

WHY WAS THE INDUSTRIAL REVOLUTION A EUROPEAN PHENOMENON?

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Introduction

The new growth economics has restored technological progress to the center of the debate about why economic growth occurs. There is no question that in some way new technology can bring about a period of rapid economic growth, whether measured in terms of productivity growth or in the more subtle improvements in the quality of life that occur through improvements in product diversity and attributes. The conventions of National Income accounting truncate to some extent the richness of the process, since they downweight inexpensive improvements that represent very large improvements in consumer surplus such as indoor plumbing, anaesthesia, and vitamin supplements.

Yet it remains an open question to what extent technology played an important role in economic growth before the Industrial Revolution. Most scholars tend to emphasize institutional changes that made more efficient allocations possible. These institutional arrangements form the core of the new Comparative Institutional Economics pioneered by Douglass North and Avner Greif, which has placed the spontaneous emergence of institutions that enforced contracts through better property rights, acceptable arbitration arrangements, and the kind of institutions that created strong incentives that overcame opportunistic behavior, rent-seeking, and reduce uncertainty. Such arrangements, it has long been understood, created a revival of commercial activity thus securing gains from trade, and allowed for a more efficient allocation of resources. For much of the pre-1750 periods, what growth there was seemed to emanate from such institutional changes. The rise of the Italian city states and the Dutch miraculous golden age were largely based on such historical processes. True, there were technological components to this expansion (especially those improving navigation and shipbuilding, providing defense against predators, and streamlining communications), but it is hard to argue that before the Industrial Revolution there was sufficient momentum to these changes to trigger much growth.

The reason for this is not the lack of inventiveness as such; from the early middle ages, Europe was in many ways a technologically creative society, as many authors have emphasized, none with a richer grasp of the facts and more élan than the late Lynn White. The reason why these inventions did not turn into a self-sustaining process of growth are explored in my book and I cannot only summarize them here. One explanation which has been quite influential has to do with *diffusion*: the inventions spread only slowly because of poor communications, the difficulty of adapting to local circumstances, and so on. Yet the speed at which some of the more spectacular medieval inventions, from eyeglasses to mechanical clocks to gunpowder to mapmaking spread, while slow by modern standards, still implies that knowledge flowed across regional and national boundaries without too much difficulty.

This was much aided by the invention of the printing press, of course, the growing mobility of people and goods, the existence of a lingua franca, and the creation of an international community of knowledge that corresponded with one another, read each others' books, and began to share standards for what was to be believed and what was to be rejected.

The real culprit for the lack of technologically-induced growth was that not enough was known. This seems to be a tautology, and requires some elaboration. Basically, the argument in a nutshell is that technology consists of *techniques* or *routines* which in the final analysis are sets of instructions – tacit or codified – that tell people how to produce. Yet these routines rest on some underlying body of “useful knowledge” about the natural phenomena and regularities that make them possible.¹ All techniques rest on some *epistemic base* that contains the knowledge of nature and the environment that makes it possible. Early farming still exploited knowledge of the seasons and the regularity that the offspring of two animals with some salient characteristic was more likely to display this characteristic. The popular distinction between “science-based” techniques and empirical techniques refers to the degree of formalization and generality of the knowledge, but this seems less than useful for the economic historian. Natural regularities may be as “unscientific” as the cataloguing of trade winds and the realization of the movements of the tides, which were harnessed for the techniques of transportation and shipping. Especially in the second half of the eighteenth century natural philosophers became less obsessed with “truth” and more with the cataloguing of measurable relations between variables, preferring to learn what could be computed and what worked (Heilbron, 1990). The modern notions of “science” may look as primitive to some future person as pre-Copernican astronomy and pre-Lavoisier chemistry do to us.

An epistemic base can be narrow or it can be wider. In the extreme case, *all* that is known is that a technique works. The measure of the epistemic base can just be bound between zero and infinity, since it is inconceivable that *everything* will be known. What we can say is that epistemic bases can become wider as more is known. To some extent, this is associated with the rise of modern science. But epistemic bases can also increase with engineering and artisanal knowledge, better understanding of the characteristics of animals and materials, improved knowledge of geography and topography and many other areas in which useful knowledge expanded but which are not necessarily part of the formal and

¹The term “useful knowledge” is defined in some detail in Joel Mokyr, *The Gifts of Athena: Historical Origins of the Knowledge Economy*, 2002. The term has been used by economists asking similar questions such as Machlup and Kuznets. See Fritz Machlup, *Knowledge: Its Creation, Distribution and Economic Significance*. 3 Volumes, 1980-84., Simon Kuznets, *Economic Growth and Structure*, 1965. For this paper it will be limited to knowledge pertaining to natural phenomena and regularities that can be harnessed for physical production.

generalized body of knowledge we call “science.” But the distinctions between these different “levels” of useful knowledge are of degree, not of essence. On the other hand, the distinction between knowledge “how” and knowledge “what” is a useful one, reflecting a genuine hierarchy: the former has to rest on the latter.

Historically, the epistemic base of techniques matters for two reasons. First, the relation between the epistemic base and the technique that rests on it in a static sense is much like the ratio of the fixed and variable factor in economics: if the epistemic base of a technique is narrow, it will be difficult to expand and improve the technique, to find new applications, and to adapt it to changing circumstances. The broader the epistemic base, the more likely it is that technological progress can be sustained for extended periods before it starts to run into diminishing returns. Second, however, if the epistemic base itself is changing alongside the technique (and perhaps because of it), positive feedback can create an unstable system due to the interaction between the knowledge of “what” and the knowledge of “how.” Before 1750, on the whole, the relation was stable. New inventions appeared and created considerable social and economic change, but inevitably reached a plateau from which further improvements became more and more difficult: whether we look at ship-building, textile machinery, fire-arms or pumping technology, we see breakthroughs, followed by a gradual petering out of further improvements.

The Industrial Revolution changed all that: the remarkable thing about it was not that between 1760 and 1800 a “wave of gadgets” appeared, but that after 1820 this process not only did not peter out but gathered force in continuous improvements, new applications, and extensions. While the inventions of the 1820s and 1830s – excepting the railroad – perhaps do not figure as prominently in high school textbooks as those of Watt, Cort, and Crompton, they are the ones that made the difference between what would have become another technological blip and the expansion of the British and other European economies after 1830. Those inventions included, of course the high pressure steam engine and its applications, but also the extensions of the techniques used in cotton to other fabrics, the introduction of the self-acting mule (1825), Neilson’s hot blast (1829), the telegraph, and the growing use made of chemical and physical knowledge in manufacturing and agriculture after 1840. These techniques rested on epistemic bases that were getting wider. That is not to say that they were, by our standards, well-understood, only that they were *better*-understood.

Since so much depended on the growth of these epistemic bases, we may well ask what determined their historical evolution. We can, of course, establish some arguments as to the institutional arrangements under which knowledge will expand and grow. Repressive and reactionary regimes, in which heretics and deviants are mercilessly persecuted, or introverted cultures in which educated and creative people spend their mental efforts reflecting on the meaning of the soul and spirit rather than

on what makes machines tick and fields sprout are of course not likely to generate much new useful knowledge. But among those societies that have the potential to create such knowledge, it is simply impossible to predict why a particular scientific area sustained a great deal of progress and knowledge moved in a particular direction rather than in another. Scientific advance is of course a sequential process, in which steps follow from one another and a fair amount of serial correlation is built into the system. At the same time research agendas are set in part as the result of perceived needs (or at least areas in which advances will have a high payoff). There is a great deal of uncertainty in these agendas, however, and they are influenced and constrained by religious, social, and political factors in ways that are poorly understood. What should be stressed is that this knowledge is often influenced by the rather unpredictable advances in research and observation technology. This point was made by Derek Price in 1984, who has termed such advances “artificial revelation.” The invention of the telescope or the Petri dish may have been fairly minor advances relative to what was known before, but they changed the knowledge base of society dramatically by creating better research tools. Such “adventitious” advances as Price calls them explain why astronomy and microbiology advanced as rapid as they did.²

It is in part because of this lack of historical determinacy that many historians and philosophers of science feel attracted to an “evolutionary” approach to knowledge. This school, which originated in the 1950s and 1960s in the writing of Stephen Toulmin, Karl Popper, and above all Donald T. Campbell, feels that much like the historical evolution of living beings, the development of knowledge is subject to contingent forces that cannot be fully predicted.³ The analogy, despite many pitfalls elaborated elsewhere, has the advantage of highlighting what we can and cannot know about innovation.⁴ This mode of thinking has been applied to the history of technology with some success.⁵ The lessons we learn from the evolutionary approach is that we can identify the elements that make a particular social environment more innovative, but the general direction of innovation, to say nothing of its exact form,

²Derek 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. 1984.

³Stephen E Toulmin, “The Evolutionary Development of Natural Science,” *American Scientist*, Vol. 55, No. 4 (December 1967), pp. 456-471. Donald T. Campbell, “Variation and Selective Retention in Socio-Cultural Evolution” in *Social Change in Developing Areas: a Reinterpretation of Evolutionary Theory*, edited by Herbert Barringer, George I Blanksten and Raymond W. Mack. Cambridge, MA: Schenkman Publishing Co., pp. 19-47. id., “Unjustified Variation and Selective Retention in Scientific Discovery.” in *Studies in the Philosophy of Biology* edited by Francisco J. Ayala and Theodosius Dobzhansky, 1974, 139-61. Id., “Evolutionary Epistemology” in *The Philosophy of Karl Popper*, edited by P.A. Schilpp, 1974, 413-63.

⁴Joel Mokyr, “Science, Technology, and Knowledge: What Historians can learn from an evolutionary approach.” Max Planck Institute for Research into Economic Systems, Working Papers on Economics and Evolution, # 98-03, 1998.

⁵Walter Vincenti, *What Engineers Know and How They Know It*, 1990. John Ziman, ed., *Technological Innovation as an Evolutionary Process*, 2000.

are no more predictable than the emergence of giraffes or llamas were when the dinosaurs were wiped out at the end of the Jurassic and mammals got their chance. Contingencies have an enormous role to play in the history of technology, not just in determining between more or less equivalent outcomes (say, the qwerty keyboard as opposed to any other, or the use of Windows operating software), but also in the emergence of techniques without which economies and individuals would look quite different. Evolutionary thinking focuses the attention away from a sole occupation with averages and population distributions, and stresses that what matters to history is that very rare events get amplified and ultimately determine the outcome.⁶ A small number of individuals – though perhaps rarely *one* single person – discovered, imagined, and created the new knowledge, then managed to persuade others to accept and “select it.” Robert Hooke wrote in 1666 that the men who created “something of use to themselves or mankind” were much like a “Cortesian army, well-disciplined and regulated, though their numbers be but small.”

Such evolutionary analogies should be tempered. Unlike mutations, new knowledge is not orthogonal to the perceived needs of society. All the same, the correlation is not so strong as to disarm “selection” as a means of direction. This dual mechanism, in much altered form, carries over from a Darwinian world: the emergence of new knowledge and techniques is conceptually governed by one set of forces, their selective retention is governed by another – though at times of course the two blend into one another, as the literature of induced innovation has abundantly shown.⁷ Institutions, then, are crucial not only in the efficient allocation of resources and the reduction of uncertainty in exchange relations, but also in the emergence of new techniques. Institutions determine the resources allocated to produce new knowledge and the agendas of what is to be explored and what is taboo. But they also determine the selection mechanisms of new techniques. These selection mechanisms are normally blends of market mechanisms and centralized decision making. In a pure *laissez faire* competitive world, consumer sovereignty in the end determines which techniques “live” (that is, are actually used) and which are abandoned. All economies, in one form or another, constrain such choices for a variety of ethical, social or political reasons.

There is a deeper difference between the evolution of knowledge and that of species. One extreme view argues that science – as opposed to the symbols it uses – is not really socially contexted, but simply discovers what is already there. The analogy is the discovery of the New World in 1492; it

⁶John Ziman, “Selectionism and Complexity.” in John Ziman, ed., *Technological Innovation as an Evolutionary Process*, 2000, pp. 41-51.

⁷Vernon W. Ruttan, *Technology, Growth, and Development: an Induced Innovation Perspective*, 2001.

is hard to argue that America was a social construction and that only by being persuasive and powerful did Columbus and Vespucci convince others of its existence. Similarly, the germ theory worked not because of Pasteur's political adroitness but because these germs are really there.⁸ Relativity, quantum mechanics, the structure of DNA are all "discovered," in this view. The more extreme versions of this positivist and Whiggish approach to the history of science have justly fallen in disrepute. After all, the supporters of phlogiston, the humoral theory of disease, and the ether enveloping the earth were just as certain that they were correct. At the same time, there must be natural regularities and laws we do not even suspect could be true any more than Lord Kelvin suspected quantum theory could exist or than Jean Baptiste Lamarck had any clue of molecular genetics. Somewhere between the nihilism of the social constructivists and the absolutism of the positivists, social scientists and economic historians have to carve out a reasonable position. Constrained contingency seems to me is such a position, and it is perfectly consistent with evolutionary thinking. There was nothing inevitable about the emergence of homo sapiens, of giraffes, or of platypuses. But a lot of life forms are impossible, excluded by the laws of physics, chemistry, or by history. Within the limits of the possible, similarly, useful knowledge and technology emerged. But they picked certain avenues, and not others.

The sources of contingency in the development of technology are thus multiple.⁹ For one thing, the development of the knowledge underlying technology is itself very hard to predict, as I noted above. Secondly, the institutions governing (1) the emergence of such underlying knowledge, (2) the likelihood of it being applied to new techniques ("invention"), and (3) the chances of such new techniques being "selected" are themselves contingent. We do not have a good theory of why some societies developed one kind of institutions or another, why some adopted the rule of law and constrained taxation, whereas others seem to end up in a very different, low-level state. Clearly, the complex interactive processes that determined what kind of institutions predominate in each society allowed for multiple stable equilibria. The uniqueness of the Industrial Revolution is that it somehow changed the parameters that determined the stability of one subsystem to the point where they violated what economists refer to as the second order conditions. Once that happens, in a global system, no other system – no matter how stable in and of itself – was safe. Tokugawa Japan, central Africa, Romanoff Russia, and Qing China may have been relatively stable societies (at least as far as long-term change was concerned), but once things started to

⁸For an approach that seems to be uninterested in that fact, see for instance Bruno Latour, *The Pasteurization of France*. Cambridge, Mass 1988.

⁹A *contingent* event is one that requires many necessary causes that are not perfectly correlated with one another. The larger the number of such factors, and the lower their correlation, the more we can define the event as contingent. This is not the same as saying that the event was accidental or unlikely, which requires a statement on the likelihood of the necessary causes to occur.

change in Europe and its offshoots, these stability parameters were no longer invariant.

I will therefore argue that the changes in the generation and utilization of useful knowledge during the Industrial Revolution were central to irreversible historical turn that occurred. To be sure, we can trace the historical roots of the institutional background for the Industrial Revolution quite well. I have elaborated on these elsewhere, and reader is referred to these papers. Here I wish to explore a slightly different question: had the institutions that favored it in western Europe not existed, would any other institutional set-up brought about a similar outcome? Were cotton-spinning machines, diesel engines, and freeze-dried coffee inevitable, so that if Europeans had not thought of them some other civilization would have? Or was the Industrial Revolution and the modern technological age it spawned a uniquely “Western” phenomenon?

Useful Knowledge in History

The *specific* forms and manifestations that western technology took were certainly contingent, but they may not have mattered. Had the West “selected” lighter-than-air instead of fixed-wing aircraft or funicular instead of locomotive-pulled railroads, its economic success and political domination would have been little changed. However, if the useful knowledge on which western techniques are based is allowed to change, and if the meta-rules by which intellectual resources were allocated, research agendas chosen, and hypotheses formulated and tested had been radically different, the technological face of society would have ended up very different indeed.

Moreover, if the selection rules by which new techniques are chosen were changed, the same would have been true. The religious strictures that prevented Islam from adopting the printing press for centuries and the politics of insulation and the ban on firearms practiced by Tokugawa Japan should remind us that such selection rules may have profound influence even when the underlying S-knowledge has become available elsewhere. For the present purpose, however, I shall focus on the knowledge alone, since the issue of selection would get me into profound social and cultural issues beyond the already quite ambitious scope of this paper. Can we picture what Western technology would have looked like in the absence of certain epistemic bases?

For instance, the growth in the understanding of electricity in the eighteenth century was slow and halting. Many scientists, such as the great eighteenth century French physicist Coulomb, and a pioneer of electricity theory, believed that magnetism and electricity were unrelated. But in 1819 a Danish physicist, Hans Oersted, brought a compass needle near a wire through which a current was passing. It forced the needle to point at a right angle to the current. It turned out that electricity and magnetism were related after all. From this point on, the knowledge basis started to increase quickly,

and what happened subsequently may well be considered close to inevitable. Electro-magnetism, once discovered, was turned into a legitimate field of inquiry by the work of William Sturgeon, Michael Faraday and above all Joseph Henry. Their work in turn informed Charles Wheatstone, the scientist consulting William Cooke, as well as that of Samuel Morse. The first successful submarine cable was laid by Thomas Crampton's Company between Dover and Calais in 1851, and became a technological triumph that lasted thirty seven years. The knowledge of natural phenomena uncovered by Oersted thus served as the basis for the utilization of electrical current to affect a magnetized needle that transmitted information at a speed much faster than anything previously possible, a classic "macroinvention." But the technique and its underlying epistemic base kept enriching and improving one another. The positive feedback between formal useful knowledge, that is, science, and the techniques in question took place in this case through the interest and ingenuity of William Thomson, later Lord Kelvin.

The early nineteenth century was a period in which "demand" for rapid communications was increasing, in part because the French revolution and the pursuant wars increased the need for rapid long-distance communications, but also because of the integration of capital markets and the development of railroads. Was the electromagnetic telegraph "inevitable"? It seems to depend crucially on whether we think that the advances in the understanding of electromagnetic phenomena, above all Oersted's discovery, was inevitable. It is inconceivable that Oersted would have been able to conduct his famous experiment without the Voltaic battery invented 20 years earlier. But we can be more precise than that. In this particular case, it is fairly straightforward to speculate that in the presence of electricity, but without Oersted, electrochemical telegraphs were a viable alternative, though they too depended on Voltaic piles.¹⁰ Until deep into the 1840s inventors experimented with electrochemical telegraphy. It never did attain practical success, but it could have, had it not been for the greater effectiveness of electromagnetic techniques.

In the absence of Voltaic piles or similar devices relying on a growing understanding of how to generate a weak electrical current -- which would have thwarted all electrical telegraphy -- something quite different would have emerged. Chappe's semaphore system, a mechanical telegraph based on a much simpler knowledge base, was used quite widely in the first decades of the century. In the absence of sufficient knowledge, it might conceivably have become the "norm" for long-distance commu-

¹⁰The idea of using the chemical effects of electricity as a means of long-distance communication was proposed as early as 1795 by the Catalan scientist Francisco Salvá and worked out in some detail by the Bavarian S.T. Von Soemmering in 1809.

nications albeit in forms modified beyond anything we can imagine.¹¹ It would have been less “efficient” than what actually emerged, but nobody would have known, just as we cannot know of possible techniques that were for some reason beyond our reach but just never occurred to anyone.

This example is meant to illustrate the basic point that, given a certain basis of knowledge, the right institutional set-up and a certain amount of luck, many inventions or their equivalents seem to have been quite probable *ex ante* and some perhaps inevitable. But this only pushes the question one step back: how likely was it for the background knowledge itself to emerge? As I have argued elsewhere, the scientific revolution of the seventeenth century created what might best be called an “industrial enlightenment” in which natural philosophers and experimentalists teamed up with industrialists and engineers, and jointly created the kind of environment that was uniquely favorable to rapid innovation.¹² Suppose these intellectual developments had not happened in Western Europe. Would some other area in the world have followed a somewhat similar pattern? Would, for example, Africans have eventually invented a steam engine if left alone by Europeans? The critical question is not whether there is coal in Africa (there is) or whether Africans had the iron-working skills (they did), but whether the underlying knowledge of atmospheric pressure would ever have occurred in an African setting.

The assumptions underlying any such analysis should be made explicit. First, they assume that there are natural regularities and phenomena that transcend social context, and that while their representation may vary amongst different cultures, they ultimately represent self-evident properties that are naturally determined but discoverable and comprehensible by humans. Nature poses certain challenges and constraints that matter to the human material condition, and overcoming these constraints is what technology is all about. To overcome them, we need to *know* things that can serve

¹¹The Chappe semaphore telegraph, operating through France as well as in other parts of Western Europe, was quite successful: it could transmit under optimal conditions a bit of information from Paris to Toulon in 12 minutes in contrast with the two full days it would take a messenger on horseback. A 100-signal telegram from Paris to Bordeaux in 1820 took ninety five minutes, in 1840 half that. Given that a “signal” was picked from a code book with tens of thousands options, this was a huge amount of information. The optical telegraph at its peak covered 5000 miles and included 530 relay stations. The Chappe system was a government monopoly and did not serve as a means of transmission of private information, yet in the absence of the electrical telegraph there is no reason why it could not have played a much larger role. Another widely used visual telegraph was developed in 1795 by George Murray in England. This system rapidly caught on in England and in the United States, where a number of sites bearing the name Telegraph Hill or Signal Hill can still be found, particularly in coastal regions. Cf. Alexander J. Field “French optical telegraphy, 1793-1855: hardware, software, administration.” *Technology and Culture* 35 (1994): 315-48; Daniel Headrick, *When Information Came of Age: Technologies of Knowledge in the Age of Reason and Revolution, 1700-1850*. New York: Oxford University Press, 2000.

¹²Particularly in Scotland the connection between scientists such as William Cullen and Joseph Black and an audience that demanded that knowledge be made socially useful was quite close. Such connections of course could converge within a single mind: Humphry Davy, Count Rumford, and later Charles Wheatstone and Lord Kelvin all represent examples of scientist-inventors, in which the epistemic base and its application to a specific technique took place in the confines of a single mind.

as epistemic bases.¹³ But the form that the search for this knowledge takes, the effectiveness and results of the search, and the way societies use this knowledge are all quite variable.

In any event, asserting that certain natural regularities are knowable does not guarantee that they will be known. For that to happen, three conditions have to hold. First, society needs to create the incentives that make it worthwhile to investigate nature. Individuals who discover natural facts or laws that are in some way useful need to be rewarded by society or at least not punished as potential heretics or troublemakers. Such rewards may be purely financial through the patronage of wealthy and powerful sponsors, as was often the case during the seventeenth and eighteenth centuries, or some sinecure like a tenured professorship or a pension. Societies that rewarded distinguished scientists, promising a great deal of social prestige by elevating them to a peerage or awarding them Nobel prizes for breakthroughs in useful knowledge will find themselves allocating more resources to natural investigations and have a better chance at expanding their epistemic bases. Yet the intellectual property rights to this knowledge need to be arranged with caution, since excluding others will violate welfare maximization given the non-rivalrousness of knowledge, and will reduce sharply the chances of this knowledge being applied.

Second, the research agenda needs to reflect topics that can serve as the epistemic base for growth-inducing inventions. These agendas are of course to some extent set by social priorities. Researchers realize that progress in areas of high social demand, such as cancer research or Alzheimer's disease will be more rewarded than the reproductive habits of amphibians. Such priorities need to be signaled clearly through the incentive structure and they create what may be called "induced research." But they alone do not set the agenda. What matters too is that techniques in use themselves raise issues of why and how they work. They serve as focusing devices, to use Rosenberg's term. History offers many examples of such research being inspired by techniques with a narrow epistemic base, widening the base, improving the technique and so on. This kind of cumulative, divergent positive feedback mechanism between the epistemic base of a technique and the technique itself is widely observed in post-Industrial Revolution history, but rare before. I already mentioned the telegraph. Another classic example is the use of aspirin, for many decades a technique resting on a very narrow epistemic base indeed. Only in the 1960s did John R. Vane, Bengt Samuelsson, and Sune Bergström discover the operation of prostaglandins, and with it the development of a whole new series of analgesics that

¹³I am abstracting here from the problem who "we" are. Suffice to say that the formal definition of social knowledge as the union of all sets of individual knowledge, so in principle if only *one* individual in society knows a particular fact or regularity, he or she can transmit this to others who can then formulate techniques based on it.

extended the uses of aspirin but also found other applications such as anti-allergy medications.¹⁴

Finally, new knowledge is limited by research technology, and this creates another feedback loop from techniques to the underlying bases. The human senses and mind are inherently limited in what they can observe and how fast they can process information. The research technology constrains what society can “know.” Without X-ray diffraction, the structure of large molecules could not have been deciphered, and we would not have molecular biology in its present form any more than we would have had the electrical telegraph without the Voltaic pile. Our senses limit us to a fairly narrow slice of the universe which have been called a “mesocosm”: we cannot see things that are too far away, too small, or not in the visible light spectrum, but microscopes and telescopes can extend it beyond measure.¹⁵ We can only compute so fast, but we can extend our limits by adopting roman numerals, logarithmic tables, modern calculators and fast computers.

Technology only becomes “self-evident” when these epistemic bases have been created. When that has happened, techniques often – but by no means always — are so obvious that simultaneous invention has been widely observed.¹⁶ One should not overstate this case: even when the knowledge base is “available” there is nothing *automatic* about invention. Even a scholar as sophisticated as Eric Jones (2002, ch. 3, p. 20) believes that “Technology seems to offer ‘free lunches’ but its spectacular gains are really secondary; they are attainable by any society that invests in institutions to encourage invention and enterprise.”¹⁷ Yet throughout history things that were knowable but not known were the chief reason why societies were limited in their ability to provide material comforts. Once the knowledge is created, society needs to set up the incentives to reward those who apply the knowledge after it was created. This means a different set of intellectual property rights, which in the modern west took the form of patent legislation as well as personal rewards and pensions to distinguished inventors. Such rewards and incentives could however have other dimensions such as socially prestigious titles,

¹⁴Another example is the use of aluminum. The hardening-process of aluminum in which the metal hardens slowly over the week following heating and quenching was discovered accidentally by Alfred Wilm in 1909 and eventually led to the use of aluminum in all aircraft construction. Metallurgists had a difficult time explaining the phenomenon of age hardening, and it took years until even a partial epistemic base had been uncovered (Alexander, 1978, p. 439). Advances in metallography due to electron microscopy eventually provided the understanding that hardening is caused by the dispersion of very fine precipitates from the supersaturated solid solution; controlling these raises the strength of the metal. The principles of precipitation hardening discovered from aluminum have been applied to the strengthening of a large number of alloys.

¹⁵Franz Wuketits, *Evolutionary Epistemology and Its Implications for Humankind*. 1990, pp. 92, 105.

¹⁶Such simultaneity has often been interpreted as evidence for the importance of demand factors, arguing that when market conditions are “ripe” someone will make an invention. In fact, simultaneity may reflect little more than different inventors having access to common pools of useful knowledge.

¹⁷Eric Jones, *The Record of Global Economic Development*, 2002, ch. 3, p. 20.

political influence promotions within the civil service, and so on. The West, of course, experimented with such non-pecuniary incentives (William Thomson became Lord Kelvin and Fritz Haber, the inventor of the Haber-Bosch nitrogen-fixing process, became quite influential in the German political hierarchy), but relied primarily on monetary incentives.

The Industrial Revolution and its significance

For over a century now, scholars have written extensively about the meaning of the Industrial Revolution and its relation to the events that followed. The literature has reached a number of rather contradictory conclusions that seem to add up to a confused picture. On the one hand, the events in Britain after 1760 clearly constituted the beginning of something quite novel in human history, namely *sustained* economic growth based on constantly growing useful knowledge. At the same time, however, as scholars examine the details, they find more and more that it was a local event, and neither quantitatively particularly impressive in terms of its impact on the overall economy nor very unusual. As is by now widely accepted, the Industrial Revolution was a period of very slow economic growth in Britain. Most estimates find that income per capita growth in the years 1760-1830 grew about as fast as it had done in the years 1700 to 1760. These numbers to some extent underestimate the macroeconomic achievements of the age: the years of the Industrial Revolution were years of war, in which many of the traditional gains from trade with Britain's partners across the Atlantic and the Channel were seriously disrupted; they were years of bad harvests and high food prices; and above all, they were a period of very rapid population growth which, if one takes the standard economic model literally, should have pushed the economy into a sharp decline in living standards. No such decline took place, and that was no mean achievement. All the same, the capability of modern economic growth that emerged in the nineteenth century, to improve living standards for a growing population, clearly was not there yet.¹⁸ Modern scholarship seems to converge on the consensus that the Industrial Revolution was not intrinsically different from earlier episodes, a case of "Growth recurring."¹⁹

Periods of clusters of technological progress had occurred before in human history. The fifteenth century was an unusually creative era, in which blast furnaces emerged in Europe (the Chinese

¹⁸It can be computed that in the absence of any technological progress during the Industrial Revolution, living standards between 1760 and 1830 might have declined on account of population growth alone by 10-20 percent, depending on what one assumes about capital accumulation. See Joel Mokyr, ed., *The British Industrial Revolution* 2nd ed., 1998, p. 76.

¹⁹This argument was made originally by Eric Jones, *Growth Recurring: Economic Change in World History*, 1988. For an elaborate recent restatement, see Jack A. Goldstone, "Efflorescences and Economic Growth in World History," unpublished ms., University California, Davis, 2001.

has been able to cast iron since the 2nd century), shipbuilding and navigational instruments reached the point that enabled Europeans to venture out of the well-charted waters of the Mediterranean and Baltic seas, the printing press revolutionized communications, and firearms changed war. The significance of these inventions was enormous, and perhaps in the very long run they helped bring about modern economic growth, though there was nothing ineluctable about it.²⁰ Yet none of these resulted in much economic growth in the kind of orders of magnitude that we would recognize today as leading to a final and irreversible liberation from the Malthusian shackles that kept most European living standards at subsistence levels for another three centuries.

The European economies during the Renaissance and Baroque centuries remained essentially “stable.” Their dynamics converged to what we now call a “basis of attraction” that prevented the kind of unconstrained growth we see in the nineteenth century. In that regard, then, the Industrial Revolution represented a sea change unprecedented in human history. It was not just “another productivity shock” – it fundamentally changed the parameters of the dynamic economic system in Europe.

This is not to say that there was no growth in these economies. We should not overstate this stability: between Charlemagne and Louis XVI, the material conditions of life in Western Europe changed a great deal. Graeme Snooks, Gregory Clark, and E.A. Wrigley have all argued forcefully – coming from different directions – that economic growth was not unique to the period of the Industrial Revolution and that by the late seventeenth century Britain was an advanced and sophisticated economy.²¹ In pointing this out, these scholars are joining the company of Alan MacFarlane and David Levine (check) who insist in pinpointing the beginning of Britain’s modernity to the late middle ages.²² It is clear by now that far from being a “traditional” and “static” society, Britain on the eve of the

²⁰Elizabeth Eisenstein has argued that the printing press was responsible for the intellectual changes that eventually led to the scientific breakthroughs of the seventeenth century. See Elizabeth Eisenstein, *The Printing Press as an Agent of Change*, 1979. The importance of the discoveries on economic life in Europe came not just from the growth in trade and the huge increase in supplies of goods that previously had been very scarce and expensive such as sugar and codfish, but also in what I have called elsewhere “exposure effects”: Europeans observing techniques in use elsewhere and trying to copy or imitate them. Thus tobacco and potatoes were transplanted onto Europe, and the attempts to copy Chinaware (successful only in the early eighteenth century) led to the development of pottery and ceramic industries in a number of regions. Indian calicoes, of course, were the model of a product that British manufacturers tried to imitate in the eighteenth century.

²¹Snooks’s belief in pre-modern growth is based essentially on his comparison between the income per capita he has calculated from the Domesday book (1086) and the numbers provided by Gregory King for 1688. While such computations are of course always somewhat worrisome (what, exactly, does it mean to estimate the nominal income of 1086 in the prices of 1688 given the many changes in consumption items?), the order of magnitude provided by Snooks (an increase of real income by 580 percent) may survive such concerns. See Graeme D. Snooks, “New Perspectives on the Industrial Revolution.” In Graeme D. Snooks, ed., *Was the Industrial Revolution Necessary?*, 1994.

²²Alan MacFarlane, *The Origins of English Individualism*, 1978. David Levine, *At the Dawn of Modernity* –check.

Industrial Revolution was a country of sophisticated markets, in which profit-hungry homines economici did what they are supposed to do to help a country develop. But Britain was of course not alone in this: the Low Countries, Northern Italy, large parts of Germany, Iberia and Scandinavia at some time or another displayed unmistakable signs of rapid economic progress.

All of those outbursts of economic growth (or “efflorescences” as Jack Goldstone has proposed to term them), however, eventually petered out. Growth occurred through relatively brief and limited periods of expansion during which the solution to a particular problem raised the ceiling of the asymptote, thus creating something of a “ratchet effect.”²³ There are three classic types of explanations for this stability, and all of them depend on some form of negative feedback. One of them is standard Malthusian dynamics, still taken quite seriously in many circles. When income per capita rises, Malthusian models predict a population increase. It is then widely asserted that such a population increase at some point will run 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. This fixity creates a concavity in the production function that, together with the Malthusian response, guarantee stability. Many scholars have seriously questioned whether this model is historically accurate.²⁴ The best answer I can give it that its application is historically contingent on the particular situation: if all other things are equal, including the stock of human knowledge and the infrastructure of the economy, the concavity is simply ineluctable. But if these other things are not only variable but actually a sufficiently steep positive function of population – a rather strong condition – we can see how these Malthusian constraints may be overcome and eventually they have lost all relevance.

A second source of negative feedback is institutional. When economic progress took place, it frequently generated a variety of social and political forces that, in almost dialectical fashion, ended up terminating it. Prosperity and success led to the emergence of rent-seekers and parasites in a variety of forms and guises who eventually slaughtered the geese that laid the golden eggs. Tax collectors, foreign invaders, and distributional coalitions such as guilds and government-enforced monopolies in the end extinguished much of the growth of Northern Italy, Southern Germany and the Low Countries. The great commercial expansions of the sixteenth 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 a

²³Fernand Braudel, *Civilization and Capitalism*, 1981, Vol. I, p. 430.

²⁴For a particularly trenchant recent criticism, see Julian Simon, *The Great Breakthrough and its Causes*, 2000.

document that tried to point out this basic point. It seems reasonable to surmise that much of the economic decline of the Iberia in the sixteenth century and that of the United Provinces in the eighteenth can be explained in part by such mechanisms. Perhaps the most insidious of these forms of institutional feedback was organized resistance to new technology by vested interest groups, a phenomenon still quite visible in our own time.²⁵

The third mechanism is the one most relevant to the interpretation I am suggesting here. Simply put, before 1750 the vast bulk of techniques in use anywhere in the world rested on very narrow epistemic bases that constituted a “fixed” factor that lent the system a kind of concavity that we do normally *not* associated with knowledge. But what people used in production was engineering without thermodynamics or mechanics, iron-making without metallurgy, farming without organic chemistry, and medical practice without physiology or microbiology. What was known, had been discovered serendipitously or through trial-and-error experimentation. The point is not that the operators of techniques (that is producers) 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. Techniques that worked, from animal breeding to steelmaking, soon reached ceilings that might have been broken through 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, and the raising of edible crops and animals, were little informed by theory, because there was little theory.

Needless to say, the marginal product of widening these epistemic bases varied from activity to activity. A dexterous and brilliant mechanic like Watt or Roberts might make very substantial improvements in a piece of equipment without a complete understanding of why this turned out to be correct. But in organic chemistry, the use of electromagnets in telegraphy, or the design of steam turbines, there simply was no substitute for formal science. Moreover, the Industrial enlightenment created ways of getting around narrow epistemic bases. It became gradually clear that it was possible to generate enough data to catalog and describe patterns that some phenomena could be harnessed and exploited even without a thorough understanding. What Layton has termed “engineering science,” seeks a more concrete level of knowledge of how things work in actual situations, under conditions of varying pressure, stress, heat, and friction rarely examined by pure theorists. This is what Nathan Rosenberg calls “engineering knowledge” – based on a limited and perhaps even shallow understanding

²⁵See Joel Mokyr, “The Political Economy of Technological Change: Resistance and Innovation in Economic history” in Maxine Berg and Kristin Bruland, eds., *Technological Revolutions in Europe*, 1998, pp. 39-64; *ibid.*, *Gifts of Athena*, ch. 6.

of the process, but by systematic trial and error settling on techniques that work.²⁶ These methods are never as efficient as those based on sound and deep principles, but they themselves can be made to work better through the methods of parameter variation and experimentation models, and today through computer simulation. This methodology has been attributed to the great eighteenth century engineer, John Smeaton, whose impact on the Industrial Revolution was no less than Watt's despite his lesser fame.²⁷ A century later, William Rankine formalized engineering science in these terms, and made it a respectable discipline at the University of Glasgow.²⁸

The framework I delineated above, and through which western technology expanded beyond any conceivable boundaries differs from the standard accounts that attribute its success to the scientific breakthroughs of the nineteenth century. Very few techniques are ever designed from first principles alone. Epistemic bases are almost always too narrow to work this way, even relatively late in the development stage. Instead, there is always a great deal of experimentation and trial-and-error that reflects the inability of "pure theory" to take into account all the variables that come into play in "real" situations. The point, however, is that a wider base in useful knowledge allows people to rule out larger and larger areas that are excluded, restrict the searches and thus make them more efficient. Such knowledge prepare the minds that fortune (and hard work) favors. An evolutionary framework suggests that if *nothing* is known, the search will be totally random, much like happens in a pure Darwinian framework. In the other limit, if *everything* is known, we need not experiment, since we can design what we need optimally. Historically, all societies find themselves between these extremes, but the Industrial Revolution and the unprecedented growth of technology rested on moving on the line in between, perhaps from a world in which *very little* was known (before) to one in which *a little more* was known. That may have made all the difference.

Between 1750 and 1850, all of these three negative feedback mechanisms were gradually transformed and neutralized or turned into positive feedback. We may call this the Industrial Revolution, but the sources of these changes go back to the institutional changes we associate with the enlightenment. We do not usually associate the enlightenment and the scientific revolution that

²⁶Nathan Rosenberg, "Engineering Knowledge," unpublished ms., Stanford University, 2001.

²⁷Smeaton is credited with the development of the method of parameter variation through experimentation, which is a systematic way of gradual improvements in the absence of a wide epistemic base. It establishes regularities in the relationships between relevant variables and then extrapolates outside the known relations to establish optimal performance. Vincenti (1990, pp. 138-140) and Cardwell (1994, p. 195)

²⁸David F. Channell, 1982. "The Harmony of Theory and practice: the Engineering Science of W.J.M. Rankine." *Technology and Culture* Vol. 23, No. 1 (January), pp. 39-52.

preceded with it (and overlapped with it) with a particular nation or region in Europe, though there were differences in style and intensity. Europe, from Edinburgh to St. Petersburg, participated in these historical phenomena, no matter how we define them. Yet they were specifically European. By the time they had occurred, most of the rest of the Eurasian continent had cut itself off as well as it could from the European continent, and were not affected by these intellectual currents until centuries later.

European and Chinese Technology

I hope that it would not be considered a “Eurocentrist” attitude to point out that the contact with European civilizations interrupted and altered the course of evolution in all non-European societies. This is as true for pre-Columbian America as it is for Afghanistan and Africa. China and Japan were aware of the West, but not until the nineteenth century were their histories shaken-up and disrupted by it. The understanding of the real impact of Europeans must face the counterfactual what would have happened without Europe? Could East Asia have experienced an Industrial Revolution in the absence of the West? The issue is particularly interesting because recent research in World History has moved in the direction of minimizing the differences between the Orient and Europe even as late as 1750.²⁹ Recent scholarship has increasingly realized that China, and in a different way Japan, on the eve of the Industrial Revolution were monetized, commercially sophisticated well-integrated economies, in no way inferior to Europe when it came to the rule of law, the ubiquity of commerce, enforceable contracts, predictable fiscal systems, and opportunities for entrepreneurial behavior.³⁰ To be sure, in terms of the “ideal conditions” we would like to see for economic growth, they were far from perfect, but so – in different ways – was Europe. Cultural or institutional differences between the two seem decisive mostly *ex post*. Had China experienced an Industrial Revolution before Europe, economic historians would have no doubt explained it by its meritocratic government, economies of scale, and its relative absence of internal war after law and order were re-established following the 1644 revolution. Had Tokugawa Japan become an industrial nation, the advantages of an Island nation and the stimulus provided to technological change by resource scarcities would surely be widely cited.

The difference was useful knowledge, that is, technology and its underlying epistemic base in

²⁹See especially Goldstone, “Efflorescences,” Bin Wong, *China Transformed: Historical Change and the Limits of European Experience*, 1997 and Kenneth Pomeranz, *The Great Divergence: China, Europe, and the Making of the Modern World Economy*, 2000. On Japan, see Alan Macfarlane, *The Savage Wars of Peace*, 1997 and Susan Hanley, *Everyday Things in Pre-modern Japan*, 1997. Philip Richardson?

³⁰There is a regrettably vitriolic strand in this literature, as represented by the works of A.G. Frank and James Blaut, that makes the issue into of “Eurocentric history” a matter of ideology and belief rather than a difficult and inherently subjective historical question. See for instance the almost personal attacks in James Blaut, *Eight Eurocentric Historians*, 2000.

natural philosophy, chemical, medical, and engineering knowledge. It is a gargantuan task to chronicle the exact divergence between East and West, which differs a great deal from area to area. By 1840, however, it surely is impossible to find many areas in which Europe had not pulled ahead, a point dramatically driven home not only by the opium wars but by the enthusiasm with which Meiji Japan set out to emulate the West.³¹ The hard truth is that by 1840 the gap between what Europeans “knew” and what others knew was enough for a puny British expeditionary force to humiliate a proud Chinese Empire. Needham’s life mission was to document that it had not always been thus, and his work and that of his students has documented that as late as 1500, Europe was perhaps only pulling even with the Orient in iron-making, textiles, power, printing, and shipbuilding.³² But after that, the signs that the two paths had very different slopes became too clear to ignore. It may well be true that at the economy-wide *level* the effects of these different paths did not translate into an unambiguous difference in living standards until much later. The difference is not just in the slope, but in the second derivative. Europe was not only advancing faster than the Orient, but its progress was accelerating.

The technology that created the Industrial Revolution, then, was not exclusively British: it was European. Taking what Eric Jones has called the “little England” view and focusing on *Britain’s* Industrial Revolution is a bit misleading. While Britain pulled ahead of the rest of Europe for a while between 1760 and 1820, its technology relied heavily on epistemic bases developed elsewhere in Europe, especially in France, but also in Germany, Scandinavia and Italy. Comparing Europe with China is therefore to some extent misleading: the various European societies complemented one another, and their internal competition gave it a dynamism that China lacked. Thus, for instance, when in Britain chemical and engineering education began to fall behind, its potential competitors on the continent made up the slack. It also tends to divert attention too much to Britain’s special conditions such as its coal and its colonies, while industrialization in the nineteenth century happened in places without coal (Switzerland, New England) and without early colonies (Belgium, Germany).³³

All the same, it seems reasonable to ask: could China have done it? Could it have created a

³¹The best text on this event and its technological significance is still Daniel Headrick, *The Tools of Empire*, 1981.

³² It is rather odd that Needham’s students now criticize him for formulating the “Needham question” which “subverts his fundamentally humanist enterprise of writing a non-exclusionary history of science and technology.” Francesca Bray, “Towards a Critical History of non-Western Technology” in Timothy Brooks and Gregory Blue, eds, *China and Historical Capitalism: Genealogies of Sinological Knowledge*, 1999, pp. 162-63. The notion that we study the “non-event” of Chinese technological development after 1500 because our discourse itself is dominated by capitalist theory squares poorly with the revisionist view that the West did not have a monopoly on capitalism and other institutions that promoted the growth of commerce and economic performance, and that many of these were equally found in China.

³³Pomeranz, *Great Divergence*. See the insightful review by Peer Vries of Kenneth Pomeranz, *Great Divergence* in *Journal of World History*, 2001, forthcoming.

technological civilization resembling the one we actually have if, for some reason Europe had not existed in the form it did in 1750? Such counterfactual narratives are quite “probable” with a minimal “re-write” of history. Examples include a Moslem victory at Poitiers in 732 and the creation of a Moslem society in western Europe; a complete Mongol conquest of Europe after Batu’s defeat of the Europeans in the battle of Legnica in 1241 accompanied by a devastation of its urban enclaves; an epidemic catastrophe in Europe following the Colombian voyages on the order of what the Europeans inflicted on the indigenous populations of the new world; a military victory of the counter-reformation in the late sixteenth century that would have imposed Iberian standards on the intellectual pursuit of useful knowledge on the rest of the Continent from 1580 on, and thus no Bacon, Galileo, Descartes, Huygens, or Newton.³⁴

It is always difficult to test a counterfactual argument, but we are not completely in the dark. China developed a large and substantial body of knowledge of nature separate from the West, catalogued in great detail in the volumes put together by Joseph Needham and his collaborators. The question “if some invention had not been made in the West, would it have been made anywhere else?” is not entirely answerable. But the least we can do is ask whether there is a high probability that it would have been made in China. Needham, whose work on Chinese science and technology led him to view the great divergence between East and West as the central historiographical issue of our time, viewed science and technology as “inseparable”.³⁵

The nature and characteristics of useful knowledge as it developed in China were not “less” or “worse” than the Western experience, but its ability to serve as an epistemic base for Chinese technology clearly did not work as well.³⁶ Chinese technology, no matter how sophisticated and advanced, remained grounded on a narrow epistemic base. Needham cites with approval the verdict of a ninth century Arab author that “the curious thing is that the Greeks are interested in theory but do not bother about practice, whereas the Chinese are very interested in practice and do not bother much about the theory”.³⁷ As a general statement about scientific knowledge in China, this is not entirely accurate. In

³⁴For such possible counterfactual scenarios, see many of the papers in Philip Tetlock, Ned Lebow, and Geoffrey Parker, eds., *Counterfactual Analysis in History and the Social Sciences*, 2002, forthcoming.

³⁵Nathan Sivin, “Science and Medicine in Imperial China – The State of the Field.” *Journal of Asian Studies* Vol. 47, No. 1 (Feb 1988.), p. 47.

³⁶We should not turn the story into what Sivin has called “a saga of Europe’s success and everyone else’s failure” (Sivin, “Why the Scientific Revolution”, p. 542). Yet he himself notes a few pages (p. 537) earlier that “the privileged position of the West comes ... from a head start in the technological exploitation of nature.” It is unreasonable to explain such a head start without admitting that something that Westerners learned about nature was different from what was learned in China.

³⁷Joseph Needham, *Clerks and Craftsmen in China and the West*, 1970, p. 39.

medicine, “theory” and practice were never separated. But, as Huff has noted, medicine was the exception.³⁸ In engineering, mechanics, chemistry, mining, and agriculture, the *savans* and the *fabricans* in China were as far or further apart as they ever were in Europe.³⁹ It is perhaps telling that while a considerable number of Chinese *techniques* in one form or another found their way to the West, there are few instances of Chinese useful knowledge (not to mention science proper) being adopted by the West.

Another “test” of what might have happened to non-Europeans in the absence of Western technology is the history of Tokugawa Japan. Here, too, the natural experiment is seriously flawed, because their best efforts notwithstanding, Japan was not entirely closed to western influences. All the same, the idea that they would have been entirely stagnant and hopelessly poverty-stricken in the absence of the West is convincingly refuted by modern research. Material culture on the eve of Commodore Perry’s visit was not stagnant and, by many measures, not obviously inferior. It was just *different*. The Japanese had no guns, brick homes, metal flatware, coal, or railroads, ate no beef and drank no beer. But they were far more efficient in using the fuel and raw materials they had, and the quality of their food, public sanitation, housing, and personal care implied a level of physical health and life expectancy that was equal to the very best Europe could show in 1850. Moreover, Hanley has argued that this was an economy that grew substantially in the eighteenth century, continuing into the early Meiji years.⁴⁰ This was certainly an economy capable of growth, but could it ever have been a knowledge-based growth like Western Europe without the infusion of European knowledge?

To return to the previous example, would the Orient have invented electrical telegraphy if the West had not? As is well known, the Chinese in the Song period had discovered magnetism and developed a floating needle that served as a compass. They had figured out some fairly advanced properties of magnetism such as magnetic declination (the error term in the compass due to the difference between the magnetic North pole and the geographical north of the planet), known as early as the ninth century A.D., and magnetic remanence (acquisition of magnetic properties due to cooling), known in the 11th century. Yet the understanding of electricity seems to have eluded them, let alone the

³⁸Sivin, “Science and Medicine,” Toby Huff, *The Rise of Early Modern Science*, 1993.

³⁹Needham points out that the Greek distinction between theory and practice, the former suitable to a gentleman and the latter not, has a precise equivalent in the Chinese distinction between *hsüeh* and *shu*. Cf. Joseph Needham, *The Grand Titration*. Toronto: University of Toronto Press, 1969, p. 142.

⁴⁰Hanley, *Everyday Things*, pp. 17-19. She rightfully points out that the income comparisons by Angus Maddison and others that show that in 1870 Japan’s per capita GNP was just a quarter of the UK is deeply flawed because the two economies were consuming largely non-overlapping baskets.

connection between electricity and magnetism.⁴¹ The trajectory followed by Chinese science is therefore an obvious one: given their understanding of the properties of magnetized needles, they expanded this knowledge into obvious directions (above all the compass), but they failed to make the less probable leaps made by Oersted and Henry. In the absence of Western influence, China would probably not have gone in that direction in historical times.

The issue of steampower is more complex. Pomeranz has argued that the Chinese had the “basics” for the steam engine.⁴² The minimum epistemic base for the use of atmospheric pressure in order to convert heat into work are the notion of atmospheric pressure and the understanding of the physical changes in water under different temperatures. In addition, it required the workmanship and materials that could create a pump capable of producing a vacuum inside a cylinder or a globe. Knowledge of the atmosphere, the understanding of water-condensation, and the ability to construct advanced pumps can surely be found in China, and if *all* that was required to make a steam engine was the knowledge of physics of, say, a Denis Papin or a John Smeaton, it is indeed likely that in the absence of the West, the Chinese would have stumbled upon something like it. But it is telling that the earliest reference to the epistemic base of steam power in China dates from the Han period and predate Newcomen by almost two millennia, and yet nothing happened in China that we know of with certainty.⁴³ In the West, by contrast, models of a working steam engine appeared within about half a century after Torricelli’s demonstration of atmospheric pressure and Pascal’s *Traité de l’équilibre des liqueurs et de la pesanteur de la masse de l’air*. Furthermore, Needham points out that the mechanical bellows described by Wang-Chên in 1313 has the structure of a reciprocating steam engine “in reverse” incorporating double-action and a transmission mechanism similar to Watt’s famous sun-and-planets gears.⁴⁴ However, the essence of the steam engine is the conversion of heat into work, a problem cracked before Watt’s ideas of double-acting. Thus the transformation of Newcomen’s clumsy and noisy pump to Watt’s industrial source of power may well have had Oriental antecedents (whether Watt was aware of them or not), but the concept of an engine was novel. Needham concedes that in this regard Europe

⁴¹Needham, *Science and Civilization* Vol. 4, pt. 1: Physics;1962, p. 238.

⁴²Kenneth Pomeranz, in Tetlock, Lebow and Parker.

⁴³In his famous essay on the topic, Needham, “The Pre-natal History of the Steam Engine” published in *Clerks and Craftsmen* p. 145 tells of a document from the 2nd century BC in which a Chinese author explains that “to make a sound like thunder, put boiling water in a vessel and sink it into a well. It will make a noise that can be heard several dozen miles away,” an experiment that anticipated Magdeburgian effects.

⁴⁴ Joseph Needham, *The Grand Titration*, 1969, pp. 96-97.

did something that the Orient did not.⁴⁵ All the same, early steam engines in Europe were constructed on a very narrow epistemic base and in that regard it is hard to argue that the Chinese *could* not have invented it – if they had discovered the concept of atmospheric pressure. It is the latter, however, that is the perhaps the less likely.

The emergence of a minimum epistemic base is therefore a necessary but insufficient condition for a new technique to be made. Even *with* the knowledge, techniques could fail to emerge when this knowledge was confined to a small number of people who were uninterested in or ignorant of technical problems in production, and when the knowledge was inaccessible to those most in need of it. Expressions like “the Chinese had knowledge of...” are thus misleading. In the late eleventh century, someone in China could make the Su Sung clock, a model of enormous horological sophistication. Yet unlike Europe, no class of clock- and watchmakers emerged in China, the epistemic base of the waterclocks under the Song disappeared. Here, then, is a case in which a society was able to produce the knowledge, but the opportunity was lost. After 800 AD, cases in which knowledge in Europe is “lost” become rare. More typical is for an invention or insight to emerge somewhere and then spread throughout much of the continent. This is what happened with mechanical clocks, windmills, Arabic numerals, printing, and the new geography after 1450. Of course there were areas that proved immune or resistant to such novelty. The difference between China and Europe was that in Europe there always was sufficient diversity. When in one European area the conditions for adoption were not met, it simply moved elsewhere. China, especially in the Ming and Qing periods, seems to have lost that ability.

Invention remains historically contingent: the useful knowledge underlying the wheelbarrow had been available for thousands of years, yet it seems not to have occurred to anyone in Europe before the twelfth century. On the other hand, the Japanese could have created the functional button, yet apparently did not and were most amazed and delighted when they saw it on the garments of Portuguese traders and retained the Portuguese word for it in their language. A technique has to be “imagined,” that is, it has to occur to someone. There is nothing inexorable or self-evident about this process. A lot depends on the connections between intellectuals who had the time and education to give free reign to their imagination and creativity, and the people slaving away in fields and workshops who

⁴⁵Needham points out that “Newcomen ... appears more original, and also at the same time more European, than [was previously realized] ... he stands out as a typical figure of that modern science and technology *which grew up in Europe only*” (*Clerks and Craftsmen*, pp. 136, 202, emphasis added).

faced the actual challenges of production.⁴⁶

One can find other examples in which Chinese society did not come up with the knowledge that would have led them to techniques that would have been of use to them. Consider optics. Optical advances are not at the center of the Industrial Revolution, but the invention of eyeglasses extending the effective lifetime of craftsmen and intellectuals cannot be overestimated, and the improvements in the optical microscope in the 1820s led to medical breakthroughs that equaled the Industrial Revolution in importance. At some point, there seems to have been a strong interest in the topic in China.⁴⁷ Optics is not an exactly delineated area of useful knowledge since it involves physical and physiological phenomena (the nature of light and the process by which it is received and processed by the human body). Optics was born in classical civilization, but remained essentially unapplied, the myth about Archimedes constructing concave mirrors that burned Roman ships notwithstanding. The greatest advances before Kepler's celebrated essay *Expounding the Optical Part of Astronomy* (1604), were made by Alhazen (Al-Haytam, early 11th century) who studied curved mirrors and lenses and first established that light travels from the source to the eye and not vice versa. Yet from a technological point of view, the first successful application was the emergence of eyeglasses in the 1280s.⁴⁸ Without some underlying epistemic base, the probability of this technique emerging was low indeed.⁴⁹ Given that this knowledge came about, the eventual occurrence of even better spectacles (correcting for myopia in addition to presbyopia), telescopes, and microscopes were quite likely.

Yet how probable was the development of useful optics in the Orient? As Needham has

⁴⁶Needham points out that Chinese artisans were remarkably good at carrying out empirical procedures of which they had no scientific understanding. The real work in engineering was "always done by illiterate or semi-literate artisans and master craftsmen who could never rise across that sharp gap which separated them from the 'white collar literati'" (Needham, *Grand Titration*, p. 27). Pomeranz points out the networks diffusing certain types of scientific knowledge clearly existed in China, but that artisans were largely outside such networks. Pomeranz in Tetlock et al.,

⁴⁷Graham and Sivin produce an interesting early beginning of Chinese Mohist studies (4th century BC) in certain areas of optics but the insights of these writing led nowhere, presumably because they were incompatible with the mainstream of Chinese natural philosophy. Cf. A.C. Graham and Nathan Sivin, "A Systematic Approach to the Mohist Optics." In Shigeru Nakayama and Nathan Sivin, eds., *Chinese Science: Explorations of an Ancient Tradition*, 1973, pp. 105-152. Whether they would have led to applied optics if Mohism had become mainstream in China is hard to know, but Graham and Sivin (p. 107) note that the optical propositions have no direct connection with technology. Other scientific sections of the Mohist Canon, however, do have such applied interest, and perhaps Mohist thinking is an example of a technological equivalent of an extinct "could-have-been" much like the one Stephen Jay Gould argues for in his *Wonderful Life: the Burgess Shale and the Nature of History*, 1989.

⁴⁸It can hardly be a coincidence that Alhazen's *Optics* had been translated into Latin in 1269, about a decade and a half earlier.

⁴⁹G.N. Cantor, "Physical Optics." In R.C. Olby et al., eds., *Companion to the History of Modern Science*. London: Routledge.1990.

demonstrated, the Chinese tried.⁵⁰ It is true that glass, although known in China, was not in wide use, in part perhaps the result of supply considerations (expensive fuel), and possibly in part due to lack of demand (tea was drunk in porcelain cups, and the Chinese examined themselves in polished bronze mirrors).⁵¹ Some past societies might well have made lenses given enough time and better luck: Islamic civilization for centuries had a magnificent glass industry, yet never came up with either spectacles or a telescope, despite the ubiquity of presbyopia and a strong interest in astronomy. In the later Middle Ages, glass making in the Islamic world declined, in part because of the devastation inflicted by the Mongols.

But elsewhere *knowledge* must have played a central role. Tokugawa Japan had a flourishing industry making glass trinkets and ornaments, but no optical instruments emerged there either until the Meiji restoration. Not having access to the Hellenistic geometry that served not only Ptolemy and Alhazen, but also sixteenth century Italians such as Francesco Maurolico (1494-1575) who studied the characteristics of lenses, made the development of optics in the Orient difficult. The probability of a microscope being invented by someone who does not have access to geometry is very low, although it cannot be ruled out that a different kind of mathematics, not imagined by us, could have achieved the same results. Had China been the world, or had the West never had “western” science, optical devices similar to the ones we have would in all likelihood never have been developed.⁵² One might then seriously wonder whether bacteriology and metallography, which both depended on microscopes, would ever have emerged.

The complexity of the question of the critical role of useful knowledge is demonstrated by a later invention, anaesthetics. Much like eyeglasses, the “demand” or necessity for anesthetics were hardly time- or society-specific, although the willingness and ability to tolerate and inflict pain are of course to some extent culturally determined. For hundreds of years Europeans suffered unspeakably from operations carried out without anesthesia. The discovery that a number of substances could knock a patient unconscious without long-term damage must have increased total consumer surplus (if not

⁵⁰Thus in the *Hua Shu* (Book of Transformations) dated to the middle of the tenth century there is clear-cut reference to four types of lenses that enlarge, reduce, upright and invert. The author points out that when he looks at people he realized that there was no such thing as largeness or smallness, beauty or ugliness. (Needham, *Science and Civilization: Physics*, p. 117).

⁵¹On this, see Alan MacFarlane and Gerry Martin, *The Glass Effect: Glass and World History*, 2002.

⁵²It is telling that when Western applied optics arrived in China through Jesuit travelers in the seventeenth century, Chinese artisans such as Po Yü and Sun Yün-Chhiu soon constructed microscopes, searchlights, and magnifying glasses. Needham himself concedes that the view that regarded spectacles to have been a Chinese invention is a myth. Subsequent to their invention in the West, they found their way to China rather quickly. One must conclude that the Chinese were not indifferent to applied optics, but simply were unable to create the techniques. Colin Ronan and Joseph Needham, *The Shorter Science and Civilization in China*, Vol. I, 1978, p. 257. Needham, *Science and Civilization: Physics*, pp. 118-19.

necessarily GDP) by a considerable amount. Yet the discovery seems to have been not just accidental but made almost in a wave of absent mindedness, underlining the lack of inevitability and determinacy in invention. Ether was first synthesized in 1540 and known as “sweet vitriol” -- why did it take three centuries till its properties were fully recognized?⁵³ It could have happened a century earlier, alleviating unspeakable agony for hundreds of thousands of “patients” of the surgeons of the time.

Could anesthesia have been invented in China? Unlike optics, in this case there was no need here for some breakthrough in the underlying knowledge base, since little of that existed in the West either. Nobody in the mid nineteenth century had any idea *how* precisely ether, chloroform, or other substances knocked out the patient. The Chinese embarked on another route toward pain relief: instead of chemical intervention, their path led to physical means through acupuncture. Yet much of Chinese medicine was based on the use of herbal medicine and the prevalence of opium in the nineteenth century indicates that chemical intervention in sensory bodily processes was by no means alien to them. Perhaps more plausible is the explanation that surgery itself was rare in China.⁵⁴ Conditional on that premise, perhaps the Chinese should not have been interested in anesthesia. But this argument does not seem wholly satisfactory. Childbirth suffering presumably was not wholly culturally-determined.

We need to ask what it was, if anything, in Chinese culture that made surgery unacceptable. To maintain simply that Chinese medicine was “different” from Western and therefore failed to develop surgery, anesthesia, aseptic methods, and so on strikes me as a simplification. There was not one but many types of Chinese medicine, just as there were different approaches to other parts of natural science. Yet none of them resulted in the adoption of surgery as a widely practice form of medicine outside cataract surgery.⁵⁵ It must be concluded, therefore, that Western medicine itself was not “inevitable.”

⁵³Nitrous Oxide (laughing gas) was discovered by Joseph Priestley in 1772. No less an authority than the great Humphry Davy – the leading applied scientist of his day – suggested in 1799 that it “appears capable of destroying physical pain, it may be possibly be used during surgical operation.” Ether had also been manufactured since the eighteenth century for use as a solvent, but although its anesthetic properties were known in the early nineteenth century and mentioned in an anonymous note in the *Quarterly Journal of Science and the Arts* in 1818, they were never applied to surgery until 1842. In that year Crawford Long in Jefferson, Georgia removed the diseased toe of a slave boy under anesthesia. The technique was publicized widely in 1846 by an American dentist, W.T.G. Morton, who extracted a tooth using ether. Two years earlier, Horace Wells had used laughing gas for similar purposes. The celebrated Scottish gynaecologist, James Simpson discovered at about the same time (1847) the properties of another chemical solvent, chloroform. Within a few years the idea “caught on” and surgery went through the greatest revolution ever. Ulrich Tröhler, “Surgery (Modern).” In W.F. Bynum and Roy Porter, eds. *Companion Encyclopedia of the History of Medicine*, Vol. 2. London: Routledge.1993. Arthur W. Slater, “Fine Chemicals.” In Charles Singer et al., eds., *A History of Technology* Vol. V. Oxford: Oxford University Press. 1958. Sherwin B. Nuland, *Doctors: The Biography of Medicine*. New York: Knopf, 1988.

⁵⁴Paul Unschuld, *Medicine in China: A History of Ideas*. Berkeley: University of California Press.1985, pp. 150-52.

⁵⁵The Chinese are known to have experimented with cataract surgery, influenced by Indian medicine, in the ninth and tenth centuries, yet the initiatives did not take off. When an American medical missionary, Peter Parker, opened a clinic in Canton in 1835, cataract patients flocked to him by the thousands. Chloroform anesthesia was reportedly used in China in 1848, within two years after its use in the West. Unschuld, *Medicine in China*, p. 152. S. Yung, “History of Modern Anesthesia in China.” In Joseph Ruprecht et

Even given that it existed, the discovery of anesthesia was not inevitable, it did *not* occur just when the time was “ripe,” and provides a powerful illustration of the historical contingency of techniques even when their social usefulness is unassailable and they can be made without a wide epistemic base.

The history of useful knowledge and science in China, then, is a good example of an “alternative” route that knowledge can take in different settings. It is easy and indeed tempting to attribute the differences between the growth of useful knowledge in China and that in Europe entirely to different institutional settings and social environments or even the differences in geographic endowments.⁵⁶ But this ignores the sequential nature of the growth of knowledge. The evolution of useful knowledge is a stochastic branching process: each step is conditioned by the state of knowledge at that time, and the direction of movement has a contingent element. By allowing for the possibility that at any point the evolution of knowledge could have gone on to a different branch than it actually did, we are implicitly allowing for a world that “knows” nature in a different manner than we do and thus exploits it in a different way.

Even in similar institutional environments, the trajectory of useful knowledge may end up being much different because a crucial ingredient was absent or present by accident, or some decision that could easily have gone one way ended up going another. To visualize the contingent nature of what actually emerged, we should carry out the following thought-experiment: think of a hypothetical society that regards the “modern” and “progressive” West in the same way that Western historians such as Huff and Bodde have thought about Islamic and Chinese Science: admirable in some ways, but ultimately unsuccessful by the standards of another economy. Such a society, if left alone for a long time, might have spawned technologies we can only guess at.

The alternative is to take an arch-Whiggish view and to argue that Western science is the only “true” knowledge. Given that in this view there is only one objective truth, the question is then whether given enough time the Chinese or someone else would have found a road to electromagnetism, the germ theory, and quantum mechanics. But if there is more than one scientific “truth” just as there is more than one “true religion,” then that likelihood must be viewed as vanishingly small. Such are the philosophical issues involved in the counterfactual analysis of technology. This is not the place, and I am not the author to resolve them. What is not in dispute, as I noted in the introduction, is the effectiveness of Western technology in the battlefield, the factory, the mine, the hospital, and the research laboratory. No single element can entirely explain it by itself. The question has bothered the

al., eds., *Anaesthesia: Essays on Its History*. Berlin: Springer Verlag. 1985.

⁵⁶Huff, *Rise*, chs. 7-8. Pomeranz, *Great Divergence*.

greatest historical minds of our century, Max Weber, Lynn White, Eric Jones, Joseph Needham, Nathan Sivin, and David Landes, to name just a few.

It would be as pretentious as it would be pointless to survey or add to this debate in this paper. But the evolutionary framework I proposed before may help to place one or two issues in sharper perspective. The argument I am making is *not* that for most of the time the epistemic base of technology in Europe was broader than in the Orient. As late as the middle of the seventeenth century, the differences between the epistemic bases on which technology rested in the West and China was probably not large.⁵⁷ It is rather that the culture and institutions that generated and diffused useful knowledge in Europe and the institutions that supported it, eventually developed characteristics that allowed the epistemic bases of technology to become eventually ever wider in part as a result of the techniques that it supported. This created a self-reinforcing virtuous cycle that created the huge gap between West and East in technology in a relatively short time in the late eighteenth and early nineteenth century.⁵⁸

In reflecting on this question, it is important to realize that not only the social environment of knowledge differed. In the West, the selection environment of useful knowledge was more stringent than elsewhere. The physical world was viewed as *orderly*, that is, the same causes lead to the same effects, and one could separate between the logical and comprehensible sphere of the natural world and the theological issues of creation. These views have clear medieval roots and link back to Plato's *Timaeus*.⁵⁹ But it is hard to see why such interpretations themselves would be inevitable.⁶⁰ Western science did have a large random component in it. Not everything that could have been discovered was

⁵⁷Derk Bodde makes this point very strongly when he claims that by 1668, "the traditional technologies of Europe and China alike were both based more on practice than on theory and had both reached approximately the highest point possible for such technologies before the advent of modern science." Theory, however, was not really the issue. By 1700, Europeans had already vastly expanded the horizons of their useful knowledge in geography, hydraulics, optics, the manipulation of domesticated animals, graphical representation, astronomy, scientific instruments, crop rotations, and so on. Like Needham, Bodde seems too closely wedded to the linear connection between "scientific knowledge" and technical progress. His notion that "in 1687 Newton's *Principia* was published ... less than a century after, steam was beginning to turn the wheels of Britain" implies a linear causal connection between the two that cannot be defended. See Derk Bodde, *Chinese Thought, Society, and Science*. Honolulu: University of Hawaii Press. 1991, p. 235.

⁵⁸Bodde (*Chinese Thought*, p. 362) provides a list of Chinese inventions such as the astronomical clock, mathematical navigation, and the seismograph which became "magnificent dead ends" (to use David Landes's term) and were not further developed. Bodde ascribes this to a Chinese lack of interest in theory. In my view, they all represent examples of singleton inventions or at least inventions with very narrow epistemic bases.

⁵⁹The twelfth century mini-renaissance that included such writers as Peter Abelard, William of Conches, Hugh of St. Victor, Adelard of Bath, and others, might be thought of as "neo-platonist" in this regard, as it laid down the foundations of a rational and mechanistic view of the Universe that became the foundation of seventeenth century natural philosophy.

⁶⁰Indeed, Huff (*Rise*, p. 105) notes that twelfth century Islamic writers developed philosophical views that were Platonist enough to be offensive to the Islamic religious elite but did not elaborate the rationalistic and mechanistic world view that Western Europeans built on Plato's edifice.

discovered at the right time, and some things were not discovered at all.

Indeed, Chinese thinking about useful knowledge has had a different interpretation of the idea of “laws of nature,” as Needham pointed out. All the same, the statement that they completely replaced Western laws of nature by “an organic world of two primary forces and five phases ... the explanation of the patterns of existence is not to be sought in a set of laws of mechanical processes , but in the structure of the organic unity of the whole” seems perhaps too strong.⁶¹ The idea that there are regularities in nature that are predictable and exploitable is too obvious to be completely cast aside by any culture and no production is possible without it.⁶² Translation becomes a key here, as the Chinese employ words like *thien fa* (laws of heaven), yet, as Needham insisted, these are laws without a lawgiver. In that sense, of course, the Chinese may have been closer to a twentieth century way of thinking about nature than to the thinking of Kepler and Newton. For the ancient Chinese, the world looked more like a “vast organism, with all parts cooperating in a mutual service which is perfect freedom.”⁶³ Needham compares this to an endocrine system in which causality is hard to pin down and notes that modern science cannot do without it. Others have found different ways in which Western and Oriental knowledge diverged. Sivin has stressed the lack of a unity and a coherence in Chinese science caused by the absence of an overarching philosophical view of nature. In his words, China had sciences but no Science.⁶⁴

In any event, given that the useful knowledge that had emerged in China was profoundly different from the West, technological history would have taken a very different course without Western useful knowledge. There is thus no reason to believe that a world without the West would have come upon the internal combustion engine, the microprocessor, electron microscopy or stereotaxic surgery. The Chinese might have stumbled on smallpox vaccination, semaphore telegraph, hot air ballooning, Bessemer steel, aspirin or other inventions requiring narrow epistemic bases. But the mutually reinforcing interaction between science and industry that created modern metallurgy, chemical

⁶¹Id., p. 251.

⁶²Needham, *Grand Titration*, p. 322 cites Wang Pi, a Chinese writer from 240 AD as “We do not see Heaven command the four seasons and yet they do not swerve from their course, so we also do not see the sage ordering the people about, and yet they obey and spontaneously serve him.” The thought, he adds, is extremely Chinese. Yet the regularity of the seasons can be interpreted as a “law” even if it is unclear who legislated it. Other texts confirm the recognition of such regularities (*Ch’ang*) such as the one cited in Bodde (*Chinese Thought*, pp. 332-343). Bodde, however, stresses that such texts do not invalidate Needham’s belief in the absence of a Chinese equivalent of natural laws, because such views remained a minority view and could not have survived the rise of neo-Confucian thinking from the eleventh century on.

⁶³Ronan and Needham, *The Shorter* Vol. I, p. 167.

⁶⁴Sivin, “Why the Scientific”, p. 533.

engineering, biological technology, and such would simply not have taken place in the same form it did. Had there been a Chinese Industrial Revolution that would have overcome the negative feedback constraints of their epistemic bases, it would not have much resembled the one that actually occurred.

This is not to say that without the Rise of the West, the Orient would forever have been inward looking and stagnant. An Asian culture without the intrusion of the West might have once again have built a grand fleet and explored the world. A Japanese-Korean-Chinese collaborative effort, under the right set of circumstances, could have created a dynamic not unlike the North Atlantic semi-competitive research program that produced the second Industrial Revolution. Material wealth and even a degree of technological sophistication can be and were created with narrow-based techniques. At some point, however, this process would have run into the kind of ceilings that both East and West had experienced repeatedly before 1750. It is the removal of these ceilings and the negative feedback mechanisms behind them, that would have been difficult to remove.

And yet, at the end of the day it is hard to know precisely whether Oriental science, had it been left alone long enough by the West, would not have developed into something so radically different from what we are used to that we cannot even imagine it. Bray, in her critical review of much writing on Chinese history of technology, exhorts us to imagine “alternative trajectories of technical development” that might have stayed away from engineering sophistication or economic growth.⁶⁵ An evolutionary interpretation of history suggests that there are possible states of the world that are not imagined, but that *might* have occurred, given the opportunity. The problem is that such opportunities, too, depended on historical contingency. Just as a lot of indigenous flora and fauna in isolated demes have their evolutionary path cut short or altered irreversibly by a catastrophic event or the adventitious invasion of a fitter species, the path of technological evolution can be irreversibly altered by the invasion of a “fitter technology.” There is no way of knowing whether Pre-Columbian Peru or Maori New Zealand would ever have developed forms of technology that would astound us the way Marco Polo was astounded by China and the way New Guinea natives were astounded by Western technology. We can be pretty sure, however, that unless they somehow managed, against all odds, to produce a world of knowledge similar to that produced by Galileo, Lavoisier, Darwin, and Maxwell, the technology in use in these areas would have looked very different from what it looks like now.

⁶⁵Bray, “Critical History”, p. 163. One clue as to what Chinese technology, if left alone by the West, might have looked like is provided by all technological history, namely that it differed from the west in that the “state” played a much larger role in developing and choosing techniques than it did anywhere in the West. Thus for instance Bray (p. 173) explains agricultural change in China repeatedly as “the state’s efforts,” “the state tried” and “the state intervened.” This of course means that an “alternative” course of Chinese technology would have been largely politically determined – which alone marks a major difference between it and the West, where innovation was largely left to the private sector. Cf. Joel Mokyr, *Lever of Riches*, 1990, p. and Nathan Rosenberg and L.E. Birdzell, *Why the West Grew Rich: The Economic Transformation of the Industrial World*, 1986.