The Relevance of Skills to Innovation during the British Industrial Revolution, 1651-1851

WORKING PAPER
(NB: the final sample will be double the size, and extended back to 1551)

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What role did skills and education have in causing the rate of innovation to accelerate during the British Industrial Revolution? I present new evidence on the educational and professional backgrounds of 677 people who innovated in Britain between 1651 and 1851. Almost a third of innovators improved at least one industry or process for which they had no prior professional experience or training. And a fifth of innovators had professional experience irrelevant to all of their innovations. Yet common to almost all innovators was that they had prior contact with other innovators, suggesting the spread of an improving mentality. Where people lacked the skills to realise their envisioned improvements, they engaged in self-education. Even of the majority of innovators who improved familiar industries, it was not the skills training itself that influenced their decisions to become innovators, but that they were trained by other innovators. Skills and education often influenced what people chose to improve – people tended to stick to what they knew best – but not their decisions to become innovators.

Introduction

In the two centuries between the end of the English Civil War in 1651 and the Great Exhibition of 1851, Britain became the world's technological leader.[1] The Great Exhibition was symbolic of the transformation from war-torn country to innovation superpower. Between May and October of 1851 over six million people, equivalent to a fifth of the country's population, flocked to a glass hall, a Crystal Palace, purpose-built to celebrate the latest innovations.[2] The transformation – an Industrial Revolution – was brought about by an unprecedented acceleration in the rate of innovation. In 1651 transparent glass had to be imported from Venice because nobody in Britain knew how to produce it. By 1851 the Crystal Palace, the largest enclosed space on earth, was constructed of 300,000 panes of the largest glass sheets ever produced.[3] Similar technological leaps occurred in nearly all industries, beyond the famous examples of cotton, iron, and steam. Innovation accelerated in agriculture, medicine, pottery, furniture making, navigation, and even gardening.[4]

Economic historians debate just how much the economy grew, yet all agree that innovation accelerated.[5] The sustained growth that Britain experienced by the mid-nineteenth century had its roots in the innovations of the two centuries after 1651. Innovations simply affected the economy to different degrees, and often after a delay. The steam engine, for example, contributed most to economic output after 1850:[6] fifty years after Richard Trevithick's first high pressure steam engines; almost a century after James Watt's development of low pressure steam engines in 1769; and over 150 years after Denis Papin's initial application of atmospheric pressure to pistons in 1690.

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[1] "British" in this context refers to the British Isles: the geographical area that today comprises the United Kingdom and the Republic of Ireland. This is to avoid confusion: "Britain" as a political entity was formed in 1707 from the union of Scotland and England, which had been under the same monarch since 1603. Ireland was formally added to the union in 1801 to form the United Kingdom.
[2] Auerbach, *The Great Exhibition of 1851*, 1, 32.
[3] Ibid., 135.
[4] Mokyr, *The Enlightened Economy*.
[5] See for example: Deane and Cole, *British Economic Growth 1688-1959*; Crafts, *British Economic Growth During the Industrial Revolution*; Crafts and Harley, 'Output Growth and the British Industrial Revolution'; Berg and Hudson, 'Growth and Change'; Temin, 'A Response to Harley and Crafts'; Crafts, 'Productivity Growth in the Industrial Revolution'; Clark, 'Macroeconomic Aggregates for England'; Broadberry et al., *British Economic Growth, 1270-1870*.
[6] Crafts, 'Steam as a General Purpose Technology'.

Skills and education were undoubtedly prerequisites to innovation. Some argue that Britain became a society capable of having sustained economic growth because of an increase in general investment in human capital.[7] School creation, book production, literacy, and numeracy, all certainly increased.[8] And some suggest Britain had better nutrition than other European countries, such that its workers had superior cognitive skills and were more productive.[9] But the general increase in skills and education did not necessarily cause an acceleration of innovation. Both Mitch and de Pleijt find that neither literacy nor primary schooling had much impact on economic growth.[10] Highly literate societies like Sweden failed to achieve an acceleration of innovation, and higher literacy could even discourage innovation when channelled through highly bureaucratic societies like in China.[11]

Having a more literate or numerate population could improve the productivity of some industries, largely because they allowed for the more efficient operation of new technologies.[12] But this is not the same as such skills increasing innovation. Computer literacy today helps people to use computers, allowing them to be more productive. It may even speed up the adoption of computers, affecting economic growth. But the spread of computer literacy does not necessarily encourage people to *improve* computers. Knowing how to use a word processor or surf the web does not, on its own, make one an innovator.

Of course, knowing something about computers is still a prerequisite to improving them. Margaret Jacob emphasises the reliance of innovation on access to scientific knowledge and applied mechanical training, which involved the experimental method in the Newtonian tradition and a sophisticated understanding of the interaction of forces.[13] De Pleijt finds correlations between levels of higher education and growth

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[7] Galor and Moav, "Natural Selection and the Origin of Economic Growth"; Galor, "From Stagnation to Growth."

[8] Boucekkine, De La Croix, and Peeters, "Early Literacy Achievements, Population Density, and the Transition to Modern Growth"; Baten and van Zanden, "Book Production and the Onset of Modern Economic Growth."

[9] Kelly, Mokyr, and O'Grada, "Precocious Albion."

[10] Mitch, "The Role of Human Capital in the First Industrial Revolution"; de Pleijt, "The Role of Human Capital in the Process of Economic Development."

[11] McCloskey, *Bourgeois Dignity*, 162–64.

[12] Nelson and Phelps, "Investment in Humans, Technological Diffusion, and Economic Growth"; Becker, Hornung, and Woessmann, "Catch Me If You Can"; van Lottum and van Zanden, "Labour Productivity and Human Capital in the European Maritime Sector of the Eighteenth Century"; Squicciarini and Voigtländer, "Human Capital and Industrialization"; Kelly, Mokyr, and O'Grada, "Roots of the Industrial Revolution."

[13] Jacob, *The First Knowledge Economy*, 221–23.

up to 1750,[14] and Squicciarini and Voigtländer find a strong association between economic development and the presence of scientific intellectual elites, as demonstrated by subscriptions to the *Encyclopédie* in French cities.[15] Skills like clock-making and watch-making were also invaluable to the early stages of mechanisation.[16] And Britain's highly skilled workers were certainly in demand abroad.[17]

But the superiority of British skilled workers might have been as much a result of innovation as its cause. Feldman and van der Beek note that after the invention of machines, mechanical skills become better paid, then leading to increased investment to acquire those skills.[18] Britain, after all, was not alone in having an apprenticeship system.[19] And the importance of scientific knowledge is disputed. Cormac O'Grada posits that it only became important in the 1850s, during the second wave of industrialisation.[20] Meisenzahl and Mokyr also emphasise the role of tacitly communicated, technical competence, finding that levels of schooling and higher education among innovators were lower than Jacob's analysis might suggest.[21]

Rarely mentioned, however, is whether the skills and education of innovators were actually relevant to their innovations. The presence of amateur innovators is almost entirely ignored. Edmund Cartwright, who invented the power loom, was an Anglican clergyman. And even the skills of the commercially-minded are glossed over. Richard Arkwright, for example, had no direct experience of carding or spinning textiles – he was a barber, wigmaker, and publican. The largest scale attempt thus far to measure the human capital acquisition of British innovators merely counts how many went to school, were apprenticed, and went to university.[22]

Yet what mattered for innovation was not the level of education, but its content. William George Armstrong was an inventor of steam engines, electrostatic machines, hydraulic cranes, breech-loading guns, and submarine mines. He attended primary

[14] de Pleijt, "The Role of Human Capital in the Process of Economic Development."
[15] Squicciarini and Voigtländer, "Human Capital and Industrialization."
[16] Allen, *The British Industrial Revolution in Global Perspective*, 204–6; McCloskey, *Bourgeois Dignity*, 114–18; MacLeod and Nuvolari, "'Glorious Times.'"
[17] Kelly, Mokyr, and O'Grada, "Precocious Albion."
[18] Though they hypothesise that this initial lead may have then had a dynamic effect, with the expanded population of mechanics contributing toward further inventions. Feldman and van der Beek, 'Skill Choice and Skill Complementarity in Eighteenth Century England'.
[19] Kelly, Mokyr, and O'Grada, "Precocious Albion."
[20] O'Grada, "Did Science Cause the Industrial Revolution?," 33.
[21] Meisenzahl and Mokyr, "The Rate and Direction of Invention in the British Industrial Revolution."
[22] Ibid.

school and grammar school, was twice apprenticed, attended a higher education institution, and embarked on a successful professional career, all before becoming an innovator. We know his father's profession too. Armstrong's experience 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 tacit knowledge.

Yet both of Armstrong's apprenticeships were to lawyers, and the higher education institution he attended was Lincoln's Inn, where he also studied law. His professional education was as a partner in a law firm, and his father was a corn merchant and a local politician. With regards to his primary and secondary education, we know little about it other than the fact of attendance. Judging by what we know about such education in general, however, it likely only covered basic literacy and numeracy. The cement pioneer Isaac Charles Johnson described his experiences at a dame's school and a commercial school as being useful for nothing more than the "three R's" of reading, writing, and some basic arithmetic.[23] Such schooling was not immediately conducive to innovation, albeit a prerequisite. Nothing in Armstong's education or training had anything 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".[24]

The Sample of Innovators

And Armstrong's case, it turns out, was not exceptional. I compiled a sample of 677 people who became innovators in the two hundred years between 1651 and 1851 – an exercise for which there is ample precedent.[25] 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 colleagues to wash their hands before operations; the razor-strop

[23] Johnson, *Autobiography of Isaac Charles Johnson*, 7.
[24] Heald, *William Armstrong*, 40.
[25]See: Allen, *The British Industrial Revolution in Global Perspective*, 242–71; Khan and Sokoloff, "Institutions and Democratic Invention in 19th-Century America"; Khan, "Knowledge, Human Capital and Economic Development"; Khan and Sokoloff, "'Schemes of Practical Utility'"; MacLeod and Nuvolari, "The Pitfalls of Prosopography"; Meisenzahl and Mokyr, "The Rate and Direction of Invention in the British Industrial Revolution."

seller George Packwood, a pioneer of direct advertising; and James Dodson, pioneer of modern life insurance.[26]

Innovators are sometimes distinguished by importance, labelled “macro-” and “micro-inventors”, or “stars” and “tweakers”.[27] But this sample does not do so. Innovation is a process with many steps, from noticing an opportunity for improvement, to designing a solution, implementing it, and then adjusting it further. The designers, the implementers, and the tweakers were all still innovators. Some people innovated more than others, or in ways that were more immediately obvious. Some innovators were more successful than others, or have since received longer-lasting recognition. A few innovators collaborated, and many worked alone. But all innovators improved, to varying degrees, on the achievements of predecessors. These men and women all had in common that they innovated *at all*. To understand the cause of the British Industrial Revolution we must understand why these people became innovators, rather than passing judgement on their eventual impact.

Note, however, 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 that understanding towards improvement. Sir Isaac Newton is included in the sample for his invention of a reflecting telescope in 1669, not for his celebrated contributions to our understanding of physics. Robert Hooke is not included for Hooke’s Law of elasticity or for coining the use of “cell” in biology, but for his various improvements to scientific instruments, glass-making, and even spring-suspension coaches.

The sample was compiled from some existing lists of innovators, and corrects for biases by adding innovators from other sources too. It fully incorporates a list compiled by Allen, and a list compiled by MacLeod and Nuvolari from the nineteenth century

[26] Unless otherwise stated, all biographical details about innovators are taken from their respective entires in the online *Oxford Dictionary of National Biography* or the *Biographical Dictionary of Civil Engineers in Great Britain and Ireland*.

[27] Such categorisations are used, for example, by Allen, *The British Industrial Revolution in Global Perspective*, 239–42; and by Meisenzahl and Mokyr, ‘The Rate and Direction of Invention in the British Industrial Revolution’.

Dictionary of National Biography and its modern descendant, the *Oxford Dictionary of National Biography*.[28] MacLeod and Nuvolari 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.[29] To correct for this bias, the sample includes all innovators mentioned in some works by Maxine Berg and by Kristine Bruland:[30] Berg's works emphasises consumer tastes, providing the sample with innovators like the furniture designer Thomas Chippendale; and Bruland's work on other neglected industries provides the sample with innovators like Admiral Sir Isaac Coffin, who developed an oven for the mass production of biscuits. The sample also includes all innovators mentioned in Joel Mokyr's *The Enlightened Economy*, which names innovators active in an especially broad range of industries. [31]

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 the bias toward patentees, the sample includes all innovators mentioned in the "Manufactures" and "Agriculture" categories of *A History of the Royal Society of Arts*.[32] The work is a rich source of non-patentees: between 1765 and 1845 patented innovations were not (officially) allowed to win the Society's prizes. And it generally emphasises industries where patenting was uncommon, such as agriculture, agricultural machinery, horticulture, telegraphy, brewing and textile design.[33] It also emphasises those people whose improvements had humanitarian aims such as George William Manby, who developed lifeboats, portable fire extinguishers, and a means of preventing accidents on ice.

Though the sample includes innovators from some older lists, some innovators who feature in those lists were omitted because they only started innovating after 1851. Their decision to become innovators would have been influenced by factors that were not present before 1851 (such as significant reforms to the patent system that took

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[28] Allen, *The British Industrial Revolution in Global Perspective*; MacLeod and Nuvolari, "The Pitfalls of Prosopography."
[29] MacLeod and Nuvolari, "The Pitfalls of Prosopography," 775–76.
[30] Berg, *The Age of Manufactures, 1700-1820*; Berg, *Luxury and Pleasure in Eighteenth-Century Britain*; Bruland, 'Industrialisation and Technological Change'.
[31] Mokyr, *The Enlightened Economy*.
[32] Wood, *A History of the Royal Society of Arts*.
[33] Textile design is a particularly neglected area, especially as compared to the prominence usually given to textile machinery. Pioneers in this industry include the tapestry and pile carpets producers Thomas Moore and Thomas Whitty.

effect from 1st October 1852). Similarly, though they appear in some other lists, the sample excludes hoaxes and frauds like Samuel Alfred Warner, who in 1819 convinced the British government that he had invented an invisible shell. The aim is to understand why people innovated, rather than why people pretended to innovate. The aim is also to understand why innovation accelerated in Britain. The sample includes immigrants like the Saxon-born Friedrich Koenig, inventor of the steam-driven printing press, but excludes British-born innovators who never innovated in Britain. John William Draper and Hugh Orr are mentioned in other lists of innovators, but only became innovators after they moved to the United States.

The Relevance of Skills to Innovation

Innovators, as shown in Table 1, were more highly educated than has previously been measured. The proportion of innovators with some kind of schooling was 38%, much higher than the 7% found by Meisenzahl and Mokyr. Primary and secondary education, moreover, is not fully represented by attendance at schools. At least 9% (63) of innovators were privately tutored on a formal or semi-formal basis. The engineer and compiler of patent records Bennet Woodcroft, for example, was tutored by the chemist John Dalton. A few additional innovators (15) attended extra-curricular schools that are not easily categorised as primary or secondary, such as night schools, foreign schools, a Congregational Fund Academy (attended by the amateur inventor Humphry Gainsborough), and a Mathematical Academy (by the engineer Davies Gilbert). When both private tutoring and extra schools are added to the total, the rate of primary and secondary education rises to 44% (though even this higher figure is likely an underestimate – records of schooling are the hardest to find, if kept at all).

The rate of university attendance was also higher than that recorded by Meisenzahl and Mokyr (at 22% compared to 15%). And they also underestimate the levels of higher education, which is not fully represented by university attendance alone. The higher education rate stands at 28% when one includes the innovators who attended Mechanics' Institutes, and the physicians and surgeons who were enrolled at the various London hospitals (Guy's, St Thomas', St George's, St Bartholomew's) or anatomical schools. Others attended Royal military academies, artists' academies or lawyers' Inns of Court.

Table 1
The Education and Training of Innovators
(%)

Primary & Secondary	298 (44)
Skills-Based	427 (63)
Higher Education	187 (28)
Unknown	142 (21)

Further evidence can also be identified for skills-based training. Meisenzahl and Mokyr recorded only apprenticeships, finding a rate of 40%, and the rate for the present sample is similar, at 38%. But apprenticeships were not the only indicator of the acquisition of skills and tacit knowledge – they were simply the most formal institution through which to acquire on-the-job training. We must also count informal apprenticeships (often informal training by family members, particularly fathers), assistantships, and early work experience as employees. The pioneering architect and interior designer Robert Adam never did any formal apprenticeship, yet was employed for some years at his father's architect's office. The civil engineer Benjamin Outram, assisted his father as a surveyor and then assisted William Jessop in his work on the Cromford Canal. When taking cases such as these into account, the proportion of innovators with skills-based training almost doubles, to 63%.

The number of innovators with wholly unknown educational backgrounds stands at 21%. This compares particularly favourably with Meisenzahl and Mokyr, who did not find any evidence of human capital acquisition for 41% of their list. We can, however, obtain some further idea of the professional backgrounds of innovators by measuring the professional backgrounds of their fathers, and by recording the professions they engaged in before becoming innovators. Though we know nothing of James Caleb Anderson's education, nor his professional activities before innovating (he was most likely living a life of leisure off his inheritance), we do know that his father was the founder of an innovative mail coach company in Ireland, as well as a banker. Anderson's first major innovation was to establish a steam carriage and wagon company, so his father's experience as a transport pioneer would have been useful, and ought to be taken into account. Table 2 shows that the inclusion of this additional information leaves only 3% of innovators with wholly unknown educational or professional backgrounds.

Table 2
Number of Innovators by Rates of known Pre-Innovation Experience (%)

Father's Profession	503 (74)
Primary & Secondary	298 (44)
Skills-Based	427 (63)
Higher Education	187 (28)
Profession	504 (74)
Unknown	17 (3)

Assessing the relevance of training and education to innovation requires the categorisation of both their skills and their innovations. Innovators in the sample had remarkably broad interests. John Kay, famous for the flying shuttle, also developed a wind-powered pump, a malt-drying kiln, and a new method of digging canals. Edmund Cartwright is most famous for inventing the power loom, but he also developed agricultural machinery, designed fireproof building materials, designed a horse-less "centaur carriage" (operated by two men driving cranks), and experimented with manures and potatoes as superintendent of the Duke of Bedford's model farm. Indeed, one of the reasons skills and innovations have never been assessed for relevance may be because no attempt has been made to recognise this extraordinary breadth. All other lists treat innovators as capable of belonging to only a single industry (Meisenzahl and Mokyr 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).[34]

Table 3 shows that, when split among 39 different industries, most innovators (55%) improved more than one industry. And almost a third improved more than two industries. How could one choose a single industry for Joseph Whitworth, who is equally well-known for his improvements to steel, textile machinery, machine tools, and weaponry? James Watt, though most famous for improving steam engines, could also be

[34] Meisenzahl and Mokyr, 'The Rate and Direction of Invention in the British Industrial Revolution', 17.

categorised as a pioneer of civil engineering (he surveyed the Caledonian Canal in 1773), the decorative arts (he invented sculpturing machines), chemicals (he developed new methods of producing chlorine), and consumer hardware (he invented a letter-copying press).

Table 3
Number of Innovators by number of Industries they improved (% of Total Innovators)

1	305 (45)
>1	372 (55)
2	162 (24)
>2	210 (31)

Instead of 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 different categories. Lifeboats might be categorised as safety-oriented inventions, in the same category as fire escapes, and ventilation hoods for brass-gilders handling mercury; or they might be categorised as shipbuilding inventions, alongside improvements to canal boats or sails. The safety lamp for mines might be categorised according to its use (in this case "Light"), or its effect ("Safety").

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 industries. The choice of industry categories is arbitrary, but by choosing more categories we can more clearly distinguish what innovators were actually doing. A single category of improvements to machines, for example, can be split between steam engineering, and machinery for textiles, printing, and agriculture. Each involved different tacit knowledge. I identify 39 industries, listed in Table 4, thereby achieving greater accuracy than other lists.

Table 4 Number of Innovators engaged in each Industry, by Date of First Innovation (%)					
	1651-1700	**1701-1750**	**1751-1800**	**1801-1851**	**Total**
1. Actuarial	1 (3)	3 (3)	2 (1)	3 (1)	**9 (1)**
2. Agriculture	3 (10)	2 (2)	30 (12)	18 (6)	**53 (8)**
3. Agricultural Machines	1 (3)	4 (4)	20 (8)	11 (4)	**36 (5)**
4. Brewing & Distilling	0 (0)	1 (1)	8 (3)	5 (2)	**14 (2)**
5. Ceramics	3 (10)	10 (11)	15 (6)	4 (1)	**32 (5)**
6. Chemical	4 (13)	10 (11)	28 (11)	40 (13)	**82 (12)**
7. Civil Engineering	3 (10)	8 (8)	31 (13)	51 (17)	**93 (14)**
8. Coachbuilding	0 (0)	0 (0)	17 (7)	9 (3)	**26 (4)**
9. Communications (Non-Electric)	0 (0)	0 (0)	5 (2)	10 (3)	**15 (2)**
10. Construction	0 (0)	1 (1)	24 (10)	36 (12)	**61 (9)**
11. Decorative Arts	0 (0)	1 (1)	14 (6)	5 (2)	**20 (3)**
12. Electric	0 (0)	1 (1)	5 (2)	47 (16)	**53 (8)**
13. Food Processing	3 (10)	3 (3)	9 (4)	18 (6)	**33 (5)**
14. Gas	0 (0)	0 ()	4 (2)	24 (8)	**28 (4)**
15. Glass	2 (6)	2 (2)	1 (0)	7 (2)	**12 (2)**
16. Hardware Durables	0 (0)	3 (3)	26 (11)	21 (7)	**50 (7)**
17. Instruments	11 (35)	23 (24)	42 (17)	61 (20)	**137 (20)**
18. Interior Design	0 (0)	4 (4)	6 (2)	1 (0)	**11 (2)**
19. Light	0 (0)	1 (1)	8 (3)	17 (6)	**26 (4)**
20. Medical & Pharmaceutical	2 (6)	14 (15)	20 (8)	23 (8)	**59 (9)**
21. Metals	4 (13)	11 (12)	18 (7)	41 (14)	**74 (11)**
22. Misc. Machinery	5 (16)	10 (11)	41 (17)	56 (19)	**112 (17)**
23. Musical Instruments	0 (0)	2 (2)	8 (3)	4 (1)	**14 (2)**
24. Naval / Shipbuilding	1 (3)	1 (1)	26 (11)	58 (19)	**86 (13)**
25. Navigation	1 (3)	4 (4)	7 (3)	4 (1)	**16 (2)**
26. Organisational	3 (10)	5 (5)	16 (7)	6 (2)	**30 (4)**
27. Other	1 (3)	1 (1)	11 (4)	18 (6)	**31 (5)**
28. Photography	0 (0)	0 (0)	0 (0)	17 (6)	**17 (3)**
29. Printing Techniques	0 (0)	2 (2)	12 (5)	15 (5)	**29 (4)**
30. Printing Machines	0 (0)	0 (0)	7 (3)	16 (5)	**23 (3)**
31. Railway Engineering	0 (0)	0 (0)	6 (2)	27 (9)	**33 (5)**
32. Safety	1 (3)	1 (1)	11 (4)	27 (9)	**40 (6)**
33. Steam Engineering	2 (6)	8 (8)	29 (12)	71 (24)	**110 (16)**
34. Electric Telegraphy	0 (0)	0 (0)	0 (0)	22 (7)	**22 (3)**
35. Textile Design	0 (0)	0 (0)	4 (2)	1 (0)	**5 (1)**
36. Textile Machines	2 (6)	5 (5)	23 (9)	25 (8)	**55 (8)**
37. Tools	3 (10)	6 (6)	20 (8)	28 (9)	**57 (8)**
38. Transport Services	0 (0)	0 (0)	0 (0)	6 (2)	**6 (1)**
39. Weapons, Ordnance & Fortifications	1 (3)	1 (1)	16 (7)	29 (10)	**47 (7)**

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. The sample also errs on the side of identifying too many categories rather than too few, improving its accuracy. 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). Table 5 shows that the skills of innovators were extremely diverse – no single type accounted for a majority, though significant minorities had backgrounds in commerce or retail (18%), mechanics (16%), and medicine (15%).

Table 5
The Skill Background of Innovators
(% of Total)

Agriculture & Horticulture	82 (12)	Military	44 (6)
Ceramics	15 (2)	Mining	19 (3)
Chemistry	54 (8)	Music	11 (2)
Clergy	55 (8)	Naval Construction	18 (3)
Clerical, Law & Journalism	80 (12)	Other	25 (4)
Coachbuilding	7 (1)	Precision Instruments	57 (8)
Commerce & Retail	125 (18)	Printing	40 (6)
Construction & Building	22 (3)	Sailor	25 (4)
Decorative & Artistic	32 (5)	Science	26 (4)
Distilling & Brewing	12 (2)	Surveying	58 (9)
Food Processing	14 (2)	Teaching	56 (8)
Gasworking	3 (0)	Textile Finishing	42 (6)
Gentleman	83 (12)	Textile Manufacturing	66 (10)
Mechanics	108 (16)	Transport	3 (0)
Medicine	103 (15)	Weapon Making	7 (1)
Metalwork	84 (12)	Woodworking	39 (6)

The categories for higher education were obviously different to those for skills-based training, as shown in Table 6. Although they studied many different subjects, the most common subjects were medicine (11%), natural philosophy (9%), and mathematics (5%). These figures are unsurprising considering the similar proportion of innovators who improved medicine (9%), and the near-universal applicability to innovation of scientific understanding and mathematical principles.

Table 6
The Higher Education of Innovators
(% of Total Innovators)

Art	7 (1)
Chorister	1 (0)
Divinity & Religious Studies	24 (4)
Humanities, Arts, Classics, Languages	18 (3)
Law	10 (1)
Mathematics	34 (5)
Medicine	72 (11)
Natural Philosophy & Science	58 (9)
Unknown	18 (3)

Assessing the relevance of skills to innovations requires a high degree of judgement, with few hard rules. Higher educations in natural philosophy, science, or mathematics were treated as universally relevant. Backgrounds in teaching that plausibly involved teaching science or mathematics were also automatically assumed to be universally relevant. Backgrounds in mechanics (professional experience as millwrights, engineers, mechanics, and civil engineers), in metalwork (including iron founders as well as smiths of various kinds), and in precision instruments (such as clock-making, or the making scientific instruments) were assumed to be relevant to any improvements to machines. In 55 cases (8%) backgrounds were either unknown, or relevance seemed highly improbable yet plausible – in these case I absolved myself from judgement and categorised them as unclear.

These assumptions err on the side of categorising an innovator's skills as relevant. Yet Table 7 shows that almost a fifth (19%) of innovators, like William George Armstrong, improved only industries that were entirely unrelated to their education, training, professional background, and even the professions of their fathers. Relaxing these assumptions, the true proportion of innovators whose innovations were wholly unrelated to their skills may be even higher still. Skills were also often grouped together for the sake of convenience, in a way that may further understate the number of cases like Armstrong. Backgrounds as physicians, anatomists, surgeons, and apothecaries, for example, were all categorised as medical, to reflect that improvements to treatments, surgical techniques, and medicines were also all categorised as medical. Though closely related, however, not all dentists have the skills to develop drugs, not all apothecaries can practise surgery, and so on.

Table 7
The Relevance of Innovator Skills to their Innovations No.1

Date of First Innovation	Irrelevant Skills (%)	At least one Innovation Related to Skills (%)	All Innovations Related to Skills (%)
Unknown	0 (0)	5 (100)	5 (100)
1651-1700	7 (23)	18 (58)	16 (52)
1701-1750	20 (21)	70 (74)	63 (66)
1751-1800	52 (21)	174 (71)	146 (59)
1801-1851	47 (16)	229 (76)	170 (57)
Total	**126 (19)**	**496 (73)**	**400 (59)**

Cases like Armstrong's were extreme, but a further 14% of innovators in the sample (97 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. His improvements to agricultural machines, agricultural techniques, instruments, and civil engineering, might all plausibly be explained with reference to his experience of construction and land management. Less obviously relevant, though still counted as such, were his designs for a humane man trap, a method of transferring pictures from painted surfaces, improvements to window guards, a candle apparatus, and a method of refrigerating liquors. Entirely irrelevant to his skills, however, was his invention of an artificial abdomen to treat hernias, and his improvements to surgical instruments for treating urethral and bladder complaints.

Taking cases like Armstrong and Salmon together then, at least a third of innovators in the sample improved industries of which they had no background or experience. How might the activities of this substantial minority be explained? One explanation is that innovation was independent of knowledge, that improvement was a *mentality*. Innovators saw room for improvement, even in wholly unfamiliar areas, and envisioned how such improvement might be brought about. Guided by their vision, they self-educated or relied upon others, developing their own understanding of the problem so that they could bring about solutions. Once possessed of the improving mentality, innovators could see room for improvement anywhere, irrespective of their skills. Thus Lancelot Brown looked out over the gardens of the wealthy and declared them "capable" of improvement, earning him the nickname Capability Brown. A young engineer, William Fairbairn, even got carried away and tried to improve romance. By reverse-engineering the correspondence of a pair of lovers published in a magazine, he maintained that he "inadvertently rendered one of the strongest passions of our nature subservient to the means of improvement".[35]

And the improving mentality spread from person to person – for the third of innovators who branched out into the unfamiliar it was not their skills that mattered, but their inspiration to see improvement. William George Armstrong, for example, had repeated contact with innovators before himself becoming an innovator. His father, though a corn merchant by trade, was also member of the Newcastle Literary and Philosophical Society – the city's social hub for innovators as well as for natural philosophers and antiquarians. Armstrong also reportedly developed a childhood fascination with mechanical contrivances, regularly visiting the works of the engineer William Ramshaw in his after-school hours (he later married Ramshaw's daughter, so his visits may have had other motivations too). And Armstong's master and then law partner, Armorer Donkin, was an amateur scientist who strongly encouraged his interest in innovation, introducing him to innovators like Thomas Sopwith and Isambard Kingdom Brunel. Armstrong was surrounded since childhood by innovators and their allies. Inspired, he educated himself despite his schooling and on his own time: "for a good many years I stuck to the law, while all my leisure was given to mechanics".[36]

Robert Salmon demonstrated an early tendency towards self-education, and, like Armstrong, 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. In his spare time Salmon disassembled and reassembled watches, and learned how to construct and play flutes, fifes and a violin. When a clerk of works, managing the legal affairs of construction, he was employed by Henry Holland, a particularly innovative architect who had also been partner to the innovative gardener Lancelot "Capability" Brown. Through Holland, Salmon attracted the attention of Francis Russell, 5th Duke of Bedford, who employed him in 1794 as the first resident architect and mechanist in England. The Duke at the same time employed other innovators such as the surveyor

[35] Fairbairn, *Life of Sir William Fairbairn*, chap. 4.
[36] Heald, *William Armstrong*, 21.

John Farey senior and the civil engineer William "Strata" Smith, and he hosted trials of Joseph Elkington's innovative drainage methods. The 6th Duke, who succeeded to the title in 1802, patronised innovators like Sir Humphry Davy and Humphrey Repton while continuing to employ Salmon.

Once possessed of the improving mentality, which might have been inspired in him by any one of the innovators he knew, Salmon self-educated when he recognised problems outside of his expertise. His personal sufferings from a hernia prompted him to research and contrive a superior treatment, despite his lack of medical training. And 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.[37] 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.

The timber merchant and carpenter George Smart in 1800 developed a method of combining hollow poles to form ship masts and in 1803 contrived a chimney-cleaning device that operated on similar principles. His professional familiarity with wood was likely useful to such innovations, but he also invented a corn grinding mill, and later embarked on a career as a civil engineer, developing iron lattices for bridges. Smart, once again, had prior contact with other innovators. He had been an active member of the Society of Arts since 1796, his early experiments on the strength of timber were observed by the Scottish agricultural innovator Dr James Anderson, and he struck up a correspondence with the polymathic naval improver Mark Beaufoy.[38] Once possessed of the improving mentality, Smart initially applied himself to fields that were most familiar – those directly informed by his skills in carpentry and timber. Yet when his attention was directed to improving areas outside of his immediate expertise, he relied upon self-education and consultation with others.

University Education

The majority, 59% (400 innovators in the sample), stuck only to what they knew. These were the potters who stuck to improving pottery, and the mechanics who stuck to

[37] *The Annual Biography and Obituary*, 6:487–90.

[38] 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.

improving machines. A quarter of them (99 people) studied at university, and were mostly those who studied natural philosophy or chemistry or mathematics (those subjects that were automatically categorised as relevant to all innovations). 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, instruments, and machines. An understanding of vacuums was essential to Denis Papin's development of early steam engines, and informed James Watt's later improvements too.[39]

But knowledge of science does not imply its application. Many scientists contented themselves with collecting data and interpreting it with a view to advancing understanding alone, never using that understanding to develop improvements. Many mathematicians contented themselves with purely theoretical investigations, and many medical practitioners 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 to become an innovator. It did not matter that innovators were educated in the sciences, but by whom.

Table 8 shows that of the university-educated innovators in the sample, most attended Scottish universities, particularly Edinburgh University.[40] And this concentration was even more pronounced among those innovators whose innovations were all related to their education and training. Yet British innovators had a wide choice of universities. Scotland boasted five, with Edinburgh, Glasgow, St Andrews, and two colleges at Aberdeen (and then from 1796 the Andersonian Institution, which later became the University of Strathclyde). England had two – Oxford and Cambridge – until the 1830s, when they were joined by Durham, King's College London, University College London, and the Royal Polytechnic Institution (later the University of Westminster). Ireland had Trinity College Dublin (Queen's University Belfast opened in 1849, too late to affect any innovators in the sample). And a number of innovators were educated abroad, particularly at Leiden, but also at Angers, Orange, and elsewhere.

[39] For further details of Watt's scientific understanding see Jacob, *The First Knowledge Economy*, 28–29.
[40] The figures are not mutually exclusive, because some innovators attended multiple universities.

Table 8
Number of Innovators, by selected University Attendance

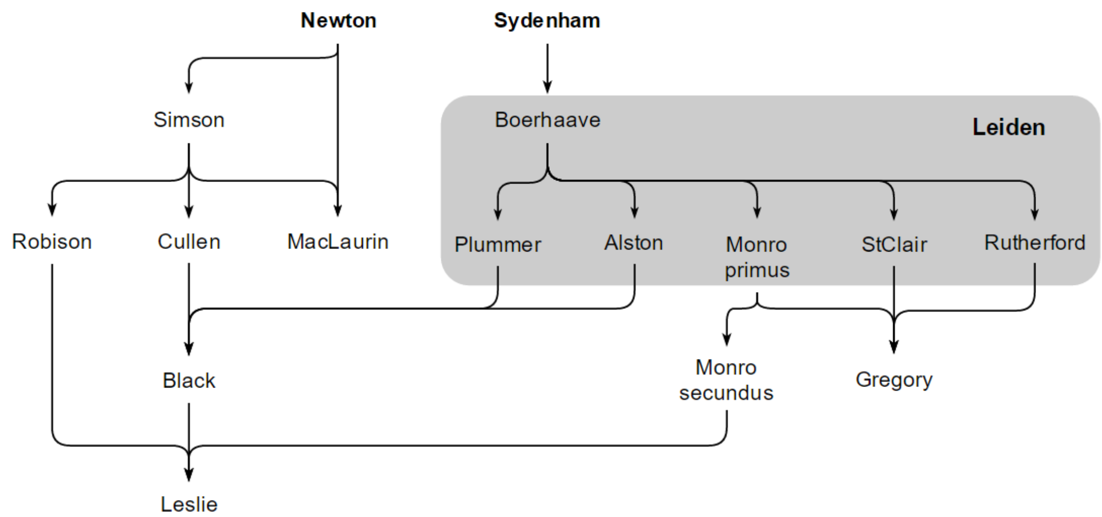
	University-Educated Innovators (%)	...with innovations wholly relevant to education (%)
Scottish Total	82 (55)	62 (62)
Edinburgh	52 (35)	41 (41)
Glasgow	25 (17)	18 (18)
Aberdeen	8 (5)	4 (4)
Anderson	2 (1)	2 (2)
St Andrews	6 (4)	5 (5)
English Total	59 (40)	32 (32)
Cambridge	34 (23)	19 (19)
Oxford	25 (17)	13 (13)
London Universities	4 (3)	4 (4)
Dublin	4 (3)	2 (2)
Leiden	10 (7)	7 (7)
Total	**148**	**99**

Medicine, natural philosophy and mathematics had been taught at universities, especially all Scottish universities, for decades. Yet innovators were unusually likely to be inspired not just after attending Edinburgh, but after being taught by a few of its lecturers in particular. What made Edinburgh so unusual was its faculty.

Edinburgh's ascendancy as a source of the improving mentality began when in 1709 the son of a minister, Colin MacLaurin, enrolled at Glasgow to study classics. At Glasgow MacLaurin came under the influence of Robert Simson. Simson was originally a student of divinity and classics too, but after spending a year in London with Edmond Halley and other innovators associated with the Royal Society, in 1711 he returned to Glasgow 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 spent time in London with Halley and Newton. Newton himself secured MacLaurin's position at Edinburgh in 1725 to teach mathematics (offering to pay £20 per year towards his salary 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 mathematics, astronomy, and experimentation. It was in his rooms in the early 1730s that James Short, a later prolific improver of telescopes and agricultural machinery, first learned to construct scientific instruments. And his lectures in the 1740s were attended by Robert Adam, the pioneering architect and interior designer. More importantly, however, Simson transmitted the improving mentality to other lecturers –Figure 9 illustrates its spread among Edinburgh's faculty.

Figure 9
The Spread of the Improving Mentality among Scottish Lecturers who taught Innovators



Though he continued to teach at Glasgow rather than Edinburgh, two of Simson's later students stand out in particular, not just as innovators, but as proselytisers of the improving mentality: William Cullen and John Robison. It was Cullen who, encouraged by the Scottish Board of Trustees, cheapened the manufacture of lime for bleaching linen. John Robison, encouraged by Simson, turned his mind to improving the Newcomen steam engine and collaborated with James Watt on various other endeavours too. Robison tried to inspire others outside of the university too – he was author of the entry on steam power in the 1797 edition of *Encyclopaedia Britannica*.

Yet Simson's students tended to end up spending most of their teaching careers at Edinburgh. The time spent teaching at a university mattered, because students with both the interest to adopt the improving mentality and the aptitude to become successful innovators appeared only very rarely. Though inspiration to innovate might be repeatedly offered, it 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, but an approach.

Robison initially taught chemistry at Glasgow for four years, where he did not inspire any innovators in the sample (though he did befriend James Watt and Joseph Black). After a brief stint teaching mathematics at Kronstadt in Russia, he taught at Edinburgh for 32 years. There he taught the innovative civil engineers Peter Ewart and John Rennie, and the chemical pioneer John Leslie, who was later a tutor to the children of the pottery innovator Josiah Wedgwood.

Leslie in particular would prove an exceptional source of inspiration for many more innovators at Edinburgh into the early nineteenth century. Amid great controversy over his supposed atheism, he eventually secured a teaching place there in 1805, where he remained until his death in 1832. 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 the electromagnetic rotary devices, Michael Faraday). Leslie also gave much advice and encouragement to Thomas Drummond, an improver of surveying instruments, and to the remarkably 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's reputation as a centre of medicine led some students to prefer it to the other Scottish universities. Joseph Black, for example, despite being taught by Cullen at Glasgow, transferred to Edinburgh to complete his degree. Edinburgh's medical reputation in turn stemmed from the influence of Alexander Monro *primus* – another crucial carrier and disseminator of the improving mentality. Monro *primus* had studied under the Dutch physician Herman Boerhaave, whose work established Leiden University's reputation as a centre for medicine. Boerhaave, in turn, had been inspired to apply systematic experimentation to medicine after reading the works of an English innovator, Thomas Sydenham. Samuel Johnson's obituary of Boerhaave noted that, by his own attestation, “none engaged him longer, or improved him more, than Sydenham”.[41]

Monro *primus* taught James Lind, who as a naval surgeon conducted the first controlled clinical trials on scurvy; and he was another of Robert Adam’s teachers. Monro *primus*, most importantly, ensured the hiring of many more teachers inculcated with the improving mentality of Sydenham and Boerhaave. In 1726 he was joined at Edinburgh 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’s, and in 1754 Monro *secundus* began to teach alongside his father. It was under Alston, Plummer, and Monro *secundus* that Joseph Black completed his thesis. Plummer’s students also included the sulphuric acid manufacturer and metallurgist John Roebuck; James Keir, who developed copper sheathing for ships; the agricultural improver and geologist James Hutton; and probably the serial inventor Erasmus Darwin, whom Keir befriended during their course together. Rutherford was another teacher, alongside Cullen, of the medical pioneer William Withering.

Rather than the specific knowledge imparted, what mattered for inspiring innovators was the presence of particular people. Not all students, of course, became innovators. But for so many university-going innovators to have had an education at Edinburgh in common required the presence of teachers who were themselves innovators. Prior generations had for decades been taught medicine or mathematics or natural philosophy – but Edinburgh’s lecturers in particular encouraged their students to apply that knowledge to improvement.

Mechanics

Of the 400 innovators who stuck only to what they knew, almost a quarter (93), were trained as mechanics, engineers or millwrights. The proportion also grew, from just 7% in 1651-1751, to 35% in the early nineteenth century. Mechanical training could be applied to anything, from textile machinery, to agricultural machinery, to

[41] Atkinson, ‘Samuel Johnson’s “Life of Boerhaave”’. According to Boswell, it was while writing Boerhaave’s obituary that Johnson first discovered “that love of chymistry which never forsook him”. Kurzer, ‘Chemistry in the Life of Dr Samuel Johnson’.

coachbuilding, or iron founding; and associated skills of draughtsmanship and precise measurement could be applied to fields like civil engineering (it was, like a scientific education, almost always categorised as relevant to innovation).

Yet the possession of mechanical skill does not imply its application to innovation. A modern plumber would, by the standards of the eighteenth century, be extremely knowledgeable about how to supply water to a house, but might not ever think to improve upon existing plumbing systems. We generally expect engineers to build or repair things, but only rarely to devise new machines. Modern electricians are also highly trained, but very few invent new switches, circuits, or fuses. Within the millwright's profession, from which mechanical engineering sprang, innovation was sometimes even 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".[42]

Once again, training alone was insufficient cause of innovation – people needed to be inspired to apply those skills to improvement. From 1750 Brindley 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 (though his early life is relatively undocumented, and he was likely inspired even earlier). What mattered was an engineer's connections to innovators. Connections between prominent mechanical engineers have been identified before, in particular that many firms in London 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.[43]

Focusing exclusively on the connections between engineers also obscures the fact that many engineers who innovated had had prior contact with innovators outside of the profession. Henry Beighton, one of the earliest improvers of steam engines, was

[42] Smiles, *James Brindley and the Early Engineers*.
[43] MacLeod and Nuvolari, "'Glorious Times.'"

descended from surveyors and engineers. Yet his earliest innovation was not mechanical, but 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, Beighton's local colliery. Beighton studied Newcomen's engine with one of Isaac Newton's disciples, John Theophilus Desaguliers, 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 his innovation's direction. Yet he became an innovator, mechanical or otherwise, only following contact with innovators associated with the Royal Society like Desaguliers.

A generation of mechanical engineers in the late eighteenth century owed their inspiration to the millwright Andrew Meikle, who improved agricultural and bleaching machinery, and to his protégé John Rennie. Meikle's source of inspiration was likely his father, James, who in 1710 introduced barley mills to Britain from Holland. John Rennie started assisting Meikle in his spare time after school, aged only 12, and was likely inspired by others too. Meikle was on the Rennie estate at all because of Rennie's elder brother, George, who was interested in agricultural improvement (George Rennie's improving mentality was, in turn, instilled when his father sent him to examine the agricultural innovations 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.

Rennie's influence, in turn, was widespread. One of his earliest apprentices, Peter Ewart, later improved water wheels, looms, and spinning mules (he was also John Robison's cousin and pupil, and worked with Rennie for Boulton and Watt). Rennie also trained James Green, who became one of the South West's most prolific civil engineers; Henry Bell, a pioneer of marine steam propulsion; and William Tierney Clark, another innovative civil engineer, whom he noticed on a visit to Coalbrookdale (itself a place full of innovators). Bell in particular had already been trained as a millwright, engineer, and shipwright – yet it was only after 18 months working for Rennie that he started innovating. 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, the plausible sources of inspiration are so many that it becomes difficult to trace the improving mentality's spread. William Fairbairn, who greatly improved steam ships, could have listed Rennie as only one of many possible influences. 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 in London after his apprenticeship had ended (though guild rules prevented him from being hired). Fairbairn also worked briefly for the inventive civil engineer John Grundy junior, and shared lodgings with a Scottish clergyman named James Hall, who introduced him to the Society of Arts and to Alexander Tilloch (the editor of the *Philosophical Magazine*), and collaborated with him on developing an unsuccessful steam-driven sand-digging machine.[44] Fairbairn's commitment to self-education started even earlier, when he was apprenticed to John Robinson, an engine-wright to the Percy Main colliery who had been appointed by the innovative mining engineer John Buddle (it was during this apprenticeship that he first tried to apply the improving mentality to romance). Presumably via his association with Robinson, Fairbairn at that time also befriended the up-and-coming George Stephenson, later famous for his improvements to steam locomotives and the miner's lamp.

Fairbairn's younger brother Peter also had many potential sources of inspiration before becoming an innovator (even beyond his brother, whom he assisted). After an apprenticeship to a millwright at Percy Main colliery, a John Casson, he worked abroad and then for John Rennie. He was also apprenticed again, to Henry Houldsworth, a Nottingham cotton industrialist who helped spread spinning techniques to Scotland. After moving to Leeds, Peter Fairbairn became a business associate of John Marshall, the pioneer of mechanised flax spinning (who may also have directed his attention toward improving spinning machinery). The skills Peter Fairbairn learned from Casson during his formal training as a mechanic were likely valuable, and determined the initial direction of his attentions. Yet his contact with so many notable innovators surely inspired him to apply those skills to innovation.

[44] 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, *The Philosophical Magazine*, 35:186.

Beighton, Meikle, Rennie, and the brothers Fairbairn all show that innovators with mechanical skills were not just highly connected with one another, but with innovators in other industries too. Beighton's connection with a hub of innovators involved with the Royal Society was by no means unusual, just as Rennie and Ewart were both taught by John Robison at Edinburgh University. Though William Fairbairn was heavily inculcated in Newcastle's innovative tradition stemming from Buddle, he also drew inspiration from London's societies and magazines, its innovation-promoting institutions.

Perhaps the most significant source of inspiration for mechanical engineers 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 served the company for six decades, during which he 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 isinglass. Via Murdoch, the strand of the improving mentality flowing from Boulton and Watt affected innovators in non-mechanical fields like gas lighting: his friend George Augustus Lee, his apprentice Samuel Clegg (who became chief engineer to the Imperial Gas Light and Coke Company), and 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 ill treatment at the hands of Trevithick's father during his first forays into the Cornish market.[45] Despite the inherited antagonism, Trevithick was likely inspired by Watt's employee, Murdoch. Murdoch lived next door to the Trevithicks during his years in Redruch, 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,

[45] Trevithick, *Life of Richard Trevithick*, 30–32.

they were certainly on friendly terms.[46] Trevithick's father employed an Arthur Woolf at the Dolcoath colliery, father of the inventor Arthur Woolf, who developed high-pressure compound steam engines.[47] Woolf later worked for Bramah as a millwright, and assisted the younger Jonathan Hornblower with his low-pressure compound engine, which he eventually adapted for high-pressure steam.

Crucially, although Watt inspired many of their mechanically-trained employees to become innovators, he received the improving mentality from non-mechanics. Watt had been an associate of Joseph Black and John Robison at Glasgow University, where he had worked as a scientific instrument maker. Black introduced him to the innovative metallurgist and chemical manufacturer John Roebuck, a former student at Edinburgh and Leiden, who became Watt's business partner (before Watt's more celebrated association with Boulton).

Conclusion

Skill and understanding enabled people to solve particular technological problems, but it was the improving mentality, inspired in them by prior contact with other innovators, that led them to apply those skills to improvement. To better understand why innovation accelerated in Britain before 1851, we need to pay attention to the relevance of human capital to innovation – doing so reveals a substantial minority whose actions may be explained with reference to inspiration rather than skill. The third of innovators who lacked the training or education for implementation still saw room for improvement – they were still innovators who contributed to the Industrial Revolution. Once inspired, they could remedy their lack of skill or understanding by educating themselves and by relying upon the aid of others.

Even among innovators who stuck to what they knew best, the content of their training and education may not matter as much who did the educating. Skilled mechanics have always existed under various guises, whether we call them millwrights

[46] 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." Ibid., 22–28, 62–65.

[47] Ibid., 19.

or engineers. And people have since time immemorial sought to understand the forces that govern the natural world, whether we call them natural philosophers or scientists. Yet the improving mentality made all the difference between expertise and innovation, between understanding and application.

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