Thoughts On The Industrial Revolution

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I am mightily impressed with efforts to more tightly measure the development of industry in the British industrial revolution. However, after reading the following essays:

Nicholas Crafts, "*Productivity Growth in the Industrial Revolution: A new Growth Accounting Perspective*"

C. Knick Harley, "*Cotton Textiles and the Industrial Revolution*"

Ian Inkster, "*Potentially Global: A Story of Useful and Reliable Knowledge and Material Progress in Europe circa 1474-1914*"

Margaret Jacob and Larry Stewart, *Practical Matter: Newton's Science in the Service of Industry and Empire 1687-1851*

Joel Mokyr, "*The Great Synergy: the European Enlightenment as a factor in Modern Economic Growth.*"

Peer Vries, "*Is California the Measure of all things Global? A rejoinder to Ricardo Duschesne, 'Peer Vries, the Great Divergence, and the California Schoo*l.'",

I feel I should respond to several issues:

(1) "New industries" vs. "general improvement" and Total Factor Productivity (TFP)

Crafts and Harley both examine the extent to which productivity gains in 'new sectors' and cotton in particular contributed to overall economic growth in from 1760 to 1860. Harley argues that the spectacular gains in

cotton had few spillovers, in that the technological improvements in cotton production were quite specific to that industry. He thus argues one must look elsewhere than technological change to explain the overall growth in the English economy in this period. Crafts looks more broadly at several ‘modern sectors’ – cotton, wool, shipping, railways, iron, and canals – and at the impact of steam power. He too finds that the impact of modern industries on overall economic growth was quite small before 1830, and that steam power in particular contributed little to overall growth until after that date.

Crafts does, however, find that the modern industries contributed significantly to such improvements in labour productivity as did occur in the industrial revolution. Decomposing total labour productivity growth of .78% per year in Britain from 1780 to 1860, he finds that capital deepening and TFP gains in the modern sectors contributed .46%, while corresponding gains in the ‘other’ sectors contributed .32%. Thus although the modern sectors were only a small portion of the total economy, they contributed well over half of total gains in labour productivity. Thus Crafts concludes that it is ‘perfectly feasible … to regard technological innovation as responsible for the acceleration in labour productivity growth that marked … the industrial revolution.” Nonetheless, much of the productivity growth during this period, and most of the economic growth, came from ‘other’ sectors. In addition, according to Crafts’ own calculations, increases in the rate of TFP growth did not become substantial until after 1830 (.75% after that date vs. .3% earlier), and prior to 1830 the largest contributions to overall economic growth came neither from capital deepening nor increases in TFP but from labour force growth.

While I endorse Crafts’ conclusion on the importance of technological innovation to gains in labour productivity, I nonetheless believe these

analyses are wrongly conceived. Crafts, Harley, and others have demonstrated that the overall impact of the ‘modern sectors’ on total output remained quite low up to 1830. Thus if cheaper cotton, cheaper iron, and cheaper coal (which were the main effects of increased steam power and other technological improvements) had any effects on the aggregate economy, it was not through increased output of those commodities or expansion of those industries, but through the effect of lower prices of these items on the rest of the economy. To the extent that new industries contributed important inputs (in higher quality and quantity at constant or lower marginal prices) to older industries, their effect was more generally dispersed. Thus cheaper wrought iron helped all industries in which metal tools were used (ploughs and sickles to saws and machine tools) or metal was an input (nails, cutlery, buckles, buttons). Expanding supplies of coal at constant prices supplied metal working, residential heating, but also pottery, breweries and brick and tile. Cheaper and plentiful cotton yarn and cloth stimulated the traditional trades for dying, finishing, tailoring, printing, warehousing, merchandising, frame-knitting, lacemaking, etc. of cotton. And the expanding import of raw cotton and the export of cotton and metal manufactures had impacts on shipping, insurance, brokerage, and information (newpapers, coffeehouses) among other trades.

Part of this is simply arithmetic. Consider the expansion of the iron industry from 1800 to 1830. Improvements in technology between 1800 and 1830 allowed the iron industry to triple its output of pig iron from 250,000 tons in 1800 to 750,00 tons by 1830 while the price of bar iron fell in this same period by 60%. Two main technical improvements – the widespread use of coke for smelting and the use of steam engines to power the blast in furnaces – combined with lower costs of inputs (mainly coal) to produce this increased volume of output at reduced prices. However, if we examine the

total *value in pounds sterling* that iron output *itself* contributed to economic growth in this period, it is tiny – total growth in the value of iron output in this period was only 20% (3 times the output at 0.4 times the price = 1.2 times total value), for an average growth rate of 0.6% per year. Not bad, but clearly not a figure that would lift an economy even if it was a large sector, which it was not. So the real impact of the changes in the iron industry would in no way appear in changes in the value of output in that industry, which was small, since increases in output and declines in price offset each other in growth accounting. The contribution to growth would instead appear in the impact on the rest of the economy of having three times as much iron available at forty percent of its previous price. The effect of this cannot be calculated simply by using constant elasticity, because the greater availability of iron at much lower prices in this period spurred a transformation in the uses and demand for iron, such that iron output tripled again in the next twenty years to over 2 million tons, while growing demand for iron was such that prices remained stable.

There were also more general increases in the technology of transport, including Macadamizing road surfaces, and improved postal coaches that greatly reduced travel time for people and information that Crafts does not include in his 'modern sectors.' Improvements in tools for working wood and metal expanded the capabilities of traditional trades, ranging from a host of improvements in the accuracy and capabilities of lathes, most notably Ramsden's screw-cutting lathe of 1770, later enlarged with unprecedented accuracy and uniformity to 1/10,000 of an inch by Maudslay in 1797, to the development of circular saws for cutting and milling lumber, to Naysmith's development of the steam hammer in 1839 which made it possible to forge much larger metal items. There were also major improvements in the production of chemicals, such as sulphuric acid in 1746

(by Roebuck) and soda in 1780 (by Keir). Indeed, Crafts does not include mining, machine tools, road transport, chemicals, water works, potteries, milling, threshing, and a host of other areas in his 'modern sectors,' even though they all had been impacted by technological improvements by 1860; thus his estimate of the portion of labour productivity gains produced by technological change is very conservative.

Finally, and perhaps most important, Crafts and others divided GDP growth into portions due to population growth, capital deepening, and TFP. but population growth too was endogenous. Britain's population growth from 1760 to 1830 was highly exceptional in Europe, being far faster than in any area other than land-rich Russia. I have shown (in my 1986 paper in *Population Studies*, and this was accepted by Wrigley & Schofield – see their intro to the paperback edition of *English Population History* if you wish) that England's population growth in this period can be attributed with good precision to a large shift (5+ years) in the age at first marriage of about 20% of the population, and this appears to be very tightly linked to shifts of population out of agriculture and to opportunities for employment in regions that were home to the 'new industries." Combined with a slight decrease in the death rate, the increased fertility of this fraction of the population raised the Net Reproductive Rate to unprecedented levels and created the population boom. Recent research by the Cambridge Population group shows that most of the population increase in England in this period shows up as growth (including migration) in Lancashire, the areas around Birmingham, the Northumberland Coal region, and London. Without such employment opportunities, it is unlikely that marriage would have accelerated and birth rates would have grown in this fashion. So calculated rightly, the majority of the population increase during the industrial revolution was almost certainly an endogenous product of technological change. And

the growth of population centres in London, Lancashire and Birmingham further stimulated more intensive effort and investment in agriculture – again not involving new technology, but reconfigurations of stock fattening and grain farming and drainage and other investments to raise output to respond to a changing market.

Part of the answer to the riddle that has arisen around the Crafts/Harley results – why was economic growth during the industrial revolution so slow? – can be found by finding the proper point of reference. Prior to the Industrial Revolution, if one examines economic history over the prior five centuries, growth was *truly* slow. Real wages in most European countries were no higher in 1750 than they had been five hundred years earlier, and population growth was nil as well – England and France appear to have had as many people (over 6 and 20 million, respectively) in 1250 as they did in 1750. In other words, for the five hundred years prior to the industrial revolution, net *total* output growth was effectively zero. Moreover, even in relatively 'Golden Ages,' such as the Dutch growth experience from 1630 to 1730, *total* output growth, including population growth and gains in per capita income, never exceeded 1% per annum. In China, where the Qing 'economic miracle' is lauded for producing an unprecedented tripling of population between 1620 and 1820 with no decline in living standards, this still implies an annual growth in output of only 0.56 percent per annum. Thus for the English economy to grow by 1.7% per annum from 1780 to 1831, even if much of that was accomplished through population increase, was a major breakthrough in proper historical perspective (the only prior period of similar population growth, in 1550-1660, involved a doubling of population but a halving of real wages, so that total net output grew only slightly if at all). By comparison, economic growth from 1700 to 1789 in France (in constant prices), a typical mature late pre-industrial economy,

was only 0.34 % per year, and this in an economy participating in the Atlantic trade boom and the centre of the Enlightenment. British growth, at about double that rate during the same period, was already starting to come up against the limit of previously seen pre-industrial growth rates, so for growth to accelerate further after 1780 was quite surprising.

The big reason for the apparent paradox of 'slow growth' in the IR was the misguided expectation that the industrial revolution would somehow take a mature pre-industrial economy (for which we would expect long term zero growth net, and positive growth periods of 1% increase per annum at best) and immediately raise its growth rate to that of a mature industrial economy (3% per year or better). In fact, the transition from mature pre-industrial economy to mature industrial economy took a little over a hundred years, during which aggregate growth rates stepped up from an initial breakthrough rate of 1.7% in 1780-1831 to 2.4% in 1831-73 and then still higher in the late nineteenth and twentieth century. But that such a transition began and took place at all was certainly, in historical terms, an economic revolution.

In sum, I would argue that one of the main impacts of technological changes in the period up to 1830 was demographic -- to spur population growth and redistribute population by increasing opportunities for wage employment in certain regions. Yet since for this added population, only some will find employment in the new industries, and for all the bulk of their consumption demand will inevitably be for products of the 'old' economy (food and shelter and warm wool clothing), the old economy will initially be stimulated to grow along with the new.

It seems that behind the Crafts and Harley analyses are models of the impact of technological change that see either (1) technologically advanced sectors growing wholly separate and independently from the rest of the economy if their technology is only of use in that sector, or (2)

technologically advanced sectors growing by displacing or squeezing out other sectors. Neither of these, however, is accurate, as technologically advanced sectors usually are initially *complementary* to older sectors. Workers and managers at new jobs still need to be housed and fed and served and supplied, and that means expansion of the old sector. In addition, technical change in sectors that provide inputs to other sectors (or potential inputs) leads to changes in demand and output in those sectors as well. Just as providing a railway spur may greatly increase the production of horse-drawn carts in that region to move goods to the railhead, growth in technologically-leading sectors may promote growth in other sectors that do not directly employ the technology or even the products of those sectors, but are responding to opportunities created by advances in the leading sectors – including in this case population growth.

I believe that up until 1850 it is the *complementarity* stage of technological development, rather than the displacement of older industries, that dominates in the British economy. Thus one can see the 'new industries' as the 'leading sectors' of a broader economy that were propelled to exceptional growth rates by technological breakthroughs; but such leading sectors bubbled up through an economy whose overall capacity and character was affected by the diffusion of supply and demand emanating from the leading sectors and their workforces, and in which varied other sectors responded by their own combination of qualitative and quantitative growth. It thus makes no sense to measure the 'proportion' of total growth produced by the 'new industries' in comparison to the overall economy by assuming that one can somehow isolate the 'new sectors' and that all technical change occurred there, and that growth in the rest of the economy was wholly independent of the growth in the new sectors and would have occurred anyway.

Finally, analyses that begin in 1780 and end in 1860 are hardly appropriate for examining the effect of industrial productivity gains on the restructuring of the British economy, and particularly of the impact of steam power, as the age of steam has really only just begun by 1830. Steam *power* could not become a truly general purpose technology (GPT) until steam *engines* became compact and portable, something that did not happen until the production of high-pressure self-contained engines in the 1830s. In 1830 installed horsepower of steam engines was only 160,000 hp; in 1907 it was 9.7 million hp. Britain had about 3,000 tonnage of steamships and 157 kilometres of railways in 1830; by 1900 it had over 7 million tons and 30,000 km of rail. It is no wonder that the term 'industrial revolution' was not coined until the 1880s – the industrial revolution is not important for what it did to Britain's economy before 1830, but for what it did in the seventy years afterwards. It is precisely because the industrial revolution had only modest aggregate impact before 1830 that the California school can argue that overall material conditions elsewhere in Asia were comparable to those in Europe c. 1800.

In short, it is a mistake to search for the source of British economic growth from 1760 to 1860 in either steam power alone as a new prime mover, or in the isolated growth of a few leading sectors. Both are inappropriate to that time frame. Steam power had direct application in only a few industries prior to 1830, and due to declines in price that accompanied growth in output, the initial growth of the 'new industries' had only modest impact on the value of total output. But this does not mean that technical change was unimportant. Rather, what we see in this period is a few industries transforming rapidly due to technological change and providing stimulation to the growth of population and the trades that used their products, along with a varied range of technical innovations that improved

productivity in smaller ways throughout the economy. New industries and technological innovation stimulated, but did not yet transform, the overall economy in this period. One might say that from 1760 to 1830 the British economy was 'becoming modern;' but it did really begin to look or act like a 'modern' industrial economy until later in the 19th century.

Yet these new industries put Britain on a growth trajectory that was novel. The aggregate of these effects had already raised overall growth rates to historically unprecedented levels by 1860, even though most of the growth still occurred outside the 'new sectors.' And from 1830 to 1900 steam became the dominant source of British power, and the new sectors became key contributors to the overall economy and its growth rate.

(2) Steam power vs. other technologies

I find it remarkable that Mokyr and Crafts and others contrast water power and steam power as substitutes, and treat the former as a traditional input and only the latter something as technologically new. The use of water wheels greatly expanded from 1770 to 1830, but this was *in large part due to technical improvements that were themselves attributable to the industrial revolution*. The growth in water wheel power was driven by the substitution of overshot or breastshot wheels for far less efficient undershot wheels – but this improvement was the result of an experimental program carried out by Smeaton as part of his effort to improve the efficiency of both steam (Newcomen) and water power sources, and could not have occurred without the development of concepts and measures of power and efficiency that were wholly absent in the traditional, pre-1700 economy. In addition, Smeaton and Rennie pioneered the use of iron instead of wood in water wheels (a product of post-1760 metallurgy), and new forms of drive (pinion

drive and suspended wheel construction) that allowed lighter wheels to drive a given load, and hence the construction of larger wheels with greater power. Finally, many factories used water wheels whose ability to deliver smooth power regardless of fluctuations in stream levels was maintained by the use of Newcomen steam engines to raise water to propel the overshot wheels during periods of low flow. Thus the availability of steam power itself helped many factory owners keep or choose primary water-wheel drivers instead of converting fully to steam for primary power. In other words, water power may be an 'old' technology, but what needs to be explained is why the efficiency and output of waterwheels increased far more in the century from 1730 to 1830 than they had in the previous seven centuries in which their use had been widespread.

In sum, tracking 'modernization' of industry by plotting steam vs. water power after 1760 is a complete fallacy. *The expansion of both kinds of power was driven by exactly the same underlying culture and practice of engineering and development of mechanical power and its application to production.*

One should probably distinguish between steam power serving as a vital input to the coal and other mining industries and as an adjunct to the textile and canal industries (Newcomen steam engines were used to raise water for locks throughout the great canal-building era), until the 1830s, and then a second phase of steam power from the 1830s to the 1880s in which it becomes a primary power source throughout the economy. But the application of steam was but one small measure of modernization that included a comprehensive modification of the energy and power industry in general, including water wheels, machine tools, and improved utilization of coal in a variety of industries. It would be interesting to know the expansion

in the number of mechanical pulleys and pumps and other power-amplifying technologies brought into use in the eighteenth century, if we ever could.

(3) "Organic vs. Inorganic" and other such distinctions

The above paragraphs suggest that the industrial revolution is best conceived not merely in terms of leading industries (although they existed and had a notable impact), nor simply as a transition to an 'inorganic economy' (which did occur, but really only from the 1840s on, after much other fundamental change had already occurred.) What happened from roughly 1700 to 1840 was a revolution in the way natural philosophers, craftsmen, industrialists, and entrepreneurs approached their tasks.

If before 1700, philosophers stuck to abstract arguments about the nature of things, craftsmen aimed to master a set of traditional skills and control knowledge of technique, industrialists sought to control markets, and entrepreneurs sought to get the best prices for buying and selling, all this began to change. By the early 1700s, natural philosophers aimed to unlock the secrets of nature that would allow men to increase nature's bounty, not by secret procedures like the alchemists, but by publicly presented demonstrations with instruments that reliably revealed regular relationships in nature. Craftsmen sought to learn the latest news of chemistry and mechanics and use these insights to create new tools and machines or improve existing ones; industrialists sought to hire craftsmen who could help them improve their products or processes to expand their markets or capture old ones from less skilled competitors; and entrepreneurs sought to join with craftsmen and scientifically trained or literate engineers to create new products or processes that could change market structures.

Altogether, these changes in behaviour eventually led to a series of breakthroughs in certain individual industries (which became the leading sectors), and later to the development of inorganic economies with broad-based use of new power and material technologies. But it was the underlying behavioural changes – not any specific inventions or technologies or industries as such – that created and sustained the industrialization of pre-industrial economies.

(4) "Useful knowledge" and the "Industrial Enlightenment."

Inkster and Mokyr discuss much of this under the heading of the production of "useful knowledge" and the "industrial enlightenment." But I believe both of these notions are fundamentally misconceived.

First, the concept of an increase in "useful knowledge" as a cause of the IR is a tautology. Yes, the IR depended on an expansion of useful knowledge, but how would we know what knowledge was useful if not for pointing to its application in the IR? After all, knowledge of botany and geography, celestial mechanics, number theory, and crop rotations all increased after 1700 with no direct input to the IR. Knowledge of opium, tea and tobacco helped trade, but not industry. Knowledge of court etiquette, Plato's dialogues, Sanskrit, Mayan archaeology, and other esoterica also increased, but how did this matter to IR? China, after 1700, had a huge expansion in useful knowledge in such areas as new seeds, crop rotations, silk processing, wet-basement cotton spinning, ceramics production, harbour dredging and maintenance, not to mention multi-national administration, botany and geography of southeast and central Asia, and famine relief administration. So why no IR in China?

To specify why an IR arose in Britain and not elsewhere in China (or, in the first instance, Europe), one cannot simply point to the vague concept of a growth in useful knowledge, which simply does not imply any specific growth trajectory unless we specify “knowledge of what?”

The specific knowledge that mattered for an IR was greatly improved and expanded knowledge of the physical processes underlying power generation and applications, and the manipulation and creation of physical materials. In other words, mechanics and chemistry, in the first instance from 1700 to 1850, and their application to practice through scientific engineering.

Moreover, specific techniques for measuring power and efficiency and work, and familiarity with the production and use of instruments for measurement and their application to industrial improvement, which involved formal mathematization and precise quantification of these processes, were essential. So the issue of ‘useful knowledge’ separating Britain from other regions must be posed as why Britain led the way in developing systems of knowledge production that were more fruitful for insights into mechanics and engineering (that were then adopted and developed esp. in France after 1790 and Germany after 1830) than any other society in the world.

It is here that the idea of an “industrial enlightenment” is too late and too broad. Yes, after 1750 there was an increasingly pan-European interest in mechanics and production processes, heralded in the great *Encyclopedie*. But in fact there was more than one Enlightenment in Europe, and the Continental Enlightenment had rather little to do with generating the kind of mechanical and chemical and engineering principles and applications that brought the IR to Britain.

I know that sounds bold. However, let me state why I believe this is the case. The Enlightenment on the Continent stands for a very specific

intellectual movement that sought to replace knowledge, authority, and institutions based on tradition or revelation with knowledge, authority, and institutions based on rational deductions from everyday experience. The Enlightenment *philosophies* and ideologues – as Mokyr rightly observes – sought to overturn local traditions, privileges, and institutions because they were seen to encourage rent-seeking; they thus fought clerics, guilds, and inherited privilege. Initially, they cooperated with monarchies who also wanted to undermine the traditional and local and clerical institutions that limited royal power – hence Enlightened Absolutism. But their goal was to enthrone *reason*. That is, of course, the Enlightenment of Rousseau and Voltaire. Of course, they favoured the accumulation and dissemination of any kinds of knowledge that might be useful, and Mokyr is quite right that interest and periodicals about nature, science, and techniques abounded, but the Enlightenment per se had no program for the *generation* of useful knowledge, as opposed to its collection and dissemination, beyond replacing traditional knowledge and revelation with properly reasoned knowledge.

This is not to say that there were not many leading scientists in France and throughout Europe (more on that below) – Lavosier was founding modern chemistry through a series of laboratory experiments, and there were other major engineers and experimenters at the Academie Royale and the engineering academies. But this approach was not widespread in French education or among all Enlightenment thinkers. In fact, in the 1790s, when the revolutionaries sought to reform French science education and bring it up to date, they turned to a text by Desgauliers published in Britain in the 1750s. Cartesian deductive reasoning, theoretical physics, and research in higher mathematics, all involving the search for the certainty of logical proof, dominated the French Enlightenment – not to mention the German! (Kant). French science *did* do great things, but it was not propelled by the

Enlightenment, rather by its own theoretical research programs, which remained distinct from the great attack on traditional authority and vested institutions that was the main event. Nor was French scientific accomplishment closely tied to a program of realizing industrial applications for its findings.

The Scottish Enlightenment, on the other hand, was deeply steeped in scepticism (Hume), empirical scientific research, and efforts to understand the new commercial society and industry and find ways to improve it. The Scottish Enlightenment was less radical, more practical, and far more productive of industrial improvements than its counterpart on the Continent.

I say all this because even if we grant that 18^{th} century Europe discussed and disseminated knowledge of practices that played a role in the Industrial Revolution, it is not helpful to simply point to all activities associated with any kind of knowledge production and dissemination and label them the "Enlightenment," and then assert that this led to the IR. This again is dangerously close to tautology (as with "useful knowledge.") I think one really must identify precisely WHICH knowledge and practices were intimately involved with industrial advances, identify which people or groups and programs were so involved in the generation and application of that specific knowledge and practices, and then make causal claims. I think it is evident that the Scottish Enlightenment, joined to the Royal Society and urban provincial societies in Britain, was much more intimately involved in industrial advances in the 18^{th} and early 19^{th} centuries than the thinkers and writings we associate with the French or Continental Enlightenment.

By 1800 (and the Enlightenment is properly an 18^{th} century phenomenon) England was so far ahead of France in the development and application of steam power, the use of coal, machinofacture, bulk production of iron and potteries – France still of course dominated in silk, luxury

production, fine arts, etc. – that it seems difficult to say the "Enlightenment" produced the IR, since the centre of the Continental Enlightenment remained virtually untouched by industrialization, while the diffusion zone of the Scottish Enlightenment was precisely the vanguard of the IR. So we have two rather different styles of 'Enlightenment' with distinct local effects, not one.

(5) Explaining the "IR"

Here we face the difference between an economist's and a historian's explanandum. If by the "IR" is meant a marked acceleration in productivity that raised *income per capita* to unprecedented levels, there is nothing to explain before 1830, as it is only from 1830 onward that such an acceleration occurred. This acceleration after 1830 seems clearly linked to expanded use of steam, coal energy, and iron and steel in manufacturing and construction and transportation and war – including items from steam hammers and steam shovels to steam-driven mint presses that for the first time produced non-counterfeit-able, non-clippable coins to steam threshers in agriculture and steam-powered warships and so many other applications it is difficult to count them all -- and to the stimulation imparted to the whole economy and Britain's trade status vis-a-vis other parts of the world economy by the growth of these leading sectors to 1880, and the emergence of new technologies such as telegraphy, industrial chemicals, and many others. As a shorthand, we can note that, according to Kanefsky, by 1870 90% of the power in British mining and manufacturing came from steam. I don't think one can deny that that the growth in the British economy from 1830 to 1870 could not have occurred without the invention and

development of steam power and its application to industries from mining and iron and steel production to transport and textiles.

However, if by the “IR” is meant a marked acceleration in the development of new techniques for producing and using energy and materials to improve output (even if gains in income per head, or in the proportion of the economy that is industrial, change only slowly because of the modest initial impact of the leading sectors, including their spurring of population growth and growth in the ‘old’ sectors of the economy), then we want to explain something that clearly is evident from 1760 onwards. I favour this latter explanandum, so I would try to explain the IR by asking what changed from 1660 to 1760 that shifted the behaviour of the several complementary groups in Britain – natural philosophers, craftsmen, industrialists, entrepreneurs – whose joint efforts created that acceleration.

Here I have to delve into the sociology of knowledge and history of science in some detail. Prior to 1700, all major civilizations used four basic sources for justifying knowledge and authority (which were generally, to a greater or lesser degree, connected). These were:

1. Tradition – knowledge that was revered for its age and long use
2. Revelation – knowledge that was based on sacred texts or the sayings of prophets or other spiritual leaders
3. Reason – knowledge that was obtained from logically demonstration, either in arithmetic and geometry or by verbal construction from basic premises
4. Everyday experience – knowledge that was taken for granted and confirmed by direct common experience, such as that day follows night, the sun rises in the East, objects fall, heat rises, and including

various agricultural and manufacturing techniques that were proven in use.

These were usually more-or-less reconciled, or even synthesized (as in the *summa* of Acquinas), and provided an adequate basis for the growth of knowledge and techniques. But because of the weight of tradition and revelation, reason was often hemmed in, and everyday experience rarely provided reasons for radical change. Thus change was normally sporadic and slow. Progress was most common when different traditions were brought into contact by conquest or trade, leading to contention and an expanded role for reason and insights based on reflections on everyday experience.

Most societies reacted to trauma (the Black Death, conquest, schism, rebellion) by reinforcing or slightly modifying tradition and revelation. Europe was no exception. After the Black Death, although the growth of trade with the East, first centred in Italy, and the recovery of additional classic texts after the Ottoman conquest of Constantinople, led to a 'Renaissance' that sought to revalue and restore a 'better' classical tradition, the secular humanism of the Renaissance before 1500 sought to perfect classical ideals, not overturn them.

After 1500, however, information about the New World, its peoples, plants, and animals as well as its simple existence, called the classical tradition (which had been ignorant of this geography) into question. In addition, increased awareness of new work in anatomy and mathematics developed by Islamic scholars building on the Greek heritage also spread. By the late 1500s, scepticism about classical knowledge had increased, and a renewed attention to reason and closer inspection of everyday experience began to raise new challenges to older traditional and revealed knowledge.

In 1604, the appearance of a major supernova overturned one of the core principles of Aristotelian cosmology – that the heavens were not changeable. And in 1610 Galileo' *Starry Messenger* reported his observations of the heavens with the newly-invented telescope, identifying such phenomena as sunspots, the phases of Venus, and the moons of Jupiter that completely overturned such basic truths as that the Sun was pure, and that the earth was the centre of all heavenly motions. From 1600 to 1638, a series of books presenting new knowledge or proclaiming the need for a "new science" made a compelling case that the knowledge of the ancients was seriously flawed.

1600: Gilbert: On the Magnet
1620: Bacon: Novum Organon (A New Method)
1620 Kepler: The New Astronomy
1626: Bacon: New Atlantis
1628: Harvey: On the Motion of the Blood
1638: Galileo: Discourse on Two New Sciences

It must be recalled that, just as Chinese scholars looked back to the sages of the pre-Imperial period for true wisdom, Europeans had continued to rely on an essentially 1500-year old set of guides to knowledge, including Aristotle for physics and zoology, Ptolemy for astronomy, Galen for medicine, Dioscorides for botany and herbology, and Euclid and Archimedes for Geometry. These authors' texts had been used as the basis for advanced education throughout Renaissance Europe. The striking observations from the New World and the telescope, the more detailed observations of human biology, magnetism, and planetary motion by Harvey, Gilbert, and Brahe (as interpreted by Kepler), and the advances in medicine, algebra, and optics made by the Islamic commentators and scientists whose work was now available in Europe posed an enormous, even overwhelming

challenge, to the body of inherited classical wisdom. I think it is fair to say that no other axial age civilization in Eurasia found its classical heritage so directly challenged by a new volume of observations and texts.

The seventeenth century was, of course, also a period of sharp religious schism and conflict, capped by the Thirty Years' War. There were thus powerful political as well as academic reasons to find a new basis for certain knowledge to supersede the many conflicts among churchmen, scholastics, schismatics, scholars, alchemists, magicians, and others claiming to offer a preferred path to knowledge.

After 1650, there were three major directions taken to deal with this dilemma. One was to set aside traditional and revelation-based assumptions and try to get down to rational bedrock principles and a solid deductive system based on logic. This approach was strongly influenced by two major elements of the ancient Greek heritage – the geometric tradition of the Alexandrians (mainly Euclid and Archimedes), and the atomist tradition of Democritus and Epicurus. The critical figure was Descartes, who argued for a logically consistent world based on geometric space (the plenum) that was fully occupied by particles in motion. In this world, there was no vacuum, and all forces and motions were communicated by the collisions of particles with other particles. Reasoning from these postulates, Descartes filled out a mechanical model of the universe. This approach was also adopted by Thomas Hobbes, who further insisted on the need for an all-powerful state to keep order in this material world.

A second approach was to avoid *a priori* assumptions and the certainty of logical demonstration, and instead develop an empirical program of investigation for the compilation of facts that could then be organized to reveal the underlying relationships of nature. This approach, led by Boyle and endorsed by Newton, had roots in the inductive approach espoused by

Francis Bacon, and in the alchemical and magical practices of the early Renaissance. Borrowing from the English legal tradition the principle of ascertaining facts by the presentation of evidence to a qualified jury, this approach as advocated by Bacon and developed by Boyle and his associates in the Royal Society became a program of instrument-driven research, such that a large variety of investigations could be carried out in front of an audience who could vouch for the results. The favourite apparatus was initially the vacuum chamber – a glass sphere that could be emptied of air and in which dozens of different experimental objects and apparatuses could be observed reacting to the vacuum. Later, a wide variety of mechanical, optical and electrical instruments were used to explore and demonstrate nature’s behaviour. Although Newton utilized geometric analysis to explain his experimental results, in both his studies of gravity and optics, Newton never claimed that nature’s laws could be deduced geometrically from self-evident first principles. The key relationships that he used in building his physics, the inverse square law of attraction between masses, and the variation of refraction among colours of the spectrum, were empirically discovered by ordering observations and identifying key patterns.

A third approach, adopted by the Jesuits and Counter-reformation authorities, was to adopt as little of the new knowledge as possible, and reason ways to reconcile it with revealed scripture. Thus the Jesuits did adopt the Brahe model of the solar system (in which all planets except Earth circled the Sun, which dragged all the other planets around a stationary, central Earth) and much of Descartes’ mathematics and some of his mechanics, while insisting that God and men had free will to guide the ultimate motions of some particles, and avoiding what they considered the “mystical” forces of Newton’s gravity.

The first approach swept most of the intellectuals of northern Europe, who found persuasive the powerful deductive logic of the Cartesian system, and threw themselves into perfecting its mathematical, geometric, and mechanistic deductions. Systematic experiment, however, was not part of this program. Rather, empirical results were used to confirm conclusions or raise puzzles. Thus when Torricelli invented the barometer (a glass tube filled with mercury then inverted in a dish), Cartesians found themselves embroiled in endless debates over whether the 'space' left in the top of the tube when the mercury column fell was a true vacuum (the existence of which had been logically ruled impossible by Descartes) or not. The behaviour of colliding bodies and heavenly bodies were all explained in terms of the collisions of moving particles that conserved 'motion.' The rotation of the earth, and the revolutions of the planets, were explained by the movement of vortices of particles that kept the earth rotating and the planets revolving around the sun. A variety of other phenomena, such as heat and cold, taste, and pain, were explained by motions, arrangement, and collisions of certain kinds of particles (sharp or hooked) with others, such as taste or nerve receptors. The Cartesian approach was also terrifically productive in mathematics, where French, Swiss, and German mathematicians led the way in the eighteenth century in refining the mathematical analysis of fluids, heat diffusion, differential equations, infinite series, and many other topics.

However, the Cartesian approach was something of a disaster in mechanics, because Descartes' deductive approach continued to borrow heavily from scholastic principles regarding the 'nature' or 'quality' of motion. This led to numerous errors in his studies of motion and attempts to formulate principles of force. For example, Descartes maintained that a small body in motion could never impart motion to a larger body at rest,

while a large body in motion colliding with a smaller body at rest would always impart some of its motion to the smaller body. In fact, according to Descartes' own laws of relative motion, these two conditions should be completely identical, and indistinguishable, since there is no 'absolute' rest. Moreover, in regard to collisions, Descartes treated changes in speed but not changes in the direction of motion as involving the application of force. By contrast, Newton got these basic principles right, and thus laid the basis for a valid and useful mechanics, or analysis of force and motion.

Yet the second, or British, approach, was initially highly unpopular outside of Britain, and even widely mocked and criticized within. Outside of Britain, the wholly inductive experimental practices of Boyle had few followers. Torricelli and Pascal, who had pioneered experimentation with the barometer and air pressure, increasingly gave themselves over to pure mathematics. Von Guericke in Germany, who produced the first vacuum pump, failed to follow up with an experimental program because his apparatus emptied solid spheres, unlike the glass chamber used by Boyle, and so could not be used to examine behaviour inside a vacuum. Even Huygens, the most brilliant experimental physicist in continental Europe, who used his experiments to correct and challenge the Cartesian system, was unable to dislodge the favor of that system in Europe, and even as a leader of the Academie Francaise confessed that his sympathies were often more with the British Royal Society, of which he also became a member and to which he sent his assistant Denis Papin. Meanwhile, the varied empirical results of Boyle's experiments on the vacuum were lost in the Continent's vigorous metaphysical arguments over whether a true vacuum could exist in nature.

There was also criticism at home. In late 17th century Britain, Hobbes sharply rebuked Boyle and his followers, saying that philosophy required

proofs, and that playing with apparatus for the public was best left to vulgar craftsmen and entertainers. Satirists such as Pepys mocked the Royal Society, saying they wasted their time in efforts “to weigh the ayre.”

Nor were Newton’s findings greeted with acclaim. With the exception of Holland’s universities, where Newton’s physics were taught up to the 1720s before falling into disuse, they were not taught in the Colleges of France or anywhere in southern Europe until after the French Revolution. Despite the flaws in Cartesian physics, scholars found it even harder to swallow Newton’s idea that the force of gravity operated instantaneously and over vast distances without any intermediary to convey it between bodies. Huygens, despite his admiration of Newton’s mechanics, thought Newton’s reliance on such a mystical force was a grave mistake. Even Newton’s optical research, which used experiments with prisms to demonstrate that white light was not pure, but composed of numerous colours, was rejected as unsatisfying, since Descartes had postulated white light as pure and primary, with colours generated by the spinning of particles at various speeds.

It is important to recognize the depth of the difference between the Cartesian and the British or experimentalist programs for generating “useful knowledge,” and to understand why the British program initially seemed unappealing. The Cartesian system drew its inspiration from the certainty of mathematical demonstration, and sought to resolve precisely the metaphysical problems that had bedevilled scholastic philosophy, on such issues as the nature of matter, space, and motion. It could be seen as exalting principal source of knowledge number 3 above (reason) at the expense of numbers 1 and 2, with an eye to reordering information gained from number 4.

It thus was a more natural way to attack and overturn scholastic and Aristotelian natural philosophy, working in some ways within existing frameworks to replace their priority and contents.   Yet these strengths also implied weaknesses: because Cartesianism remained tied to metaphysics and emphasized deductive proof over experiment, it was prone to becoming mired in metaphysical debate (plenum or vacuum?) and to major errors in analyzing nature. It tended to generate debate and efforts at abstract proof and argument, rather than systematic experimental programs of research. Nonetheless, it remained the decisive frame of reference for physical science on the continent for roughly a century.

By contrast, Boyle sought to avoid metaphysical debates entirely (which he felt could only lead to endless argument and errors) by focusing on what could be publicly demonstrated and thus verified. He refused to debate on the nature of the 'vacuum' in his apparatus, being content to say it was being emptied of air. If others wanted to postulate a remaining "ether" fine, but the question then remained to show whether that ether had any effects that could be observed and demonstrated. If not, the notion was neither right nor wrong but simply irrelevant – what mattered was what could be shown by the instruments in the laboratory or demonstration setting. Thus the goal was to accumulate as many different laboratory results as possible so that they could be systematically organized and generate questions for further experiment, along the lines laid out by Bacon in *New Atlantis* (where in his utopia experiments were to be interpreted by experts for the purpose of generating new questions for the experimenters).

Similarly, Newton refused to debate over what "gravity" was, or how it was communicated between bodies. It sufficed to show that the motion of heavenly and earthly bodies was consistent with a rule of inverse square attraction, and that using Newton's concepts of force, motion, and gravity,

the empirical results regarding the speed and shape of planetary orbits determined by Kepler could be derived, and a host of other observed and experimental results – from the tides to the motion of pendulums – could be explained.

The British scientific program, therefore, amounted to erecting for the first time a novel source of knowledge in opposition to the traditional 1-4. This program proposed that knowledge gained from demonstrable experiments with instruments designed to investigate natural properties was more certain and less subject to dispute than information gained from tradition, revelation, reason, or everyday experience. Although we take this for granted today, in our age of Hubble telescopes, cyclotrons, and particle detectors, in the seventeenth century this was a profoundly novel and often unsettling idea. To Continental philosophers, the investigations of Boyle and Newton and Hooke and other British empiricists were intriguing, but deeply unsatisfying.

Newton's physics, oddly enough, were most widely publicized in Britain by the preachers of the Anglican Church. In 1687, the year of the publication of Newton's major work on gravity, King James II of England was preparing to shift more positions in the state and the Universities to Catholics, and to weaken the independence of Parliament and the courts. In 1688, a number of leading English Protestants supported an invasion of William of Orange, Stadtholder of the Netherlands, that resulted in James fleeing England and William obtaining the throne. Seeking to shore up support for Anglican belief and for the new King, and to dissociate themselves from the Catholics of France, Italy, and Spain, where Cartesianism or the Jesuit version of it reigned, Anglican preachers developed a discourse in which Newton's gravity was a manifestation of divine intervention in shaping the universe, and the simplicity of the inverse

square law of gravity and the laws of mechanics were signposts that God had written in the book of nature as proof of his divine wisdom to be deciphered by the faithful. Of course, the full detail of the Newtonian system was beyond the grasp of all but the most dedicated professional scholars. But simplified versions were widely written up and disseminated to illustrate the harmony and divine order of the universe as understood by proper Anglicans.

With support from the Anglican establishment and the prestige of Newton, the Royal Society attracted the support and interest of gentlemen from across the country for its experimental programs. It also spawned provincial societies that sought to reproduce the latest experiments and add their own contributions to empirical knowledge. For roughly fifty years, from 1690 to 1740, Newton was large rejected in the major countries of Europe, while Newtonian mechanics and the experimental program of the Royal Society were lauded, presented, and imitated in public demonstrations that drew participation all across Britain.

In this half-century, England developed a large stratum of mechanics, engineers, craftsmen, and even industrialists who became familiar with the basics of mechanics, and perhaps even more importantly, with the production and use of instruments for expanding the bounds of technique and knowledge. Experimental programs using microscopes, telescopes, thermometers, barometers, hygrometers, vacuum pumps, pendulums, springs, and other scientific instruments were carried out not only in the Royal Society and the Universities of Scotland and the Dissenting Academies, but by gentlemen, doctors, clerics, mechanics, and craftsmen. All were inspired by the public proclamations of the Baconian ideal that experiment and study would yield great advantages in enjoying nature's bounty and multiplying men's perceptions and skills. By the mid-eighteenth

century, even members of Parliament had some familiarity with computing the force of falling water in waterworks, and tens of thousands of individuals had been exposed by lecture or education to information about experiments, instruments, and pumps.

Meanwhile, nothing of a similar scale occurred in the major states of the continent. From the 1680s onward outstanding experimental and mathematical work was done throughout Europe, but it did not unseat the Cartesian world-view.

For the next fifty years, the triumph of mechanical philosophy over the scholastics comprised the triumph of Cartesian thought. The tide only began to turn against Descartes' system in 1638 when a team led by the French scientists Maupertuis and Clairaut led a team of observers to Lapland to measure the curvature of the Earth. They found that the Earth did in fact bulge at the equator and was flattened at the Poles, precisely as predicted by Newton's theory of gravity but not by Descartes' vortex theory. Still, scepticism remained strong; Newton's *Principia* was not translated into French until 1756, and his theories were not widely taught in France until after 1790. Regarding such leading French mathematicians as d'Alembert, who continued to treat mechanics as simply a branch of mathematics and obtained results by deduction rather than grounding in careful experiment, Clairaut was moved to write in the 1740s: "In order to avoid delicate experiments or long tedious calculations, in order to substitute analytical methods which cost them less trouble, they often make hypotheses which have no place in nature; they pursue theories that are foreign to their object, whereas a little constancy in the execution of a perfectly simple method would have surely brought them to their goal." (http://www-groups.dcs.st-and.ac.uk/~history/Mathematicians/ Clairaut.html). d'Alembert later fell out

with his co-editor Diderot before completing the *Encyclopedie*, as d'Alembert felt that biology did not deserve the same scientific status as mathematics.

Moreover, the experimenters and theorists at the Academie Royale remained an elite group engaged in internal debates; their work was not widely dispersed, preached, or taught to the French public in the 18th century. The debates in leading salons were much more focused on politics and rational vs. traditional institutions than on experimental science.

During this time in Britain, from the late 1600s, Denis Papin, who had left France to continue his work and become curator of experiments at the Royal Society, working closely with Boyle, experimented with designs for using Boyle's discoveries about atmospheric pressure and his own work on steam in practical matters. He produced a successful pressure-cooker, and an unsuccessful design for a piston-driven atmospheric engine. However, Papin's idea of using steam condensation to create a vacuum that would lead atmospheric pressure to do useful work was taken up and improved upon by Thomas Savery – who developed a steam-based pump that worked moderately well. The next step was taken by Thomas Newcomen, a mechanic who developed a useful engine driven by atmospheric pressure pushing a piston into a chamber vacated by condensing steam. Newcomen's first working engine was installed in 1712, and over the next fifty years dozens of Newcomen engines were put to work pumping out coal and copper and nickel mines, lifting water for waterwheels, and hauling materials from mine pits.

The installation of hundreds of Newcomen engines from 1710 to 1760 involved many hundreds if not thousands of workmen in the construction and maintenance of boilers, pipes, gears, drive systems, and hundreds of engineers in the measurement of fuel use and work performed. In addition, London became the leading centre in Europe for the production of scientific

instruments, a trade that was well established by 1750 to serve a domestic market for teaching, work, research, and amusement.

Further improvements were made by Smeaton and Watt by the 1760s, who were moved by measurements of the inefficiency of the Newcomen engines to seek improvements. Using insights from Joseph Black's theory of latent heat, Watt redesigned components of the engine and greatly boosted its efficiency and range of applications.

The steam engine provided new sources of power, and allowed Britain to profit mightily from its plentiful reserves of coal – but such coal was both plentiful and useful *only* because steam engines and a host of other technical innovations in haulage, lighting, and ventilation made it possible to continue to work mines deep below the surface and even extended into the continental shelf. The striking contrast here is with China, where Bejing, like London, had used coal for centuries from surrounding coal pits for cooking and space heating. But in China, coal mines were abandoned when flooding could no longer be controlled, usually at depths of around 30 feet. Similar problems arose in Britain, where "the depths of the workings was limited for the most part by the level at which free outlet for the water could be obtained… so that in 1610 it was stated in Parliament that the mines of Newcastle would not last out more than about 20 years." (http://www.genuki.org.uk/big/wal/GLA/Coal.html#History)

However, from the 1650s major improvements were made in horse-powered chain pumps (pioneered in German mining) so that by 1700 coal mines, using the best horse-powered pumps of the day, were dug to 300 feet; after the introduction of the Newcomen engine to work the pumps, depths increased to 600 feet by 1765. Newcomen engines were also used to power mine ventilators (from the 1750s) and haul coal (from the 1770s). The result is that British coal output increased from 2.5 million tons in 1700

to 10 million tons in 1800. Yet this barely had scratched the surface of Britain's coal reserves or the potential of steam power.

The great expansion of the coal industry dates from the time when the steam engine came into general use, after 1800. This was not only owing to the power which could then be applied to raising coal and water from deep shafts, but also to the immense demand for coal in the country created by the machine itself. Driven by the rapid succession of important innovations in the design of steam engines and the application of steam power, the output of coal rose from 10 million tons in 1800, to 50 million in 1850, 185 million in 1891, and 227 million in 1902.

Yet if steam was perhaps pivotal, the development of steam power was, as noted, only one element in a vast stream of innovations in power, materials, and production, that also included textile machinery, potteries, ironworks, machine tools, construction, water works, mills, etc. etc. I find it remarkable that people point to the burst of mechanical and chemical inventions in eighteenth century England – the Newcomen engine, the overshot water wheel, the use of coke (coal) for smelting and later puddling and rolling iron, sand-casting of brass and iron, the flying shuttle, the sextant, the assembly line, the marine chronometer, the screw-cutting lathe, cylinder borers, the spinning jenny, the Arkwright spinning frame, the Crompton mule, soda production, the Cartwright power loom, gas lighting, etc. etc. – as merely a 'cluster of innovations,' without realizing that many if not most emerged from explicit experimental and/or laboratory research programs (Smeaton, Darby, Harris, Papin/Savery/Newcomen, Cartwright, Wedgewood, Watt, Keir, Murdock at the least).

Arkwright is often described as a 'tinkerer' who came up with a machine unrelated to any scientific advances of the day. This is wholly incorrect. Arkwright was a wig-maker who in his travels encountered many

people who were working to develop machinery for the textile industry. He eventually hired John Kay, a clockmaker, and several other craftsmen, who succeeded in developing the water-frame, for which Arkwright then raised funding to put into production. Arkwright was thus neither a solitary inventor nor unscientific tinkerer – he was one of many entrepreneurs who tapped into the ongoing search for mechanical improvements that was pervasive, found and backed the craftsmen who could develop them, and then gathered the capital and built the firm to exploit the innovation.

It also is absurd to focus on the cluster of textile and engine innovations in the 1760s (Hargreaves, Arkwright, and Watt) as marking any kind of change (this can only be attributed to an earlier search for sharp 'turning points' to embody the IR, going back to Toynbee), when these were clearly just blips in a continuous process of mechanical inventions in highly disparate fields that had been accelerating in Britain since 1700. Indeed, one could argue that either the Newcomen/Darby innovations of 1712-1713, or the high-pressure steam engine and transport innovations of the 19th century (portable steam engines for farm and factory, steamships, railways) were more important. What really was happening was not any sharp break-point, but a continuous acceleration in the rate and range of mechanical and chemical inventions in Britain from 1700 onward, building on the knowledge and skill base that developed out of the emphasis on widespread teaching, demonstrating, and experimenting of Newtonian mechanics and the Boyle/Bacon inspired experimental search for methods to improve material life that was characteristic of early eighteenth century Britain but *not* the rest of Europe.

I believe it is precisely because of these divergent developments in science that Britain developed a roughly 60-80 year lead in the development, teaching, and application of accurate and practical mechanics and

mechanical engineering over other European countries. This lead took place in the accumulation of specific varieties of knowledge, in the widespread use of experimental programs in practical and especially industrial matters, and in the accumulation of skilled human capital. Together, these created the broad British ‘scientific culture’ described by Jacob, although I would add it had a very specific instrumental/engineering component. I think this is what helps explain the fact – often noted by Mokyr – that many ‘pure’ scientific advances in the late 18th and early 19th century made elsewhere in Europe were only turned into profitable industrial processes in Britain.

(6) Could the IR have developed otherwise?

It is possible of course, that given the progress of science outside of Britain, and the eventual experimental disproofs of Cartesian mechanics, that other scholars would have developed a more accurate mechanics corresponding to that of Newton. Leibniz’ calculus could have been utilized for that purpose, added to the skill of continental mathematicians. And the European experimental tradition in chemistry and biology, which became so strong by the late 18th century, might have turned to experiment in the mechanical arts as well. So perhaps all would have happened as it did, but only a hundred years later, when Descartes’ errors were internally corrected.

On the other hand, if there had been no Bacon, Boyle, or Newton, or if their writings were suppressed, perhaps the Cartesian model of logic and abstract mathematical deduction would have led to the kind of downgrading of experimental programs that had happened with astronomy and geography in the Middle Ages, when these ‘mixed mathematics’ fields were considered ignoble for their connection to craftsmen and utility, and separated from the

pure and noble callings of philosophy, pure mathematics, and theology. As with the lapse of Newtonian teaching in the Netherlands after the 1720s, or with Huygens' decision to send Papin to London to further his experimental work, if not for the success and stimulation presented by English experimenters and mechanical engineers, perhaps the practical program of instrument-based experiments would have simply re-merged with the ongoing alchemical/magical tradition and never emerged to join with the goal of identifying mathematical laws in nature as the basis of modern science. D'Alembert, for example, continued to believe that mechanics was simply a branch of mathematics resting on deductions, and for all his genius remained both uninterested in experimental work and often made erroneous assumptions regarding physical realities.

What was crucial for the advance of practical scientific engineering and its adoption by industrialists and entrepreneurs, and its spread among thousands of craftsmen and technical workers, were two factors that were unique to Britain and might never have caught on elsewhere. One was the elevation of instrumental experimental research programs, and the discovery and demonstration of empirical relationships, to the status of an independent, even superior, method of establishing knowledge, even in the absence of an underlying metaphysics. Within Britain, this approach had to fight many critics, and on the Continent the majority of scholars were reluctant to accept it. A pertinent example is Holland, where a rich experimental program of physical research with strong interaction with Newton's work was undertaken by such distinguished scientists as Snell, van Leewenhoek, Huygens, s'Gravesande, and Boerhaave, but this program faded out after Boerhaave's death in the 1730s, in favour of a focus on medicine and anthropology.

The second was the adoption of the experimental method, scientific instruments, and awareness of current scientific research as a proper element in the education and lives of ordinary people and especially for those seeking work in industry. In most of Europe, distinctions between craftwork and scientific work remained very strong, and industrialists and manufacturers focused more on knowledge of their products, trade secrets, and markets than on scientific knowledge or methods that would lead to new products or processes. Whether this bridge would have been crossed, so that without the example of British success, results obtained even in a corrected European science would have been incorporated into programs of industrial improvement, must remain uncertain. It is striking, however, that even in the late 18th and early 19th centuries, after the correctness of Newton's mechanics had not only been accepted but amplified and extended by d'Alembert, Lagrange, Euler, and others, and Lavosier had led an experimental revolution in chemistry, the application of scientific discoveries to manufacturing and industrial processes lagged well behind Britain. What if there had been no British successes in engineering, metallurgy, and manufacturing to emulate?

It is striking that in the 1750s, even while leading mathematicians on the continent including Euler and Bernoulli were doing theoretical mathematical analyses of hydraulics and even attempting to examine the waterwheel, it was Smeaton's experimental program in Britain that first demonstrated the clear superiority of the overshot wheel. Despite their more advanced mathematical analysis of fluids, the French made no significant improvements in waterwheel engineering until Poncelet's and Fourneyron's innovations in the late 1820s and early 1830s, seventy years after Smeaton's work.

We cannot know, nor can I argue as to which possibility is more likely. What I believe we can say about the origins of the IR is the following:

1. In 1500, natural philosophy in Europe, resting mainly on 1500 year old classical sources, was in no way more advanced or promising than natural philosophy in other major societies, and had fallen rather behind Islam which had been building upon and improving the Greek opus especially in the areas of astronomy, mathematics, optics, and medicine. The mechanical arts were no more advanced than in other major societies either, and agricultural technology and manufacturing processes were clearly lagging compared to Asia in such varied fields as textile production, ceramics, shipbuilding, canal-building, plough construction, smelting and casting of iron, and other agricultural tools, among others
2. From 1500 to 1610, a combination of discoveries and empirical observations from the New World to the heavens, plus the absorption of the Islamic commentaries and additional preserved classical texts, created enormous pressures undermining the authority of the established key texts and classical principles of knowledge in Europe, perhaps to a degree not experienced by any other major axial age civilization.
3. From 1610 to 1650, Europeans developed a new approach to natural knowledge, based on borrowings from the Greeks and enriched by Islamic scholars -- including the concepts of a mathematical structure in nature, matter as invisible particles – and from the native alchemical/magical tradition, that replaced the classical framework based on “natures” and “humours” with a mechanical model of the

universe as occupied by bodies in motion, guided by mathematical relationships describing that motion.

4. From 1650 to 1750, this new science developed in two distinct directions. In Britain, there developed an empirical/experimental style that favoured instrument-driven investigative results over metaphysical and deductive reasoning and led to the correct formulation of the basic laws of mechanics. On the continent, there developed a deductive/mathematical style that led to incorrect and conflicted principles of mechanics and continued metaphysical debates. In Britain, moreover, mechanical/experimental explorations and findings were widely dispersed and participated in by diverse strata of society, while in other parts of Europe scientific research remained more confined to an elite and limited circle of practitioners.

5. In most of a Europe, the response to the turmoil and rebellion of the mid 17th century was the strengthening of absolute monarchies and their imposition of uniformity in worship – this was true in countries as diverse as France (where the revocation of the Edict of Nantes abruptly ended toleration), Prussia, and Holland (where the Dutch reformed and Pietist churches grew highly suspicious of the atheistic tendencies of mechanical philosophy). This reinforced the tendency of European philosophers to focus on mathematics and abstract reasoning in the late seventeenth and early eighteenth centuries, and led to the Jesuit 'solution' gaining ascendancy in the lands of the Counter-Reformation. By contrast, the Revolution of 1688 and the Act of Union in 1707 left Britain with two established Churches and an official policy of toleration, plus a hostility to Catholicism. This allowed, indeed encouraged, both the Anglican diffusion of Newton's work, the continued Baconian experimental program of Boyle, Hook,

and the Royal Society, and the development of the Scottish Enlightenment focused on fusing economic and scientific development. As a result, Britain gained a substantial early advantage in the training and deployment of craftsmen, engineers, and scientists who worked with experimental programs and accurate principles of mechanics, and their application to the construction of a wide variety of machines and processes for research and industry. During the 18th century, Britain took a substantial lead in the development of new instruments and processes and tools and machines for the use and generation of power, and the processing of materials.

6. By 1780, other countries in Europe had become aware of this gap and started to catch up by absorbing the methods and developing the human capital training in empirical science and engineering to compete with Britain. However, until 1850 at least, Britain enjoyed a clear lead in those industries that it had developed during the 18th century, including the applications of steam power, iron and steel, textile machinery, and a variety of other machine tools and processes (e.g. casting and cylinder boring).

7. From 1850 to 1880, the specific innovations developed in the previous 150 years – steam power, coal-based production of iron and steel, iron and steel construction, the use of power machinery to amplify labour and handle materials – proved capable of combining to produce varied trajectories in production processes that created unprecedented gains in productivity and income in Europe. These also had military applications that led to European dominance of the globe.

8. From 1800 onward, the scientific method of experimental research programs based on publication and demonstration of instrument-

driven findings combined with precise measurement and mathematical formulation of discovered relationships increasingly became 'standard practice' in the education and training of scientists and engineers throughout Europe, and led to 'rapid-fire' discovery in many branches of knowledge and engineering, e.g. electronics, magnetism, chemical engineering. This led to the rise of new industrial powers (esp. Germany, US) who exploited the new knowledge and caught up with or – in certain industries – surpassed Britain. It also continued the accelerated discovery of productivity-enhancing processes and materials.

9. Although Islamic society, by the twelfth century, had gone far in the direction of building on Greek thought, and improving its empirical analysis and observations in astronomy and optics, it showed no sustained movement toward an instrument-based experimental research program as the way to generate new knowledge. After the disruptions of the Black Death and the Turkish conquests, the rise of a new great Islamic society under Islam from 1500 might have led to further progress. But Islamic society – which had been sending mariners up the coasts and into the interior of Africa and into the Indian ocean for centuries – was not so disturbed as Europe (which had always thought itself on the western edge of the planet) by the discovery of new lands in the western Atlantic. And by the 1600s, when the real intellectual ferment of new discovery was developing in Europe, the Ottoman empire was already breaking down in internal rebellions which then led to a conservative resolution that rejected further innovations or importations of foreign knowledge.

Neither India nor China, whose basic concepts of nature remained anchored in axial-age texts (like Europe before 1500), showed any signs of a major revolt against those concepts. Indeed, in the twelfth century China had developed a new synthesis based on Confucian texts (Zhu Xi neo-Confucianism) that guided its studies for the next millennium. Although there was some heterodoxy and movement toward new concepts and experimental studies in the Ming in the fifteenth and sixteenth centuries, these were halted and reversed by the Qing, who after 1644 insisted on a revival of a more rigid Confucian orthodoxy. In both India's and China's nature philosophy, as with the Aristotle/Galen views, the emphasis was on dynamic forces, essences, and natures. Although there was a great deal of incredibly accurate observational work, and applied sciences of herbology, geography, hydraulics, agronomy, astronomy were developed, these were never likely to be married to anything like the Alexandrian tradition of precise mathematical idealization of nature. Nor was instrument-driven experimental research programs ever likely to emerge as a 'fifth' mode of knowledge creation.

It thus seems unlikely, in the absence of the very particular combination of events and directions taken in Europe and especially in Britain in the sixteenth and seventeenth centuries, that most of the inventions of the 18^{th} century, and their later development, exploitation, and multiplication in the 19^{th} and 20^{th} centuries would have occurred.

Thus the IR was neither an acceleration of previously existing processes, nor an outgrowth of material well-being or special forms of social or business organization. It was certainly not a matter of good fortune in resource endowment, nor was it inherent in the core Western tradition – much of which had to be overturned and abandoned before it could occur. It was rooted in a marked change in the way one group of societies thought

about how to acquire knowledge, and in how one society in particular made unusual efforts to diffuse and apply that new knowledge.