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Economic growth related to mutually interdependent institutions and technology

RICHARD G. LIPSEY*
Emeritus Professor of Economics at Simon Fraser University, Vancouver BC, Canada

Abstract: This paper argues that technological advance is a necessary condition for sustained economic growth. Technologies and institutions co-evolve in a system of mutual causation. Although some institutions inhibit growth while others encourage it, no single institution is either necessary or sufficient to produce sustained growth. However, some non-unique bundle of encouraging institutions is necessary. Sustained growth began with the Industrial Revolutions that did not just 'fall out of the blue' but were instead the culmination of three trajectories of technological advance in steam power, electric power, and the mechanization of textile manufacturing. These stretched over several centuries. Growth then became sustained when the West 'invented how to invent'. A necessary condition for the Industrial Revolutions was Western science whose roots lie as far back as the scholastic philosophers and the medieval universities. Its absence elsewhere is a sufficient reason why no other place developed its own indigenous industrial revolution.

1. Introduction

In this paper, I consider relations among economic growth, institutions, and technological change. After introducing some definitions and a key behavioural assumption, I argue in Section 3 that capital accumulation with given technology could not produce sustained growth because it would sooner or later be constrained by diminishing returns to investment, diminishing marginal utility of income, resource exhaustion and increasing pollution. Similarly, scale economies made available by new technologies must sooner or later be exhausted. Thus, growth cannot be sustained in the long term without significant technological advance, which is brought about by the invention and innovation of new products, new processes, and new forms of organization.

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*Email: rlipsey@sfu.ca

This is a revision of a paper first presented to the 10th International Workshop on Institutional Economics held at the University of Hertfordshire, England, 17–18 June 2008. Many of the ideas in it are the common property of myself and my two co-authors, Clifford Bekar and Kenneth Carlaw. I have reorganized and added to them in order to deal with the questions set to by the conference organisers. See Lipsey *et al.* (2005).

In Section 4, I consider some aspects of the role of institutions in the growth process. Institutions have important influences on growth, some inhibiting it while others enable and/or encourage it. The existence of an effective subset of potentially helpful institutions is a necessary condition for sustained growth. However, the list of such institutions is long and there are many subsets that can be effective in encouraging growth. It follows that no single institution is either necessary or sufficient for sustained growth, although the existence of some favourable set is necessary. Thus, there is no paradox in finding in some non-growing economies one or more of the institutions that were part of the package that enabled the West's growth.

In Section 5, I consider the advent of sustained growth in the West. There have been periods of rapid growth in the past but these all petered out sooner or later. In contrast, the West's rapid growth that began with the two industrial revolutions was different from all that went before, not necessarily because of its speed, but because of institutional developments that made it self-sustaining. Although this sustained growth was a flower of the two industrial revolutions, its emergence cannot be understood unless one goes back to a series of developments in the Medieval and early modern periods. My colleagues and I argue that Western science was a necessary condition for the Industrial Revolutions and its absence elsewhere is a sufficient reason why no other part of the world did produce, or could have produced, its own endogenous industrial revolutions. We go on to argue that key players in the rise of Western science were the scholastic philosophers, and a key institution was the Medieval university which provided the institutional memory that allowed science to take on a path-dependent, cumulative trajectory that was not found anywhere else in the world in spite of the many isolated scientific discoveries elsewhere, especially in China and Islam.

2. Some definitions

Extensive economic growth refers to the rate of growth of total output, which is typically measured by the rate of growth of gross domestic product (GDP). Intensive growth refers to the rate of growth of per capita output, which is typically measured by GDP/population. In this paper, I am concerned with extensive growth. This is the variable that virtually all conventional growth models attempt to explain and I follow normal practice in using the term 'growth' to refer to extensive growth. An explanation of intensive growth requires not only a theory of extensive growth but also a theory of population growth.[1]

The development of some new product, process, or form of organization is referred to as invention. The commercialization of that invention, which itself

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[1] After Galor and Weil (2000), and Lipsey *et al.* (2005: Chapters 9 and 10) provide theories of population growth that yield different explanations of how intensive growth has been related to extensive growth historically.

may require further inventions as one learns by making the product (called 'learning by doing') and using it (called 'learning by using') is called innovation. I argue below that both invention and innovation are necessary for sustained economic growth.

In Lipsey, Carlaw and Bekar (2005, hereafter LCB) we separate technological knowledge from the things in which it is embodied, such as machines, assembly lines and factory layouts.

> Technological knowledge, technology for short, is the set of ideas specifying all activities that create economic value. It comprises: (1) knowledge about product technologies, the specifications of everything that is produced; (2) knowledge about process technologies, the specifications of all processes by which goods and services are produced; (3) knowledge about organisational technologies, the specification of how productive activity is organised in productive and administrative units for producing present and future goods and services (which thus includes knowledge about how to conduct R&D). (LCB: 58)

There is a vast literature on all aspects of institutions, including many different definitions. Many writers who have dealt with the importance of institutions have not needed to define the term because they were dealing with specific examples that clearly were institutions. However, when one talks about institutions in general, definitions do matter. This is illustrated by Richard Nelson (undated) who cites two empirical studies that come to contradictory conclusions about the importance of institutions in the growth process, but do so by using different definitions of institutions, one being the type of government either democratic or autocratic,[2] the other related to property rights and the rule of law.[3] As long as one knows what is being measured, such different uses are harmless. But the danger is that the specific definition will be ignored and results generalized to all types of institutions, saying that the evidence shows them all to be (or not to be) important in the growth process.

While being aware that many different meanings that have been given to the term institutions, the simple definition from the *New Oxford English Dictionary* (1998: 946) will do for my purposes. It defines the term to cover both of the following two generic senses: ***meaning 1*** *, societies or organizations (i) founded for particular purposes such as care of the sick or handicapped, (ii) used for official purposes that play an important part in the country, such as the central bank and the parliament, (iii) doing commercial and financial business such as corporations and insurance firms; and,* ***meaning 2*** *, an established law, practice or custom.*

These are the senses in which I use the term institutions here.

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[2] Glaiser *et al.* (2004).

[3] Rodrik *et al.* (2004).

3. Behavioural assumptions

To discuss innovation, and to compare innovating and non-innovating societies, we need a theory of the incentives for the agents who make decisions with respect to inventions and innovations.

Although many types of animals use tools, humans are the only ones that routinely invent new ones. Early hominids made tools to do things done by many different types of animals, putting them into competition with a much wider range of animals than any other species. Tool use created a positive feedback system:[4]

> technology is probably *the* most significant element in determining what we are today, not just in forming modern 'civilization', but in directing the course of our evolution from a distant apelike ancestor. Genetically, anatomically, behaviourally, and socially, we have been shaped through natural selection into tool makers and tool users. This is the net result of more than 2.5 million years of evolutionary forces working upon our biology and behaviour. (Schick and Toth, 1993: 17–18)

This evolutionary path has led my co-authors and I to introduce a basic assumption: *humans are inventive creatures; faced with a challenge that threatens to worsen their situation, or perceiving an opportunity to better it, they will typically seek solutions that involve invention and innovation.*

We could assume that these activities are their own reward; people do them because they are enjoyable and fulfilling. Without denying that this type of behaviour does sometimes exist, we assume the following: *invention and innovation are risky and costly; people will usually only engage in these activities if they anticipate a gain that exceeds the expected personal cost.*[5]

Our assumptions imply that we do not need to explain the existence of inventive and innovative behaviour. What requires explanation is why it is sometimes absent, and when present, why it sometimes fails to lead to growth-creating cumulative advances in technology.[6]

4. Drivers of economic growth

Economic historians typically identify three main proximate determinants of economic growth: capital accumulation (physical and human), scale effects, and technological change (see, e.g., Mokyr, 1990). We use the conceptual experiment of allowing these to change one at a time to argue that the existence

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[4] Most issues concerning evolution are hotly debated, including this one. However, even the view that the evolution of the big brain was an accidental bi-product of other evolutionary pressures allows for modification of the brain in the light of new survival abilities, such as superior tool use.

[5] So the invention and innovation that goes on without being motivated by personal gain is random behaviour that provides a background against which gain-motivated activity occurs.

[6] We give the argument leading to our two key assumptions in some detail in LCB: 65–68.

of technological change is a necessary condition for long-term growth. The essence of the argument is as follows.[7] First, given capital accumulation without technological change, growth would sooner or later peter out, as the classical economists emphasized long ago. Consider, for example, freezing all technologies at any past level, say for illustration the level existing in 1900, and accumulating more and more capital in the form of more Victorian factories spewing smoke into the environment, producing more and more of the then known goods, which could not be altered by new innovations that take account of changes in factor availabilities and costs. Such growth would soon peter out as the market value of yet another piece of identical capital equipment fell steadily (diminishing returns to capital), as consumers wondered what to do with a third horse and buggy, another steam train trip to the nearby seaside resort, and another ice box, carpet sweeper, and washing board (diminishing marginal utility of income),[8] as specific inputs became scarce and could not be replaced by newly invented materials and techniques, and as pollution became increasingly serious and could not be alleviated by the substitution of new technologies. Second, for any given technology there are only so many scale economies that can be exploited. Third, technological change can produce endless growth as long as there is investment to embody it in physical and human capital. Indeed, we are better off materially today than we were one hundred years ago because we have new products, made with new processes and new forms of organization, not because we have more of the same products, production processes, and organizational forms as existed then.

Nonetheless, the three causes are interdependent. Since investment in new physical and human capital is the vehicle by which technological change is embodied in people and things, its availability can affect the rate of embodiment of new technologies and hence the growth rate. New possibilities for exploiting the scale effects that are embedded in the physical world are made possible by the invention of new techniques. Scale effects pervade the three-dimensional, physical world in which we live, although this is seldom stressed by economists

[7] Although this argument is implicit in Lipsey (1993, 1994), it is first made explicit in Lipsey and Beker (1995). A referee has suggested that an analytical proof of this proposition is needed, rather than the argument given in the text, which is based on what Richard Nelson calls ‘appreciative theorizing’. My co-authors and I argue that propositions such as the one in question cannot be proved by theoretical arguments since alternative models can always be constructed in which growth is driven either by technological change or by capital accumulation. Carlaw and Lipsey (2006) develop one of the former. It is a three sector model in which a basic research sector develops occasional general purpose technologies (GPTs) that drive long-term growth and an applied research sector uses these GPTs to develop products and processes useful in the consumption goods sector. In this model, if basic technologies embodied in new GPTs are no longer developed, applied R&D keeps growth going for some time but at an ever-diminishing rate that eventually reaches zero.

[8] The diminishing marginal utility of income that would set in when more and more of the same was offered for consumption is offset when technological change produces wholly new products as it has over the last two or three centuries.

whose theories often exist in a spaceless, non-physically specified world and hence they ignore such matters. New technologies allow further exploitation of such scale effects, which is why they are often associated with a period of falling costs that last until these economies have been fully exploited.[9]

Because there can be no sustained economic growth in the long term without the development of new technological knowledge, that is a necessary condition for such growth. Furthermore, an economy that produced sustained technological advance without growth would have to be one that failed to put any of its new knowledge into practice. Although it is possible to imagine such an economy, it would be difficult if not impossible to achieve in practice because if new technology was never used, it would become increasingly difficult to erect further new knowledge on the basis of *untried* existing knowledge. Be that as it may, this discussion tells us that the invention of new technological knowledge does not guarantee growth over any finite time horizon. Such knowledge must be put into practice; that is, it must lead to innovation. Innovation in turn requires the provision of sufficient capital investment to embody new technological knowledge in physical and human capital.

So capital accumulation on its own with constant technologies will not produce long-term, sustained growth. Invention that develops new technological knowledge is necessary but that must lead to innovation, which requires the provision of sufficient capital investment to embody the new knowledge.[10] Scale effects exploited by new technologies can increase the growth effects of many new technologies, but on their own would not sustain long-term growth because for any given state of technology the exploitation of scale effects soon reaches limits.

5. Institutions and economic growth

So invention innovation and sufficient capital investment to embody new products, processes, and forms of organization are necessary for economic growth. But these are only proximate causes and we need to ask what lies behind these? An important part of the answer to this question is ‘appropriate institutions’. Many economists throughout the history of our subject have emphasized the importance of institutions for the effective working of a market economy. More recently, the importance of institution in the growth process has been stressed, particularly after the experience of marketizing formerly socialist economies in which the supporting institutions were either non-existent or existed in only rudimentary forms.

[9] This process that LCB refer to as ‘historical increasing returns’, is discussed at length in LCB Chapter 11.

[10] Strictly speaking, all that is needed is gross investment. If all depreciation funds are invested in new technologies, growth can proceed but at a much slower rate than if there is net investment in which to embody a larger flow of new technologies.

I do not have space to review the voluminous literature on institutions and so will only add some points related to our research. In this section, I deal with these issues in general terms and in the next section, I illustrate them through a discussion of the emergence of sustained growth in the West in which institutions played critically important roles.

Institutions as incentives and disincentives

On the one hand, it is clear that given sufficiently repressive institutions, growth can be stifled. Three aspects of the former USSR seem important here: a perverse pricing system that led to waste rather than economization of resources; an incentive structure for producers that led to shoddy production of unchanged products because the main reward came from fulfilling quantity-of-output targets with little attention to quality; most importantly, an incentive structure that severely penalized unsuccessful attempts at innovation, while providing few rewards for successes.

Two points need to be made about such institutional disincentives to growth. First, they are not either-or characteristics but matters of degree. The degree to which centrally administered prices encourage inefficiency can vary with the design of the system and its responsiveness to market conditions. The extent to which institutions emphasize quantity rather than quality of output can vary between wide extremes. The disincentives to invention and innovation are also variables. However, since innovation is a necessary condition for long-term growth, the absence of institutions that come close to totally repressing the incentive to innovate is a necessary condition for continued innovation. But as long as some innovation is tolerated and rewarded, there is a wide range of institutional arrangements that are compatible with growth. Consider, for example, the wide range of policies that encourage and discourage invention and innovation in market economies that are currently growing.[11]

Second, one specific inhibiting institution is usually not enough to stop growth (with the exception of an institution that more or less totally inhibits innovation) since examples of most can be found in successful countries as well as in unsuccessful ones. The observation of a wide range of societies over history that went through long periods, often covering centuries, without significant growth suggests that there are sets of inhibiting conditions that are sufficient to stop growth. But this set is not unique, as different non-growing societies have not all had the same set of institutions.

However, there are institutions that clearly encourage growth. Some in fairly immediate ways, such as high rewards for invention and innovation, and some in more diffuse but nonetheless important ways, such as respect for the rule of law, and pluralistic governmental and business institutions. Countries with a

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[11] For example, R&D tax credits, the effective tax rate on new investment and the encouragement of specific new technologies all vary greatly across modern industrialized economies.

wide range of institutions and policies have succeeded in growing sufficiently to remain in the top tier of high-income countries, as, for example, a comparison of welfare provisions (in the widest sense) between the US and many European countries will demonstrate. So, as with institutions that inhibit growth, there are many that encourage it and any one is probably not sufficient but neither are all of them necessary. So there are many subsets of the helpful institutions that are sufficient to encourage the stream of inventions and innovations needed to sustain growth in the long term.

Finally, and probably most important, new technologies require new institutions to support them. Without these institutional innovations, growth might slow to a halt, because, if new technologies are not exploited, further inventions and innovations that build on them are unlikely to occur.

In summary, because steady streams of inventions and innovations are necessary and sufficient, one might be tempted to argue that technological change is more important than institutions. But if we go behind invention and innovation, we find another set of necessary conditions for invention and innovation not to be stifled: the absence of a set of harmful institutions sufficient to suppress either of these necessary activities and the development of institutions that accommodate the new technologies. We also find a string of conditions in the form of bundles of other helpful institutions that generally encourage invention and innovation without one specific one of them being either necessary or sufficient.

Note that this absence of a clear causal link between growth and any one institution (or a small set of related ones) makes it extremely difficult to measure the importance of institutions empirically by correlating the existence and non-existence of a selected set (usually containing two or three items) with various national growth performances.[12] This absence also lies behind the endless debates of whether some specific institutions, such as pluralistic political and economic structures or well-developed property rights, are necessary for growth. It follows from the above arguments that although these and other similar ones may encourage growth, none of them is necessary. Thus, there is no paradox if their presence (absence) is noted in some societies that grow and some that do not.

From what has been said above, we should not be surprised to find that technology and institutions are linked in a system of mutual interaction. The evidence for this is voluminous. I look first at the causal link from technology to institutions, then at the reverse link from institutions to technology. It must be remembered, however, that they typically co-evolve.

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[12] Analysing the conditions under which the effect of a particular institution on growth might be measured requires a full paper-length analysis, something that is not typically done by those who do empirical work in this area.

New technologies induce institutional changes

New process technologies often require institutional re-organization before their full potential can be realized. For example, the early medieval European villages used a two field system in which individually owned plots could be farmed independently. When the heavy plough was introduced, the difficulty of turning the large team of draft animals needed to draw it led to an organizational innovation: the strip system in which individual holdings were spread out in long, sometimes widely separated, strips. Managing production in this environment required collective village decisions about when to plough, plant, and harvest. This new requirement for coordinated, collective decision making had profound effects on the social and political institutions of European villages, causing these to differ greatly from those of villages where the heavy plough was not necessary for wheat farming or where rice or corn were the staple crops.[13]

New technologies often require new kinds of human capital and new institutions, or revised forms of existing ones. For example, the forms of business organizations that grew up with the mature First Industrial Revolution required a large force of literate, numerate clerks who could, among other things, 'copy out the letters in the hand so free'.[14] Later the computer age required a somewhat different type of literacy and numeracy among a much larger proportion of the work force – a demand that has been much better satisfied in some countries than others, to the benefit of the former.

New management structures are often required to make new process technologies work efficiently. For example, the capital intensive forms of Mesopotamian hydraulic agriculture that were enabled by the invention of writing in the late fourth century BC required centralized decision taking with respect to investment. The priesthood developed the array of institutions needed to make and enforce such decisions efficiently, including a strict division of labour, regular taxes, and book keeping. They also developed a highly efficient command system in which work was accounted for and food distributed by the priesthood using a sophisticated set of accounting prices.[15]

Bronze introduced scale economies in warfare because a large phalanx of well-drilled soldiers, wielding bronze spears and protected by interlocking bronze shields, could outflank, surround, and destroy a smaller army with little loss to itself. As a result, the age of imperial wars began (and survived until the mid

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[13] For full discussion see White (1962).

[14] This phrase from Gilbert and Sullivan's *HMS Pinafore* reminds us of the pre-typewriter days when clear penmanship was an essential for all office staff and, later still, for clerks dealing with numbers. As an indication of how long it takes to adapt old institutionalized practices to the new technologies, I was plagued in my pre-Second World War early school days by long lessons in penmanship where we were drilled, unsuccessfully in my case, in a flowing style of penmanship required in Victorian days.

[15] We know more about this ancient economy than many more recent ones because they wrote on clay tablets that were baked into highly durable form.

twentieth century),[16] the city states expanded into multi-city empires; market transactions became important because the command economies of the city states could not cope with the economic needs of multi-city jurisdictions; and the leaders in war, the kings, slowly supplanted the priests as rulers. The range of institutions that were ultimately created or altered because of the use of this material and all the technologies that depended on it was so vast that the whole period is referred to as the 'Bronze Age'. This must come close to being history's greatest example of institutional changes brought about by a new technology.[17]

For a final example, electronic computers added little to productivity when they were first installed in a structure designed for paper records and verbal communications. Slowly over time, the organizations of management, and production were drastically altered to take advantage of the power of computers. Electronic data archiving, retrieval, and manipulation slowly took the place of paper systems for filing and transmitting information. Firms became flatter and less hierarchical in organization. Computers also revolutionized practices in design departments and on the shop floor.

New technologies typically require new infrastructure and supporting institutions. For example, the internal combustion engine enabled cars, trucks and airplanes, all of which required a massive infrastructure in such things as roads, airports, guidance, and control systems, as well as everything that was needed for the discovery, manufacturing, and distribution of petroleum products. Similarly, electricity required very large investments in production and distribution systems. Many new institutions were required to create, operate, and sometimes provide government control of such infrastructure.[18]

Major new technologies typically present many challenges to governments looking for helpful reactions. Old policies become irrelevant or even harmful and new policies are needed as well as the institutional structures to give them effect. In earlier times, competition policy could be guided by national concentration ratios. But globalization (itself the result of two major groups of new technologies that reduced shipping costs dramatically and allowed activities to be coordinated worldwide) has made such indices largely irrelevant. A local 'monopoly' may be in fierce competition with other local 'monopolies' located in several different countries.

Individual governments and international organizations can monitor and control the production of nuclear armaments due to advanced means of surveillance. This makes it possible to have policies with respect to certain armaments that were impossible when such activities could be kept secret.

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[16] There was a lot of violence in earlier times, but organized warfare dates only from the introduction of bronze weapons.

[17] The best treatment of the economic effects of writing and bronze is in Dudley (1991).

[18] Christopher Freeman and Carlotta Perez emphasize this, along with many of the other matters discussed in this section, with their concept of a techno-economic paradigm. See, e.g., Freeman and Perez (1988).

At the end of the twentieth century, biotechnology presented difficult policy issues concerning what should be patentable. Ethical considerations related to such contentious issues as choice of a child's sex (legal in the US and illegal in Canada), cloning, and brain stem research (mainly illegal in the US and legal in the EU). These led to debates and legislation that controls development and in some cases slows it. Similar problems will no doubt arise with nanotechnologies.

Today, new organizational structures are needed to create and enforce international cooperation caused by globalization and to apply a host of new policing techniques, such as genetic identification and TV camera surveillance.

Intuitional changes induce changes in technology

So far, we have seen how public policies, and the institutions needed to give them effect, often must be changed in response to changes in technology. But causal forces also work in the opposite direction, in that public policy and its institutions influence technological change.

This may be done directly through such policies as R&D subsidies and tax credits. It may also be done indirectly. Monopolies many be broken up with the intention of inducing more inter-firm competition in innovation. Tax, education, and the research systems may be altered to encourage more entrepreneurial activities. Technological change may also be affected inadvertently when, for example, policies designed to protect the environment lead to a burst of innovative activities, or when controls designed to support the exchange rate inhibit the importation of new technologies embodied in foreign-produced capital goods. Policies with respect to inputs, may also have indirect effects on technology – usually inadvertently. For example, prohibition of clear-cut logging and certain mining practices have led to innovations to improve the efficiency of those production methods that are still permitted.

Importantly, few major modern technologies have been developed without substantial public sector assistance in early stages of their development.[19] The list includes commercial aircraft, computers, lasers, biotechnology, and nanotechnology. Such institutions as publicly funded research bodies, including universities and research laboratories, are active in most countries. In many countries, some of the assistance comes directly from the government. In the US, it often comes through the procurement activities of the Department of Defense. Currently, there is debate in the US about what further institutions are needed to maintain the American prominence in developing new technologies.[20]

A prime example of how institutions can influence technological change is the post-war Japanese automobile industry. At the end of World War II, there were several Japanese producers of motor vehicles. MITI, the Japanese Ministry of International Trade and Industry, refused to allow US firms to produce in Japan.

[19] For documentation, see Ruttan (2001).

[20] For one strong view of this issue, see Ruttan (2006).

If they had not done so, the Japanese automobile industry would in all likelihood have become a branch of US industry as happened in Canada. The protected Japanese market was too small for the many competing Japanese firms to reach efficient scale using US mass production technology. In two decades of induced innovation, the Japanese, led by Toyota Motors, invented a whole new system of design, production, and sales, often called lean production. This system greatly reduced the minimum scale needed to achieve efficiency and, in the process, reduced production costs and design times, often in totally unexpected ways. After perfecting their new techniques, the Japanese firms went on the challenge the world with their new and efficient cars. This is a wonderful example of institutionally induced technological change, where the institution provided the opportunity, while private initiative responded with its inventive and innovative talent.[21]

6. The emergence of sustained economic growth in west

In the past, the West had seen long periods of growth that have lasted for centuries, as long as, or longer than, the present period that began sometime in the eighteenth century. To mention just two: the period that followed the invention of writing in Sumer in the late fourth century BC saw massive growth over several centuries as did the period the followed the introduction of bronze in the early third century BC.[22] But such spurts of rapid growth eventually petered out. The current growth is different in that the inventions and innovations that lie at the root of growth have been institutionalized, thus providing good reason to believe growth has become self-sustaining without any binding limit.

My colleges and I disagree with two common approaches to explaining the emergence of sustained growth in the West over the last two centuries. First, the explanation is often couched in terms of highly abstract models that use an aggregate production function. A current example is the popular unified growth theory (UGT) that combines an aggregate growth model with an endogenous population to produce a period of Malthusian output growth with constant real incomes, followed by a period of growth that raises living standards.[23] Endogenizing population is an interesting attempt, but these models contain nothing that distinguishes one country from another and, therefore, have the

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[21] The whole story is well told in *The Machine that Changed the World*, Womack *et al.* (1990). Having got it right the first time, MITI almost undid its good work by trying to force the competing companies to amalgamate into a series of monopolies, each specialized in one type of vehicle, on the assumption that this would put each at the scale required to produce efficiently using US technologies. Fortunately for them, the Japanese firms resisted this pressure and went on to invent the lean production technologies that changed the entire industry worldwide. MITI had many significant successes in its early days, although its later performance is more subject to debate.

[22] For details see Dudley (1991: Chapters 1 and 2), and LCB (2005: Chapter 5).

[23] The original article that set this research program off is Galor and Weil (2000).

implicit assumption that there were no country-specific causes of the Industrial Revolution, so that it would have eventually happened *endogenously* in each and every country given enough time. This seems to my co-authors and I to deny the specific characteristics of European growth that caused Europe (and its offshoots, especially in North America) to dominate the world technologically by the mid ninteenth century, while countries in the rest of the world caught up only after they were able to adopt European technologies.[24]

Second, the emergence of the Industrial Revolution is often explained in terms of contemporary or near-contemporary events, even when highly abstract models are eschewed. This seems to us like explaining why a flower blooms so well by looking at the flower alone as if it was suspended in mid air.

In contrast to these approaches, our theses are as follows:

- Sustained growth was established in the West during the Second Industrial Revolution when the West institutionalized invention and innovation.
- The Second Industrial Revolution could not have happened without nineteenth century science, as is generally agreed.
- More contentiously, the First Industrial Revolution also depended on the existence of Western science.
- Even if, in what we regard as an extremely unlikely event, others could have got as far as Britain in 1850 by purely trial and error procedures, inventing, among other things, the high pressure steam engine, mechanized textile machinery, and nineteenth-century metallurgical technologies, they surely would have stropped there, being totally unable to get to the Second Revolution by trial and error methods devoid of science.
- Thus, a necessary condition for establishing sustained growth was the development of Western science.
- The absence of anything remotely approaching Western science anywhere in the non-Western world right up to the twentieth century explains why the West and the West alone produced the Industrial Revolutions and the sustained growth that they issued in.
- To explain the development of science in the West and nowhere else, we need to go back to the origins of the Christian and Islamic religions and to some crucial institutional developments in the second half of the medieval period.[25]

In what follows, we use the flower analogy to outline our answer to the heading's question. To explain why the flower is what it is, we need to know the climate that surrounded its growth, the nature of the seeds from which it

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[24] Our model of endogenous population that does contain country-specific specifications is in Chapter 9 of LCB: 'Population Dynamics: The Relation between Extensive and Intensive Growth'.

[25] Much of the novelty in our view lies in (i) the stress we place on Western Science as a necessary condition for the Industrial Revolutions, (ii) the absence of Western science as a sufficient condition for explaining why those revolutions did not happen, and could not have happened, endogenously elsewhere, and (iii) the importance of the Medieval universities in providing an institutionalized memory that allowed scientific discoveries to be cumulative.

grew, the soil in which it was planted, the roots that took hold in that soil, the stem that grew upwards, the leaves that fed the plant, and finally the flower that was the end result of all that earlier activity. We see the climate as Western pluralism as compared with the theocratic governments that unified religion and state authority in Islam and the highly centralized form of government under the Chinese emperors; the *seeds* in the human propensity to innovate in general and specifically in Europeans' drive to mechanize industrial activities; the *fertile soil* as several key Medieval institutions; the *roots* as medieval science as practiced by the scholastic philosophers; the *stem* as three important trajectories of technological advance that began in the early modern period and culminated in the dramatic innovations of the late eighteenth and early nineteenth centuries; the *leaves* as early modern science that culminated in Newton's *Principia;* finally, the *flower* as the two Industrial Revolutions that culminated in Europeans' institutionalizing of the processes of invention and innovation in the later part of the nineteenth century. The flower analogy also underlines our evolutionary view of the growth process as opposed to an equilibrium one that is more in the neoclassical tradition. This outline also makes it obvious that we reject explanations that can be expounded in simple aggregated and abstract models.[26]

The climate: pluralism versus centralization

The West's pluralism developed throughout the Medieval period but it had its roots in earlier times. In an important historical accident, of which there are many in our story, Christianity was initially spread by persuasion. It had to make its way in the highly sophisticated world of the Roman Empire and, as a result, the church fathers became versed in contemporary learning. When Christianity finally became the official religion of Rome in 391 AD, the government of the empire was well established so that a separation of power between the lay and the religious authorities was the only mutually acceptable arrangement.

In contrast to all this, Islam was spread through conquest in the first century of its existence. As a result, religion and government were unified in a theocracy, a form of government that is still found in many Islamic countries. Also, no attempt was made to convert the conquered people, most of whom voluntarily adopted Islam in their self-interest over the next couple of centuries. (Although other religions were tolerated, many laws and practices favoured believers over infidels.) Thus, there was no pressure for the religious authorities to become knowledgeable in contemporary learning and they largely remained aloof from it. These Islamic governing institutions gave religious extremists much more influence over non-religious matters than in the pluralist states of the West. Although religions extremism was no less a force in the West than in Islam,

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[26] We discuss many of the issues touched on in this section in Chapters 7 and 8 of LCB and in Bekar and Lipsey (2004). Here the treatment must be sketchy, omitting much of the corroborative detail.

its targets differed. Because the Catholic church had embraced Greek science, the destructive force of Western extremism was directed at other groups, such as heretics and usurers, rather than natural philosophers. In contrast, because Greek science was regarded as suspect by the Islamic authorities, the force of extremism was often directed at natural philosophers and institutions, such as the observatories and hospitals, where they resided. Because it was a vast empire that was difficult to control from the centre, there was substantial pluralism in various activities in various parts of the Islamic empire, particularly in the Islamic parts of Spain. But the political-religious unity in the theocratic form of government contrasted with the constant stress between church and state in the West and this had lasting effects – effects that eventually contributed to the suppression of the centuries-old tradition of advancing science and technology in the Islamic countries, which included the destruction of the major observatories and hospitals by religious extremists.

Unlike the West's pluralism, China had a highly centralized form of government in which all authority stemmed from the emperor. When the emperor commanded, the country followed, as when China was closed to outside influence by official decree in the sixteenth century, banning all foreign travel and trade.[27]

It is important to keep in mind my thesis that although some set of favourable institutions is necessary for sustained growth, no one element in what ever set did the job, was either necessary or sufficient. Thus, although pluralism was an important part of the Western set, there is no contradiction in it existing in many other places that did not produce sustained growth – as it no doubt did.

The seeds: the drive to mechanize[28]

The seeds of all technological flowers lie in the human propensity to innovate that we discussed in an earlier section. These generalized seeds took one specific form in the European drive to mechanize productive activities during and after the medieval period and after, a drive that eventually led to the Industrial Revolutions.

For one example, the water wheel that had been used to grind grain for centuries was adapted in the medieval period to mechanize a wide range of activities, making use of the newly invented cam that turned rotating motion into reciprocal motion.[29] Early uses of water wheels in Europe, together with the dates at which this use of each has been first substantiated, include: making

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[27] 'By 1500, anyone who built a ship of more than two masts was liable to the death penalty, and in 1525 coastal authorities were enjoined to destroy all ocean-going ships and to arrest their owners. Finally, in 1551, it became a crime to go to sea on a multitasked ship, even for trade' (Landes, 1998: 96).

[28] This propensity to mechanize has been documented in many places. See, e.g., Gimpel (1993), Gies and Gies (1994), and White (1962 and 1969).

[29] These data are drawn largely from Gies and Gies (1994).

beer (987), treating hemp (1040), fulling cloth (1086), tanning leather (1138), sawing logs (1204), making paper (1238), grinding mustard (1251), drawing wire (1351), grinding pigments (1348), and cutting metal (1443).[30]

Importantly, the iron industry was transformed by water power. Stamping mills broke up iron ore prior to smelting. Trip hammers forged the blooms. Water-wheel driven bellows allowed blast furnaces to become hot enough to melt iron so that it could be cast just as bronze had been for millennia. Cast iron became an important new product with many uses. Note also that although the Europeans did not invent paper, shortly after it was introduced from the East, Europeans replaced the production methods that have existed everywhere since paper's initial invention by mechanizing it.

A later example is Leonardo di Vinci's program to mechanize all aspects of textile production. As we have seen, this began a trajectory of mechanization that lasted several centuries and eventually led to the First Industrial Revolution.

The soil: medieval institutions

Four key institutional developments that occurred in the second half of the Medieval period provided the rich soil in which the plant's roots were established: the rise of a pluralistic and evolutionary concept of law, the development of the concept of the corporation, pluralism in government, and the development of universities. Although we must discuss them separately, their evolution was interrelated.

The legal revolution:[31] After the victory of the church over the kings in the investiture controversy (1050–1122), the church created a body of cannon law, including the new concept of natural law. This was rooted in both divine revelation and in human reason. Because natural law is also God's will, neither the King's nor the church's law is superior to it. This was a major achievement in that reason and conscience was held to be at least as important as royal proclamations and revelation – a proposition unthinkable both in Islam and imperial China.

> What took place in the eleventh, twelfth, and early thirteenth centuries in Western Europe was a radical transformation that created, among other things, the very concept of a legal system with its many levels of autonomy and jurisdiction and its cadres of legal experts… . [This] was not only an intellectual revolution, but a social, political, and economic revolution whereby new legal concepts, entities, procedures, powers, and agencies came into being and transformed social life. (Huff, 1993: 124–125).

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[30] There is debate about how extensively these innovations were used, but there is no doubt that each did occur and that they revealed a desire and an ability to mechanize many productive activities.

[31] This important issue is discussed in detail in Huff (1993: Chapter 4): 'The European Legal Revolution'.

Western law was now able to evolve and adapt to changing circumstances. In contrast, thinkers of many other religions, including Islam, held that laws had been laid down for once and for all by prophets and could only be changed when they had been misinterpreted or misunderstood. In China, laws could be changed, but only when the emperor willed it. This European split between civil and ecclesiastical law gave rise to the concept of degrees of jurisdiction absent from both Islam and China.

The concept of a corporation: One of the West's greatest institutional innovations was to develop the concept of a corporation, separate from the state and distinct from its members. This gave the corporate body a life that stretched beyond that of its current members and facilitated the development of a body of rules, practices, and standards that had not only continuity, but also flexibility. Corporations also encouraged pluralism by creating a split between civil and ecclesiastical law on the one hand, and the corporate law on the other. No equivalent institution developed in either Islam or China.

Medieval universities: The West's early teaching institutions evolved into universities, first as mere collections of scholars and then as corporations. The corporate structure provided a neutral space where new ideas could be developed more or less free from state and religious censure. It also allowed the development of curricula and examination standards that were more than just the expression of the views and whims of the current staff.

It has been argued (Makdisi, 1981) that the concept of a university, as a place where scholars and their pupils gathered to study the full range of known scholarship, was an Islamic invention. Be that as it may, Islamic universities remained collections of scholars, each one of whom set his own standards and issued his own certificate of competence to his students. So they never developed the corporate structure that was critical in protecting Western universities from excessive outside interference. Thus, as with so many other innovations, the West was not the original inventor; instead it critically improved on technologies and institutions that it had copied from elsewhere.

The Western universities taught many subjects, but, most important from our point of view, was the enormous importance put on Greek science that was taught to, and debated by, the entire body of students in the arts faculty. Through its universities, 'the West took a decisive (and probably irreversible) step toward the inculcation of a scientific worldview that extolled the powers of reason and painted the universe – human, animal, inanimate – as a rationally ordered system' (Huff, 1993: 189). In contrast, because Greek science was suspect in Islam, it was largely taught outside the universities by isolated scholars, instead of being at the heart of the university curriculum as it was in the West. In China, educational institutions took their curriculum almost exclusively from the examinations to enter the imperial bureaucracy. Although these were highly sophisticated, they were almost totally devoid of scientific content.

The roots: medieval science

When lay learning more or less disappeared in the centuries following the dissolution of the Western Roman Empire, learning was maintained and cultivated by the monasteries, carrying on the tradition of learning within the church that was established in the early days of Christianity in the Roman Empire. So, when the lay interest in education arose in the eleventh century, clerics were prominent in helping it to develop. Clerics taught first in the schools and then in the universities, while students were granted temporary clerical status.

In yet another important historical accident, the Greek works that were available in the early stages of the Western revival of learning were all in the form of Latin translations. These included the works of Plato and many others, but not Aristotle. Plato's mysticism sat easily with Christian doctrine, while many other Greek works on such subjects as astronomy, mathematics, medicine, and logic were of obvious practical value. During this time, the church, led by the scholastic philosophers, became committed to the view that there was no conflict between Christian dogma and Greek science, and both were taught to all students. Then much later on, the works of Aristotle became available in new translations. Here there was obvious conflict because of Aristotle's views, such as that the world had no beginning and no end and that the soul died with the body's death. After a major doctrinal battle that lasted almost a century and in which Thomas (later Saint Tomas) Aquinas was central, those who supported Greek science as compatible with Christian doctrine won the day.

Aristotle's naturalistic doctrines were placed at the centre of the arts curriculum and were important in developing the religious-intellectual mindset of the Medieval period. 'Anyone who reads these works [of Aristotle] or compares them with the philosophical writings of China cannot fail to see the uniqueness of the Aristotelian emphasis on explaining the natural world in terms of fundamental elements, causal processes, and rational inquiry' (Huff, 1993: 335). When this had been done, 'a powerful, methodologically sophisticated, intellectual framework for the study of nature had been institutionalised' (Huff, 1993: 337). By the fourteenth century, most Western academics and church thinkers regarded the world as subject to natural laws, which had been promulgated by God and were meant to be discovered by his human subjects. Thus doing so was a reverent activity.

In contrast, when the Islamic religious authorities decided to translate Greek learning into Arabic (and in the process greatly enriched that language), they immediately encountered Aristotle. Not surprisingly, therefore, his works were rejected and Greek science was placed in an inferior position to the knowledge from the Koran. Science was tolerated where it was useful, but not taught in the universities. Also, after much debate, Islamic thinkers accepted the doctrine of 'occasionalism', that God recreates the universe each day. If effect *B* follows cause *A* today, it may not do so tomorrow because God may will differently. It followed that to attempt to discover laws that predict the future behaviour of natural things was an attempt to predict what God would do in the future. That was a blasphemous activity.

We can only speculate as to what would have happened if the early Christian thinkers had encountered Aristotle as soon as they began to explore Greek learning. At the very least, those who felt that Greek science should not be placed on a par with religious knowledge and those who favoured rejecting it completely would have had a much stronger case. They might well have won the day with anti-intellectual consequences similar to those that ensued in the Islamic world. Such historical accidents illustrate that there was no direct and inevitable road that led from the dissolution of the Roman Empire to the Industrial Revolutions of the eighteenth and nineteenth centuries.

We now come to what my co-authors and I argue is the most important contribution that the Western universities made to Western science. All cumulative advances require some form of 'memory' so that present advances can build on those of the past. Artefacts provide an unplanned, and unmanaged, memory for technological knowledge. They have a physical existence and improvements are embodied in better artefacts to be used and improved in their turn. In contrast, there is no automatic memory for scientific knowledge. Creating an institutional memory for science was an important contribution of the Medieval Western universities: it was recorded in libraries; it was taught in class rooms; scholars contributed to its evolution.[32]

Because the institutions to provide continuity were lacking in both China and Islam, many scientific discoveries were made but subsequently forgotten.[33] The impressive list of Chinese scientific discoveries, many of which were subsequently forgotten, is too long to include here. A partial list would include, advances in mathematics, understanding fossil evidence, and advances in optics. But none of these discoveries was pursued in ways that established sustained cumulative trajectories.

Europe was not unique in its early scientific and technological discoveries, many of which were made even earlier in China and Islam. But what was unique in generating the incremental, cumulative advances that were necessary to produce modern mechanistic science, which was the science of the First Industrial Revolution, and the more advanced science that was necessary for the Second Industrial Revolution, was the institutional memory provided by the medieval universities.

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[32] Then, after the Catholic church turned against early modern science by rejecting the heliocentric view of the universe, the printing press provided the necessary memory for scientific discoveries and a means of disseminating them. Both Chinese and Islamic authorities rejected this innovation because it would encourage independent thought in opposition to official positions (see the discussion of printing in LCB: 175–182).

[33] See Qian (1985) for detailed discussion and illustrations of this important point.

The contrast between physical memory for technologies and institutional 'memory' for scientific discoveries is important in answering the question: Why is it that other regions in the world, especially those with important historical achievements in science and technology, failed to produce modern mechanistic science and the sustained innovations that came to depend on it and that were the basis of the First Industrial Revolution? Our answer is that they lacked the independent institutions that provided an effective memory needed for cumulative scientific advances. This is why there is no contradiction in the Chinese being close to the West in technology (and many other facets of civilization) in 1700 as argued by Pomeranz (2000), but already far behind in science.

The stem: three trajectories

The transition to sustained growth brought about by the two Industrial Revolutions was to a great extent the result of the culmination of three trajectories that combined scientific and technological developments over several centuries.[34] The first was the steam engine whose modern trajectory began in the sixteenth century with investigations into the nature of steam and of vacuums and culminated with the development of the high-pressure engine at the beginning of the nineteenth century. The second was automated textile machinery, whose research program was charted and begun by Leonardo di Vinci late in the fifteenth century and culminated when the centuries-long trajectory of myriad inventions and improvements produced machines that it paid to transfer textile production from cottages to proto-factories in the latter part of the eighteenth century. The third was electricity whose modern development began with the publication of Gilbert's *De Magnete* in 1600. It put the West decisively ahead of China in understanding magnetism and electricity by making it a science rather than a piecemeal collection of individual observations.[35] This began the long chain of linked discoveries that eventually led to the invention of the dynamo in 1867.

In this context, it is important to remember that the existence of a trajectory does not imply historical inevitability. A trajectory is a path-dependent process in which each step is influenced by the preceding steps, as, for example, each new scientific discovery and technological invention builds on previous discoveries and inventions. But although the next step is influenced by the past steps, its size and direction are not inevitable. For example, when we decide to develop some forms of alternative energy, what we are able to do depends partly on what we have done and learned in the past. But there is nothing inevitable as to whether we put our major efforts into geo-thermal, wind, or solar power, or equally

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[34] We describe these three critical trajectories in detail in LCB, pages 243–244 for mechanized textile machinery, 249–252 for the steam engine, and 254–255 for electricity.

[35] For full discussion see Pumfrey (2002).

among all three. The past will influence what we are able to do along these lines, but it does not determine which line we take.[36]

The leaves: early science and technology

For the scholastic philosophers, *a priori* reasoning was the major road to new knowledge. The early modern scientific revolution was based on a change in method: accepting experiment as *the* way to settle debates about empirical issues. As a result, early modern science developed mainly through piecemeal empirical discoveries concerning issues that had been long debated by the scholastic philosophers. While new answers were given, the investigators were continuing a research agenda laid down by the scholastics. Importantly, 'a scientific revolution could not have occurred in Western Europe in the seventeenth century if the level of science and natural philosophy had remained what it was in the first half of the twelfth century. . . .' (Grant, 1996: 170).

In the first two centuries (the sixteenth and seventeenth) of the three main technological trajectories that led to the Industrial Revolutions, investigators settled many issues that had been debated for centuries and at the same time made technological applications of what they discovered. Indeed, these two activities were not distinguished and were typically done by the same person. The distinctions between pure science, applied science, and engineering did not emerge until the last half of the nineteenth century: 'We separate science from religion, science from technology, theories from practices. They did not' (Jacob, 1997: 104).

We detail these interrelations in LCB Chapter 7. I only have space here for one illustration. Investigations into the nature of steam began in the sixteenth century. It was originally thought that steam was just a form of air. Early work by Cardan and Porta provided a better understanding of the relation between the two. De Caus (1576–1630) showed that steam was a form of water that returned to its liquid state on cooling. Pascal and Torricelli's showed that the atmosphere had weight. Otto von Guericke produced the first workable airtight cylinder and piston, which provided a technological advance that was necessary for the subsequent development of engines first driven by atmospheric pressure and then by steam. 'The discovery of the atmosphere thus profoundly affected the development of science ... [and] it was no less important in its impact on technology' (Cardwell, 1971:11). Although none of these early discoveries resulted in scientific laws as we now understand them, and although many seem obvious to us today, they 'were scientific discoveries of the utmost importance. They were the principles upon which the work of Worcester, Savery, and Papin

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[36] Similarly, England might have had remained a Catholic country at the time when the Catholic church was persecuting those who accepted the new heliocentric view of the solar system because the Royalist had won the civil war and the glorious revolution of 1688 had not occurred. The trajectory of English science and technology might then have been quite different from what it was and those countries that did become Protestant might have developed mechanical science and technology before the British.

[who developed the first engines that used steam and air pressure] was largely based' (Usher, 1988: 343).

The new world view of a mechanical universe that was generated by the scientific discoveries of the Early Modern Period reinforced the long-standing European interest in mechanizing human activities wherever possible – an interest illustrated by our earlier discussion of the windmill and textiles. As the accumulating evidence slowly refuted much of Aristotle's writings, a new overarching framework was required to systematize the new knowledge and Newton's *Principia* (1687) provided it. Its laws of motion were the first modern scientific laws as we understand them. They explained in mechanical terms the behaviour of all things in the universe. They were 'used not merely to calculate the movement of heavenly bodies, but also in practical arts such as navigation, cartography, ballistics, mining, and surveying, and these gave rise to the craft of instrument-making: the manufacture of telescopes, microscopes, barometers, chronometers, micrometers, dividing and gear-cutting engines, etc.' (Musson and Robinson, 1989: 23).

With the invention of the calculus, the mathematical language of Newton's general laws, science and technology took a decisive step by providing the mathematics of instantaneous motion and rates of change at a point in time and space. Its impact was revolutionary. It provided a mechanical world view that influenced most of science over the next 200 years. Its practical applications influenced many subsequent generations of innovators, particularly in Britain and later throughout all of Europe. 'In the eighteenth century, thanks primarily to Newton's work, mechanics became an organized body of readily accessible knowledge' (Jacob, 1997: 8). In our view, Newtonian mechanics provided the intellectual basis for the First Industrial Revolution, which was almost wholly mechanical.

The scholastic philosophers had taught that God created the universe and its laws and endowed humans with free will. It seemed to the British that Newton had completed the research program started by Aristotle and continued by the scholastics: discovering the laws of God that governed everything in the physical universe. Whereas the Catholic Church on the continent was still rejecting the Copernican heliocentric view of the universe (as were many of the early protestant reformers on the continent such as Calvin and Luther), many British clerics were preaching it from the pulpit as revealing the grandeur of God's creation. These laws were also spread throughout the land by a band of lecturers who taught science to ordinary citizens to an extent that would be unthinkable today.[37]

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[37] For a detailed account of how Newtonian mechanics came to permeate British society and its important place in the First Industrial Revolution, see Jacob (1997)

The flower: the industrial revolutions

The influence of mechanistic science was felt not just in the development of machinery, but also in canals,[38] harbours, mines, and a host of other applications. The role of science in all of this was not that of general laws leading to the development of specific applications. Instead, it permeated the thoughts and attitudes of ordinary people, providing them with the theoretical mechanics and the practical mathematics that facilitated technological change. This illustrates the fusion of theoretical and applied science, as well as engineering, that characterized the scientific world until well into the nineteenth century.

> Brought together by a shared technical vocabulary of Newtonian origin, engineers, and entrepreneurs – like Boulton and Watt – negotiated, in some instances battled their way through the mechanization of workshops or the improvement of canals, mines, and harbors ... [B]y 1750 British engineers and entrepreneurs could talk the same mechanical talk. They could objectify the physical world, see its operations mechanically and factor their common interests and values into their partnerships. What they said and did changed the Western world forever. (Jacob: 115, footnote removed)

The early part of the Industrial Revolution was *not* produced by the invention of radically new technologies. Instead, it was, as we observed earlier, the end result of technological trajectories that stretched over several centuries, most importantly, the trajectory marked out by Leonardo di Vinci (1452–1519) who conceived a program to mechanize most of the operations in the textile industry. His vision was slowly realized over the next three centuries by a host of piecemeal discoveries and innovations. By the late eighteenth century, the program had progressed far enough that it paid to transfer textile production from cottages to proto-factories – the putting out system that had lasted for several centuries was being replaced by an evolving factory system. No central authority had to engineer this change, it came about through market forces as innovators sought new sources of profit. (This illustrates the importance of another institution, the market. From the Bronze Age onwards, markets have played an important role in Western civilization, sometimes waxing and sometimes waning in importance, but never disappearing altogether.)

Some economic historians have characterized the inventors of these mechanized textile machines as 'tinkerers' who made mere 'gadgets'. I mention this because those views contribute to the belief that any group of people

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[38] Jacob notes that the accelerated construction of canals in the late eighteenth century brought many industrialists in close contact with engineers, both to provide expert knowledge to improve the efficiency of canals, and to provide testimony to Parliament to secure approval of various projects. In these efforts: 'They had come to accept the professionalization of scientific knowledge of a mechanical sort, to rely solely on engineers, preferably famous ones – if they were to be found. The promoters sat through parliamentary cross-examinations of experts, following in detail their estimates of the weight of water lost through the diversion of river water into a canal' (Jacob, 1997: 203).

anywhere in the world could have produced the First Industrial Revolution solely by empirical trail and error. In reply, I would like to make the experiment of taking apart one of the 1790-vintage, automated textile machines and asking one of these historians to reassemble it. Perhaps after that he would agree that these were, for their time, engineering masterpieces; machines that took several centuries to be developed under the guidance of very skilled and sometimes highly educated inventors and innovators.

By the early nineteenth century, developments in the three-century long trajectory that led to efficient steam engines had gone far enough that it became efficient to replace water and human power with steam power. Once again, no decree from the Emperor or the Pope was needed here, the market provided sufficient incentives to innovators seeking private profits. Production moved from sheds and water-powered mills to steam-powered factories. New machines and new factories had to be designed and built. Metal replaced wood in most machines and a whole new machine tool industry was developed. Industry became more concentrated as the scale economies of steam-powered factories required much larger productive units than did water power. Freed from the need to locate near fast-moving water, factories were moved to the new industrial towns. Major adjustments to the whole structure of the economy were required as masses of people followed, urbanizing the society to an extent not seen since Classical times. Fuel, raw materials, and finished goods, needed to be transported. This required an extensive network of canals and railroads. The new modes of transport introduced by the railway and later by the iron steamships altered many economic relations. The changes also initiated rising wages as steam power served to raise productivity. The age of steam was in full flower.

So the First Industrial Revolution produced radical changes in society, its institutions, and its infrastructure. As we have seen, however, it did not result from a sudden radical change in technology. Its technologies of textile machinery and the steam engine were the result of centuries-long trajectories of incremental improvements and a few radical changes made by a long line of inventors and innovators.

During the Second Industrial Revolution, starting in last half of the nineteenth century, industrial development was lead by many non-mechanical sectors that were heavily science-based. Chemicals and steel were two of its key products, while electricity and the internal combustion engine were its new energy sources. Advances in chemistry, especially as it was applied to textile production, were particularly important in supporting continuing innovations in such products as dyes, bleaches, detergents, and fertilizers. All of these, and many more products and processes, required applications of fairly advanced Western science. As Rosenberg and Birdzell (1986: 252) put it:

> About 1875, the frontier of Western industrial technology began to move from the visible world of levers, gears, cams, shafts, pulleys and cranks to the

> invisible world of atoms, molecules, electrons flows, electromagnetic waves, inductance, capacitance, magnetism, amperes, volts, bacteria, viruses, and genes. The consequence was to change the main source of advances in Western industrial technology. The new sources were the interaction between work done by basic scientists, functioning in what amounted to an autonomous sector of their own, pursuing knowledge for its own sake, and funded by grants and subsidies not directly linked to economic values on the one hand and work done by industrial scientists functioning in the economic sector, and funded on the basis of the economic value of their work.

The flower becomes a perennial

Ever since humans ceased to be hunter gatherers during the Neolithic Agricultural Revolution, there have been bursts of growth, often based on the invention of some major new technology. But these have been episodic, usually petering out in decades, although sometimes lasting for centuries. What was different this time was that the growth became self-sustaining, building on itself in a positive feed back loop in which each scientific invention and its technological applications led to others in, as far as we can see, a never-ending evolution.

Three developments, two of them institutional, were key in allowing the growth initiated by the Industrial Revolutions to be sustained. First, as noted above, science and technology became increasingly linked. Not only did science contribute in a general way to technological developments, as it had in the past, new technological innovations increasingly stemmed directly from new scientific discoveries. Second, science itself began to develop much more rapidly as its teaching and advancement became institutionalized, particularly in universities. The number of practicing scientists increased exponentially over the decades of the late nineteenth and much of the twentieth centuries. As a result, the rate of advancement of scientific knowledge increased dramatically over what it had been throughout all earlier times. Third, firms, often operating in oligopolistic market structures, competed with each other by inventing and innovating new products and processes. As a result, technological invention was institutionalized with the development of the applied research laboratory. The ‘invention factory’ established by Thomas Edison at Menlo Park in 1876 ‘is usually credited with pioneering the organization of invention in the field of communications and electricity’. (Rosenberg and Bridzell, 1986: 249). Many firms followed Edison’s example and by the turn of the century the involvement of industry in organized R&D was significant and growing. David Mowery (1981: 51) has shown that 112 research laboratories had been established in the US manufacturing sector alone by 1898 with another 553 being established by 1918.

> By the early years of the twentieth century, industrial research had clearly turned toward the development of new products and processes. If the knowledge required for innovation lay on (or even a little beyond) the frontiers

> of science, the industrial laboratories worked the frontiers. (Rosenberg and Bridzell: 251)

Today, R&D is a major activity encouraged by significant tax incentives in most Western countries. Large oligopolistic firms in many branches of manufacturing and service industries engage in organized research as a major weapon in competition with their rivals. These efforts are conspicuous in drugs, medical supplies, aeronautics, transport equipment, lumber products, agricultural machinery, information and communication technologies, and biotechnology, to mention but a few of the most obvious examples. Also, small start-up firms on the cutting edge of new technologies do significant amounts of applied research.

7. The end of the beginning

This concludes my answer to the question: *How do we explain the emergence of rapid, sustained economic growth in the last 300 years?* With the institutionalization of invention and innovation, growth became sustained, and also rapid – at least by the standards of most of the world's previous history. Industrialization spread first to continental Europe and the United States then, much later, to many other parts of the world as they adapted Western technology and science and its key institutions such as Western style universities and research laboratories. Other areas experienced significant growth by being suppliers of food and materials to the industrialized nations. Later many of these areas learned to produce their own inventions and innovations endogenously in developments that are the direct progeny of the Western science and technology of the First and Second Industrial Revolutions.

But these are all parts of another story that goes well beyond the study of how growth became sustained in the West in the nineteenth and early twentieth centuries. So I say no more about them here.

8. Why not elsewhere?

If humans are inventive by nature, why did this propensity only result in the one Industrial Revolution that initiated sustained growth in Europe and not elsewhere, and why do some countries still not grow even when they have access to technologies already in use in other countries?

Note first that human inventiveness is not confined to science and technology. It is manifested in architecture, literature, painting, music, and other arts, as well as in social and political arrangements. Nonetheless, all societies, including hunter gatherers, have devoted substantial efforts to technological advance and many have also done so in science. But before the twentieth century, both efforts had reached plateaus in virtually all societies other than Europe, so that inventive and innovate urges were transferred to other lines of activity. Briefly, the explanation for these plateaus is that these efforts did not produce anything like the trajectory of cumulative scientific discoveries that characterized European science from at least the fifteenth century onwards. This failure is critical because the Second Industrial Revolution of the latter half of the nineteenth century could not have happened without fairly advanced science. We also argue that the First Industrial Revolution required science in the form of Newtonian mechanics. That is more contentious, but even in what seems to us the highly unlikely event that some other part of the world had succeeded through purely trial and error methods in inventing the mechanized textile machinery that inhabited early nineteenth century European factories and the steam engines that powered them, it could not have sustained growth though the next phase of the Second Industrial Revolution without the equivalent of Western science. Nor could it have institutionalized the invention process as was done by a union of science and technology in the research laboratories that were developed in the late nineteenth and early twentieth centuries. So their growth would have petered out at about the level of early nineteenth century technology, even if against all the odds it could have got that far.

Behind this proximate explanation, we need to ask why something like western science did not develop elsewhere.[39] The answer differs by country, but the Islamic countries and China seemed the most obvious candidates for doing so, at least up to the late medieval period. In Islam, the decline of science and technological advance that took place around the thirteenth and fourteenth centuries was the result of attacks by religious extremists who were given strong support by the theocratic form of government that did not distinguish between religious and lay laws and practices. These extremists attacked, often burned, and generally shut down, the astronomical observatories and hospitals that, in the absence of a corporate structure for the universities, were the two main Islamic institutions in which free scientific enquiry could be conducted, remembered, and hence develop along a cumulative trajectory.[40] The absence of a corporate structure for Islamic universities also left them with no institutional barriers to resist religious attack.

In China, although technological advance continued well into the early modern period, the absence of a mechanism to provide a collective memory for scientific advances was crucial in explaining why the many important but isolated Chinese scientific discoveries never produced a cumulative scientific trajectory of the sort that produced Western science. For example, the trajectory of cumulative discoveries that led to the steam engine and the dynamo never even began in China.

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[39] The whole of Chapter 8 in LCB is devoted to this issue.

[40] For a discussion of the rise and fall of these two institutions, see Huff (1993), pages 170–179 for hospitals and 179–186 for observatories.

9. Conclusion

I do not pretend to have presented here a full story of how the West grew rich, such as is found in Rosenberg and Birdzell (1986). I have concentrated instead on the more narrow question of how growth became sustained. While the details of the answer are subject of debate and revision, my co-authors and I believe that we have presented an incontrovertible case that to discover why growth become sustained, first in the West, and then spread throughout much of the rest of the world, requires detailed historical analysis of country-specific forces that cannot be captured by mathematical models (at least in the present state of the art) that, of necessity, omit almost everything that seems to have been important.[41] Two parts of our thesis are much disputed: that science was also highly important in the First Industrial Revolution, and our specific reasons why cumulative scientific discoveries developed in the West and nowhere else. Two other parts are, we think, incontrovertible. First, growth could not have been sustained through the Second Industrial Revolution without Western science. Second, the existence of Western science explains why the Industrial Revolutions happened where and approximately when they did, while the total absence of that science elsewhere is a sufficient reason why a similar industrial revolution did not happen, and could not have happened, endogenously elsewhere – and could not have so happened within some further centuries absent learning the relevant science from the West. We say ‘not within centuries’ because the path that started in the early modern period (and had earlier roots) and led to nineteenth century science could not been trodden overnight; the cumulative nature of learning imposed a trajectory that needed several centuries to complete. Yet it had not even begun elsewhere.

Finally, I note that my colleagues and I are not arguing for any superior form of Western ‘particularism’. Our view of agents and technological change is that all humans are innovative creatures. In a non-repressive environment, we expect all societies to innovate in reaction to the problems, challenges, and opportunities that they face. If some societies are more innovative than others, this is not due to anything inherent in their members but to differences in circumstances, often in institutions, many of which arose because of historical accidents. After all, once Western science and technology became available to the rest of the world, many other jurisdictions developed the institutions of universities and research laboratories designed to produce inventions and innovations locally. When freed from inhibiting forces, presented with opportunities, and possessed of the necessary institutions, inventive and innovative activity flourished. Local conditions are now needed to explain why some countries still do not

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[41] Anyone who wants to argue that mathematical models can explain ‘why in the West, and not elsewhere’, needs to construct a model, so far not done, that has aspects that will distinguish one economy for another and explain why one produced sustained growth endogenously while the others did not.

grow. Heavy handed government intervention,[42] such as characterized earlier communist regimes, is one explanation, and such intervention still persists in a few countries today. Lack of the basic necessary institutions such as the rule of law, plus ruinous civil wars are other contributory causes that have often slowed or halted growth. But the full and complex stories of today's growth successes and failures are beyond the scope of this already long paper.

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[42] Many types of government interventions can be useful in fostering growth, but not the heavy-handed intervention that characterized command economies.

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