

Oct 2014

No.205

Did Science Cause the Industrial Revolution?

Cormac Ó Gráda

WORKING PAPER SERIES

Centre for Competitive Advantage in the Global Economy

Department of Economics

Did Science Cause the Industrial Revolution?

1

Cormac Ó Gráda

University College Dublin

and

CAGE, University of Warwick

Keywords: economic history, science, human capital

JEL classification: N13, O10, O30

¹ Review of Margaret C. Jacob, *The First Knowledge Economy: Human Capital and the European Economy, 1750-1850*. Cambridge: Cambridge University Press. The comments of John Kanefsky, Morgan Kelly, Liam Kennedy, Deirdre McCloskey, Joel Mokyr, Peter Solar, and Eric Vanhaute are gratefully acknowledged. The standard disclaimer applies.

Did Science Cause the Industrial Revolution?

‘We are not anxious about the honour of acquiring gold medals nor of making an eclat in philosophical societies.’

Matthew Boulton to James Watt, 1783²

Margaret Jacob believes that economists and economic historians have got some key elements of the British Industrial Revolution wrong. In *The First Knowledge Economy (FKE)* she pleads with them to focus more on James Watt’s improved steam engine and less on Richard Arkwright’s water frame (the water-powered device that revolutionized cotton-spinning); more on the complexities of science-based technological change and less on its determinants and quantitative impact. She wants to lure them away from their stubborn belief that ‘skilled artisans, who seldom cracked a book, held the key to British industrial prowess’ (p. 85)³. And she berates them for their over-emphasis on relative factor prices and resource endowments and for their failure to give the culture of applied science its due.

Economic models of the Industrial Revolution increasingly emphasize the role of human capital (e.g. Becker *et al.* 2011; Galor and Moav 2004; Kelly *et al.* 2014). But what did that capital consist of? Was it literacy, numeracy, and affective traits learned at school? Or was it skills and discipline learned on the job? Or did it consist in better nutrition and health, with perhaps associated gains in cognitive ability? It could well have been an amalgam of these. But Jacob’s focus is much narrower, for

² Cited in Cookson 1994: 154.

³ All unattributed page references are to *FKE*.

she concentrates only on science-based knowledge acquired by entrepreneurs and mechanics.

FKE is a combative contribution by a distinguished historian of science to an old debate about the role of science-based technology at the dawn of modern economic growth. That debate flourished in the 1960s and 1970s and centred around the argument by Albert E. Musson and Eric Robinson (1969: vii) that the technology underpinning the Industrial Revolution required something more than the ‘unlettered empiricism’ of traditional historiography. Work by historians of science such as Cardwell (1972) and Hall (1974) and economic historians such as Mathias (1972) and Harris (1998) called into question Musson and Robinson's emphasis on science in the development of the new industrial technology and reaffirmed the primacy of artisanal knowledge. Subsequent work, notably by Cookson (1994), has tended to reinforce this position. As a result, for the period before the mid-nineteenth century the history of science and the history of technology have become increasingly independent of each other (Wengenroth 2000; compare Berg *et al.* 2007).

What new does Jacob bring to this old debate? In *FKE* her focus is less on the development of science from the sixteenth century on—the so-called ‘scientific revolution’—than on the culture that forged the link between science and industry in the eighteenth and early nineteenth centuries. Her depiction of that culture through ‘a series of microcosms’ (p. 221) or case studies encapsulating the values and the informational transmission mechanisms that she champions is done with skill and conviction. Her emphasis on innovative entrepreneurs, embodiments of what she long ago (1981) dubbed the ‘moderate Enlightenment’, is in line with recent work by Joel Mokyr (2002, 2009), though he takes a much broader view of the Enlightenment's

effects on economic development. Also, and again unlike both Mokyr and participants in the earlier debate, Jacob wants to argue that England's precocious industrialization was chiefly the result of its being more enlightened in its attitude to science than countries on the continent. This reading of scientific and industrial history is informed by Jacob's (1981, 1987, 1997) own extensive research on science during the Enlightenment. She does not bring to the problem any major or systematic collection of data in the sense known to economists. Instead she offers vivid storytelling based on wide reading and rich qualitative archival material.

This review essay pays tribute to Jacob's feisty case for the role of science, but takes issue with her characterization of the human capital that made the Industrial Revolution and defends the role of more modest forms of learning and of artisanal genius.

1. Lunatics and Mechanicks:

Europe on the eve of industrialization saw economist François Quesnay wowing the court in Versailles with his physiocratic 'zig-zags', Benjamin Franklin hobnobbing with the Birmingham industrialist Matthew Boulton, and George Washington exchanging notes with agronomist Arthur Young. In *FKE* Jacob populates her England with similarly urbane 'cosmopolitans' (p. 35), spindle-makers versed in theoretical and applied mathematics (p. 16), 'ubiquitous engineers' learning from 'Newtonian textbooks' (p. 114), noblemen familiar with 'the mechanical knowledge necessary to interrogate surveyors and engineers' (p. 133; also pp. 8, 222, 224), travelling lecturers and mathematics teachers who 'criss-crossed the country', and

study groups organized to brush up on Newtonian mechanics (pp. 55-56).

In this land of science-based innovation Matthew Boulton's paradigmatic partnership with James Watt is so resonant of the marriage between manufacturing and science that Birmingham, where 'the dandy and the Scot' (p. 27) made their steam engines, becomes 'the epicenter of the nascent Industrial Revolution' (pp. 12, 21, 49). This is the land of the Lunar Society, where scientists and businessmen brushed shoulders and talked science, and of the Literary and Philosophical Society of Manchester (1781), which joined the intellectual curiosity and 'useful knowledge' (Mokyr 2002) at the heart of Jacob's story (pp. 104-6). Thirteen of the Lit and Phil's original membership of fifty were textile manufacturers, and its honorary members included Wedgwood and Lavoisier. James Watt Junior would become its secretary in 1790 at the age of twenty-one and atomic scientist John Dalton the Society's leading light. Manufacturers mingled with surgeons, lawyers, clergymen, and merchants and discussed topics ranging from a clergyman's 'Attempt to Shew that a Taste for the Beauties of Nature has no Influence Favourable to Morals' to Dalton's 'Extraordinary Facts Relating to the Vision of Colours'.⁴

Yet while such societies lent scientific knowledge respectability, their role in spreading it was limited. The Lunar Society had no more than about a dozen members, met rarely, and some of its meetings were poorly attended (Jones 2009: 86-94). And although one of the reasons given for the foundation of the Manchester Phil and Lit was the perception that 'few of our mechanics understand the principles of

⁴ These presentations may be found *Memoirs of the Literary and Philosophical Society of Manchester* (1789) 1: 223-40; (1798) 5(1): 28-45.

their own arts and the discoveries made in other collateral and kindred manufactures’ (cited in Cardwell 1972: 23), its membership was highly selective. Birmingham’s ‘Lunaticks’ excluded even the most gifted of Boulton and Watt’s employees. Such societies operated more like private clubs than open forums for the spread of ideas, and were more interested in the scientific topics of the day than in their links with industry. Industrialists who joined them saw them as a stairway to social mobility and gentility (Cardwell 1970; Cookson 1994: 154-5; Uglow 2002: 353; Jones 2009: 82-94).⁵

Agronomist Arthur Young was a member of the Society for the Encouragement of the Arts, Manufactures and Commerce and was elected Fellow of the Royal Society in 1774, but those links post-dated his famous tours of English agricultural districts. His role was recognized by the Enlightenment, but not inspired by it, because the gradual improvement in agricultural productivity that he documented preceded the Enlightenment, and the information that he gathered on his early tours owed little to book-learning or science. Ironically, Boulton and Watt were quite paranoid about protecting their own ‘useful knowledge’,⁶ so much so that Young was ‘no where more

⁵ To add to the irony, before Boulton and Watt began steam engine production in Soho in 1795, they relied heavily on outsourcing to other manufacturers and consultant erectors who in turn were heavily dependent on skilled artisans unversed in science and mathematics.

⁶ Jacob (p. 12) notes the prevalence of industrial espionage, against which patents offered little protection. Probably more ‘useful knowledge’ was transmitted through espionage than through learned societies. Lieven Bauwens (1769-1822) and Samuel Slater (1768-1835) spread the new spinning technology to Belgium and Rhode Island, respectively, with ideas or machinery smuggled out of England in the late 1790s. Slater had worked in Belper for Jedediah Strutt; soon New England blacksmiths and wheelwrights were duplicating Slater’s designs (compare Jeremy 1973; Ben-Atar 1995; Harris 1997; Mokyr 1976: 27-8). And while the legend that Benjamin Huntsman’s steel-making process was pirated by a Sheffield rival who gained

disappointed than in Birmingham' where he 'could not gain any intelligence even of the most common nature', including data on wages (Young 1771: III, 279).

FKE also makes much of the mechanics' institutes that sprouted up all over Britain in the 1820s and taught workmen the knowledge of 'scientific principles' (pp. 99, 104, 106-9, 115). Products of a campaign to educate and reform the working classes, they represented a mass movement in the sense that 'every large town and many a small one' had its own institute (Inkster 1976). The biggest of them, offering courses in mechanics, drawing, and the like, attracted memberships of a thousand or more. The institutes won support from the stratum that also supported the savings banks movement—including David Ricardo and James Mill. But like the savings banks, the mechanics' institutes ultimately failed to retain the interest of the people they were supposed to benefit (Tylecote 1957: 259-60; Fishlow 1961; Cookson 1994: 151). Soon attendances began to fall off; attempts were made to lure people back with classes on mesmerism, phrenology, and literature (Cardwell 1972: 71). In any event, the institutes came much too late to have had an impact on that crucial period of the Industrial Revolution c. 1785-1820, when the economic and geographic landscape of Britain was transformed.

2. *The Identikit Entrepreneur?*

access by seeking a warm place to sleep sounds apocryphal, Huntsman was indeed prey to continental pirates (Hey 2004).

How reliant were the inventors and entrepreneurs of the Industrial Revolution on the ‘rocket science’ of their day? Who was the more typical: potter Josiah Wedgewood, who could hold forth on ‘Acids & Alkalies, Precipitation, Saturation, &c’, or Jedediah Strutt, whose education was ‘narrow and contracted’; Matthew Boulton, who was ‘more at home in courtly society than on the workshop floor’, or ironfounder Isaac Wilkinson, who attended a school for aspirant churchmen (Uglove 202: 56; Jacob 2014: 25; Fitton and Wadsworth 1958: 3; Chaloner 1960: 33)? Jacob devotes disproportionate attention—three chapters of *FKE*—to Boulton and Watt in Birmingham, James McConnel and John Kennedy in Manchester, and John Marshall in Leeds. The first two were associated with the improved steam engine; the others were textile producers who employed such engines. Jacob’s pen pictures of them are well done and compelling. All five fit an identikit innovator wedded to scientific and technological culture and to steam. But how typical were they?

Describing what was ‘typical’ is not easy⁷, but Allen (2009) and Meisenzahl and Mokyr (2012) have produced databases directed at this question. About half of the eighty high-profile inventors in Allen’s database had enlightenment connections (2009: 248-9), although a few, such as the agronomist Arthur Young, the textile baron John Kennedy, and the clock- and instrument-maker Henry Hindley, made the connection late in the day. But those were the Who’s Who: Meisenzahl and Mokyr focus instead on 759 more modest ‘tweakers and implementers’ who merely improved on existing inventions. Less than one-fourth of those had any schooling other than an

⁷ Compare Honeyman 1982; Crouzet 1985; MacLeod and Nuvolari 2006; Cantrell and Cookson 2002.

apprenticeship, while only one in seven was a member of a society such as the Manchester Lit and Phil (Meisenzahl and Mokyr 2012; Tables 2 and 6).

In reality, most of the foremost inventor-entrepreneurs of the Industrial Revolution were of rather modest, artisanal origins. The list includes Arkwright, Strutt, ironmaster John Wilkinson (inventor of the precision boring machine used in the construction of steam engines), Henry Maudslay (machine-tool inventor), James Hargreaves (inventor of the spinning jenny), Charles Tennant (who discovered bleaching powder), and Matthew Murray (machinist, rival to Boulton and Watt). Watt described Henry Cort, inventor of the puddling process, as ‘a simple good-natured man but not very knowing’ (McLeod 2007: 40), while Samuel Crompton ‘possessed only such tools as he purchased with his little earnings acquired by labour at the loom or jenny’ (Kennedy 1831: 319-20)⁸. The history of smallpox inoculation, a technique developed in the 1750s by a group of provincial surgeons/apothecaries without formal medical training, is another example.⁹ These artisans-made-good were the most talented and ambitious products of a system that combined basic schooling in literacy and arithmetic with apprenticeships based mainly on learning-by-doing. That system yielded workers so valuable that it was a crime for them to emigrate before the mid-1820s (Cookson 1994: 145; Bensimon 2011).

Yet even focusing on the likes of those named above ignores the incremental,

⁸ John Kennedy, ‘A brief memoir of Samuel Crompton’, *Memoirs and of the Literary and Philosophical Society of Manchester*, ser. 2, vol. 5 (1831) 5: 319-20 [http://books.google.ie/books?id=xAZ_56mG2-4C&pg=PA318&lpg#v=onepage&q&f=false].

⁹ Indeed, many academically trained physicians opposed their methods. I owe this example to Peter Razzell.

low-tech, and anonymous nature of much technological change in this era. During the eighteenth century, for example, watchmaking benefitted from no major technological breakthroughs apart from the dead-beat escapement (c. 1715) and the invention of cast steel (c. 1740). Yet productivity growth was continuous and significant—though not quite as fast as implied by Adam Smith (Smith 1976: 260-1; Kelly and Ó Gráda 2014). Ship design in Britain was mainly artisanal in this period. The major breakthrough was copper sheathing, an idea that was never patented and whose inventor is unknown. Its development owed most to the Royal Navy's willingness and ability to finance experimental voyages (Solar 2013).

Captivated by Boulton and Watt's struggles with their patents, Jacob asserts that 'in Britain, innovations meant patents' (pp. 22, 24, 40-42, 159). But this is to embrace a very narrow view of technological change during the Industrial Revolution. It is also to ignore an extensive literature that deems Britain's patent system cumbersome and unreliable and expensive, with the result that most inventors shunned it (Dutton 1984; McLeod 1988, 2009; McLeod and Nuvolari 2011; Moser 2012). Several high-profile inventions were never patented; more importantly, the incremental changes that were occurring throughout the economy were impossible to patent. Significantly, most British goods and processes on show at the Great Exhibition of 1851 had been developed without a patent. Perhaps a system closer to the American model would have spurred more inventive activity; as matters stood, Britain achieved and maintained technological leadership until mid-century with little resort to patents.

3. *Textiles, Coal, and Steam:*

‘Whoever says industrial revolution says cotton’ (Hobsbawm 1999: 34). This enduring *cliché* remains a useful exaggeration, since estimates of the textile sector’s contribution to measured productivity growth between the 1780s and the 1860s range from a quarter to between a half and three quarters when agriculture is added on (McCloskey 1981: 114; Harley 1993; Clark 2014: Table 2). Productivity growth in textiles (cotton, woolens, worsteds, linens) mattered because the sector accounted for about half of British industrial output throughout the eighteenth century (Crafts and Harley 1995: 729). By c. 1830 cotton goods accounted for half of all British exports.

Yet because Jacob dislikes the old orthodoxy ‘that the industrialization of cloth production required not steam, but jennies and water power’, she is not interested in textiles except insofar as they were linked to steam engine technology (Jacob 2007: 200). She is aware (p. 90) of people like the ‘two Journeymen Clock-Makers, or others that understands Tooth and Pinion well’, the ‘Smith that can forge and file’, and the ‘two Wood Turners that have been accustomed to Wheel-making, Spole-turning, &c.’ sought by Arkwright and Strutt for their revolutionary water-powered spinning mill in Cromford in 1771 (Fitton and Wadsworth 1958: 65), but in *FKE* neither Crompton nor Strutt represent ‘the first generation of cotton manufacturers’ (p. 85). Fine cotton spinners McConnel and Kennedy, who installed a 16 h.p. steam engine in 1797, are allocated that role. But there was nothing special about their steam engine.

Kanefsky’s database of eighteenth century steam engines (Kanefsky 1979a and personal communication for the author) records around two hundred steam engines, including over fifty by Boulton and Watt, as having been installed in British cotton

mills before 1797; over half of these engines were in Lancashire. Nearly one hundred are known to have driven textile machinery directly (at least forty re-circulated water to water wheels and the use of the remainder is not known), and of these direct drive engines over forty had again been installed in Lancashire, including seventeen by Boulton and Watt, starting over a decade earlier. So, whatever their scientific leanings, McConnel and Kennedy were followers rather than leaders in their use of steam power.

The water wheel may have lacked the steam engine's versatility but most English textile manufacturers would continue rely on waterpower for a few more decades (von Tunzelmann 1978: 183, 224). Nor did waterpower technology stand still: Cardwell (1965) and Kanefsky (1979) have highlighted advances in waterpower technology well into in the nineteenth century.¹⁰ And Jacob is silent on the widely cited finding by von Tunzelmann (1978; compare Crafts 2004) that before the early nineteenth century the contribution of steam power to economic growth was minimal. Jacob's undue focus on McConnel and Kennedy refuses to acknowledge the stubborn facts that 'all the major technical breakthroughs in cotton-spinning' predated steam power and that in the early years the use of steam power was confined to carding and mule spinning (van Tunzelmann 1978: 182-3). These examples also highlight the tendency of *FKE* to treat the entire period between c. 1750 and c. 1850 as timeless and homogenous.

Data on professional prizes and other rewards to 'tweakers' across a range of

¹⁰ The most important (described in detail by Kanefsky 1979: 48-62) include Fairbairn's rim drive, lighter and stronger steel wheel frames, Jean-Victor Poncelet's curved buckets and, from the 1840s, water turbines (the invention of French engineer Benoît Fourneyron).

sectors, as a measure of the link between science and commerce, point to a stark contrast between textiles and the rest of the economy (Meisenzahl and Mokyr 2012). Before 1800, only 16 per cent of the 124 ‘tweakers’ in textiles won awards, compared to 67 per cent of the remainder. Post-1800, the percentages were 20 and 81, respectively. Pre-1800, only 2 of 124 ‘tweakers’ in textiles became members of the Royal Society, compared to 31 of 73 instrument-makers (derived from Meisenzahl and Mokyr 2012: Table 6). And the proportions whose education was minimal or unknown were higher than in any other sector.

Steam—and therefore coal (pp. 57-82)—are at the heart of Jacob’s case for science. In the long run, certainly, coal and James Watt—and Richard Trevithick, who pioneered the railway locomotive¹¹—were more important than cotton and Richard Arkwright. The part played by coal in freeing humanity from dependence on vegetal energy sources was as important in its day as the role of non-fossil fuels in protecting this and future generations against global warming (Wrigley 2010). However, steam’s role at the height of the Industrial Revolution, both as a source of energy relative to waterpower and in terms of its contribution to overall economic growth, was distinctly secondary (Table 1).

Year	Steam	Water	Wind	Total
1760	5	70	10	85
1800	35	120	15	170

¹¹ My thanks to John Kanefsky for insisting on this.

1830	165	165	20	350
1870	2060	230	10	2300
Source: Crafts 2004: 342, after Kanefsky 1979a				

For all their novelty, the average horsepower of Boulton and Watt rotative engines was only 15 h.p. c. 1800 (von Tunzelmann 1978: 28-29], and 60 h.p. was still considered large in the 1820s. Moreover, Kanefsky's review of the evidence c. 1870 suggests that while steam was of fundamental importance in mining, textiles, transport, and metallurgy, across large swathes of industrial Britain, the diffusion of steam power was still far from complete. Agriculture and the service sector remained largely untouched. Even in coal mining, the expansion of output consisted of hiring more men with picks and shovels to extract the coal (Kanefsky 1979b; Samuel 1977; Crafts 2004: 341-2).

Jacob devotes a chapter to Leeds, a city transformed by woolen and linen mills and major engineering firms during the Industrial Revolution.¹² Leeds textile manufacturers did take up steam power quite rapidly, but by the 1820s and 1830s this was no longer good evidence of reliance on the 'scientifically informed, factory based experimentation' (p. 110) that she champions. Ironically, Leeds provides the best witnesses against the centrality of 'scientific knowledge of a mechanical sort, and chemistry' (p. 114). Jacob's depiction of Leeds industrialist Matthew Murray (1765-1828) as 'mechanically literate entrepreneur' (p. 125) is not easily squared with the artisan-genius who continued to make 'his calculations with a carpenter sliding rule',

¹² Leeds' population grew from about 30,000 in 1770 to 222,189 in 1841.

and 'had nothing to do with scientists during his most productive and innovative years' (Cookson 1994: 150, 154-5; Cookson 2004). Another famous Leeds engineer and inventor, Peter Fairbairn, began work in a colliery at the age of eleven; he set up business 'in a small room in Lady Lane in 1826, where a 'stalwart Irishman' powered the lathe' (Cookson 1994: 219).

4. Artisan Human Capital:

Today the key role of education and literacy in promoting economic growth is admitted on all sides, but economic historians disagree about the role of education in the Industrial Revolution. It is often noted that because Britain's record on literacy was mediocre and that mass literacy was not a prerequisite for early industrialization. Jacob's focus is not on mass literacy but on the sort of scientific training she deems necessary for a career in industry during the Industrial Revolution: that required, besides literacy and numeracy, an education in geometry, algebra, and 'basic mechanics of a Newtonian sort' (p. 157).

One local case study may be instructive in this respect. Prescott in southwestern Lancashire had been epicenter of England's watchmaking industry since the early eighteenth century (Bailey and Barker 1969). Its Anglican parish registers reveal that the overall literacy rate in Prescott, located within eight miles of Liverpool, was very low, and showed little sign of any increase before the mid-nineteenth century. But there was considerable variation in literacy across occupations. Colliers were nearly all illiterate throughout the period, as were shoemakers and laborers. Farmers were much less likely to be illiterate—and Thirsk (1985: 571-4) has highlighted

the role of print in hastening the diffusion of agricultural techniques—but they were not reluctant to marry illiterate women. White-collar workers, invariably literate themselves, married literate women. But what is surely significant is that Prescott's watchmakers and artisans generally were much more likely to be literate than the average. Of the 183 watch- and watch-tool makers who married in Prescott between 1773 and 1845 more than two-thirds (131) signed the marriage register. Their wives were nearly all illiterate, which suggests that watchmakers saw literacy as an investment, whereas for the white-collar elite it was consumption. In sum, artisans tended to invest in literacy, if factory hands and miners did not.¹³

Jacob repeatedly states that how 'scientific knowledge' was acquired—and therefore how widespread it was—remains a black box (pp. 8, 133, 223). But she fails to note that even some of the discoveries of better-educated inventors such as George Stephenson and Richard Roberts were based, not on 'scientific knowledge' but on 'tinkering' (compare McCloskey 2010: 43-4). Even Tennant's discovery of bleaching powder in 1799 was the product of trial and error and 'could have been made by any observant artisan' (Coley 2000: 37). And although Jacob concedes the ubiquity of trained artisans, she underrates their central role in the Industrial Revolution (pp. 12, 157; compare Tann 1974). Apprenticeship in England was far removed from the caricature painted by Adam Smith in the *Wealth of Nations*. Resilient and adaptable, it was a far more effective means of transmitting 'useful knowledge' than the learned societies, secondary schools, or mechanics' institutes given pride of place by Jacob. So open was access to apprenticeships that in 1700 over one young adult male in four had

¹³ This pattern is broadly replicated in the neighboring parish of Warrington.

completed one (Mokyr 2009: 118). This was a productivity-augmenting, market-driven, and self-regulated institution, in which masters and servants cooperated in a well-recognized way (Humphries 2003; Minns and Wallis 2012; van der Beek 2014). Less distanced from the traditional textbook stereotype, the French apprenticeship system was much more restrictive than the English (Kaplan 1993; Crowston 2005).

5. French and Dutch Retardation:

Jacob attributes Britain's lead over France to an elite that was 'at least a generation ahead' in terms of 'scientific knowledge and education of a mechanical sort' (p. 132, 138). Britain's other continental rivals, the Dutch, were highly literate but failed to concentrate on 'technological learning' (p. 205-8). But there is an alternative explanation of her evidence: the private supply of such training was usually ample where there was a demand for it. And so it is hardly surprising that the University of Durham, sitting in the midst of Britain's largest coalfields, would offer courses in mining engineering in the 1830s while there was little enthusiasm for mechanics in institutions of higher learning in 'Harderwijk, Deventer, and Gelderland' (pp. 74, 193, 207).

Economic historians have long debated why France and the Netherlands failed to industrialize when Britain did (e.g. Kindleberger 1964; O'Brien and Keydar 1978; Mokyr 2000; Crouzet 2003). For Jacob the main reason for French economic retardation is that 'scientific education occurred in fits and starts' (p. 188), while the contrasting fortunes of industrializing Belgium and the laggard Netherlands stemmed from their respective stance on 'education with an industrial focus'. Maastricht is the

Dutch exception that proves the rule: the *only* reason Jacob gives for its relative success is its relative strength in science-based education (pp. 207-11). She might have also noted the additional effect of the events of 1789-1815 in both the Netherlands and France, which clearly diverted resources and ingenuity from productive to other ends.

But French precocity in this sphere suggests that science was not the key, because France had been generating science-based knowledge in spades long before the Industrial Revolution. It was still ahead of Britain in applied science c. 1800, and the French Revolution arguably accentuated its lead for a time (Cardwell 1972: 22, 26-27; Mathias 1972; Hobsbawm 1962: 29-30).¹⁴ Nor were English scientists and mathematicians that adept at spreading their gospel: Cardwell describes English mathematics textbooks of the early Industrial Revolution era as 'belonging to an earlier century' and 'far removed from practice'; moreover they were incomprehensible to mechanics and expensive as well (Cardwell 1972: 124; Cookson 1994: 146).

What France lacked was not an enlightened elite, but the mechanics and artisan-entrepreneurs so plentiful in Britain. On the eve of the Industrial Revolution British workers were taller, healthier, savvier, and more productive than their French counterparts. Wages in Britain were higher than elsewhere not because labor was costlier, but because British workers were more productive (Kelly *et al.* 2014). French retardation depended less on what Jacob calls the 'expansion of human knowledge' (p. 15) than on the relatively poor quality of its labor force.

¹⁴ Diderot and d'Alembert's *Encyclopédie* (1751-72), which highlighted such knowledge, had sold 25,000 copies by 1789, half of them in France (Darnton 1979: 37). And whereas Newton wrote the *Principia* in Latin, Voltaire and Emilie du Chatelet popularized its findings through their *Eléments de la philosophie de Newton* in 1738 and Chatelet's full French translation of the *Principia* followed in 1756.

6. *Timing*

Nobody doubts the centrality of technological change to the Industrial Revolution, but the timing of its impact is still debated. Macroeconomic data imply that rapid, self-sustaining economic progress did not begin in the 1760s (p. 1); moreover, economic growth during the following century was very slow by later standards, certainly no more than 1.5 per cent per annum. More interestingly, the latest attempts at estimating British output and productivity in the more distant past reveal an upward trend in GDP that began long before the ages of cotton and steam and, indeed, before the Enlightenment could have had any impact (Broadberry *et al.* 2014; Nuvolari and Ricci 2013).

Figure 1 describes the movements in GDP and GDP per head (both measured in logs) in 20-year blocks between 1390-1409 and 1850-69 implied by Broadberry *et al.*¹⁵ Over this period, GDP grew about ten times as fast as GDP per head. Note that from the early seventeenth century on, GDP per head was higher in each period than in the previous period: growth had somehow become built-in. Note too the rather intriguing implication that the growth rate of GDP per head fell during the eighteenth century before accelerating again early in the nineteenth.

¹⁵ These numbers are the best available but not definitive: see Kelly and Ó Gráda 2013.



Figure 1. Economic Growth Before and During the Industrial Revolution

Other indicators point to progress in this pre-Industrial Revolution era. One is the remarkable increase in literacy; between 1600 and 1750 England moved from being essentially a pre-literate society to one where more than half of all adults could sign a marriage register. And although literacy (thus defined) did not increase much for some decades thereafter, the number of books published and the circulation of newspapers did. Other indicators are the increasing urbanization and openness of the economy, and the integration of its regional markets. With increasing commercialization came increases in the variety of goods consumed, and those increases were not confined to the rich. Adult life expectancy began to rise too, that of the elite during the seventeenth century, that of the population at large during the eighteenth (Edwards 2008; Johansson 2010; Razzell 2014). In sum, the slow take-off of the British economy antedated the Enlightenment and the steam engine by a century or more.

None of this rules out a ‘first knowledge economy’. But if one is to feature in the macroeconomic landscape described in Figure 1, its birth must have been a

gradual, long drawn out process. This is problematic for interpretations that emphasize the revolutionary role of a few inventions such as Watt's and Arkwright's, but more congenial to a slow-burning but eventually all-embracing diffusion of ideas and technologies that is actually more in line with the older arguments for the importance of science-based change. A process with roots in the pre-industrial era in sectors other than cotton and coal and in forms of knowledge distinct from 'applied science' seems most likely.

In her claims for the centrality of science and knowledge, for the importance of mechanics' institutes, and for the pivotal role of coal and steel, Jacob's chronology of timing of economic change in Britain lets her down. Her claims for science and steam are perfectly plausible for the so-called Second Industrial Revolution of the later nineteenth century, but they carry far less conviction for the period before 1830 or 1840.

7. Stretching the Evidence

FKE's case for applied science is weakened by a propensity to spread evidence too thin or else, occasionally, to misread it. Thus it makes much of episodes involving members of the House of Lords interrogating canal builders in engineering language in 1769. These episodes, which Jacob has already discussed repeatedly elsewhere (1987: 240-2; 1997: 203-5), are recycled seven times here (pp. 8, 13, 23, 56, 133, 222, 224). Nor is the evidence as clear-cut as claimed. While some nobles with a financial interest in the proposed canals asked very technical questions—on which presumably they were closely briefed—most found it hard to concentrate and were reluctant to

attend the hearings (Schofield 1982: 270-71). More telling is the low quality of some of the expert witnesses brought in to criticize a canal project designed by England's foremost engineer, and the easy ride given to 'engineers generally' by lawyers for whom engineering mechanics was a foreign language (Schofield 1982: 265, 268).

Another example is Jacob's use of a letter from one 'Mr. Clark', uncovered in a Belgian archive. This again is invoked repeatedly in *FKE* (at least nine mentions) to underpin broader points about science's role in industry. Clark's letter from his base in Mons, dated 6 Messidor Year XII (25 June 1804, *not* 1812 as claimed), describes an attempt at raising capital to produce an improved mule spindle under the trade name of 'Clark's Mathematical Spindles, for muslin &c.' At that point Clark was manufacturing spindles and carding cylinders; his local partners had invested a modest seventy guineas in 'steel, grinding stones, bellows, and other tools'.

Nothing further is revealed in *FKE* about Clark beyond what is in the letter—not even his given name. But a little sleuthing reveals that he was far from being the 'lone' mechanic (p. 133) that Jacob imagines him to be. Indeed David Clark's career spanned England (where he had gone bankrupt twice), Ireland (where he managed a new spinning mill in Malahide outside Dublin in the early 1780s)¹⁶, Paris (c. 1800-4), and Belgium (where in 1804 he began the business mentioned above in Hyon, next to the city walls of Mons, and where he disappears from view in the late 1810s). Clark, a serial entrepreneur, was involved in various partnerships in the Mons area and was in

¹⁶ *Minutes of the evidence taken before a committee of the House of Commons, ... to whom the bill for repealing the duties on tobacco and snuff... ; was committed.* London, 1789, pp. 208-10; Aspin 2010.

close contact with other expatriate Englishmen on the make.¹⁷ Given his long experience, he must have been a competent mechanic but there are no grounds whatever for inferring from his ‘mathematical spindles’ that he was familiar with ‘mathematics... and the applied science of mechanics’ (p. 16).

Several other readings of the literature are questionable. Jacob refers to London porters who were proficient in algebra (p. 154), and to clockmakers being key players in machine making (pp. 15, 90). But Gillian Cookson, whose authoritative research on the West Riding machine-making industry Jacob mentions but otherwise ignores, is at pains to de-emphasize the role of clockmakers (1994: 51ff), and Cookson’s overall assessment, that ‘most significant technological progress was achieved in a workshop rather than in a laboratory, by machine-makers who apparently had little or no exposure to scientific books or any education in science’ flies directly in the face of *FKE*. Finally, few economic historians will take seriously Jacob’s assertion that ‘by

¹⁷ The ‘Kennion’ mentioned in the letter presumably refers to William Kenyon and Sons, proprietors of a cable-manufacturing plant in Armentières, northern France). Farrar and Mather (apparently Clark’s brother-in-law), also mentioned, are listed in Chassagne (1991). Jacob’s proneness to stretch her evidence too far produces a ‘howler’: she misreads Clark’s proposal to employ prison labor as a source of energy for his determination to pay workers (‘offenders’) as little as possible (p. 16):

I do not well understand the word of Maison de force (*i.e.* prison: CÓG) but if it imploys (=implies) this—to make their offenders to work, and that there will be very little to pay in[?], I then could make a simple machine, so that 12 or 18 men may go slowly round, and they being relieved each hour, so by this means the stones will be turned—but their price of wages must determine that, as soon as I know it.

That is a far cry from ‘mathematical spindles’.

European standards most English hand workers and their families lived at best at a subsistence level precisely in the period when industrialization began in earnest (p. 65, emphasis added). On the contrary, most will be convinced by Allen's demonstration that on the eve of the Industrial Revolution unskilled male workers in Britain earned three to four times a 'barebones subsistence' wage.¹⁸

8. Conclusion:

Human capital indeed mattered, as Margaret Jacob claims. The big increase in the quality of English literacy and numeracy during the century or so leading up to the Industrial Revolution—reflected not just in book publishing and newspaper circulation, but in increased familiarity with 'counting, classifying, cataloguing' (Mokyr 2009: 43)—was an important ingredient of the Baconian program that she champions. But between the 1760s and the 1830s—the period of the Industrial Revolution—that human capital resided mainly in the skills, dexterity, and occasional genius of Britain's craftsmen and artisans-made-good, not in sophisticated 'mechanics in the Newtonian tradition' (pp. 221, 222).¹⁹ It accounted for the relatively high wages of such workers, and it rested mainly on their mechanical ingenuity and on what they learned by doing. In the meantime, England's endowment of science-based knowledge was growing, but only during the so-called 'second' Industrial Revolution, when steam and coal occupied center-stage, would the sort of human capital

¹⁸ Allen 2001, 2009: 33-42. And Kelly and Ó Gráda (2013) have argued that the nutritional value of their diet was commensurate.

¹⁹ McCloskey (2010: 355-65; 2014: 439) has repeatedly articulated this point.

championed by Jacob come into its own. The 'supreme self-confidence' (p. 106) that Jacob attributes to Manchester manufacturers refers to the 1850s, not the 1780s.

A key feature of the Enlightenment was its faith in progress. Ironically, its optimism was not shared by a majority of economists during the Industrial Revolution. The dismal scientists emphasized instead the limited prospects for technological change, particularly in agriculture, and the power of the 'principle of population' to keep down wages. The utopian optimism of William Godwin and the Marquis de Condorcet famously fuelled Malthus's *Essay on Population*. And, indeed, as noted earlier, growth rates during the Industrial Revolution were modest.

Yet Mokyr has persuasively emphasized another important aspect of the Enlightenment that classical economics embraced, but on which Jacob says little: its role as a force against rent seeking and monopoly. When Mokyr (2010) claims that 'enlightenment ideas... created the prosperity that we enjoy today' he is referring not just to the spread of 'useful knowledge', but also to a political philosophy that stood for freedom of expression and an end to mercantilist restrictions on trade. But while the likes of Adam Smith and David Hume favored competition and free trade, Matthew Boulton lobbied against the free export of buckle-chapes and brass in the 1760s and the emigration of skilled workmen in the 1780s. And while in 1786 Josiah Wedgewood was a vociferous opponent of Pitt's 'Commercial Propositions', which would have gained Irish manufacturers freer access to the British market (Uglow 2002: 62, 391-2), when it came to trade with France, Jacob's hero Boulton was all in favor of bartering 'our buttons... for pipes of champagne' (Roll 1930: 139). Boulton's and Wedgewood's commercial interests always trumped broader Enlightenment principles.

BIBLIOGRAPHY:

- Allen, Robert C. 2001. "The great divergence in European wages and prices from the middle ages to the first world war." *Explorations in Economic History* 38: 411-47.
- Allen, Robert C. 2009. *The Industrial Revolution in Global Perspective*. Oxford: Oxford University Press.
- Ashton, T. H. 1948. *The Industrial Revolution*. London: Oxford University Press.
- Aspin, Christopher. 2010. *The Unfortunate Philanthropists: A History of the Cotton Trade in Ireland*. Helmsore: Helmsore Local Historical Society.
- Bailey, F. and T. C. Barker. 1969. "The seventeenth-century origins of watch-making in south-west Lancashire." In J. R. Harris, ed. *Liverpool and Merseyside*. London: Cass.
- Becker, Sascha, Eric Hornung, and Ludiger Woessmann. 2011. "Education and catchup in the Industrial Revolution." *American Economic Journal: Macroeconomics* 3(3), 92-126.
- Ben-Atar, Doron. 1995. "Alexander Hamilton's alternative: technology piracy and the report on manufactures." *William & Mary Quarterly* 52(3): 389-414.
- Bensimon, Fabrice. 2011. "British workers in France, 1815-1848." *Past & Present* No. 213: 147-89.
- Berg, Maxine, Joel Mokyr, Larry Stewart, Liliane Hilaire-Perez, and Kristine Bruland. 2007. "Reflections on Joel Mokyr's *The Gifts of Athena*," *History of Science* 45[2]: 125-96.
- Broadberry, Stephen, Bruce Campbell, Alexander Klein, Mark Overton, and Bas van Leeuwen. 2014. *British GDP ca. 1270-1870*. Cambridge: Cambridge University Press, forthcoming.
- Cantrell, John, and Gillian Cookson, eds. 2002. *Henry Maudslay and the Pioneers of the Machine Age*. Stroud, Gloucs.: Tempus Publishing.
- Cardwell, Donald S. L. 1965. "Power Technologies and the Advance of Science, 1700-1825." *Technology and Culture*, 6(2): 188-207.
- Cardwell, D. S. L. 1970. "Review of *The Lunar Society of Birmingham*". *English Historical Review*, 85(334): 185.
- Cardwell, D. S. L. 1972. *The Organisation of Science in Britain* 2nd ed. London: Heinemann.
- Chaloner, W. H. 1960. "Isaac Wilkinson, pot founder." In Lionel Pressnell, ed. *Studies in the Industrial Revolution Presented to T. S. Ashton*. London: Athlone Press, pp. 23-

Chassagne, Serge. 1991. *Le coton et ses patrons: France, 1760-1840*. Paris: Editions de l'EHESS.

Clark, Gregory. 2007. "The Long March of History: Farm Wages, Population, and Economic Growth, England 1209-1869." *Economic History Review* 60(1): 97-135.

Clark, Gregory. 2014. "The Industrial Revolution." In Philippe Aghion and Steven Durlauf, eds. *Handbook of Economic Growth*, vol. 2 <<http://old.econ.ucdavis.edu/faculty/gclark/papers/HEG%20-%20ofinal%20draft.pdf>>.

Coley, N.G. 2000. "The shape of the British chemical industry." In Colin A. Russell, ed. *A New History of the British Chemical Industry* Cambridge: Royal Society of Chemistry, pp. 13-42.

Cookson, Gillian. 1994. "The West Yorkshire textile engineering industry, 1780-1850." Unpublished D.Phil. thesis. University of York.

Cookson, Gillian. 1996. "Millwrights, clockmakers and the origins of textile machine-making in Yorkshire." *Textile History*, 27(1): 43-57.

Cookson, Gillian. 2004. "Murray, Matthew (1765-1826)." *Oxford Dictionary of National Biography*, Oxford: Oxford University Press [<http://www.oxforddnb.com/view/article/19641>, accessed 15 July 2014].

Crafts, N. F. R. 2004. "Steam as a general purpose technology: a growth accounting perspective." *Economic Journal*. 114 [no. 495]: 338-51.

Crafts, N. F. R. and C. K. Harley. 1995. "Cotton textiles and industrial output during the Industrial Revolution." *Economic History Review*, 48[1]: 134-144.

Crouzet, François. 1985. *The First Industrialists: the Problem of Origins*. Cambridge : Cambridge University Press.

Crouzet, François. 2003. "The historiography of French economic growth in the nineteenth century." *Economic History Review*, 56(2): 215-242.

Crowston, Clare H. 2005. «L'apprentissage hors des corporations. Les formations professionnelles alternatives a Paris sous l'ancien régime.» *Annales HSS*, 60(2) : 409-41.

Crowston, Clare H. 2007. "From school to workshop: pre-training and apprenticeship in old regime France." In Bert de Munck, Hugo Soly and Steven L. Kaplan, eds. *Learning on the Shop Floor*, New York and Oxford: Berghahn Books.

Darnton, Robert. 1979. *The Business of Enlightenment: a Publishing History of the Encyclopédie, 1775-1800*. Cambridge, Mass.: Harvard University Press.

Dutton, Harry I. 1984. *The Patent System and Inventive Activity during the Industrial Revolution*. Manchester: Manchester University Press.

- Edwards, Ryan D. 2008. "Declining mortality of British scientists during enlightenment." *Population and Development Review* 34S: 103-25.
- Fishlow, Albert, 1961. "The trustee savings banks, 1817–1861." *Journal of Economic History*, 21(1): 26-40.
- Fitton, R.S. and A.P. Wadsworth. 1958. *The Strutts and the Arkwrights 1758-1830*. Manchester: Manchester University Press.
- Galor, Oded and Omer Moav. 2004. "From physical to human capital accumulation: inequality and the process of development." *Review of Economic Studies* 71(4): 1001-26.
- Hall, A. Rupert. 1974. "What did the Industrial Revolution in Britain owe to science." In Neil McKendrick, ed., *Historical Perspectives: Studies in English Thought and Society in Honour of J.H. Plumb*. London: Europa Publications: 129-151.
- Hardie, D.W.F. 1966. "Review of Robert Schofield, *The Lunar Society of Birmingham*." *Business History* 8: 73-74.
- Harley, C.K. 1993. "Reassessing the Industrial Revolution." In Joel Mokyr, ed. *The Economics of the Industrial Revolution* Totowa, N.J.: Rowan & Allenfeld.
- Harris, John R. 1997. *Industrial Espionage and Technology Transfer: Britain and France in the Eighteenth Century*. Aldershot: Ashgate.
- Hey, David. 2004. "Huntsman, Benjamin (1704–1776)." *Oxford Dictionary of National Biography*, Oxford University Press, 2004; online edn, Oct 2008 [http://www.oxforddnb.com/view/article/14247, accessed 4 Aug 2014]
- Hobsbawm, Eric. 1996. *The Age of Revolution: the Birth of the Industrial Revolution* (originally published in 1962) New York: Vintage Books.
- Hobsbawm, Eric. 1999. *Industry and Empire* (originally published in 1968). London: Penguin.
- Honeyman, Katrina. 1982. *Origins of Enterprise: Business Leadership in the Industrial Revolution*. Manchester: Manchester University Press.
- Humphries, Jane. 2003. 'English apprenticeship: a neglected factor in the first industrial revolution', in Paul David and Mark Thomas, eds. *Economic Challenges of the Twenty-First Century in Historical Perspective: Celebrating the Scholarly Career of Charles H. Feinstein*, British Academy, pp. 73–102.
- Inkster, Ian. 1976. "Science and the Mechanics' Institutes, 1820–1850: The Case of Sheffield." *Annals of Science*, 32: 451–74.
- Jacob, Margaret C. 1981. *The Radical Enlightenment: Pantheists, Freemasons and Republicans*. London: Allen & Unwin.

Jacob, Margaret C. 1987. *The Cultural Meaning of the Scientific Revolution*. New York: Alfred Knopf.

Jacob, Margaret C. 1997. *Scientific Culture and the Making of the Industrial West*. Oxford: Oxford University Press.

Jacob, Margaret C. 2007. "Mechanical science on the factory floor: the Industrial Revolution in Leeds." *History of Science* 45(2): 197-222.

Jacob, Margaret C. 2014. *The First Knowledge Economy: Human Capital and the European Economy, 1750-1850*. Cambridge: Cambridge University Press.

Jeremy, David J. 1973. "British Textile Technology Transmission to the United States: The Philadelphia Region Experience, 1770-1820." *Business History Review* 47(1): 27-52.

Johansson, Sheila Ryan. 2010. "Medics, monarchs, and mortality: origins of the knowledge-driven health transition in Europe" <available at:http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1661453>

Jones, Peter M. 2009. *Industrial Enlightenment: Science, Technology and Culture in Birmingham and the West Midlands 1760-1820* Manchester: Manchester University Press.

Kanefsky, John. 1979a. "The diffusion of power technology in British industry." Unpublished PhD dissertation. Exeter University.

Kanefsky, John. 1979b. "Motive power in British industry and the accuracy of the 1870 factory return," *Economic History Review*, XXXII 360-75.

Kanefsky, John and John Robey. 1980. "Steam Engines in 18th-Century Britain: A Quantitative Assessment", *Technology and Culture*, 21: 161-186.

Kaplan, Steven L. 1993. «L'apprentissage au XVIIIe siècle: le cas de Paris.» *Revue d'histoire modern et contemporaine*, 40[3]: 436-479.

Kelly, Morgan and C. Ó Gráda. 2013. "Numerare est Errare: Agriculture Output and Food Supply before and during the Industrial Revolution." *Journal of Economic History*, 73[4]: 1132-1163.

Kelly, Morgan and C. Ó Gráda. 2014. "Watch-making: a Case-study of Productivity Change before the Industrial Revolution." UCD Centre for Economic Research Working Paper No. 2014/12.

Kelly, Morgan, Joel Mokyr, and C. Ó Gráda. 2014. "Precocious Albion: Human Capital and the Industrial Revolution." *Annual Reviews of Economics* 6.

Kennedy, John. 1831. "A Brief Memoir of Samuel Crompton." *Memoirs of the Literary and Philosophical Society of Manchester*, ser. 2, vol. 5: 318-45 [http://books.google.ie/books?id=xAZ_56mG2-4C&pg=PA318&lpq#v=onepage&q&f=false].

Kindleberger, Charles P. 1964. *Economic Growth in France and Britain, 1851-1950*. Cambridge, Mass.: Harvard University Press.

McCloskey, D. N. "The Industrial Revolution 1780-1860: a Survey." In Roderick Floud and D. N. McCloskey, eds. *The Economic History of Britain since 1700: 1. 1700-1860*. Cambridge: Cambridge University Press, pp. 103-27.

McCloskey, Deirdre. 2010. *Bourgeois Dignity: Why Economics Can't Explain the Modern World*. Chicago: University of Chicago Press.

———. 2014. "The Treasured Bourgeoisie: How Markets and Improvement Became Virtuous, 1600-1848, and Then Suspect." Unpublished ms.

McLeod, Christine. 1988. *Inventing the Industrial Revolution: the English Patent System, 1660-1800*. Cambridge: Cambridge University Press.

MacLeod, Christine. 2009. "Patents for Invention? Setting the Stage for the British Industrial Revolution?" *Empiria: Revista de metodología de ciencias sociales* 18: 37-58.

Heroes of Invention: Technology, Liberalism and British Identity, 1750-1914. Cambridge: Cambridge University Press.

MacLeod, Christine and Alessandro Nuvolari. 2006. "The Pitfalls of Prosopography: Inventors in the "Dictionary of National Biography." *Technology and Culture*, 47(4): 757-776.

MacLeod, Christine and Alessandro Nuvolari. 2011. *Patents and Industrialisation: an Historical Overview of the British Case, 1624-1907*. London: UK Intellectual Property Office <<http://www.ipo.gov.uk/ipresearch-pindustrial-201011.pdf>: accessed 10 January 2014>.

Mathias, Peter. 1972. "Who Unbound Prometheus?" In Peter Mathias, ed., *Science and Society 1600-1900*. Cambridge: Cambridge University Press.

Mathias, Peter. 1975. "Skills and the diffusion of innovations from Britain in the eighteenth century." *Transactions of the Royal Historical Society*, 25: 93-113.

Mathias, Peter. 1976. *The Transformation of England: Essays in the Economic and Social History of England in the Eighteenth Century*. London: Routledge.

Meisenzahl, Ralph and Joel Mokyr. 2012. "The Rate and Direction of Invention during the Industrial Revolution: Incentives and Institutions." In Josh Lerner and Scott Stern, eds. *The Rate and Direction of Inventive Activity Revisited*. Chicago: University of Chicago Press, pp. 443-79 [<http://www.nber.org/chapters/c12364.pdf>].

Minns, Chris and Patrick Wallis. 2012. "Rules and Reality: Quantifying the Practice of Apprenticeship in Premodern England." *Economic History Review*, 65 (2): 556-579.

- Mokyr, Joel. 1976. *Industrialization in the Low Countries 1795-1850*. New Haven: Yale University Press.
- Mokyr, Joel. 2000. "The Industrial Revolution and the Netherlands: Why did it not Happen?" *De Economist* 148 (4): 503-520.
- Mokyr, Joel. 2002. *The Gift of Athena: Historical Origins of the Knowledge Economy*. Princeton: Princeton University Press.
- Mokyr, Joel. 2009. *The Enlightened Economy: An Economic History of Britain 1700-1850*. New Haven: Yale University Press.
- Mokyr, Joel. 2010. "Enlightened and Enriched. *City Journal*." 20[3]: http://www.city-journal.org/2010/20_3_enlightenment-ideas.html
- Moser, Petra. 2012. "Innovation without Patents: Evidence from World's Fairs." *Journal of Law and Economics* 55(1): 43-74.
- Musson, Albert E. and Eric Robinson. 1969. *Science and Technology in the Industrial Revolution*. Manchester: Manchester University Press.
- Nuvolari, Alessandro, Bart Verspagen, and Nick von Tunzelman. 2011. "The Early Diffusion of the Steam Engine in Britain: a Reappraisal." *Cliometrica* 5: 291-321.
- Nuvolari, Alessandro and Mattia Ricci. 2013. "Economic Growth in England, 1250-1850: Some New Estimates using a Demand Side Approach." *Rivista di StoriaEconomica* 29: 31-53.
- Razzell, Peter. 2014. 'Mortality, Population Growth and Economic Development in England, 1600- 1850.' Unpublished.
- Roll, Eric. 1930. *An Early Experiment in Industrial Organization: History of the Firm of Boulton and Watt 1775-1805*. London: Cass.
- Samuel, Raphael. 1977. "Workshop of the world: steam power and hand technology in mid-Victorian Britain." *History Workshop Journal* 3: 6-72.
- Schofield, R. B. 1982. "The promotion of the Cromford canal act of 1789: a study in canal engineering." *Bulletin of the John Rylands Library* 64(2): 246-78.
- Smith, Adam. 1976 [first published in 1776]. *An Inquiry into the Nature and Causes of the Wealth of Nations*. Oxford: Oxford University Press.
- Solar, Peter M. 2013. "Opening the East: Shipping between Europe and Asia, 1770-1830." *Journal of Economic History* 73(3): 625-661.
- Tann, Jennifer. 1974. "The Textile Millwright in the Early Industrial Revolution." *Textile History* 5: 80-89.
- Thirsk, Joan. 1985. 'Agricultural Innovations and their Diffusion' in J. Thirsk, ed. *The*

Agrarian History of England and Wales, vol. 5[II], Cambridge: Cambridge University Press, pp. 533-89.

Tylecote, Mabel Phythian. 1957. *The Mechanics' Institutes of Lancashire and Yorkshire Before 1851*. Manchester: Manchester University Press.

Uglow, Jenny. 2002. *The Lunar Men: The Friends who Made the Future*. London: Faber & Faber.

Van der Beek, Karine. 2014. "England's eighteenth century demand for high-quality workmanship: evidence from apprenticeship, 1710-1770". In John Nye, Avner Greif, and Lynne Kiesling, eds. *Institutions, Industrialization, and Innovation*. Princeton: Princeton University Press.

Von Tunzelmann, G. N. 1978. *Steam Power and British Industrialization Until 1860*. Cambridge: Cambridge University Press.

Wengenroth, Ulrich. 2000. "Science, technology, and industry in the 19th century". Münchner Zentrum für Wissenschafts- und Technikgeschichte, working paper [available at: http://www.mzwtg.mwn.tum.de/fileadmin/woobmt/www/Arbeitspapiere/Wengenroth_sci-tech-ind-19c.pdf].

Wrigley, E. Anthony. 2010. *Energy and the English Industrial Revolution*. Cambridge: Cambridge University Press.

Young, Arthur. 1771. *A Six Months Tour through the North of England*. 4 vols. London: Strahan.