Bridging Science and Technology During the Industrial Revolution*

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Abstract

Using academic articles published in the *Proceedings of the Royal Society* from 1800-1869 linked to British patent data, I study the connections between science and technology during the Industrial Revolution. I find that a substantial fraction of authors of *Proceedings* articles also produced patented inventions, a share that grew across the study period. These scientist-inventors were more productive than other types of patentees but their work was concentrated in just a few technology types. I also show that one specific group, engineers, played a key role in providing the bridge between science and technology development during this period.

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1 Introduction

How important was science for technological progress during the Industrial Revolution? This question has been the focus of a long and unsettled debate. Some, such as Musson & Robinson (1969) and more recently Jacob (2014), argue that scientific knowledge played a critical role. A number of others disagree, instead emphasizing the importance of craft knowledge and artisanal skills (Cardwell, 1972; Mathias, 1969; Mokyr, 2002; O'Grada, 2016), at least until the middle of the nineteenth century. This debate has been largely driven by historical studies of notable inventions, important scientific developments, or the biographies of individual scientists, inventors, and craftsmen. Depending on the technology or inventor studied, historical evidence can be found for both views. Thus, while careful historical studies have yielded valuable insights into the links between science and technology during the Industrial Revolution, they also leave open questions about the representativeness and generalizability of any particular finding. This is where a broader quantitative analysis approach can be helpful.

This study offers a data-driven approach to studying linkages between science and technology during the Industrial Revolution. Specifically, I bring together two data sets, one based on scientific articles and the other on patented technological invention, and then link individuals across them to identify a set of "scientist-inventors." I then analyze the characteristics and contribution of these scientist-inventors, and how that contribution evolved over time.

My measure of scientific activity is based on articles in the *Proceedings of the Royal Society of London* (hereafter *Proceedings*), which provides a listing of papers presented to the Royal Society from 1800 onward.[1] Within this data set, I also identify those more important papers which were published in the *Philosophical Transactions of the Royal Society of London* (hereafter, *Transactions*), the most important English-language scientific journal of the era. Of course, having a project appear in the *Proceedings* or the *Transactions* is just one indicator of scientific activity, but these were important journals that attracted work by many of the most eminent scientists of the era across a wide range of scientific disciplines.

My measure of technology development is based on patent data. While patent data are not a perfect measure of technological progress, they are widely used to study technological progress, including during the Industrial Revolution, because they provide detailed information on thousands of inventors and inventors, including many of the most important. The patent data that I use, which come from Hanlon (2022), include the name of the patentee, a technological categorization of the patented invention, as well as measures of patent quality.

[1]Prior to 1850, the title was *Abstracts of Papers Printed in the Transactions of the Royal Society of London*, and prior to 1830 this publication was composed entirely of abstracts of papers published in the *Philosophical Transactions*. Typically, 1830 is taken as the true starting year of the publication that would eventually be called the *Proceedings*.

Importantly, patents before 1850 have been linked to individual inventors, a feature that allows me to analyze individual characteristics, such as inventor output or average patent quality.

Using these two data sets, I manually link the 995 authors appearing in the 1705 scientific articles in my study period (1800-1869) to the patent data. These linked data allow me to measure the extent to which individuals were active in both spheres, as well as to study the characteristics of those individuals and how the connections were changing over time.

Using the linked data, I find that the share of authors of scientific articles who also appear in the patent data was substantial, and rising over time. In the first decade of my study period, 1800-1809, around 9% of articles had authors that also appeared in the patent data, a share that rose to around 20% by 1860-1869. These scientist-inventors were mainly active in scientific fields such as mechanics/physics, metallurgy, chemistry, sound, scientific equipment, electricity, and of course engineering and applied science. In contrast, scientists working on topics such as zoology, astronomy, mathematics, or meteorology, were much less likely to appear in the patent data. However, I show that even controlling for scientific field there was a substantial increase in the share of scientific authors appearing in the patent data over time.

Next, I look for differences between patentees who were also involved in scientific activities and other inventors. This analysis shows stark differences between scientist-inventors and other patentees. In particular, on average scientist-inventors produced, individually, almost twice as many patents as other patentees. Moreover, their patents were of substantially higher quality based on available quality measures. These patterns appear even when controlling for the stated occupation (e.g., engineer, chemist) of the inventor listed in the patent data.

I also assess the contribution of scientist-inventors to technology production. Scientist-inventors accounted for a small share of overall patents, a necessary result of the fact that there were a very large number of patenting inventors compared to the small number of authors of scientific articles. However, this contribution was growing across the first half of the nineteenth century. It was also highly concentrated in a few technology categories. Scientist-inventors filed no patents in most technology areas, but they made important contributions in a few. These included emerging technologies such as photography, copying, telegraphy, and refrigeration, chemical technologies such as bleaching and chemical salts, mechanical technologies such as steam engines, railroads, and motive power, civil engineering innovations such as bridges and aqueducts, precision equipment and instruments for mathematics, navigation, and astronomy, timepieces, and medical treatments. Thus, the technological contribution of scientist-inventors was concentrated in a few technology areas, but these are areas that are typically thought to have been particularly important to economic growth during the nineteenth century.

Finally, I study the types of individuals that provided the bridge between science and technology. Specifically, using the occupation information contained in the patent data, it is possible to look at how different groups contributed to the bridge between science and technology. The main take-away from this analysis is that one group, engineers, played a crucial role in bridging science and technology. While engineers accounted for only around 20% of the scientist-inventors, they account for roughly one-half of the patents produced by this group. This reflected the fact that engineers individually produced nearly twice as many patents per individual as any of the other types of scientist-inventors, such as medical doctors, chemists, or instrument manufacturers.

In evaluating these results, it is important to keep in mind that they reflect only one of the potential links between science and technology, those embodied in individuals active in both arenas, and only to the extent that that activity is captured in patent data or *Proceedings* articles. Given this, we would not want to rule out a role for science based only on my results. However, since I do find meaningful connections between science and technology, this analysis provides affirmative evidence in favor of the existence of important, and growing, linkages between science and technology concentrated in a specific set of technology types. Given this approach, it is reasonable to interpret my results as representing a lower bound on the linkages between science and technology during the Industrial Revolution.

Whether the link between science and technology that I document was causal is a more difficult issue to sort out. Causality may have run in either direction; while scientific insights may have contributed to the development of new technologies, new technologies may have also led to new scientific insights. Regardless of the direction of causality, the mere fact that a number of individuals were active in both scientific and technological pursuits, and that this group was relatively more productive than other types of inventors, suggests that these individuals saw benefits in combining both activities rather than specializing in one or the other.

This study contributes to a large literature debating the contribution of science to technology development during the Industrial Revolution (Musson & Robinson, 1969; Wise & Smith, 1989; Smith & Wise, 1989; Jacob, 2014; Cardwell, 1972; Mathias, 1969; Mokyr, 2002, 2009). Relative to this existing work, the main contribution of this study is to offer a broad-based quantitative approach spanning a range of different scientific and technical endeavours, but getting at the same basic set of questions. Both approaches have strengths and weaknesses, so I view them as largely complementary. In terms of substantive results, my findings suggest that there were important links between science and technology development during the first half of the nineteenth century, and that these links were growing over time. They were also, however, concentrated in just a few technology categories.

Another related line of work emphasizes the important role played by individuals at the "upper tail" of human capital during the Industrial Revolution (Mokyr, 2005; Meisenzahl

& Mokyr, 2012; Squicciarini & Voigtländer, 2015). Within this area, the closest paper is Hanlon (2022), which documents the emergence of the engineering profession during the Industrial Revolution and shows the growing contribution that engineers made to innovation, particularly in the first half of the nineteenth century. The results of this paper, which show that engineers played a key role in bridging science and technology development, offer further support to that argument.

This paper is also related to a substantial body of work using patent data to study technology development during the nineteenth century. Contributions to this extensive literature include, among others, Dutton (1984), MacLeod (1988), Sullivan (1989), Sullivan (1990), Nuvolari & Tartari (2011), Bottomley (2014), Nuvolari *et al.* (2021), and Khan (2020). Relative to this extensive literature, the main innovation here is linking the patent data to academic articles, which to my knowledge has not been done in the historical context.[2] In contrast to the large body of work using patent data, there are relatively few studies that have taken advantage of systematic data on scientific publications in the historical context. One exception is Hanlon *et al.* (2022), which uses citations gathered from articles in the *Philosophical Transactions*, as well as patent data, to study the impact of the introduction of the Uniform Penny Post in Britain in 1840 on the production of scientific knowledge and new technology. While that study examines how cheap postage affected both scientific and technological progress, it does not examine in detail the links between these two outcomes.

2 Data

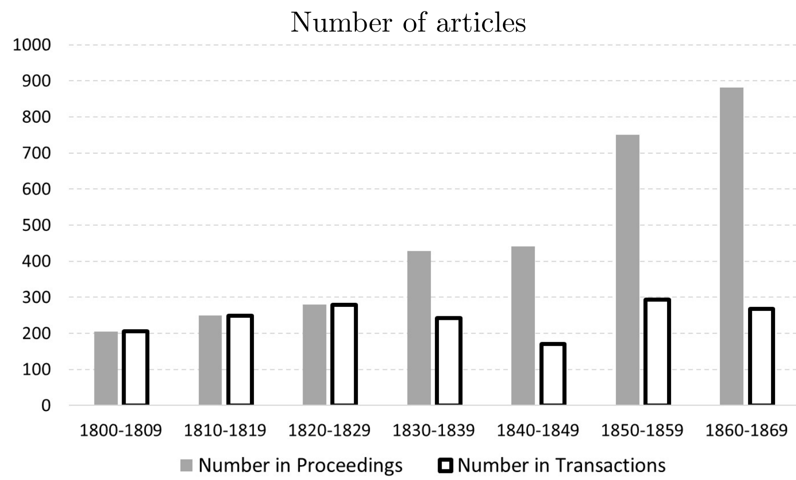
The data on scientific articles used in this study comes from the *Abstracts of the Papers Printed in the Philosophical Transactions of the Royal Society of London*, which became the *Proceedings of the Royal Society of London* after 1854. To avoid repetition I will refer to this source simply as the *Proceedings*. From 1800-1829, the *Proceedings* was a retrospective list of papers actually printed in the *Philosophical Transactions of the Royal Society of London* (hereafter, *Transactions*), the premier English-language scientific journal of the age. Starting in 1830, the *Proceedings* began to include abstracts and short articles describing projects or discoveries that were presented to the Royal Society but not actually selected for inclusion in the *Transactions*.[3] This served as a more rapid means for scientists to inform others about their ongoing work or new discoveries than waiting for publication in the *Transactions*, somewhat like a modern working paper series. We can see these patterns in Figure 1, which describes the number of articles published, and the number of active

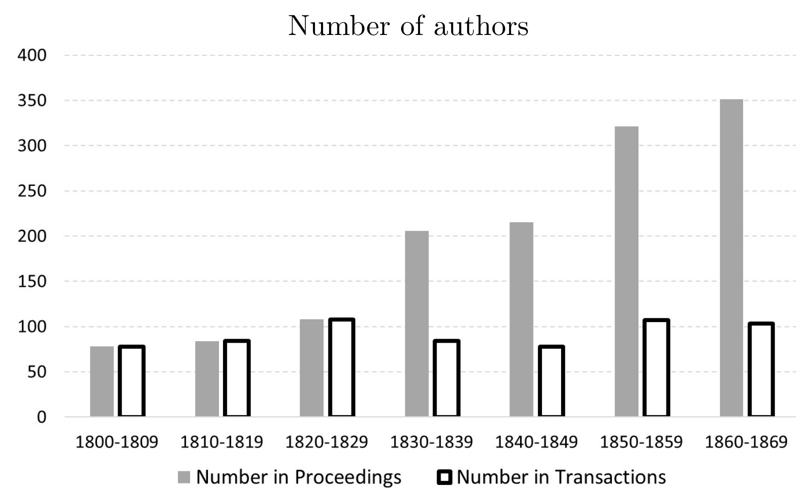
[2] A number of more modern studies look at connections between academic research and technology development using the citations to academic studies included in modern patent filings. Unfortunately, similar citations were not included in historical patents.

[3] See `https://royalsocietypublishing.org/rspl/about`.

authors, in the *Proceedings* in each decade, and the number of those which appeared in the *Transactions*. The number of articles in the *Proceedings* increased substantially through the study period, while the number of those that were printed in the *Transactions* was relatively stable.[4] Thus, the latter series will be particularly useful when we want a consistent way to look at trends over time. Another benefit of identifying articles printed in the *Transactions* is that those will be higher quality studies which would have undergone peer review.

Figure 1: Number of articles and authors in each data series by decade





[4]The set of articles from the *Proceedings* that were printed in the *Transactions* covers almost every article that was included in the *Transactions*. However, it is useful to note that the dates of publication in the *Proceedings* typically predates publication in the *Transactions*.

Table 1: Scientific topics in the Proceedings data

Category	**Articles**	**Category**	**Articles**
Archeology and Paleontology	61	Units of measurement	11
Astronomy	234	Mechanics/Physics	119
Botany	75	Medicine	472
Chemistry	525	Metallurgy	43
Demography	13	Meteorology and Atmospheric Science	175
Electricity	185	Navigation	40
Geography and Oceanography	166	Scientific equipment	139
Geology	116	Sound	23
Light and heat	194	Technology, applied, and engineering science	156
Magnetism	230	Timekeeping	35
Mathematics	271	Zoology	300

An important step in preparing the articles data for analysis is classifying them into topic groups. This was done through a manual review of article titles through which each article was classified as related to between one and three standard branches of scientific inquiry. When constructing this classification system I focus on the primary contribution of the article rather than other features such as the methods used.[5] In the majority of cases, articles were easily classified into one category based on the article title. In some cases, an additional review of the actual text of the article was required. Most articles clearly fit into one category, though a number fit into two or even three categories. For example, David Brewster's 1841 article "On the Compensations of Polarized Light, with the description of a Polarimeter for Measuring Degrees of Polarization" is classified into both the "studies on light and heat" category as well as the category on "advances in scientific equipment." The categories I use, together with a count of the number of articles appearing in the *Proceedings* associated with each category, are shown in Table 1. Example articles for each category are available in Appendix A. Clearly, the articles covered in this analysis spanned a wide range of scientific pursuits, ranging from astronomy to zoology, with chemistry and medicine receiving the most attention.

To measure technology development, I rely on patent data. Going back at least to the work of Richard Sullivan (Sullivan, 1989, 1990), patent data have been a widely used tool for studying technological progress during the Industrial Revolution. While not all useful innovations were patented (Moser, 2012), and some patented technologies turned out to be useless (MacLeod *et al.*, 2003), patent data provide a rich set of information on a wide set of useful innovations, including many of the most important. The patent data used in this

[5] An article on a chemical analysis of the atmosphere, for example, would be categorized as a meteorology/atmospheric science article rather than a chemistry article unless it was clear that it made a contribution to the chemistry field, rather than just applying chemistry to better understand the atmosphere.

study, from Hanlon (2022), cover 1700-1869 and include several useful pieces of information: patent title, application date, the inventor(s) name, and inventor occupations. A unique feature of the patent data from Hanlon (2022) is that for the period before 1850, patents from the same inventor have been manually linked, allowing an analysis of the output of individual inventors. The individually linked dataset ends in 1849, just before the new patent law of 1852, which led to a substantial increase in the number patents, making it infeasible to manually link individual patents after that point. It is worth keeping this 1852 change in patenting law in mind when we come to the analysis.

In addition to the raw patent data, I also use two standard measures of patent quality. The first, from Nuvolari & Tartari (2011), called the Woodcroft Reference Index (WRI) is based on citations to patents from a variety of contemporary publications. The second is an improved version introduced in Nuvolari *et al.* (2021) which augments the WRI using additional citations from modern sources such as the *Oxford Dictionary of National Biography* (ODNB). Nuvolari *et al.* (2021) show that this improved "BCI" measure does a better job of capturing patent quality than the WRI, though both can be informative. I also use information on the technology category of each patent. These categories were assigned to patents by the British Patent Office. The digitized versions are also from Hanlon (2022), and further details about the categories are available in that paper.

The key data preparation step in this study is matching the authors of scientific articles to the patent data. Because obtaining high-quality matches is crucial for this study, a laborious manual matching approach was used. Starting with the author names from the *Proceedings* dataset, I manually searched the patent data for a matching individual. Using a manual search procedure here is important, since it allows me to accommodate wide variation in the extent to which first or middle names were included, represented by initials, or completely missing. It also allows me to deal with the fact that some scientists came from aristocratic backgrounds (or were elevated for their achievements) and so their names changed as they succeeded to (or were awarded) titles. William Thomson, for example, is better known as Lord Kelvin, and appears under the two different names at various points in time. Undertaking a careful manual review helps me reduce the impact of such factors on the quality and comprehensiveness of the matches. Once I find a possible match based on name information, I then reviewed all available information from both data sets in order to verify a match. In cases where a match is in doubt, I also review additional biographical information from other sources, such as the ODNB, which can be used, for example, to see whether a scientist was residing in a location identified in the patent data at the time the patent was filed. In the relatively rare set of cases where a match seems possible but I cannot conclusively verify that the entries below to the same individual, I do not assign a link. Thus, my data set will represent a conservative estimate of the total number of links between the two data sets.

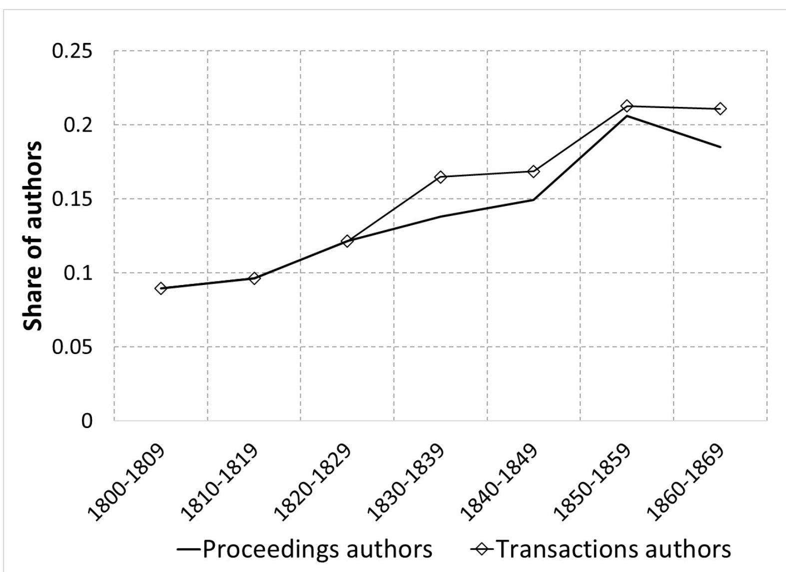
3 Analysis

3.1 Bridging Science and Technology

This section analyzes the extent and nature of the connections between scientific pursuits and technology development during the first seven decades of the nineteenth century. A natural place to start is by looking at the share of authors of scientific articles that were also involved in patenting new technologies, and how this share evolved over time. This is done in Figure 2, which describes the share of authors publishing in either the *Proceedings* or the *Transactions* in a particular decade that also appeared in the patent data (not necessarily in the same decade).

Two broad patterns jump out from Figure 2. First, a meaningful share of authors of scientific articles were also involved in technology development. Second, this share is consistently increasing across the study period, rising from around 9% in 1800-1809 to around 20% of authors by 1860-69. The fact that a substantial fraction of individuals were active in both the scientific and technological spheres suggests that even at the dawn of the nineteenth century there were important links between science and technology.

Figure 2: Share of article authors who also appear in the patent data, 1800-69



These patterns come into better focus when we study the share for authors contributing to different branches of science. It is natural to expect that certain scientific pursuits, such as zoology, meteorology, or astronomy, are unlikely to offer insights of direct relevance for technology development, while technologically useful insights are more likely to come from others, such as chemistry, the study of electricity, or mechanics. We can see these patterns in Table 2, which describes the share of authors active in each scientific area who also appear in the patent data. As we might have expected, individuals who author articles in areas such as engineering and applied science, mechanics, metallurgy, chemistry, scientific equipment, and electricity, were quite likely to also be involved in patenting activities.

Table 2: Share of authors who also patent by scientific area

Category	Share	Category	Share
Engineering and applied science	0.37	Geology	0.16
Mechanics/Physics	0.30	Magnetism	0.14
Metallurgy	0.29	Medicine	0.13
Chemistry	0.26	Geography/oceanography	0.13
Sound	0.25	Meteorology	0.09
Scientific equipment	0.25	Mathematics	0.08
Electricity	0.24	Zoology	0.07
Navigation	0.21	Astronomy	0.07
Light and heat	0.21	Archeology/paleontology	0.06
Timekeeping	0.20	Demography	0.00
Botany	0.19	Units of measurement	0.00

There are several different mechanisms that may be behind the increasing share of scientists also involved in developing new technologies. For example, over time individuals mainly engaged in developing technologies may have also become more interested in writing scientific articles. Or, individuals working in science may have become more interested in also applying their insights in patentable technologies. Established scientists may have been growing more open to allowing articles by technologists into their academic journals. Table 3 presents a set of regression results that can help shed light on some of these alternative channels. The top panel presents results based on the following simple regression specification,

$$PAT_{it} = \beta_0 + \sum_{\tau=1810-19}^{1860-69} \Gamma_\tau DECADE(\tau)_t + \epsilon_{it} \tag{1}$$

where PAT_{ijt} is an indicator variable that takes a value of one if a scientist i associated with a *Proceedings* entry in decade t was associated with a patent (at any point in time), and zero otherwise. $DECADE(\tau)_t$ is an indicator variable for each decade τ associated with coefficients Γ_τ, and ϵ_{it} is an error term.

The bottom panel presents results from an alternative specification that focuses on the change over time:

$$PAT_{it} = \beta_0 + \Gamma TT_t + \epsilon_{it} \quad (2)$$

where TT_t is a time trend.

The results in Column 1 of Table 3 show that, relative to the 1800-1809 decade, the probability any individual associated with an abstract in the *Proceedings* was also a patentee was increasing over time. In the top panel, this effect becomes statistically significant starting in the 1850-1859 decade while the bottom panel shows that the increasing time trend is strongly statistically significant.

In Column 2, I add in a vector of controls for each of the scientific categories that the author's articles contributed to in decade τ. We can see that the introduction of category controls reduces the magnitude of the rise in patenting probability in every period, but that we still see clear evidence of an increase over time. Thus, the increase in the probability that a *Proceedings* author was also a patentee was not driven solely by shifts in the types of science being undertaken, or the type of science being accepted into the *Proceedings*.

In Column 3, I switch to focusing only on authors of articles that were published in the *Transactions*. The comparison between these results and those in Column 1 are informative in part because these represent higher-quality science, and also because established scientists played a more important gatekeeping role, through peer review, in determining which articles made it into the *Transactions*. We can see that, if anything, the rise in authors who also patented was larger when focusing only on the *Transactions* group, though the difference compared to the results in Column 1 is not statistically significant. This suggests that established scientists may have been becoming somewhat more open to the contribution of technologists over time, but this is not likely to be driving the main patterns I observe.

Finally, Column 4 focuses on the *Transactions* authors but adds in controls for the scientific category of the articles each author produced. As before, this only moderately reduces the observed increase in the share of patenting authors. Thus, it appears that even within different types of science, authors were becoming more likely to also be involved in patenting activities.

3.2 The Productivity of Scientist-Inventors

This section looks at whether individuals involved in scientific pursuits produced more or better technologies than other inventors. To do so, I take as the universe of observations the set of patentees active between 1800 and 1849. The start of this period corresponds to the beginning of the *Proceedings* data set, while the end is dictated by the availability of individually-matched patent data from Hanlon (2022), which is needed if we want to study the productivity of individual inventors. Within this group, I ask two questions. First, did patentees who were also authors of scientific studies in the *Proceedings* produce more

Table 3: Regression results looking at the evolution patenting by scientists over time

	DV: Probability author also patented			
	Proceedings authors		Transactions authors	
	Panel A: Decade-by-decade results			
	(1a)	(2a)	(3a)	(4a)
1810-1819	0.00664	-0.0170	0.00664	-0.00638
	(0.0459)	(0.0454)	(0.0460)	(0.0458)
1820-1829	0.0318	0.00931	0.0318	0.0364
	(0.0453)	(0.0460)	(0.0454)	(0.0469)
1830-1839	0.0482	0.0305	0.0752	0.0714
	(0.0405)	(0.0403)	(0.0499)	(0.0492)
1840-1849	0.0598	0.0473	0.0788	0.0646
	(0.0406)	(0.0411)	(0.0514)	(0.0536)
1850-1859	0.119***	0.0890**	0.123***	0.0979**
	(0.0398)	(0.0394)	(0.0475)	(0.0459)
1860-1869	0.0965**	0.0653*	0.121***	0.101**
	(0.0386)	(0.0381)	(0.0469)	(0.0462)
Category controls		Yes		Yes
Observations	1,345	1,345	742	742
R-squared	0.011	0.117	0.016	0.129

	Panel B: Time trend results			
	(1b)	(2b)	(3b)	(4b)
Time trend	0.0194***	0.0156***	0.0230***	0.0190***
	(0.00515)	(0.00507)	(0.00643)	(0.00643)
Constant	0.0647**	0.0746**	0.0605**	0.0700*
	(0.0258)	(0.0323)	(0.0282)	(0.0363)
Category controls		Yes		Yes
Observations	1,345	1,345	742	742
R-squared	0.009	0.115	0.016	0.128

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

patents than other patenting inventors? Second, did they produce higher quality patents?

The first two columns of Table 4 look at whether individuals who had scientific articles in the *Proceedings* produced more patents than other patentees. Baseline regression results, in Column 1, show that scientist-inventors produced about 1.5 more patents than other patentees. Since the average number of patents per individual in the database is 1.52, this coefficient suggests that scientist-inventors were roughly twice as productive as the average. We may wonder if this was simply because more scientist inventors were wealthy gentlemen who could afford to patent more. Columns 2 adds fixed effects controlling for the modal occupation of the inventor. This leads to only a small reduction in the estimated coefficient, which shows that even within occupation groups, inventors who were also involved in science were more productive than other types.

The next four columns look at whether scientist-inventors produced higher quality patents as indicated by the patent quality indices constructed by Nuvolari & Tartari (2011) and Nuvolari *et al.* (2021). Columns 3-5 focus on the BCI measure from Nuvolari *et al.* (2021). They argue that the BCI measure is a more accurate gauge of patent quality than the older WRI index, but for completeness I also examine results using the WRI index in Column 6. In both cases, I have standardized the indices to have mean of zero and standard deviation of one. Column 3 shows that on average patents by scientist inventors are just under one standard deviation better than those by other types of inventors. This finding is largely unchanged when I control for the year of the patent, in Column 4, and the modal occupation of the inventor, in Column 5. Qualitatively similar results, though with a smaller magnitude, are observed when using the WRI index in Column 6.

Overall, these results show that inventors who were also involved in scientific pursuits, as measured by publications appearing in the *Proceedings*, were more productive than other patenting inventors in terms of both the number of patents produced and the quality of those patents. Obviously, these results should not be interpreted as reflecting a causal impact of science on technology development. It may be just as likely that developing new technologies led to scientific insights that were subsequently published in the *Proceedings*, and that these insights were more likely to come to individuals producing more or better technologies. Alternatively, it may be that some individuals were simply more productive at both activities. While any of these three explanations may be behind the results shown in Table 4, all of them are suggestive of a meaningful link between scientific endeavors and technology development.

3.3 The Technological Contribution of Scientist-Inventors

This section looks at the contribution of scientist inventors within the set of patented technologies. It is useful to note at the outset that the number of authors appearing in the *Proceedings* is small relative to the very large number of inventors found in the

Table 4: Output and quality of patents by inventors involved in science

Dependent variable:	**Number of patents per person**		**Quality of patents as measured by:** BCI index	BCI index	BCI index	WRI index
	(1)	(2)	(3)	(4)	(5)	(6)
Proceedings author	1.518*** (0.549)	1.390*** (0.534)	0.941*** (0.207)	0.935*** (0.209)	0.830*** (0.218)	0.303*** (0.103)
Patent year				Yes	Yes	Yes
Occ. FEs		Yes			Yes	Yes
Unit of obs:	Person	Person	Patent	Patent	Patent	Patent
Observations	6,401	6,401	12,623	12,617	11,740	11,740
R-squared	0.006	0.032	0.009	0.035	0.052	0.115

patent data. Thus, scientist-inventors will necessarily account for a small fraction of overall patents, despite the fact that they tended to produce more patents per person than other inventors. However, it is useful to keep in mind that raw patent counts will understate their contribution since, as shown in the previous section, patents by scientist-inventors were also of higher quality, on average, than those from other types of inventors.

Table 5 describes the share of patents with at least one scientist-inventor patentee by decade from 1800-1849.[6] We can see that the share of patents associated with a scientist-inventor grew over time, particularly in the decades around 1820. This pattern is consistent with the increasing number of articles in the *Proceedings* and the *Transactions* by individuals who also patented, shown in Figure 2

Table 5: Share of patents by scientist-inventors over time, 1800-49

1800-1809	1810-1819	1820-1829	1839-1839	1840-1849
0.0044	0.0075	0.0211	0.0203	0.0132

While the number of patents by scientist-inventors was small relative to the large number of patents filed, the aggregate share conceals substantial heterogeneity across technology areas. In most technology categories, there were no patents associated with scientist-inventors, but in others scientist-inventors accounted for a substantial fraction of patents. Table 6 highlights those technology areas where scientist-inventors accounted for the largest share of patents. While these categories are varied, it is not surprising to see important contribution of scientist-inventors to emerging technologies such as photography, copying, telegraphy, and refrigeration, to chemical technology areas such as bleaching and chemical

[6] Only around 10% of patents had more than one author, so for most of these the only patentee was the scientist-inventor.

Table 6: Technology categories where the share of patents by scientist-inventors was largest

Technology category	Share of category patents by scientist-inventors
Drawing And Photography	0.154
Telegraphs	0.092
Writing And Copying	0.087
Bridges, arches, viaducts, aqueducts	0.079
Bleaching, Washing, And Scouring	0.071
Refrigerating and Freezing	0.071
Mathematical, Nautical, and Astronomical Instruments	0.068
Air And Gas Engines and Windmills	0.052
Clocks, Watches, Chronometers, and Other Timekeepers	0.047
Motive-Power and Propulsion	0.035
Nails, Bolts, Nuts, and Screws	0.031
Medical and Surgical Treatment	0.031
Boilers and Pans	0.030
Chemical Salts, Compositions, Gases, and Processes	0.029
Water and Fluids (pumps, etc.)	0.028

Notes: This table shows the top 15 technology categories where patents by scientist-inventors made up the largest share of category patents, excluding those smaller categories where scientist-inventors contributed only one patent. For the shares, the numerator is the number of patents in a category associated with patentee who also authored an article in the *Proceedings*, while the denominator is the total number of patents in that technology category. Both of these counts are based on data for 1800-1849.

salts, to civil engineering innovations in bridges, to precision equipment such as mathematical, nautical and astronomical instruments and timepieces, and to medical treatments.

While Table 6 shows the technology categories where scientist-inventors accounted for the largest share of patents, it is also useful to look at the technology categories that attracted the largest number of patents associated with scientist-inventors. This is done in Table 7. We can see that the largest number of patents by scientist-inventors were in categories associated with steam engines, motive power, shipbuilding, railroads, etc. However, because these categories were large, scientist-inventors did not contribute a large share of patents within them, which is why they do not also appear in Table 6.

There are two main results to take from the analysis in this section. First, the number of patents produced by scientist-inventors was small relative to the total number of patents, but growing over time. Second, these patents were highly concentrated in a few technology areas. In many other technology categories–buttons, boring equipment, soap manufacture, and wearing apparel, to name a few–scientist inventors made no contribution. However, it is also worth noting that those technologies categories where scientist-inventors were most active were likely to have played a particularly important role in economic growth during

Table 7: Categories with the largest number of scientist-inventor patents

Technology category	Number of patents	Share of scientist-inventors patents in the category
Motive-Power and Propulsion	22	0.125
Steam Engines and Boilers	18	0.102
Ship-Building, Rigging, and Working	9	0.051
Railways and Railway Rolling-Stock	9	0.051
Water and Fluids	8	0.045
Smoke Prevention; Consumption of Fuel	8	0.045
Metals and Metallic Substances	8	0.045
Fireplaces, Stoves, Furnaces, Ovens, and Kilns	7	0.040
Telegraphs	6	0.034
Boilers and Pans	5	0.028
Air and Gas Engines and Windmills	5	0.028
Heat, Heating, Evaporating, and Concentrating	5	0.028
Building and Relative Processes	5	0.028
Drawing and Photography	4	0.023
Bleaching, Washing, and Scouring	4	0.023
Clocks, Watches, Chronometers, and Other Timekeepers	4	0.023
Medical and Surgical Treatment	4	0.023
Chemical Salts, Compositions, Gases, and Processes	4	0.023
Light and Lighting	4	0.023
Bridges, Arches, Viaducts, Aqueducts	3	0.017

Notes: This table shows the 15 technology categories that accounted for the largest share of scientist-inventor patents. For the shares, the numerator is the number of patents in a category associated with patentee who also authored an article in the *Proceedings*, while the denominator is the total number of patents by scientist-inventors across all categories. Both of these counts are based on data for 1800-1849.

the nineteenth century.

3.4 Types of Scientist-Inventors

What can we say about the types of individual who were operating on the margin between science and technology? One way to approach this question is to use the occupation information contained in the patent data.[7] Table 8 describes the key patterns in the data. Specifically, this table breaks down the share of scientist-inventors falling into different occupation categories.[8]

The top two rows in Table 8 show that most of the authors of scientific studies that were

[7]Sometimes, we can also learn information about an individual occupation in the articles data. However, for most individuals the articles do not provide that type of information, which is why I focus on the occupation information available in the patent data.

[8]These categories are roughly based on those used in Hanlon (2022) except that I separately break out chemists and medical doctors.

also engaged in patenting activities fall into two groups: engineers, and gentlemen/esquires, the latter group comprised mainly of individuals from the aristocratic classes. Together, these two groups constitute about 40% of the "bridge" between science and engineering. Medical doctors, chemists, and the "other professionals" group, which mainly includes professors, lawyers, and clergy, also played an important role. It is notable that there are very few manufacturers who were involved in both science and technology, particularly since Hanlon (2022) shows that this was the largest occupation type within the patent data. Of the small number of manufacturer-inventors that also produced scientific articles, almost all were manufacturers of instruments or timepieces. The importance of engineers and gentlemen/esquires is even more pronounced in the first two rows of Panel B, which focuses on the more exclusive group of authors with articles published in the *Transactions*.

The middle rows in Panel A show that engineers accounted for an even larger share, 46%, of the patents generated by individuals who were also involved in scientific pursuits. This is a much larger share than any other group. This is because engineers generated, on average, more than eight patents each, more than double the number of any other group. However, while engineers generated far more patents per person than other authors, the bottom rows of Panel A show that they tended to generate fewer scientific articles than gentlemen, chemists, or other professionals such as professors and lawyers. Thus, relative to other types of scientist-inventors, engineers appear to have been relatively more specialized in technology development while dabbling in science, while others appear more specialized in science while dabbling in technology development. Panel B shows that these patterns are, if anything, even stronger when we focus only on authors of articles published in the *Transactions*. Thus, the overriding message from this table is that one group, engineers, played a key role in bridging science and technology during the first few decades of the nineteenth century.

4 Conclusion

This study provides a quantitative assessment of one potentially important link between science and technology development during the first seven decades of the nineteenth century. The link that I focus on is embodied in individuals active in both science, as indicated by publications in a leading academic journal, and technology, as revealed by patent data. My results reveal substantial connections between scientific and technical pursuits which were growing over time and concentrated mainly in just a few technology categories.

This study provides a natural complement to existing work, most of which involves case studies that carefully trace out the connections between scientific and technical knowledge for specific technologies or using the biographies of individual inventors. Those studies have the advantage of revealing the direct connection between a particular scientific insight and

Table 8: Breakdown of authors and patents by occupation group

A. Proceedings authors with a patent

	Total	Engineers	Gentlemen/Esq.	Manuf.	Doctors	Chemists	Other prof.
Authors	132	28	24	9	19	16	11
Share		0.21	0.18	0.07	0.14	0.12	0.08
Patents	520	241	64	37	34	52	28
Share		0.46	0.12	0.07	0.07	0.10	0.05
Patents per author		8.61	2.67	4.11	1.79	3.25	2.55
Articles	561	90	121	19	53	182	96
Share		0.16	0.22	0.03	0.09	0.32	0.17
Articles per author		3.21	5.04	2.11	2.79	11.38	8.73

B. Transactions authors with a patent

	Total	Engineers	Gentlemen/Esq.	Manuf.	Doctors	Chemists	Other prof.
Authors	75	16	16	4	7	8	8
Share		0.21	0.21	0.05	0.09	0.11	0.11
Patents	304	155	42	22	14	18	13
Share		0.51	0.14	0.07	0.05	0.06	0.04
Patents per author		9.69	2.63	5.50	2.00	2.25	1.63
Articles	233	42	76	8	18	38	51
Share		0.18	0.33	0.03	0.08	0.16	0.22
Articles per author		2.63	4.75	2.00	2.57	4.75	6.38

the subsequent development of a useful technology. However, such a case-study approach raises questions about the representativeness of the examples considered and thus the generalizability of any conclusions. By taking a broader, quantitative approach, this study helps deal with these sorts of concerns, complementing existing work. Putting together these two varieties of evidence suggests that science likely played an important role, and one that was growing during the period I study, but that this influence in a limited to a relatively specific set of technology types.

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A Classification of topic groups

Table 9: Categories of scientific articles with examples: A-M

Archeology and Paleontology 61 articles
Example: On the Molar Teeth, Lower Jaw, of Macrauchenia patachonica. By Richard Owen, 1868.

Astronomy 234 articles
Example: On the extensive atmosphere of Mars. By Sir James South, 1832.

Botany 75 articles
Example: An Experimental Inquiry into the influence of Nitrogen on the Growth of Plants. By Robert Rigg, 1838.

Chemistry 525 articles
Example: On the Synthesis of Succinic and Pyrotartaric Acids. By Maxwell Simpson, 1860.

Demography 13 articles
Example: On the Construction of Life-Tables; Illustrated by a New Life-Table of the Healthy Districts of England. By William Farr, 1857.

Electricity 185 articles
Example: On the Influence of Temperature on the Electric Conducting-Power of Alloys. By A Matthiessen and C Vogt, 1862.

Geography and Oceanography 166 articles
Example: On the empirical Laws of the Tides in the Port of London, with some Reflections on the Theory. By William Whewell, 1834.

Geology 116 articles
Example: The Lignites and Clays of Bovey Tracey, Devonshire. By William Pengelly, 1860.

Light and heat 194 articles
Example: On the Affections of Light transmitted through crystallized Bodies. By David Brewster, 1814.

Magnetism 230 articles
Example: Geometrical Researches concerning Terrestrial Magnetism. By Thomas Stephens Davies, 1835.

Mathematics 271 articles
Example: On the Differential Equations Which Determine the Form of the Roots of Algebraic Equations. By George Boole, 1863.

Measurement (Units of) 11 articles
Example: An Account of the Comparison of various British Standards of Linear Measure. By Captain Henry Kater, 1821.

Mechanics/Physics 119 articles
Example: On the Thermal Effects of Elastic Fluids. By William Thomson (Lord Kelvin) and J. P, Joule, 1853.

Medicine 472 articles
Example: On the Nerves of the Uterus. By Thomas S. Beck, 1845.

Metallurgy 43 articles
Example: On some of the Compounds of Chromium. By Thomas Thomson, 1827.

Meteorology and Atmospheric Science 175 articles
Example: On the Finite Extent of the Atmosphere. By William Hyde Wollaston, 1822.

Table 10: Categories of scientific articles with examples: N-Z

Navigation 40 articles
Example: On the Errors in Longitude as determined by Chronometers at Sea, arising from the Action of the Iron in the Ships upon the Chronometers. By George Fisher, 1820.

Scientific equipment 139 articles
Example: Description of an improved Hygrometer. By Thomas Jones, 1826.

Sound 23 articles
Example: On the Mathematical Theory of Sound. By S Earnshaw, 1857.

Technology, applied, and engineering science 156 articles
Example: Experiments to Determine the Effects of Impact, Vibratory Action, and a Long-Continued Change of Load on Wrought-Iron Girders. William Fairbairn, 1863.

Timekeeping 35 articles
Example: An Account of Experiments to determine the Acceleration of the Pendulum in different Latitudes. By Edward Sabine, 1821.

Zoology 300 articles
Example: On the Urinary Organs and Secretions of some of the Amphibia. By John Davy, 1818.