights. Even if we could assign such rights perfectly, however, there remains the further problem that most of the benefits—80 percent, in a recent calculation—accrue to others beside the inventor. Unless inventors are very altruistic beings, societies will tend to underproduce new knowledge.

To be sure, institutions exist to some extent to reward people who make such contributions to society beyond the purely monetary. The French kings under the pre-revolutionary *ancien régime* awarded medals and pensions to persons who had distinguished themselves in their service to "the Kingdom."[6] Today, we do the same with Nobel prizes, national medals, and presidential honors for unusually distinguished inventors and scientists. Fortunately, moreover, money and honors are not the only things that make researchers and innovators click. Such external motives as curiosity, a desire to impress one's peers, a dedication to one's nation or humanity at large, or just a single-minded obsession with an unsolved problem—all tend to reduce the built-in propensity of society to *underproduce* useful knowledge, but there is no sure way of knowing whether this fully bridges the gap to make the social rate of return on R & D equal to the private one. Most evidence suggests that it does not, and that knowledge is still underproduced.

The other problem with innovation as a market-produced commodity is that its supply curve is not well defined. It is easy to say that R & D is sensitive to market demand and that the production of new technology has become, to a large extent, routinized and inevitable. But what technology will emerge? The constraint on new technology is in our minds. It is ultimately what we know how to do and what is beyond us because we simply do not know enough. It is easy to think about many inventions that would have made someone hugely wealthy and done society a lot of good, but which have not yet come forth, largely because society does not know enough. Examples include an effective means to kill harmful insects without killing other living beings; cures for a host of diseases from the common cold to AIDS; laptop batteries that will hold a charge for the length of a flight to Tokyo; controlled nuclear fusion as a source of cheap energy; or a way to gorge down huge meals without becoming obese. The failure of such techniques to emerge despite huge research efforts indicates that the growth of technology and that of economies using them is governed not just by market forces but also by the evolution of more abstract human knowledge underpinning these techniques.

It seems proper to ask what we can possibly mean when we say that "something is known." The only possible interpretation of such a statement is that *at least one person* included in the society knows.[7] But from an economic point of view this is not terribly meaningful. If one person has some knowledge but does not share it with anyone, its usefulness will be limited. What matters above all is the question of what access those who could apply this knowledge have to it? What is the cost of acquiring it? These access costs are in part determined by technology and by the costs of storing, reproducing, and transmitting knowledge. Inventions such as writing, paper, printing, the telegraph, and so on, affect these costs. In part, however, they are determined by the culture and institutions that govern the communications between scientists and experimentalists on the one hand, and the farmers in the fields and the technicians in the workshops who might use it. These flows of information are essential if an economy is to grow as the result of inventions.

The third way in which economies can grow is through institutional change, sometimes known as "Northian Growth."[8] Institutions are the rules of the economic game played by society. They include formal rules (laws, regulations) as well as informal ones (customs, conventions, manners, traditions), and the penalties for their violation. The general idea is that in order for an economy to grow, it needs to become more efficient, and that the main way economies grow is through the development and expansion of markets. But markets are often limited and incomplete because it is costly and risky to operate in them. Institutions are the mechanism by which such transaction costs are reduced. To most political scientists and historians, this argument sounds so obvious and commonplace that it barely needs reiteration. But the mechanisms by which institutional change leads to economic growth are often left unspecified. Let me propose a number of quite different stories one can tell here.

The best-known mechanism through which institutions facilitate economic growth is through the support of commerce and trade. Economists since Ricardo have delighted in showing how mutually advantageous exchange can benefit both sides, a classic example of growth occurring through a positive-sum game (sometimes referred to as "Smithian growth"). What appears today to be so obvious to all but Congressman Gephart was, in fact, misunderstood by politicians and philosophers until the great minds of the Scottish Enlightenment, Adam Smith and David Hume, pointed it out. But to have such trade, one needs more than good transportation and communications. It requires the ability to write contracts that are enforced either by a formal set of laws or by informal customs such as trust and reputation. It requires above all curbing the opportunistic behavior of dishonest or violent economic agents (including, of course, pirates and highwaymen, but also rulers, generals, and priests in charge of society). The idea that the "rule of law" ensures the realization of the gains from trade has become commonplace. What is perhaps less obvious is that markets and exchange depend greatly upon solutions to problems of asymmetric information. Employers cannot watch their employees continuously, so the employees know more about how much effort and skill they put in. Customers cannot examine the full characteristics of the product or service they buy. Stockholders have but limited knowledge of what CEOs really do and depend on the same CEOs to tell them. The more these so-called principal-agent issues can be resolved, the more efficiently the market mechanism can operate and the faster an economy can become wealthy.

Before the Industrial Revolution of the later 18th century, much, if not most, economic growth was spawned by such trade-generating mechanisms. Medieval Europe, Song China, and South Asia experienced considerable economic growth due to the expansion of markets and long-distance trade. Yet most of the gains must have been due to the operation of local markets, growing trade between neighboring villages and towns, and the specialization in farming and crafts that this trade implied. Recognizing this allows us to define the concept of economic modernity with some precision. The most important change over the past two centuries following the Industrial Revolution is not only the huge expansion of such trade, but the growth of exchange between perfect strangers who may never trade with one another again.[9]

Historically, however, economic systems whose wealth was based on local and long-distance trade have been quite vulnerable to political shocks. The wealth of the Roman Empire, based on the legal and political cohesion of the empire, is a prime example. The loss of the Mediterranean to the Muslims in the 7th century caused much of the international trade of Europe to cease, and helped plunge Europe into a few centuries of destitute economic backwardness.[10] The Thirty-Years War in Germany in the first half of the 17th century reduced most local markets to ashes and set the country's economic development back by a century or more. The global economy that emerged after 1870—thanks to the train, the steam ship, the telegraph, and the gold standard—was abruptly terminated in 1914 and took decades to recover.[11] Even today, it is felt that a few determined terrorist acts could well inflict enormous damage to the flow of goods and services across the world. The need to inspect every shipping container for unconventional weapons, for instance, would impose intolerable costs and delays on the effectiveness of trade.

In addition to those institutions that make markets for *goods and services* work properly, there are those that make the market for *factors of production* work well. Each worker that is moved from a low productivity job in the countryside to a high productivity job elsewhere increases output, and such flows can generate a great deal of growth. For this to happen at a continuous rate, institutions have to be in place that may reallocate factors of production to those who can use them most efficiently. Smoothly functioning real estate markets (through well-defined title registration systems) are an example of institutional support for the better allocation of resources simply because they would allow those economic agents who can best take advantage of a resource to exploit it. Through much of history, such markets have done a poor job, and farmers of vastly differing competence and ability have been tilling the land side by side, although economic efficiency would suggest that the more competent farmer buys out his neighbor. Labor mobility, financial institutions, well-organized insurance markets, and the free flow of economic information are very much a part of growth. As Hernando De Soto stressed in his widely discussed book, just rearranging and properly assigning the property rights on real estate may lead to a great deal of efficiency.[12] One reason is that well-defined property rights and enforced contracts are needed to secure collateral on loans. But credit markets need a lot more institutional support than just the proper assignment of formal title in order to work correctly. Rules that ensure that the information put out by borrowers (or those who issue equity) is reliable and trustworthy, and that those in charge of verifying it are themselves worthy of trust, are clearly part and parcel of it. (Enron shareholders would wistfully agree.)

Institutions also determine the payoff to human effort and talent. Nations have finite supplies of talented, original, and ingenious minds. Whether such individuals will become mafia chiefs, military leaders, priests, philosophers, or entrepreneurs and engineers is determined by the payoffs that society sets up for these people. Recent research has recognized that a dollar made in what is known as rent-seeking activities, such as insider trading, manipulating regulators, and ensuring monopolies through raising entry barriers, as well as extortion, corruption, and kickbacks, is just as much a dollar as one made in developing new markets and products. From the point of view of the economy, however, entrepreneurial activity is enriching, while rent-seeking is impoverishing. The choices of where to allocate their talents and energies are made by economic agents on the margins, determined by the payoffs and penalties set by institutions.[13] One such institution, of course, is "culture," or, better put, *ideology*, which claims that some activities are morally superior even if their payoff is not quite high enough to allocate the right amount of resources to this activity. Public service is viewed as in some sense "good" in order to make up for the low pay compared to alternative occupations.

Institutions have in recent years made a triumphant comeback to the mainstream of economics after having been banished for many decades to such unspeakable places as sociology departments. Economists increasingly stress that the rules of the economic game are themselves the outcome of complex interactive multiplayer games, and if game theory predicts anything, it is that in such settings many different outcomes are possible, and therefore we should not be surprised that different historical circumstances have produced very different institutional outcomes, with obvious economic implications.[14] Even within the industrialized West, the legal and social environment in which the economy operates differs greatly. Switzerland, Japan, and the United States have quite different institutions, yet all have been amenable to generating and absorbing advanced technology. Unlike Tolstoy's observation that all happy marriages are the same and only the unhappy ones are unhappy in their own unique way, not all roads to economic prosperity have followed the same institutional pattern.

To summarize, we have three ways in which an economy can grow. We can carry out mental experiments to have one without the other two. It is easy to show, for instance, how in an economy with a completely fixed technology, we can have growth simply due to better allocations and gains from trade. On the other hand, even with fixed institutions, some inventions can suddenly augment the economic potential of a society. But history is rarely kind enough to allow us to experiment with such "pure" forms of economic change. Only models allow us to do that. Models are simplifications that strip away much of reality to focus on a particular aspect in order to establish causal connections. History is a confused and complex mess. Unfortunately for theorists and contrary to the protestations of the postmodernists, history—unlike models and metaphors—is real.

III. The Beginnings of Modern Growth

The economic history of the twin-peak syndrome seems to have started in Europe at around 1750.[15] Until that time, economic growth had been slow, spasmodic, and in some cases reversible. Although by 1700 a few enclaves of wealth and prosperity had been established in the great commercial and manufacturing centers of the United Provinces and England, most of Europe still consisted of a poor rural class, desperately trying to eke out a living between an unproductive agriculture and an unmechanized manufacture. Europe had experienced periods of growth, but with a few exceptions these had fizzled out. Perhaps the comparison between Western Europe and the richest parts of China in the Yangtze valley or Japan is misleading, as some have argued, since living standards in Africa and Oceania were clearly lower than anywhere in Eurasia.[16] But Europe as a whole was not as rich as the Netherlands. In southern, central, and eastern Europe, the vast bulk of the population was rural, and as late as 1750 lived on the verge of subsistence. A good way to characterize the economic history of the "big picture" is to say that each episode of growth ran into some obstruction or resistance that put an end to it.[17] Growth occurred in relatively brief spurts punctuating long periods of stagnation or mild decline. After such episodes, the economy asymptoted to a higher steady state, creating something of a "ratchet effect," but growth could not be sustained.[18]

What explains this dynamic pattern? Until 1750, the slow economic growth in the world can be explained in terms of negative feedback effects. This occurs when the result of an input tends to weaken the supply of that very input, so that whatever movement occurs in the relevant variable eventually settles down. Negative feedback is *stabilizing* in that change tends to produce forces that weaken the forces of change and eventually cause it to come to an end. These feedback mechanisms in the economies of pre-Industrial Revolution Europe (and other areas) worked through a variety of different channels, but they all resulted in a self-negating pattern of economic growth. In truly dialectical fashion, economic expansion created the causes of its own demise. Thus, inexorably, each period of economic expansion was followed by a slacking off and sometimes a reversal of economic growth. Three basic mechanisms account for these feedback effects.

One such mechanism is standard Malthusian population dynamics, still taken quite seriously by many scholars as a good description of pre-modern population change.[19] When income per capita rises, Malthusian models predict a population increase since fewer people die from starvation and disease, and perhaps people become more fertile when they are wealthier. Such a population increase will at some point run up against some fixed resource, often believed to be food supply or fertile farmland, but quite possibly some other resource such as energy supply or clean fresh water. The fixed physical environment creates what economists call "concavity" in the production function that, together with the Malthusian response, guarantees stability.[20] The existence of Malthusian negative feedback does not guarantee stability. Overshooting can occur, in which overpopulation can trigger a mechanism that wipes out far more than the number of people needed to restore demographic equilibrium. Many scholars have seriously questioned whether this model is historically accurate.[21] The best answer I can give is that its application is historically contingent upon the particular situation. If all other things are equal, including the stock of human knowledge and the infrastructure of the economy, the concavity of the production function is simply ineluctable. But if these other things are not only not fixed but actually a sufficiently steep positive function of population size (a rather strong condition), we can see how these Malthusian constraints may be overcome systematically and eventually lose all relevance. Thus, it has been argued that invention itself is a function of population size and density, since sparsely populated areas do not generate enough organized and shared knowledge to make technological progress possible. Whether that kind of relation can be extrapolated into higher and higher densities, as Julian Simon has argued, seems more doubtful.[22]

A second type of stabilizing mechanism deals with the limitations on human knowledge. Techniques are supported by background knowledge about natural regularities in the behavior of the physical world and the properties of materials, energy, machines, plants, and animals. Before 1750, the bulk of the techniques in use anywhere in the world rested on very little understanding. Production processes were based on knowledge that certain techniques worked and others did not, without much understanding of why and how they worked. What was known had largely been discovered serendipitously or through trial-and-error experimentation. It is not an exaggeration to say that most technology consisted of engineering without mechanics, iron making without metallurgy, farming without organic chemistry, animal breeding without genetics, water power without hydraulic theory, food preparation without nutritional science, and medical practice without physiology and microbiology. This very limited and essentially steady state base constituted a "fixed factor" that lent the system a kind of concavity that we normally do *not* associate with knowledge. Great inventions were almost inevitably followed by a process of trial-and-error improvement that soon fizzled out and stabilized at a technological level far below what could have been attained with a little better understanding. This may sound somewhat patronizing in the "if they only knew what we know" mode, but no such attitude is intended. All the same, we need to realize that it is precisely the growth of what societies knew that loosened the constraints on economic performance.

There can be little doubt that knowledge has imposed such constraints on all societies, including our own, and that we can see how when these ceilings were hit, growth was checked. The growth of agricultural productivity due to the adoption of convertible husbandry in the 17th century increased agricultural output, but despite improved crop rotation, the growth of output slowed in the 18th century.[23] The techniques used in metallurgy, printing, shipbuilding, mining, and water mill construction (which had all advanced remarkably in the 15th and early 16th century) seem to have stabilized for centuries, simply because the knowledge base had been exhausted. The point is not just that the operators of techniques (that is, producers, artisans, farmers) themselves were unaware of the principles of physics and chemistry that underlay the techniques they carried out; that remained true much later and is largely the case in our own time as well. The point is that *nobody* knew. Operational techniques soon reached ceilings that might have been broken had someone understood a bit more as to *why* they worked. The processing and manipulation of materials, the use and design of instruments and machines, the utilization of energy, and the raising of edible crops and animals were little informed by theory because there *was* little theory. What this implied was that even when certain techniques were known to work, it was exceedingly unlikely that they would be constantly improved, adapted to new applications, or combined with others to form novel ones. Even those groups of people that engaged in systematic searches for better techniques made few advances, simply because they did not know why things worked, and hence could not predict what would not work. Alchemists (scientists in search of the Philosopher's stone, the fountain of youth, and perpetual motion machines) spent huge amounts of time and resources exploring what we know today to have been blind alleys.[24]

The third source of negative feedback is institutional in nature. When economic progress took place in a society or region, it frequently generated a variety of social and political forces that ended up terminating it. Above all, the prosperity and success of any society or town led to the emergence of predators and parasites in a variety of forms and guises who eventually slaughtered the geese that laid the golden eggs. Tax collectors, foreign invaders, pirates, and rent-seeking coalitions (such as guilds and government-enforced monopolies) eventually extinguished much of the growth of northern Italy, southern

Germany, and the Low Countries.[25] The great commercial expansions of the 16th century were followed by the rise of mercantilism, which, in one interpretation, was little more than an attempt to capture the rents generated by growth. What was not fully understood was that trade was not a zero-sum game, and thus an attempt to increase a share had the inevitable result of reducing everyone's income. The *Wealth of Nations* was in part an attempt to make this basic point. It seems reasonable to surmise, for instance, that much of the economic decline of Iberia in the 16th century and that of the United Provinces in the 18th can be partially explained by such mechanisms. Perhaps the most insidious of these forms of negative institutional feedback was organized resistance to new technology by vested interest groups, a phenomenon still quite visible in our own time.[26]

IV. A New Interpretation of Modern Growth

One way of looking at modern economic growth using this simple framework is that these three negative feedback mechanisms have been turned around and become positive. That is, we have moved from a world in which success bred failure to one in which success breeds more success and failure breeds more failure. Such models give rise to growing disparities and "twin peaks," since they imply either what economists call multiple equilibria or, in some extreme cases, perhaps no equilibrium at all. In such a world, luck plays a bigger role and history's path is determined by contingency as much as by deterministic forces that social scientists can analyze.[27] The AIDS epidemic, much like the Black Death, may have a bigger impact on many economies than all the social forces of production rolled into one.

But even when the forces at work are not due to accident, the destabilizing influence of positive feedback can be discerned. Let's take the example of *demographic* negative feedback first. In the old demographic regime described by Reverend Malthus, a rise in income per capita led to increased fertility and reduced mortality, thus to more mouths to feed on the same land and declining income. But in the modern world, this has been turned around. Economies that are rich and industrialized have sharply reduced demographic growth, preferring a few well-educated, high-quality, and happy children to large families. In many of them, in fact, birth rates have fallen beneath replacement rates. Poor countries, at least for the time being, are still subject to growing populations. If they were to grow as rich as the industrialized West, world population could well take a sharp nosedive.

To turn to *technological progress*, the limitations of the knowledge base also no longer impose as much of a constraint on the development of the economy as before. The limitations of primitive techniques have slowly made way for a better understanding. Modern science has made us understand, at least to some extent, *why* the techniques we have work, and how we can build on them and improve them. Farmers today fertilize the soil understanding soil chemistry and breed animals understanding genetics, which makes both processes more effective, even though neither of them is a modern invention. Not all production techniques are equally well understood, but in many areas it is clear that an engineer today has a far better grasp of the physics and chemistry at work than his forebears did in 1750. What this does for us is exclude a large number of avenues that are known to be blind alleys, and so research is made vastly more efficient. All the same, by the standards of efficiency employed by economists, the search for new useful knowledge remains unbelievably wasteful. New inventions cannot be custom ordered according to need.

Of course, there are still many things we would like to do and cannot—and an infinity of things that are in principle feasible, which we do not even know that we do not know. It is also quite plausible that the science of the 21st century will be sneered at by future scientists, as we do at phlogiston theory and the notion of miasmas. All the same, at least in the sense of its ability to perform in the economic arena, our knowledge has experienced a huge advance in the past centuries.

When did all this begin? There is a long and inconclusive debate between specialists on the role of the Scientific Revolution of the 17th century in bringing about the Industrial Revolution of the late 18th century.[28] Be that as it may, the period between the Industrial Revolution and the late 20th century has given rise to a strong complementarity between science and technology that has replaced the old model of production. Science and technology affect one another in complex ways. The most obvious story is that science prepares the ground for technology. The "standard linear model" has long been abandoned in which scientific discovery precedes inventions, and technology is nothing but applied science which itself stems from "pure" science. Technology leads to more science just as much as science provides the knowledge base for new technology. It has created a positive feedback circle the likes of which has never been witnessed.

The feedback from technology "back" to science works in a variety of ways, including:

1. Focusing Devices

In a classic article first published in 1969, Nathan Rosenberg coined the concept of "focusing devices."[29] Technology poses well-defined problems to engineers and scientists, and focuses their attention on some areas that turn out to be fruitful for further research. Techniques that are found to be working, for one reason or another, raise the curiosity of scholars: Why do they work? What are the principles behind them? It influences the research agenda of society. If such research is undertaken, then it enriches the base upon which technology rests and at the same time raises further puzzles. Many classic examples can be cited of such compulsive sequences, none more famous than the steam engine, which became operational in 1712 with the first Newcomen engine. This spurred a great deal of research into the laws governing energy efficiency, leading eventually to the development of thermodynamics. Thermodynamics, in its turn, could suggest how to make the engines more efficient as well as the limits to their efficiency.

2. Artificial Revelation

The other channel through which the feedback from technological knowledge to abstract knowledge works, especially stressed by Derek Price, is through research tools, instruments, and laboratory equipment.[30] The basic point is very simple. Our senses limit us to a fairly narrow slice of the universe that has been called a "mesocosm." We cannot see things that are too far away, too small, or not represented in the visible light spectrum. The same is true for our other senses, for the ability to make very accurate measurements, for overcoming optical and other sensory illusions, and for the computational ability of our brains. Technology helps us overcome the limitations that evolution has placed on us and learn of natural phenomena that we were not designed to see or hear.[31] Without sophisticated computers, most branches of modern science would today be unimaginable. And the same is true for a variety of instruments, from precision clocks to fine scales and measuring instruments, without which experimental science is impossible.[32] Many such inventions were quite adventitious, as Price has noted.

3. Rhetoric of Knowledge

A third way in which technology "feeds back" into science is through the rhetoric of technology. Techniques are not "true" or "false." Either they work or they do not, and thus they help confirm or refute the knowledge on which they are based. Science is consensual, and mathematics and experiment are used to persuade others to accept propositions. Nothing, however, persuades us that knowledge is true as well as the day-to-day demonstration of its efficacy in production. To put it crudely, the way we are convinced that science is true is that its recommendations visibly work.[33] Chemistry works — it makes nylon tights and polyethylene sheets. Physics works — airplanes fly and pressure cookers cook rice. Every time. Strictly speaking, this is not a correct inference because a functional technique could be based on knowledge that turns out to be false. However, successful techniques transform conjecture and hypothesis into an accepted fact, ready to go into textbooks and to be utilized by engineers, physicians, or farmers. At the same time, the interaction may work the other way as well. Techniques may be "selected" because they are implied by a set of knowledge that is gaining acceptance, or by an "authority" whose social position in the world of knowledge induces others to pick techniques on the basis of his or her opinions. This is true when the efficacy of a technique is hard to observe directly. Consumers do not actually observe the positive long-term effect that daily doses of aspirin have on preventing heart disease, but trust the scientific insights that suggest it. Such techniques can be highly unstable in their popularity if the knowledge on which they are based is not very solid, as the recent case of hormone replacement therapy demonstrates.

The idea that techniques in use can buttress the knowledge on which they are based is not new. The 18th-century British potter Josiah Wedgwood felt that his experiments in the pottery actually tested the theories of his friend Joseph Priestley, and professional chemists, including Lavoisier, asked him for advice. During the 19th century, the general confidence in scientific knowledge was reinforced by the undeniable fact that the techniques based on it worked. Thus, the Scottish engineer and scientist William Rankine, one of the first to apply the newly discovered science of thermodynamics to engines, studied the effects of steam expansion, which led him to recommend applying steam-jacketing to heat the cylinder (a technique previously tried but abandoned). One of his students, John Elder, used his work to develop the two-cylinder compound marine engine in the 1850s, which sealed the eventual victory of steam over sailing ships. The superior performance of these new machines served as confirmation of the new physical theories. In a different area, once biologists discovered that insects could be the vectors of pathogenic micro-parasites, insect-fighting techniques gained wide acceptance. The success of these techniques in eradicating yellow fever and malaria was the best confirmation of the hypotheses about the transmission mechanisms of the diseases, and helped earn them wide support.

Finally, the period after 1750 witnessed a slow and rather uneven decline in the *institutional* negative feedback. Rent-seeking and opportunistic behavior have never disappeared from any society, but the rise of the bureaucratic Western nation-state, strongly influenced by Enlightenment ideals of the role of the state, the rule of law, and the notions of political economy, produced governments that limited their own ability to tax their citizens and increasingly protected entrepreneurs and innovators from those who would try to expropriate the fruits of their labor. Monopolies and exclusive, entry-limiting organizations, such as guilds, were restricted and, when possible, eliminated. Tariffs, the most widely used tool to protect local interests from competition, became less popular while in the decades after 1815, free-trade doctrines won uncertain and at times temporary triumphs over protectionism. The notion that states were social contracts between citizens and rulers, and that the function of the state was to protect private property, enforce contracts, and step in only if and when free markets demonstrably failed, slowly gained ground in Europe after 1789. The liberal bourgeois states that emerged created the institutional support that industrial capitalism needed, and placed limits on rapacious rent-seekers. Fraud, corruption, graft, and opportunistic activity became recognized as antisocial behavior. Reform, whether carried out by zealous French administrators in occupied regions or by nations like Prussia carrying out defensive reforms, was inevitably influenced by the concepts of the 18th-century Enlightenment. Moreover, on the global level, between 1815 and 1914, attacks of strong but poor states against smaller but economically successful units did not take place. Indeed, the Pax Britannica essentially meant that power and wealth coincided, and that industrialized nations did not have to fear predators threatening their wealth. Imperialism meant that the military balance shifted, temporarily, in favor of the *haves* against the *have-nots*, so that the rich could rob the poor and get even richer. Unfair and unjust as that may sound, it is another example of a negative feedback being replaced by a positive one.

V. Feedback between Institutions and Technology

I have discussed the transformation in the internal dynamics of technology and institutions, showing how the old negative feedbacks lost their strength. This next model looks not just at feedback within technological or institutional factors but at the interactions *between* them. As we have seen, institutions and technology can make an economy grow through quite different mechanisms, but historically, of course, interacted in complex ways. That technology affects institutions and vice versa seems perfectly obvious. Let us consider the two directions in turn.

A. From Technology to Institutions

The most obvious mechanism of feedback is when technology creates the means by which markets operate. The developments in shipbuilding technology and navigation in the 15th century in Europe not only helped Europeans find the way to the Orient and America, but also created a dense network of international trade both within Europe and across the globe. The great commercial expansion of the 19th century that generated so much wealth was made possible by declining transport costs due to technological changes in land transport, shipbuilding, and shipping techniques. The telegraph and other means of communication helped create and streamline the financial institutions and information networks that made late 19th-century globalization possible.[34] Technology also altered the military balance of power between individuals and the government, and helped create the centralized nation-state, the institution that in the end set up and enforced many of the rules by which the economic game is played in the modern age. It made the rule of law feasible. The nation-state also created global wars, mayhem, terror, and oppression. As always, technology can act as a double-edged sword.

Another mechanism of feedback is that the new technology of the Industrial Revolution created forms of business that were appropriate to its special needs. At least two revolutionary forms of business organization emerged as a response to the new technology of the Industrial Revolution. One of them is the factory. The factory is an inevitable consequence of the new technology, if not, perhaps, through the standard mechanisms elucidated in the literature.[35] It might be argued that factories proper are "organizations," not institutions in the Northian sense, but the *factory system* is a far deeper and more pervasive economic phenomenon than the big, ugly, chimney-ridden brick buildings often referred to as the "dark, Satanic mills." The factory system implies rules of behavior that differ from earlier work habits: discipline, punctuality, coordination and cooperation with perfect strangers, the willingness to accept monitoring and guidance (even when one was no longer an apprentice), and the need to spend a large part of one's life away from home, working in an ordered environment and subject to rules over which one has no control. This is what the new system stood for and what the young Marx called alienation. Today's corporate cubicle and rush-hour traffic jam are the descendants of this transformation.

The other institutional response to the new technology is the large business corporation, run by professional management, with a hierarchical structure, a separation between ownership and control, and the emergence of sophisticated capital markets designed to cater to techniques whose technical structure demands a large fixed investment upfront. The technology that helped trigger these far-reaching institutional changes in the United States was the railroad, as shown by Alfred Chandler.[36] The weakest part of this system, perhaps, was venture capital, that is, investment willing to take a chance on a new technology. Late 19th-century investment banks and the growth of securities markets allowed investors to diversify enough to provide innovators with some access to capital, even if this system did not function perfectly by a long shot. Universal banks on the continent carried out this function with considerable success, whereas in Britain, institutional co-evolution with the new technology had a much more tortuous history.[37] All of these institutional changes were inspired and driven by technology.

One can think of other interactions between technology and institutions. Education and schooling have always been regarded as key to the emergence and absorption of technology.[38] Such assumptions may have to be modified. Technical education was, for centuries, learned effectively through apprentice-master channels, and many schools insisted on teaching material that was worthless (or more drilling and social conditioning than anything we would recognize as skill). In the 19th century that became insufficient. The new techniques demanded engineers, chemists, accountants, metallurgists, electricians, and many other specialists with at least some understanding of the formal underpinnings of the techniques they were to operate. Technical universities and polytechnic schools were founded throughout the continent in the 19th century, and these schools interacted closely with business enterprises to create advances in the frontier industries.[39] They adapted to industry's needs, and industry changed its institutional structure to accommodate them—a classic example of co-evolution.

B. From Institutions to Technology

The institutional framework helps determine the effectiveness of societies in generating new technology. It does so through a variety of mechanisms. The first is the ability of society to generate new knowledge. What is the *research agenda* regarding natural regularities, what is motivating it, and in which areas is a society most interested? Do philosophers, alchemists, and modern scientists receive signals about what society might need and are they inclined to respond to them? Or are they largely driven by epistemic motives, that is, their own curiosity or the curiosity of a small peer group? Many societies in antiquity spent a great deal of time studying the movements of heavenly bodies, which did little to butter the turnips (though it helped work out the calendar). For many generations, Jewish sages spent their lives on the exegesis of the scriptures, adding much to wisdom and legal scholarship, but little to useful knowledge that could affect technology.

Beyond the question of the agenda, there is the question of *allocation*. How many and what kinds of resources are spent on generating this new knowledge? How many people are engaged in the study of natural regularities and how are they recruited and compensated? What tools and instruments are employed?

Less obvious to economists but equally important is the matter of selection criteria. How do we choose between competing theories, if indeed we do? These standards are invariably socially set within paradigms. For example, what constitutes logical "proof"? What is the acceptable power of a statistical test? Do we always insist on double blindness when testing a new compound? How many times need an experiment be replicated before the consensus deems it sound? Who are the "experts" and "authorities" who make these decisions, and who appoints them? Much like in selection models in biology, we can see environments in which selection was stringent. But this is not a necessary condition. A high-pressure intellectual environment forces choices between incompatible views. In a low-pressure intellectual environment, many "species" of knowledge can coexist in one mind, even if by some logical standard they are mutually inconsistent. People might believe that even if there are natural laws, they can somehow generate exceptions, such as magic or miracles. Moreover, the selection criteria are culturally contingent, and it is easy to envisage a cultural climate in which the question "but is it true?" can be routinely answered by "sometimes" or "maybe" or "if God wills it."[40] Furthermore, the selection criterion "is it true?" might have to compete with such criteria as "is it beautiful?" or "is it morally uplifting?" or "is it consistent with our traditions?" Western science, to be sure, is largely consensual, and glaring inconsistencies are frowned upon. People have to choose between incompatible or incommensurate theories and will do so if they can, in some sense, rank them.[41]

The second channel is what happens to this knowledge once it is generated. Who shares in it and how many share? What is the culture of *access*? Is knowledge kept secret or inaccessible through impenetrable codes and jargon or is it publicized as fast and as widely as possible and further disseminated to wider audiences through popularizing books, magazines, and TV programs? What kinds of languages and symbols exist for practitioners to communicate with one another? Beyond that, the people who are engaged in production need to communicate with those who study nature at a more experimental or theoretical level. The institutions that matter most here are the ones that determine the communications and trust between those who know things and those who make them. Do artisans, peasants, navigators, and physicians have access to the cumulative scientific and other knowledge bases they need? If not, can they approach or hire people who do? Through much of history, the elite classes of philosophers and mathematicians had little or no contact with the peasants and artisans, and were little concerned with their needs. It is a hallmark of technologically progressive societies that they have intellectuals with "dirt under their fingernails," as Lynn White once put it. Knowledge has to "filter down" to the classes in charge of putting bread on the table and clothes on the body, but the institutions that did this were often absent.

The third channel is the application of this knowledge to the creation of "techniques." Institutions set up the *incentives* — the payoffs and penalties of innovation—and what the likelihood would be of successful resistance to the innovation, to suppress it and discourage others. How will the person who makes the invention be compensated and what other incentives are there to carry out the often dreary and frustrating task of actually making techniques work? It should be kept in mind that the history of science and technology is a history of "winners." We rarely have much information about the failed inventor or investigator who spent a lifetime of search on an unattainable objective. Yet all researchers take that chance when they embark on a project that may result in an invention.

Finally, the fourth channel is the *diffusion* of innovation. Assuming that an invention is created, will it be adopted and find widespread use in the economy? Historically, many societies have set up conservative institutions that explicitly or indirectly discourage and even block innovators.[42] In the past, technological innovation has run into conservative resistance from a number of corners. First, vested interests, thinking that inventions would cause unemployment or make assets (including human capital like skills) less valuable, tried to fight innovations when they could. Second, conservative organizations, for instance governments worried about political instability or churches worried about heresies, have tried to block innovation. Finally, well-meaning groups, who felt that new technology for one reason or another was undesirable in and of itself, have fought it. Today, some of these groups target specific techniques (nuclear power, genetically modified crops) and not others. Others find the techniques of modern industrial capitalism abhorrent as a whole (e.g., the so-called Frankfurt School).

But other institutional factors matter as well. For instance, will there always be enough entrepreneurs who will take the initiative and accept the risks of adopting a new technique? If there are, can they control the resources needed to make the technique work properly? Do capital markets provide the venture capital and do labor markets supply the necessary complementary skills? Many technological disappointments can be attributed to coordination failures. Such failures might be resolved by an agent acting as coordinator, if other agents recognize him as such. (Often, but not always, government agencies carry out that function.) Yet, it is easy to demonstrate that in many such cases the coordination failed, and industries, sectors, and entire countries remain stuck in "poverty traps."[43]

Institutions interact with innovations in that they determine the likelihood that innovations will yield economically significant results.

Without entrepreneurs, venture capital, and schools that train technicians to build and maintain the new equipment, new techniques will not diffuse rapidly. One might say that innovations open doors, and institutions invite or prohibit the economy from walking through. Institutions will affect the way knowledge is created as well as the way it is diffused. To start with, they determine the payoffs or penalties to innovators. One can see, on the one extreme, a set of reactionary institutions such as the Holy Inquisition, which threatened Giambattista Della Porta, the Neapolitan inventor of an egg-hatching incubator (circa 1588), with the stake as a dangerous heretic. At the other extreme, there is a society, such as ours, in which great inventors like William Shockley and Jack Kilby are rewarded with both enormous riches and hugely prestigious awards, such as the Nobel Prize. Each society has to come to grips with the deep ambiguities of technology. On the one hand, innovation is the key to riches. On the other hand, it is an act of rebellion, of disrespect toward tradition and custom, as well as a destabilizing, disruptive, and potentially dangerous force. In between those two poles, most societies have taken some kind of middle ground, trying to maintain safeguards on social stability without freezing technology in place.

VI. The Enlightenment and the Origins of Growth

With the stage set, I now argue that in the European historical experience of the late 17th and 18th centuries, we can find an event that turned the feedback from negative to positive. That event is something that I will call the *Industrial Enlightenment.* We typically associate the Enlightenment with mid-18th-century political and social thinkers, especially in France and Scotland, where great minds like Rousseau, Diderot, Montesquieu, David Hume, and Adam Smith were rethinking the relationship between the individual and society. But part of it concerned the generation and diffusion of the useful arts, and the application of this knowledge to industry and agriculture. It is arguable that the intellectual roots of this movement go back all the way to Francis Bacon in the early 17th century and the argument that knowledge of nature should serve our material needs. For most of the century, this idea, though widely circulated by those who tried to peddle their intellects to rich and powerful patrons, remained more an ideal than a policy recommendation. The institutions that governed access costs were slowly changing, however, and these changes make the Industrial Revolution less difficult to understand.

The Industrial Enlightenment had a triple purpose. First, it sought to reduce access costs to technological knowledge by surveying and cataloging artisan practices in the dusty confines of workshops in order to determine superior techniques and propagate them through the publication of technical manuals and encyclopedias. Thus, it would lead to a wider adoption and diffusion of best-practice techniques and a rationalization of the production process. Second, it sought to understand why techniques worked by generalizing them, trying to connect them to one another and relate them to what was then known as "natural philosophy." The bewildering complexity and diversity of the world of techniques in use was to be reduced to a finite set of general principles governing them. These insights would lead to extensions, refinements, and improvements, as well as speed up and streamline the process of invention. Third, it sought to facilitate the interaction between those who catalogued and understood natural phenomena (or thought they did) and those who carried out the techniques.[44] The *philosophes* of the Enlightenment echoed Bacon's call for cooperation and the sharing of knowledge between those who investigate nature and those who might use their conclusions to put more bread on the table. Yet in the 1750s, when the first volumes of the *Grande Encyclopédie* were published, this was still little more than a dream. A century later, it had become a reality. What made Bacon's vision into a reality was the Industrial Revolution. In their zeal for looking for economic factors in the Industrial Revolution, what economic historians may have overlooked is its intellectual origins in the Enlightenment.

The Industrial Enlightenment took many concrete forms. Above all, it established clear channels of communication between those who knew things, the *savants*, and those who made them, the *fabricants*. Scientific organizations, often known confusingly as literary and philosophical societies, sprung up everywhere in Europe. They organized lectures, symposia, public experiments, and discussion groups, in which the topics included the best pumps to drain mines or the advantages of growing clover and grass.[45] The British Society of Arts, founded in 1754, was a classic example of an organization that embodied many of the ideals of the Industrial Enlightenment. Its purpose was "to embolden enterprise, to enlarge science, to refine art, to improve manufacture and to extend our commerce." Its activities included an active program of awards and prizes for successful inventors; over

6,200 prizes were granted between 1754 and 1784.[46] The society took the view that patents were a monopoly, and that no one should be excluded from useful knowledge. It therefore ruled out (until 1845) all persons who had taken out a patent from being considered for a prize, and even toyed with the idea of requiring every prizewinner to commit to never take out a patent.[47] It served as a clearinghouse for technological information, reflecting the feverish growth of supply and demand. But France and the rest of the continent were never far behind and in some areas led Britain. The greatest Enlightenment document, d'Alembert's and Diderot's *Grande Encyclopédie*, was also a great technological document, with thousands of minute descriptions of machines, devices, chemical processes, farming techniques, and so on.[48] The Industrial Enlightenment also created an accessible language of technology by defining units and terms, and insisting on the unification and standardization of weights and measures. It did all it could to lower the barriers that national boundaries and languages imposed and to fight the inertia imposed by conservatism, selfishness, and ignorance.

The Industrial Enlightenment could occur, in part, because of a major institutional change. In the 16th and 17th centuries, practical knowledge in Europe underwent a transformation. Discoveries about nature were no longer kept secret, as had been customary in the Middle Ages, but were diffused as soon as possible, with credit going for priority.[49] This notion, still very much in force today, vastly reduced access costs within and across different countries. At the same time, it was also increasingly understood that inventions (new production techniques, as distinct from scientific discoveries) needed to be protected and awarded some form of intellectual property rights if would-be inventors were to allocate the required time, effort, and resources.

How to reward those whose patience and ingenuity enriched society remained a dilemma. There were a number of alternative mechanisms, all imperfect, that this could be done. First, there was always the first-mover's advantage. The inventor usually enjoyed a few years of relative peace before imitators could pick up the idea and encroach upon his monopoly. Second, such advantages could be extended by keeping a novel technique secret. Of course, some techniques were easy to copy or reverse engineer, and for those secrecy probably was not an option. Even when it was, industrial espionage was well developed and labor mobility was sufficient to make this option fairly weak.[50] Third, the inventor could apply for a subsidy or a prize. In the

British case, it could come from the Society of Arts or, in a few cases, from Parliament itself. In France, a formal government committee appointed by the Royal Academy routinely awarded such prizes and medals. Fourth, the patent system provided a legal underpinning in which the inventor "owned" the right to the invention and could either exploit it himself (collecting the temporary monopoly rents) or license it out for a fee. Once a patent was taken out, secrecy was no longer an option because, in 1778, the British courts decreed that patent specifications should be sufficiently precise and detailed so as to fully explain it to a technically educated person.

In this fashion, the intellectual changes in the 18th century gradually transformed the way in which institutions affected technology. Behind it lay the deeper utilitarian notion of classical political economy that institutions are to be *rational*, that is, measured and tested by the degree to which they serve the material well-being of society as a whole. The main event of the Industrial Revolution was still technological change. Other factors, such as credit, labor, transportation, urbanization, foreign trade, and demographic change, all played roles in bringing it about, but it is the positive feedback mechanisms *within* the sphere of useful knowledge and those *between* useful knowledge and institutions that changed the course of history. But these intellectual origins themselves were forged in the previous century through what we call the Scientific Revolution and through the Industrial Enlightenment.

These linkages go some way toward explaining the rise of the West. The historiography of Western economic change in the past centuries is always torn between those who praise it and view it as mankind's salvation from poverty and backwardness, and those who, with the gloom-and-doom of the Frankfurt School, view it as a curse and a catastrophe that has turned civilization into barbarism. The extreme pessimists believe that technology will eventually bury us all, whether through a nuclear war, environmental disaster, or the insidious effect of crass materialism and free enterprise commercialism. Such debates are inherently inconclusive and almost always about half-full, half-empty glasses. What seems undeniable is the enormity of the event.

At first glance, Europe in 1700 seems not all that different from the rest of the world. To be sure, it had just found the sailing routes to every continent, established trade routes, and engaged in an aggressive program to adopt crops and techniques it had found in other cultures. But these activities involved only a small proportion of the population and affected only a small fraction of all economic activity. The further one lived from the Atlantic ports, the less access one had to these goods. What set Europe apart were intellectual changes: the Renaissance followed by the Scientific Revolution and the Enlightenment. No other society experienced anything like it. It was a deep intellectual transformation into the possibility and desirability of social and material progress and the social potential of human reasonableness—a belief that survived the refutation of the perfectibility of humans and human institutions. But beyond the fragile belief in progress, the Industrial Enlightenment created something much more lasting: the means and tools for technological progress to actually occur. Two centuries after Bacon's program, European societies created the institutions that could bring it about and that ended the processes of self-extinction that had characterized earlier episodes of economic expansion.

VII. Final Thoughts

Returning to the question of differences in income, we can phrase the issue perhaps most meaningfully as the two following propositions. The first proposition is that differences in institutions help explain differences in income levels in cross-section at a given moment. Knowledge can and does flow across national boundaries, if not always with the frictionless ease and speed that some economists imagine. If the *only* reason that Germany is richer than Zimbabwe today is that Germany possesses more useful knowledge, the difference might be eliminated in a relatively short time. In reality, the chief reason for the difference is that the institutions in most Western nations are more amenable to economic growth than in many non-Western ones. These institutions tend to be persistent and, unlike knowledge, better institutions do not easily "diffuse" across national boundaries.[51] It turns out to be easier for countries like Pakistan to import Western nuclear technology than to import institutions that will allow its economic and political processes to allocate resources in an efficient way and to avoid the worst excesses of rent-seeking.

The second proposition is that in recent history differences in knowledge have become increasingly important in explaining growth *over time.* If we were to ask why Germany is richer today than it was in 1815, the importance of technology becomes unassailable — though better institutions might still be of importance as well. The statements are thus of degree, not of absolutes; but in economic history, degree is everything.

Whether one is an optimist or a pessimist about the effects of economic growth on the human condition, it is undeniable that the Industrial Revolution remains the central event of the economic and social history of the past half millennium, simply because it altered the material lives of more people in more radical ways than any other event in recorded history. It is not only that worldwide income increased by a huge factor. The Industrial Revolution meant that technological progress turned from a sporadic stroke of brilliance or luck that allowed a society suddenly to build windmills or print books, to a steady, continuous string of events. Because of relentless innovation, we have come to *expect* things to get better. We *demand* that human knowledge be applied to all our material problems and that things improve all the time; newer cars and computers are more efficient and have more options because they embody this year's technology, which is more advanced than last year's. We demand that technology solve the scourges of our age — AIDS, traffic jams, pollution, terrorism. When it does not, we feel frustrated and disappointed. We expect technology to help solve our mental and spiritual problems as well. If we are depressed, give us Prozac. If Prozac has bad side effects, invent something that does not. We fully expect technology to extend youth and life itself. This expectation itself is new. Before the Industrial Revolution, and even during much of the 19th century, people were happy with innovation, delighted in cheap cotton clothes, rode their new trains, and enjoyed technology's achievements, from telegraph to anesthetics. They saw these as temporary windfalls, however, not as harbingers of a society in which the only constant thing about technology was change itself, to paraphrase Heraclitus.

Knowledge is not like any other economic entity. Science fiction is full of techniques that are imaginable but not feasible. History is full of examples of techniques that were feasible but simply did not occur to anyone—and there is no reason why our age should be all that different. Some things, however, may well be beyond us, and others may well be physically impossible. Technological history illustrates, over and over again, that it is human fate that we cannot always tell the possible from the impossible. All the same, what seem to be failures of technology are often the failures of institutions.

Progress in useful knowledge has not been accompanied everywhere by more enlightened institutions. Science and technology have not brought universal bliss, let alone the perfection of humans. There have been deep disappointments, and we are slowly but certainly reaching a better understanding about why the institutions that govern our lives are so hard to "get right." The history of the West shows asymmetric progress, with advances in technological knowledge steadily progressing whereas "progress" in institutions seems to be much less pronounced and monotonic. Rational, well-meaning people often designed institutions that completely misfired and inflicted endless misery. Unraveling the mysteries of nature has turned out to be much easier than unraveling the complexities of human interaction. One can easily point to the great institutional failings of the 20th century, such as the rise of totalitarianism, racism, and genocide. Yet even in our own time, the many difficulties and obstacles in combating AIDS and global pollution, for example, are not only in the technology, nor in a will to succeed, but in the failure to overcome opportunistic behavior and coordination problems.[52] The positive feedback between technology and institutions has improved both, but the effects have still been highly unevenly distributed between the two. Institutions and the human behavior that gives rise to them are far more difficult to refine and perfect than human control over the natural environment. Without those improvements, however, the enormous control that homo sapiens now exert over the forces of nature may become a frightful development indeed.

All the same, for much of humanity, life is longer, more comfortable, and less painful and uncertain than before. The material pleasures that once were only attainable by the very rich and powerful have become increasingly available to more and more people, to the point that many feel it unjust that they are not yet available to the rest of humanity. Such a thought would have been sheer insanity in 1750. ◉

Notes

Parts of this paper are based on my *The Gifts of Athena: Historical Origins of the Knowledge Economy* (Princeton: Princeton University Press, 2002).

1. The classic work on this topic, still unsurpassed, is W. O. Henderson, *Britain and Industrial Europe* (Leicester: Leicester University Press, 1954). For the migration of technology across the Atlantic, see David J. Jeremy, *Transatlantic Industrial Revolution: The Diffusion of Textile Technologies between Britain and America, 1790* – 1830s (Cambridge, Mass.: MIT Press, 1981).

2. The seminal articles are Danny T. Quah, "Twin Peaks: Growth and Convergence in Models of Distribution Dynamics," *The Economic Journal* 106 (July 1996): 1045 – 55; and

Charles I. Jones, "On the Evolution of the World Income Distribution," *Journal of Economic Perspectives* 11 (Summer, 1997): 19–36.

3. The most recent examples are Landes, *The Wealth and Poverty of Nations: Why Some are So Rich and Some So Poor* (New York: W. W. Norton, 1998); and Jared Diamond, *Guns, Germs and Steel: The Fates of Human Societies* (New York: Norton, 1997). Earlier works in this tradition are Nathan Rosenberg and L. E. Birdzell, *How the West Grew Rich: The Economic Transformation of the Industrial World* (New York: Basic Books, 1986). In recent years, economists have tried their hand at the question as well, for instance, Stephen L. Parente and Edward C. Prescott, *Barriers to Riches* (Cambridge, Mass.: MIT Press, 2000); and William Easterly, *The Elusive Quest for Growth* (Cambridge, Mass.: MIT Press, 2001).

4. The original formulation of this way of looking at growth is in William N. Parker, *Europe, America, and the Wider World* (Cambridge: Cambridge University Press, 1984). For a restatement, see Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* (New York: Oxford University Press, 1990).

5. For a persuasive and properly nuanced argument of this nature, see William J. Baumol, *The Free-Market Innovation Machine: Analyzing the Growth Miracle of Capitalism* (Princeton, N.J.: Princeton University Press, 2002).

6. For a recent analysis of the "reward system" in pre-1789 France, see especially Liliane Hilaire-Pérez, *L'invention technique au siècle des lumières* (Paris: Albin Michel, 2000).

7. For a more detailed discussion, see Mokyr, *Gifts of Athena*, chapter 1.

8. The literature on the institutional underpinnings of growth has become enormous following Douglass C. North's path-breaking *Structure and Change in Economic History* (New York: W. W. Norton, 1981) and *Institutions, Institutional Change, and Economic Performance* (Cambridge: Cambridge University Press, 1990). Among recent notable contributions are C. Mantzavinos, *Individuals, Institutions, and Markets* (Cambridge: Cambridge University Press, 2001); and John N. Drobak and John V.C. Nye, eds., *The Frontiers of the New Institutional Economics* (San Diego: Academic Press, 1997).

9. Merchandise exports between 1870 and 1998 grew worldwide at a rate almost four times faster than GDP — and that despite a sharp setback between 1913 and 1950. See Angus Maddison, *The World Economy: A Millennial Perspective* (Paris: OECD, 2001), p. 127.

10. This is sometimes known as the "Pirenne thesis," after Henri Pirenne, *Mohammed and Charlemagne* (New York: W. W. Norton, 1937).

11. A recent and penetrating discussion of the rise and fall of globalization in the 20th century is Harold James, *The End of Globalization* (Cambridge, Mass.: Harvard University Press, 2001).

12. See Hernando De Soto, *The Mysteries of Capital: Why Capitalism Triumphs in the West and Fails Everywhere Else* (New York: Basic Books, 2000).

13. See especially Kevin M. Murphy, Andrei Shleifer, and Robert W. Vishny, "The Allocation of Talent: Implications for Growth," *Quarterly Journal of Economics* 106, no. 2 (May 1991): 503–30; and William J. Baumol, *Entrepreneurship, Management, and the Structure of Payoffs* (Cambridge, Mass.: MIT Press, 1993).

14. Avner Greif, *Comparative and Historical Institutional Analysis: A Game-Theoretical Perspective* (Cambridge University Press, forthcoming in 2003).

15. This is widely asserted in recent writings by economists, for instance, Robert Lucas, *Lectures on Economic Growth* (Cambridge, Mass.: Harvard University Press, 2002); and

Oded Galor and Omer Moav, "Natural Selection and the Origins of Economic Growth," *Quarterly Journal of Economics* (forthcoming in 2002). Historians have been more prudent, recognizing episodes of economic growth in many areas before 1750, especially Eric L. Jones, *Growth Recurring* (Oxford: Oxford University Press, 1981). Yet as a "stylized" fact, it remains true that the gap in per capita living between Europe and the rest of the world was probably not large in 1750 but had grown to huge proportions by 1914. See especially R. Bin Wong, *China Transformed: Historical Change and the Limits of European Experience* (Ithaca: Cornell University Press, 1997); and Kenneth Pomeranz, *The Great Divergence: China, Europe, and the Making of the Modern World Economy* (Princeton, N. J.: Princeton University Press, 2000).

16. Jared Diamond, *Guns, Germs and Steel: The Fates of Human Societies* (New York: Norton, 1997).

17. This point has been stressed by Jones, *Growth Recurring.* An early use of the idea of such feedback is found in Needham's description of the social dynamics of Imperial China, which he describes as a "civilization that had held a steady course through every weather, as if equipped with an automatic pilot, a set of feedback mechanisms, restoring the status quo [even] after fundamental inventions and discoveries." See Joseph Needham, *The Grand Titration* (Toronto: University of Toronto Press, 1969), pp. 119–20. Needham may have overstated the degree of technological instability in pre-1750 Europe, but his intuition is sound about the difference between the two societies being centered in the dynamic conditions of stability.

18. Fernand Braudel, *Civilization and Capitalism, 15th – 18th Century: The Structures of Everyday Life*, Vol. 1 (New York: Harper and Row, 1981).

19. Oded Galor and David Weil, "Population, Technology, and Growth," *American Economic Review* 90, no. 4 (September 2000): 806–828. See also, Gary D. Hansen and Edward C. Prescott, "Malthus to Solow," unpublished manuscript, presented to the Minneapolis Federal Reserve Bank Conference on Economic Growth and Productivity, October 1998; and E. A. Wrigley, *Continuity, Chance and Change: The Character of the Industrial Revolution in England* (1988).

20. A recent statement, elegant along Malthusian lines, is E. A. Wrigley, "The Divergence of England: the Growth of the English Economy in the Seventeenth and Eighteenth Centuries," *Transactions of the Royal Historical Society* 10, 6th series (2000): 117–41.

21. For a particularly trenchant recent criticism, see Julian Simon, *The Great Breakthrough and its Causes*, edited by Timur Kuran (Ann Arbor: University of Michigan Press, 2000).

22. Ibid.

23. Robert C. Allen, "Agriculture during the Industrial Revolution," in *The Economic History of Britain since 1700,* Vol. I: 1700 – 1860, edited by Roderick Floud and D. N. McCloskey (Cambridge: Cambridge University Press, 1994).

24. The 18th-century Scottish chemist and physician, William Cullen, predicted that chemical theory would yield the principles that would direct innovations in the practical arts. This ambition remained, in the words of the leading expert on 18th-century chemistry, "more in the nature of a promissory note than a cashed-in achievement" (Jan Golinski, *Science as Public Culture: Chemistry and Enlightenment in Britain, 1760 – 1820*, Cambridge: Cambridge University Press, 1992, p. 29). Manufacturers needed to know why colors faded, why certain fabrics took dyes more readily than others, and so on, but

as late as 1790, best-practice chemistry was incapable of helping them much. See Barbara Keyser, "Between Science and Craft: the Case of Berthollet and Dyeing," *Annals of Science* 47, no. 3 (May 1990): 222. Before the Lavoisier revolution in chemistry, it just could not be done, no matter how suitable the social climate.

25. The Venetian wealth generated by its Mediterranean trade was destroyed by the ruthless competition of well-organized Dutch traders. See Richard Rapp, "The Unmaking of the Mediterranean Trade Hegemony: International Trade Rivalry and the Commercial Revolution," *Journal of Economic History* (1975). In turn, the Dutch saw their wealth diminished in the 18th century by the mercantilist policies of France and Britain.

26. See Joel Mokyr, "The Political Economy of Technological Change: Resistance and Innovation in Economic History," in *Technological Revolutions in Europe,* edited by Maxine Berg and Kristin Bruland (1998), pp. 39–64; and *Gifts of Athena*, chapter 6.

27. See especially William Easterly, *The Elusive Quest for Growth* (Cambridge, Mass.: MIT Press, 2002), chapter 10. It might be added that a pre-modern world may have been more vulnerable to accidents and disasters in the short-run, but the movement toward a path of sustained growth may well have been contingent to a greater degree than we normally allow for.

28. Neil McKendrick, "The Role of Science in the Industrial Revolution," in *Changing Perspectives in the History of Science*, edited by Mikulá, Teich, and Robert Young (London: Heinemann, 1973); A. Rupert Hall, "What did the Industrial Revolution in Britain Owe to Science?," in *Historical Perspectives: Studies in English Thought and Society*, edited by Neil McKendrick (London: Europa Publications, 1974); Peter Mathias, "Who Unbound Prometheus?," in *The Transformation of England* (New York: Columbia University Press, 1979), pp. 45 – 72; and Margaret Jacob, *Scientific Culture and the Making of the Industrial West* (New York: Oxford University Press, 1997).

29. Nathan Rosenberg, "The Direction of Technological Change: Inducement Mechanisms and Focusing Devices," in *Perspectives on Technology* (Cambridge: Cambridge University Press, 1976), pp. 108–25; id., "How Exogenous is Science?," in *Inside the Black Box: Technology and Economics* (Cambridge: Cambridge University Press), pp. 141–59.

30. Derek J. de Solla Price, "Notes towards a Philosophy of the Science/Technology Interaction," in *The Nature of Knowledge: Are Models of Scientific Change Relevant?*, edited by Rachel Laudan (Dordrecht: Kluwer, 1984). id., "Of Sealing Wax and String," *Natural History*, no. 1 (1984): pp. 49–56. A similar idea can be found in Freeman Dyson, *Imagined Worlds* (Cambridge: Harvard University Press, 1997).

31. This point is made by Franz Wuketits, *Evolutionary Epistemology and its Implications for Humankind* (Albany: SUNY Press, 1990), pp. 92, 105.

32. Much of the late 18th-century chemical revolution was made possible by new instruments like Allesandro Volta's eudiometer, a glass container with two electrodes intended to measure the content of air, and used by Cavendish to show the nature of water as a compound. The famous mathematician Pierre-Simon de Laplace was also a skilled designer of equipment and helped to build the calorimeter that resulted in the celebrated "Memoir on Heat," jointly written by Laplace and Lavoisier in 1783, in which respiration was identified as analogous to burning.

33. Jack Cohen and Ian Stewart, *The Collapse of Chaos: Discovering Simplicity in a Complex World* (Harmondsworth, England: Penguin, 1994), p. 54.

34. See, for example, James Foreman-Peck, *A History of the World Economy* (New York: Harvester Wheatsheaf, 1995), pp. 67 – 72; and Maurice Obstfeld and Alan M. Taylor, *Global Capital Markets: Growth and Integration* (Cambridge: Cambridge University Press, forthcoming in 2003).

35. Joel Mokyr, "The Rise and Fall of the Factory System: Technology, Firms, and Households since the Industrial Revolution," *Carnegie-Rochester Conference Series on Public Policy* 55 (December 2001): 1–45; and *Gifts of Athena,* chapter 4.

36. Alfred Chandler, *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass.: The Belknap Press, 1977), pp. 81–121. For a classic early analysis of management problems during the early stages of the Industrial Revolution, see Sidney Pollard, *The Genesis of Modern Management* (London: Penguin, 1968). Richard Nelson has pointed to a classic example of the co-evolution of institutions and technology, namely, the growth of the large American business corporation in the closing decades of the 19th century, which evolved jointly with the high-throughput technology of mass production and continuous flow. See Richard R. Nelson, "Economic Growth through the Co-evolution of Technology and Institutions," in *Evolutionary Economics and Chaos Theory: New Directions in Technology Studies*, edited by Loet Leydesdorff and Peter Van Den Besselaar (New York: St. Martin's Press, 1994).

37. William P. Kennedy, *Industrial Structure, Capital Markets, and the Origins of British Economic Decline* (Cambridge: Cambridge University Press, 1987).

38. Richard A. Easterlin, "Why Isn't the Whole World Developed?," *Journal of Economic History* 41, no. 1 (1981): 1–19.

39. Robert Fox and Anna Guagnini, *Laboratories, Workshops, and Sites: Concepts and Practices of Research in Industrial Europe, 1800*–1914 (Berkeley, Cal.: University of California, Berkeley, Office for History of Science and Technology, 1999); and Wolfgang König, "Science-Based Industry or Industry-Based Science? Electrical Engineering in Germany before World War I," *Technology and Culture* 37, no. 1 (January 1996): 70–101.

40. An example is the Jain belief of *syadvada*, which can be summarized by the statement that "the world of appearances may or may not be real, or both may and may not be real, or may be indescribable, or may be real and indescribable, or unreal and indescribable, or in the end may be real *and* unreal *and* indescribable," cited by Robert Kaplan, *The Nothing That Is* (Oxford: Oxford University Press, 1999), p. 45, emphasis added.

41. Steven N. Durlauf, "Reflections on How Economic Reasoning can Contribute to the Study of Science," Santa Fe Institute Working Paper 97-05-043 (1997).

42. Stephen L. Parente and Edward C. Prescott, *Barriers to Riches* (Cambridge, Mass.: MIT Press, 2000); Martin Bauer, ed., *Resistance to New Technology* (Cambridge: Cambridge University Press, 1995): and Mokyr, *Gifts of Athena*, chapter 6.

43. Kiminori Matsuyama, "Economic Development as Coordination Problems," in *The Role of Government in East Asian Economic Development: Comparative Institutional Analysis*, edited by Masahiko Aoki et. al. (Oxford: Oxford University Press, 1997), pp. 134 – 159; Kevin Murphy, Andrei Shleifer, and Robert Vishny, "Industrialization and the Big Push," *Journal of Political Economy* 97, no. 5 (October 1989): 1003–26; Henning Bohn and Gary Gorton, "Coordination Failure, Multiple Equilibria and Economic Institutions," *Economica* 60 (August 1993): 257–80; and William Easterly, *The Elusive Quest for Growth* (Cambridge, Mass.: MIT Press, 2002), p. 168.

44. Somewhat similar views have been expressed recently by other scholars such as John Graham Smith, "Science and Technology in the Early French Chemical Industry," unpublished paper, presented to the colloquium on "Science, Techniques, et Sociétés" (Paris 2001); and Antoine Picon, "Technology," in *Encyclopedia of the Enlightenment*, edited by Michel Delon, (Chicago: Fitzroy Dearborn, 2001), pp. 1317–23.

45. The most famous of these societies were the Manchester Literary and Philosophical Society and the Birmingham Lunar Society, where some of the great entrepreneurs and engineers of the time mingled with leading chemists, physicists, and medical doctors. But in many provincial cities, such as Liverpool, Hull, and Bradford, a great deal of activity also took place.

46. For details, see Henry Trueman Wood, *A History of the Royal Society of Arts* (London: John Murray, 1913); and Derek Hudson and Kenneth W. Luckhurst, *The Royal Society of Arts, 1754*–1954 (London: John Murray, 1954).

47. Lilane Hilaire-Pérez, *L'invention technique au siècle des lumières* (Paris: Albin Michel, 2000), p. 197; and Henry Trueman Wood, *A History of the Royal Society of Arts*, pp. 243–45.

48. John R. Pannabecker, "Representing Mechanical Arts in Diderot's Encyclopédie," *Technology and Culture* 39, no. 1 (January 1998): 33–73.

49. Betty J. T. Dobbs, "From the Secrecy of Alchemy to the Openness of Chemistry," in *Solomon's House Revisited: The Organization and Institutionalization of Science*, edited by Tore Frängsmyr (Canton, Mass.: Science History Publishing, 1990), pp. 75 – 94; and William Eamon, "From the Secrets of Nature to Public Knowledge," in *Reappraisals of the Scientific Revolution*, edited by David C. Lindberg and Robert S. Westman (Cambridge: Cambridge University Press, 1990), pp. 333–365.

50. John R. Harris, *Industrial Espionage and Technology Transfer* (Aldershot, England: Ashgate, 1998). Samuel Smiles tells us in his *Industrial Biography* that the inventor of the crucible steel-making process, Benjamin Huntsman, "had not taken out any patent for his invention, his only protection being in preserving his process as much a mystery as possible. All the workmen employed by him were pledged to inviolable secrecy; strangers were carefully excluded from the works; and the whole of the steel made was melted during the night." See Samuel Smiles, *Industrial Biography: Iron Workers and Tool Makers* (Newton-Abbot: David & Charles [1863], 1967).

51. See Robert E. Hall and Charles I. Jones, "Levels of Economic Activity across Countries," *American Economic Review Papers and Proceedings* 87, no. 2 (May 1997); and Parente and Prescott, *Barriers to Riches.*

52. One can think of the sad fates of the 1992 Rio conference or the 1997 Kyoto Protocol as examples in point. The *Economist* quoted Mario and Luisa Molina as reckoning that "technology is less important than the institutional capacity, legal safeguards and financial resources to back it up" (July 6–12, 2002, p. 15).