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INVENTING THE PROFESSIONAL INVENTOR DURING THE INDUSTRIAL REVOLUTION

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ABSTRACT

Why was the Industrial Revolution successful at generating sustained growth? Some have argued that there was a fundamental change in the way that new technology was developed during this period, but evidence for this argument remains largely anecdotal. This paper provides direct quantitative evidence showing that how innovation and design work was done changed fundamentally during the Industrial Revolution. This change was characterized by the professionalization of innovation and design work through the emergence of the engineering profession. I also propose a theory describing how this change could have acted as one mechanism behind the transition to modern economic growth.

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Technological progress played the central role in the Industrial Revolution. Much of the research on innovation during this event has focused on the factors that led to the burst of inventive activity that took place in Britain in second half of the 18th century. Yet, as Joel Mokyr has pointed out, short bursts of technological progress have occurred many times in history. "The true miracle" he argues, "is not that the classical Industrial Revolution happened, but that it did not peter out like so many earlier waves of innovation" (Mokyr, 2004, p. 15).

Why was technological progress sustained? Some have argued that the explanation for this miracle of sustained technological progress is that the system through which new technology was developed changed in a fundamental way during the Industrial Revolution. Alfred North Whitehead, for example, believed that, "The great invention of the nineteenth century was the invention of the method of invention."[1] Did such a change in the process of innovation take place during the Industrial Revolution? And if it did, what did the change look like?

This paper provides evidence showing that an important change took place in the way that innovation and design work was done in Britain, that the timing of this change corresponds closely to the onset of the Industrial Revolution, and that this change was a specifically British phenomenon. The change I highlight was the professionalization of invention and design work through the emergence of the engineering profession. Engineering work, ranging from the invention of new mechanical devices to the design of new types of infrastructure, had been done before the emergence of professional engineers. However, historical evidence suggests that how engineering work was done changed in a fundamental way in the last quarter of the eighteenth century. Watson (1989), in his history of the Society of Civil Engineers, describes how (p. 1), "When John Smeaton described himself as a civil engineer for the first time...he identified a new profession" which combined "The craftsman's fund of knowledge, based on natural genius and practical experience...with the assimilation of scientific principles."

Such a change could have important implications for our understanding of this seminal event in economic history. However, current evidence on this change remains largely anecdotal. The primary contribution of this paper is to provide direct

[1] Whitehead (1925), p. 96.

quantitative evidence documenting the changes in the innovation process that took place in Britain during the Industrial Revolution as well as a theory describing how this change could have acted as a mechanism through which the British economy transitioned into modern economic growth.

My empirical analysis begins with a brief examination of the characteristics that defined the new professional engineers that emerged during my study period. This is done using both historical evidence – how contemporary engineers saw their own profession – as well as through a quantitative text-analysis approach using biographical information from the *Oxford Dictionary of National Biography* (ODNB). This analysis shows that activities such as "design," "invent," and "patent" were core functions of early engineers, while engineers were also involved in activities related to the implementation of new designs and ancillary activities such as consulting, reporting, and surveying. Notably, these defining characteristics changed very little across the study period and they are similar regardless of whether I identify engineers using the judgment of historians or on individual's own self-reported occupations.

Next, I document the emergence of professional engineers and the impact of this group on the development of new inventions and designs in Britain during the Industrial Revolution. The engineering profession that emerged during this period was diverse, ranging from civil engineers such as John Smeaton and James Brindley to mechanical engineers such as Henry Maudslay and Joseph Bramah, with many engineers, such as James Watt and Marc Isambard Brunel, making contributions across multiple branches of engineering. To account for this, I use several empirical approaches to study different aspects of the emerging engineering profession.

First, I examine biographical information from the ODNB, which has the advantage of covering all types of engineering. The ODNB data reveal a dramatic increase in the share of engineers among the noteworthy Britons beginning in the third quarter of the eighteenth century. By the middle of the nineteenth century, engineers made up around 20% of all noteworthy individuals associated with science or technology, and over 2% of all of those who merited an ODNB biography.

Second, I study patent data. This analysis is of particular interest because it reflects exactly the type of reproducible inventions thought to have been central to driving economic growth. Confirming the patterns observed in the biographical data, British patent data show the growing importance of engineers to invention in Britain during the Industrial Revolution. Engineers were almost completely absent from the patent record prior to 1760, but they appeared in growing numbers after that point. By 1800-10, they accounted for around 10% of all patents, a share that rose steadily to 20% by the 1840s and then just under 30% by the 1860s. This rising importance of engineers, which closely corresponds to the timing of the acceleration of productivity growth in Britain, has not, to my knowledge, been systematically documented in existing work.[2]

The patent data also show that engineers were fundamentally different from other common types of inventors, particularly manufacturer-inventors, the other major group of patent holders. Most importantly, I document that engineers were more productive, generating more patents per decade than any other type of inventor, and patents of higher quality based on several available patent quality indicators. Engineers also operated differently than other types of inventors. For example, they were more likely to work with coinventors, a feature that may help explain their greater productivity. In addition, individual engineers patented across a substantially broader set of technology categories than any other type of inventor. Even within the career of individual inventors, I provide evidence that once someone began to describe their occupation as engineer they also began to operate differently, by working with more coinventors, and they became more productive. These patterns indicate that engineers represented a new type of inventor, rather than simply a relabeling of some existing type.

Third, I conduct an international comparison, contrasting the patterns observed in British patent data to data on French patents from 1791-1843. As in the British analysis, I find that individuals describing themselves as engineers in the French patent data were more productive than other types of patent holders, produced higher quality inventions, and operated across a broader set of technology categories. This provides further evidence that engineers were fundamentally different than other types of inventors, even in France. However, I also show that French innovation system did not exhibit the same changes that took place in Britain. In particular, there was no take off in the number of engineers patenting in France commensurate with

[2]This claim is discussed in detail in Section 1.

the pattern observed in the U.K. Instead, the French innovation system remained relatively stable from 1791-1843: dominated by manufacturer-inventors, a structure that was similar the British innovation system in the mid-18th century. Moreover, many of the engineers that were active in France were of British origin. Thus, the at least before the middle of the nineteenth century, the rise of the engineer appears to be a uniquely British phenomenon.

Fourth, I examine the professionalization of civil engineering that occurred in parallel with the shifts in other types of engineering work. Using a combination of historical evidence and data covering major infrastructure projects undertaken in Britain after 1500, I provide evidence that the way civil engineering work was done changed in the second half of the eighteenth century. As Skempton (1996, p. vii) describes, "Works of engineering had been executed before 1760, some of considerable magnitude, but they could not provide sufficient employment to support a body of men trained in work of this kind..." However, "The state of civil engineering changed decisively in the 1760s... Engineers forming a small but distinguished group were now fully employed in consulting, designing, giving evidence to Parliament and directing works..." (Skempton *et al.*, 2002, p. xxiv). Supporting this historical narrative, I provide evidence showing that, prior to 1750, most major civil engineering projects were overseen by engineers without substantial prior training or experience. After 1750 major civil engineering projects were increasingly overseen by experienced engineers that headed established firms and undertook numerous major projects. They also trained the next generation of civil engineers, most of whom had gained extensive experience working for established firms before being awarded major projects of their own. Thus, we can trace out the professionalization of civil engineering work occurring in parallel with the arrival of engineers as important producers of mechanical inventions documented in the patent data.

Together, these mutually-reinforcing strands of empirical analysis highlight the fundamental changes that took place in the way invention and design work was done in Britain during the Industrial Revolution. These changes were characterized by the emergence of a new profession, engineering, where design and invention were among the core occupational functions. These changes began in roughly the third quarter of the eighteenth century, just as the Industrial Revolution was taking off, and accelerated through at least the middle of the nineteenth century. Moreover, the emergence of professional engineers as a key group of inventors appears to have been a largely British phenomenon, which may help explain why Britain pulled ahead of other European countries during this period. These empirical findings can help us better understanding how the innovation system changed during this seminal event in economic history.

Finally, I provide a simple theoretical model that describes how the changes documented in my empirical analysis could have contributed to the take-off into modern economic growth. The core of the model takes Adam Smith's insight that specialization can increase productivity and applies it to productivity in the development of new inventions and designs, by a new group of specialists: professional engineers. This idea is then embedded into a standard endogenous growth model following Romer (1990). The model shows how a change in the way new innovations were developed may act as the mechanism through which an economy transitions from a slow "pre-modern" growth regime into rapid "modern" economic growth. In addition, the model shows how my findings fit together with existing theories of the Industrial Revolution, such as those emphasizing the role of institutions (North & Thomas, 1973; Acemoglu *et al.*, 2005) or the importance of upper-tail human capital (Mokyr, 2005, 2009). In particular, the model describes how these factors, highlighted in existing work, could have initiated the emergence of engineering in the late eighteenth century, and how that emergence could have acted as the mechanism that pushed the economy onto a new, more rapid, growth trajectory.

1 Related literature

Naturally, this paper is closely related to the enormous literature focused on understanding the Industrial Revolution. Two strands within this broad literature are particularly related. One existing set of papers uses biographical sources to look at the careers of important inventors or innovators (Allen, 2009b; Meisenzahl & Mokyr, 2012; Howes, 2017; Khan, 2018). A second closely related set of work uses patent data to examine the British innovation system during the Industrial Revolution. Important contributions to this literature include Dutton (1984), MacLeod (1988), Sullivan

(1989), Sullivan (1990), and Bottomley (2014), as well as a number of other papers discussed later.

Surprisingly, with few exceptions, existing work has generally failed to document the emergence and growing contribution of the engineering profession during the Industrial Revolution.[3] One exception is Nuvolari *et al.* (2021), which finds that what they define as macroinventions were more likely to be produced by engineers. However, Nuvolari *et al.* (2021) does not document the emergence of engineering, nor, without individually-linked patent data, are they able to study differences between engineers and other inventors in terms of output, average patent quality, coinventors, etc.[4]

This study also goes substantially beyond previous work using patent data by (1) identifying the emergence of engineers as an important group of inventors of patented technologies, (2) bringing together a wide range of additional data to show that this emergence was not confined to patented inventions, (3) comparing patterns observed in Britain to another country to show that this emergence was a specifically British phenomenon, and (4) providing a theoretical model that describes how the empirical patterns I identify could have contributed to the economy's transition into modern economic growth.

This study has implications for two lines of recent work related to the Industrial Revolution. One of these is a set of recent studies highlighting the importance of upper-tail knowledge during this period (Mokyr, 2005; Squicciarini & Voigtländer, 2015).[5] My results provide clear support for the argument that upper-tail knowledge mattered for technological progress during this period. Another long-standing debate

[3] The "quasi-professional" inventors discussed by Dutton (Ch. 6) are closely related to the engineers I focus on. However, without closely examining occupation data, Dutton did not make the connection to the emerging engineering profession. MacLeod (1988) did review inventor occupations, but surprisingly, she failed to identify the rise of the engineering profession documented here, which leads her to conclude that the era of the professional inventor did not begin until well into the nineteenth century.

[4] Another closely related study is MacLeod & Nuvolari (2009), which focuses on the mechanical engineering industry (essentially machine and tool making). Despite including the term engineering, this sector should not be confused with the engineers I study, who worked across a wide range of industrial sectors and technology types.

[5] Mokyr (2005), for example, argues that "what mattered above all was the level of sophistication of a small and pivotal elite of engineers, mechanics and chemists."

has to do with the importance of scientific knowledge in the Industrial Revolution.[6] As discussed in the next section, engineers clearly saw themselves as a key link between scientific insights and practical application. While I do not examine the role of engineers in applying scientific insights to technology development in this paper due to space constraints, I provide support for this important role in a companion paper, Hanlon (2022). That paper uses patent data linked to scientific articles, shows that engineers provided a key bridge between science and technology development in the early nineteenth century.

This paper is also related to existing work emphasizing the importance of engineers in more recent time periods. The closest paper in this vein is Maloney & Valencia Caicedo (2017), which highlights the contribution of engineers to growth during the Second Industrial Revolution, roughly one century after the main focus of my study. The key difference here is that I study the emergence of engineers and their contribution during the key decades of the Industrial Revolution.

Finally, my theoretical framework is related to existing theories describing the transition from pre-modern to modern economic growth, most notably Unified Growth Theory (Galor & Weil, 2000; Galor, 2011).[7] What differentiates my theory from existing work is a focus on how a change in the innovation process, and specifically the emergence of a group specializing in invention and design work, could have provided a mechanism through which the transition to modern economic growth occurred. Naturally, I am not claiming that this was the only mechanism at work; there is plenty of evidence that other factors, such as the accumulation of human capital and a beneficial institutional environment, mattered. However, when coupled with my empirical results, my theory suggests that changes in the inventive process may have also been important.

[6]This debate stretches back to work by Landes (1969), Rosenberg (1974), and Mokyr (2002) and includes recent papers by Squicciarini & Voigtländer (2015), Khan (2018), Kelly & Ó Gráda (2020), and a recent book by Jacob (2014).

[7]Other related work includes Jones (2001), Hansen & Prescott (2002), and Peretto (2015).

2 Defining an Engineer

What defined an engineer during the study period? Because the development of engineering education lagged the emergence of the engineering profession, engineers were not defined by a particular educational qualification, as they might be today. Nor were engineers defined by working in a specific type of industry or technology. As my later results show, engineers were in fact uniquely broad in the range of technologies they worked on. Here, I offer two approaches to defining an engineer, focusing both on the specific functions that the occupation involved as well as how it related to other occupations. I begin by looking at how contemporary engineers described their own occupation as it was emerging. I then augment this view using a data-driven approach based on applying text-analysis to descriptions of the lives of engineers in the ODNB.

Contemporary descriptions of engineers and engineering reveal a group that thought of themselves as a unique profession, lying between working mechanics and scientists, one that drew on a combination of mechanical skills and scientific or mathematical knowledge and applied these to invention and design activities ranging from new mechanical devices to major infrastructure projects. For example, James Watt, perhaps the most famous of the engineers in my study period, wrote in 1781 that an engineer "requires invention, discriminating judgement in Mechanical matters, boldness of enterprise and perseverance..."[8] Watt would also write to another friend that an engineer one needed to know drawing, geometry, algebra, arithmetic, and the elements of mechanics.[9] Rees' *Cyclopaedia* of 1819 defined *Engineer* as "in its general sense...applied to a contriver or maker of any kind of useful engines or machines," together with a separately defined *Civil Engineer*, "an order or profession of persons highly respectable for their talents and scientific attainments...as the canals, docks, harbours, light houses, etc. amply and honorably testify."[10] At the first meeting of what would become the Institution of Civil Engineers in 1818, Henry Robinson Palmer stated that, "An Engineer is a mediator between the Philosopher and the

[8]Letter from James Watt to Mrs. Campbell, 15 September 1781. Quoted from Musson & Robinson (1969).

[9]See Jacob (2014), p. 29 and p. 30, footnote 24.

[10]Rees (1819), Vol. XIII.

working Mechanic; and like an interpreter between two foreigners must understand the language of both."[11]. While disparate, these statements reveal some of the defining features of the new profession, as seen by those witnessing its emergence.

This historical evidence can be augment using a more quantitative approach that allows me to identify the functional activities of working engineers during the Industrial Revolution. This is done using biographical data from the ODNB covering all engineers born before 1850 (439 in total), as well as two natural comparison groups: manufacturers (349 biographies) and those non-engineers classified as involved in science or technology (1547 biographies).[12] Naturally, we should keep in mind that these biographies cover only a select sample of the most successful engineers, manufacturers, scientists and inventors. However, this upper-tail group is likely to have played a particularly important role in technology development, so they are a primary focus of this paper.

As discussed in detail in Appendix C, I use natural language processing methods to parse the ODNB biographies to identify all verb stems (similar to the approach used by Michaels *et al.* (2019)). I then apply a regression approach to identify those verbs that had the strongest association with engineers, compared to other types of inventors. These verb stems reflect the types of activities that individuals undertook during their lifetime. Table 1 presents the twenty verb stems most strongly associated with engineers.[13] For all of these, the association is statistically significant at the 99% level after adjusting for multiple hypothesis testing (sharpened p-values below 0.01). The presence of verbs such as "design", "invent" and "patent" indicate the important role of inventive activities to the engineering profession; out of all the verbs, the one most closely associated with engineers is "design". There are also terms indicating the role that engineers played in implementing their new designs and inventions, words such as "build," "erect," "employ," "lay," and "supervise." Other important

[11] Quoted from ICE (1928), p. 2.

[12] Within the ODNB, these are the two natural comparison groups. Most engineers were classified as part of those involved in science and technology, so it is natural to compare to that group. Manufacturers were the other major group of inventors during the study period, as the patent data will show. I exclude military engineers from the engineers group. I also include iron masters as manufacturers. Of those individuals classified as working in science or technology, I do not include manufacturers, artists/engravers, alchemists, or fossil collectors.

[13] See Appendix C for additional results and alternative specifications.

Table 1: Top twenty verb stems associated with engineers

Verb	t-stat	Verb	t-stat	Verb	t-stat	Verb	t-stat
design	14.61	employ	6.74	complete	5.10	advise	4.40
build	11.53	report	6.23	open	5.01	supply	4.36
construct	9.58	erect	6.10	supervise	4.87	connect	4.24
consult	8.16	survey	5.59	improve	4.83	propose	4.11
patent	6.74	drive	5.27	lay	4.56	invent	4.01

This table presents the 20 words most strongly associated with engineers as well as estimated t-statistics from OLS regressions based on robust standard errors. Engineers are compared to manufacturers and non-engineers categorized as involved in science or technology in the ODNB. All of the coefficients associated with these verbs have sharpened p-values below 0.001. N=789,230 (2335 biographies x 338 verbs).

roles played by engineers are indicated by the presence of "consult," "report," and "survey." These terms give us a sense of the types of activities or functions that set engineers apart from other highly successful individuals.

The words least associated with engineers can also be informative. When compared to manufacturers, the five verbs most associated with that group, relative to engineers, are "sell," "expand," "produce," "manufacture," and "buy." For non-engineers involved in science and technology, the verbs most associated with that group, relative to engineers, are "publish," "graduate," "write," "study," and "collect." The contrast between these terms and the words in Table 1 highlights the defining differences, in terms of activities, between these various groups.

Three other results emerge from my analysis of these textual data.[14] First, splitting the sample by time period, I find no evidence that the verbs associated with engineers changed substantially over time. Most importantly, design and invention remained core functions of the occupation throughout the study period. Second, using data where I have matched patentees to ODNB biographies, I find that the results are very similar regardless of whether I identify engineers based on the labels applied by historians in the ODNB or the self-reported occupations from the patent data.[15]

[14]See Appendix C for additional details and results.

[15]Of those with engineer as their modal occupation in the patent data who match to the ODNB, 84% are also classified as engineers in the ODNB data. Of those classified as engineers in the ODNB that also appear in the patent data, 71% appear as engineers in at least one patent.

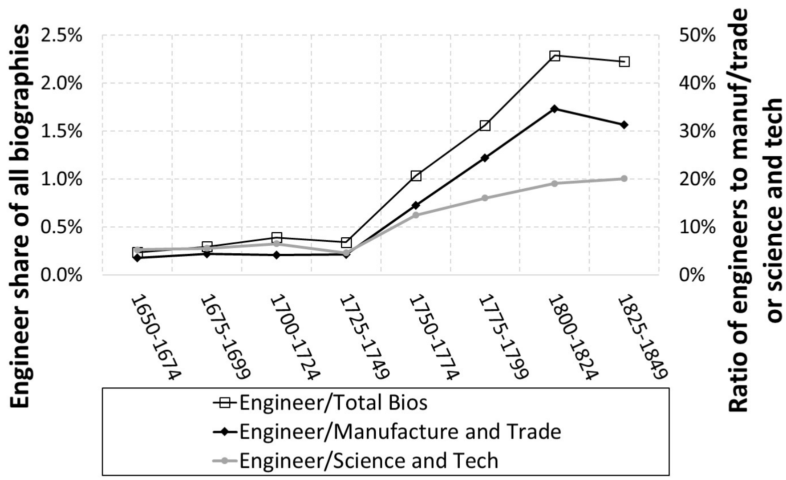
Third, also using the linked patent-ODNB data, I find that the results are very similar if I focus on patent holders as the comparison group. Thus, the core functions of engineers appear to be similar regardless of whether we are relying on the patent data or the ODNB to identify who qualifies as an engineer, or whether engineers are compared only to other patent holders, or to other individuals in the ODNB.

To summarize, both the descriptions that contemporary engineers provide about their own occupation and the quantitative analysis of biographical descriptions from modern historians indicate that engineering was an occupation where design and inventive activity were core functions, together with associated activities such as overseeing construction, consulting, surveying, etc. As inventors and designers, engineers filled a gap between scientists and working mechanics and provided a bridge between theoretical insights and practical applications (see Hanlon (2022) for more evidence on the role that engineers played in bridging science and technology). Next, I document the rise of this new occupation.

3 Rise of the Engineer: Evidence from Biographical Data

This section uses information from the ODNB to provide an initial view of the rising importance of engineers in Britain during the Industrial Revolution. This analysis provides a valuable complement to the more extensive analysis of patent data coming next, because the ODNB covers successful individuals regardless of whether they obtained a patent. Figure 1 plots the share of engineers found in the ODNB relative to all ODNB biographies (left axis) or relative to all individuals classified as either in 'science and technology' or 'manufacturing and trade' (right axis). We can see that, up to the cohort born from 1725-49, engineers account for a very small share of ODNB biographies. However, starting with the cohort born in 1750-74, there is a dramatic rise in the share of engineer biographies, which accounted for over 2% of all biographies by the cohorts born in the first half of the nineteenth century. A similar increase in apparent when we compare engineers to all individuals classified as working either in science and technology (which includes most engineers) or relative to those working in manufacturing and trade (which also includes some engineers). By the first half of the nineteenth century, engineers accounted for over 20% of all notable individuals associated with science or technology.

Figure 1: Share of engineers in ODNB biographies, 1650-1849



Data collected from the ODNB.

Note that the time-scale here is based on the year of birth, so it is not strictly comparable to some of the graphs I will present later, which are based on patent filing dates. However, as we will see, the rise of the engineer shown in Figure 1 will also be reflected in the patent data, despite the fact that these two analysis rely on alternative ways of identifying who is an engineer. A similar rise is also found when studying Google Ngrams, which show a sharp rise in the appearance of the term “engineer” after 1740 (see Appendix B). These patterns are also consistent with existing historical evidence. As Christine MacLeod has carefully documented (MacLeod, 2007) engineers experienced a rising stature beginning in the 1760s and 1770s. This contrasts with the rather poor reputation of “the engineer” (often denoting a maker of engines, rather than engineer as we understand it today) in the first half of the 18th century. In 1744, for example, J.T. Desaguliers warned the readers of his *Course in Experimental Philosophy* about being “over run with Engineers and Projectors” who “draw in Numerous People into ruinous and unpracticable schemes.”[16] This poor reputation had been overturned by the early 19th century, as symbolized by the

[16]Desaguliers (1744), p. 415.

erection of a colossal statue of James Watt in Westminster Abbey in 1834. What had changed? MacLeod (2007) argues (p. 59) that "the strongest case for revising the inventor's reputation as an untrustworthy 'projector' stemmed from the country's growing awareness of major technological achievements."

4 Rise of the Engineer: Evidence from British Patent Data

This section analyzes the emergence of engineers as a key group of inventors, drawing on information available from British patent data. I begin by describing the data before turning to the analysis.

4.1 Patent data

Patent data provide a unique window into the development of technology during the Industrial Revolution, including details on thousands of individual inventors and inventions. Of course, not all innovations were patented (Moser, 2012), and not all patents were for useful innovations (MacLeod *et al.*, 2003). For this reason, it is important that the patent data analysis is complemented with results from the biographical data, discussed above, as well as evidence on civil engineering, in Section 6. However, many of the most important inventions of the Industrial Revolution, as well as thousands of other useful, if less famous, ideas, can be found in patent filings.

The patent data used in this study include the full listing of patents filed from 1700-1851, with details including inventor name, inventor occupation, patent title, and inventor address.[17] The core of this data set was digitized from the two-volume *Titles of Patents of Invention, Chronologically Arranged*, produced by the British Patent Office (BPO) and published in 1854.[18] I focus mainly on the information about inventor occupations, while also using the names to track the output of each inventor. Excluding patents communicated from abroad, this data set includes 12,622 patent-inventor observations covering 11,243 patents.

One reason to focus primarily on the 1700-1849 period is that patent laws were

[17]Because I often estimate results by decade, I end my main dataset in 1849.
[18]Woodcroft (1854b).

largely stable during that period.[19] In 1852, there was an important patent reform act that lowered the cost of patenting substantially, leading the number of patents filed annually to increase from several hundred to several thousand (see Appendix Figure 5). Thus, while I have digitized additional data for the 1850s and 1860s, and I will use them in some of the analysis, it makes sense to focus my main results on the 1700-1849 period.[20]

The most important step in preparing the data for analysis was linking patents associated with the same individual. Because making these links as accurate as possible is important for this study, this was done using a careful manual linking procedure, described in detail in Appendix D.2. For each of the patent-inventor observations from 1700-1849, I match up patents filed by the same inventor using inventor name, year of patent, inventor address, patent subject matter (based on the patent title), and in some cases additional biographical information. Because I link manually using a fairly rich set of linking information, the chance that patents are incorrectly linked to a common inventor is low, though it is possible that I have failed to link some patents by the same inventor because insufficient information to form a conclusive link was available. However, there is no reason to expect that missing links are common or systematic across inventor types. This matching process identifies 8,328 unique inventors active during 1700-1849. Appendix Table 17 lists the most prolific patent filers during that period.

The raw patent data include over 2,000 unique occupation strings. Several of these, such as "gentleman", "esquire", and "engineer" appear regularly. Many others, particularly those reflecting specific manufacturing trades (e.g., "Britannia-ware manufacturer", "Candle-wick maker") appear irregularly. To make this set of occupation strings manageable, I have cleaned them and grouped them into broad sets of related occupations. Table 2 provides counts of the occupation groupings used in the analysis for 1700-1849, while examples of specific occupations falling into each group

[19] Dutton (1984).

[20] Patent data for years after 1851 were digitized from the *Chronological Index of Patents* prepared by the British Patent Office. A second reason to focus primarily on the 1700-1849 period is that, before the 1852 patent law change occupations were provided for most patent entries, but after 1852 the share of patents with missing inventor occupation data is substantial (around 20%).

are available in Appendix D.4.[21]

Table 2: Broad occupation categories used in the main analysis, 1700-1849

Industry	**Patents**	**Industry**	**Patents**
Ag/Food/Drinks	269	Merchants	635
Chemical Manuf.	474	Mining & Metals	759
Construction	410	Misc. Manuf.	1562
Engineers	1726	Textile Manuf.	957
Esquire	754	Prof. services	635
Gentry	1745	Other	833
Machinery & Tools	1068	Unknown	795

Data cover 1700-1849. Excludes communicated patents.

Comparing the names and occupations listed in the patent data reveals that the occupations associated with specific inventors were sometimes not constant across all of their patents. This typically reflected changes in occupation over the career trajectory of an inventor. An example is provided by the engineer Joseph Bramah, famous as a lock and tool maker. Bramah was trained as a carpenter and worked installing waterclosets before he turned his attention to developing new inventions.[22] He first appears in the patent records, in 1778 (patent 1177) as a cabinet maker (consistent with constructing waterclosets). He appears as a cabinet maker again in 1783 and 1784 and then as an engine maker in 1785, 1790 and 1793. Only in 1795 does he begin appearing in the patent record as an engineer (a hydraulic press,

[21] Given my focus on engineers, a couple of additional points about that occupation grouping are warranted. First, some inventors listing "engineer" as an occupation also list another occupation. This is not very common, but typically when it occurs the other occupation is some type of manufacturing. Individuals who list engineer together with a second occupation are counted as engineers in my analysis. Second, civil and other types of engineers (e.g. "consulting engineers") are also counted as engineers for the purposes of my analysis. Third, I exclude from the engineers category those described as "engine makers" as well as mining engineers (which includes "coal viewers"). There is some question about whether these should be treated as engineers or instead classified with, respectively, the machinery manufacturers and miners so, in the Appendix, I also consider robustness results including these groups as engineers. Ultimately, this makes little difference because neither engine makers nor mining engineers are common. Military engineers are also excluded from the engineers category. They are treated the same as other military officers.

[22] See his ODNB biography.

his most important invention according to his ODNB biography). Thereafter his interests broaden and he appears in the patent record eleven more times, always as an engineer, with inventions ranging from a beer engine, a planing machine, a paper-making machine, a banknote numbering machine, and a fountain pen. This progression from manufacturer-inventor to engineer was a common pattern in the early days of engineering.

To deal with these changing occupations, when analyzing data at the patent level, I generally assign patents to the occupation group based on the occupation that appears in that patent's entry. When an analysis is conducted at the level of individual inventors rather than patents (such as when looking at patents per inventor), it is necessary to identify a unique occupation for each inventor. In those cases, I typically use the modal occupation that appears across the patents that the inventor filed.[23] In robustness exercises, I consider alternative approaches. In some of the analysis I also exploit changes in an inventor's occupation over time to study whether inventors begin to behave differently once they start describing themselves as engineers.

I also use data that provide comprehensive categorizations of the technology type represented by each patent, constructed by the British Patent Office.[24] The BPO index categorizes each patent into one, and occasionally more than one, out of 147 technology categories.[25] To my knowledge this is the first use of the full digitized BPO categorization data for the period before 1852. As a check on the results obtained using the BPO classifications, I also replicate my analysis using an alternative classification from Billington & Hanna (2018) generated by applying machine learning to the patent titles.

This study also uses several patent quality measures. During my study period, standard patent quality measures such as patent citations are not available. Instead, I use four alternative approaches to measuring patent quality. The first is based on the payment of patent renewal fees. The fees I study were introduced by the

[23]If an inventor does not have a unique modal occupation, then that inventor is excluded from the analysis. However, this results in the exclusion of just 362 out of the over eight thousand inventors in my analysis.

[24]These categorizations were published as the *Subject Matter Index of Patents of Invention* in 1854 (Woodcroft, 1854a).

[25]Appendix Table 20 provides a listing of the top ten technology categories, by patents filed, in the three 50-year periods from 1700-1849.

1852 patent reform, so this measure is available only for patents in the 1850s and 1860s.[26] The second set of quality measures that I use, based on references to patents in contemporary or modern publications, are from Nuvolari & Tartari (2011) and Nuvolari *et al.* (2021). This is the only quality indicator that is available across the full study period. The third quality measure is based on exhibits in the Great Exhibition of 1851, which has previously been used by Petra Moser to study innovation patterns (Moser, 2005, 2012). This measure is constructed by manually linking patent holders to Moser's database of exhibits of patented inventions in the Great Exhibition.[27] A fourth measure of patent quality is constructed by matching patent holders with at least two patents to the individual profiles of famous Britons in the ODNB.

4.2 Analysis of the British patent data

Figure 2 describes the rising importance of engineers as inventors of patented technologies. Specifically, the figure shows, by decade, the share of patents with at least one inventor in a particular occupation group (top panel), and the number of patents with at least one inventor in each occupation group (bottom panel, log scale).[28] The rise of the Engineer, starting in the 1760s and 1770s, is apparent. By 1800-10, 10% of patents had at least one engineer inventor. This rose to 20% by the 1840s. By the 1860s, engineers accounted for over 29% of patents for which an occupation was reported. No other group shows a similar pattern of growth across the study period. In the bottom panel we can see that patents by all types of inventors were growing during this period, but no other group experienced growth similar to the rate that we see for engineers after 1760. By the 1860s engineers produced far more patents than any other occupation group.[29]

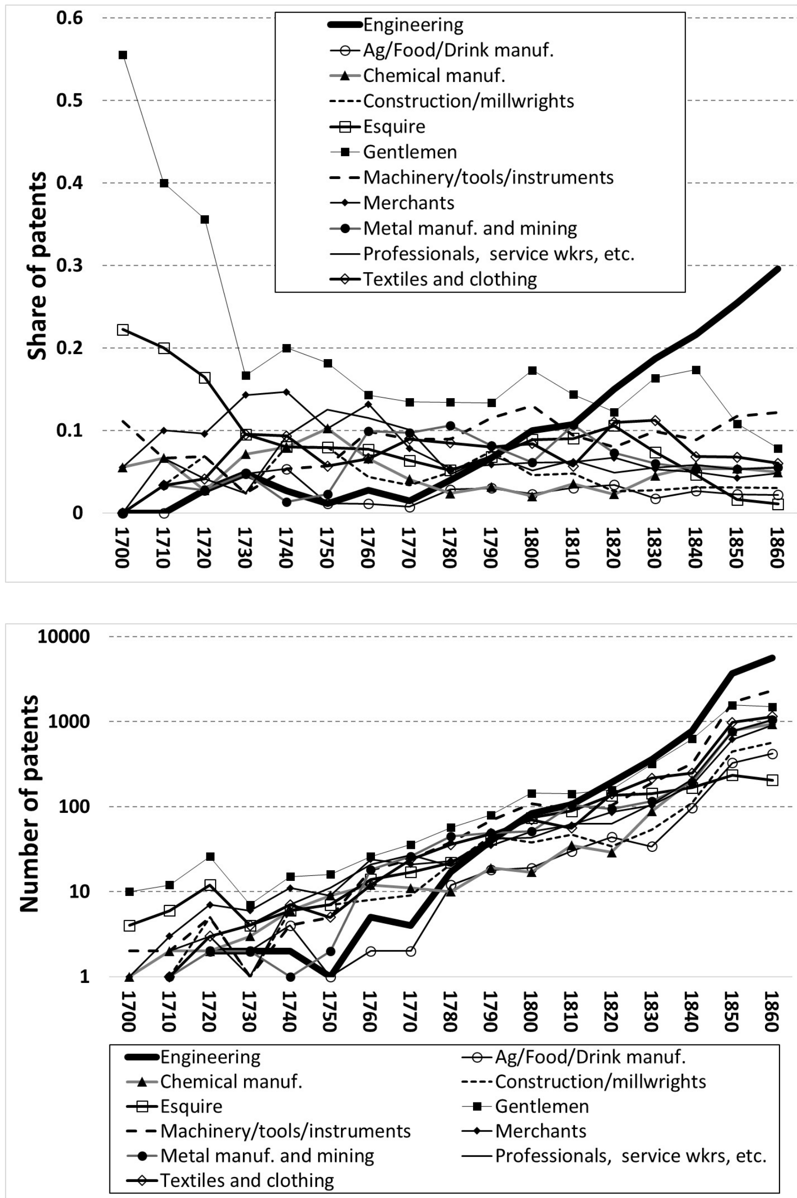
[26] These data come from Hanlon (2015). See that paper for further details on the source and construction of the renewals data.

[27] See Appendix E.6 for further details on the exhibition data.

[28] The shares in the top panel are relative to all patents for which an occupation is reported. This makes very little difference before the 1850s, but it matters for the last two decades because there was a large increase in patents that did not list an occupation after the 1852 patent reform.

[29] For a sense of the individuals that listed their occupation as "engineer", Appendix D.5 provides a list of the top-five engineer patent filers in each decade. Prior to the 1760s, very few engineers appear in the patent data and even the top patenting engineers were generally obscure, with the exception of John Kay in the 1730s. However, this had changed by the 1780s, when we see the list topped by James Watt and William Playfair (inventor of the bar chart and pie graph, among other

Figure 2: Number of patent observations by occupation category, 1700-1849



Occupation groups are based on the occupations listed in the entry for each patent. Excludes communicated patents. Note that patents with multiple inventors may be counted in more than one category, so the shares may sum to more than one.

things), followed by Joseph Bramah and Richard Trevithick in the 1790s and the first decade of the 19th-century, Marc Isambard Brunel and Bryan Donkin in the 1810s, etc.

Three broad types inventors, described by MacLeod (1988, p. 78-9), can be discerned in Figure 2. First, there are the amateur inventors, for whom invention was "an amusing diversion that might one day open up a lucrative sideline." Many of the gentlemen in Figure 2 probably fall into this group. The second group were the professional inventors, for whom "inventing was not a hobby but a livelihood. Typically, he obtained a large number of patents across a wide field of industries..." We will see that engineers fit this description quite closely. The third group MacLeod called the businessman, "those who were ready to engage in manufacturing or trade...while they sometimes obtained more than one patent, these usually related only to their own branch of business." This group, which I will call manufacturer-inventors, were the most common type of inventor outside of engineers. In the remainder of the analysis I will make a special point to study the differences between engineers and these manufacturer-inventors.

In Appendix E.1, I compare the pattern of patents by engineers to other groups thought have made an important contribution to innovation during the Industrial Revolution, such as watchmakers, millwrights, instrument makers, and machinists, or those that may have been related to engineers such as "engine makers" or mining engineers.[30] The main take-away from that analysis is that none of these groups are large compared to engineers, at least after 1760, and none of them experienced the type of explosive growth in patenting that engineers exhibited.

4.2.1 Differences in productivity, quality, and coinventors in Britain

In this subsection, I look at whether engineers were different from other types of inventors. Specifically, I study how many patented inventions individuals produced, the quality of their inventions, and whether they worked in teams with other inventors.

Productivity: Table 3 describes the average number of patents per inventor for inventors in each occupation group, where occupations are based on the modal occupation

[30]On watchmakers, see Kelly & Ó Gráda (2016). The role of millwrights is emphasized by Mokyr *et al.* (2020). Kelly & Ó Gráda (2020) highlight the role of instrument makers. Kelly *et al.* (2020) discuss the importance of artisanal mechanical skills such as those possessed by machinists and machine makers.

listed across each individual's patents. We can see that Engineers generated far more patents per inventor than those in any other occupation group.

Table 3: Average patents per inventor in each occupation group, 1700-1849

Occupation group	**Avg. patents per inventor**	**Occupation group**	**Avg. patents per inventor**
Ag/Food/Drinks	1.258	Merchants	1.246
Chemical Manuf.	1.586	Mining & Metals	1.436
Construction	1.188	Misc. Manuf.	1.372
Engineers	**2.069**	Textile Manuf.	1.463
Esquire	1.727	Prof. services	1.349
Gentry	1.571	Other	1.265
Machinery & Tools	1.473	Unknown	1.152

Inventor occupations groups are based on each inventor's modal occupation. Those without a unique modal occupation group are excluded. Communicated patents are not included. Data cover 1700-1849, the years when matched data are available.

Table 4 verifies that the difference between engineers and other types of inventors is statistically significant and present in various sub-periods. The first column presents results looking across the full sample period. The estimates show that, indeed, engineers produced significantly more patents than other types of inventors. Moreover, magnitude of the coefficient on engineers, 0.689, is very large relative to the average number of patents per inventor, which is 1.52 across the full sample. For comparison, I also estimate results for manufacturer-inventors, a group that includes the Machinery & Tools, Metals & Mining, Chemicals, Textiles, and Misc. Manufacturing occupation groups. Unlike engineers, manufacturer-inventors are not more productive than other types of inventors.

We may worry that this difference is simply because engineers were operating in technology areas where patenting was more common.[31] In Column 2, I include controls for the modal technology category that each inventor was working in. This has very little impact on my estimates, which indicates that differences in the propensity to patent across technology categories is not behind the higher productivity of engi-

[31] As Moser (2005) has shown, patenting rates can vary substantially across sectors.

neers relative to other types of inventors. It is also useful to look at how these patterns look in various sub-periods of the sample. The results in Columns 3-6 show that I also obtain clear results within each twenty-year period from 1770-1849 (as shown above, there are few engineers before 1770 so I do not include results for that period). In contrast to engineers, those with manufacturing occupations did not generate more patents than the average inventor in any sub-period.

Table 4: Number of patents per inventor regressions

	DV: Number of patents per inventor					
	All years	All years	1770-1789	1790-1809	1810-1829	1830-1849
	(1)	(2)	(3)	(4)	(5)	(6)
Engineer	0.689***	0.616***	1.023**	0.802***	0.339***	0.448***
	(0.0865)	(0.0903)	(0.468)	(0.237)	(0.131)	(0.0921)
Manufacturer	0.0618*	0.0272	0.0136	-0.0240	-0.0285	-0.00298
	(0.0325)	(0.0368)	(0.0579)	(0.0585)	(0.0580)	(0.0529)
Tech. cat. FEs		Yes	Yes	Yes	Yes	Yes
Observations	7,966	7,966	652	1,209	1,802	4,215
R-squared	0.018	0.044	0.187	0.121	0.061	0.055

*** p<0.01, ** p<0.05, * p<0.1. OLS regressions with robust standard errors in parenthesis. The unit of observation is an inventor. Data cover 1700-1849. The outcome variable is the number of patents per inventor across all years (Column 1-2) or with 20-year periods (Columns 3-6). The explanatory variable is an indicator for whether the inventor's modal occupation is engineer. Inventors without a unique modal occupation are not included. The regression in Column 2 controls for the modal technology category for each inventor looking across all of that inventor's patents by including a full set of technology category fixed effects. In Columns 3-6, I control for the modal technology category for each inventor within each period. In all of these, if there is a tie for the modal category then one is selected randomly. Data cover 1700-1849, when matched data are available.

While the results in Table 4 identify engineers using the modal occupation appearing in an individual's patents, and excluding those without a unique modal occupation, there are other reasonable alternative ways to classify engineers. I explore several of these in Appendix E.2 and find that all of the alternatives I consider show that engineers patented substantially more inventions than other types of inventors.

At this point it is worth considering whether the decision not to include engine builders or mining engineers as part of the engineers category has any bearing on the results I obtain. To examine this, in Appendix E.3, I present additional results following the approach used in Table 4 but classifying these groups as part of the engineers category. The results are effectively identical to those presented in Table 4, which signals that the decision of whether or not to classify engine builders and mining engineers in the engineers category has no impact on my overall results.

Patent quality: Next, I provide evidence showing that, in addition to producing more patents, engineers also produced higher quality patents and achieved greater overall career success. In Column 1-2 of Table 5, I measure patent quality using the payment of renewal fees to keep patents in force after, respectively, three or seven years. Renewals were expensive: £50 at three years and £100 at seven years, compared to the initial patent application fee of £25.[32] As a result, only 18% of patents were renewed at year three and just 6.3% at year seven. The results in Columns 1-2 show that patents with at least one engineer inventor were substantially more likely to be renewed. The effects are large in magnitude compared to the sample averages and strongly statistically significant. While patents by manufacturer-inventors were also more likely to be renewed, they were substantially less likely to be renewed than patents by engineers. Additional results using the patent renewal data are presented in Appendix E.4.

In Column 3 and 4 of Table 5, I consider a second measure of patent quality based on references in contemporary or modern sources. Column 3 uses the WRI (for Woodford Reference Index) compiled by Nuvolari & Tartari (2011), which is based only on contemporary sources. Column 4 uses the BCI (for Bibliographic Composite Index) from Nuvolari *et al.* (2021). The BCI augments the WRI with references in modern sources. In both cases the indexes have been standardized. The results suggest that patents with at least one engineer inventor were of higher quality than other patents. These patterns are particularly strong in the BCI index, which Nuvolari *et al.* (2021) argue is the more reliable measure. In contrast to the results in Columns 1-2, these measures suggest that manufacturer-inventors generated lower-

[32]For comparison, average annual nominal earnings for a worker in full time employment in 1851 were about £33. See `measuringworth.com`.

quality patents than the average. More complete results obtained using the patent quality indices are available in Appendix E.5.

In Column 5, I use exhibiting in the Great Exhibition of 1851 as an indicator of quality. The sample is the set of all inventors who patented from 1830-1849 and the outcome variable is an indicator for whether a patent holder subsequently appeared as an exhibitor or inventor in the Great Exhibition. The regression estimates reflect how the probability of being in the Great Exhibition varies by occupation group. The results show that engineer patent holders were substantially more likely to exhibit patented inventions in the Great Exhibition than other patent holders. Further details and additional results using the Exhibition data can be found in Appendix E.6.

Finally, in Column 6, I look at an indicator of the overall career success of patent holders, as indicated by their inclusion among the noteworthy individuals in the ODNB. For each of the 2,053 inventors with two or more patents, I manually search for each individual in the ODNB. Engineers, identified based on the occupations listed in the patent data, made up 15.5% of the group that I attempted to match to the ODNB database, but they account for 26.9% of those found in ODNB, and 34.2% of those matched who were born after 1780, an indication that engineers were more likely to achieve substantial career success than other types of inventors.

Column 6 of Table 5 provides further evidence on this pattern. The regression presented in that column is run over all inventors searched for in the ODNB database (those with two or more patents) and the outcome is an indicator for whether an individual is found in the ODNB. The explanatory variable is the modal occupation of each inventor. These results indicate that engineer inventors were about 8 percentage points more likely to appear in the ODNB than other inventors with at least two patents, while manufacturer-inventors were less likely to be noteworthy enough for inclusion. These are large differences given the sample average rate of inclusion is 12.8%.[33] Further ODNB results are available in Appendix E.7.

Overall, the results in Table 5, together with the more complete regression results available in the associated appendices, shows that, across a range of different quality indicators, engineers generated higher quality patents and had greater overall career

[33]This sample mean differs from the 11.9% of inventors with 2+ patents found in the ODNB because it includes only inventors with a unique modal occupation.

Table 5: Patent quality regressions

	Patent renewals		**Reference indices**		**Great**	**ODNB**
	Year Three	Year Seven	WRI	BCI	**Exhibition**	**Biography**
	(1)	(2)	(3)	(4)	(5)	(6)
Engineer	0.0462***	0.0200***	0.0400	0.231***	0.0441***	0.0808***
	(0.00899)	(0.00637)	(0.0307)	(0.0434)	(0.0131)	(0.0262)
Manufacturer	0.0140*	0.00870*	-0.0486*	-0.104***	0.0159*	-0.0374**
	(0.00772)	(0.00520)	(0.0253)	(0.0307)	(0.00835)	(0.0149)
**See table notes for details on fixed effects included in different specifications.*						
Observations	54,742	41,215	18,473	18,473	4,469	1,987
R-squared	0.020	0.015	0.134	0.058	0.003	0.013
Testing difference between engineer and manufacturer coefficients						
F-statistic	10.0	2.37	7.42	55.9	4.18	20.92
P value	0.002	0.124	0.007	0.000	0.041	0.000

*** p<0.01, ** p<0.05, * p<0.1. OLS regressions. Results in Column 1 use data on renewals paid at year three for patents filed from 1856-1869. Results in Column 2 use data on renewals paid at year seven for patents filed from 1853-1866. In Column 1-2, patents that are classified into multiple technology categories appear more than once. To deal with this, standard errors are clustered by patent. The regressions in Columns 1-2 included both year and technology category fixed effects. Results in Column 3 use the (standardized) WRI index from Nuvolari & Tartari (2011) as the outcome variable. Results in Column 4 use the (standardized) BCI index from Nuvolari *et al.* (2021). The data in Columns 3-4 cover 1700-1849. Patents that fall into multiple technology categories appear more than once in these data. To deal with this, standard errors are clustered by patent. Results in Column 3-4 also include year and technology category fixed effects. In Column 5, the sample is composed of all individuals who filed patents from 1830-1849 and the outcome variable is whether they match to a patented invention exhibited in the Great Exhibition of 1851. Since the Exhibition analysis is based on matching individual inventors, the explanatory variable in Column 5 is the modal industry of the inventor. In Column 6, the sample includes all inventors with two or more patents and the outcome variable is whether the inventor appears in the ODNB. The explanatory variables are based on the modal occupation of each inventor.

success than other types of inventors. This is true relative to all inventors or to manufacturing-inventors in particular. Next, I consider other ways in which engineers differed from other inventors.

Coinventor teams: One reason that engineers may have been more productive is that, because invention and design was central to their profession, they may have been better able to form coinventor teams. Coinventor teams may have been beneficial either because they brought together individuals with complementary technical skills, or because they helped inventors partner with those who were more able to fund or commercialize inventions.[34] Across the study period, coinvention was generally rising, a pattern that has also been documented in more recent periods (Jones, 2009).

Table 6 presents regression results where the unit of observation is the patent, the outcome variable is whether the patent has more than one inventor (10.7% of all patents), and the key dependent variable is whether one of the inventors is an engineer. Column 1 presents baseline results using OLS regressions while Columns 2 and 3 add in decade and technology category fixed effects respectively. Columns 4-6 follow the same format, but using Probit regressions.[35] These results show that patents by engineers involved significantly more co-inventors than patents filed by other types of inventors. The results are strongly statistically significant as well as large relative to the average rate of multi-inventor patents of 0.107 across the full sample. Thus, these findings indicate that engineers went about the process of invention in a way that differed markedly from other inventors.

Summary: The results in this subsection show that engineers generated more patents than other inventors, that on average these patents were of higher quality than those produced by other inventors, and that they worked with more coinventors. One may wonder at this point whether these differences were due mainly to the selection of more productive individuals into engineering. To address this issue, in the next section I consider how the behavior of individuals change when they begin to think of themselves as engineers rather than manufacturer-inventors.

[34]It is not possible to clearly differentiate these alternative motivations. However, in Appendix E.8 I explore the composition of these coinventor teams. This analysis indicates that engineers often coinvented with manufacturers or gentlemen, which may reflect the formation of partnerships between inventors and those who were well-placed to commercialize a new invention, or those who could contribute financing or political connections to a project, though it could also reflect different types of skills useful in the invention process.

[35]Note that in Columns 3 and 6 the number of observations increases because patents listed in more than one technology appear more than once, and to account for this standard errors are clustered by patent.

Table 6: Patenting with coinventors

	DV: Indicator variable for patents with multiple inventors					
	OLS regressions			Probit (marginal effects)		
	(1)	(2)	(3)	(4)	(5)	(6)
Engineer	0.0663***	0.0582***	0.0441***	0.0663***	0.0550***	0.0446***
	(0.00974)	(0.00984)	(0.00841)	(0.0097)	(0.0094)	(0.0087)
Decade FEs		Yes	Yes		Yes	Yes
Tech. Cat. FEs			Yes			Yes
Observations	11,243	11,243	15,679	11,243	11,243	15,185
R-squared	0.006	0.013	0.087			

*** p<0.01, ** p<0.05, * p<0.1. Data cover 1700-1849. In Columns 1-2 and 4-5 the unit of observation is a patent and robust standard errors are used. In Columns 3 and 6 the unit of observation is a patent-by-technology-category, so patents listed in multiple technology categories may appear more than once. To account for that, standard errors are clustered by patent. The explanatory variable is an indicator for whether one or more of the inventors is listed as an engineer in the patent entry.

4.2.2 Changes upon becoming an Engineer

As the description of Joseph Bramah's career in Section 4.1 illustrates, when engineering was still a relatively new profession a number of engineers first appear in the patent data as manufacturer-inventors or other types, and then eventually began to think of themselves instead as engineers. Using these occupation switchers, I can study whether the behavior and output of an inventor changes when they begin to describe themselves as an engineer.

To undertake this analysis, I begin by focusing on only those inventors with two or more patents (around 1900 inventors). For each inventor, I construct a dataset that covers all years from their first to their last patent and indicates the number of patents they filed in each intervening year. There are 380 inventors with multiple patents that list themselves as engineers in at least one patent. For these, I identify the first year that they list their occupation as engineer and generate an indicator variable that takes the value of one for that year and all subsequent years until the last patent that they filed. I then run regressions looking at how outcomes for each of these inventors changes after they began describing themselves as an engineer, with individual fixed effects included so that identification is driven entirely by changes within inventors over time. Specifically, I study how becoming an engineer is related to whether an inventor works with coinventors (their behavior) and how many patents they produce per year (their productivity).[36]

The results are presented in Table 7. The first three columns of this table focus on one observable measure of the behavior of inventors: the share of their patents filed with at least one coinventor. The results in the first column show that individuals began working with more other inventors once they became engineers. To ensure that this wasn't just due to becoming more experienced as inventors, the second column includes a control for the number of years since each inventor's first patent. In the third column, I drop observations from the first year in which an inventor listed their occupation as engineer. This changes the sample, since it eliminates those who did not have patents in years after they first list their occupation as an engineer (about 18% of engineers), but we still see evidence that inventors worked with more coinventors after becoming engineers.

In Column 4-6, I look at the output of inventors, specifically the number of inventions they produced per year, between the first and last year that they patented.[37] The results in the first column shows that individuals generated about 0.25 more patents per year after they started describing themselves as engineers. This is a large increase relative to the sample average of 0.32 patents per year. Column 5 shows that this is not due to a general increase in patenting as inventors' careers progressed. In Column 6, I drop from the sample the first year in which an individual described themselves as an engineer. This is done because to become an engineer the individual must appear in the patent database, which causes a direct link between becoming an engineer and generating a patent. Dropping this ensures that this mechanical effect is not behind my results. I still observe clear effects in Column 6 despite the fact that these results are likely to be biased toward zero (the true magnitude of the

[36]Unfortunately, it is not possible to also assess how patent quality changes when inventors become engineers, since the only quality measures available across the full study period, the reference-based indexes, are too noisy to generate clear results given the sample size used in this analysis.

[37]Note that the sample size is larger in Columns 4-6 than in Column 1-3 because the sample in Column 4-6 includes inventors who never had a multi-inventor patent.

change should lie between the estimates in Columns 5 and 6). Additional results, in Appendix E.9, show that even stronger effects are estimated if quadratic controls for time since first patent are included.

Table 7: Within-inventor regressions

	DV: Share of patents with multiple inventors			**DV: Patents per year**		
	(1)	(2)	(3)	(4)	(5)	(6)
Engineer	0.0513**	0.0620***	0.0915***	0.252***	0.266***	0.0686**
	(0.0229)	(0.0235)	(0.0305)	(0.0334)	(0.0335)	(0.0328)
Years since		-0.000928	-0.000755		-0.00123***	-0.000624
first patent		(0.000605)	(0.000587)		(0.000458)	(0.000431)
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes
Dropping first year as Eng.			Yes			Yes
Observations	5,333	5,333	5,152	18,787	18,787	18,641
R-squared	0.547	0.548	0.552	0.234	0.234	0.233

*** p<0.01, ** p<0.05, * p<0.1. Standard errors are clustered by individual. The Engineer variable is an indicator for each individual that takes a value of one starting from the first year in which an individual listed their occupation as engineer in a patent, and zero otherwise.

The fact that the same individuals begin to behave differently, and produce more, once they begin describing themselves as an engineer indicates that the broad differences between engineers and other inventors documented above are not merely due to the selection of more productivity individuals into the engineering profession. Instead, these results suggest that once an individual began to think of themselves as an engineer, their behavior changed in a way that led to increased inventive output.

4.2.3 Differences in technology type and scope in Britain

In the next stage of the analysis, I bring in the British Patent Office technology categorizations and use them to study differences between engineers and other inventors in terms of the types of technologies that they worked on. It is useful to begin by discussing some of the technology categories in which engineers were particularly active. As detailed in Appendix E.10 engineers accounted for a high fraction of patents in key Industrial Revolution technology categories, including mechanical tools for boring, drilling, and punching, steam engines, boilers, railways and rolling stock, gas manufacturer and use, as well as advances related to civil engineering (arches, bridges, tunnels, embankments, etc.). However, engineers patented across a wide range of different technology types.

Table 8 presents the average number of technology categories patented in by inventors falling into each occupation group. Clearly engineers worked across a broader set of technology categories than any other type of inventor. This was not due to the fact that many patents by engineers were filed later in our study period. Regression results in Appendix E.11 show that not only did engineers work on significantly more technology types when looking across the full sample period, but the same is true in every two-decade sub-period from 1770 forward (we know from above that there were few engineers before 1770). In contrast, inventors holding manufacturing occupations consistently patented in fewer technology categories, most likely those closely related to their manufacturing activities.

Thus, engineers were not merely generating more inventions of the same type. Instead, they were producing both more inventions and inventions that spanned a wider set of different technologies. In this, they appear to have been fundamentally different than other types of inventors.[38] It is worth noting that engineers typically did not produce patents in more technology types per patent filed. Rather, their diversity on technology categories covered was closely tied to the fact that they were producing more patents overall. However, this does not detract from the fact that they were able to patent in a broader set of technologies, because it may be that their greater overall productivity was possible exactly because they possessed the ability to pursue promising ideas across a broader range of technology types.

One might wonder about the extent to which the technology category results are

[38]It is important to note that these results do not contradict the idea, emphasized in recent work by Jones (2009), that inventors become more specialized as knowledge advances. Rather, the growth of specialized inventors (engineers) should be interpreted as the first step in this specialization process. Moreover, the fact that engineers were more likely to work in coinventor teams is also consistent with what we would expect given the results in Jones (2009).

dependent on the specific features of the BPO classifications. To allay this concern, Appendix E.12 shows that equivalent results are obtained using a very different set of patent classifications generated by Billington & Hanna (2018).

Table 8: Average number of technology categories per inventor, by occupation type

Occupation group	Avg. number of tech. categories per inventor	Occupation group	Avg. number of tech. categories per inventor
Agric., food/drink makers	1.548	Merchant	1.483
Chemical manuf.	1.740	Metals and mining	1.589
Construction	1.470	Misc. manuf.	1.462
Engineering	**2.459**	Textile Manuf.	1.388
Esquire	1.897	Prof. services	1.605
Gentry	1.822	Other occ.	1.490
Machinery and tool manuf.	1.547	Unknown	1.519

Based on the modal occupation group of each inventor. Inventors without a unique modal occupation group are not included. Excludes patents that are communications. Data cover 1700-1849.

4.2.4 Background of engineers

Using patent data that has been manually matched to ODNB biographies (discussed in more detail in Appendix E.13), it is possible to extract biographical information on the background of patenting inventors. Briefly, the most common educational background for engineers (as identified by the patent occupations) was an apprenticeship. Prominent engineers apprenticed in a wide variety of older occupations, such as millwrights, watchmakers, carpenters, merchants, land surveyors and civil engineers, shipbuilders, coal viewers, etc. Of these, the most common for engineers was carpenter or joiner. In later years, some engineers also apprenticed at famous engineering firms. The wide range of different apprenticeship backgrounds emphasizes the broad set of paths that led into engineering as well as the fact that engineering was not merely a relabeling of an older occupation such as millwright. Engineers were also more likely than other types of inventors to have a purely working background (beyond basic primary schooling). A number of prominent engineers fell into this group, such as the famous railway engineer George Stephenson. Engineers were less likely than other inventors, particularly gentlemen and other professionals, to have formal higher education. This suggests that what higher education they did have was probably primarily due to self-study, a feature that appears regularly throughout the ODNB biographies. One implication of this fact is that it would be a mistake to classify this important group of inventors based on their formal educational background.

5 International comparison: Engineering in France

This section compares the changes in the British innovation system to France, a natural comparison country, during the same period. Specifically, I focus compare patterns observed in patent data, using data on French patents.

5.1 French patent data

I study French patents, following the work of Hallmann *et al.* (2021), using data that span the inception of the system in 1791 to 1843, just before a major patent reform was undertaken in 1844. Similar to the British patent data, the 11,804 patents filed in France during this period include the patentee name and, in most cases, patentee occupation and location, patent title, and technology category. I clean and prepare the French patent data using essentially the same procedures applied to the British data, including standardizing occupation information and conducting a laborious manual matching of patents to identify unique individuals.[39] Starting with 14,161 patent-inventor observations, this matching procedure identifies 10,559 individual inventors (filing 1.35 patents per inventor on average).

Three differences in the French data are worth noting. First, patentees in France could apply for protection over 5, 10, or 15 years, with higher fees for a longer duration. This feature is useful because it provides an indicator of expected patent quality. Second, the occupations appearing in the French data differ from those found in

[39]Individual matches in the French patent data are particularly reliable because there were few common surnames and the data often included multiple first and middle names.

Britain, with almost no one described as a "Gentleman" or "Esquire".[40] Thus, if one is concerned about how the presence of many gentlemen in the British data affect the results, this issue will not be present in the French data. Third, the French system distinguished between patents of *invention* of new technologies, *improvement* to existing technologies, and *importation* of technologies discovered abroad. All three types are included in my analysis.

5.2 Analysis of French patent data

A first question to ask is whether engineers (ingénieure) in France differed from other inventors, as they did in Britain. This issue is examined in Table 9. Column 1 shows that engineers filed more patents per person than other types of inventors, while manufacturer-inventors filed fewer patents.[41] As I will discuss later, some of the engineers that patented in the French data were based in Britain. To ensure that these British inventors are not driving the results, Column 2 presents results in which any inventor declaring an address in the U.K. in any of their patents is excluded.

Columns 3-4 conduct a similar exercise looking at the average length of the patent term applied for by different types of inventors. This is interesting because it may be an indicator of the ex ante assessment of the quality of an invention, though it should be considered with caution because it may also be influenced by factors such as credit constraints. The results in Column 3 (all inventors) and Column 4 (excluding British inventors) indicate that engineers applied for significantly longer patent terms than other types of inventors, suggesting that they may have been producing higher-quality innovations. Columns 5-6 of Table 9 show that engineers in France also filed patents across a wider range of technology categories than other types of inventors.

Thus, my analysis of the French patent data confirms the main patterns found in the British patent data: engineers were more productive, in terms of the number of patents they produced, there is evidence suggesting that they also produced higher

[40] However, a number of inventors described themselves as either working in government (e.g., mayor) or as a member of the military. These are probably the most comparable occupations to the "gentleman" category found in the British data given that the military and public service were two of the primary occupations for the British upper classes.

[41] As in the the British patent analysis, the manufacturer-inventor category includes those working in machinery and tools, metals and mining, chemicals, textiles, and misc. manufacturing.

quality patents, and they also patented across a broader set of technology categories. Moreover, not only were engineers more productive than the average non-engineer inventor, they were also more productive than every other occupation group (see Appendix Table 39).

Table 9: Differences between engineers and other patentees in France

	Patents per person		Avg. length of patent term		Tech. categories per person	
	All inventors	Excluding UK-based	All inventors	Excluding UK-based	All inventors	Excluding UK-based
Engineer	0.965***	0.838***	1.156***	1.045***	0.690***	0.594***
	(0.147)	(0.137)	(0.204)	(0.218)	(0.108)	(0.0993)
Manuf.	-0.0589***	-0.0589***	-1.195***	-1.047***	-0.0954***	-0.0949***
	(0.0179)	(0.0181)	(0.0736)	(0.0740)	(0.0201)	(0.0212)
Observations	10,556	9,980	10,541	9,967	10,557	9,981
R-squared	0.032	0.025	0.031	0.026	0.011	0.008

Robust standard errors in parenthesis. Occupations are based on the modal occupation of each inventor. Inventors without a unique modal occupation group are not included.

Next, I ask: did the French innovation system undergo the same changes documented in the British innovation system? In particular, do we observe a similar emergence of engineers as an important group of inventors in France? Figure 3 presents the key patterns, comparing the share of patents filed by engineers in Britain and France relative to all inventors (left panel) or those inventors who reported an occupation (right panel). Unlike Britain, we can see that France did not experience a rise of patents by engineers in the first few decades of the nineteenth century. Instead, the types of inventors that patented in France remained essentially stable throughout 1790-1843 period and dominated by manufacturer-inventors (see Appendix Figure 8), similar to the patterns observed in Britain before the emergence of engineering. This contrast may help explain why it was Britain, rather than France, that emerged as the technology leader during this period.

The fact that we do not observe the emergence of engineers as an important part of the French innovation system before the mid-1840s may be surprising given the well-established system of engineering education that existed in France at this time. However, as discussed in Appendix H, the French system was largely directed by the government and focused on producing engineers skilled at designing public infrastructure, mainly for military purposes. In contrast, the engineering profession that developed in Britain did so with very little government intervention, resulting in a profession with more of a focus on developing economically-valuable new technologies. British engineers may have also benefited from the availability of skilled craftsmen in Britain, which made it easier to implement new inventions (Kelly *et al.*, 2014). These differences can help explain why it was in Britain, rather than France, where engineers emerged as a major part of the innovation system.

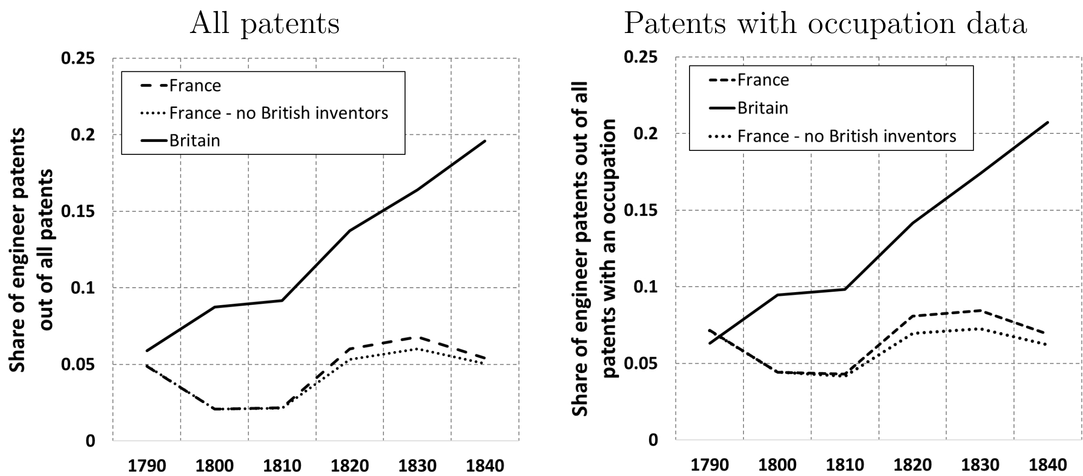
A final aspect of interest in the French patent data is the contribution of foreign inventors, particularly the British. Of the inventors with an address listed in the French data, 92% had a modal location in France. The next largest group by far was the British, accounting for 5.8%, followed by the U.S. (0.5%) and all of the various German territories (0.47%). While British inventors accounted for just 5.8% of all French inventors, they accounted for 11.7% of all engineers, and 13.8% of patents by engineers, in France. Moreover, within the group of British inventors that reported an occupation, 37.4% were engineers. Since engineers accounted a lower fraction of all British patentees during this period, this tells us that engineers were much more likely than other British inventors to also patent their inventions abroad. This provides yet another indicator that engineers differed in important ways from other types of British inventors.

6 The Professionalization of Civil Engineering

Civil engineering work is perhaps the most closely associated with the engineering profession, and it was the first to develop many of the features of a profession, such as dedicated professional societies. This section reviews available historical evidence on the development of the civil engineering profession, supported with some new quantitative analysis.

While civil engineering work has been undertaken for millennia, historians highlight the fundamental changes that took place in how this work was done during the eighteenth century. Bill Addis, in his monumental history of 3000 years of building engineering (Addis, 2007), titles the chapter covering 1750-1800, “Engineering be-

Figure 3: Share of patents by engineers in Britain and France



Source: Engineers are identified as those listing engineering as their modal occupation. The French data spans 1791-1843. The British data cover 1790-1849.

comes a Profession." In it, he describes how this professionalization was reflected in the career of John Smeaton, one of the leading civil engineers of the age (p. 239-240):

> *[John] Smeaton was able to apply general principles, based on science and tested using full-sized and scale model experiments, to an engineering problem in a field entirely unfamiliar to him...the translation of real engineering problems into simplified theoretical models was becoming a matter of course for the few engineers who were scientifically and mathematically educated...from Smeaton's calculations of the size or number of water wheels needed to perform pumping duties, we can see that he had already established our modern approach to engineering design...While Smeaton has become an engineering icon...many other engineers where treading similar paths.*

I provide quantitative support for this narrative using a list of 338 major British civil engineering projects. These data, from Skempton *et al.* (2002), have been digitized and combined with biographical information on the engineers involved.[42] While

[42]Further details on these data can be found in Appendix G.

the data cover 1500-1830, I focus mainly on the period after 1600, since there were few major projects before that point. These data show that from 1600-1760, roughly 75% of major engineering projects were overseen by someone who had not previously overseen another major project (see Appendix Figure 10). After 1760, however, the pattern changes. From that point until 1830, roughly 35% of all major projects were overseen by a chief engineer who had not already overseen a major project. Moreover, after 1760, and unlike before that point, very few major projects were overseen by engineers who did not either have prior experience or training under a more experienced engineer. Thus, the engineers chosen to oversee major projects were becoming a more experienced group.

What changed in the middle of the eighteenth century? Before 1760, major infrastructure projects were often designed and overseen by skilled craftsmen as one-off endeavors.[43] Many of these "proto-engineers," with backgrounds that included millwright, architect, surveyor, mason, and mining engineer, were skilled, and some were brilliant. What was different was that they had rarely developed their skills by working on previous major engineering works, and they rarely undertook more than one or two important engineering projects in their lifetime.

One striking example of this pattern is provided by the construction of the Westminster Bridge, the most expensive infrastructure project undertaken in Britain the first half of the eighteenth century. Parliament chose Charles Labelye as the engineer in charge of this project. Labelye was skilled and knowledgeable, but up to that time he had not a single major engineering project to his name, either as chief engineer or as an assistant engineer under someone more experienced (Skempton *et al.*, 2002). That Parliament chose him to undertake the most important engineering project of the period was emblematic of how civil engineering was done up to that point.

After about 1760, this pattern begins to change, with the emergence of a more professional body of engineers, each overseeing numerous major engineering works. From 1700-1750, for example, the most prolific individuals on Skempton's list, Thomas Steer and John Reynolds, oversaw four major projects each. From 1750-1800, the most prolific engineer, John Smeaton, oversaw eighteen, followed by William Jessop

[43]Certainly there were some exceptions, such as Cornelius Vermuyden or George Sorocold.

(15 projects), John Rennie (9 projects), James Brindley (8 projects), etc.[44] By 1800, the idea that a project such as the Westminster Bridge would have been awarded to an engineer with no prior experience would have seemed absurd.

One aspect of the professionalization of the civil engineering that took place after 1760 was that young engineers typically gained extensive experience as assistant engineers before overseeing major projects. From 1700-1760, my data show that only 20 percent of engineers undertaking their first project had prior experience working under an engineer who had previous experience on a major project. This changed in the following generation. After 1760, more than half of all engineers overseeing major projects were trained by more experienced engineers. John Smeaton, one of the most influential early civil engineers, trained five engineers who would go on to oversee major projects, including William Jessop. James Brindley, another important early engineer, trained six, including Robert Whitworth. Jessop would go on to train or partner with seven later engineers who oversaw major projects. Whitworth would train six. Thus, we can see the profession of civil engineering develop after 1760, as the knowledge and experience of the first generation of professional civil engineers was passed on to the next.

The growth of engineering into a distinct and respected profession was accompanied by the development of institutions that helped engineers meet one another and exchange ideas. The Society of Civil Engineers was founded in 1771, followed by the Institution of Civil Engineers 1818 and the Institution of Mechanical Engineers in 1846. These provided a forum for engineers to engage, a way to present and publish their new ideas, and a representative of their interests. There was also a growing specialized press focused on disseminating engineering knowledge, including William Nicholson's *Journal of Natural Philosophy*, founded in 1797, Alexander Tilloch's *Philosophical Magazine* (1798), and, later, *Mechanic's Magazine*, founded in 1823 by Joseph Clinton Robertson, an engineer. Thus, by the middle of the nine-

[44] Between 1750 and 1770, for example, Smeaton was responsible for the Eddystone Lighthouse, the Colstream Bridge, work on the Perth Bridge, the Potteric Carr Drainage, work on the London Bridge Waterworks, and the Adlingfleet Drainage. In just the first decade of the 19th century, John Rennie built the Kelso Bridge, the Leith East Docks, the London Docks, the East India Docks in London, the Humber Dock in Hull, and oversaw the drainage of the Wildmore Fens. Further evidence on this patterns is provided in Appendix Table 41.

teenth century British engineers were immersed in a rich intellectual milieu based on networks formed through the learned societies and information transmitted through a vibrant scientific and technical press, while the profession itself rested on institutional foundations that would survive to today.

So, the rise of engineers as an important group of *inventors* shown in the patent data paralleled by the professionalization of civil engineers as *designers* of a wide variety of civil infrastructure. These various strands of engineering were closely tied to one another, with many engineers moving between them, and in a number of cases we see civil engineers filing patents, or mechanical engineers relying on income from civil and consulting work while developing new inventions.

7 A Growth Theory Featuring the Professionalization of Invention

This section briefly describes a theory illustrating how the professionalization of invention documented in the previous sections could have contributed to the acceleration in the rate of growth that took place during the Industrial Revolution. Full details are provided in Appendix A. The central feature of the model is the process through which new technologies are developed. This can be done either by non-specialists, who are mainly engaged in other productive activities (manufacturer-inventors), or by specialist researchers (engineers). A key assumption, supported by the empirical analysis above, is that specialist researchers are more productive at generating new technologies than non-specialists. Thus, the core of the model reflects Adam Smith's insight that specialization can increase productivity. Specialized research also involves some fixed cost, a standard assumption in models of innovation, while non-specialists may develop new ideas simply as a byproduct of their productive activities (e.g., learning by doing) without an up-front investment.

To connect my theory to existing work on the Industrial Revolution, the model incorporates two factors that seem likely to play a role in determining whether a professional research sector emerges. The first is the institutional environment, and specifically, whether existing institutions provide sufficient property rights protection for inventors to profit from their new inventions. This feature connects the model to existing work, dating back to (North & Thomas, 1973), which argues that Britain's unique institutional environment may have played an important role in allowing the Industrial Revolution to take off. The second factor is the ease with which potential professional researchers are able to access skills and useful knowledge. The rise of modern engineering would almost certainly not have been possible had access to certain practical skills and scientific knowledge not been readily accessible, or if Britain did not have a ready supply of the high-skilled craftsmen needed to implement new ideas. This feature connects the theory to existing work, such as Mokyr (2009) and Kelly & Ó Gráda (2020), which emphasize the importance of knowledge in the Industrial Revolution and argue that Britain was particularly well-endowed with such knowledge by the eighteenth century.[45]

Starting from an initially low level of technology, the model exhibits three phases of development, though not all phases will necessarily occur. In the first, "pre-modern phase," there is a low level of technology, all individuals specialize in production activities, and all new ideas are the result of serendipitous discoveries generated by workers mainly engaged in generating output. There is no professional research sector in the pre-modern phase because the limited knowledge base means that professional research is not sufficiently productive to make it worthwhile for any individual. Over time, serendipitous discoveries raise the overall level of technology in the economy (similar to the pre-modern period in Unified Growth Theory), but this process may be very slow.

As the technology level slowly rises, it *may* reach a point where enough knowledge is available to support the emergence of a dedicated research sector and the transition to modern economic growth begins. This occurs because, in the standard Romer (1990) framework, the productivity of inventors is increasing in the knowledge base that they have to work with. However, the model makes it clear that the transition to modern economic growth is not inevitable. In particular, for a specialized research sector to emerge, the cost of acquiring the necessary skills must not be prohibitive and there must be institutions in place that allow professional researchers to profit from their discoveries.

[45] Existing work highlights a variety of factors that contributed to the availability of useful knowledge and craft skills in England during this period, ranging from the influence of Enlightenment culture to Britain's well-developed apprenticeship system.

If institutions provide inventors with sufficient protection, and they have access to knowledge at a sufficiently low time cost, then the slow accumulation of knowledge during the pre-modern period will eventually allow a dedicated research sector to emerge. If this occurs, then the emergence of a professional research sector causes an acceleration in the rate at which new technologies are developed. This acts as the mechanism through which the economy transitions toward a new balance growth path characterized by more rapid economic growth. As the transition occurs, the share of the population employed as professional researchers initially grows and then stabilizes. Concurrently, the overall share of the population acquiring skills increases and then stabilizes. Serendipitous discoveries as a by-product of production continue to occur, but over time this source of new technology diminishes relative to the contribution of dedicated researchers.

The way that slowly rising technology during the pre-modern period eventually leads (under the right conditions) to a tipping point that launches the economy toward modern economic growth is a standard feature of models that aim to describe the transition from pre-modern to modern growth, such as Galor & Weil (2000) and Hansen & Prescott (2002). This feature also connects to the historical context I study. The discovery of key macroinventions such as Newcomen's steam engine and Arkwright's water frame provided incentives for follow-on research of the type that over time would come to be dominated by engineers. Viewed through the lens of the model, these inventions represent the final increment that pushed the economy over the tipping point, allowing a professional research sector to emerge. We should not lose sight, however, of the fact that the model does not predict that such a transition was inevitable.

Finally, it is important to recognize that the core mechanism in the model, a change in the production process through which new technology is developed, differs from existing work emphasizing, on the one hand, changes in the availability of inputs into the technology production process (such as human capital) and, on the other, changes in the rewards for producing new technology (such as increasing market size or better institutional protections for inventors). While those factors are likely to be important, and are therefore incorporated into my theory, they are distinct from the mechanism I emphasize.

8 Conclusions

This paper documents the emergence of a new division of labor, characterized by the emergence of professional engineers, and by doing so it provides a new perspective on the Industrial Revolution. Central to this perspective is the idea that there was a change in the process through which new technology developed, an innovation in the process of innovation. I am certainly not the first to argue that the innovation process changed in important ways during this period. What is new here is backing that argument up with quantitative evidence, describing in more detail the nature of the change, and showing, theoretically, exactly how such a change might have contributed to the transition to modern economic growth.

It is not my intention to argue that the changes documented here mattered to the exclusion of other factors that may have influenced the innovation rate during the Industrial Revolution, such as an increasing stock of human capital, the inducements created by an expanding market, the influence of Enlightenment thinking, or the protections provided by the institutional environment. Most likely, such factors worked together, just as they do in my theoretical framework.

The question of what *caused* the acceleration in innovation and economic growth that took place during the Industrial Revolution remains debated. However, in order to make progress in understanding the causes of the Industrial Revolution, it is necessary to first establish the nature of the changes that occurred, particularly those that directly affected the rate of technological progress. Documenting, quantitatively, the nature of the changes that took place in the British innovation system during the Industrial Revolution is the primary contribution of this paper.

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