NBER WORKING PAPER SERIES

THE RATE AND DIRECTION OF INVENTION IN THE BRITISH INDUSTRIAL REVOLUTION: INCENTIVES AND INSTITUTIONS

Ralf Meisenzahl
Joel Mokyr

Working Paper 16993
http://www.nber.org/papers/w16993

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
April 2011

Prepared for the 50th anniversary conference in honor of The Rate and Direction of Inventive Activity, ed. Scott Stern and Joshua Lerner. The authors acknowledge financial support from the Kauffman Foundation and the superb research assistance of Alexandru Rus. The opinions expressed are those of the authors and do not necessarily reflect views of the Board of Governors of the Federal Reserve System or those of the National Bureau of Economic Research.

The Rate and Direction of Invention in the British Industrial Revolution: Incentives and Institutions
Ralf Meisenzahl and Joel Mokyr
NBER Working Paper No. 16993
April 2011
JEL No. N13,N73,O31,O34,O43

ABSTRACT

During the Industrial Revolution technological progress and innovation became the main drivers of economic growth. But why was Britain the technological leader? We argue that one hitherto little recognized British advantage was the supply of highly skilled, mechanically able craftsmen who were able to adapt, implement, improve, and tweak new technologies and who provided the micro inventions necessary to make macro inventions highly productive and remunerative. Using a sample of 759 of these mechanics and engineers, we study the incentives and institutions that facilitated the high rate of inventive activity during the Industrial Revolution. First, apprenticeship was the dominant form of skill formation. Formal education played only a minor role. Second, many skilled workmen relied on secrecy and first-mover advantages to reap the benefits of their innovations. Over 40 percent of the sample here never took out a patent. Third, skilled workmen in Britain often published their work and engaged in debates over contemporary technological and social questions. In short, they were affected by the Enlightenment culture. Finally, patterns differ for the textile sector; therefore, any inferences from textiles about the whole economy are likely to be misleading.

Ralf Meisenzahl
Board of Governors of the Federal Reserve System
20th Street and Constitution Ave NW - MS 153
Washington, DC 20551
Ralf.R.Meisenzahl@frb.gov

Joel Mokyr
Department of Economics
Northwestern University
2003 Sheridan Road
Evanston, IL 60208
j-mokyr@northwestern.edu

Introduction.

The Industrial Revolution was the first period in which technological progress and innovation became major factors in economic growth. There is by now general agreement that during the seventy years or so traditionally associated with the Industrial Revolution, there was little economic growth as traditionally measured in Britain, but that in large part this was to be expected.[1] The sectors in which technological progress occurred grew at a rapid rate, but they were small in 1760, and thus their effect on growth was limited at first (Mokyr 1998, pp. 12-14). Yet progress took place in a wide range of industries and activities, not *just* in cotton and steam. A full description of the range of activities in which innovation took place or was at least attempted cannot be provided here, but inventions in some pivotal industries such as iron and mechanical engineering had backward linkages in many more traditional industries. In the words of McCloskey (1981, p. 118), "the Industrial Revolution was neither the age of steam, nor the age of cotton, nor the age of iron. It was the age of progress." A similar point has been made by Temin (1997).

Outside the familiar tales of cotton textiles, wrought iron, and steam power, there were improvements in many aspects of production, such as mechanical and civil engineering, food processing, brewing, paper, glass, cement, mining, and shipbuilding. Some of the more famous advances of the time may have had a negligible direct effect on growth rates, but improved the quality of life in other ways; one thinks above all of smallpox inoculation and vaccination, the mining safety lamp, hot air and hydrogen balloons, food canning, and gas lighting (Mokyr, 1990, 2009a). Britain was the world leader in innovation for a period of about a century, after which its

---

[1] The main explanations for the low level of income per capita growth during the decades of the Industrial Revolution are the unprecedented rate of population growth in this period, as well as the incidence of bad weather and war.

dominance slowly dissolved. Yet Britain retained a place as one of many western nations that collaborated in a joint program to apply a rapidly growing knowledge base to economic production.

What drove British leadership, and why was Britain the most technologically advanced economy in the world for so long? The question has been attacked many times, and with many different answers.[2] In the spirit of this volume, it seems to make sense to make a distinction between the rate of technological progress and its direction, which have often been confused in the literature. In his recent influential work, Allen (2009a, 2009b) has resurrected induced innovation theory and re-emphasized the role of factor prices in generating the inventions that formed the Industrial Revolution. Yet the high wages that Allen emphasized may have imparted a labor-saving direction on the innovations, but it is hard to use them to explain the "engine of growth" which is the growing body of useful knowledge and its ever-greater accessibility in the eighteenth century. As an alternative many scholars, led by Wrigley (2004, 2010) have emphasized the importance of the availability of coal in Britain; this may explain a bias toward fuel-intensive and perhaps the replacement of water- and animal-powered plants by steam-driven ones. Yet the improvements in coal technology point to the fact that coal production itself was subject to deeper forces.[3] Moreover, the progress in water power technology in the eighteenth century indicates that even without coal, energy-saving technological progress was feasible, and even that without coal Britain would have had experienced an Industrial Revolution, albeit one that would have a somewhat different dynamic (Clark and Jacks, 2007).

---

[2] For a slightly dated survey, see Mokyr (1998, pp. 28-81). Recent contributions focus on institutions (North and Weingast, 1989; Mokyr, 2008; Acemoglu and Robinson, 2010), and the roles of factor prices and coal discussed below.

[3] Two examples should suffice: the pathbreaking work in using stratigraphic data to locate coal (Manchester, 2001) and the "miner's friend" invented by Humphry Davy (James, 2005).

In what follows, we will take a closer look at one particular aspect: the importance of technological competence and the incentives of those people who were the practical carriers of technological progress in this era.[4] Competence is defined here as the high-quality workmanship and materials needed to implement an innovation, that is, to follow the blueprint with a high level of accuracy, carry out the instructions embodied in the technique, and to have the ability to install, operate, adapt, and repair the machinery and equipment under a variety of circumstances. Beyond those, competence often involved minor improvements and refinements of a technique, which may not have qualified as a "microinvention" stricto sensu, but clearly enhanced the innovative effort in economy.[5] In principle, it is easy to see that there are deep complementarities between the small group of people who actually invent things and can be identified as such, and the somewhat larger group of skilled workmen who possessed the training and natural dexterity to actually carry out the "instructions" contained in the new recipes and blueprints that inventors wrote with a high degree of accuracy, build the parts on a routine basis with very low degrees of tolerance, and still could fill in the blanks when the instructions were inevitably incomplete.[6] We argue that of Britain's industrial precocity owed a great deal to the high level of competence of those engineers and mechanics who provided the support for the inventors.

But who were they? Identifying competence falls somewhere the two extremes of either

---

[4] In his contribution to the 1962 *Rate and Direction* volume, Fritz Machlup (1962) discussed at some length the concept of "inventive labor." Part of our purpose is to unpack that term into those "inventive workers" who are truly innovative, and those who fill in the gaps and improve the original insights whom we refer to as tweakers. While the context here is historical, there is little doubt that this concept can readily be extended to our own time.

[5] In this paper we will be little concerned with truly epochal or *macro*inventions.

[6] In another paper in the original volume, John Enos (1962) distinguishes between the "alpha" stage (the original invention) and the "beta" stage (improvement). This parallels our distinction. His finding is that most of the productivity growth in the petroleum refining industry occurred during the beta stage (p. 319).

studying a handful of heroic inventors whose names are well known, and searching for variables that measure the overall national level of some critical input such as human capital or the supply of entrepreneurship in the population. Neither of those is satisfactory. Modern economic history has long ago distanced itself from the heroic hagiographies in which the Industrial Revolution was attributed to the genius of a few superstar inventors. On the other hand, it may seriously be doubted whether the *average* level of education of the laboring class (say, the bottom two thirds of the income distribution) made much difference to the outcome (Mitch, 1998).

Moreover, did Britain have a comparative advantage in macroinventions such as steampower and cotton spinning? While Britain did have a large number of "hall of fame" inventors, it was equally able to adopt inventions made overseas. It may be surmised that Britain may have had an absolute advantage in macroinventions, its *comparative* advantage was in smaller improvements and competence — as illustrated by the large number of highly skilled technicians that Britain "exported" to the Continent. At the same time a flow of substantial continental inventions found their first applications in Britain, presumably because other factors, complementary with the innovations, were present in larger quantities.[7] But what were these complementarities? Britain provided a freer market, and overall may have had an institutional environment that was more conducive to innovation. But its human capital advantage in the form of skilled workmen is the one element that has not been sufficiently stressed.

We may distinguish between three levels of activity that drove innovation in this period. One were the macroinventions and other major breakthroughs that solved a major bottleneck and opened

---

[7] Among the better-known of these inventions were the Robert continuous paper-making machine, the Jacquard loom, Berthollet's bleaching process, Leblanc's soda-making process, Lebon's gaslighting technique, De Girard's spinning machine for linen yarn, Friedrich Koenig's steam-driven printer, Appert's invention of food canning, and the Argand lamp.

a new door.[8] We will refer to these inventors as major inventors, and they are, by and large, the ones that made it into economic history textbooks. Another was the myriad of small and medium cumulative microinventions that improved and debugged existing inventions, adapted them to new uses, and combined them in new applications. The people engaged in those will be referred to as *tweakers* in the sense that they improved and debugged an existing invention. Some of the more important advances among those may have been worth patenting, but clearly this was not uniformly the case. A third group, and perhaps the least recognized of Britain's advantages, was the existence of a substantial number of skilled workmen capable of building, installing, operating, and maintaining new and complex equipment. The skills needed for pure implementers were substantial, but they did not have to be creative themselves. We will refer to these as *implementers*. It goes without saying that the line between tweakers and implementers is blurry, but at the very least a patent or some prize for innovation would be a clear signal of creativity.

Some of the greatest technical minds of the Industrial Revolution clearly were good at all three, but the vast majority of highly skilled mechanics did not invent much that posterity remembers.[9] It has been argued that artisans alone, without the help of any "great inventors," could have generated much of the technological progress of the period simply by incrementally improving

---

[8] We will use a somewhat wider definition for these major inventions than the one in Mokyr (1990a), which defines macroinventions in terms of their epistemic innovativeness and effect on the marginal product of further improvements. Here even inventions that were not dramatic new insights but had a major impact on the economy, such as the mule and the puddling and rolling process would be classified as such.

[9] A notable exception was the Dartmouth blacksmith Thomas Newcomen, who in the phrase of a recent author was "the first (or very nearly) and clearly the most important member of a tribe of a very particular, and historically original, type: the English artisan-engineer-entrepreneur" (Rosen, 2010, p. 40).

and adapting existing technology.[10] Yet sophisticated artisanal economies had thrived in Europe since the late middle ages, and there was no reason for them to be delayed to the second half of the eighteenth century if they had been capable of generating an Industrial Revolution by themselves. At the same time, "great inventors" without the support of high-quality competence, were equally doomed to create economically meaningless curiosa (of which Leonardo's myriad inventions are just one example).

The strong complementarity between the three forms of technological activity is critical to the understanding of the question of "why Britain." A nation that possessed a high level of technical competence could successfully implement major inventions wherever made. The economic success of inventors depended, among other things, on their ability to find tweakers to get the bugs out of the invention, and implementers to construct, install and operate it. To quote a famous example, James Watt, the paradigmatic "heroic" inventor depended for his success not only on the ability of John Wilkinson to bore the cylinders for his machine with great accuracy, but also some of his brilliant employees such as William Murdoch (Griffiths, 1992) as well as highly competent engineers such as John Southern and James Lawson (Roll, 1930, pp. 260–61).[11] Their ability to build and maintain equipment embodying new technology inevitably spilled over to small adaptations and adjustments that would have to be regarded as minor incremental innovations.

---

[10] Hilaire-Pérez (2007) and Berg (2007) believe that "an economy of imitation" could lead to a self-sustaining process of improvement, driven purely by artisans. Such sequences of microinventions, without any shifts in the technological paradigm, were doomed to bog down into diminishing returns.

[11] Some of the unsung heroes of the Industrial Revolution were these less-known tweakers. Thus Josias C. Gamble (1775–1848), an Irishman trained in Glasgow, was essential to James Muspratt's introduction of the Leblanc process in Britain (Musson and Robinson, 1969, p. 187); a variety of mechanics, such as William Horrocks of Stockport and many others who improved upon Cartwright's powerloom (Marsden, 1895, pp. 70-72); William Woollat was Jedediah Strutt's brother in law and helped him develop a mechanized stocking frame that could make ribbed hosiery (Fitton and Wadsworth, 1958, p. 24).

The emphasis on mechanical skills and dexterity has major implications for the assessment of the role of human capital in the British Industrial Revolution. The group to focus on is not so much the few dozens or so major inventors and scientists that can be denoted as “great inventors”(Khan, 2006), nor should we concentrate on the human capital of the mass of factory workers, many of whom were still poorly educated and illiterate as late as 1850. Instead the focus ought to be the top 3-5 percent of the labor force in terms of skills: engineers, mechanics, millwrights, chemists, clock- and instrument makers, skilled carpenters and metal workers, wheelwrights, and similar workmen. Their numbers were in the tens of thousands, and the vast bulk of them are impossible to trace. Many of them were independent artisans and entrepreneurs; others were in the employ of others. A considerable number were both or switched from one to the other. But we shall make an effort to find at least the best-known of them, although survival bias here is impossible to avoid and we can make no presumption that those who end up in our sample are representative.

Skills and Competence

What evidence is there to support Britain’s advantage in tweakers and implementers? In a famous letter to his partner, John Roebuck, James Watt wrote in 1765 that “my principal hindrance in erecting engines is always smith-work” (Smiles, 1874, p. 92) and he had considerable difficulty finding “workmen capable of fitting together the parts of a machine so complicated and of so novel a construction” (id. p. 196; see also Roll, [1930], 1968, p. 61). Yet, while competence was thus a binding constraint, Watt‘s engines, and those of many other machine-builders did get built and were of high quality.[12] Foreign observers, perhaps more than local writers (who took Britain's superiority for granted) noted the comparatively high level of *competence* of British skilled workmen.[13] The flows of the kind of useful knowledge associated with workmanship are quite unambiguous. Industrial spies from the Continent converged on Britain to study the fine details of British engineering and iron-making (Harris, 1998), and British technicians, mechanics, and skilled workmen left the country in droves to find employment in France, Germany, Belgium, as well as Eastern Europe, and this despite the fact that such emigration was prohibited by law until 1824 and that a state of war existed between Britain and many of these countries for most of the years between 1780 and 1815 (Harris, 1998; Henderson, 1954). It is telling, for example that one of the best-known eighteenth century engineering migrants to the Continent, John Holker (1719–1786), made his career when he moved a number of highly skilled Lancashire workmen to the embryonic cotton industry in Rouen after which he rose to the position of "inspector-general of foreign manufactures" in 1756. His mandate in that job was, among others, to recruit more British workers.[14] After 1815, the number

---

[12] A typical description of a competent British worker was provided by the engineer William Fairbairn in a book first published in 1863 "The millwright of former days was to a great extent the sole representative of mechanical art ... a kind of jack of all trades who could with equal facility work at a lathe, the anvil, or the carpenter's bench... a fair arithmetician who could calculate the velocities, strength and power of machines...Such was the character and condition of the men who designed and carried out most of the mechanical work of this country up to the middle and end of the last century" (Fairbairn, 1871, p. ix-x).

[13] A Swiss visitor, César de Saussure noticed in 1727 that "English workmen are everywhere renowned, and justly. They work to perfection, and though not inventive, are capable of improving and of finishing most admirably what the French and Germans have invented" (de Saussure, [c. 1727], 1902, p. 218, letter dated May 29, 1727). Josiah Tucker, a keen contemporary observer, pointed out in 1758 that "the Number of Workmen [in Britain] and their greater Experience excite the higher Emulation, and cause them to excel the Mechanics of other Countries in these Sorts of Manufactures" (Tucker, 1758, p. 26). The French political economist Jean-Baptiste Say noted in 1803 that "the enormous wealth of Britain is less owing to her own advances in scientific acquirements, high as she ranks in that department, as to the wonderful practical skills of her adventurers [entrepreneurs] in the useful application of knowledge and the superiority of her workmen" (Say [1803], 1821, Vol. 1, pp. 32–33).

[14] His colleague Michael Alcock modernized the famed St. Etienne ironworks in France in the 1760s with the help of skilled workmen that his wife had recruited in England. A third striking case of such migration is that of William Wilkinson, the brother of the famous Broseley ironmonger, who was charged with setting up cannon foundries and blast furnaces, at an astronomical salary of 60,000 livres per year.

of British engineers and mechanics that swarmed all over the Continent increased, including especially in such early industrializers as Belgium and Switzerland. The most famous family here were William Cockerill and his sons, who set up the most successful machine-toll manufacturing plant in continental Europe in Verviers in eastern Belgium (Mokyr, 1976).[15] The same was true in civil engineering. The first permanent bridge across the Danube connecting Buda and Pest was commenced in 1839 under the engineering control of William Tierney Clark. At the same time, highly original and creative minds from the European Continent found their way to Britain, in search of an environment in which their inventions could be exploited and the complementary skills that made the development of their inventions possible.[16]

On the supply side, Britain's apprenticeship system worked exceptionally well in producing highly skilled workers that could serve as implementers, despite (or perhaps because) of the weakness of British guilds (Humphries, 2003).[17] The Statue of Artificers of 1563, which regulated apprenticeship, did not cover many mechanical occupations and its regulations were often ignored (Wallis, 2008). All this contributed to labor markets that on the eve of the Industrial Revolution were more flexible and less encumbered than on the Continent.

---

[15] As late as 1840, a British official informed a Parliamentary Committee that in the cotton mills in the Vienna area "the directors and foremen are chiefly Englishmen or Scotsmen from the cotton manufactories of Glasgow and Manchester" (Henderson, 1954, p. 196). In countries with even less supplies of local skilled workmen, the importance of foreigners was even more important; much of the iron used to build St. Petersburg's famed bridges came from a local ironworks managed by Charles Baird (1766–1843), working with his son and his nephew.

[16] The Swiss inventor Aimé Argand, designed a new oil-burning lamp but his attempts to build and sell it in Paris failed. He went to Britain in the 1780s, where he sought and found the help of the great entrepreneur Matthew Boulton; sadly, commercial fortune eluded him here as well. More luck had the Saxon Rudolph Ackermann (1764– 1834), who arrived in London in 1787 to make major contributions to the technology of coachmaking and lithography and whose firm survived until 1992.

[17] The relative weakness of the guilds was in part the result of the declining power of their traditional ally, the monarchy. Second, guilds were an urban phenomenon, yet some crucial mechanical occupations such as mining engineers emerged on the countryside. Last, industry had the continuous option to produce on the countryside which also weakened the power of the urban guilds.

The fact that millwrights were entirely produced through the apprenticeship system highlights its importance for the formation of skill and competence in Britain. In a recent paper, Karine van der Beek (2010) has shown that in the period 1710-1772 at least, the English system produced larger numbers of apprentices in high-skilled occupations, especially in machinery-building and precision instruments, and that this took place in the industrializing midlands, where the demand for such skills was highest. At the same time the relative tuition paid to masters in high skill occupations did not increase in the long run, indicating that the apprenticeship system was sufficiently flexible to supply enough competent craftsmen . Much of the competence of these skilled workers still was in the nature of tacit knowledge, which could not be learned only from books and articles but required hands-on instruction and personal experience. The degree of tacitness varied from industry to industry, but was especially marked in the iron industry (Harris, 1988, 1992).[18] Yet whether tacit or not, there can be little doubt that this strength of Britain played a central role in its success. Its skilled workers, freed from enforceable labor market restrictions, often moved from area to area, diversifying their human capital portfolios and at the same time enhancing innovation by applying ideas from one field to another, a kind of technological hybridizing.[19]

At the top of the pyramid emerged a small group of professional inventors, the kind of person of whom Smith wrote his famous lines that inventions were often made by "men of speculation, whose trade is not to do anything but to observe everything" ([1776], 1976, p. 14). Some of the great

---

[18] The puddlers, an expertise that emerged quickly after Henry Cort's pathbreaking invention in 1785 were, in the words of one scholar trained "by doing, not by talking, and developed a taciturnity that lasted all their life" (Gale, 1961–62, p. 9).

[19] Reflecting on the supply of the craftsmen he employed , Watt noted in 1794 that many of them had been trained in analogous skills "such as millwrights, architects and surveyors," with the practical skills and dexterity spilling over from occupation to occupation (cited by Jones, 2008, p. 126–27).

inventors of the Industrial Revolution, such as Crompton, Cartwright, Smeaton, and Harrison should be seen as full-time inventors, although their mechanical abilities probably exceeded their knowledge of "experimental philosophy." Others were educated part-timers who dabbled in invention and engineering; some of those were scientists such as Humphry Davy and Joseph Priestley, but gifted and obsessed amateurs also made considerable contributions.[20] Smith's inventive philosophers would, however, have had no effect on the economy had there been no dexterous and ingenious workmen to carry out and improve their designs.

How were these individuals incentivized? Britain, of course, had a patent system, which has been discussed at length in the literature (Mokyr, 2009b) and to which we will return below. But there were other ways in which ingenuity was rewarded. One was the awarding of prizes, set either ex ante for someone who solved a known problem, or ex post for someone whose contribution was widely recognized but who was not able to reap the rewards. The Society of Arts (f. 1754) set clear targets, such as machines that would encourage the manufacture of lace, to reduce both the dependence on French imports and encourage the employment of women (Griffiths, Hunt, and O'Brien, 1992, p. 886). These premiums were set in advance, yet the condition for their award was that no patent was taken out. In other cases, the Society awarded medals to inventors who had little interest in taking out patents (e.g., the engineer and educational writer Richard Lovell Edgeworth, who won numerous medals). It clearly provided an alternative model to the patent system (Harrison, 2006). In a few notable cases, Parliament stepped in and awarded grants or pensions to inventors

---

[20] Thus Patrick Miller (1731–1815), a wealthy Scottish banker, was a pioneer in the mechanical propulsion of boats and one of the first to experiment with steam power on a vessel, yet this was obviously more of a hobby than a serious occupation (although Miller did take out a patent on a shallow-draft vessel). Another famous amateur inventor (at least in the sense of not being motivated by financial gain) was Charles Earl of Stanhope (1753–1816), a radical member of the House of Lords who also made notable contributions to the technology of early steamship design and whose improved printing press was purchased by *The Times* and Oxford University Press.

of considerable merit. For others, especially those who were in business for themselves, a major form of reward was what we would call today "first-mover" advantage: by producing goods and services that were just a little better and more reliable or cheaper than their competitors', they could make an excellent living.

Many of the most successful innovators in the Industrial Revolution were thus incentivized by multiple mechanisms: although in many cases they relied on patents or secrecy to protect the rent-generating intellectual property rights, as often they placed their knowledge in the public domain and relied on superior technology or competence. The reality on the ground was, however, that it is in many cases impractical to distinguish between those who lived off their reputation as consultants or employees and those who were in business for themselves. In the course of a career, many mechanics and engineers switched back and forth from entrepreneurial activity and self employment to hired employees.[21]

Beyond the standard economic notions of incentives, the rate and direction of technological progress during the Industrial Revolution were affected by a *Zeitgeist* that may be termed a *mechanical culture*, in which science and chemistry found their way to the shopfloor where entrepreneurs and engineers tried to apply them in their stubborn attempts to achieve "improvements" (Jacob, 2007). Mechanical culture was part and parcel of the Industrial Enlightenment. It implied that many of the efforts to improve machinery fed on a culture that placed technological questions at the center of the social agenda. The second half of the eighteenth century

---

[21] One well-known example is the Scottish engineer Peter Ewart (1767–1842), who worked for a time for Boulton and Watt, then went into business with Samuel Oldknow and Samuel Greg, then opened his own mill in 1811, and eventually ended up employed by the admiralty. His colleague, William Brunton (1777–1851) was also employed in Boulton and Watt's Soho work, which he left in 1808 to take another employment. Eventually he became a partner at a iron foundry in Birmingham and then moved to London where he practiced as an independent civil engineer.

witnessed the maturing of the Baconian Program, which postulated that useful knowledge was the key to social improvement. In that culture, technological progress could thrive. The signs of that culture were everywhere: in which books and articles were published, in what people discussed in coffeehouses and pubs, in the establishment of scientific clubs and societies, and through all of them what happened in the workshops and factories. None of this is to deny that economic incentives were central to the story, just that they were neither "everything" nor "the only thing." The best-known people affected by this culture were the famous enlightened industrialists such as Josiah Wedgwood, Matthew Boulton, Benjamin Gott, Richard Crawshay, John Kennedy, and John Marshall. Their commitment to the culture of improvement through the application of useful knowledge to issues in manufacturing are paradigmatic examples of the Industrial Enlightenment (Jones, 2008). Economic motives were not always central to the men who made the Industrial Revolution.[22] Those who came from science, such as Davy and Faraday were probably close to the Frenchman Berthollet, the inventor of the chlorine bleaching process, who famously wrote that "When one loves science, one has little need for fortune which would only risk one's happiness" (cited by Musson and Robinson, 1969, p. 266). But did this culture "filter down" to the layer of lesser known people in the layer just below them?

In what follows, we try to build a database not so much of "superstar inventors" but of the

---

[22] A rather striking example of this is the case of Samuel Crompton, the inventor of the mule, arguably the most productive invention of the Industrial Revolution. It was said of him that he was "or a retiring and unambitious disposition," and hence he took out no patent on his invention. His only regret was that public curiosity would "not allow him to enjoy his little invention in his garret" and to earn undisturbed the fruits of his ingenuity and perseverance (Baines, 1835, p. 199). Yet even Crompton had to make ends meet and in the end appealed to Parliament for a reward for having made an invention that so palpably benefitted the realm. In 1812 Parliament awarded him £ 5,000, which he subsequently lost in a failed business venture (Farnie, 2004). Another, much less famous, example is that of the Scottish plowmaker James Small (1740-1793) who redesigned the all-iron plow according to formal principles and wrote the standard text on plow design. Small insisted that this knowledge be made generally available and declined to take out a patent. He enjoyed the patronage of the two great Scottish agricultural innovators, Lord Kames and John Sinclair. His workshop in Berwickshire produced fine plows, though they were not universally popular.

layer of technically competent individuals just below them: the engineers, mechanics, chemists, and skilled craftsmen who improved and implemented the inventions of the more famous men. We show how these "tweakers" were trained, what incentives drove them (that is, how they made their living), and how deeply they were immersed in the intellectual life of the Industrial Enlightenment.

Database

Our main purpose is to shed light on the technological environment that bred technological success and innovation in the British Industrial Revolution. Rather than focus primarily on "great inventors," our argument concentrates on "competence" — that is, we look for the persons whose dexterity and training allowed them to tweak and implement the new techniques. To be in the sample, they had to have made some inventions themselves (the bulk of them would be microinventions and adaptations), but their main activity was implementation. It would be futile to distinguish between inventors and pure non-inventors in a strict sense, simply because the process of innovation consists of both the new technique *and* its implementation, and during the implementation process inevitably problems are resolved and the technique is tweaked and adapted to the particular needs of the user. Most inventors spent much of their lives working on existing techniques that they or others had generated.

It must be stressed that this kind of project inevitably runs into a "tip-of-the-iceberg" problem. We have no illusions that the bulk of competent technicians who determined both rate and the direction of the Industrial Revolution in Britain simply did not leave enough of a record to become known to posterity.[23] To leave a record, an individual had to do something more than just be a competent and productive employee or artisan. The argument we make is one of continuity: if we can uncover some of the layer of competent workers below the superstars, we may be able to say something about what motivated these people and how they interacted with their institutional, and cultural environments.

We are interested in the "classical" Industrial Revolution and so we use primarily sources that focus on activities before 1860. To this end we have constructed a prosopographical database that is composed of men (there is one woman in the sample), born before 1830, of a technical ability that was sufficient to make it into the literature (we excluded all persons whose role was purely entrepreneurial or commercial). We are interested in tweakers, engineers and mechanics who made minor improvements on existing inventions. Hence for them to have taken out a patent is a sufficient condition to be included in the sample, but so would a mention of any kind of some innovation, invention, or improvement of existing technology. However, only a small subset of persons listed as having taken out any sort of patent before 1850 are included, because the majority of patentees left no other record. Our sample, then, consists of what we judge to have been successful careers at the cutting edge of technology: engineers, chemists, mechanics, clock- and instrument makers, printers, and so on.

One source is the collection of biographies of British engineers put together by Skempton et al (2002). It is quite detailed, and many of the essays are written by experts, but because it is focused on engineers, it is biased toward road- and canal builders, contractors, architects, surveyors,

---

[23] Moreover, the population of known inventors consists mostly of the population of successful inventors — it stands to reason that many of the engineers and mechanics also made additional efforts in that direction that either failed, or for which they failed to receive credit. Some "failed" inventions, such as the Stirling engine, invented by clergyman Robert Stirling in 1816, have become famous, but the vast bulk of such failures will remain unknown.

military engineers and similar occupations. While it covers some mechanical engineers, they clearly were not the main interest of the editors.[24] It leaves out many areas, most notably chemicals, paper, glass, food processing, and by and large textiles. It hence needs to be complemented with other sources. Two other biographical compendia were used. One is Day and McNeil (1996), with high-quality essays but with fairly thin coverage for Britain, since it is international in coverage. There are the various biographical studies carried out by Samuel Smiles (1865, 1884, 1889), which, despite their hagiographic character, contain a lot of useful information about minor players as well. A number of recently compiled online databases, overlapping to some extent with Skempton and Day-McNeil were also used.[25] Finally, economic historians have carried out considerably detailed studies of a number of industries that have produced information on many relatively minor actors in the history of technological advances in the Industrial Revolution. Among the most notable and useful of these studies, we should mention Turner (1998) and Morrison-Low (2007) on scientific instruments; Burnley (1889), Heaton (1965), and Jenkins and Ponting (1982) on wool; Barlow (1878) and Chapman (1967; 1972; 1981) on textiles; Barker and Harris (1954) on paper, glass and chemical industries; Marshall (1978) on railroad engineers.[26] All entries were cross-checked and complemented with information from the Oxford *Dictionary of National Biography*.[27] To ensure the accuracy of the number of patents, we verified the information in the bibliographies with the

---

[24] The article on instrument maker Henry Maudslay is a page and a half, while that on civil engineer John Rennie is over fourteen pages and William Jessop is nine pages.

[25] These are: http://www.steamindex.com/people/engrs.htm; http://www.steamindex.com/people/civils.htm; http://www.steamindex.com/manlocos/manulist.htm

[26] The database was augmented with information from Crouzet (1985), Henderson (1954), Honeyman (1983), Marsden (1895), Rimmer (1965), Sussman (2009), and Thorton (1959).

[27] The DNB provides a high level of detail for some individuals, but as pointed out by MacLeod and Nuvolari (2006), there is considerable selection bias in the DNB.

“Alphabetical index of patentees of inventions” by Woodcroft (1854), which includes all patents in Great Britain until the reform of the patent system in 1851.

We include people born between 1660 and 1830. For each individual we have recorded beside the name and dates of birth and death, information about their education, their occupation, what inventions and innovation they made, what rewards and pay they received, patents they took out, publications, whether they were managers, employees, and/or self-employed (with or without partners), membership in societies, and a variety of other details and remarks recorded in the respective sources. Entries with unknown birthdates contain information when the person flourished (fl.). We subtract 30 years from this date to calculate the date of birth.

Our database consists of 759 entries: 758 men and Elenor Coade, who invented a new process for making artificial stone, and who is the only woman included in the database. We assigned a sector to each individual by his main area of activity, which in some cases was difficult because a large number of our tweakers were polymaths who applied their ability in many distinct areas of activity and contributed materially to more than one sector. Hence 35 entries were assigned to two different sectors with weight 1/2, hence the fractions in Table 1.

Table 1: Tweaker-and-implementer database, descriptive statistics

Sector \ Period	Pre-1700	1700-1749	1750-1774	1775-1799	1800- 1814	1815-1830	Sector Total
Textiles	2.0	39.0	41.0	42.0	45.0	24.0	**193.0**
Ships	1.0	3.0	7.5	7.5	6.0	2.0	**27.0**
Road & Rail & Can	2.0	2.0	11.5	26.5	24.5	23.0	**89.5**
Other Eng	11.0	19.0	32.5	44.0	27.0	14.5	**148.0**
Med & Chem	1.0	6.0	6.0	10.0	3.0	3.5	**29.5**
Instruments	8.0	26.0	12.0	27.0	12.0	5.5	**90.5**
Iron & Met	4.0	13.0	11.0	11.5	7.0	4.5	**51.0**
Mining	2.0	3.0	8.0	9.5	3.0	0.0	**25.5**
Agr & Farm	2.0	7.0	2.5	4.5	3.0	2.0	**21.0**
Constr	0.0	10.0	11.5	15.5	5.0	0.0	**42.0**
Print & Photo	0.0	4.0	4.5	6.5	2.5	2.0	**19.5**
Others	1.0	6.0	5.0	3.5	4.0	3.0	**22.5**
Period Total	**34.0**	**138.0**	**153.0**	**208.0**	**142.0**	**84.0**	**759.0**
% of Total	***4.5%***	***18.2%***	***20.2%***	***27.4%***	***18.7%***	***11.1%***	

Table 1 displays the main descriptive statistics of the sample by birth-year and sector. The number of persons included (per annum) peaks in the 1800-14 period, but this is largely because many of those born in the fifteen years after 1815 were active in the second half of the nineteenth century and much of what they did would not be included in many of our sources. The table reflects the rise to prominence of the textile industry in the eighteenth century, yet it also warns that even at its peak this industry did not involve more than a third of all tweakers, and for the sample as a whole they are slightly under a quarter of the "modern" (that is, technologically advanced) economy. Transportation and "other" engineering together were larger than textiles, and many other sectors were important areas for technological creativity.

Results

Training: One important question is the training and education of highly skilled artisans. If our argument that Britain's advantage on other European countries derived primarily from its cadres of skilled and creative tweakers, how should we explain that? How was this human capital created and how were these artisans incentivized? The origins of the highly skilled labor force in Britain have been discussed elsewhere, and need only briefly stated here (Mokyr, 2009a). On the demand side, Britain had sectors that generated a need for a high level of skills, above all coal mining which spawned the steam engine as well as the railroad (Cardwell, 1972, p. 74).[28] It had, for a variety of reasons, a high number of clock- and instrument makers, optical craftsmen, millwrights, and workers involved in shipbuilding and rigging. The origins of this group of high-skill workers were at least in part due to geography; but the pre-existence of a substantial British middle class with a demand for luxury goods meant a considerable market for consumer durables that required a high degree of precision and skill, such as watches, telescopes, and musical instruments. Finally, Britain was the beneficiary of the migration of Huguenots after 1685 and thus its more tolerant institutions can be seen to have paid off. All the same, the main reason for the high levels of skills in this economy were the effectiveness of its education system embedded in flexible labor markets. While the record of British schools and universities was decidedly mixed, skills were produced in the personal sphere of master-apprentice relation, where British institutions performed remarkably well (Humphries, 2003; Mokyr, 2009a).

The 759 persons in our sample confirm, as far as can be ascertained, this interpretation. Two thirds of those whose educational background could be established were apprenticed. This share is

---

[28] Almost all the engineers who worked on the development of a locomotive from 1803 to 1830 were originally employed in the mining sector.

the highest in textiles, but the share of those about whom we do not know their educational background is *highest* in textiles. Clearly this is the sector in which any kind of education mattered the least, largely because the mechanical issues, while often subtle and delicate, required little formal learning and success was often the result of a combination of dexterity, luck, perseverance, and focus.[29] On the other hand, a quarter of our tweakers with known background had attended University; many of these were upper class youngsters, some of whom turned into improving landlords or the kind of amateur inventors such as Lord Stanhope mentioned above. It may be safely surmised that little of what they learned in English universities was of much help furthering their technical competence, although the same was probably not true for Scottish universities. Engineers, whether in shipbuilding, railroads, canals, or mining usually apprenticed and/or attended a university. The same can be said about instrument makers. The consistency of the high proportion of tweakers classified as engineers or instrument makers who were apprenticed leaves no doubt that this mode of skills-transmission was the dominant form of human capital accumulation of the age. Interestingly enough, the famous Statute of Apprentices and Artificers that mandated such training was repealed in 1814, but the percentages of men born after 1800 who acquired their skills in this fashion did not change and remained at about two-thirds of the entire sample of tweakers with known educational background. As a comparison of panels A and B of Table 2 shows, there is little evidence that the role of formal education changed a lot in the training of the British technological elite: the share of people with known training who attended universities fell from 27 to 24 percent and those who only attended school only rose from 12 to 13 percent.

---

[29] The two best-known inventors of the industry, Richard Arkwright and Edmund Cartwright were trained as a wigmaker and a clergyman respectively. But many others, insofar as we know their background, came from other sectors. Henry Houldsworth (b. 1796), the inventor of compound gear in powerlooms, was trained as a grocer. Jedediah Strutt, one of the early partners of Richard Arkwright, was trained as a wheelwright; his son of Jedediah (a successful tweaker in his own right) had a wide-ranging education and among others was active as a successful architect.

Table 2-A: Sample breakdown by education, individuals born before 1800

Sector \ Education	Apprenticed	*% of Sector Total*	Schooled	*% of Sector Total*	University	*% of Sector Total*	None / Unknown	*% of Sector Total*	Sector Total
Textiles	19.5	*16%*	5.0	*4%*	1.5	*1%*	100.5	*81%*	**124.0**
Ships	10.0	*53%*	1.0	*5%*	5.5	*29%*	3.5	*18%*	**19.0**
Road & Rail & Can	19.0	*45%*	4.0	*10%*	7.0	*17%*	13.0	*31%*	**42.0**
Other Eng	42.0	*39%*	6.5	*6%*	22.5	*21%*	39.5	*37%*	**106.5**
Med & Chem	9.0	*39%*	2.0	*9%*	8.0	*35%*	5.0	*22%*	**23.0**
Instruments	38.0	*52%*	4.5	*6%*	15.5	*21%*	17.0	*23%*	**73.0**
Iron & Met	17.0	*43%*	4.5	*11%*	4.0	*10%*	15.0	*38%*	**39.5**
Mining	13.0	*58%*	1.5	*7%*	3.0	*13%*	6.0	*27%*	**22.5**
Agr & Farm	3.5	*22%*	1.0	*6%*	7.0	*44%*	5.0	*31%*	**16.0**
Constr	17.0	*46%*	4.0	*11%*	2.5	*7%*	13.5	*36%*	**37.0**
Print & Photo	9.0	*60%*	1.0	*7%*	2.5	*17%*	3.5	*23%*	**15.0**
Others	5.0	*32%*	2.0	*13%*	2.0	*13%*	6.5	*42%*	**15.5**
Category Total	**202.0**	***38%***	**37.0**	***7%***	**81.0**	***15%***	**228.0**	***43%***	**533.0**

Notes:

1. Apprenticed + School + University > Known background due to overlaps

Table 2-B: Sample breakdown by education, individuals born 1800-1830

Sector \ Education	Apprenticed	*% of Sector Total*	Schooled	*% of Sector Total*	University	*% of Sector Total*	None / Unknown	*% of Sector Total*	Sector Total
Textiles	14.0	*20%*	1.0	*1%*	0.5	*1%*	54.0	*78%*	**69.0**
Ships	4.0	*50%*	2.0	*25%*	2.0	*25%*	0.0	*0%*	**8.0**
Road & Rail & Can	36.0	*76%*	3.0	*6%*	4.0	*8%*	6.5	*14%*	**47.5**
Other Eng	25.5	*61%*	5.0	*12%*	9.0	*22%*	5.5	*13%*	**41.5**
Med & Chem	1.5	*23%*	1.0	*15%*	4.0	*62%*	0.0	*0%*	**6.5**
Instruments	6.0	*34%*	2.0	*11%*	6.0	*34%*	5.0	*29%*	**17.5**
Iron & Met	4.5	*39%*	2.0	*17%*	4.0	*35%*	1.0	*9%*	**11.5**
Mining	1.0	*33%*	0.0	*0%*	0.0	*0%*	2.0	*67%*	**3.0**
Agr & Farm	0.5	*10%*	0.0	*0%*	1.0	*20%*	3.5	*70%*	**5.0**
Constr	1.5	*30%*	1.0	*20%*	2.0	*40%*	0.5	*10%*	**5.0**
Print & Photo	1.5	*33%*	0.0	*0%*	2.5	*56%*	1.0	*22%*	**4.5**
Others	5.0	*71%*	2.0	*29%*	0.0	*0%*	2.0	*29%*	**7.0**
Category Total	**101.0**	***45%***	**19.0**	***8%***	**35.0**	***15%***	**81.0**	***36%***	**226.0**

Notes:

1. Apprenticed + School + University > Known background due to overlaps

The apprenticeship system clearly figured highly in the creation of British competence. The modes of cultural transmission, as so often happens, can be seen in the creation of “dynasties” in which technical knowledge was passed on along vertical lines. Some famous father-and-son dynasties, such as the Darby’s, the Stephensons, and the Brunels are widely known. But there were many others.[30] Of the dynasties of master-apprentices, the best-known is the Bramah-Maudsley-Nasmyth one. Especially among coal viewers, a highly skilled and specialized branch of mining engineering, such dynasties were common: John Blenkinsop (1783-1831) was trained by Thomas Barnes (1765-1801), who himself was trained by an (unknown) viewer.

Incentives. How were these members of Britain's technological elite incentivized? There were essentially four different mechanisms through which these men were compensated: intellectual property rights in their knowledge; first mover advantage by independent businesses; reputation effects leading to permanent employment; and non-pecuniary rewards. We shall discuss those in turn.

Intellectual Property Rights. A standard argument in the literature has been that the patent system in Britain provided the most effective incentive toward invention. This view is not just found in the writings of modern institutionalists such as Douglass North (1981) but also in many of contemporary writers, many of them hugely influential such as Adam Smith and Goethe.[31] But the high cost of

---

[30] Among them the microscope-makers George Adams Sr. and Jr. active in the second half of the eighteenth century; John Rastrick (1738-1826) and his son John Urpeth Rastrick (1780-1856), both civil engineers; the hugely inventive and versatile engineer Bryan Donkin ((1768–1855) and his son and later partner John (1802–1854); the engineers William (1762-1834) and James (1795-1862) Sims.

[31] Goethe wrote that the British patent system's great merit was that it turned invention into a "real possession, and thereby avoids all annoying disputes concerning the honor due" (cited in Klemm, 1964, p. 173). Some modern economic historians have agreed with him, however (North and Thomas, 1973, p. 156). In his Lectures on Jurisprudence ([1757], 1978), pp. 11, 83, 472), Adam Smith argued that intellectual property rights were "actually real rights" and admitted that the patent system was the one monopoly (or "priviledge" as he called it) he could live with,

patenting in Britain before the patent reform of 1851 assured that most of the smaller inventions (and many of the larger ones) were not patented (MacLeod, 1988; Griffiths, Hunt and O'Brien, 1992; Mokyr, 2009b). Many inventors, especially those who were trained as scientists, were averse to the monopolistic nature of patent rights and felt that useful knowledge should be shared and that access to it and the use of it should not be limited in any way. Others were more ambivalent and circumspect about the patent system and patented some of their inventions while conspicuously failing to patent others.[32]

Given that complete patent records exist, we were able to to check how many of our sample took out patents at all. As Table 3 indicates, for the entire period 40 percent of our tweakers never took out a patent. The interpretation of this table is rather tricky: all we can tell is that a person in our sample took out a particular patent. As Dutton (1984), MacLeod (1988) and many others have pointed out, there were major differences in the propensities to patent between different sectors, for a variety of reasons.[33] Textiles turn out to be a high-patenting sector, in part perhaps because reverse engineering was fairly easy. In fact, "one thing that all these textile machines have in common is that they satisfy Bacon's criterion for a certain kind of invention: they incorporated no principles,

---

because it left the decision on the merit of an invention to the market rather than to officials.

[32] For a number of inventors this is well-known. For example William Murdoch, who took out three patents for minor advances but failed to patent more important inventions. Henry Maudslay, one the great mechanical engineers of his age, had six patents to his name but did not patent his micrometer or any screw cutting invention for which he was famous. Among lesser-known people, a striking example is William Froude (1810-1879), a ship designer and inventor of the helicoidal skew arch bridge on ships, yet his only patent is a railroad valve patented in 1848; John Benjamin MacNeill (1792-1880) a road engineer who worked for Telford, and took out three patents but failed to patent his best invention, which was an instrument to be drawn along roads, to indicate their state of repair by monitoring the deflections produced by irregularities in the road surface

[33] One reason was the likely payoff. The ratio between alternative means of cashing in on an invention relative to patenting was one consideration. The cost of issuing a patent before 1851 was very substantial and may simply have been unaffordable or simply unlikely to be covered by the returns relative to keeping the invention details secret. The likelihood of a patent being upheld in court also differed substantially by sector. However, in some sectors - especially engineering - the culture of the profession was quite hostile to the patent system.

materials or processes that would have puzzled Archimedes" (Cardwell 1994, pp. 185-86). Even without extensive mechanical knowledge improvements could be made and especially in cotton small changes in the production process led to huge improvements in the product's quality.[34] Hence the payoff of inventing and patenting in textiles was perceived to be high. The propensity of patenting in textiles was also higher because constructing and improving textiles machinery required different but not necessarily sophisticated mechanical skills. The textiles sector therefore attracted relatively fewer people much associated with science who had been much affected with the "open-source" scientific culture that viewed knowledge to be a public good and objected to patenting as a matter of principle. As a result, only 19 percent of all tweakers active primarily in textiles never took out a single patent, compared to 40 percent for the economy as a whole.[35] Most of our tweakers are fairly minor players in the patent game, and so of the people who patented at all, 83 percent patented fewer than 5 inventions. All the same, our sample does include 78 individuals who had six or more patents to their name. Some of these may have been "professional inventors" but others simply were in a position to take advantage of the patent system.

None of this implies that patenting was a particularly successful ex post strategy. Securing a patent even on an economic viable invention did not ensure economic success. Patents were frequently challenged, infringed, or voided. In our data, even individuals who took out patents for some inventions failed to do so for others, and the patents they took out, especially before 1830, proved to provide little protection against infringers and challengers - especially if the invention

---

[34] Different findings for textiles are not only observed for Britain, the technological leader, but also for technological followers. Becker, Hornung, and Woessmann (2009), studying the impact of literacy on technology adaption in Prussia - a technological follower, find that literacy foster industrialization in all sectors but textiles. The authors argue that the incremental nature of technological change in textiles leads to more sector-specific knowledge that cannot be acquired through formal education.

[35] As a consequence, studies that see the textile industry as a typical Industrial Revolution sector in terms of its intellectual property rights development such as Griffiths, Hunt and O'Brien (1992) are likely to be misleading.

proved profitable.[36] Judges were often unsympathetic to patentees, reflecting to a large extent the suspiciousness of the age of anything that reeked of monopoly. Tales of inventors ruined by patent suits at this time are legion, and it is reasonable to surmise that given their cost, the mean rate of return may have been negative.[37] One might then legitimately ask why people kept applying for patents, and a number of replies can be given, among them the "lottery effect" (a small number of

Table 3: Patentees breakdown, by sector (number of patents issued)

Sector \ Patents issued	**0**	***% of Sector Total***	**1**	***% of Sector Total***	**2-5**	***% of Sector Total***	**6-10**	***% of Sector Total***	**10+**	***% of Sector Total***	**Sector Total**
Textiles	37.0	*19%*	64.0	*33%*	71.0	*37%*	9.0	*5%*	12.0	*6%*	**193.0**
Ships	8.0	*30%*	9.0	*33%*	7.5	*28%*	2.5	*9%*	0.0	*0%*	**27.0**
Road & Rail & Can	50.0	*56%*	17.5	*20%*	16.5	*18%*	4.0	*4%*	1.5	*2%*	**89.5**
Other Eng	57.0	*39%*	32.0	*22%*	29.5	*20%*	20.0	*14%*	9.5	*6%*	**148.0**
Med & Chem	12.0	*41%*	11.0	*37%*	4.5	*15%*	0.0	*0%*	2.0	*7%*	**29.5**
Instruments	59.0	*65%*	16.0	*18%*	12.0	*13%*	0.5	*1%*	3.0	*3%*	**90.5**
Iron & Met	15.0	*29%*	11.5	*23%*	20.5	*40%*	2.0	*4%*	2.0	*4%*	**51.0**
Mining	15.0	*59%*	7.0	*27%*	2.5	*10%*	1.0	*4%*	0.0	*0%*	**25.5**
Agr & Farm	10.0	*48%*	5.5	*26%*	4.5	*21%*	1.0	*5%*	0.0	*0%*	**21.0**
Constr	27.5	*65%*	6.5	*15%*	5.5	*13%*	1.0	*2%*	1.5	*4%*	**42.0**
Print & Photo	7.5	*38%*	2.0	*10%*	4.5	*23%*	2.0	*10%*	3.5	*18%*	**19.5**
Others	6.0	*27%*	10.0	*44%*	6.5	*29%*	0.0	*0%*	0.0	*0%*	**22.5**
Category Total	304.0	*40%*	192.0	*25%*	185.0	*24%*	43.0	*6%*	35.0	*5%*	**759.0**

---

[36] Thus the Scottish inventor George Meikle, son of the inventor of the threshing machine, took out a patent for a "scutching machine" (with his father) but the patent was repeatedly challenged and infringed upon and eventually abandoned. Nathaniel Worsdell (1809-1886) patented a device to sort mailbags in 1838, but the Post Office introduced a competing device that infringed on his invention; Worsdell refused to sue because his Quaker beliefs would not permit it (Birse, 2004).

[37] John Kay, the inventor of the "flying shuttle" was effectively ruined trying to defend his patents. Disillusioned he moved to France in 1747 after failing to maintain patents right in England. Similarly, Henry Fourdrinier's continuous papermaking machine was shamelessly copied and he could never recover the £60,000 he and his brother had spent on the innovation. To circumvent infringement, James Beaumont Neilson (1792–1865), the inventor of the hot blast in iron manufacture (1829), issued licenses at 1 shilling per ton. Neilson and his partners hoped to make the patent remunerative, but sell it at a fee low enough to prevent widespread evasion or attacks on the patent's validity. Nevertheless the patent was disputed.

highly visible successful patents may have created a false ex ante belief that they were more profitable than they were in reality) and a “signaling effect” (inventors took out patents to indicate to would-be financiers that their invention was worthwhile and secure) (Mokyr, 2009b). Interestingly enough, British society realized how imperfect the patent was, and some of the big inventors who, for some reason, did not patent or whose patent failed, were compensated by Parliament or by grateful colleagues. But such grants were awarded to technological superstars, not to tweakers who made a minor improvement.

Secrecy was a viable alternative to patenting. Some tweakers relied on secrecy to secure a competitive advantage and to avoid costly legal battles. There was Sir Titus Salt (1803-1876) , a textiles manufacturer, who overcame problems in utilizing alpaca wool, who never patented his processes but kept them as trade secrets. This strategy made him the richest citizen in Bradford. John Braithwaite, Sr, in the business of retrieving goods from sunken shipwrecks, kept his improved diving machine, his machinery for sawing apart ships underwater, and his underwater gunpowder charges under lock and key and never took out a patent (which would have made him divulge his knowledge).[38] Joseph Gillot, a pen manufacturer and the Pen Maker to the Queen, also preferred secrecy for years before taking out patents and the masticating process — a process in the production of rubber invented by Thomas Hancock — was also never patented, but remained as a secret in the factory. For others, of course, secrecy was a risky strategy, such as the famous case of Benjamin Huntsman, the inventor of crucible steel whose secret eventually leaked out.[39]

---

[38] Of course, some patentees such as the metal manufacturer William Champion, worded their patents in as obscure a manner as possible to try to prevent infringement.

[39] Modern entrepreneurs face the same choices. Much like their counterparts during the industrial revolution, they rely on first mover advantage, secrecy, and patents to capture the competitive advantage. Graham et al. (2009), examining entrepreneurs in the high-technology sector using the 2008 Berkeley Patent Survey, show at the only sector in which entrepreneurs find patents more important than first mover advantages is Biotechnology — a sector that arguably did not exist during the Industrial Revolution. Secrecy is rated almost as important as patents.

*First-mover and reputation effects***.** Signaling quality to potential costumers and outshining the competition was crucial to ensure the economic success of the woman and men in our sample. As Table 4 shows, most of our tweakers were at least for some part of their careers self-employed: A full 385 (51 percent of our sample and 64 percent of all those whose means of livelihood could be established) were identifiable entrepreneurs and independent operators or consultants, owning or establishing a company at some point. Another 82 (11 percent) were owners at least some of their careers.[40] A respectable 18 percent were hired engineers and managers. Again, it is striking how exceptional textiles were as an industry: for a considerable number of individuals, we were unable to establish exactly the way in which they made their living. But for the entire rest of the sample, of those for whom we could establish these facts, we found that 68 percent were owners and independent contractors throughout their careers, and another 16 percent were so through part of their career. Given that only few of those had successful patents, better quality of product and services leaning on reputation effects were central to economic success.

---

[40] Some of them were successful employees who then tried to go into business for themselves; other had the reverse career and were failed entrepreneurs who then took a job with another firm.

Table 4-A: Sample breakdown by ownership status

Sector \ Reward	**Owners (full-time)**	***% of Sector Total***	**Owners (some time)**	***% of Sector Total***	**Managers (non-owners)**	***% of Sector Total***	**Employed (non-managers)**	***% of Sector Total***	**Unknown**	***% of Sector Total***	**Sector Total**
Textiles	58.5	*30%*	5.5	*3%*	3.0	*2%*	6.5	*3%*	119.5	*62%*	**193.0**
Ships	17.5	*65%*	3.5	*13%*	0.0	*0%*	5.0	*19%*	1.0	*4%*	**27.0**
Road & Rail & Can	36.0	*40%*	26.0	*29%*	21.0	*23%*	5.5	*6%*	1.0	*1%*	**89.5**
Other Eng	84.0	*57%*	19.5	*13%*	9.0	*6%*	26.0	*18%*	9.5	*6%*	**148.0**
Med & Chem	16.5	*56%*	3.0	*10%*	0.0	*0%*	8.0	*27%*	2.0	*7%*	**29.5**
Instruments	54.0	*60%*	7.0	*8%*	0.0	*0%*	17.5	*19%*	12.0	*13%*	**90.5**
Iron & Met	38.5	*75%*	4.5	*9%*	1.0	*2%*	2.0	*4%*	5.0	*10%*	**51.0**
Mining	9.5	*37%*	5.0	*20%*	4.0	*16%*	5.0	*20%*	2.0	*8%*	**25.5**
Agr & Farm	12.5	*60%*	1.0	*5%*	1.5	*7%*	1.0	*5%*	5.0	*24%*	**21.0**
Constr	30.0	*71%*	4.0	*10%*	3.0	*7%*	3.0	*7%*	2.0	*5%*	**42.0**
Print & Photo	16.5	*85%*	0.0	*0%*	0.0	*0%*	3.0	*15%*	0.0	*0%*	**19.5**
Others	11.5	*51%*	3.0	*13%*	0.5	*2%*	5.5	*24%*	2.0	*9%*	**22.5**
Category Total	**385.0**	***51%***	**82.0**	***11%***	**43.0**	***6%***	**88.0**	***12%***	**161.0**	***21%***	**759.0**

Notes:
1. "Owners (full-time)" category includes independent contractor, entrepreneur, self-employed, manager/owner with or without partner
2. "Owners (part-time)" category includes inventors that were owners and managers/employees at the same time at different companies or at different points in their lifetimes

The centrality of first-mover advantage is hard to document in a systematic way, but examples abound. In the textile industry, first-mover advantage was common: Arkwright's patent was voided, but his technological advantage was such that he died a wealthy man. Others were able to cash in on fairly minor advantages. An example can be seen in the hosiery industry, where Jedediah Strutt came up in the 1750s with a major improvement to lace made on stocking frames, subsequently improved further by the idea of the "point net." The idea of this more efficient method was conceived by one Mr. Flint, who hired a Thomas Taylor of Nottingham to build it for him, who then acquired the invention and patented it. Years later, the point net was further improved by

William Hayne, whose patent was declared invalid in 1810 (Felkin, 1867, pp. 133-41).

Table 4-B: Sample breakdown by ownership status, including partnerships

Sector	Owners (full-time)	*% of Sector Total*	Owners (part-time)	*% of Sector Total*	Partnerships	*% of Owners Total*	Sector Total
Textiles	58.5	*30%*	5.5	*3%*	55.5	*87%*	**193.0**
Ships	17.5	*65%*	3.5	*13%*	10.0	*48%*	**27.0**
Road & Rail & Can	36.0	*40%*	26.0	*29%*	25.0	*40%*	**89.5**
Other Eng	84.0	*57%*	19.5	*13%*	54.0	*52%*	**148.0**
Med & Chem	16.5	*56%*	3.0	*10%*	7.0	*36%*	**29.5**
Instruments	54.0	*60%*	7.0	*8%*	31.5	*52%*	**90.5**
Iron & Met	38.5	*75%*	4.5	*9%*	29.5	*69%*	**51.0**
Mining	9.5	*37%*	5.0	*20%*	9.0	*62%*	**25.5**
Agr & Farm	12.5	*60%*	1.0	*5%*	6.0	*44%*	**21.0**
Constr	30.0	*71%*	4.0	*10%*	11.5	*34%*	**42.0**
Print & Photo	16.5	*85%*	0.0	*0%*	8.5	*52%*	**19.5**
Others	11.5	*51%*	3.0	*13%*	9.5	*66%*	**22.5**
Category Total	**385.0**	***51%***	**82.0**	***11%***	**257.0**	***55%***	**759.0**

Many of the great clock- and instrument makers of the age, a pivotal group in the realization of the Industrial Revolution, were essentially self-employed and depended on reputation for quality and reliability.[41] John Kennedy, co-owner of M'Connel and Kennedy, one of the most successful cotton spinners in Manchester, made a number of adjustments to the fine-spinning capabilities of the mule which allowed a much higher count (finer) yarn to be spun. Kennedy never took out a patent. In 1826 Kennedy retired from one of the best-known and prosperous enterprises in the Industrial Revolution. Another striking case was that of Joseph Aspdin, the inventor of Portland cement.

---

[41] The great instrument makers of the age mostly seem to fall into that category. Thus John Bird (1709–76) supplied instruments to Greenwich Observatory as well as to the one in Stockholm. Bird established in 1745 his own workshop in London making machine tools and small mathematical instruments. He received orders to design and make large astronomical instruments for major observatories at home and abroad. Two generations after him, Robert Bretell Bate (1782-1847) was appointed optician to King George I, an honor that was renewed on the accessions of William IV and Queen Victoria; he won government contracts with a number of government agencies. By 1820, his workshop employed twenty employees (McConnell, 2004a; 2004b).

Although he did take out a patent in 1824, his advantage was relatively brief. His son, William Aspdin, was the first to invent true "Portland Cement" in the early 1840s, by discovering the necessity of clinkering (grinding the product of the cement kilns and adding gypsum) but did not patent it. William's early-mover advantage did last long because others such as Isaac Charles Johnson were following his idea on his heels. After two years, Johnson was able to develop a superior product, and yet Aspdin's advantage in time was enough to assure him financial success for a while, although in 1855 he went bankrupt and his works were sold to Johnson (Francis, 1977, pp. 116–25, 151–58).[42]

For many of our tweakers, being innovative and able to tweak technology in use, was part of the job description. Innovation meant job security for employees or new commissions for the self-employed. James Watt employed a number of highly creative engineers, most of all the ingenious William Murdoch. Railway companies expected their locomotive pool managers to invent in order to cut cost, improve the quality of transportation, and deal with excessive smoke emissions. Hence for railroad engineers like Charles Markham, who adjusted fire holes in locomotives for the use of coal, innovative activity that adapted existing techniques to specific purposes was simply taken for granted and reflected in their comfortable salaries.

Innovativeness was a strong signal of competence, and competence was what people hiring consultants wanted. Self-employed engineers such as James Brindley and John Rennie, or architects like Joseph Jopling, (who won a Society of Arts gold medal for arch construction improvements), made their living by signaling their professional competence through coming up with improvements in the techniques they used. This, too, was a function of the patent office: having taken out a patent

---

[42] Johnson, who lived from 1811 to 1911, remained a major player in the British cement industry for much of his life, and thus perhaps exemplifies the benefits of second-mover advantage.

was seen, whether correctly or not, as an official imprimatur of technological expertise.[43] Reputation for expertise resulted in new commissions for their workshops.[44] Again, it is not easy to quantify this, but professional engineers, especially civil and mechanical engineers, often worked on specific commissions and consultancies.

Some of these commissions came from the government, others from overseas, but most of them were local manufacturers and colliers who needed something specific installed or built.[45] The model for this way of organizing the engineering profession was set by the great John Smeaton, after James Watt the most influential engineer of the eighteenth century. Smeaton took out but one patent in his life, despite a vast number of inventions and improvements, but he was in huge demand as a consulting engineer, and in fact is often said to have established engineering consultancy as a formal profession. As table 4-B shows, more than half of the independent contractors and self-employed had partners (at some stage), although that proportion was especially high in textiles, iron, and mining and a bit lower elsewhere.

For the self-employed artisans and independent engineers who would be in the group of tweakers and implementers, the reward was first and foremost a reputation for competence that led to customers and commissions and in some case the patronage of a rich or powerful person. Many

---

[43] Studying the motivations for patenting of present day entrepreneurs, Graham et al. (2009) find that enhancing the company's reputation and improving chances of securing investment or additional financing are still important reasons for entrepreneurs to take out patents.

[44] It is interesting to note that for modern data hiring inventive employees seems also a good strategy to maximize the impact of innovations. Singh and Agrawal (2010) estimate (using modern US patent citation data) that when firm recruit inventors, the citation of the new recruits' prior inventions increases by more than 200 percent even if these patents are held by their previous employer. They also argue that the effect is persistent even though one might expect that the tacit knowledge of the inventor diffuses fast within a firm.

[45] Thus Bryan Donkin, a prodigiously gifted tweaker, with 11 patents to his name and a reputation to match, received commissions from the excise and stamp ofice, the East India office and none other than Charles Babbage (to estimate the cost of building his calculating machine).

of the engineers and best mechanics in the Industrial Revolution were engaged in a signaling game: in a market with imperfect information about quality, establishing a reputation for skills was a key to economic security if not perhaps to extraordinary riches. This was true for the superstar engineers in the Industrial Revolution such as John Rennie and John Smeaton, but it was equally true for lesser-known people. For many of the best mechanics and engineers reputations meant well-paying positions in good firms or tickets for commissions and contracts. Reputation and being in very high standing among one's professional peers could lead to cash awards from the government (who relied on expert opinion in making these awards). Such cash prizes were also awarded by some private societies (such as the Society of Arts, founded in 1754). These awards were often financially significant, and with any of these rewards the reputation of an inventor grew. It was also associated with peer recognition and social prestige associated with mechanical achievement to a degree never before witnessed.[46] Some engineers became technological authorities and their imprimatur could make or break the career of a young engineer. Among those authorities, John Smeaton and Thomas Telford were the towering figures during the Industrial Revolution.[47]

Not all cash prizes or medals were given for meeting specified criteria such as the famed Board of Longitude award made to John Harrison for his marine chronometer. Cash reward were

---

[46] Consider the career of Edward John Dent (1790-1853), who won a first Premium Award at the Seventh Annual Trial of Chronometers (1829) and then won the esteem of Sir George Airy, the Astronomer Royal, who recommended him as the maker of a large clock for the tower of the new Royal Exchange. Dent later enjoyed the patronage of Queen Victoria, the Royal Navy and the Czar of Russia. In 1852 he won the commission to make the Big Ben for the Houses of Parliament at Westminster, but he died before completing the project.

[47] Telford, in his design for an all-iron bridge over the Thames to replace London Bridge (which was not built), hired a young engineer named James Douglas, whose mechanical genius earned him the epithet "the Eskdale Archimedes. Douglas was a versatile engineer who had attracted the notice of the British Ambassador in the US, who paid his expenses home to England " so that his services might not be lost to his country." In 1799 it is known that Douglas worked for Telford, but then absconded to France in around 1802. Telford disapprovingly remarked that Douglas was "always too impatient for distinction and wealth, in the race for which in his country he found too many competitors."

also given to inventors in the public service like the civil engineer and road builder John Loudon McAdam, who received £6,000 from public funds for his improvements on the British road system; to Edward Jenner, for his spectacular discovery of smallpox vaccination; to Sir Francis Pettit Smith who was awarded £20,000 by the Admiralty for his screw propeller; and to William Symington who received £100 from Parliament for the first steam boat. As noted, in few cases such awards were regarded as a correction to an often-malfunctioning patent system. Sir Thomas Lombe the inventor (really importer) of mechanized silk spinning technology, was awarded £14,000 as a special dispensation in 1732 in lieu of a renewal of his patent. Of the "heroes of the Industrial Revolution," Samuel Crompton, Edmund Cartwright, and Henry Fourdrinier were among those who, after much haggling, were voted an award.

Reputation effects were often international: as noted already, many British engineers and mechanics found positions on the Continent or received commissions and assignments from overseas, as one would expect in an economy that was more richly endowed with competence than its neighbors and were often honored by them. Charles Gascoigne, the manager of the Scottish Carron ironworks in the 1760 received a lucrative commission from the Russian government in 1786; ironmaster John Wilkinson's brother William was commissioned by the French government to set up the ironworks at Le Creuzot. In the nineteenth century this process continued with renewed force. Richard Roberts, perhaps the most ingenious tweaker of his generation, was invited to help install cotton-spinning machinery in Mulhouse. William Fairbairn (1789–1874), another leading engineer and one of the pioneers of the iron-hulled ships, consulted in Turkey, Switzerland, and the Netherlands. Robert Whitehead, a ship designer who made major improvements to the design of the torpedo, started his career as a naval designer working for the Austrian government and gathered a great many foreign decorations including a French *Legion d'honneur*.

Nonpecuniary rewards Many of the cutting edge inventors and tweakers of the age professed to be uninterested in financial rewards. Economists are trained to regard such statements with suspicion, but that it is not to say that considerations other than money did not play a role. The distinction is hard to make because prizes, medals, and other distinctions operated as signals of quality and thus enhanced reputations that themselves were correlated with patronage (steady employment) or commissions. A few "cash" prizes were also to a large extent honorary, much like book prizes today. Such rewards took a variety of forms. Some associations appointed "fellows" (the Royal Academy being the primary example), others such as the Society of Arts, organized competitions and awarded medals and other distinctions for technological achievements. In Britain, of course, the highest distinction that could be awarded to someone of a working class origin was an honorary aristocratic title. Table 5 summarizes the awards earned by our sample.

The data show a considerable variation in the number of medals awarded. In textiles, medals were rare, and it seems to have been the one industry in which monetary considerations were probably more or less the main incentive.[48] The categories are overlapping, so quite a few people received more than one reward. All the same, the data show that for tweakers in fields such as civil engineering, instrument-making, construction, and to a lesser extent metallurgy, such prizes were a reality, and the probability of earning such a prize was far more likely than actually cashing in on a patent (and there was no application fee). There can be little question that, as with all such prizes,

---

[48] To be sure, nine textile engineers were elevated to an aristocratic title, which, at 5 percent, is only marginally below the overall mean of 7 percent. But these were men such as Richard Arkwright, James Oldknow, and Robert Peel, who were rewarded for a successful career as entrepreneurs.

personal connections and background played a role. Indeed, in a recent paper Khan (2010) has concluded that “In Britain the most decisive determinants for whether the inventor received a prize were which particular university he had graduated from and membership in the Royal Society of Arts, characteristics that seem to have been somewhat uncorrelated with technological productivity. Thus, rather than being calibrated to the value of the inventor’s contributions, prizes to British inventors appear to have been largely determined by noneconomic considerations.” One could, of course quibble with how to measure “technological productivity” (to say nothing of the distinction between economic and non-economic considerations). But what counts here is that the probability

Table 5-A: Cash prizes and non-pecuniary rewards, individuals born before 1800

Sector \ Reward	**Medal**	***% of Sector Total***	**Cash prize**	***% of Sector Total***	**Title**	***% of Sector Total***	**Appointment**	***% of Sector Total***	**Royal Society**	***% of Sector Total***	**Sector Total**
Textiles	3.0	*2%*	8.0	*6%*	3.0	*2%*	5.0	*4%*	2.0	*2%*	**124.0**
Ships	3.5	*18%*	5.5	*29%*	0.5	*3%*	0.5	*3%*	4.5	*24%*	**19.0**
Road & Rail & Can	1.0	*2%*	3.0	*7%*	2.0	*5%*	4.5	*11%*	5.5	*13%*	**42.0**
Other Eng	19.0	*18%*	5.5	*5%*	8.5	*8%*	11.5	*11%*	21.0	*20%*	**106.5**
Med & Chem	4.0	*17%*	2.5	*11%*	0.5	*2%*	2.5	*11%*	7.5	*33%*	**23.0**
Instruments	18.5	*25%*	11.5	*16%*	2.0	*3%*	24.0	*33%*	31.0	*42%*	**73.0**
Iron & Met	1.0	*3%*	1.0	*3%*	3.0	*8%*	3.0	*8%*	5.0	*13%*	**39.5**
Mining	2.0	*9%*	1.0	*4%*	0.0	*0%*	2.0	*9%*	3.0	*13%*	**22.5**
Agr & Farm	1.0	*6%*	2.0	*13%*	1.5	*9%*	0.0	*0%*	0.5	*3%*	**16.0**
Constr	7.5	*20%*	4.0	*11%*	1.5	*4%*	8.0	*22%*	5.0	*14%*	**37.0**
Print & Photo	1.0	*7%*	2.0	*13%*	2.0	*13%*	2.0	*13%*	3.0	*20%*	**15.0**
Others	3.5	*23%*	1.0	*6%*	1.5	*10%*	4.0	*26%*	3.0	*19%*	**15.5**
Category Total	**65.0**	***12%***	**47.0**	***9%***	**26.0**	***5%***	**67.0**	***13%***	**91.0**	***17%***	**533.0**

Table 5-B: Cash prizes and non-pecuniary rewards, individuals born 1800-1830

Sector \ Reward	**Medal**	***% of Sector Total***	**Cash prize**	***% of Sector Total***	**Title**	***% of Sector Total***	**Appointment**	***% of Sector Total***	**Royal Society**	***% of Sector Total***	**Sector Total**
Textiles	3.0	*4%*	0.5	*1%*	6.0	*9%*	3.5	*5%*	0.5	*1%*	**69.0**
Ships	1.0	*13%*	0.0	*0%*	2.0	*25%*	1.0	*13%*	2.0	*25%*	**8.0**
Road & Rail & Can	1.0	*2%*	0.0	*0%*	3.0	*6%*	5.5	*12%*	5.0	*11%*	**47.5**
Other Eng	14.0	*34%*	5.5	*13%*	8.0	*19%*	7.0	*17%*	10.5	*25%*	**41.5**
Med & Chem	2.0	*31%*	0.0	*0%*	4.0	*62%*	1.0	*15%*	3.5	*54%*	**6.5**
Instruments	7.0	*40%*	0.5	*3%*	2.5	*14%*	8.5	*49%*	3.5	*20%*	**17.5**
Iron & Met	5.0	*43%*	1.0	*9%*	3.0	*26%*	1.0	*9%*	3.0	*26%*	**11.5**
Mining	0.0	*0%*	1.0	*33%*	0.0	*0%*	0.0	*0%*	1.0	*33%*	**3.0**
Agr & Farm	1.0	*20%*	1.0	*20%*	1.0	*20%*	0.0	*0%*	1.0	*20%*	**5.0**
Constr	1.0	*20%*	0.0	*0%*	0.5	*10%*	0.5	*10%*	0.0	*0%*	**5.0**
Print & Photo	3.0	*67%*	1.0	*22%*	0.0	*0%*	1.0	*22%*	1.0	*22%*	**4.5**
Others	0.0	*0%*	0.0	*0%*	0.0	*0%*	2.0	*29%*	0.0	*0%*	**7.0**
Category Total	**38.0**	***17%***	**10.5**	***5%***	**30.0**	***13%***	**31.0**	***14%***	**31.0**	***14%***	**226.0**

of winning such a social recognition was non-zero and correlated with some achievement even if the correlation was not as high as one would wish in a perfect world. It stands to reason that in such distinctions, then as now, accomplishment and personal connections were complementary. As such, there can be little doubt that these institutions provided a considerable incentive for technically brilliant and industrious men. Networking counted too — but such networks by themselves held considerable technological advantages.

Were Tweakers Enlightened?

The Baconian program alluded to before was a product of the Enlightenment, and it emphasized the diffusion and dissemination of useful knowledge in addition to its creation (Mokyr, 2009a). That such beliefs were held by some of the leading figures of the Industrial Revolution such as Josiah Wedgwood, Matthew Boulton, and Benjamin Gott has long been known. But Robert Allen (see Allen 2009a) has questioned the degree to which such beliefs were common in the wider population of technologically relevant people. It is, of course, impossible to verify, with few exceptions, what these people believed about what they were doing. But we can see to which extent they tried to network by joining a variety of professional societies, or bring their knowledge to a wide audience by publishing. Again, such actions could be explained by other factors. Publishing, for example, served as a signal of expertise and respectability, and professional societies were social as well as professional networks.[49]

The measures are, of course, not independent. Inventions, new methods, and explanation were published in the journals edited by professional societies, such as the *Philosophical Transactions of the Royal Society* or *Transactions of the Institution of Civil Engineers*. Membership and rewards in some professional societies were granted for papers read to them. Some of our tweakers participated in public debates or provided descriptions and puzzles for the *Ladies' Diary*, an eighteenth century journal aimed at the "fair" sex explaining improvements in the Arts and Sciences.[50] Beyond articles, many of our tweakers published treatises and books on matters of new technology.[51]

All the same, the fact that engineers and mechanics were networked and interacted in this

---

[49] The perhaps most striking example is the instrument maker Edward Troughton (1753-1835). Having kept one crucial method of his dividing machine secret, he later wrote a description for the *Astronomer Royal* as a "valuable present to young craftsmen." The paper was read to the Royal Society, which earned him a Copley medal and opened all doors to him.

[50] The *Ladies Diary* was edited between 1714 and 1743 by the surveyor, engineer, mathematician, and paradigmatic tweaker, Henry Beighton (1683-1743).

[51] For instance, Edmund Beckett Grimthorpe, who used gravity escapes in public watches, published his knowledge on watch making in *A Rudimentary Treatise on Clocks and Watchmaking* and William Jones shared the insights he gained with his improved solar telescope in *The Description and Use of a New Portable Orrery*.

fashion, if sufficiently widespread, indicates that the Industrial Revolution took place in a different cultural environment than the one that prevailed at the time of the Glorious Revolution. It should be added that the estimates presented in Table 6 are lower bounds; the absence of evidence is not evidence of absence, and especially for some of our more obscure tweakers it has been hard to unearth all the evidence of their exploits. Many may have been members of small provincial intellectual societies and published in obscure provincial journals or anonymously. At the same time, we acknowledge that because of the way the sample was constructed, it may suffer from selection bias in the sense that engineers and inventors of the second and third tier may have been in the sample because either publication or membership left a record and thus ended up in our sample.

Table 6: Publishers and societies members

Sector	**Publishers only**	***% of Sector Total***	**Societies members only**	***% of Sector Total***	**Publishers and societies members**	***% of Sector Total***	**Sector Total**
Textiles	7.5	*4%*	6.0	*3%*	3.0	*2%*	**193.0**
Ships	6.5	*24%*	2.0	*7%*	11.0	*41%*	**27.0**
Road & Rail & Can	11.0	*12%*	29.5	*33%*	23.0	*26%*	**89.5**
Other Eng	25.0	*17%*	31.0	*21%*	55.0	*37%*	**148.0**
Med & Chem	4.0	*14%*	3.5	*12%*	13.5	*46%*	**29.5**
Instruments	13.0	*14%*	13.5	*15%*	40.5	*45%*	**90.5**
Iron & Met	6.5	*13%*	9.0	*18%*	6.5	*13%*	**51.0**
Mining	4.5	*18%*	3.0	*12%*	8.0	*31%*	**25.5**
Agr & Farm	6.5	*31%*	1.5	*7%*	3.5	*17%*	**21.0**
Construction	8.0	*19%*	2.5	*6%*	18.0	*43%*	**42.0**
Print & Photo	3.0	*15%*	2.5	*13%*	4.0	*21%*	**19.5**
Others	1.5	*7%*	1.0	*4%*	5.0	*22%*	**22.5**
Category Total	**97.0**	***13%***	**105.0**	***14%***	**191.0**	***25%***	**759.0**

Again, the data show that of all sectors, textiles on which Allen relies heavily were the exception. It was the “least enlightened” and thus any inferences about the Industrial Revolution based primarily on the technological history of textiles may be misleading. Only about 10 percent of the individuals in textiles either published, belonged to a professional society, or both. For the sample as a whole, however, 52 percent of all tweakers were enlightened in the sense defined above. Indeed, roughly speaking, around two-thirds of all engineers in our sample either published or belonged to scientific or technical societies. The shortcoming of our sources notwithstanding, therefore, it is fair to say that an Enlightenment culture was rooted deeply in the top 3-5 percentile of the skill distribution – the highly competent craftsmen and engineers.

Not only did our tweakers place their knowledge in the public sphere and participated in discussions in formal societies, but although like most engineers anywhere they had limited interest in politics, quite a few were involved in liberal or progressive politics of one kind or another.[52] Some of our engineers such as Richard Reynolds, an ironmonger, can be shown to have been active in the anti-slavery movement. To be sure, the Enlightenment meant different things to different people, and its influence on wider British society was limited before the 1830s. However, it was an elite ideology, and our tweaker sample was drawn from an elite population. The technological momentum in the Industrial Revolution was supplied by a small, elite group of highly skilled engineers, artisans, and workmen. Our sample represents the right tail of this group, the most successful and highly skilled members of an elite, yet their characteristics tell us a lot about the sources of British success.

To what extent were our tweakers different from the better-known “superstars” of the

---

[52] John Mercer (1791-1866), like many other leading figures in the technological elite, was a member of the Anti-Corn Law League. Others spent their time and money on the improvement of society, like the garden architect John Claudius Loudon, who supported a scheme for decent housing for the poor or toolmaker and engineer Joseph Whitworth who devoted various sums, amounting in all to £594,416, to educational and charitable purposes. Sir George Cayley (1773–1857), the famous aeronautic pioneer, was a Whig Member of Parliament for Scarborough, and strongly supported Parliamentary reform and abolition.

Industrial Revolution? The issue is relevant because of the assumption of “continuity” in the distribution we are making (since we are observing a highly selective sample). To test for this, we selected 72 members of our sample who are mentioned in two recent books on the Industrial Revolution by one of us, namely Mokyr (1990 and 2002). That yielded 72 names of such technological luminaries as Arkwright, Watt, Smeaton, Wedgwood and Trevithick. We checked to what extent they resembled the rest of the sample. As they were obvious the very top of the competence distribution, more is known of them. Yet they appear to be, on the whole, much like the rest of our sample, if naturally more distinguished and more likely to be owners-entrepreneurs (see Table 7). It is worth noting that while superstars hold, on average, more patents, a full 25 percent of the superstars did not patent all of their inventions.

TABLE 7: Comparison of tweakers and stars

Education	**Apprenticed**	**School**	**University**	**Unknown/None**	
Full Sample	40%	7%	15%	41%	
Stars	54%	10%	24%	18%	
Patents	**0**	**1**	**2-5**	**6-10**	**10+**
Full Sample	40%	25%	24%	6%	5%
Stars	19%	17%	28%	15%	21%
Employment	**Owned**	**Managed**	**Employed**	**Unknown**	**Partnerships (% of owners)**
Full Sample	62%	6%	12%	21%	55%
Stars	79%	8%	13%	0%	54%
Rewards	**Cash**	**Medal**	**Title**	**Appointment**	**Royal Society**
Full Sample	8%	14%	7%	13%	16%
Stars	14%	25%	18%	29%	24%
Publish/Society	**Published**		**Membership in Society**		**Both**
Full Sample	13%		14%		25%
Stars	14%		14%		35%

Conclusions: The Rate and Direction of Technological Progress during the British Industrial Revolution

What determined the rate and direction of technological change during the Industrial Revolution? Explanations can be, very crudely, be classified into demand and supply based explanations. In his recent book, Allen (2009a) has argued that high wages drove a search for labor-saving innovation. While we do not propose here an explanation of the macro-inventions that form the backbone of usual accounts of the Industrial Revolution, we argue that a key ingredient that complemented these inventions and made them work came from human capital: it was the technical competence of the British mechanical elite that was able to tweak and implement the great ideas and turn them into economic realities. The story presented here is entirely supply-based. There is a global question, "why Europe?", and a local question, "why British leadership?" The answer is based on an unusually felicitous combination of Enlightenment culture, which characterized much of Western Europe, and technical competence, where Britain had a comparative advantage. Had it had only one of those two, it seems unlikely that its economic performance would have been as spectacular.

The story, however, was not a national but by and large a local one: innovations in textiles, iron, mining, hardware, and instruments, to pick a few examples, were all local phenomena, relying largely on local resources including talent. To be sure, our tweakers were mobile even in the pre-railroad age. Moreover, there were at least two national institutions that gave a certain unity to these local developments. One was the patent office; despite the consensus view of the literature that patenting was a fairly minor source of progress, it remained in some ways a national technological institution whose presence was felt even if it was decided not to use it or if it let its users down. The other was the Royal Society and similar national institutions such as the Society of Arts, the Royal

Institution, and the British Association for the Advancement of Science (f. in 1831).

Are there any policy lessons from this for our age? The one obvious conclusion one can draw from this is that a few thousand individuals may have played a crucial role in the technological transformation of the British economy and carried the Industrial Revolution. The *average* level of human capital in Britain, as measured by mean literacy rates, school attendance, and even the number of people attending institutes of higher education are often regarded as surprising low for an industrial leader. But the useful knowledge that may have mattered was obviously transmitted primarily through apprentice-master relations, and among those, what counted most were the characteristics of the top few percentiles of highly skilled and dexterous mechanics and instrument-makers, mill-wrights, hardware makers, and similar artisans. This may be a more general characteristic of the impact of human capital on technological creativity: we should focus neither on the mean properties of the population at large nor on the experiences of the "superstars" but on the group in between. Those who had the dexterity and competence to tweak, adapt, combine, improve, and debug existing ideas, build them according to specifications, but with the knowledge to add in what the blueprints left out were critical to the story. The policy implications of this insight are far from obvious, but clearly if the source of technological success was a small percentage of the labor force, this is something that an educational policy would have to take into account.

Finally, the supply of competence reminds us of something rather central about the direction of innovation, which seems very generally relevant. The direction is dependent on those supply factors that reflect what engineers and skilled workers actually can do regardless of what they would like to do. The drive toward improvement was quite general in the eighteenth century, but the results were highly uneven, with major productivity improvements in textiles, iron, civil engineering, and power technology, but few in farming, medicine, steel, chemicals, and communications. These reflected the difficulties on the supply side rather than any obvious demand-side bias. Competence as defined here was an integral part of the supply side, as inventors would not be able to carry out their ideas without the trained workers they employed.

References

Allen, Robert C. 2009a. *The British Industrial Revolution in Global Perspective*. Cambridge: Cambridge University Press.

———. 2009b. "The Industrial Revolution in Miniature: The Spinning Jenny in Britain, France, and India." *Journal of Economic History,* Vol. 69, Issue 04, (December), pp. 901-927.

Barker, T.C. and Harris, John R. 1954. *A Merseyside Town in the Industrial Revolution: St. Helens, 1750–1900.* Liverpool: Liverpool University Press.

Baines, Edward. 1835. *History of the Cotton Manufacture in Great Britain.* London: H. Fisher.

Becker, Sascha O., Hornung, Erik, and Woessmann, Ludger. 2009. "Catch Me If you Can: Education and Catch-up in the Industrial Revolution." *Stirling Economics Discussion Paper,* No. 2009-19.

Berg, Maxine. 2007. "The Genesis of Useful Knowledge." *History of Science*, Vol. 45, pt. 2, No. 148 (June), pp. 123–34.

Birse, Ronald M. 2004. "Worsdell family (per. c.1800–1910)," *Oxford Dictionary of National Biography*, Oxford University Press, online edn.

Cardwell, Donald S. L. 1972. *Turning Points in Western Technology.* New York: Neale Watson, Science History Publications.

———. 1994. *The Fontana History of Technoloy*. London: Fontana Press.

Chapman, S.D. 1967. *The Early Factory Masters: the Transition to the Factory System in the Midlands Textile Industry.* Newton Abbot, David & Charles.

Clark, Gregory and Jacks, David. 2007. "Coal and the Industrial Revolution." *European Review of Economic History*, Vol. 11, No. 1 (April), pp. 39–72.

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

Day, Lance and McNeil, Ian. 1996. *Biographical Dictionary of the History of Technology.* London and New York: Routledge.

Enos, John. L. 1962. "Invention and Innovation in the Petroleum Industry." In National Bureau of Economic Research, *The Rate and Direction of Inventive Activity; Economic and Social Factors.* Princeton: Princeton University Press, pp. 299–321.

Fairbairn, William. 1871. *Treatise on Mills and Millwork Vol. 1. 3rd edition.* London : Longmans, Green and Co.

Farnie, D. A. 2004. "Crompton, Samuel (1753–1827)", *Oxford Dictionary of National Biography*, Oxford University Press.

Fitton, R.S. and Wadsworth, A.P. 1958. *The Strutts and the Arkwrights.* Manchester: Manchester University Press.

Felkin, William. 1867. *A History of the Machine-wrought Hosiery and Lace Manufactures*. Cambridge: Printed by W. Metcalfe.

Francis, A.J.1977. *The Cement Industry 1796-1914: a History.* Newton-Abbot: David & Charles.

Gale, K.W.V. 1961–62. "Wrought Iron: a Valediction." *Transactions of the Newcomen Society* Vol. 36, pp. 1–11.

Graham, Stuart J.H., Merger, Robert P., Samuelson, Pam, and Sichelman, Ted. 2009. "High Technology Entrepreneurs and the Patent System: Results of the 2008 Berkeley Patent Survey," *Berkeley Technology Law Review*, Vol. 24, No. 4, pp. 1255-1328.

Griffiths, John. 1992. *The Third Man: the Life and Times of William Murdoch.* London: André Deutsch.

Griffiths, Trevor, Hunt, Philip A. and O'Brien, Patrick K. 1992. "Inventive Active in the British Textile Industry, 1700-1800," *Journal of Economic History* Vol. 52, No. 4 (Dec.), pp. 881-906.

Harris, John R. 1988. *The British Iron Industry, 1700–1850.* Houndmill and London: Macmillan Education Ltd.

———. 1992. "Skills, Coal and British Industry in the Eighteenth Century," in *Essays in Industry and Technology in the Eighteenth Century.* Ashgate: Variorum.

———. 1998. *Industrial Espionage and Technology Transfer: Britain and France in the Eighteenth Century.* Aldershot: Ashgate.

Harrison, James. 2006. *Encouraging Innovation in the Eighteenth and Nineteenth Centuries.* Gunnislake, Cornwall: High View.

Heaton, Herbert. 1965. *The Yorkshire Woollen and Worsted Industries, From the Earliest Times up to the Industrial Revolution.* Oxford: Oxford University Press.

Henderson, W.O. 1954. *Britain and Industrial Europe, 1750–1870; Studies in British Influence on the Industrial Revolution in Western Europe.* Liverpool: Liverpool, University Press.

Hilaire–Pérez, Liliane. 2007. "Technology as Public Culture." *History of Science*, Vol. 45, pt. 2, No. 148 (June), pp. 135–53.

Honeyman, Katrina. 1983. *Origins of Enterprise: Business Leadership in the Industrial Revolution.* New York: St. Martin's Press.

Humphries, Jane. 2003. "English Apprenticeships: A Neglected Factor in the first Industrial Revolution." In Paul A. David and Mark Thomas, eds., *The Economic Future in Historical Perspective.* Oxford: Oxford University Press, pp. 73–102.

Jacob, Margaret C. 1997. Scientific Culture and the Making of the Industrial West. 2nd edn., New York: Oxford University Press.

———. 2007. "Mechanical Science of the Factory Floor." *History of Science*, Vol. 45, part 2, No. 148 (June), pp. 197–221.

James, Frank A.J.L. 2005. "How Big a Hole?: The Problems of the Practical Application of Science in the Invention of the Miners' Safety Lamp by Humphry Davy and George Stephenson in Late Regency England." *Transactions of the Newcomen Society*, Vol. 75, pp. 175–227.

Jenkins, D.T. and Ponting, K.G. 1982. *The British Wool Industry, 1750-1914.* London: Scolar Press.

Jones, Peter M. 2008. *Industrial Enlightenment: Science, Technology, and Culture in Birmingham and the West Midlands, 1760–1820.* Manchester and New York: Manchester University Press.

Khan, B. Zorina 2006. "The Evolution of Useful Knowledge: Great Inventors, Science and Technology in British Economic Development, 1750–1930." unpublished paper, Bowdoin College.

———. B. Zorina Khan, "Premium Inventions: Patents and Prizes as Incentive Mechanisms in Britain and the United States, 1750-1930" in Naomi Lamoreaux (ed), *Understanding the Sources of Long Run Economic Growth*, NBER and University of Chicago (forthcoming, 2010).

Klemm, Friedrich. 1964. *A History of Western Technology.* Cambridge, Mass.: MIT Press.

Machlup, Fritz. 1962. "The Supply of Inventors and Inventions." In National Bureau of Economic Research, *The Rate and Direction of Inventive Activity; Economic and Social Factors.* Princeton: Princeton University Press, pp. 143–69.

MacLeod, Christine. 1988. *Inventing the Industrial Revolution: The English Patent System, 1660–1880.* Cambridge: Cambridge University Press.

MacLeod, Christine and Nuvolari, Alessandro. 2006. "Pitfalls of Prosopography: Inventors in the Dictionary of National

Biography." *Technology and Culture* Vo. 47, No. 4, pp. 757-776.

Marsden, Richard. 1895. *Cotton Weaving: Its Development, Principles, and Practice.* London: George Bell.

Marshall John. 1978. *A Biographical Dictionary of Railway Engineers.* Newton Abbot : David and Charles.

McCloskey, Deirdre. N. 1981. "The Industrial Revolution: A Survey." In Roderick C. Floud and D. N. McCloskey, eds., *The Economic History of Britain Since 1700,* 1st edn., Vol. 1. Cambridge: Cambridge University Press, pp. 103–27.

McConnell, Anita. 2004a. "Bird, John (1709–1776)", *Oxford Dictionary of National Biography*, Oxford University Press.

McConnell, Anita. 2004b. "Bate, Robert Bretell (1782–1847)", *Oxford Dictionary of National Biography*, Oxford University Press.

Mitch, David. 1998. "The Role of Education and Skill in the British Industrial Revolution." In Joel Mokyr, ed., *The British Industrial Revolution: An Economic Perspective,* 2nd edn. Boulder, CO: Westview Press, pp. 241–79.

Mokyr, Joel. 1990a. *The Lever of Riches: Technological Creativity and Economic Progress.* Oxford and New York: Oxford University Press.

———. 1998. "Editor's Introduction: The New Economic History and the Industrial Revolution." In Joel Mokyr, ed., *The British Industrial Revolution: An Economic Perspective.* Boulder, CO: Westview Press, pp. 1-127.

———. 2008. "The Institutional Origins of the Industrial Revolution." In Elhanan Helpman, ed., *Institutions and Economic Performance.* Cambridge, Mass.: Harvard University Press, pp. 64–119.

———. 2009a. *The Enlightened Economy.* New Haven and London: Yale University Press.

———. 2009b. "Intellectual Property Rights, the Industrial Revolution, and the Beginnings of Modern Economic Growth." *American Economic Review* Papers and Proceedings, May, pp. 349-355.

Morrison-Low, A.L. 2007. *Making Scientific Instruments in the Industrial Revolution.* Aldershot, Hampshire: Ashgate.

Musson, A.E. and Robinson, Eric. 1969. *Science and Technology in the Industrial Revolution.* Manchester: Manchester University Press.

North, Douglass C. and Weingast, Barry. 1989. "Constitutions and Commitment: Evolution of Institutions Governing Public Choice in Seventeenth Century England." *Journal of Economic History*, Vol. 49, No. 4 (Dec.), pp. 803–32.

Rimmer, Gordon. 1965. *Marshalls of Leeds, flax-spinners, 1788-1886.* Cambridge: Cambridge University Press.

Roll, Eric [1930]. 1968. *An Early Experiment in Industrial Organization.* Reprint ed., New York: Augustus Kelley.

Rosen, William. 2010. *The Most Powerful Idea in the World.* New York: Random House.

De Saussure, César. [c. 1727]. 1902. *A Foreign View of England in the Reigns of George I. & George II. The Letters of Monsieur César de Saussure to his Family,* trans. and ed., Madame Van Muyden. London: J. Murray.

Say, Jean-Baptiste. [1803]. 1821. *A Treatise on Political Economy.* 4th ed., Boston: Wells and Lilly.

Singh, Jasjit and Agrawal Ajay K. 2010. "Recruiting for Ideas: How Firms Exploit the Prior Inventions of New Hires." *NBER Working Paper*, No. 15869.

Skempton, A.W. et al., eds. 2002. *A Biographical Dictionary of Civil Engineers in Great Britain and Ireland, Vol. 1: 1500–1830.* London: Thomas Telford for the Institution of Civil Engineers.

Smiles, Samuel. 1859. *Self Help.* Available on http://www.emotionalliteracyeducation. com/classic_books_online/selfh10.htm

Smiles, Samuel. 1865. *Lives of Boulton and Watt*. Philadelphia: J.B. Lippincott.

———. 1874. *Lives of the Engineers: The Sateam Engine*. London: John Murray.

———. [1889]. 1901. *Industrial Biography: Iron-workers and Tool Makers*. London : John Murray.1897. Available at http://www.fullbooks.com/Industrial–Biography6.html

———. 1884. *Men of Invention and Industry*. London: J. Murray.

Smith, Adam. [1757], 1978. *Lectures on Jurisprudence*, eds. Ronald Meek et al. Oxford: Clarendon Press.

Sussman, Herbert L. 2009. *Victorian Technology: Invention, Innovation, and the Rise of the Machine*. Santa Barbara, CA: Praeger Publishers.

Temin, Peter. 1997. "Two Views of the British Industrial Revolution." *Journal of Economic History*, Vol. 57, No. 1 (March), pp. 63–82.

Tucker, Josiah. 1758. *Instructions for Travellers*. Dublin: Printed for William Watson at the Poets Head in Carpel Street.

Van der Beek, Karine. 2010. "Technology-skill complementarity on the Eve of the Industrial Revolution: new evidence from England." Presented to the Economic history Association Meetings, Evanston, Sept. 2010.

Wallis, Patrick. 2008. "Apprenticship and Training in pre-modern England." *Journal of Economic History* Vol. 68, pp.832–61.

Woodcroft, Bennet. 1854. *Alphabetical index of Patentees of Inventions [1617-1852]*. London: Evelyn, Adams & McKay.

Wrigley, E.A. 2004. "The Divergence of England: The Growth of the English Economy in the Seventeenth and Eighteenth Centuries." In E. A. Wrigley, *Poverty, Progress, and Population*. Cambridge: Cambridge University Press, pp. 44–67.

———. 2010.*Energy and the English Industrial Revolution*. Cambridge University Press.