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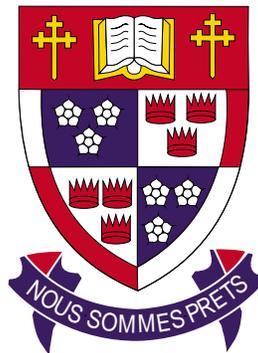
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Science, Institutions, & the Industrial Revolution

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**SCIENCE, INSTITUTIONS,
AND THE INDUSTRIAL REVOLUTION**

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by

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ABSTRACT

In Part I, we argue that science as it was then understood was more important for the Industrial Revolution than is generally accepted. Newton's mechanics, which were a generalization of early modern piecemeal scientific discoveries, permeated British society and provided the necessary intellectual basis of the British Industrial Revolution. In Part II, we use our thesis to explore some contentious issues in long-run growth: Why did the IR occur in Europe? Why in Britain? Why not in China or Islam?

Key words and phrases: Industrial Revolution, Newtonian science, medieval universities, steam engine, technological trajectories

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SCIENCE, INSTITUTIONS, AND THE INDUSTRIAL REVOLUTION.¹

In this paper, we argue that western science was much more important in determining the when, where, and how of the Industrial Revolution than is generally accepted. Indeed, the development of science was a necessary precondition of the Industrial Revolution. Many economic historians have rejected the idea that science was central to the development of the IR. We argue that these writers deny a link between *modern* science (implicit in their definition of science) and the IR. Central to our argument is the proposition that the early modern science that developed prior to Newton was different from the modern science that developed in the 19th and 20th centuries. What was important then 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. Isaac Newton, the first thinker to develop truly modern scientific laws of nature, synthesised much of this earlier piecemeal work into universal laws. Newton’s mechanics—and equally important, his methods—came to permeate British society, ultimately providing the intellectual basis for the British Industrial Revolution.

Arguing that science was a necessary condition for the IR, which was by no means an inevitable stage in British development, requires paying close attention to the growth and evolution of institutions that supported and contributed to the development of early modern science. It developed in a series of contingent events going back to the early Middle Ages. The scientific revolution of the Early Modern Period, dating from roughly 1450 to 1700, was unique to the West. No other society showed signs of generating such a revolution. As a result, no other society was on the verge of an Industrial Revolution. Whatever other indicators of industrialization were present in China and Islam in earlier centuries, these countries did not possess the required science—they did not, therefore, possess one of the necessary conditions for modern industrialization.

We proceed by briefly outlining some highlights of early modern science. We then argue the “science matters” thesis in two ways. In Part I we detail the importance of science to the Industrial Revolution, arguing that Newtonian mechanics was a necessary condition for British industrialization and that early modern science was necessary to Newtonian mechanics. In Part II we argue that our thesis sheds light on some much-debated issues in the study of long-run growth. Why did the IR happen in Europe? Why in Britain? Why not in China? Why not in Islam?

I. THE PLACE OF SCIENCE IN THE INDUSTRIAL REVOLUTION

Most modern students of the history of science and technology have argued that before the 19th century, trial-and-error-based advances in technology led advances in science—not the converse. Arguments to this effect have usually concentrated on the direct links between technology and universal scientific laws. This version of the argument is persuasive.² 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.³

We accept this view but add a critical caveat: before Newton science contained none of the universal laws that today make up modern science. To go further, we need to consider how

the term “science” is used, carefully distinguishing between modern science and the science of earlier periods.

What is Meant by Science?

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.

In Classical and Medieval times, all science was contained in one discipline, natural philosophy. Until well past the time of Isaac Newton, there was no clear distinction between science and religion. The distinction between pure science and applied science and engineering did not emerge until the last half of the 19th 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 20th century interpretation of science. If instead we view science through pre-19th century eyes, we gain a different perspective. 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-19th 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).

Early Modern Science

Medieval scholastic philosophers demonstrated remarkable flexibility in reconciling revealed religion with natural-law-based science—something many other societies found difficult. Their great achievement was a synthesis of Greek science and Christian religion. The criticisms of the Medieval scholastic synthesis of Greek science and Christian religious doctrine led directly to the revolution that became early modern science. It was as much a revolution in method as in substance. Medieval natural philosophers were not opposed to observation and relied heavily on the works of Aristotle, an astute observer of nature. But *a priori* reasoning was held to be the major road to new knowledge. Scholastic philosophers indulged in much detailed and sophisticated discussion of many important scientific issues, such as the existence of a vacuum and the possibility of plural worlds. In contrast, the early modern scientific revolution was marked by an acceptance of experiment as *the* way to settle empirical debates. As a result, much pre-Newtonian science developed through myriad piecemeal discoveries concerning issues that had plagued scholastic philosophers for centuries—the existence of vacuums, the nature of atmospheric pressure, the behavior of

rolling and free falling bodies, and many other similar issues. All of these advances between 1450 and 1687 are found in any standard history of science, although none are universal laws. In a sense they can be seen as piecemeal discoveries made in attempts to test existing hypothesis, most of which were due to Aristotle. The accumulating evidence that refuted much of Aristotelian science called out for new explanations. But it was not until Newton that much of this evidence was incorporated into new scientific laws.⁴

In astronomy, Copernicus reinterpreted existing observations into a startling new heliocentric model. Galileo provided observations that substantiated it. Kepler used old and new observations (mainly from Tycho Brahe) to develop his three laws of motion. However, these applied solely to heavenly bodies and were quite distinct from one another. Newton unified these by deducing them from a single theory of motion that applied to all things terrestrial and celestial. These laws of motion were the first truly modern scientific laws.

The early flexibility of the scholastic philosophers in creating a system of thought that reconciled Christianity with Greek science had given way to rigidity once the system was fully developed.

[All this vast scheme had been so riveted into the Ptolemaic view by the user of biblical texts and theological reasonings that that resultant system of the universe was considered impregnable and final. To attack it was blasphemy. \(White: 120\)](#)

So it was too much when Galileo insisted that the heliocentric system described reality rather than just a useful hypothesis. The Catholic Church responded by declaring the new heliocentric view as heretical early in the 17th century. Protestant leaders such as Calvin and Luther also rejected it. However, by 1670 many English churchmen 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 as an impressive example of the sublime works of God who had created the universe and its laws (Jacob: 60).

The scientific discoveries of the Early Modern Period generated a new worldview of a mechanical universe. This view fostered an interest in mechanizing human activities wherever possible. The greatest visionary of this program was Leonardo di Vinci(1452-1519). His drawings predicted much of what happened over the next three centuries. Indeed, he charted the trajectory along which the mechanisation of textile production proceeded cumulatively over the these centuries. 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.

Although the mechanistic worldview was developed in the Early Modern Period, non-mechanical views remained influential well into the 18th century. Transitional periods are like that, key thinkers have one foot in the old system and one in the new. They contribute substantially to changes whose revolutionary implications they only dimly perceive, and do not always approve. This was true even of Newton.⁵ Only with Newton's popularisers was the mysticism stripped away from his theories—presenting an uncompromisingly mechanical view of the universe.

In 1662 a group of moderate reformers founded the *Royal Society of London for the Promotion of Natural Knowledge*. It became a prestigious society whose membership included both scientists and interested laypersons. Because it was a private institution (unlike the French equivalent, which was a 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 20th century 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 Society provided an important institution through which science as it was then understood influenced the knowledge and attitudes of those who made technological advances.

To consider the relation between science and technology further, 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).
- Early-Factory Phase (1760-1820): proto-factories—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.
- Science-Led Phase (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 IR, the second and third are usually referred to as the First Industrial Revolution and the fourth phase as the Second Industrial Revolution.

Early Modern Mechanization

The Industrial Revolution was not a sudden discontinuity but the end result of a centuries long trajectory of mechanisation. This early phase owed much to science. In the late 15th century, Leonardo di Vinci conceived a program to mechanize most of the operations in the textile industry. 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).

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. The long history of slow 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. 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.”⁶

The Early Factory Phase

The second half of the 18th century witnessed a discontinuity in the evolution of the key elements of the economic structure. 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 into sheds filled with human powered machinery and smallish water powered mills. Although these relatively sudden changes in the economy's structure have often been misconstrued as sudden changes in technology, what happened is that textile machinery evolved incrementally until it became efficient to transfer production from cottages to mills.⁷

While what we *now* think of as science played a role in some of the developments in the mechanization of textile manufacturing (i.e., the development of the Jacquard loom was influenced by new ways of organizing information), most developments were influenced by 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. Accumulating knowledge allowed those we would now call engineers to do 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 program to mechanize all aspects of textile production. If what was invented in the 18th century seem mere “gadgets” to modern eyes they were engineering triumphs to contemporaries.⁸

Isaac Newton (1642-1727) was the single most important figure in the new science. Although his towering place in science is well known, less attention has been paid to his place in the popular culture of the century that followed the publication of the *Principia* in 1687.⁹ This work was the great synthesizing work for the new science. Its laws of motion presented a mechanical interpretation of the behavior of all things in the universe, large and small, near and far. His mechanical laws soon came to permeate British thinking. Indeed, it does not seem an overstatement to say that Newtonian mechanics provided the intellectual base for the Industrial Revolution, which in its two stages, 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). This required some mathematical skill. The relevant mathematics 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 20th century lecture on modern science. Popular journals, including one addressed mainly to women,

helped to spread the new knowledge. While all Catholic and most 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. This knowledge entered into the public domain in a world in which science was 'all the rage.' It was in the air and practical engineers and inventors breathed it every day.

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)

[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. Smeaton's work demonstrated the superiority of the over-shot wheel to the under-shot, and the superiority of the breast-wheel to both the under- and over-shot wheels. Many of Smeaton's results were published by the Royal Society, ultimately proving to be widely influential.¹⁰ 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.¹¹ This illustrates the fusion of theoretical and applied science, as well as engineering, that characterized the scientific world until well into the 19th century. Indeed to contemporary thinkers, these had always been one subject. Only later, as knowledge accumulated, did the need for a division of labour create a clear distinction between the theoretical and the applied.¹²

Landes (1969) was an early proponent of the view that technology owed little to science before the 19th century. Lynn White (1978) has argued a similar position. (A careful perusal of Landes (1998) shows no change in his position on this issue.) But Jacob's research has revealed just how deeply Newtonian science permeated the thinking of British industrialists, engineers, entrepreneurs, and ordinary people. Many aspects of British

industrialization that puzzled Landes are explicable when seen in the light of Britain's scientific development. After pointing to the "higher level of technical skill and general interest in machines" in England compared with other European countries, Landes argues that this "...should not be confused with scientific knowledge" (Landes 1969: 61). We argue that these British abilities and interests were derived from scientific knowledge. Britain's technological developments were stimulated and assisted by such knowledge, particularly Newtonian mechanics. Landes goes on to say that his view "...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. Instead, when one takes Britain's unique development of a Newtonian mechanistic research program into account, there is no mystery. The British comparative advantage 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," in which Mokyr (1990) asserts Britain had a comparative advantage. Mokyr (1990:242), argues that "Britain did not have a significant 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 (itself based on some of the most profound scientific discoveries of all time) provided Britain with the knowledge base that underlay the mechanics of the Industrial Revolution and, in the absence of which, British inventions could not easily diffuse to Europe, even after they were made.

Steam-Driven Phase

The classic study of the development of the steam engine is von Tunzelmann (1978).¹³ By the early 19th century, developments in steam engines made it efficient to replace water and human power with steam power. Production moved 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 most machines and a whole new machine tool industry was 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 the whole structure of the economy were required as masses of people moved to the new industrial towns, urbanising the society to an extent not seen since Classical times. Fuel, raw materials, and finished goods, needed to be transported. This required an extensive network of canals and railroads. The new modes of transport introduced by the railway and iron steamships altered many economic relations. The changes also initiated rising wages as steam power served to raise productivity, which itself was the result of other incremental innovations in textile technologies (e.g., number of spindles employed, strength of yarn spun, etc.). 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 applied technology.

The development of the steam engine

The development of steam power—the first major new source of power for Europe since windmills—starts with early modern science. It is an example of a positive feedback relation running in both directions 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, relied not on trial and error empiricism but on science as defined in this paper, and that reliance began well before the rise of the factory system.

Although inanimate power in the form of water and wind was used for many purposes throughout the Middle Ages, the English power problems of the 16th and 17th centuries mainly concerned the pumping of water from ever-deepening mines and supplying municipal water systems. The principles underlying the suction pump were not understood because little progress had been 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 that contained several new features that were critical for further development. Most important was the principle of having a plunger work 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 understanding the nature of steam. Investigations of steam began in the 16th century, but work was hampered by the mistaken theory that steam was just a form of air. Early work by 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 discoveries about the nature and properties of steam "...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. This was a conclusion that did not pass unnoticed by practical Europeans on the lookout for a new power source. 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, scientific knowledge of what was possible was well in advance of technological knowledge of what was feasible.

The first workable steam engine, the “water commanding engine,” was developed by Edward Somerset, the second Marquis of Worcester who, in turn, benefited extensively from the studies on mechanics by Caus and Porta (Thurston 1878: 16). His engine used both atmospheric and steam pressure. Although it never seems to have been used commercially, its principles were sound. Thomas Savery used them in the first commercial steam engine. The vacuum created by the condensation of steam raised water from its source into a container at pump level, the injection of steam forced the water out of the container and up to the desired destination. To get sufficient energy for the second stage of the lift, the pressure had to be higher than current metallurgy safely allowed for. The engine’s boiler was therefore liable to explode. The Savery engine had limited use in mines but was used to pump water to reservoirs above water wheels and to supply water tanks located on top of large structures.

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 Abbe 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.¹⁴ The honour of developing a functioning steam engine belongs to Thomas Newcomen. Although country bred, Newcomen kept in touch with the latest scientific developments by corresponding with Robert Hooke of the Royal Society. Using steam in a cylinder to drive a piston connected to a driving mechanism was a fundamental breakthrough. 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 Savery’s engine did, 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 the engine to be converted into an engine in which steam rather than the atmosphere was 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 used 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 since direct links between the two have not been discovered. But in a world in which all those associated with the Royal Society were aware of what each other was doing and discovering, it is difficult to believe that Watt did not know of, and use, Black’s work.¹⁵

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 patent in 1800, as well as improvements in iron making that produced boilers and cylinders that could withstand increasingly higher pressures, allowed Trevithnick to develop a working high pressure engine in 1801.

These were all stationary applications of steam power. The development of an effective locomotive required the solution to two further problems. First, how to develop enough steam in the boiler, eventually solved by using tubes in the firebox. Second, how to get sufficient draft to pull the exhaust from the smokestack quickly enough, solved by Booth’s invention of a jet to force exhaust into the stack. At about the same time, George Stevenson came to understand the importance of a properly graded roadbed and curves appropriately designed to minimize resistance. Together, all of these insights went into the Rocket, which introduced the age of steam transportation.

Science and the Steam Engine

Thurston (1878) notes that the developers of the steam engine’s principles were mathematicians, physicists, and/or practical engineers (e.g., Cardan and Porta were mathematicians, Porta and Huygens knew of chemistry and physics, Savery was familiar with mechanics and mathematics). These people accomplished something that practitioners using trial and error empiricism could not.

The story of the steam engine is a story of the interrelationship of the new piecemeal scientific knowledge and practical engineering. 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. The character of atmospheric pressure, and of the pressure of gases, had become understood. The nature of a vacuum was known, and the method of obtaining it by the displacement of the air by steam, and by the condensation of the vapor, was understood. The importance of utilizing the power of steam, and the application of condensation in the removal of atmospheric pressure, was not only recognized, but had been actually and successfully attempted by Morland, Papin, and Savery. Mechanics had succeeded in making steamboilers capable of sustaining any desired or any useful pressure, and Papin had shown how to make them comparatively safe by the attachment of the safety-valve. They had made steam-cylinders fitted with pistons, and had used such a combination in the development of power. *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 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 [16th and 17th centuries] had utilitarian applications, and there is no doubt that the underlying principles of the steam engine—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):

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.

Science, then, played an important role in the development of the steam engine.

In contrast, Landes (1969) argues that science contributed little to the development of the technologies of the First Industrial Revolution, and 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)¹⁶ 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 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.¹⁷

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.¹⁸

The lessons of steam's development apply to most technologies of the first two phases of the Industrial Revolution. Virtually all of the 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, 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 ...” (Landes: 63).

Surely this is a telling observation when we realise 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-19th century science, and the degree to which Newtonian mechanics permeated and influenced British society, there is no mystery in what Landes observes.

Science-Led Phase

Innovations in the leading sectors of Early Factory and the Steam-Driven Phases were virtually all mechanical. Of the non-mechanical innovations in other sectors many 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

In contrast, during the Science-Led-Phase—the so-called Second Industrial Revolution— industrial development was lead by many non-mechanical sectors. It is generally agreed that the Second Industrial Revolution was heavily science based. Chemicals and steel were two of its key products and they both required applications of fairly advanced Western 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 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.

II. APPLICATIONS

In this second part of our paper we apply our view on the importance of science in enabling the Industrial Revolution to analyse a number of long-standing controversies: Why generally in Europe? Why specifically in Britain? Why did Britain lose its lead? Why not in China? Why not in Islam?

Why in Europe? Pluralism and institutional memory

Much research has established that many of the conditions generally believed to have been favourable to the Industrial Revolution have occurred in other societies at various times in the past. We argue that the missing condition everywhere else was Western science. So the question “Why in Europe?” boils down to “Why did science as we know it develop in Europe?” This is a complex question and we can only touch on two important parts of the answer here. First, Medieval universities provided a neutral space in which science could develop cumulatively. Second, the Christian church—largely as a result of historical accident—accepted and encouraged the natural philosophy that evolved into early modern science.

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.¹⁹

One of the first corporations was the university. The rising urban prosperity that began in the 11th century led to a revival of 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 Edward Grant (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.” A natural next step was for the corporation, rather than individual scholars, to impose standards, grant students a license 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.

Universities provided places where scholarship could develop free from day to day censorship. During the early development of Medieval science, most of the available works 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. But possible conflicts were suggested by works on such broader subjects as the nature of the cosmos, free will versus determinism, and the creation of the world, all of which came under the rubric of “natural philosophy.” 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 program of the 12th and 13th 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).

In an important historical accident, the first Greek works discovered by Medieval scholars did not include those of Aristotle since these had not been translated into Latin in Classical times. The Christian church had already committed itself to the view that Christianity was compatible with Greek learning by the time Aristotle was translated. This did not preclude attempts by conservatives to prohibit specific teachings due to Aristotle and contemporary philosophers. The prohibitions were never fully effective for at least two important reasons. First, the church never sought to suppress Greek learning, only to reconcile it with Christian teaching. Prohibition of certain doctrines was a drastic last resort, not a first reaction to apparent conflict. Second, the university was a corporation with substantial independence. It provided protection to its scholars to teach and think what they wished within only very loose requirements to conform with church doctrines. Scholars learned to circumvent the prohibitions by various dodges, such as 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 that 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 13th and 14th centuries, the church, academics, and most religious people were on side with those who understood the world to be 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).

Out of Medieval science came early modern science. 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.” Medieval science gave a number of vital legacies to the early modern era. 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, bequeathing to early modern scientists a worldview that they found appealing—although they rejected many specific Medieval theories. 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 produced the capacity for incremental cumulative advances seen in Europe. 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 necessary memory is usually provided by the embodiment of technological knowledge in such artefacts as tools, machines, and new crops, and in their continued use.²⁰ First, the artefacts have a physical existence. Improvements are embodied in better artefacts; they are there for all to use and to improve on in their turn.²¹ Second, continued use of the artefacts, and long apprenticeships passed to successive generations the explicit and tacit knowledge needed to employ the artefacts effectively. Thus, throughout most of history, the continued use of the artefacts that embodied most technological knowledge provided an unplanned, and largely unmanaged institutional memory.

In contrast a memory is not automatically 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. The explanation of these Western institutions begins with early Christianity.

Early Christianity

Early Christians were a minority struggling for existence in the presence of other established religions and a strong central government. After they became the dominant religion, they often sought to convert others by force. However, during the first nearly 400 years after the birth of Christ—until they became the official religion of Rome—Christians had to convert others by persuasion. This meant they had to accept the existing lay authority, making a theocracy impossible. Although in later centuries the church and the state often struggled over their boundaries of authority while a complete union of the two was never accomplished throughout Europe—although at times they did co-operate to suppress heresy. It also required that the early church fathers come to terms with the sophisticated Greco-Roman culture in which they were operating. For this they needed to become philosophers. After many debates about how revealed religious knowledge related to Greek scientific knowledge, Greek science came to be seen as inherently neither good nor bad, its value depending on how it was used. Thus, Christianity reconciled itself with Greek learning rather than rejecting it as an alien and evil force.

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 is then seen as a blasphemous attempt to predict the behavior 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.

This naturalism is one of the most salient features of twelfth-century natural philosophy. [The philosophers]...shared a new conception of nature as an autonomous, rational, entity, which proceeds without interference according to its own principles. There was a growing awareness of natural order or natural law and a determination to see how far natural principles of causation would go in providing a satisfactory explanation of the world. (Lindberg: 198-200).

Why in Britain?

The sections on the first two stages of the Industrial Revolution give much of our answer to the question: "Why in Britain?" In essence, Newtonian science was necessary for the Industrial Revolution and only in Britain had this science permeated the whole society with both a mechanist world view and the techniques to handle what were at the time complex problems in mechanics. For example, "...educated 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).

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 took the technology to the continent and made it work. If the continental countries were on the verge of an Industrial Revolution, and had the scientific prerequisites for it, diffusion would have been faster and easier than it actually was.

On "causes" more generally, many forces no doubt contributed to Britain's technological success and there were probably more than enough sufficient causes. 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,²² 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, Western science in general and Newtonian mechanics in particular would be a necessary element in any of these subsets. 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. Our point is illustrated by Elvin (56):

It seems that none of the conventional explanations tells us in convincing fashion why technological progress was absent in the Chinese economy...Almost every element usually regarded by historians as a major contributory cause to the industrial revolution in north-western Europe was also present in China...Only Galilean-Newtonian science was missing; but in the short run this was not important.

We argue in a later section, in agreement with Elvin, that the Chinese did indeed lack Galilean-Newtonian science. We also argue, however, that this lack of modern science is the key to explaining why China never achieved the technologies of the Industrial Revolution.

Kenneth Pomeranz has argued that the two important conditions for the British Industrial Revolution were the existence of easy to reach coal and colonies (Pomeranz 2000). In order for coal to be an important distinguishing cause of the IR, China would have to be on the verge of developing an efficient steam engine. They were not. There is no evidence that Chinese engineers were devoting attention to all the problems associated with the development of the steam engine that we discussed above, let alone coming close to solving them.

We agree with Pomeranz on the historical importance of colonies. However, it is generally accepted that colonies were not necessary for Britain's industrialisation. Domestic markets provided ample outlets for British industrial goods, and any raw resources secured through colonies could have been obtained through alternative trading arrangements. This may have transferred wealth from Britain to her colonies, but not stalled her industrialisation. Further, even if colonies were necessary, that does not preclude the necessity of science, the explanations are complementary.

Joel Mokyr (1999) deals with issues similar to those in this paper. Although he casts his argument in terms of time rather than place, we believe that our analysis is in line with the main thrust of his: "...the Industrial Revolution's timing was determined by intellectual development [found]...in the scientific revolution of the seventeenth century..." (p. 1) and that "...any historical account of...the Industrial Revolution and its aftermath, need[s] to incorporate *knowledge* explicitly" (p. 34). Mokyr 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 goes on to define 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. 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 19th 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 18th 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 19th.)

We agree with the basic thrust of this analysis. However, we argue that the shift from λ to Ω needs to be traced much further back than Mokyr does. As with all such big changes, the shift did not happen at the same time everywhere, and we date it much earlier in the places that are key to our argument. In many fields, such as metallurgy, it was well into the 19 century before Ω and λ became sufficiently complementary to create a positive feed back loop. But in other fields, the development started in the Early Modern Period. Consider two early examples. First, 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?”). Second, the trajectory that began with Leonardo di Vinci and led to the breakthroughs in textile manufacturing in the second half of the 18th century were cumulative rather than singleton techniques. These are briefly summarized in the endnote to this sentence.²³ By no stretch of the imagination can this technological trajectory of evolving techniques that were central to the IR 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 program laid down in the middle ages and which was eventually synthesised by Newton. So although we agree with Mokyr’s model of why sustained growth took off in the late 18th and early 19th 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 Mokyr correctly identifies are rooted further back in time than he acknowledges.

Mokyr makes two other points that seem are relevant to our thesis. First, he argues that many of the things scientists were investigating in the Early Modern Period had no direct relevance for current technological problems (Mokyr 1999:14). We respond that this is as it had always been right up to the beginning of the 20th century, and still is in some fields today. Second, he makes the point, similar to the one made by Landes and discussed earlier, that 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). We have two responses. First, this is as it has always been and often still is. Second, as pointed out earlier in this paper, the knowledge possessed by British engineers and technicians that differentiated them from their counterparts in continental Europe was mechanical knowledge that had been systematized by Newton and made generally available in Britain by his publicists. As science was then understood, and as

the term is used by us, science lay behind the comparative advantage that these “practical” men had over their counterparts in continental Europe in developing and improving the basic machines that were produced by the great inventors.

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 18th 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 has never been seriously challenged in the technological dimension.

If the Chinese were more or less equal to early 18th 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. First, China lacked the Western science that was a necessary condition for the full-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 17th and possibly the 18th centuries. His views on science have been accepted by many but have been challenged by others, in particular, Bodde (1981), Huff (1993) Qian (1985), and Sivin (1980).²⁴ While accepting Needham’s evidence with respect to technology, we believe his critics are correct in respect to science. We argue that Needham’s 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.

The facts seem to be that China did not have even the beginnings of systematic cumulative modern science. Throughout history there have been great scientific thinkers in China, but quite often their ideas flourished for a while and were then lost.²⁵ One reason was the absence of institutions to encourage the cumulative nature of science—a good institutional memory and a critical capacity to build on it.²⁶ 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 end of Sung dynasty. Qian argues that the reason was that Chinese mathematics was an official enterprise. “There were not 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 13th 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.²⁷ 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 Mangnete*. So when European scholars made the study of magnetism into a science in the late 16th 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 16th 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 18th 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, Wheatston 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-IR 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. These examinations were begun under the Han dynasty about 2000 years ago, went through an expansion of curriculum in the relatively liberal Sung period about 1000 years ago, and were narrowed and solidified by the Ming dynasty in the middle of the 14th century. They changed little thereafter, until they were abolished in the 20th century.

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, which were often staffed by former or present civil servants, mostly took the content of these examinations as their curriculum. The imperial academies, some times 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. Science was all the rage in Britain. By the beginning of the 18th century, educated persons were striving, and by and large succeeding, in acquiring an understanding of Newtonian mechanics—the basis of understanding most of the science and technology on which the Industrial Revolutions were built. At the same time, the Chinese were learning about other, non-mechanical, things. (Neoclassical growth models treat human capital as a homogeneous input, but, as this example illustrates, the nature of what is known is at least as important as the quantity.)

In conclusion, 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.²⁸ Finally, if China had been on the verge of an Industrial Revolution in the 18th 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 13th or 14th centuries, science, and 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 14th 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 16th) 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 19th century, the heliocentric view of the universe, the circulation of the blood and countless other Western early modern discoveries had not been accepted in Islam (Huff: 183). Technologically and scientifically the Islamic countries remained more or less where Europe was in the 15th century.

Books have been written attempting to explain this dramatic collapse of so vibrant a scientific and technological culture. 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 with early Christianity, Islam was initially spread by the sword. Within one hundred years of the death of Mohammed, Islamic armies had conquered a vast empire. Little attempt was made to convert the conquered infidels, most of whom converted voluntarily over the next two centuries. 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. 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 with its several obvious contradictions of old testament teachings. 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, a body with a legal life of its own, independent of its individual members. 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 with 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 14th and 15th 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 behavior.

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 14th century.

III. CONCLUSION

The First Industrial Revolution was more than a few gadgets, important though some of them were; it was a habit of mind that went far beyond mere tinkering. It was a way of looking at things mechanically in terms of time and motion, based on 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.

Our view on science and the Industrial Revolution may shed light on other aspects of the period. For example, if the steam engine was a necessary condition for the Industrial Revolution, the conditions leading to efficient high pressure double acting steam engines become critical in accounting for that revolution. (See, for example, Goldstone 1999, 1998). We are sceptical about the steam engine's necessity, although it certainly played an important role. The early factory stage owed little to steam and the scientific revolution (which pre-dates Newcomen's atmospheric engine) was on its way to completing one of its most outstanding research programs, which stretched from the 17th to 19th centuries—the understanding of electricity. Another related to the internal combustion engine. Science was thus in the process of discovering new power sources that would have replaced the water- and hand-powered factories of the first phase before the end of the 19th century. To deal fully with this issue requires more research, but our approach is suggestive.²⁹

What we have said in the previous section about China and Islam applies, with necessary corrections, to all countries outside of northern Europe and English speaking North America.³⁰ 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, 1-2 centuries)?” 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 Science Driven Phase independently without the equivalent of Western science. Our answer to this revised question is that areas outside of northern 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 Exposition 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 20th 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 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 become, and remain, at the cutting edge of technological developments—developments which continue to become increasingly dependent on discoveries in what are now fully differentiated as the pure and applied sciences.

BIBLIOGRAPHY

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

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

Bodde, Derk (1981), *Essays on Chinese Civilization* (New Jersey: 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).

David, P. (1991), "Computer and dynamo: The modern productivity paradox in a not too distant mirror" (Paris: OECD).

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.

Fogel, Robert William (1964), *Railroads and American Economic Growth: essays in econometric history* (Baltimore: Johns Hopkins 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).

Hourani, Albert, (1991) *A History of the Arab Peoples*, (Cambridge: 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 S. (1969), *The Unbound Prometheus*, (Cambridge: Cambridge University Press).

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

Lipsey, Richard G. (2001 Forthcoming), "The Productivity Paradox: A Case of the Emperor's New Clothes" Special edition on the New Economy, *ISUMA*.

_____, Clifford Bekar and K.I. Carlaw (1998), "The Consequences of Changes in

GPTs”, Chapter 8 in *General Purpose Technologies and Economic Growth*, Elhanan Helpman (ed), (Cambridge: MIT Press).

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).

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.

_____ (2000), “King Kong and Cold Fusion: Counterfactual analysis and the History of Technology” (Evanston: Departments of Economics and History), manuscript.

Musson, A. E. (1963), “Introduction” in *Short History of the Steam Engine*, Dickinson H.W., (New York: Macmillan).

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

The New Oxford Dictionary of English, (1998) (Oxford: the 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).

Rosenberg, Nathan and L. E. Birdzell (1986), *How the West Grew Rich* (New York: Basic Books).

Rosenberg, Nathan 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.

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).

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

Tunzelmann, V.T. (1994), “Technology in the Early Nineteenth Century” in Floud and McCloskey.

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

While, Andrew D. (1955). *A history of the Warfare of Science with Theology in Christendom*, (New York: George Braziller).

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

END NOTES

¹ This is a much revised version of a paper presented to the conference “On the Origins of the Modern World: Comparative Perspectives from the Edge of the Millennium” University of California at Davis, 15-17 October 1999. We are indebted to the following for comment suggestions and sometimes severe constructive criticism: Kenneth Carlaw, Jack Goldstone, Peter Howitt, Joel Mokyr, Michele Platje, Alvero Pereira, Nathan Rosenberg and the members of the Canadian Institute for Advanced Research's *Economic Growth and Policy Group* to whom an earlier version of this paper was presented.

² See for example the work of Rosenberg (1982) and L. White (1978).

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

⁴ If we let a general hypothesis be defined broadly as a systematic body of thought that explains phenomena, we can see more historical continuity than is normally allowed for. The scholastic philosophers united Greek science and Christian religious views into a series of broad system of thought or general hypotheses about the nature and behavior of the universe. The early modern period can then be seen as a period of time in which these general hypotheses were subjected to empirical tests and mainly refuted. These tests provided the piecemeal knowledge that was later synthesized first by Newton and then by the other founders of modern science. From this broader perspective the emergence of Newtonian mechanics can be seen as the natural outcome of the testing and refuting of elements of the Medieval scholastic system of thought and the perceived discontinuity between Early Modern Science and everything that went before is then seen to be, in a sense, “invented?”

⁵ For a detailed discussion of the various non-modern views of many who contributed to the development of early modern science see Kearney (1971: 22-48). Christianson (1984) is a fine biography that puts Newton into the context of his times, still with one foot in the mysticism of the past and only one in the mechanistic worldview that he helped to formalize more than any other single historical figure.

⁶ The story goes back to the 15th 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. The process was completed by Jacquard early in the 19th century. Details that show for all

types of textiles an evolution over centuries rather than a revolution over decades are given in endnote 23. (Note also that knowledge about electricity showed a similar cumulative evolution over several centuries as detailed in our section “Why Not in China?”)

⁷ Elsewhere we have distinguished technology from what we call the facilitating structure and elaborated on the point that radical changes in the structure are often misinterpreted as radical changes in technology. See, for example, Lipsey, Bekar and Carlaw 1998 and Lipsey 2001 forthcoming.

⁸ For the use of the terms “tinkering” and “gadget” see respectively Mokyr (1990) and Ashton (1955).

⁹ 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).

¹⁰ 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.”

¹¹ It has been argued that since Newton’s laws mainly concerned celestial phenomena, they had little influence on applied technology. In fact, Newton’s laws of motion, and the mathematics he developed to express them, were used to understand many practical problems of terrestrial motion. For example, Parent used Newton’s calculus to estimate the maximum efficiency of the water wheel.

¹² Even then, the clear distinction between these was slow to develop. For example Lord Kelvin, one of the most important theorists in science at the end of the 19th century, and president of the Royal Society in 1890, made many applied technological discoveries.

¹³ While von Tunzelmann denies a “linear model” in which new scientific breakthroughs led directly to new technologies, his view on the relationship between science and those factors facilitating innovation are close to ours. See also von Tunzelmann (1994).

¹⁴ 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 (Musson 1963:xviii).

¹⁵ Cardwell, for example, does not accept the common view that Black had no influence on Watt. He writes (Cardwell 1995: 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.

¹⁶ All subsequent quotes in this paragraph are from page 61.

¹⁷ For example, the mid 19th century development of the 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 and could not, therefore, have been achieved outside of Europe. (See Rosenberg and Trajtenberg 2000.)

¹⁸ 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.

¹⁹ The development of the corporation was an endogenous response to economic growth and technical change. It was not, however, a necessary response. Similar growth, and even more advanced technological changes, were taking place in both Islam and China although the concept of the corporation did not evolve in either place.

²⁰ Of course, technologies are occasionally lost. At times of great upheaval they may fall into disuse and then be forgotten, as was the case with several Roman technologies. The technology may be used only by a few persons whose successors may lose interest in it, as was the case with the great Chinese water clocks that were used for astrological purposes by the emperor's court. When subsequent emperors lost interest in clocks, the technology was forgotten. But these are rare exceptions to the general rule that embodiment in useful things provides an automatic means by which technological knowledge is preserved and may be built upon.

²¹ Of course, it may help to record technological knowledge in written form and to pass it on the way scientific knowledge is passed on through formal instruction. But this was not necessary—at least before the 19th century,

²² Our view of the historical evidence is that new technologies tended to be introduced first while the property right problems they raised were settled later. This seems true in cases ranging over time from the spread of water powered machinery in the middle ages, which raised water rights problems that took a long time to resolve, to the modern bio-technology revolution, which raised its own property rights problems that are being resolved after, rather than before, the technologies were beyond their initial development stages. So it seems to us that the causal relations run more often from technology to better property rights than vice versa. This is not to say good property rights have been unimportant because, if the problems that were raised by new technologies were not satisfactorily resolved, the development and diffusion of these technologies might have been slowed. But it does argue that property rights already well adjusted to the new technologies were not necessary for those technologies to develop, which is all we need for our argument in this paper.

²³ 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 was 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 15th century and the stocking frame later in the 16th. 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 16th century and important improvements continued to be made over the next 200 years. Finally, Kay controlled the pedals by tappets whose motion could be co-coordinated with other motions of the machine (1745). Thus as early as 1760, the 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. Key developments occurred in 1803-05, 1813, and 1821 and 1822.

²⁴ 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.

²⁵ 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.

²⁶ The Chinese did have institutions that preserved other branches of learning and art. The absence of such institution to preserve scientific knowledge probably indicated a lack of sustained interest in scientific inquiries among the lay and religious authorities.

²⁷ The argument in this paragraph is drawn from Qian: 78-81

²⁸ 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 1870. Science *is* cumulative.

²⁹ The details of our argument and our disagreement with this one aspect of Goldstone's valuable paper can be found in one of the author's websites: www.sfu.ca/~rlipsey.

³⁰ 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 20th century.