The Relevance of Skills to Innovation during the British Industrial Revolution, 1547-1851

WORKING PAPER

Anton Howes
anton_howes@brown.edu

Brown University
May 2017

How necessary were training and education to the British Industrial Revolution's innovations? This article presents new evidence of the educational and professional backgrounds of 1,452 innovators active in the British Isles between 1547 and 1851. Innovators had diverse professional backgrounds, and improved a diverse range of industries, with the majority of innovators each improving more than one industry. Crucially, however, 34% of innovators improved industries for which they lacked the relevant training. To explain this, I suggest that innovators could improve industries outside of their field because they were inspired by other innovators with an improving mentality.

In the three centuries between the death of Henry VIII in 1547 and the Great Exhibition of 1851, Britain became the world's technological leader.[1] The transformation – an Industrial Revolution – was brought about by an unprecedented acceleration in the rate of innovation. Although economic historians debate the extent to which the economy grew, they

[1] I use "British" to refer to the British Isles: the geographical area that comprises today's United Kingdom and the Republic of Ireland.

agree that innovation accelerated.[2] In 1547 transparent glass had to be imported from Venice because nobody in Britain knew how to produce it. Indeed, glassmakers of any kind were said to be almost entirely lacking (Hulme, 1909, p. 127). But by 1851 the Crystal Palace, the largest enclosed space on earth, was constructed of 300,000 panes of the largest glass sheets ever produced (Auerbach, 1999, p. 135). Similar technological leaps occurred in nearly all industries, beyond the famous examples of cotton, iron, and steam. They occurred in agriculture, medicine, pottery, furniture making, navigation, and even gardening (Mokyr, 2009).

What caused the acceleration of innovation? One prominent candidate is human capital – that people in Britain were uniquely skilled or well-educated.[3] The number of new schools and books certainly increased, as did general literacy and numeracy (Baten and van Zanden, 2008; Boucekkine et al., 2007). And some suggest that Britain had better nutrition, such that its workers generally had superior cognitive skills (Kelly et al., 2014). But the role of such general skills has been questioned. Both David Mitch (1993) and Alexandra de Pleijt (2011) find that literacy and primary schooling had little impact on economic growth. And countries like Sweden, despite being highly literate, failed to achieve a comparable acceleration of innovation (McCloskey, 2011, pp. 162–4).

An alternative version of the human capital argument is that innovation accelerated because Britain was uniquely blessed with a well-educated and highly-skilled elite – a small group of innovators (Kelly et al., 2014; Meisenzahl and Mokyr, 2012).[4] Margaret Jacob (2014, pp. 221–3) emphasises their scientific knowledge. British innovators, in her view,

[2] See, for example: (Berg and Hudson, 1994; Broadberry et al., 2015; Crafts, 1985, 2004; Crafts and Harley, 1992; Clark, 2010; Deane and Cole, 1969; Temin, 2000)

[3] See, for example: (Galor, 2005; Galor and Moav, 2002).

[4] Squicciarini and Voigtländer (2015) show that in France the presence of such an elite – the upper tail of the country's human capital distribution – contributed to economic growth.

adopted the Newtonian tradition of experimentation and had a sophisticated understanding of the interaction of forces. She emphasises in particular their schooling and higher education. Ralf Meisenzahl and Joel Mokyr (2011), on the other hand, emphasise their tacitly communicated, technical competence – the kinds of skills that can only be obtained through practice, for example through apprenticeships.

Yet Britain was not alone in having an apprenticeship system (Kelly et al., 2014), and Meisenzahl and Mokyr (2012) found that only 40% of innovators were apprenticed. As for Jacob's emphasis on higher education, Cormac Ó Gráda (2016, p. 33) posits that applied scientific knowledge only became important to innovation in the 1850s, during industrialisation's second wave. Meisenzahl and Mokyr (2012) also find that levels of higher education did not even account for a majority of innovators.

Up until now the arguments in favour of either higher education or skills-based training have relied upon anecdotal evidence, or have focused on *levels* of education, not on its content. This ignores an important fact: some innovators, many of whom feature prominently in the history of the British Industrial Revolution, innovated in areas for which they lacked the requisite skills. Their skills, in other words, were irrelevant to their innovations. Edmund Cartwright, famous for his invention of the power loom, was an Anglican clergyman. Although he went to university, he there studied only classics and poetry.[5]

And such a lack of expertise was not limited to wealthy hobbyists. Richard Arkwright, before inventing machines to improve the carding and spinning of textiles, had no experience of either process. He had a trade, but this was as a barber and a wigmaker: professional experiences that gave him no special tacit knowledge with which to make his

[5] Unless otherwise stated, biographical details about innovators are taken from their respective entries in the online *Oxford Dictionary of National Biography*.

improvements. Nor were the irrelevant professional backgrounds of Cartwright and Arkwright rare exceptions. As I will show, they were representative of *at least* a third of Britain's innovators.

How then are we to account for so many innovators lacking the relevant skills? I suggest that what made an innovator, rather than any training or education, was an improving *mentality*. Innovators saw room for improvement, even in wholly unfamiliar areas, and envisioned how such improvements might be brought about. It was not a particular skill or some special knowledge, but a frame of mind – a lens through which they perceived the status quo as being imperfect, and then sought to rectify those imperfections. As an analogy, consider climbing: people generally see walls or mountains as barriers, but climbers see them as objects to be scaled and clambered over. About otherwise ordinary industries, innovators said "this could be better" – and then did something about it.

As a mentality, separate from any particular skill or understanding, its emergence and spread can also account for how improvement accelerated simultaneously in industries as different as gardening, surgery, and engineering. After all, *anything* could be better. Lancelot Brown looked out over the gardens of the wealthy and declared them "capable" of improvement. He said it so often that he earned himself the nickname Capability Brown. The architect Robert Salmon suffered from a hernia and contrived a surgical truss to alleviate it. A young engineer, William Fairbairn, even got carried away and tried to apply the improving mentality to romance: by reverse-engineering the published correspondence of a pair of lovers in a magazine, he maintained that he had "inadvertently rendered one of the strongest passions of our nature subservient to the means of improvement" (Fairbairn, 1877, chap. 4).

The improving mentality can, in the same way, account for the sheer breadth of industries that could be improved by even a single innovator. Cartwright, in addition to the power loom, also developed agricultural machinery; designed fireproof building materials;

made medical discoveries; contrived a crank-operated, horse-less "centaur carriage"; and experimented with manures and potatoes as the superintendent of the Duke of Bedford's model farm. As we shall see, this breadth has been obscured by the manner in which innovators and their human capital have hitherto been categorised. Among innovators, such polymaths were not rare – in fact, they were in the majority.

All innovations, of course, involve the application of *some* kind of knowledge or *some* kind of skill. And so where they lacked the relevant expertise to bring about an envisioned improvement, innovators either self-educated, or else relied upon the expertise of others. Patrick Bell, a farmer's boy, noted that when he invented his widely-adopted reaping machine "no man could have been less slenderly furnished with books calculated to instruct him in the science and history of mechanical invention" (Bell, 1855, p. 186). Although he was able to do his own experiments and make his own working models, the creation of a full-sized machine required outsourcing its constructon to a foundry, a wheelwright, and two blacksmiths (Bell, 1855, p. 191).

And the improving mentality trumped skill. Henry Bessemer, famous for inventing a process to mass-produce steel, recounted that when he started his career it was his "inventive turn of mind" that allowed him to overcome "the great disadvantage of not having been brought up to any regular trade or profession" (Bessemer, 1905, p. 9). He became one of the most prolific innovators of the age, obtaining at least 119 patents in a wide range of industries, including tools, textiles, chemicals, ships, railways, weaponry, and metallurgy. When discussing his work on steel in particular, he suggested that too much knowledge or training could even be a barrier to innovation:

> My knowledge of iron metallurgy was at the time very limited . . . but this was in one sense an advantage to me, for I had nothing to unlearn. My mind was

> open and free to receive new impressions, without having to stuggle against the bias which a lifelong practice of routine operations cannot fail to more or less create (1905, p. 136).

Workers could be skilled, but if they did not see room for improvement they could become complacent in their practical knowledge, sometimes believing that improvements were impossible. In a letter to a friend, Cartwright complained of how the mechanics he had hired in Manchester to build his power loom had “not even begun upon” the machine, because they “were not willing to consume their time upon a fruitless pursuit”(Strickland and Strickland, 1843, p. 72).

Most striking about the improving mentality, however, is its apparent spread from person to person. We will see how, despite the lack of relevant skills, people had extensive contact with other innovators before they themselves became innovators. In two case studies, focusing on The University of Edinburgh and on the training of mechanical engineers, I will show how the improving mentality spread even among the majority of innovators whose skills were entirely relevant – those mechanics, for example, who stuck to improving machines. Innovators were not trained or educated by just anyone: they were taught and mentored by other innovators.

THE SAMPLE OF INNOVATORS

The most significant attempt thus far to measure the training and education of British innovators counts only how many went to school, were apprenticed, and attended university (Meisenzahl and Mokyr, 2012). But this approach focuses only on the level of education, taking no account of its content. It is perhaps for this reason that innovators with irrelevant skills have thus far been ignored in the debate over human capital.

William George Armstrong, for example, was an inventor of steam engines, electrostatic machines, hydraulic cranes, breech-loading guns, and submarine mines. Looking at his level of education would, on the face of it, seem to lend to support both to Jacob's emphasis on higher education, and to Meisenzahl and Mokyr's emphasis on apprenticeships. Armstrong attended primary school and grammar school, was twice apprenticed, attended a higher education institution, and embarked on a successful professional career, all before becoming an innovator.

Yet both of Armstrong's apprenticeships were to lawyers, and his higher education was at Lincoln's Inn – an institution devoted to the training of barristers. His professional education was as a partner in a law firm, and his father was a corn merchant. His grammar school education covered only basic literacy, numeracy, and the classics (Heald, 2013, p. 13). Nothing in Armstrong's education or training, it seems, had any immediate relevance to his later innovations. As he himself put it, his early legal career, except for the slight experience it gave in matters of conducting business, "meant the waste of some ten or eleven of the best years of my life" (2013, p. 40).

To determine the proportion of innovators with similarly irrelevant skills, I compiled a sample of 1,452 people who became innovators between 1547 and 1851 (an exercise for which there is ample precedent).[6] Among their number are all the familiar names like Richard Arkwright, James Watt, and Isambard Kingdom Brunel. But the sample also includes lesser celebrated innovators like the surgeon Edward Alanson, who persuaded his fellow medical practitioners to wash their hands before operations.

[6]See, for example: (Allen, 2009, pp. 242–271; Khan, 2015; Khan and Sokoloff, 1993, 2004; MacLeod and Nuvolari, 2006; Meisenzahl and Mokyr, 2011)

Innovators are sometimes distinguished by importance, labelled “macro-” and “microinventors”, or “stars” and “tweakers” (Allen, 2009; Mokyr, 1992; Meisenzahl and Mokyr, 2012). But this sample does not do so. Assigning significance in such a manner can be biased by prevailing narratives about the Industrial Revolution, and is done with the distorted lens of hindsight. Of course, some innovators were more financially successful than others, or have since received longer-lasting recognition. Some were more prolific, or were better at advertising their achievements. But all of the people in the sample improved things. The aim is to understand why they became innovators, rather than passing judgement on their eventual impact.

Innovation is a process with many steps, from noticing an opportunity for improvement, to designing a solution, implementing it, and then adjusting it further. Many people likely only noticed opportunities and never bothered to record or exploit them – unfortunately, they very rarely, if ever, become known to us. The men and women in the sample were therefore those who at the very least put pen to paper, voiced their ideas to others, or implemented their designs. But the designers, the implementers, and the tweakers were all still innovators.

Note, however, that innovators were not always entrepreneurs (although they often were). Following on from Joseph Schumpeter (1939, pp. 80–5), innovation has taken on a meaning distinct from invention, to refer to the development of improvements to be sold on the market. But for the purposes of this paper I define innovation according to the more popular usage, as a catch-all term for improvements that are both physically tangible (usually referred to as inventions), and intantigble (such as Alanson’s technique of washing hands before operations).

Note, also, that innovators were not scientists (then called natural philosophers). Science is the practice of advancing our *understanding* of the world, whereas innovation is the distinct activity of *improving* the world, in the sense of contriving or implementing new objects and ways of doing things. Innovators often exploited knowledge of nature's laws, famously so in the case of vacuums and steam engines, but what distinguished them from natural philosophers was that they applied their understanding towards improvement. Sir Isaac Newton is included in the sample for his invention in 1669 of a reflecting telescope, not for his celebrated contributions to our understanding of physics.

The sample was compiled from some existing lists of innovators, and corrects for biases by adding innovators from other sources too.[7] It fully incorporates a list compiled by Robert C. Allen (2009), and a list compiled by Christine MacLeod and Alessandro Nuvolari (2006) from the nineteenth century *Dictionary of National Biography* and its modern descendant, the *Oxford Dictionary of National Biography* (ODNB). The sample also fully incorporates the list compiled by Meisenzahl and Mokyr (2011), which focused on inventors who possessed technical competence. Their list drew upon biographical studies of inventors (Day and McNeil, 2002), civil engineers (Skempton, 2002), scientific instrument-makers (Morrison-Low, 2007; Turner, 1998), textile machine makers (Barlow, 1879; Chapman, 1967; Heaton, 1920; James Burnley, 1889; Jenkins and Ponting, 1987), railway engineers (Marshall, 1978), and those who improved paper-making, glass-making, and the chemical industries (Barker and Harris, 1959). To these existing inventor lists I added the names of innovators who have appeared in the ODNB since the older lists were compiled, or who had otherwise been accidentally omitted (an unsurprising occurrence, because the ODNB, reliant as it is on thousands of different contributing authors, does not describe innovators or innovations systematically, instead often using more ambiguous terms such as "new designs" or "improvements").

[7] For the key findings of this paper, I provide the relevant figures that were found using the innovators mentioned in each of the older lists.

MacLeod and Nuvolari (2006, pp. 775–776) point out that their list perpetuates the biases of the *Dictionary of National Biography*'s compilers, neglecting innovators in industries such as food processing, consumer products and the decorative arts. To correct for this bias, the sample includes all innovators mentioned in works that have brought attention to such neglected industries (Berg, 2007, 1994; Bruland, 2004; Mokyr, 2009). The sample also includes innovators mentioned in the histories of other neglected areas, which nonetheless experienced considerable innovation, such as brewing (Sumner, 2013), coachmaking (Gilbey, 1903), medicine (Magner, 1992), and map surveying (Hewitt, 2013).

One limitation of the pre-existing lists is that they tend only to include innovators who were active from the eighteenth century onwards (Meisenzahl and Mokyr, for example, include those born after 1660). But innovators were active in Britain before then. 1660 was the year in which the Royal Society was founded, suggesting that there must already by then have been enough innovators to make such an organisation worthwhile. Including earlier innovators, moreover, allows for a better comparison of what was happening before and after their numbers accelerated. Thus, in order to find earlier innovators – those active between 1547 and 1700 – I checked for earlier names in the sources used by the pre-existing lists, and also included innovators mentioned in works that discuss Elizabethan and Stuart science and technology (Harkness, 2007; Jenkins, 1936).

MacLeod and Nuvolari point out that other lists of innovators use patent records to inform the compilation of samples, potentially over-representing patentees. To correct for this bias, the sample includes all innovators mentioned in the "Manufactures" and "Agriculture" sections of *A History of the Royal Society of Arts* (Wood, 1913). Between 1765 and 1845 patented innovations were not (officially) allowed to win the Society's prizes, so its history is a rich source of the names of non-patentees. It also generally emphasises industries where patenting was uncommon, such as agriculture, agricultural machinery, horticulture, nonelectric telegraphy, and textile design, as well as mentioning those people whose improvements had humanitarian aims.

Another bias in pre-existing lists is that they are overwhelmingly male. To correct for this, the sample includes all British innovators mentioned in Autumn Stanley's *Mothers and Daughters of Invention* (1995), a work that specifically sought to list female innovators. This brought the total number of female innovators to 15: still only 1% of the total, but far higher than the one or two names who tend to feature in other lists.

Although the sample includes many names from pre-existing lists, some who feature in those lists were omitted. Many, for example, only started innovating after 1851. Others were excluded for being hoaxes or frauds (like Samuel Alfred Warner, who in 1819 convinced the British government that he had invented an invisible shell). Still others were excluded, despite being British-born, for never innovating in Britain. And lastly, some names were excluded because they were not innovators at all, but rather patent agents. The names of patent agents often find their way into histories of technology because the patents were awarded in their name, and not in the names of their clients, the actual innovators. Such cases were identified by checking the chronological index of patents (Woodcroft, 1854), which describes such cases as being "communications", often from "a foreigner residing abroad".

Innovators, as indicated by Table 1, were better educated than has previously been shown. The discrepancy largely stems from reliance upon additional sources – the *Oxford Dictionary of National Biography*, for example, does not always provide a comprehensive list of all the details of a person's life, with entries varying greatly according to who authored them, and with some authors writing in the late nineteenth century. In particular, details of a person's early education were often omitted so that more space could be devoted to their achievements. But the ODNB does list the sources it used, in order of importance. So in order to find missing details, I took the additional step of reading the most important listed sources:

usually obituaries, biographies, memoirs, and collections of correspondence. Many innovators also failed to appear in biographical compilations, with so little information about them that their dates of birth and death were unknown. Such “lost” innovators are known in other lists of innovators according to their *floruit* dates – the years in which they flourished. They make up 27% of Meisenzahl and Mokyr’s list, for example, which mostly relied upon the biographical compilations for information. I was able to reduce the proportion of lost innovators to only 8%, by using patent records, the British newspaper archives, and genealogical records to reconstruct the details of their lives.

The additional research allows us to more accurately assess the education and training of innovators, so as to know how many of them were trained in areas that were irrelevant to their innovations. The proportion of innovators with some kind of schooling was 33%. And 8% were privately tutored on a formal or semi-formal basis - a type of education not measured in prior lists. When private tutoring and schooling are counted together, the rate of primary and secondary education rises to 36%. This higher figure is certainly an underestimate - records of schooling are the hardest to find, if kept at all.

The rate of university attendance was only slightly higher than that recorded by Meisenzahl and Mokyr, at 18% compared to their 15%. And the proportion who had any form of higher education was higher still, at 24%, when one includes attendance at Mechanics’ Institutes, anatomical schools, the Royal Military Academies, art academies, the Inns of Court, and the teaching hospitals in London (Guy’s, St Thomas’, St George’s, St Bartholomew’s).

There was evidence of ony 31% of innovators having undertaken apprenticeships (rather lower than the 40% figure found by Meisenzahl and Mokyr). But doing an apprenticeship was not the only way to acquire tacit knowledge, it was simply the most formal. Taking into account informal training by family members (usually fathers), assistantships, and any youthful work for employers before innovating, the proportion of innovators with skills-based training rose to 53%.

We can obtain some further idea of the skills that innovators possessed by recording the professions they engaged in before becoming innovators, as well as the professional backgrounds of their fathers. For example, there is no record of the education of James Caleb Anderson, who pioneered the use of steam carriages. But we do know that his father was the founder of an innovative mail coach company in Ireland. Such information was taken into account when assessing the relevance of backgrounds to innovations. Similarly, for wives and widows, the professions of their husbands were treated as their own. Table 1 shows that the inclusion of this additional information left only 24 innovators (2% of the total) whose educational and professional backgrounds were wholly unknown.

Assessing the relevance of training and education to innovation also requires the categorisation of both their skills and their innovations. Innovators in the sample had remarkably broad interests. James Watt, for example, though most famous for improving steam engines, could also be categorised as a pioneer of civil engineering (he surveyed the Caledonian Canal in 1773), of the decorative arts (he invented sculpturing machines), of chemicals (he developed new methods of producing chlorine), and of consumer hardware (he invented a letter-copying press). Indeed, one potential reason that skills have not hitherto been assessed for their relevance to innovation may be because no attempt has been made to recognise this breadth of interests. All other lists treat innovators as capable of improving only a single industry.[8] But when split among 39 different industry categories, the number

[8] Meisenzahl and Mokyr (2011, p. 17) make some exception, but for fewer than 5% of their innovators: where they were particularly torn between choosing two industries for an innovator, they counted the innovator as half-belonging to each industry.

who improved more than one industry were in the majority (56%), and almost a third (31%) improved more than two industries.[9]

Rather than using mutually exclusive categories, assigning each innovator to only a single industry, the sample records *every* industry that innovators improved. Doing away with mutually exclusive categories is the only way to account for a given innovator improving many different industries. And it is the only way to account for innovations themselves sometimes falling under multiple categories. Is the transfer-printing of pottery, for example, to be categorised as an improvement to ceramics, or as an improvement to printing? The dilemma is eliminated by categorising it as both.

Doing away with mutually exclusive categories has the further advantage of allowing for many more industries to be identified. Allen splits the innovators in his list between only nine industries, Meisenzahl and Mokyr split theirs between 12, and MacLeod and Nuvolari split theirs between 21. The choice of categories is unavoidably arbitrary, but by using more categories we can more clearly describe what innovators were actually doing. I identify 39 industries, listed in Table 2, thereby achieving greater accuracy than other lists.

Strikingly, no single category was improved by more than a fifth of innovators. Their interests may appear more diverse, of course, because the sample was expanded to include as many innovators from as wide a range of industries as possible. But at the same time, doing away with mutually exclusive categories ought to have increased the proportions recorded in any given industry. And it is worth noting that the categories could be subdivided even further, for greater accuracy, beyond just 39. Improvements to precision instruments, the most common category, could be split into improvements to clocks, watches, telescopes,

[9] The figures were even more pronounced for the innovators mentioned in the older lists: using Allen's list, the proportion who improved more than one industry was 57%; in Meisenzahl and Mokyr's it was 60%; in MacLeod and Nuvolari's it was 69%.

quadrants, microscopes, thermometers, and so on. The next most common category, of miscellaneous machinery, covers a hodge-podge (as its name suggests) of improvements to cranes, hydraulic machines, mining equipment, and other machinery.

Innovators thus had extraordinarily diverse interests. Some pioneered entirely new areas like photography and electric telegraphy, while others devoted their attentions to ancient industries like shipbuilding and ceramics. The 15% who improved textile machinery had an especially large impact on economic growth, but they were a minority among a much broader group who turned their minds to improving industries of all kinds.

As with the categorisation of innovations, the labels used to categorise skills are not mutually exclusive: a given innovator could have done an apprenticeship in one industry before embarking on a career in another. And some jobs involved the acquisition of many different skills too. For greater accuracy, the sample errs on the side of identifying too many categories rather than too few. It is useful, for example, to distinguish shipbuilding (involving woodworking, construction, and an understanding of buoyancy), from sailing (which may breed familiarity with ships in general, but not necessarily with their construction). Tables 3 and 4 show that the skills and education of innovators were very diverse – no single type accounted for even a fifth of the total.

This diversity of backgrounds further suggests that it was an improving mentality, as separate from any particular knowledge or skill, that was important for innovation. The sample undoubtedly had more training in certain areas as compared to the population as a whole, such as in mechanics or medicine, but if the skills themselves were important to innovation one would expect them to be more concentrated. Much is made, for example, of the importance of Britain's clockmakers and watchmakers in encouraging industrialisation (Allen, 2009, pp. 204–6; MacLeod and Nuvolari, 2009; McCloskey, 2011, pp. 114–8). Yet only 7% of the sample had any background in making precision instruments. This low figure even includes innovators like the wine merchant Joseph Jackson Lister, the son of a clockmaker, but who himself had no apparent training in the industry. Considering that Table 3 includes the professions of the fathers of innovators, the diversity of backgrounds is all the more striking.

Having categorised the innovators by the their backgrounds and by the fields they improved, I then assessed the relevance of one to the other. Such an exercise unavoidably requires a high degree of judgement, with few hard rules. I erred, however, on the side of assigning relevance. Higher educations in natural philosophy or science were treated as almost universally relevant. Backgrounds in teaching that plausibly involved science were treated similarly. Backgrounds in mechanics (professional experience as millwrights, engineers, and machinists), in metalwork (including iron founders as well as smiths of various kinds), and in precision instruments (such as clockmaking, or the making scientific instruments) were assumed to be relevant to any improvements to machines. In 29 cases (2%) the backgrounds were either entirely unknown, or relevance seemed highly improbable yet plausible – in these cases I absolved myself of making a judgement and categorised them as being unclear.

Despite erring on the side of relevance, Table 5 shows that a fifth of innovators (288 people) – like the lawyer William George Armstrong – solely improved industries that were entirely unrelated to their education, training, professional background, or even the professions of their fathers. The figure ought to be treated as a minimum. If the assumptions in favour of relevance were to be relaxed, or the professions of fathers were disregarded, the true proportion would be even higher still. It is also worth noting that skills and innovations were often grouped together for the sake of convenience, in a way that may further understate the number of cases like Armstrong's. Backgrounds as physicians, anatomists, surgeons, and apothecaries, for example, were all categorised as *medical*, to reflect the way in which improvements to treatments, surgical techniques, and medicines were also all categorised as *medical*. In reality, however, dentists do not necessarily have the skills to develop drugs, apothecaries cannot usually practise surgery, and so on.

Cases like Armstrong's were extreme, but a further 14% of innovators in the sample (199 people), had *at least one* innovation that was not related to their skills. Robert Salmon, for example, was the son of a carpenter and builder and was apprenticed to an attorney. He then had jobs as a clerk of works, as an architect, and finally as a steward to major landholders. He made a number of improvements that might all be explained by his experience of construction and land management: his improvements to agricultural machines, agricultural techniques, instruments, and civil engineering. Entirely irrelevant, however, was his invention of an artificial abdomen to treat hernias, as were his improvements to surgical instruments for treating urethral and bladder complaints. Taking cases like Armstrong and Salmon together then, 34% of the sample (487 individuals) innovated in areas where they lacked the relevant skills.[10]

Thus, by assessing skills and innovation in unprecedented detail, the sample reveals four important facts about British innovators: they came from very diverse backgrounds; they improved a very diverse range of industries; most of them individually improved more than one industry; and some improved industries even though they did not initially have the skills to do so.

To account for these facts, I suggest the presence and spread of an improving mentality. Innovators were able to see room for improvement, even in wholly unfamiliar areas, and at least envision how such improvements might be brought about. And the

[10] These figures were similar using innovators mentioned in the older lists. Using Allen's list, the proportion who innovated in areas where they lacked the relevant training was 32%; and for MacLeod and Nuvolari's it was 43%. Using Meisenzahl and Mokyr's list, it was 29% - it was likely lower because their list specifically tried to capture innovators who possessed technical competence.

improving mentality appears to have spread from person to person – of the 34% who branched out into the unfamiliar, what mattered in their decisions to become innovators was that they had extensive prior contact with other innovators. Although they lacked relevant skills, innovation could be inspired.

William George Armstrong, the lawyer, had repeated contact with innovators before himself becoming an innovator. His father, though a corn merchant by trade, was also a member of the Newcastle Literary and Philosophical Society – the city's social hub for antiquarians, natural philosophers, and innovators. Surrounded by his father's innovative friends, Armstrong developed a childhood fascination with mechanical contrivances, regularly visiting the works of the engineer William Ramshaw in his spare time after school (he later married Ramshaw's daughter, so his visits may have had other motivations too). Armstrong's master and then law partner Armorer Donkin was an amateur scientist who strongly encouraged his interest in innovation, introducing him to innovative engineers like Thomas Sopwith and Isambard Kingdom Brunel. And while studying for the law at Lincoln's Inn, during his spare time he attended the lectures of Michael Faraday at the Royal Institution. Armstrong was surrounded and encouraged from an early age by innovators and their supporters. Once inspired to emulate these innovators, he overcame his lack of formal training through self-education: "for a good many years I stuck to the law, while all my leisure was given to mechanics" (Heald, 2013, p. 21).

Robert Salmon, like Armstrong, demonstrated an early tendency towards self-education, and was encouraged to devote himself to mechanics by the lawyer to whom he was apprenticed – a man we only know as a Mr Grey living near Leicester Fields. Thus encouraged, Salmon in his spare time disassembled and reassembled watches, and learned how to construct flutes, fifes, and a violin. He became a clerk of works, managing the legal affairs of construction projects, and was employed by Henry Holland, a particularly innovative architect who had also been a partner of the innovative landscape gardener Lancelot "Capability" Brown. Through Holland's mentorship, Salmon attracted the attention of Francis Russell, 5th Duke of Bedford, an active patron of innovators, who employed him in 1794 as a resident architect and mechanist. The Duke at the same time employed other innovators such as the surveyor John Farey senior and the civil engineer William "Strata" Smith, and hosted trials of Joseph Elkington's innovative drainage methods. The 6th Duke, while continuing to employ Salmon, supported famous innovators like Sir Humphry Davy and Humphrey Repton.

Once possessed of the improving mentality, which might have been inspired in him by any one of the innovators he had contact with, Salmon himself innovated. When he recognised that problems were outside of his expertise, he educated himself and experimented. It was thus, despite his lack of any medical training, that his personal sufferings from a hernia prompted him to research and contrive a superior treatment. When demolishing a house, the discovery of some attractive plaster paintings led him to devise a way of transferring them to other surfaces for preservation (*The Annual Biography and Obituary*, 1822, pp. 487–90). Salmon's interests changed based upon where he saw room for improvement or when circumstances yielded new problems to be solved – but a lack of expertise did not stop him from having a go.

One last case indicates how, exactly, skills impacted innovation. The timber merchant and carpenter George Smart in 1800 developed a method of combining hollow poles to form ship masts; and in 1803 on similar principles contrived a chimney-cleaning device. When it came to these initial innovations, his professional familiarity with wood was undoubtedly useful. But he also invented a corn grinding mill and turned his attention to civil engineering, developing the use of lattices in iron bridges. Smart, once again, had prior contact with other innovators. By the time he first invented, he had for some years been an active member of the

Society of Arts; his early experiments on timber were observed by the Scottish agricultural innovator Dr James Anderson; and he had struck up a correspondence with the polymathic naval improver Mark Beaufoy.[11] Once possessed of the improving mentality, Smart initially applied himself to fields that were most familiar – those directly informed by his familiarity with woodwork. Yet when his attention was directed to areas outside of his immediate expertise, he relied upon self-education and consultation with others.

Although at least a third of innovators branched out into the unfamiliar, the majority, 64% (936 innovators in the sample), stuck to what they knew. These were the potters who improved only pottery, and the mechanics who stuck to improving machines. This group too, however, had prior contact with other innovators. As the following two case studies show, what appears to have mattered was not what they were taught, but exactly who did the teaching.

CASE STUDY 1: EDINBURGH UNIVERSITY

Of the innovators who stuck to familiar industries, 18% studied at university (167 people). Unsurprisingly, they were mostly those who studied natural philosophy or mathematics. The science of vacuums, for example, was essential to Denis Papin's development of early steam engines, and informed James Watt's later improvements too.[12] An understanding of chemistry could be applied to the improvement of agriculture, medicine or metallurgy; and an understanding of mathematics could be applied to improving navigation, surveying, civil engineering, and precision instruments.

[11] Later on he was elected to the Institution of Civil Engineers by Henry Robinson Palmer, Joshua Field and Francis Bramah – all innovators. He even installed a trial of Palmer's monorail at his business premises.

[12] For further details of Watt's understanding of science see Jacob (2014, pp. 28–29)

But knowledge of science does not automatically lead to its application. Many scientists stuck to collecting data and interpreting it, aiming only to advance their understanding, and never using that understanding to develop improvements. Many mathematicians contented themselves with purely theoretical investigations rather than mechanical experimentation; and many students of medicine learned only to diagnose and administer treatments rather than concocting new ones. An understanding of scientific subjects may have been a necessary prerequisite to certain technological advancements, but it was not, on its own, sufficient impulse for someone to become an innovator.

As Table 6 shows, it was not simple attendance at a university that led some of the sample to become innovators – it mattered where. Of those who received a university education, most attended universities in Scotland, and particularly the University of Edinburgh.[13] This concentration of innovators at Edinburgh was even more pronounced among those who stuck to improving familiar industries. Moreover, Edinburgh became particularly influential in the eighteenth and nineteenth centuries, as shown by Figure 1.

This concentration of innovators at a single university was not for want of choice. Scotland boasted five universities, with Edinburgh, Glasgow, St Andrews, and two colleges at Aberdeen. England initially had two, Oxford and Cambridge, which in the 1830s were joined by Durham, King's College London, and University College London. Ireland had Trinity College Dublin.[14] Innovators could choose to go abroad too – mostly to Leiden, with a few more attending Angers, Freiberg, Orange, Rheims, and elsewhere. And Edinburgh's taught subjects were not unusual. Those most relevant to innovation – medicine, natural philosophy, and mathematics – were all taught at the other universities.

[13] The figures are not mutually exclusive, because some innovators attended multiple universities.

[14] Queen's University Belfast opened in 1849, too late to educate any innovators in the sample.

The thing that made Edinburgh so unusual was its faculty. It did not just matter what was taught, but by whom. The people who innovated after attending it were taught by particularly innovative professors. The earliest of these at Edinburgh was Colin MacLaurin. The son of a minister, he in 1709 enrolled at Glasgow to study classics. There he came under the influence of Robert Simson, who had also originally studied divinity and classics. But after spending a year in London with Edmond Halley and other innovators associated with the Royal Society, Simson returned to Glasgow in 1711 to become professor of mathematics. With Simson's guidance, MacLaurin became enamoured of Newtonian methods, defended Newton's *Principia* in his thesis, and in 1719 also spent time in London with Halley and with Newton himself. Newton then secured MacLaurin's position at Edinburgh in 1725 to teach mathematics, offering to pay £20 per year towards his salary in order to encourage the appointment.

From Newton, via Simson, and then MacLaurin, the improving mentality spread. With his position at Edinburgh, MacLaurin distracted more students of divinity and classics with ideas of experimentation and innovation. It was in his rooms in the early 1730s that James Short, a later prolific improver of telescopes and agricultural machinery, first tinkered with scientific instruments. And it was MacLaurin's lectures in the 1740s that were attended by Robert Adam, the pioneering architect and interior designer.

More importantly, however, Simson inspired the improving mentality in other students who would go on to teach at Edinburgh – Figure 2 illustrates its spread. Although he continued to teach at Glasgow rather than Edinburgh, two of Simson's later students stand out in particular: William Cullen and John Robison. Cullen would go on to cheapen the manufacture of lime for bleaching linen. And John Robison, encouraged by Simson, turned his mind to improving the Newcomen steam engine, later collaborating with James Watt.

Cullen and Robison stand out most, however, not for their innovations, but as the improving mentality's evangelists. Although they were educated at Glasgow under Simson, they then spent most of their teaching careers at Edinburgh. The time spent at an institution appears to have mattered – and may explain why Simson failed to turn Glasgow into a similar source of innovators. Students who could be interested in improvement, and who possessed the aptitude to innovate successfully, only appeared once in a while. There was no guarantee that an extra year of teaching at one institution would inspire an extra student to become an innovator: inspiration could be offered, but was not always taken.

Cullen taught at Glasgow for nine years, and then held various posts at Edinburgh for the next 34. At Glasgow the only innovator in the sample that Cullen taught was Joseph Black, who had originally enrolled to study arts. At Edinburgh, however, Cullen taught William Withering (who introduced foxglove to treat angina), John Coakley Lettsom (a medical pioneer who also introduced mangel-wurzel to Britain), John Haygarth (who introduced isolated wards for infections and worked on placebos), James Anderson (an agricultural pioneer who also improved canal-boat lifts), and William Symington (who developed marine steam engines). The sheer breadth of industries that these students improved further suggests that what Cullen imparted was more than just knowledge, it was an approach.

Robison initially taught chemistry at Glasgow for four years, where he did not inspire any innovators in the sample. After a brief stint teaching mathematics at Kronstadt in Russia, however, he taught at Edinburgh for the next 32 years. There his students included the innovative civil engineers Peter Ewart and John Rennie, and the chemical pioneer John Leslie. Leslie in particular would prove a source of inspiration for many more innovators at Edinburgh into the early nineteenth century. A particularly favoured student of his was George Buchanan, who after a lengthy career as a civil engineer eventually became President of the Scottish Society of Arts (Buchanan was also brother-in-law to the inventor of electromagnetic rotary devices, Michael Faraday). Leslie also gave much advice and encouragement to Thomas Drummond, an improver of surveying instruments, and to the prolific mechanical engineer James Hall Nasmyth, perhaps most famous for inventing the steam hammer.

Parallel to the spread of the improving mentality initiated by Newton and Simson, Edinburgh gained a reputation as a centre for teaching medicine. This was due to the influence of Alexander Monro *primus* – another crucial carrier and disseminator of the improving mentality, who taught James Lind, the naval surgeon who conducted the first controlled clinical trials on scurvy. Monro *primus* had studied under the Dutch physician Herman Boerhaave, whose work had established Leiden University's reputation as a centre for medicine. And Boerhaave, in turn, had been inspired to apply systematic experimentation to medicine after reading the works of an English innovator, Thomas Sydenham. Boerhaave noted that "none engaged him longer, or improved him more, than Sydenham".[15]

Most importantly, Monro *primus* ensured that Edinburgh hired many more lecturers who could propagate the tradition of medical improvement that stemmed from Boerhaave and Sydenham. In 1726 he was joined by John Rutherford, Andrew Plummer, Andrew St Clair and John Innes, all of whom had also been students of Boerhaave at Leiden. In 1738 they were joined by Charles Alston, yet another former student of Boerhaave, and in 1754 Monro *secundus* began to teach alongside his father. It was under Plummer and Alston that the chemical pioneer Joseph Black completed his thesis. And Dr Erasmus Darwin, the founder of Birmingham's celebrated Lunar Society, was taught by Plummer, Alston, Monro *secundus*, and Rutherford. Plummer's students also included the sulphuric acid manufacturer and

[15] (Atkinson, 1942) According to Boswell, it was while writing Boerhaave's obituary that Johnson first discovered "that love of chymistry which never forsook him". (Kurzer, 2004)

metallurgist John Roebuck; James Keir, who developed copper sheathing for ships; and the agricultural improver James Hutton.

Once again, the diversity of industries that these students improved suggests that Edinburgh's lecturers were not communicating some specific knowledge – they were spreading an improving mindset, which could be applied to any industry. Not all students, of course, became innovators. But what made Edinburgh such a unique source of innovators was the presence of particular lecturers who could inspire that mentality, who were themselves innovators. Other universities taught medicine or mathematics or natural philosophy – but it was the lecturers at Edinburgh who most encouraged their students to apply that education to improvement. The improving mentality made all the difference between understanding and its application.

CASE STUDY 2: MECHANICS

Another case study, this time focusing on mechanics, confirms that it was not just their training that mattered, but by whom. Of the 937 innovators who stuck only to what they knew, 26% (240) were trained as mechanics, engineers or millwrights. This proportion changed dramatically. In the first two centuries from 1547 to 1750 it stood at just 8%, but in the first half of the nineteenth century it had risen to 37%. Mechanical training could be applied to anything, from textile machinery, to agricultural machinery, to coachbuilding, or iron founding; and associated skills of draughtsmanship and precise measurement could be applied to fields like civil engineering. Just as with a scientific education, mechanical training was almost always assigned as being relevant to innovation.

Yet having mechanical skill does not automatically imply that it will be applied to improvement. A modern plumber knows how to supply water to a house, but might not ever think to improve toilets or taps. Modern electricians are also highly trained, but very few invent new switches, circuits, or fuses. Among millwrights, from whom the profession of mechanical engineers sprang, innovation could even be discouraged. The civil engineer James Brindley was reportedly cautioned by his master not to work to a high standard, let alone to innovate: "if thou goes on i' this foolish way o' workin', there will be very little trade left to be done . . . thou knows firmness o' wark's th' ruin o' trade" (Smiles, 1864, p. 135). Although this account may be apocryphal, it is striking that even in the late nineteenth century its reporter could repeat it without expressing surprise.

Once again, training alone was an insufficient cause of innovation – people needed to be inspired to apply those skills to improvement. In Brindley's case, he rented a workshop from the Wedgwood family at Burslem, where he came into contact with many innovative potters, and for whom he designed mills to grind flint. What mattered for innovation was an engineer's prior connections to innovators.

Connections between prominent mechanical engineers have been identified before (MacLeod and Nuvolari, 2009), with a particular focus on firms in London that were created by the former employees of other firms. Central figures such as Henry Maudslay employed a wide range of future innovators, including Joseph Whitworth, Samuel Seaward, John Hall Nasmyth, and Richard Roberts. Maudslay, in turn, had been a star pupil of Joseph Bramah's, who also trained and employed innovators like Arthur Woolf and Joseph Clement. But such connections have only been offered as evidence of the diffusion of particular skills and expertise, rather than of innovation in general.

Focusing exclusively on the connections between engineers obscures the fact that many mechanical innovators had been inspired by innovators from outside of the profession. Henry Beighton, one of the earliest improvers of steam engines, was descended from a line of surveyors and engineers. Yet his earliest innovation was not mechanical, it was cartographical. After corresponding with members of the Royal Society, in 1711 he proposed an unprecedentedly accurate map of Warwickshire. The proposal was only put into action in the 1720s, by which time Newcomen had built one of his engines at Griff, a colliery in Beighton's vicinity. Beighton studied Newcomen's engine with John Theophilus Desaguliers, who had been Isaac Newton's assistant, and invented a steam engine safety valve. Given Newcomen's presence in the area and Beighton's early interest in the engine, it seems likely that they met. Beighton had some background in mechanics, which, along with his commercial interest in local mines, influenced what he decided to improve – innovation's *direction*. Yet he became an innovator, mechanical or otherwise, only after he became associated with innovators at the Royal Society like Desaguliers.

The mechanical engineer John Rennie, aged 12, had in his spare time after school assisted the millwright Andrew Meikle, who improved agricultural and bleaching machinery. And Rennie's elder brother George was an agricultural improver inspired by the work of Henry Home, Lord Kames. John Rennie was also later taught at Edinburgh University by Joseph Black and John Robison, who introduced him to Matthew Boulton and James Watt. Despite these often non-mechanical sources of inspiration, Rennie inspired a whole generation of innovative engineers.

He mentored Peter Ewart, who improved water wheels and textile machinery (and who was also taught at Edinburgh University by his cousin John Robison); James Green, who became one of the South West's most prolific civil engineers; William Tierney Clark, another civil engineer; and Henry Bell, a pioneer of marine steam propulsion. Meikle and Rennie inspired the improving mentality in their sons too. George Meikle developed a water-lifting wheel and, together with his father, a drum threshing machine. Rennie was succeeded in his business by George and another John Rennie, both of whom became prominent innovators in their own right.

By the nineteenth century, it was common for mechanically-trained innovators to have many plausible sources of inspiration. William Fairbairn, who greatly improved steam ships, could have listed Rennie as one of many possible influences before he became an innovator. Before his apprenticeship, Fairbairn worked for a few days as a labourer on one of Rennie's bridge projects. He was also well aware of Rennie's status as an innovator, immediately seeking him out after his apprenticeship had ended (although guild rules prevented him from being hired). Fairbairn also worked briefly for the inventive civil engineer John Grundy junior, and shared lodgings in London with a Scottish clergyman named James Hall, who introduced him to the Society of Arts and to Alexander Tilloch, and with whom he collaborated on developing an unsuccessful steam-driven sand-digging machine.[16] Fairbairn had also been apprenticed to John Robinson, an engine-wright to the Percy Main colliery, who in turn had been appointed by the innovative mining engineer John Buddle (it was during this apprenticeship that Fairbairn first tried to apply the improving mentality to romance). And Fairbairn befriended George Stephenson, who worked at a neighbouring colliery, later famous for his improvements to steam locomotives and the miner's lamp, but at that stage already improving engine brakes and trying to design a perpetual motion machine (Smiles, 1904, pp. 40–41).

Perhaps the most significant source of inspiration for mechanical engineers, however, was the engine-making workshop of Boulton and Watt. They trained innovative employees like John Southern, who invented the steam indicator, and William Murdoch, who improved on Watt's designs and developed an eclectic range of inventions in other areas, such as steam guns, drilling machines, pneumatic message systems, and dried cod as a replacement for

[16] Hall was an innovator himself, having won a silver medal of the Society of Arts in 1809 for a method of using beanstalks to make hemp substitutes, which he patented the following year. His submission to the Society indicates that he corresponded with the eminent scientist and innovator Humphry Davy, who bleached a sample of his bean-cloth for him (Tilloch, 1810, p. 186).

sturgeon in the production of isinglass – a substance used in making glue and clarifying ale. Via Murdoch, the improving mentality also spread to innovators in non-mechanical fields like gas lighting: to his friend George Augustus Lee; to his apprentice Samuel Clegg (who became chief engineer to the Imperial Gas Light and Coke Company); and to Boulton's pupil John Malam (who became foreman of the Chartered Gaslight and Coke Company).

Boulton and Watt disseminated the idea of improvement even inadvertently, laying the seeds for their own competition. In Cornwall they employed the brothers Hornblower, Jabez and Jonathan, and later sued them for patent infringement. The father to the brothers, another innovator named Jonathan Hornblower, had worked with Watt too. There was also a longstanding enmity between Watt and Richard Trevithick, which dated back to Watt's initial forays into the Cornish market when he was ill-treated by Trevithick's father (Trevithick, 1872, pp. 30–32). Despite the inherited antagonism, Richard Trevithick was likely also inspired by Watt's employee, Murdoch. Murdoch lived next door to the Trevithicks during his years in Redruth, and by some accounts was willing to show off some of his experiments to young Richard. Though Trevithick's later development of high-pressure steam engines may or may not have been due to Murdoch's influence, they were certainly on friendly terms.[17]

Thus, from Watt, the improving mentality rapidly spread. But Watt had himself been inspired by non-mechanics. He had been an associate of Joseph Black and John Robison at Glasgow University, where he had worked as a scientific instrument maker. Black introduced

[17] Alternative sources of inspiration abound for Richard Trevithick. His father improved steam boilers in 1775, before Watt's involvement in Cornwall. And the Cornish scientist and innovator Davies Gilbert reported how Trevithick consulted him before developing high pressure steam engines: "Our correspondence commenced. . . to ask my opinion on various projects that occurred to his mind – some of them very ingenious, and others so wild as not to rest on any foundation at all." (Trevithick, 1872, pp. 22–28, 62–65)

him to the his future business partner, the innovative metallurgist and chemical manufacturer John Roebuck, a former student at Edinburgh and Leiden.

Cases like Beighton, Meikle, Rennie, Fairbairn, and Watt, show that engineers were not just highly connected with one another, but could inspire and be inspired by innovators in other industries too. Beighton was influenced by his contacts at the Royal Society, just as Rennie and Ewart and Watt were mentored by John Robison at the University of Edinburgh. Fairbairn drew inspiration from London's innovation-promoting institutions like the Society of Arts. What spread between such different industries was not a particular skill or any special knowledge, but an improving mentality that could be applied to any industry. Mechanical skill could be applied to a broad range of industries – but engineers applied that skill to innovation after they were encouraged by other innovators. The improving mentality meant the difference between expertise and innovation.

CONCLUSIONS

Skill and understanding were applied when people solved particular technological problems. But it was the improving mentality that made all the difference between expertise and innovation, between understanding and its application. As we have seen, the impact of education and skills on innovation can only be properly understood when we examine their content, not just their level. Doing so reveals that innovators had diverse skills, that they improved a diverse range of industries, and that the majority of innovators each improved more than one industry. It also reveals that at least a third lacked the requisite skills and education for their innovations. This can be explained with reference to an improving mentality – a mindset, independent of knowledge or skill or context, which meant that people could everywhere see room for improvement. Once possessed of the mentality, people with any skills could apply themselves to any industries they chose. The lack of skill was no major barrier for innovators, but could be overcome through self-education or by relying upon the expertise of others. And the improving mentality spread from person to person. This meant that what mattered to innovation was not just what was taught, but who did the teaching.

REFERENCES

Allen, R.C., 2009. The British Industrial Revolution in Global Perspective, 1st ed. Cambridge University Press.

Atkinson, E.R., 1942. Samuel Johnson's "Life of Boerhaave." J. Chem. Educ. 19, 103. doi:10.1021/ed019p103

Auerbach, J.A., 1999. The Great Exhibition of 1851: A Nation on Display. Yale University Press.

Barker, T.C., Harris, J.R., 1959. A Merseyside town in the industrial revolution: St. Helens, 1750-1900. F. Cass.

Barlow, A., 1879. The history and principles of weaving by hand and by power. London S. Low.

Baten, J., van Zanden, J.L., 2008. Book production and the onset of modern economic growth. J. Econ. Growth 13, 217–235. doi:10.2307/41219214

Bell, R.P., 1855. Some Account of "Bell's Reaping Machine." J. Agric., 2 5, 185–204.

Berg, M., 2007. Luxury and Pleasure in Eighteenth-Century Britain. Oxford University Press.

Berg, M., 1994. The Age of Manufactures, 1700-1820: Industry, Innovation, and Work in Britain. Psychology Press.

Berg, M., Hudson, P., 1994. Growth and Change: A Comment on the Crafts-Harley View of the Industrial Revolution. Econ. Hist. Rev. 47, 147–149. doi:10.2307/2598224

Bessemer, H., 1905. Sir Henry Bessemer, F.R.S. : an autobiography ; with a concluding chapter. London, Offices of "Engineering,."

Boucekkine, R., De La Croix, D., Peeters, D., 2007. Early Literacy Achievements, Population Density, and the Transition to Modern Growth. J. Eur. Econ. Assoc. 5, 183–226.

Broadberry, S., Campbell, B.M.S., Klein, A., Overton, M., Leeuwen, B. van, 2015. British Economic Growth, 1270-1870. Cambridge University Press, New York.

Bruland, K., 2004. Industrialisation and technological change, in: Floud, R., Johnson, P. (Eds.), The Cambridge Economic History of Modern Britain. Cambridge University Press, Cambridge, pp. 117–146.

Chapman, S.D., 1967. The early factory masters: the transition to the factory system in the Midlands textile industry. David & Charles.

Clark, G., 2010. The macroeconomic aggregates for England, 1209-2008, in: Research in Economic History, Research in Economic History. Emerald Group Publishing Limited, pp. 51–140.

Crafts, N., 2004. Productivity Growth in the Industrial Revolution: A New Growth Accounting Perspective. J. Econ. Hist. 64, 521–535.

Crafts, N.F.R., 1985. British Economic Growth During the Industrial Revolution. Clarendon Press.
Crafts, N.F.R., Harley, C.K., 1992. Output Growth and the British Industrial Revolution: A Restatement of the Crafts-Harley View. Econ. Hist. Rev. 45, 703–730. doi:10.2307/2597415
Day, L., McNeil, I., 2002. Biographical Dictionary of the History of Technology. Routledge.
de Pleijt, A.M., 2011. The Role of Human Capital in the Process of Economic Development: The Case of England, 1307-1900 (Working Paper No. 0021). Utrecht University, Centre for Global Economic History.
Deane, P., Cole, W.A., 1969. British Economic Growth 1688-1959: Trends and Structure, 2nd edition. ed. Cambridge University Press.
Fairbairn, W., 1877. The life of Sir William Fairbairn, bart : partly written by himself. Longmans, Green & Co., London.
Galor, O., 2005. From stagnation to growth: unified growth theory. Handb. Econ. Growth 1, 171–293.
Galor, O., Moav, O., 2002. Natural Selection and the Origin of Economic Growth. Q. J. Econ. 117, 1133–1191. doi:10.2307/4132476
Gilbey, S.W., 1903. Early Carriages and Roads. Vinton & Company, 1td.
Harkness, D.E., 2007. The Jewel House: Elizabethan London and the Scientific Revolution. Yale University Press.
Heald, H., 2013. William Armstrong: Magician of the North. McNidder and Grace Limited.
Heaton, H., 1920. The Yorkshire woollen and worsted industries, from the earliest times up to the Industrial revolution. Oxford : The Clarendon press.
Hewitt, R., 2013. Map of a Nation: A Biography Of The Ordnance Survey. Granta Books, London.
Hulme, E.W., 1909. The Early History of the English Patent System, in: Select Essays in Anglo-American Legal History. Little, Brown, and Company, Boston, pp. 117–147.
Jacob, M.C., 2014. The First Knowledge Economy: Human Capital and the European Economy, 1750-1850. Cambridge University Press, Cambridge.
James Burnley, 1889. The History of Wool and Woolcombing. Low, Marston, Searle and Rivington.
Jenkins, D.T., Ponting, K.G., 1987. The British Wool Textile Industry, 1770-1914. Scolar Press.
Jenkins, R., 1936. The Collected Papers of Rhys Jenkins. Cambridge University Press for the Newcomen Society.
Kelly, M., Mokyr, J., Ó Gráda, C., 2014. Precocious Albion: A New Interpretation of the British Industrial Revolution. Annu. Rev. Econ. 6, 363–389. doi:10.1146/annurev-economics-080213-041042
Khan, B.Z., 2015. Knowledge, Human Capital and Economic Development: Evidence from the British Industrial Revolution, 1750-1930 (Working Paper No. 20853). National Bureau of Economic Research.
Khan, B.Z., Sokoloff, K.L., 2004. Institutions and Democratic Invention in 19th-Century America: Evidence from “Great Inventors,” 1790-1930. Am. Econ. Rev. 94, 395–401.
Khan, B.Z., Sokoloff, K.L., 1993. “Schemes of Practical Utility”: Entrepreneurship and Innovation Among “Great Inventors” in the United States, 1790–1865. J. Econ. Hist. 53, 289–307. doi:10.1017/S0022050700012924

Kurzer, F., 2004. Chemistry in the Life of Dr Samuel Johnson. Bull. Hist. Chem. 29, 65–89.
MacLeod, C., Nuvolari, A., 2009. "Glorious times": the emergence of mechanical engineering in early industrial Britain, c. 1700-1850. Bruss. Econ. Rev. 52, 215–237.
MacLeod, C., Nuvolari, A., 2006. The Pitfalls of Prosopography: Inventors in the "Dictionary of National Biography." Technol. Cult. 47, 757–776. doi:10.2307/40061119
Magner, L.N., 1992. A History of Medicine. CRC Press.
Marshall, J., 1978. Biographical Dictionary of Railway Engineers. David & Charles, Newton Abbot Eng. ; North Pomfret, Vt.
McCloskey, D., 2011. Bourgeois Dignity: Why Economics Can't Explain the Modern World. University of Chicago Press.
Meisenzahl, R., Mokyr, J., 2012. The Rate and Direction of Invention in the British Industrial Revolution: Incentives and Institutions, in: Lerner, J., Stern, S. (Eds.), The Rate and Direction of Inventive Activity Revisited. University of Chicago Press, Chicago, pp. 443–479.
Mitch, D., 1993. The Role of Human Capital in the First Industrial Revolution, in: Mokyr, J. (Ed.), The British Industrial Revolution: An Economic Perspective. Westview Press, Boulder, pp. 267–307.
Mokyr, J., 2009. The Enlightened Economy: An Economic History of Britain 1700-1850. Yale University Press.
Mokyr, J., 1992. The Lever of Riches: Technological Creativity and Economic Progress. Oxford University Press.
Morrison-Low, A.D., 2007. Making Scientific Instruments in the Industrial Revolution. Ashgate.
Ó Gráda, C., 2016. Did Science Cause the Industrial Revolution? J. Econ. Lit. 54, 224–239.
Schumpeter, J.A., 1939. Business cycles: a theoretical, historical, and statistical analysis of the capitalist process. McGraw-Hill Book Company, inc.
Skempton, A.W., 2002. A Biographical Dictionary of Civil Engineers in Great Britain and Ireland: 1500-1830. Thomas Telford.
Smiles, S., 1904. Lives of the Engineers: George and Robert Stephenson. J. Murray.
Smiles, S., 1864. James Brindley and the Early Engineers. J. Murray.
Squicciarini, M.P., Voigtländer, N., 2015. Human Capital and Industrialization: Evidence from the Age of Enlightenment. Q. J. Econ. 130, 1825–1883. doi:10.1093/qje/qjv025
Stanley, A., 1995. Mothers and Daughters of Invention: Notes for a Revised History of Technology, 1st edition. ed. Rutgers University Press, New Brunswick, N.J.
Strickland, M., Strickland, J.M., 1843. A Memoir of the Life, Writings, and Mechanical Inventions of Edmund Cartwright. Saunders and Otley.
Sumner, J., 2013. Brewing Science, Technology and Print, 1700-1880. University of Pittsburgh Press.
Temin, P., 2000. A Response to Harley and Crafts. J. Econ. Hist. 60, 842–846. doi:10.2307/2566440
The Annual Biography and Obituary, 1822. . Longman.
Tilloch, A., 1810. The Philosophical Magazine: Comprehending the Various Branches of Science, the Liberal and Fine Arts, Geology, Agriculture, Manufactures and Commerce. Richard Taylor and Company, London.
Trevithick, F., 1872. Life of Richard Trevithick: With an Account of His Inventions. E. & F.N. Spon.

Turner, G.L., 1998. Scientific Instruments, 1500-1900: An Introduction. University of California Press.
Wood, H.T., 1913. A history of the Royal Society of Arts. J. Murray, London.
Woodcroft, B., 1854. Titles of Patents of Invention, Chronologically Arranged: From March 2, 1617 (14 James I.) to October 1, 1852 (16 Victoriae). G.E. Eyre & W. Spottiswoode.

TABLES

Table 1
Education and training of innovators

Father's Profession	1,006 (69%)
Primary & Secondary	527 (36%)
Skills-Based	769 (53%)
Higher Education	355 (24%)
Profession	1,263 (87%)
Unknown	28 (2%)

Table 2:
Number of innovators engaged in each industry (% of total innovators)

Actuarial	13 (1%)	Metals	133 (9%)
Agriculture & Horticulture	104 (7%)	Misc. Machinery	254 (17%)
Agricultural Machines	67 (5%)	Musical Instruments	38 (3%)
Alcohol	45 (3%)	Naval / Shipbuilding	165 (11%)
Ceramics	41 (3%)	Navigation	78 (5%)
Chemical	162 (11%)	Organisational	50 (3%)
Civil Engineering	205 (14%)	Other	66 (5%)
Coachbuilding	69 (5%)	Photography	28 (2%)
Communications Systems	31 (2%)	Printing Techniques	65 (5%)
Construction	123 (8%)	Printing Machines	47 (3%)
Decorative Arts	31 (2%)	Railway Engineering	92 (6%)
Electric	85 (6%)	Safety	65 (4%)
Food Processing	70 (5%)	Steam Engineering	219 (15%)
Gas	44 (3%)	Telegraphy (Electric)	26 (2%)
Glass	24 (2%)	Textile Design	7 (0%)
Hardware Durables	101 (7%)	Textile Machines	219 (15%)
Instruments	310 (21%)	Tools	113 (8%)
Interior Design	16 (1%)	Transport Services	13 (1%)
Light	58 (4%)	Weapons & Fortifications	112 (8%)
Medical & Pharmaceutical	122 (8%)		

Table 3
Skill background of innovators
(% of total innovators)

Agriculture & Horticulture	152 (10%)	Military	98 (7%)
Ceramics	22 (2%)	Mining	64 (4%)
Chemistry	92 (6%)	Music	20 (1%)
Clergy	105 (7%)	Naval Construction	29 (2%)
Clerical, Law & Journalism	179 (12%)	Other	36 (2%)
Coachbuilding	10 (1%)	Precision Instruments	109 (7%)
Commerce & Retail	239 (16%)	Printing	75 (5%)
Construction & Building	53 (4%)	Sailor	66 (5%)
Decorative & Artistic	55 (4%)	Science	60 (4%)
Distilling & Brewing	43 (3%)	Surveying	192 (13%)
Food Processing	25 (2%)	Teaching	117 (8%)
Gas working	6 (0%)	Textile Finishing	68 (5%)
Gentleman	194 (13%)	Textile Manufacturing	188 (13%)
Mechanics	266 (18%)	Transport	11 (1%)
Medicine	170 (12%)	Weapon Making	14 (1%)
Metalwork	172 (12%)	Woodworking	76 (5%)

Table 4
Higher education of innovators
(% of total innovators)

Art & Music	20 (1%)
Divinity & Religious Studies	42 (3%)
Humanities, Arts, Classics, Languages	53 (4%)
Law	27 (2%)
Mathematics	81 (6%)
Medicine	122 (8%)
Natural Philosophy & Science	99 (7%)
Unclear	43 (3%)

Table 5
Relevance of innovations to the skills of innovators

Date of first innovation	All innovations irrelevant	Some innovations irrelevant	All innovations relevant
1547-1600	14 (39%)	3 (8%)	17 (47%)
1601-1650	12 (50%)	3 (13%)	8 (33%)
1651-1700	28 (42%)	4 (6%)	32 (48%)
1701-1750	42 (26%)	17 (10%)	101 (62%)
1751-1800	92 (20%)	57 (13%)	297 (65%)
1801-1851	99 (14%)	115 (16%)	481 (68%)
Total	288 (20%)	199 (14%)	936 (64%)

Table 6
University-educated innovators, by selected university attendance

	University-educated innovators (%)	...with innovations all related to education (%)
Scottish Total	133 (50)	101 (60)
Edinburgh	92 (35)	74 (44)
Glasgow	33 (12)	25 (15)
St Andrews	12 (5)	7 (4)
Aberdeen	11 (4)	5 (3)
English Total	114 (43)	55 (33)
Cambridge	64 (24)	32 (19)
Oxford	50 (19)	23 (9)
KCL & UCL	3 (1)	3 (2)
Dublin	14 (5)	9 (3)
Leiden	17 (6)	10 (6)
Total	267 (100)	167 (100)

FIGURES

Figure 1

Numbers of innovators attending selected universities, by date of first innovation

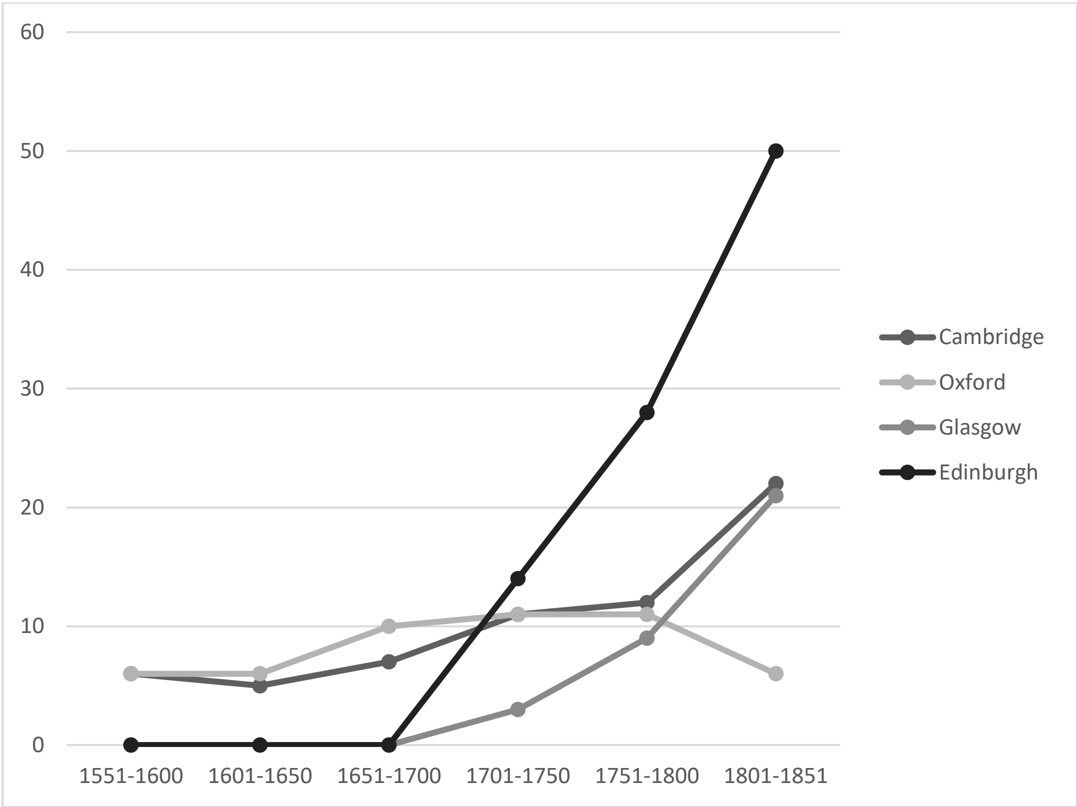

Figure 2

Spread of the improving mentality among Scottish lecturers