Science, Institutions, and the Industrial Revolution

Cliff Bekar - **Richard G. Lipsey**

Lewis and Clark College,
Portland, Oregon

Emeritus , Simon Fraser
University at Harbour Center
Fellow Canadian
Institute for Advanced Research
Vancouver British Columbia

1. Introduction[1]

Was the Scientific Revolution of the early modern period an important determinant of the "where and when" of the Industrial Revolution? For decades this question has absorbed the attention of economic historians and historians of science.[2] Musson, Robinson and Schofield argued that pure science played a crucial role in facilitating Britain's industrialization and that there were many direct links between a newly emerging body of scientific knowledge and Britain's 'wave of gadgets.' While Musson and Robinson were not convinced that they had definitively established such a link, they were confident that a renewed interest in the study of technology would soon do so.[3] It has not. In his path breaking work "*Prometheus Unbound,*" Landes made the now widely accepted argument that the technologies of the Industrial Revolution were the product of educated craftsmen engaged in empirical trial and error investigation,

---

[1] Our argument that science mattered for the Industrial Revolution was first given in a paper presented to the conference "On the Origins of the Modern World: Comparative Perspectives from the Edge of the Millennium," at the University of California at Davis, 15-17 October 1999. The present paper is a much revised version of that conference paper. We are indebted to the following for comments, suggestions, and constructive criticism: Kenneth Carlaw, Jack Goldstone, Peter Howitt, Joel Mokyr, Michele Platje, Alvero Pereira, Clyde Reed, Nathan Rosenberg, and the members of the Canadian Institute for Advanced Research's *Economic Growth and Policy Program* to whom an earlier version of this paper was presented. Elements of this paper have been included in Lipsey, Carlaw and Bekar *EconomicTransformations: General Purpose Technologies and Sustained Economic Growth* (Oxford University Press, 2005).

[2] See Jacob (1997), Kearny (1971), Landes (1969), Mokyr (1990, 2002), Musson & Robinson (1989), Stewart (1992), Schofield (1963) among others.

[3] See Musson and Robinson (1989).

and of new technologies developed fortuitously. Many, perhaps most, modern economic historians have followed Landes in arguing that the Scientific Revolution and the Industrial Revolution were not significantly causally connected.

We argue for a return to the views of earlier writers. We argue that mechanistic science was much more important in determining the when, where, and how of the Industrial Revolution than is currently accepted. Indeed, we argue that the development of early modern science was a *necessary* pre-condition for the Industrial Revolution.[4] We further argue that the roots of the West's success as a technologically dynamic society – a society whose technologies eventually surpassed those of the great societies of China and Islam – were grounded in events that occurred in the Medieval and Early Modern periods. In so far as industry and science were "revolutionized," those revolutions were made possible by a string of linked technological and scientific advances that stretched back for centuries.

The important aspect of early modern science for technology was the study of *mechanics* (often associated with the name of Isaac Newton).[5] Britain was the only country in which this specific branch of early modern science was widely taught, understood and practised throughout the XVIII^th^ century. This lead in mechanics ensured that, if the Industrial Revolution was going to start the XVIII^th^ century, it could only start in Britain. If Britain had been prevented from developing the Revolution, say for political reasons, it may well have happened elsewhere in Europe. But, if so, it would have been much delayed, as is illustrated by the actual difficulties in diffusing the early XIX^th^ century British technologies to the continent.

Science's channels of effect were subtle. It did not originate in a laboratory to be subsequently commercialised in industry as is sometimes

---

[4] Mokyr (2000: 1) makes a similar argument, "…I submit that the Industrial Revolution's timing was determined by intellectual developments and that the true key to the timing of the Industrial Revolution has to be sought in the scientific revolution of the seventeenth century and the enlightenment movement of the eighteenth century. The key to the Industrial Revolution was technology, and technology is knowledge."

[5] According to Crystal (1990: 775) "…mechanics [is] the study of the motion of objects as a result of forces acting on them." Although not then separated out, Newtonian mechanics dealt with what we now call mechanical engineering, which is, again from Crystal (1990: 775): "…the design, construction and operation of machines of all kinds. It is also concerned with the production and application of mechanical power."

posited in the traditional linear model. Instead, it facilitated the development of a cultural context in which craftsmen could talk to natural philosophers and natural philosophers took on the concerns of craftsmen. Even today science and technology exist in a positive feedback system of mutual causation in which advances in either field create pressures for advances in the other. It would be surprising to find a completely different pattern in the XVIIIth and XIXth centuries. What is clear is that without a mechanistic science, the feedback from knowledge to technology would have been much dampened and the development of technologies critical to long-run economic growth much delayed.

We offer a work of synthesis, a work that applies much new research in diverse fields to provide a new framework for analyzing British success at inventing, copying, and refining the technologies of the Industrial Revolution.[6] The synthesis includes a re-examination of the centuries-long paths of development of the technologies of the Industrial Revolution in the context of much new research done on the Scientific Revolution in the West, and on the development of science in China and Islam. The modern view among historians of science – that the roots of the Scientific Revolution lay in the medieval period[7] – complements our position that the technologies of the two Industrial Revolutions (specifically textiles machinery, the steam engine and electricity) had been evolving since the medieval period in a continual feedback process with scientific developments.

We test our ideas by applying them. To the question of why the Industrial Revolution occurred when it did, we reply that the path dependent trajectories of both technology and science made the Industrial Revolution possible in the late XVIIIth and early XIXth centuries. Various contingencies might have accelerated these evolutionary developments a bit, but not much. To the question of why not elsewhere, we first note that the work of Pomeranz in '*The Great Divergence*' has significantly changed our view of China as a possible industrializer. According to Pomeranz, mid-XVIIIth century China was similar to Britain in almost

---

[6] We accept Mokyr's (2000: 2) argument "that economic historians should re-examine the epistemic roots of the Industrial Revolution, in addition to the more standard economic theories…that focus on institutions, markets, geography and so on."

[7] See for example Grant (1996), Lindberg (1992) and Shapin (1996).

every dimension thought to matter to industrialization. We argue that establishing the necessity of science can contribute to a better understanding of why China, with developed goods and labour markets, secure property rights, high rates of saving, and all the other accepted preconditions to industrialization, nevertheless failed to industrialize. We also ask why the Islamic countries, once scientific leaders, failed to generate an Industrial Revolution of their own.

We proceed by briefly defining science and outlining some relevant aspects of its development through the Middle Ages and the Early Modern periods, offering an initial explanation for why such science developed in Europe. We then argue the 'science matters' thesis in two ways. First we detail the direct importance of science to the Industrial Revolution, arguing it was a necessary condition for industrialization. Second, we examine the channels by which science facilitated innovation. We then turn to the questions of Chinese and Islamic science.

2. Early Modern Science

Those who reject the importance of science to the Industrial Revolution's technology often argue the reverse, that before the XIXth century, trial-and-error-based advances in technology led advances in science. Arguments to this effect have usually concentrated on the direct links between technology and universal scientific laws. This version of the argument is persuasive.[8] For example, the second law of thermodynamics was developed by Sadi Carnot when studying Watt's engine in order to improve it, and Joule's discovery of the law of the conservation of energy came in the course of studying alternative sources of power for his father's brewery.[9]

We accept this view but add two critical caveats: before Newton, science contained none of the universal laws that characterise modern science, and most of the examples of feedback from technology to scientific laws relate to the XIXth and XXth centuries but not to previous periods. To go further, we need to distinguish between modern science and the science of earlier periods.

[8] See for example the work of Rosenberg (1982) and L. White (1978).

[9] These and many similar examples are cited in Rosenberg (1982:142-3).

Modern and early modern science distinguished. Modern science is a body of laws based on systematically assembled knowledge capable of predicting phenomena not observed when the laws are formulated. Today we distinguish pure science from applied science and engineering, which applies scientific laws to specific situations, developing principles and bodies of knowledge about how and why specific things work. We also distinguish between natural and social sciences, and between different disciplines within each of these. Today when people talk of science they usually mean "pure natural science," thinking in terms of universal laws such as Einstein's field equations.

What was important in the Early Modern period was not the science of all embracing generalizations – such as the laws of thermodynamics – but the piecemeal discoveries of experimenters such as Galileo, Gallen, Torricelli, Pascal, von Guericke, de Caus, and Toscanelli. Furthermore, in Classical and Medieval times, all science was contained in one discipline, natural philosophy. Well past the time of Isaac Newton there was no clear distinction between science and religion. The distinctions between pure science, applied science, and engineering did not emerge until the last half of the XIXth century: "We separate science from religion, science from technology, theories from practice. They did not" (Jacob: 104).

We argue that the view that science was not important to the Industrial Revolution depends on a XXth century definition of science; those who argue the irrelevance of science to the Industrial Revolution are only denying a link between *modern* science and the Industrial Revolution. Musson and Robinson (1989: 11) note the confusion over the role of science may be, "…the result of a false system of categories, which distorts the fact that when the scholar and the instrument-maker co-operated in the sixteenth and seventeenth centuries, as they often did, they were both acting in the character of proto-scientists."[10]

One gains a different perspective viewing science through pre-XIXth

---

[10] On XIXth century science and its connection to the mechanical arts, Ulgow (2002: xx) notes "At the time, 'science' meant knowledge; interest in the material world was 'natural philosophy.' And when people spoke of the 'arts,' they did not mean only the fine arts but also the 'mechanic arts,' the skills and techniques in agriculture, say, or printing. So the relationship of philosophy to the arts could mean the usefulness of natural knowledge to industry – almost the opposite of what we mean today."

century eyes. Science as it was then understood was critical in leading Western Europe to the threshold of the Industrial Revolution, and in taking Britain over that threshold. When we speak of Medieval and Early Modern science in this paper, we refer to what pre-XIXth century contemporaries understood as science and what is included even today in broad definitions: "the intellectual and practical activity encompassing the systematic study of the structure and behaviour of the physical and natural world through observation and experiment. ORIGIN Middle English (denoting knowledge)" (Oxford English Dictionary, 1664).

The development of early modern science. Medieval scholastic philosophers demonstrated remarkable flexibility in creating a synthesis of Greek science and Christian religion. Although they were not opposed to observation and relied heavily on the works of Aristotle, an astute observer of nature, *a priori* reasoning was held to be the primary road to new knowledge. The criticisms of this scholastic synthesis led directly to changes that would form the basis of Early Modern science. It was as much a change in method as substance. Early Modern science was marked by an acceptance of experiment as *the* way to settle empirical debates, "What was held to be overwhelmingly wrong with existing natural philosophical traditions was that they proceeded not from the evidence of natural reality but from human textual authority" (Shapin: 68). Crucially, however, many of the questions under investigation were those raised by scholastic philosophers or even the ancients. Later one of the defining elements of XVIIth century science was the mathematization of natural laws. Here again we find continuity, this time in a desire shared by prior generations of philosophers who often simply lacked the required technique (see Shapin Chapter One). But perhaps the most important characteristic of the Scientific Revolution was seeing the world as a complex 'mechanism' and the resulting view that understanding physical behaviour in mechanical terms was one of the primary goals of science.

Because it was using new methods to deal with old questions and hypotheses, pre-Newtonian science developed through myriad piecemeal discoveries concerning many of the issues that had plagued scholastic philosophers for centuries – the existence of vacuums, the nature of atmospheric pressure, the behaviour of rolling and free falling bodies, and many other similar issues. All of these advances (occurring roughly from 1450 to 1650) are found in any standard history of science, although none were formulated as universal laws. In a sense they can be seen as piecemeal discoveries made in attempts to test existing hypotheses (most of which were due to Aristotle). The accumulating evidence slowly refuted much of Aristotle's writings, and this in turn required the development of a new overarching framework that could explain the newly emerging conflicts with his work.

By the beginning of the Early Modern period, the scholastic astronomical system that united Aristotle's science, Ptolemy's cosmology, and biblical teaching was fully developed. This accomplishment left the three strands of thinking fully intertwined; to attack anyone of them was to attack the others simultaneously (White, 1986). At this point the early flexibility of the scholastic philosophers in reconciling Christianity with Greek science eventually gave way to rigidity. It was thus considered blasphemous when Galileo insisted that the heliocentric system described reality rather than just being a useful predictive device. As a result, the Roman Catholic church declared the new heliocentric view heretical early in 1633. On the continent many Protestant leaders, such as Calvin and Luther, also rejected it. However, by 1670 many English churchmen had embraced the new science – although others defended Ptolemaic orthodoxy through the next century. First, the Quakers and then liberal Anglicans began to preach Newton's mechanics from the pulpit, arguing that it was an impressive example of the sublime works of God who had created the universe and its laws (Jacob: 60). In this sense, natural philosophers saw themselves "…as doing a *better* job of interpreting God's word than the theologian" (Shapin: 137, original italics). The natural philosophers focused on efficient causes, and not God's ultimate will. As this interpretation of their activity gained acceptance it ultimately allowed them more latitude in determining the types of questions they could explore.

Although the mechanistic worldview was developed in the Early Modern period, non-mechanical views remained influential well into the XVIIIth century. Many scientists continued to work on theories born in the Middle Ages. Transitional periods are like that; key thinkers have one foot in the old system and one in the new. Many scholars contributed substantially to changes whose revolutionary implications they only dimly perceived and did not always approve. This was true even of Newton.[11] Only with Newton's popularizers was the mysticism stripped from his theories – presenting an uncompromisingly mechanical view of the universe.

The scientific discoveries of the Early Modern period generated a new world view of a mechanical universe. This view fostered an interest in mechanizing human activities wherever possible.[12] The new mechanics "…was used not merely to calculate the movement of heavenly bodies, but also in practical arts such as navigation, cartography, ballistics, mining, and surveying, and these gave rise to the craft of instrument-making: the manufacture of telescopes, microscopes, barometers, chronometers, micrometers, dividing and gear-cutting engines, etc" (Musson and Robinson: 23). This drive to mechanize was a central aspect of the new science.[13]

In 1662 a group of moderate reformers founded the *Royal Society of London for the Promotion of Natural Knowledge*.[14] Because the Royal Society was a private institution (unlike the French equivalent, which was the creation of the state), and because it admitted men of property and influence who were not scientists, it became a conduit for spreading the new scientific knowledge to a wide audience. To a XX^th^ century

---

[11] For a detailed discussion of the various non-modern views of many who contributed to the development of Early Modern science see Kearny (1971: 22-48). Christianson (1984) is a fine biography of Newton that puts him into the context of his times, revealing the extent of his mystic beliefs.

[12] Mokyr (1999) argues that many of the things scientists were investigating in the Early Modern period had no direct relevance for current technological problems. This is as it had always been right up to the XX^th^ century, and how it still is in many fields today.

[13] From Shapin (12, original emphasis), "…I think that attempts to 'mechanize' not only nature but the means of knowing about nature, as well as *conflicts* over the propriety of mechanical and experimental modes, do capture quite a lot that is worth understanding about the cultural change in this period."

[14] On the role of the Royal Society see Musson and Robinson (1989: 56-59). There were many important learned societies founded in this period such as the *Lunar Society, Society of Arts, Society for the Advancement of Arts, Commerce, and Manufactures*. By 1790 there were 220 such societies, many located in England (Armytage, 1965).

person used to hearing specialists talking jargon, the proceedings of the Royal Society, and its roster of membership, speak of another world. It was a world in which the latest scientific facts and theories were eagerly studied, discussed, and disseminated to a wide audience. The Royal Society, as well as all the other societies of knowledge that sprang up at the time, provided an important channel through which science impacted the knowledge and attitudes of those who all those who sought out technological advances.[15] Speaking of the spirit of the learned societies, Musson and Robinson (59) note that "In the pursuit of useful knowledge, in the study of the ways in which science could be applied to industry, and industry provide the material for science, class-divisions in Great Britain seem to have been largely overlooked."

It was at this time, the late XVIIth and early XVIIIth centuries, that the promise of Medieval and Early Modern science was finally being realized, with the formation of numerous learned societies, burgeoning universities, a Church unable or unwilling to resist the spread of the new science, a growing belief among many of the English clergy that to understand Newton was to understand God's purposes, and the increasing codification of empirical results into mathematical general laws of nature.

Why A Scientific Revolution In Europe? The issue of why science developed in Europe (but not elsewhere) is complex. Here we touch on three important aspects of a potential explanation. First, the Christian church – largely as a result of historical accident – accepted and encouraged the natural philosophy that evolved into early modern science. Second, medieval universities provided a neutral space in which science could develop cumulatively. Third, Europe developed an institutional memory able to facilitate the incremental nature of scientific development.

Early Christianity. Early Christians were a minority struggling for existence

---

[15] Another organization, The Lunar Society, also made important contributions to English science and industry. It was a small collection of men expressly interested in the scientific questions of the day and, importantly, how those questions could be best applied to manufacture. See Schofield (1963) and Uglow (2002).

in the presence of strong central governments and other established religions. Upon becoming a dominant religion they often sought to convert others by force. However, during the first 400 years after the birth of Christ – until they became the official religion of Rome – Christians had to convert others by persuasion. This required them to accept the existing lay authority, making a theocracy impossible.[16] It also required that the early church fathers come to terms with the sophisticated Greco-Roman culture in which they were operating. They needed to become philosophers. After many debates about how revealed religious knowledge related to Greek scientific knowledge, Christianity reconciled itself with Greek learning rather than rejecting it as an alien and evil force. From Grant (8-9), "The separation of church and state, at least in principle, and, more significantly, the Christian accommodation with Greek science and philosophy, were instrumental conditions that facilitated the widespread, intensive study of natural philosophy during the late Middle Ages. As a consequence of the emergence of natural philosophy within the unique university system of the Latin Middle Ages, the revolutionary developments in science of the sixteenth and seventeenth centuries were made possible."

Another issue faced by early Christian thinkers was the question of God's place in day-to-day affairs. According to the doctrine of occasionalism, God is responsible for all day-to-day occurrences in the world. Attempting to discover natural laws was seen as a blasphemous attempt to predict the behaviour of God. According to the religious version of the doctrine of naturalism, God created the world according to natural laws and then endowed humans with free will to determine their own affairs. After centuries of debate, Christian thinkers rejected occasionalism and accepted naturalism. The important result was that the search for nature's laws was seen as a reverent attempt to understand God's purpose. Further, to the extent that these natural laws were 'mechanical' in nature, they often provided evidence of 'intelligent design' to those predisposed to believe in a creator. As Shapin (142) notes, "...it was precisely the

---

[16] Although in later centuries the church and the state often struggled over their boundaries of authority, a complete union of the two was never accomplished throughout Europe, although at times they did co-operate to suppress heresy.

mechanical conception of nature that generated some of the most powerful and persuasive arguments that the new scientific practice was religion's truest handmaid." Natural philosophers of the day saw themselves as contributing to, not tearing down, the new Christian worldview.

Universities as corporations. One of the most important medieval institutional innovations was the corporation, which treated organisations as entities distinct from both their individual members and the state. The multitude of European corporations – the church, guilds, universities, and some cities – each with its own range of authority, was a key development in the pluralism that has characterised much of the West's institutions to this day.

The rising urban prosperity that began in the XIth century led to an increase in the demand for education. As Church schools grew in the major urban centres, some evolved into universities. Over time, universities became corporate groups of teachers and students who were self-governing with a considerable degree of autonomy from local and national interference. As Grant (1996: 173) observes: "To a remarkable extent, church and state granted to the universities corporate powers to regulate themselves, thus enabling the universities to determine their own curricula, to establish criteria for the degrees of their students, and to determine the teaching fitness of their faculty members." It was a natural step for the corporation, rather than individual scholars, to impose standards, grant students a licence to become teachers, and often to pursue courses of action unintended by the founders. This allowed universities to evolve, while maintaining standards of curriculum and examinations not subject to the whim of individual members and free from day-to-day censorship, "For the first time in history, an institution had been created for the teaching of science, natural philosophy, and logic" (Grant: 172).

During the early development of medieval science that took place within the universities, most of the works that first became available on such matters as medicine and geometry (from the Greeks) and algebra and astronomy (from the Arabs), posed no theological problems. The materials in these 'exact sciences' were clearly useful and did not intrude into Christian dogma. Nor did the existing Greek translations of Plato and the Greek literary works. In an important historical accident, these works did not include those of Aristotle whose writing had not been translated into Latin in Classical times. Certain of Aristotle's doctrines – particularly that the world had neither beginning nor end in time, that the soul perished at death, and the prime mover who left no apparent room for divine intervention in the form of miracles – seemed to contradict Christian teachings. However, the Christian church had already committed itself to the view that Christianity was compatible with Greek learning by the time Aristotle was translated. Instead of rejecting this branch of Classical learning as subversive, the church sought to Christianise it. Reconciling Classical learning, particularly the writings of Aristotle, with religious doctrine became the most important research programme of the XIIth and XIIIth centuries, "In broad terms this meant bringing together in a single whole, views based upon the amalgam of Jewish history and poetry called the Bible (in the Greek translation known as the Septuagint, which dated from c. 200-100 BC) with the philosophy and science of the advanced urban civilisation of Greece – a formidable task" (Kearney: 13). Thomas Aquinas was the most well-known scholar connected to these efforts.

In spite of Aquinas' achievements in attempting this reconciliation, conservatives sought to prohibit specific teachings due to Aristotle and contemporary philosophers. The prohibitions were never fully effective, since the church as a whole mostly did not seek to suppress Greek learning, only reconcile it with Christian teaching. Scholars also learned to circumvent those prohibitions that did exist by employing various dodges (e.g., teaching the proscribed doctrines in order to 'refute' them).

Universities went on to solidify Aristotelian naturalistic doctrines in their synthesis of Greco-Islamic learning and Christianity, which became the official curriculum of all medieval Western universities. As Lynn White (90) puts it "…the chief period of Europe's re-appropriation of Greek science extends from the later eleventh century through the thirteenth century and marks the birth of our present scientific movement. " By the XIIIth and XIVth centuries, the church, academics, and most religious people accepted that the world was controlled by natural laws – laws that it was man's duty to discover. With the new curriculum and a well developed system of examinations in place, "…the West took a decisive step toward the inculcation of a scientific worldview that extolled the powers of reason and viewed the universe – human, animal and inanimate – as a rationally ordered system" (Huff: 189).[17]

Medieval science gave a number of vital legacies to the early modern era.[18] First, it asked many specific questions that became part of the agenda of early modern scientists. Although they gave novel answers, these scientists were answering medieval questions and hence continuing the medieval research agenda. Out of these new answers came physics, biology, meteorology, psychology, and geology, all of which had once been a part of natural philosophy. Second, medieval science supplied an interest in what can be called scientific methodology: What can we hope to know about the world and how can we go about knowing it? Third, medieval scientific methodologies produced what were then new rationalistic assumptions about the nature of the world and passed that world view on to early modern scientists. As Grant (169-70) points out, "[A] scientific revolution could not have occurred in Western Europe in the seventeenth century if the level of science and natural philosophy had remained what it was in the first half of the twelfth century…."

Institutional Memory. Many other cultures, particularly those of Islam and China, have produced scientific and technological discoveries at least on par with those of Medieval Europe. But few have reproduced Europe's capacity for incremental cumulative advances in science. The cumulative development of any field of inquiry requires a memory so that what is established can be preserved and built upon generation by generation. An important contrast between technology and science lies in the structures that provide the necessary memory. With technology, the minimum

---

[17] There is some debate on the role played by universities by the seventeenth century. Many see them as playing a conservative role in this period. Grant (174) argues that, "Whatever the state of the universities in the seventeenth century, these venerable institutions had already done their foundational work. They had shaped the intellectual life of Western Europe. Their influence was everywhere."

[18] As Lynn White (86) observes, "The Scientific Revolution of the seventeenth century was in every sense the child of late medieval science, although a rebellious child."

necessary memory is usually provided by the embodiment of technological knowledge in the continued use of artefacts such as tools, machines, new crops, etc.[19] Artefacts have a physical existence and technological improvements are embodied in better artefacts; they are there for all to use and to improve on in their turn.[20] The artefacts themselves and, when necessary the associated apprenticeships, pass to successive generations both the explicit and tacit knowledge needed to employ them effectively. Thus, throughout most of history, the continued employment of the artefacts that embodied most technological knowledge provided an unplanned, and largely unmanaged institutional memory.

In contrast, there is no automatic memory provided for scientific knowledge. Institutions are usually required so that scientific knowledge can be remembered, taught to successive generations, and built upon. Creating such arrangements was one of the great contributions of the medieval European universities. They provided an institutional memory for science: libraries where the knowledge was recorded, class rooms where it was taught to each new generation, and scholars who added to the body of evolving scientific knowledge. There is little doubt that universities were important institutions for providing continuity in the evolution of medieval scientific knowledge – just as the Greek Academies did in Classical times.

This point is important in answering a key objection to our thesis. If the Chinese and Islamic countries were at least as well advanced as the West in technology, why did they not equal the West's advances in science during the early modern period? A key part of our answer is that they lacked the independent institutions that provided an effective memory that allowed scientific advances to be cumulative; they did not need such an institutionalized memory for technological advances. (This point is further discussed in later sections on China and the Islamic countries.)

---

[19] Technologies are occasionally lost. First, at times of great upheaval they may fall into disuse to be forgotten, as was the case with several Roman technologies. Second, the technology may be used by only a few persons whose successors may lose interest, as was the case with the great Chinese water clocks that were used for astrological purposes by some emperors then ignored by later ones.

[20] It may help to record technological knowledge in written form and to pass it on through formal instruction, but this was seldom necessary before the XIXth century.

3. Science and the Industrial Revolution

We divide the whole period of industrialization into four phases (which, of course, overlapped and shaded one into the other):

- Early Modern Mechanization (1450-1760): incremental development in scientific and technological knowledge the most important of which were textiles, the steam engine and electricity.
- Early-Factory Phase (1760-1820): proto-factories are sheds containing hand powered automated textile machines – and water powered factories containing automated textile machinery.
- Steam-Driven Factory Phase (1820-1880): first used for textiles and then for other products, located in the new industrial towns and extending into transport through steam ships and railways.
- Second Industrial Revolution (1880-1945): characterised by such products as steel, chemicals, internal combustion engines, and electric motors, whose development often required a clear understanding of scientific laws.

The first of these phases predated the Industrial Revolution, the second and third are usually referred to as the First Industrial Revolution.

No doubt many forces contributed to Britain's technological and industrial success. As David Landes put it:

> [W]hat sets Britain off is a question of degree. Nowhere else…was the countryside so infused with manufacture; nowhere else, the pressure and incentives to change greater, the force of tradition weaker. It was all of a piece: improving landlords, enclosures, commercial farming, village shops, putting-out, mines and forges, the active mortgage market – all combined to break the shackles of place and habit, assimilate country and city, and promote a far wider recruitment of talent than would have otherwise occurred (Landes 1969: 71).

To this list we would add: more security of real and financial property, strong restraints on arbitrary behaviour of the monarchy, better intellectual property protection, colonies that provided raw materials and markets, and a host of other factors that helped rather than hindered Britain's industrial and commercial success. Several subsets of these causes might have been sufficient for the Industrial Revolution to occur. We argue, however, that mechanistic science in general and Newtonian mechanics in particular is a necessary element of any subset. Furthermore, such science and mechanics were precisely what was missing in those other regions that some have argued were on the verge of an industrial revolution.

Early Modern Mechanization. If we are to understand the importance of science to the Industrial Revolution, it is important to understand that the Industrial Revolution was not produced by a sudden discontinuity in the evolution of technology. Instead it was the end result of a centuries long trajectory of mechanisation that owed much to science. One of the greatest visionaries of the early modern period was Leonardo di Vinci. He conceived a programme to mechanize most of the operations in the textile industry and his drawings anticipated elements of what happened over the next three centuries, charting the trajectory along which the mechanisation of textile production proceeded cumulatively over that period. His projects "…mark the opening up of invention as a conscious reaching forward to distant objectives in which the immediate possibilities are forgotten and the attention is concentrated on the complete realization of the abstract principle" (Usher: 271). Although he made important inventions in textile machinery, many of his ideas languished because mechanical technology was not yet up to delivering what he was able to conceive through the application of the mechanistic-scientific-philosophical doctrine. Technology had to catch up with scientific imagination, not the reverse.

The history of slowly evolving mechanization illustrates a general problem found with the development of each major type of textile machine. Typically, it was long after basic theoretical principles had been solved that engineers could implement them. This process required many incremental and often complex inventions; each one designed to eliminate a human task. Concentration on the final inventions that led to the transfer of textile production out of cottages and into factories has often obscured the fact that these inventions were but the later stages in a long series of path-dependent technological developments in which problems were first solved scientifically and only later technologically. For example, according to Usher (288), the history of the mechanization of draw loom weaving. "…has long been obscured by writers who were unwilling to recognize the essential cumulative character for mechanical achievements."[21]

Engineering constraints in textiles were a major determinant of the pace of mechanization – advances in spinning preceded those in weaving because the mechanical problems were less. Leonardo di Vinci was responsible for, among other things, the application of mechanical power to, and increased mechanical control of, spinning and reeling, the application of water power to silk reeling and twisting, and the development of the spindle with its building motion. In 1530, a flyer was developed for the Saxon Wheel. Methods of stopping the rebound of the shuttle in power looms were suggested in 1678 and 1745. These were unsuccessful for materials wider than ribbons, although important for ribbon production. Shearing engines, working on the principle of scissors blades, were worked on continually from Leonardo's time, until 1792 when a mechanism similar to a lawn mower solved the problem. Silk doubling and twisting were successfully mechanized soon after Leonardo pointed the way. According to Usher, the early application of mechanization to most aspects of silk manufacture strongly suggests that mechanical problems were the main detriment to applying mechanization to the spinning of wool, flax and cotton. The draw loom was developed in the XVth century and the stocking frame later in the XVIth. As well as making hose, it was the basic invention that "underlies the whole family of knitting and lace-making machines developed in the eighteenth and nineteenth centuries" (Usher: 281). The most basic ribbon loom was invented in the XVIth century and important improvements continued to be made over the next 200 years. Finally in 1745, Kay controlled the pedals by tappets whose motion could be co-coordinated with other motions of the machine. Thus as early as 1760, the

---

[21] The story goes back to the XVth century when a loom was invented that worked for narrow fabrics. A series of improvements occurred over the centuries. For example, spinning by rollers was developed in 1733 and the mounting of spindles on a moveable carriage to duplicate the operation of pulling out the yarn came soon after. Jacquard completed the process early in the XIXth century.

ribbon loom embodied all the essential mechanical principles of mechanized weaving. 1730 saw a patent for the preparation of twine, while a patent for a machine for opening and dressing wool was issued in 1733. That year also saw the momentous invention of the flying shuttle. Later in the century, came the well-known spinning jenny and the mule. Although the flying shuttle was a key invention, it created a series of mechanical problems whose solution required many decades of effort. The problems arose when the attempt was made to substitute mechanical means for the hand of the weaver on the picking stick of the flying shuttle.

The Early Factory Phase. The second half of the XVIIIth century witnessed a discontinuity in the evolution of the key elements of the economic structure of the British economy. It was in this period when the long evolution of automated textile machinery reached a stage where it became efficient to take production out of the cottages and sheds filled with human-powered machinery and into small water powered mills. Although these relatively sudden changes in the economy's structure have often been misconstrued as sudden changes in technology, in fact, as we have just seen, textile machinery evolved incrementally until it became efficient to transfer production from cottages to mills.

While what we now think of as science played a small role in some of the developments in the mechanization of textile manufacturing (e.g., the development of the Jacquard loom was influenced by new ways of organizing information), most developments were influenced by what we now think of as engineering expertise. But that engineering expertise was evolving as part of the whole mechanization program that was both encouraged and facilitated by the early modern scientific-mechanistic worldview, "and though few craftsmen wrote on anything much removed from their own skills, a corpus of knowledge on technical matters was beginning to emerge to which craftsmen began to make their contribution" (Musson and Robinson: 17-18).

Accumulating knowledge allowed engineers to accomplish things in 1650 and in 1750 that they could not do a century earlier. If these technological developments came from 'tinkering,' it was a 'tinkering' that was enabled by two centuries of accumulated 'scientific' knowledge based on an evolving research programme to mechanize all aspects of textile production. If what was invented in the XVIIth and XVIIIth centuries seem mere 'gadgets' to modern eyes, they were triumphs to contemporaries – and scientific marvels in an age in which there was no distinction between science and technology.[22]

Isaac Newton was the single most important figure in the new mechanical science. Although his towering place in science is well known, less attention has been paid to his place in the popular culture following the publication of his *Principia* in 1687.[23] Newton's work was the great synthesizing achievement of the new science. Its laws of motion presented a mechanical interpretation of the behaviour of all things in the universe, large and small, near and far. These laws, and their many applications, soon came to permeate British thinking. Indeed, it does not seem an overstatement to say that Newtonian mechanics provided the intellectual base for the First Industrial Revolution, which was almost wholly mechanical.

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

Eighteenth-century manufacturers needed to possess the skills of Newtonian mechanics (or be able to hire and converse with those who did).[24] This required some mathematical skill. The relevant mathematics

---

[22] For the use of the terms 'tinkering' and 'gadget' see respectively Mokyr (1990) and Ashton (1955).

[23] Our discussion of this aspect of Newton's work is based on the path breaking research of Margaret Jacob (1997). She has meticulously documented the degree to which Newtonian science and mechanics permeated British society, as well as being accepted by the clergy. On the spread of Newtonian science see also Stewart (1992). On the general spread of this new culture of science see Uglow (2002).

[24] Both Jacob (1997) and Uglow (2002) discuss the interface between entrepreneurs and Newtonian science. See also Musson and Robinson (1989).

was widely taught in British schools as early as the 1720s and, to this end, the number of mathematical textbooks doubled in the first half of the century (Jacob: 110). His many followers, who wrote textbooks and gave public instruction, popularised Newton's science. The science of scholars became the science of the educated layperson. Lecturers soon took the new knowledge to all parts of Britain, reaching enthusiastic audiences containing cross sections of persons that can hardly be imagined attending any XXth century lecture on modern science. Popular journals, including one addressed mainly to women, helped to spread the new knowledge. While Catholic and Protestant clerics on the Continent were still opposing Galileo's theories, many Anglicans were preaching Newton's ideas from the pulpit. The degree to which the new science permeated British society and was used by innovators and entrepreneurs, such as the Watts and the Boultons, separated England from all other European countries.

> Hence, Newtonianism was soon represented in the public world as holding the keys to the solution to a wide range of obstacles in mechanics, mining, hydraulics, and various technical enterprises….the world of the public lecturer and experimenter was prescient with meaning for the acceptance of natural philosophy and, through its practitioners, of the legitimacy of the domination and manipulation of nature upon which a materialist society came to rest, The industrialization of eighteenth-century Britain was as much a function of this attitude as a response to economic or technical factors. (Stewart: xxxiv)

Further,

> [The scientific revolution created] in Britain by 1750 a new person, generally but not exclusively a male entrepreneur, who approached the productive process mechanically, literally by seeing it as something to be mastered by machines, or on a more abstract level to be conceptualised in terms of weight, motion, and the principles of force and inertia (Jacob: 6-7).

Smeaton is a case in point, his "…work was outstanding as an example of experimental method in science, and how it could be used to shed light on engineering problems" (Pacey: 208). Smeaton actively employed Newton's 'laws of reasoning by induction' to study the properties of the waterwheel, demonstrating the superiority of the over-shot wheel to the under-shot, and the superiority of the breast-wheel to all others. Many of Smeaton's results were published by the Royal Society, ultimately proving to be widely influential.[25] According to Pacey (209) Smeaton "...clearly saw that the comparison of his maxims with experimental measurements involved the same methodological problem as Newton's comparison of theory and observation in astronomy."

Mechanical science influenced technological change, not just in machinery, but in canals, harbours, mines, and a host of other applications. It did this not through general laws from which specific applications were deduced, but by permeating thoughts and attitudes and providing people with the theoretical mechanics and the mathematics that facilitated technological change. This illustrates the fusion of theoretical and applied science, as well as engineering, that characterized the scientific world until well into the XIX^th^ century. Only as knowledge accumulated, did the need for a division of labour create a clear distinction between the theoretical and the applied.[26]

The contrast with French science and engineering is dramatic, "...[E]ducated Frenchmen of the generation prior to the 1750s missed any formal education in practical Newtonian mechanics as well as in the entire Newtonian philosophical outlook" (Jacob: 50), and "The combined legacy of Cartesian and scholastic teaching may account for the fact that by the 1790s French colleges were noticeably deficient in teaching devices needed for mechanical applications" (Jacob: 46). Because French teaching lacked the mechanical applications that were common place in England, they lacked the Newtonian applied science that was the underpinning of the First Industrial Revolution. Mokyr (1990:242) quotes Kuhn as saying that the views of the English were predominantly experimental and

---

[25] From Pacey (211): "It is perhaps significant that many of the large water-powered factories erected during the industrial revolution were equipped with breast-wheels, although this type had rarely been used previously."

[26] Even then a clear distinction was slow to develop. For example Lord Kelvin, one of the most important theorists in science at the end of the XIX^th^ century, and president of the Royal Society in 1890, made many applied technological discoveries.

mechanical while the French were predominantly mathematical and deductive "seems to have stood the test of time." The French made many inventions but the English excelled in commercial applications because they understood the mechanics that were needed to make ideas work.

Further evidence of a gulf between Britain and the continent in their understanding of Newtonian mechanics is the length of time that it took for British technology to spread to the Continent. This took more than a generation, and it was usually British technicians who made the technology work on the Continent. If the continental countries were on the verge of an Industrial Revolution, and had the scientific prerequisites for it, diffusion would have been much faster and easier than it actually was.

Landes (1969) was an early proponent of the view that technology owed little to science before the XIXth century.[27] Lynn White (1978) has argued a similar position. However, more recent research has revealed just how deeply Newtonian science permeated the thinking of British industrialists, engineers, entrepreneurs, and ordinary people;[28] laid out the importance of the scientific societies;[29] and demonstrated the historical continuity of scientific development.[30] Many puzzling aspects of British industrialization are explicable when seen in this new light. For example, Landes (1969: 61) points to a "higher level of technical skill and general interest in machines" in England compared with other European countries, but argues this "…should not be confused with scientific knowledge."[31] He also notes that his view that science was unimportant to the British Industrial Revolution "…makes the question of British mechanical skill the more mysterious." Indeed it would be mysterious if that skill had nothing to do with science, as Landes would have us believe. In the same vein, Mokyr (1990:242), argues that "Britain did not have a significant

[27] Landes (1998) shows no change in his position on this issue.

[28] See Jacob (1997).

[29] See Uglow (2002).

[30] See Shapin (1996) and Grant (1996).

[31] Mokyr makes a similar point: in the "…development stage of basic inventions in which engineers and technicians on the shop floor improved, modified and debugged the revolutionary insights of inventors…pure science played only a modest role" (Mokyr 1999:19). But this is as it has always been. Even today, science often contributes to the basic principles that govern some new technology while practical empirical work subsequently helps to debug it and widen its applications.

scientific advantage that would explain its technological leadership." Nor, according to him, did Britain have more science than continental Europe, only a "different kind." But that is just our point. The pervasiveness of Newtonian mechanics, and the mathematics on which its applications were based, (both based on some of the most profound scientific discoveries of all time) provided Britain with the knowledge that underlay the mechanics of the First Industrial Revolution and, in the absence of which, British inventions could not easily diffuse to Europe, even after they were made. The British comparative advantage in applied engineering was based on a mixture of practical and scientific knowledge (as it was then understood). It was much more than just an ability to 'tinker.'

Virtually all of the British inventors were cultured and educated persons, in touch directly or indirectly with the latest scientific advances. If the image of these technicians as white-coated scientists using fundamental scientific laws to develop their technologies is wrong, so is the image of them as grimy workers and untutored tinkerers. Even Landes (63), having argued elsewhere that science had little to do with technological developments, observes:

> Even more striking is the theoretical knowledge of these men. They were not, on the whole, the unlettered tinkerers of historical mythology. Even the ordinary millwright…was usually a fair arithmetician, knew something of geometry, levelling and mensuration, and in some cases possessed a very competent knowledge of practical mathematics. He could calculate velocities, strength and power of machines; could draw in plan and section. Whatever the reasons for British precocity in this domain, the results are clear

Surely this is a telling observation when we realize that at no previous time in history, and at no place outside of Britain in the 18th century, could one say such things about ordinary millwrights (or their analogues in other times or places). They shared in the common pool of mechanical theory and applied knowledge that underlay the great mechanical inventions of the Industrial Revolution, including the steam engine. Once one accepts the nature of pre-XIXth century science, and the degree to which Newtonian mechanics permeated and influenced British society, there is no mystery in Landes' observations.

Steam-Driven Phase. By the early XIXth century, incremental developments in steam engines reached a point at which it became efficient to replace water and human power with steam power. A major structural change then ensued when, free from the restraints of needing to locate near fast running water, automated textile factories were moved to the new industrial towns. Here again, rapid changes in the structure of the economy have often been confused with a major discontinuity in the evolution of technology itself. In the steam-driven phase, two technologies with trajectories of incremental developments stretching back for centuries were combined to create the steam-driven factory.

As well as moving production from sheds and small water-powered mills into large steam-powered factories, new machines and new factories had to be designed and built. Metal replaced wood in machinery and a whole new machine-tool industry developed. Industry became more concentrated as the scale economies of steam-powered factories called for much larger productive units than did water power. Major adjustments to many other elements of the economy's structure were required when English society became urbanized to an extent not seen since Classical times. Fuel, raw materials, and finished goods, needed to be transported. This required an extensive network of canals and railroads. The new modes of transport introduced by the railway and iron steamships altered many economic relations. This was the age of steam and the development of the steam engine is an important part of our story of the close relation between scientific understanding and the evolution of applied technology.

The development of steam power – the first major new source of power for Europe since windmills – starts with Early Modern science and is an example of a positive feedback between technology and science. While no one can definitively demonstrate that a purely empirical approach, devoid of any science, could not have produced the steam engine, three things are clear. First, that is not what happened; "The development of working steam machines and scientific understanding went hand in hand. Second, a purely empirical approach would have taken far longer. Third, if the steam engine had evolved solely through trial and error, it could not have reached the same level of efficiency or range of application that it did historically. Both the early development of the steam engine, and many of its later refinements, for example the Corliss engine,[32] relied not on trial and error empiricism but on science, and that reliance began well before the rise of the factory system.[33]

At the beginning of the early modern period, the principles underlying the suction pump were not understood because little progress was made in understanding one of the great scholastic research issues, the nature of a vacuum. Galileo considered the suction pump but to no avail. Torricelli studied the pump's failure and made the first correct analysis of air pressure. Pascal elegantly repeated Torricelli's experiments and published works that put the theory of atmospheric pressure on a firm basis. Independently, Otto von Guericke experimented with air pressure and produced the first workable airtight cylinder and piston driven by atmospheric pressure. As well as adding to knowledge about vacuums, his cylinder provided a technological advance that was necessary for the subsequent development of the steam-driven piston. From Cardwell (11): "The discovery of the atmosphere thus profoundly affected the development of science…[and] it was no less important in its impact on technology." While none of these early discoveries resulted in sweeping scientific laws, they were all scientific advances, as science was then understood.

Once the scientific principles of the suction pump had been understood, the design was extensively modified – showing the feedback from scientific understanding to technological improvements. In 1675 Samuel Moreland obtained a patent for a plunger pump in which a plunger worked through a gland and stuffing box. This principle was essential to the piston engine and was used in several other types of machine.

Another important scientific problem concerned the nature of steam.

---

[32] See Rosenberg and Trajenberg (2000).

[33] The classic study of the development of the steam engine is von Tunzelmann (1978). While von Tunzelmann denies a 'linear model' in which new scientific breakthroughs invariably led directly to new technologies, his views on the relationship between science and those factors facilitating innovation seem close to ours, which is that scientific development often led engineering applications (while the reverse was also sometime the case). See also von Tunzelmann (1994).

Earlier investigations of steam were hampered by the mistaken theory that steam was just a form of air. Cardan and Porta got close to understanding the issue, but De Caus (1576-1630) took the decisive step. He realized that steam was evaporated water, which on cooling returned to the liquid state. These "…were scientific discoveries of the utmost importance. They were the principles upon which the work of Worcester, Savery, and Papin was largely based" (Usher: 343). The realization that air and steam were different made it clear to contemporary observers that steam had greater power potential than existed in air pressure. Inventors saw the potential of steam power but, as in the case of textiles, they were held in check by practical constraints, "Men could see the possibilities clearly enough but they had no means of bringing them within the realm of the practicable" (Cardwell: 12). Here again, and in strong support of our thesis, scientific knowledge of what was possible was well in advance of technological knowledge of what was feasible.

The first workable steam engine was developed by Edward Somerset, the second Marquis of Worcester (who benefited extensively from the studies on mechanics by Caus and Porta, see Thurston 1878: 16). His engine used both atmospheric and steam pressure. Thomas Savery used the same principles in the first commercial steam engine. Because the engine required pressure that was higher than current metallurgy safely accommodated, its boiler was liable to explode.[34]

However, it was not the 'fountain engine' that led to the practical steam engine, but the use of pressure to drive a cylinder. Many experimented with pistons as a means of using atmospheric pressure. Christiaan Huygens and Abbé Hautefeuille proposed to create a vacuum by exploding a charge of gunpowder in a cylinder. The mathematician, Papin, argued that steam could push a cylinder upwards and then be removed, allowing the cylinder to cool so that atmospheric pressure pushed it downwards.[35] The honour of developing the first commercially viable steam engine belongs to Thomas Newcomen. Although country bred, Newcomen kept in touch with the latest scientific developments

---

[34] On the early uses of various types of steam engines see Musson & Robinson (1989).

[35] Papin was a mathematician who, after escaping from the persecution of Protestants in France, worked in the laboratory of Robert Boyle, the founder of the Royal Society.

by corresponding with Robert Hooke of the Royal Society. In Newcomen's engine gravity raised the cylinder through the action of a counterweighted beam. The cooling of steam that had been forced into the cylinder then created a partial vacuum and atmospheric pressure forced the cylinder downwards on its power stroke. Since it did not drive a column of water upwards, as did Savery's engine, the boiler and cylinder operated at safe levels of pressure. The engine marked "…the effective beginning of the utilization of the new sources of power with which scientists and inventors had been struggling actively for about a century" (Usher: 350).

Watt was interested in the use of steam in power generation prior to 1760. As Cardwell (42) notes, "In those days he was an instrument-maker and a scientist, not an engineer. He had no experience of Newcomen engines nor, it seems, of any other large-scale machines, and his knowledge was derived from readings of Desaguliers and Belidor." In 1765, Watt conceived of the ideas of a separate condensing chamber that would avoid having to cool and reheat the cylinder in Newcomen's engine. This saved heat loss but, more importantly, allowed steam rather than the atmosphere to become the main driving force. In 1781-2, patents were issued that embodied Watt's solution to the problem of rotary motion, creating a double-acting engine in which steam pushed the cylinder in each direction. However, the complex parts for Watt's engine proved beyond the capacity of ironworkers of the time and technical advances were needed in metal working before the new principles could be fully exploited.

Turning Newcomen's atmospheric engine into a steam engine required all of Watt's talents as an instrument maker, his draftsmanship, and his mathematical exactness. Watt's letters and diaries demonstrate that he understood basic scientific principles that were required to work on his steam engine (Jacob: 119-20). Although the second law of thermodynamics came later, Watt used the then available scientific knowledge to the utmost. Some of the key scientific work was done by Joseph Black who was "…one of the founders of the scientific study of heat" (Cardwell, 1995: 157). He developed the first truly quantitative measures of heat, and discovered the concepts of specific heat capacity and latent heat. It is not clear how much Watt learned from Black, and direct links between Black's science and Watt's innovations have been disputed by some while others have accepted it.[36] For example, Uglow (2002) details the close relationship of Black and Watt. Noting that after Black explained his theory of latent heat to Watt that "Watt now saw that the great drawback with the Newcomen engine was the loss of this extra heat through the alternate heating and cooling of the cylinder. Although Black's theory, he said, did not *suggest* his improvements to the engine, his knowledge and method…helped his work immeasurably" (Uglow 101: original emphasis).[37]

Full use of Watt's new type of engine required much higher steam pressure than Watt was willing to use. The expiry of Watt's extended patent in 1800, as well as improvements in iron making that produced boilers and cylinders that could withstand increasingly higher pressures, allowed Trevithick to develop a working high-pressure engine in 1801.

The developers of the steam engine's principles were mathematicians, physicists, and/or practical engineers. For example, Cardan and Porta were mathematicians, Porta and Huygens knew chemistry and physics, and Savery was familiar with mechanics and mathematics. These people accomplished something that practitioners using trial and error empiricism would have found much more difficult, if not impossible. Engineers frequently made use of scientific principles only recently understood. Technicians strove to develop designs that would exploit the principles effectively. Thus, as Thurston (1878: 37) puts it:

> At the beginning of the eighteenth century every element of the modern type of steam-engine had been separately invented and practically applied. *It now only remained for the engineer to combine known forms of mechanism in a practical machine which should be capable of economically and conveniently utilizing the power of steam*

---

[36] Cardwell, for example, does not accept the common view that Black had no influence on Watt. He writes (157) that Watt learned the fundamental concept of heat capacity from Black and used Black's work on heat conductivity to develop his replacement for the metal cylinders then in common use – a wooden cylinder, treated with linseed oil and baked.

[37] Along similar lines, Herman (2001:320) states: "He [Watt] and his friend and teacher Professor Joseph Black, had been arguing about its [steam's] properties for years."

> *through the application of now well-understood principles, and by the intelligent combination of physical phenomena already familiar to scientific investigators.* (emphasis added)

This idea is also shared by Musson (1963: xvii) who argued that:

> [A] great deal of experimentation of that time [XVIth and XVIIth centuries] had utilitarian applications, and there is no doubt that the underlying principles of the steam engine are the creation of a vacuum by condensation of steam in a closed vessel and the utilization of atmospheric and steam pressure were originally discovered by natural philosophers, or scientists as we would now call them, in the seventeenth century.

Finally, from Cardwell (54, emphasis added):

> In the first place, no 'common-sense' appreciation of the heat losses involved in the operation of the Newcomen engine would have justified Watt's inventions. What was needed was the measurement of the actual amounts involved. This Watt was able to provide, for he belonged to one of the most active scientific groups in the world; a group which was, moreover, pioneering the scientific study of heat.

In contrast, Landes (1969) who as we have seen argued that science contributed little to the development of the technologies of the First Industrial Revolution, states that this "…was true even of the steam engine, which is often put forward as the prime example of science-spawned innovation" (Landes: 61, n.1). Landes (104)[38] admits later that there is "some truth" to the observation that Newcomen's engine owed much to scientific discoveries, and that Watt derived ideas and technical competence from his association with contemporary scientists. But, he adds, how much "…is impossible to say." He goes on to argue, "One thing is clear, however, once the principle of the separate condenser was established, subsequent advances owed little or nothing to theory." But this is like saying that space

---

[38] All subsequent quotes in this paragraph are from page 104.

rockets owe little to chemical fuels since, once they reach orbit, they do not use chemical fuels as propellants. Just as the rocket needs chemical fuels to get into orbit, the trajectory that led to the steam engine needed science for 200 years – as the above discussion has argued. If, once it was fully developed as an efficient working steam engine, its further incremental refinement owed little to science (which we doubt but admit for purposes of argument), that does nothing to diminish the fact that science contributed greatly to the trajectory that led to the engine. Furthermore, the subsequent development of the steam engine used engineering knowledge that itself depended on earlier developments in science.[39]

Elvin takes a position close to Landes: "Had the Chinese possessed, or developed, the seventeenth-century European mania for tinkering and improving, they could easily have made an efficient spinning machine.... A steam engine would have been more difficult; but it should not have posed insuperable difficulties to a people who had been building double-acting piston flame-throwers in the Sung dynasty" (297-98). Our analysis of the complex trajectory of the steam engine's evolution is strong evidence against Elvin's assertion.[40]

The Second Industrial Revolution. Innovations in the leading sectors of Early Factory and the Steam-Driven Phases were virtually all mechanical. In contrast, the vast majority of the non-mechanical innovations in other sectors were based on empirical trial and error without a strong scientific underpinning. This was true, for example, in metallurgy. Importantly, these advances did not lead mechanical advances but instead were made largely in response to pressures coming from the mechanical sector to develop such things as better steam engines and to replace wooden machines with metal ones.

---

[39] The mid XIXth century Corliss steam engine, which was responsible for the transition of much US manufacturing from water to steam-power, relied heavily on state-of-the-art engineering knowledge. This was systematic knowledge that we include in science, not empirical knowledge developed by trial and error. It could not have been arrived at without the underpinning of early modern science in general and Newtonian mechanics in particular. (See Rosenberg and Trajtenberg 2000.)

[40] Though arguing from a different position, Joel Mokyr (2000) also concludes that China was some way from developing the key technologies of the Industrial Revolution.

In contrast, during the Second Industrial Revolution industrial development was led by many non-mechanical sectors. Chemicals and steel were two of its key products and they both required applications of fairly advanced mechanistic science. The industrial laboratory was invented at this time. It was through this institution, along with the new university departments of applied science, that the West invented how to invent. From that time on, science came to play a growing part in technological advance, a part so obvious that it needs no further elaboration from us.

An important point for our argument is that in all three phases of the Industrial Revolution the leading sectors were the ones most influenced by science and mathematics while those that were evolving purely by trail and error groping were lagging behind, and being pulled along by, the leading sectors. Science did matter.

A second important point is that the First Industrial Revolution used mechanical techniques that depended on the science and practical mathematics in which Britain had a major lead. The Second Industrial Revolution used science of a very different, more theoretical type in which continental scientists, particularly in France and Germany, had a definite lead. Again science mattered in influencing the shift to industrial leadership from Britain to the Continent that began with the Second Industrial Revolution – although in this case it would require another paper to investigate how much it mattered.

4. The Where and When of the Industrial Revolution

When In Britain? We have argued that the Industrial Revolution could only have happened in Europe because only Europe had the necessary condition of early modern science and that it happened first in Britain because that country was ahead in the Newtonian mechanical science that underlay the First Industrial Revolution. The "when?' of that revolution is implicit in our argument about the trajectories of what we today would distinguish as early modern science and technology (and what was then regarded as just natural philosophy). As we have observed, the project to mechanize all textile manufacturing was initiated by Leonardo di Vinci and stretched over two centuries as more and more complicated technological problems were solved, which required among other things improving technological abilities, better designs, and better materials. The pace of these interrelated, path-dependent developments might have been accelerated or decelerated a bit for many reasons but it proceeded until the machines were developed enough that it paid to take them out of cottages and into factories. The second part of the revolution came when the trajectory that led to the steam engine reached the type of high pressure engine that fitted well into the textile factories. So the Industrial Revolution was really the combination of a revolution in the structure of the economy, when work moved out of the cottages and into factories and later into the new industrial towns, and an evolution in technology that had been going on continuously for centuries. Thus, to the question "When did the take-off into sustained growth actually occur?" we answer: "Sometime in the early XIXth century." But to the question: "When did the take off run begin?" we answer: "Sometime at the beginning of the early modern period around 1550, while the construction of the vehicle for the take off began in the medieval period."

Joel Mokyr (2000: 34) argues that "…any historical account of…the Industrial Revolution and its aftermath, need[s] to incorporate *knowledge* explicitly." He distinguishes sharply between "the total useful knowledge in a society…defined as the union of all the pieces of useful knowledge contained in living persons' minds or storage devices" which he calls **Ω**, and techniques, which are "essentially sets of instructions or recipes on how to manipulate nature," which he calls λ. Mokyr then defines a subset of λ as singleton techniques. These have a narrow base in **Ω**, which in the limit is so narrow that all that is known is that the technique works. Because such knowledge cannot be generalized, the discovery of a singleton technique is not likely to lead to further derivative studies. He goes on to observe: "…much technological progress before the Industrial Revolution was of that nature. While new techniques appeared, they rarely if ever led to continued and sustained further improvements and attain the cumulative momentum that provides most of the economic benefits of innovation." He illustrates with Jenner's discovery of vaccination and with the development of knowledge of the correct uses of fertilizer. In contrast, the advance of knowledge becomes self-sustaining when Ω and λ are complementary so that discoveries in one set lead to discoveries in the other. According to Mokyr, "most practical useful knowledge in the eighteenth century was uncodified, unsystematic, and informal, passed on from master to apprentice or horizontally between agents"(p. 12). What happened during the Industrial Revolution was that technological knowledge became less and less of the singleton type and the complementarity of λ and Ω became stronger through the XIXth century until, late in that century, it was so strong that technological and scientific knowledge became self sustaining in a positive feed-back system. This led to the explosion of all types of knowledge, which we are still experiencing. Without being too precise as to when, Mokyr dates this change sometime in the XVIIIth century (p. 13). (But from the quote from his page 13, mentioned earlier in this paragraph, we imagine he would date it very late in that century, if not early in the XIXth.)

We agree with the basic thrust of Mokyr's model of knowledge. However, we would trace the shift from λ knowledge to Ω knowledge further back than Mokyr, highlighting the continuous nature of science's long-run development. Importantly, we would also argue that the type of Ω knowledge matters (*mechanistic* science was the key to the First Industrial Revolution). In many fields, such as metallurgy, it was well into the XIXth century before Ω and λ became sufficiently complementary to create a positive feed-back loop. But in other fields, such complementarities evolved in the Early Modern Period. Consider three examples. First, the trajectory that began with Leonardo di Vinci and led to the breakthroughs in textile manufacturing in the second half of the XVIIIth century was based on cumulative rather than singleton techniques. Second, the kind of mechanics that underlay the First Industrial Revolution in many fields, such as the building of harbours and canals as well as textiles and the steam engine, were turned into Ω knowledge by being unified by Newton's laws of motion and his calculus. Third, the trajectory of discoveries in magnetism and electricity that led to the Voltaic cell in 1800 and the dynamo in 1887 stretched cumulatively over two centuries (for details see below: "Why not in China?"). By no stretch of the imagination can these technological trajectories of evolving techniques that were central to the Industrial Revolution be regarded as a succession of isolated pieces of singleton knowledge. Similar things can be said about knowledge of the behaviour of the planets and of rolling and falling bodies on earth. Although these may have seemed isolated, they were all part of an accumulating body of knowledge that continued a research programme laid down in the Middle Ages and which was eventually synthesised by Newton. So although we agree with Mokyr's argument of why sustained growth took off in the late XVIIIth and early XIXth centuries, we argue that from 1450 to 1750 several lines of cumulative scientific and technological advance were very far from providing only singleton knowledge in several areas that were most important for the Industrial Revolution. In summary, the changes that Mokyr correctly identifies are rooted much further back in time than he acknowledges.

Why not in China? Kenneth Pomeranz (2000) has shown that Chinese living standards compared favourably with those in Europe in the Early Modern Period. He has also shown that the Chinese had a high level of literacy, probably on a par with literacy in Western Europe in the XVIIIth century. Joseph Needham's works have documented in detail the enormous contribution that China made to technological advance, including inventing many of the technologies that subsequently spread to Europe. The overall thrust of Needham's scholarship on Chinese technology has never been seriously challenged.

If the Chinese were more or less equal to early XVIIIth century Britain in their living standards, literacy, and pre-Industrial Revolution technology, were they also equal in being close to an Industrial Revolution? If the Revolution had not happened in Europe, might it have happened in China? We answer "no" for two reasons.[41] First, China lacked the

---

[41] We would add a third point, which we do not have space to argue here: the Chinese lacked the sort of pluralism that provided an insulation to the whims of central government polices. For example, when a change in power in the imperial court led to the banning of the flourishing, centrally planned, overseas exploration and trade early in the XVth century, all sea contact was cut off. Enough had been learned that private traders would have taken up where the state left off had the state not made foreign trading a capital offence and effectively eliminated such adventures, leaving a clear field for the Portuguese when they first arrived in India.

mechanistic science that was a necessary condition for the fully-fledged Industrial Revolution. Second, the nature of Chinese human capital differed greatly from that of the West.

As well as documenting the enormous advances in Chinese technology over the millennia, Needham also argued that the Chinese science was superior to that of the West during the Middle Ages, and at least its equal throughout the XVIIth and possibly the XVIIIth centuries. Several scholars, in particular, Bodde (1981), Huff (1993) Qian (1985), and Sivin (1980) have disputed his views on the state of Chinese science.[42] While we accept Needham's evidence with respect to technology, we believe his views on Chinese science are implausible in the light of what is known about the trajectories along which scientific knowledge was accumulated in the West.

We find no evidence that China had even the beginnings of systematic cumulative modern science. There have been many great scientific thinkers in China, but quite often their ideas flourished for a while and were then lost.[43] One major reason was the absence of an institutional memory that preserved scientific knowledge and allowed for a path-dependent accumulation and integration of such knowledge – an institutional memory that we argued in an earlier section has been provided in the West by independent corporate universities since the revival of learning in the medieval period.[44] For example, there was a flowering of mathematical work under the relatively tolerant Sung dynasty. But the use of mathematics rapidly declined under the Neo-Confucian revival at the end of the Sung dynasty. Qian argues that the reason was that Chinese mathematics was an official enterprise. "There were not

---

[42] It has been argued to us that these authors are unreliable, because they are strongly biased towards making China look inferior, which they accomplish by viewing Chinese science through Eurocentric eyes. Be that as it may, we have not seen convincing evidence conflicting with their conclusion that, whatever else its accomplishments, China lacked the base of modern science that was clearly a necessary condition for the Science-Led Phase, very probably for the Steam-Driven Phase, and in our opinion also for the Proto-Factory Phase of the Industrial Revolution.

[43] The impressive list of Chinese scientific discoveries, many of which provided what Mokyr would classify as singleton knowledge, and many of which were subsequently forgotten, is too long to include here, but can be found in both Needham and Qian.

[44] The Chinese did have institutions that preserved other branches of learning and art. The absence of such institutions to preserve scientific knowledge probably indicated a lack of sustained interest in scientific inquiries among the lay and religious authorities.

enough autonomous roots of mathematical scholarship among learned circles. Once official encouragement declined, mathematics declined rapidly" (Qian: 64).

Chinese scientists lacked a standard of logical proof provided by Aristotelian logic. Importantly, they also lacked trigonometry, an essential tool for mathematical astronomy. As a result, the Chinese were forced to employ Arabic astronomers from the XIIIth century onwards. Newtonian mechanics is of particular interest since we argue that it was key to the development of the mechanical technologies that formed the basis of the First Industrial Revolution. According to Qian, "...[Western] mechanics was modernized in three steps: Archimedes' theorems of the lever and buoyancy; Galileo's and Kepler's theorems on a variety of mechanical phenomena; and Newton's synthesis. [Ancient Chinese mechanics]...had fulfilled the first half step, but never moved beyond that independently" (Qian: 67).

One important illustration of the gap between Chinese and Western science is in knowledge about electricity. Although Needham contended that the Chinese knowledge of magnetism put China close to the West in early knowledge of electricity, his critics argue otherwise. Knowledge of magnetism is in six parts: (1) attraction, (2) direction, (3) declination (a compass needle does not always point to true north) (4) local variation (the direction in which the needle points varies due to local disturbing forces), (5) inclination (the needle does not always point in a horizontal plane) and (6) the earth is a giant loadstone, which attracts the compass needle.[45] The Chinese and the Greeks discovered the first two at more or less the same time. The Chinese discovered the third well before it was discovered in the West. It seems that the Chinese also knew the fourth. However, the fifth and the sixth parts were unknown to them. Yet the sixth is what turns magnetism from a wholly empirical body of knowledge into a theoretical science where the earth-is-a-loadstone hypothesis explains other observations. This is what Gilbert (1540-1603) did for the West in his famous treatise *De Magnete*. So when European scholars made the study of magnetism into a science in the late XVIth

---

[45] The argument in this paragraph is drawn from Qian: 78-81.

century, the Chinese study of magnetism "…did not surpass a qualitative description of magnetic declination" (Qian: 80).

So Chinese knowledge of magnetism was only part way to where Gilbert got to in the late XVIth century. Furthermore, it took well over 200 years of cumulative research into other aspects of electricity to complete the West's research agenda of understanding electricity and magnetism of which the following are just some of the highlights: (1) in 1670 Otto von Guericke invented a machine to produce an electric charge; (2) at the start of the XVIIIth century Du Fay showed the difference between positive and negative electric charges; (3) the earliest form of condenser, the Leyden jar, was invented in 1745; (4) in 1752, Benjamin Franklin showed that atmospheric electricity was identical in form to the charge produced by a Leyden jar; (5) in 1766 Priestly proved that the force between electric charges varies inversely with the distance between the charges; (6) De Coulomb subsequently invented an instrument to measure electric charges accurately; (7) in 1800, Volta produced the first electric battery; (8) in 1819, Oersted demonstrated that a magnetic field existed around an electric current; (9) in 1831, Faraday demonstrated that a current flowing through a coil of wire could induce a current in a nearby coil (he also developed the theory of electric lines of force); (10) in 1840, Joule and von Helmholtz demonstrated that electricity was a form of energy and that it obeyed the law of conservation of energy (Joule also showed that the magneto converts mechanical energy into electrical energy); (11) in 1845, Wheatstone and Cooke patented an electro magnet to replace a permanent magnet in telegraphs; (12) in 1866 Wilde described a machine that used an electromagnet to turn unlimited amounts of mechanical energy into electrical energy; (13) in 1887, Wheatstone and Siemens invented a practical dynamo. The electric engine had arrived. Virtually none of these discoveries were made, or known, in China. Thus, far from being on the verge of discovering how to make electric motors, telegraphs and radios, the Chinese were showing no signs of even beginning the long series of cumulative scientific advances, stretching over two centuries, that underlay Europe's development of practical uses of electricity. (This important trajectory is in clear contradiction to Mokyr's claim that most pre-Industrial Revolution scientific and technological knowledge was of the "singleton" variety.)

Now consider human capital. Chinese education was to a great extent aimed at preparing candidates to pass the examinations for entry into the imperial civil service. The system had the great advantage of being open to all and thus recruiting ambitious and successful scholars from all ranks of Chinese society. However, its content was non-scientific and non-analytical, stressing Confucian classics, poetry and official histories. A great mass of such works had to be committed to memory and reproduced in the examinations.

As a direct response to the importance of the competitive examination, the centres of learning mostly took the content of these examinations as their curriculum. The imperial academies, sometimes erroneously thought of as equivalents of Western universities, were instead "bureaucratic subdivisions of the administrative structure that could be expanded, reorganized, or abolished at a moment's notice, as they often were" (Huff: 306). In short, although it accomplished many good things, the Confucian-based system of education and training of those in charge of most aspects of life prevented "…the creation of a suitable methodology for studying the phenomena of nature" (Bodde: 307).

The high levels of literacy documented by Pomeranz for China provided only the capacity to accumulate human capital. However, as we have argued above, Chinese human capital was mainly non-scientific and non-analytical. Although Europeans may have had no more receptor capacity in term of literacy rates than the Chinese, they were acquiring a very different body of human capital. By the beginning of the XVIIIth century, educated persons were striving, and by and large succeeding, in acquiring an understanding of Newtonian mechanics. At the same time, the Chinese were learning about other, non-mechanical, things.

The Chinese lacked Newtonian mechanics and the engineering knowledge that it engendered – knowledge that underlay the early factory stage of the Industrial Revolution. The evidence with respect to the Steam-Driven Factory Phase is even more compelling. We know of no evidence that empirically-based Chinese engineers were on the verge of inventing by trial and error the advanced technologies employed in textile factories by 1840 – the steam engine, metallurgy, the machine-tool industry. The evidence with respect to the Science-Led Phase is conclusive. If, incredibly, the Chinese had stumbled through trial and error onto all that was needed to establish the structure of the English factory system of 1840, there is no way they could have gone on to the fourth phase of industrialisation that constituted the Second Industrial Revolution.[46] Finally, if China had been on the verge of an Industrial Revolution in the XVIII^th^ century, we must wonder why there was no further progress over the final hundred years of imperial rule?

Why not in the Islamic countries? Although the countries of the Islamic world were immensely dynamic in terms of technology, science, and the arts from the time of the initial Islamic conquests until around the XIII^th^ or XIV^th^ centuries, science, its technology stultified thereafter. As Lynn White (1986: 77) argues, "Even in the Middle Ages, the parts of Europe adhering to the Latin Church began to show a technological dynamism superior to that of the generally more sophisticated cultures of Byzantium and Islam." In the XIV^th^ century, many of the great astronomical hospitals and observatories were destroyed by religious zealots. These had been centres for the preservation and enhancement of learning. "During the centuries of Ottoman rule (starting in the XVI^th^) there had been no advance in technology and a decline in the level of scientific knowledge and understanding" (Hourani, 1991:259). Even as late as the XIX^th^ century, the heliocentric view of the universe, the circulation of the blood and countless other early modern Western discoveries had not been accepted in Islam (Huff: 183). Technologically and scientifically the Islamic countries remained more or less where Europe was in the XV^th^ century.

All we can do here is to point to a few important contrasts with the West – contrasts that contribute to explaining the different courses of scientific and technological events in the West and the Islamic countries. In contrast

---

[46] It has been suggested that the empirical challenge of a Chinese industrial revolution would have produced the equivalent of Western science just as it did induce Western scientists to develop more general laws. But Chinese science, lacking established methods of proof, lacking all the Western discoveries of the previous 200 years, and lacking the institutional structure that supported scientific advance, could not by any stretch of the imagination have jumped, on its own initiative, from where it was in 1800 to where Western science was in 1880. Science *is* cumulative.

with early Christianity, Islam was initially spread by the sword. Little attempt was made to convert the conquered infidels, most of whom converted voluntarily over the two centuries following their conquest. This had at least two important consequences. First, the spread of Islam through conquest ensured that the empire was, from its inception, a theocracy in which religious law was not separated from other types of law. So the Islamic empire lacked the West's pluralism in different realms of legal jurisdiction and in a splitting of power between secular and religious authorities (and among secular authorities such as was fostered by the corporation). Second, although many of the conquered regions contained highly sophisticated societies with scholars well versed in natural philosophy, the religious leaders lacked the incentives that pushed early Christian leaders to become philosophers, and they remained largely untutored in philosophy.

In contrast to the West's delayed discovery of Aristotle, when the Arab conquerors set out to study Greek science several centuries earlier, they encountered the whole of Greek learning at the outset. The conflict between Aristotle and the Old Testament was immediately apparent. Greek science was too useful to be condemned outright. Instead it was accepted in so far as it was useful but was held to be inferior to religious learning and was always open to attack by religious conservatives. Although some isolated scholars attempted to reconcile Aristotle with Islamic religious doctrine, the religious establishment rejected these attempts and remained hostile to Aristotle's science. Thus, although individual scholars were tolerated in their study of the foreign science, they were never given a secure institutional base inside the religion.

Islam never evolved the concept of a corporation. Islamic scholarship flourished for several centuries after the building of the Arab empire, but it was centred around masters who tutored students according to their own, often great, wisdom. The independent power of Western corporations, which implied a split between civil and ecclesiastical law on the one hand, and the authority of corporations on the other, never developed, and instruction in natural science occurred outside of colleges with students travelling from scholar to scholar. Furthermore, Islamic universities remained a collection of individuals, each of whom gave individual instruction and issued individual certificates of competence to graduating students. Thus collective, generalized, and impersonal standards for evaluating scholarship that developed in the West were absent in Islam. Nor, outside of some hospitals and astronomical observatories, many of which were destroyed in the XIVth and XVth centuries, did Islamic scientists develop institutions and attitudes that would provide an autonomy and continuity for scientific inquiry, safe from the restrictions on thought imposed by religious and social dogma.

Lastly, in contrast to Christianity, Islamic thinkers accepted occasionalism. This led them to hold that the search for natural laws was a blasphemous attempt to predict God's behaviour, once again undermining the security of natural philosophers.

Thus, largely through a series of historical accidents that produced an environment very different from the one in which Christianity evolved, Islamic religious attitudes and institutions were not supportive of science and innovation. This, coupled with the lack of a corporate form for universities, contributed to Islam's falling behind in science and technology after the XIVth century.

5. Conclusion

The First Industrial Revolution was more than a few gadgets, important though some of them were; it was based on an outlook that went far beyond mere tinkering. Things were viewed mechanically in terms of time and motion, which led to a desire to mechanize all production processes (bringing profits to entrepreneurs). It could only have happened somewhere in north-western Europe because only this part of the world possessed the necessary cultural and scientific attitudes and knowledge. These attitudes derived from the Western mechanical view of the world, which was based on a science unique to the West. It could only have happened when it did in Britain since only in Britain did Newtonian mechanics pervade the thinking of industrialists and engineers. Later, when technological innovations required different non-mechanical types of science in which Britain was not pre-eminent, Britain lost its overwhelming industrial supremacy.

What we have said in the previous section about China and Islam applies, with necessary corrections, to all countries other than northern Europe and English-speaking North America.[47] No one else had the scientific and engineering base that underlay the Industrial Revolution. Thus all of the debates about "Could others outside of Europe have done what Britain did (within some specified time of, say, a century)?" boil down to the question "Could others have achieved, by their own efforts, what Britain achieved in the Early Factory and the Steam-Driven Phases?" There is simply no question of others replicating Europe's Second Industrial Revolution independently without the equivalent of Western science. Our answer to this revised question is that areas outside of Western Europe were destined to be left behind technologically without achieving what Britain achieved even in the Early-Factory Phase – this for deep-rooted reasons, some of which go back to the Middle Ages, some of which are related to the long trajectories for such technologies as automated textile machinery, and some of which are related to the prevalence of Newtonian mechanics. Be that as it may, it is difficult to believe that others could have achieved what Britain did in the mature Steam-Driven Phase, unaided by the science, engineering, and the accumulated experience of learning by doing and learning by using in such technologies as the steam engine and machine tools that underlay Britain's position at the time of the Great Exhibition in 1851.

So there was nothing capricious about the location and approximate timing of the Industrial Revolution and its subsequent spread to Europe and ultimately the industrialized world of the XXth century. By 1900, for better or for worse, the West (including English-speaking countries beyond Europe) had differentiated itself from all other civilizations as far as both science and technology were concerned. No one else would come near to catching up until they learned to adapt and adopt Western technology and Western science. More or less complete catching up, which the Japanese and possibly a few others have accomplished, requires learning how to invent and innovate as well as developing the

---

[47] The United States had similar institutions to Britain. It rapidly assimilated British technology and went on to become a leader in technological development, although it relied on Europe for most of its basic science until well into the XXth century.

science base needed to sustain these activities in the modern industrial context. Although there is no reason why the West should stay dominant in science and technology over the millennium just beginning, there are reasons why many other societies will continue to be copiers of Western accomplishments. It will be a long time before they develop the institutional and knowledge bases that allow them to come to, and remain at, the cutting edge of technological developments – developments that continue to become increasingly dependent on discoveries in what are now fully differentiated as the pure and applied sciences.

BIBLIOGRAPHY

ARMYTAGE, (1965), *The Rise of the Technocrats,* (London, Routledge).

ARTHUR, BRIAN, (1988) "Competing Technologies: an overview", in G. Dosi, C. Freeman, A. Nelson, G. Silverberg and L. Soete (eds.), *Technical Change and Economic Theory,* (London, Pinter).

ASHTON, T.S., (1955), *An Economic History of England: The 18th Century,* (London, Methuin).

BEKAR C. and CARLAW K.I. (1998), "The Consequences of Changes in GPTs", Chapter 8 in *General Purpose Technologies and Economic Growth,* Elhanan Helpman (ed), (Cambridge, MIT Press).

BODDE, DERK, (1981), *Essays on Chinese Civilization,* (Princeton, Princeton University Press).

CARDWELL, DONALD, (1995), *The Norton History of Technology,* (New York, Norton).

CHRISTIANSON, GALE E., (1984), *In the Presence of the Creator: Isaac Newton & His Times,* (London, Macmillan).

CRYSTAL, DAVID (ed.), (1990), *The Cambridge Encyclopedia* (1990), (Cambridge, Cambridge University Press).

ELVIN, MARK, (1973), *The Pattern of the Chinese Past: A Social and Economic Interpretation,* (Stanford, Stanford University Press).

FLOUD, R. and MCCLOSKEY D., (1994), *The Economic History of Britain Since 1700 2nd Ed.* (Cambridge, Cambridge University Press).

GOLDSTONE, JACK, (1998), "The Problem of the 'Early Modern World' " *Journal of the Economic and Social History of the Orient* (41,3).

_________ (1999), "The Rise of the West - or Not? A Revision to Socio-economic History", (Davis, University of California) manuscript.

GRANT, EDWARD (1996), *The Foundations of Modern Science in the Middle Ages: Their Religious, Institutional, and Intellectual Contexts,* (Cambridge, Cambridge University Press).

HERMAN, ARTHUR, (2001), *How the Scots Invented the Modern World,* (New York, Three Rivers Press).

HOURANI, ALBERT, (1991), *A History of the Arab Peoples,* (Cambridge Mass., Harvard University Press).

HUFF, TOBY E., (1993), *The Rise of Early Modern Science,* (Cambridge, Cambridge University Press).

JACOB, MARGARET C., (1997), *Scientific Culture and the Making of the Industrial West,* (Oxford, Oxford University Press).

KEARNEY, HUGH, (1971), *Science and Change: 1500-1700,* (New York, McGraw-Hill Book Company).

LANDES, DAVID, (1969), *The Unbound Prometheus,* (Cambridge, Cambridge University Press).

_____________ (1998), *The Wealth and Poverty of Nations,* (W.W. Norton, New York)

LINDBERG, DAVID C., (1992), *The Beginnings of Western Science: The European Scientific Tradition in Philosophical, Religious, and Institutional Context, 600 B.C. to A.D. 1450,* (Chicago, The University of Chicago Press).

LIPSEY, R.G.L., CARLAW, K. and BEKAR, C. (2005), *Economic Transformations: General Purpose Technologies and Sustained Economic Growth,* (Oxford, Oxford University Press).

MOKYR, JOEL, (1990), *The Lever of Riches,* (Oxford, Oxford University Press).

_________ (1999), "Knowledge, Technology, and Economic Growth During the Industrial Revolution", (Evanston, Departments of Economics and History), manuscript.

_________ (2000a), "Knowledge, Technology, and Economic Growth During the Industrial Revolution", in *Productivity, Technology and Economic Growth* by Bart Van Ark, Kuipers, S., Kuper, G., (Kluwer Academic Publishers).

_________ (2000b), "King Kong and Cold Fusion: Counterfactual analysis and the History of Technology", (Evanston, Departments of Economics and History), manuscript.

_________ (2002), *Gifts From Athena,* (Princeton, Princeton University Press).

MUSSON, A. E., (1963), "Introduction" in *Short History of the Steam Engine,* Dickinson H.W., (New York, Macmillan).

Musson, A.E. and Robinson E. (eds), (1989), *Science and technology in the Industrial Revolution,* (New York, Gordon and Breach).

Needham, Joseph, (1954-), *Science and Civilization in China,* (Cambridge, Cambridge University Press).

The New Oxford Dictionary of English, (1998), (Oxford, Oxford University Press)

Pacey, A., (1975), *The Maze of Ingenuity,* (New York, Holmes and Meier).

Pomeranz, Kenneth, (2000), *The Great Divergence: China, Europe and the Making of the Modern World Economy,* (Princeton, Princeton University Press).

Qian, Wen-yuan, (1985), *The Great Inertia: Scientific Stagnation in Traditional China,* (London, Croom Helm).

Rosenberg, Nathan, (1982), *Inside the Black Box: Technology and Economics,* (Cambridge, Cambridge University Press).

________________ and Manuel Trajtenberg, (2000) "A GPT at Work: The Corliss Steam Engine and the Process of Urbanization in the Late 19th Century USA", (Toronto, Canadian Institute for Advanced Research), manuscript.

Schofield, Robert, (1963), *The Lunar Society of Birmingham : a social history of provincial science and industry in eighteenth-century England,* (Oxford, Clarendon Press).

Shapin, S., (1996), *The Scientific Revolution,* (University of Chicago Press: Chicago).

Sivin, Nathan, (1980), *Science and Medicine in Chinese History,* (Stanford, Stanford University Press).

Stewart, Larry, (1992), *The Rise of Public Science: Rhetoric, Technology, and Natural Philosophy in Newtonian Britain, 1660-1750.*

Thurston, Robert H., (1878), *A History of the Growth of the Steam-Engine,* (New York, D. Appleton and Company).

Von Tunzelmann, V.T., (1978), *Steam Power and British Industrialization to 1860,* (Oxford, Oxford University Press).

______________ (1994), "Technology in the Early Nineteenth Century" in Floud and McCloskey.

Uglow, J., (2002), *The Lunar Men,* (New York, Farrar, Straus and Giroux).

Usher, Abbott Payson, (1954), *A History of Mechanical Inventions, revised edition* (New York, Dover Publications).

White, Lynn Jr., (1986), *Medieval Religion and Technology,* (Berkeley, University of California Press).