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ORIGINAL PAPER

Human capital, knowledge and economic development: evidence from the British Industrial Revolution, 1750–1930

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Abstract Endogenous growth models raise fundamental questions about the nature of human creativity, and the sorts of resources, skills, and knowledge inputs that shift the frontier of technology and production possibilities. Many argue that the experience of early British industrialization supports the thesis that economic advances depend on specialized scientific training, the acquisition of costly human capital, and the role of elites. This paper examines the contributions of different types of knowledge to industrialization, by assessing the backgrounds, education and inventive activity of major contributors to technological advances in Britain during the crucial period between 1750 and 1930. The results indicate that scientists, engineers or technicians were not well-represented among the cadre of important British inventors, and their contributions remained unspecialized until very late in the nineteenth century. The informal institution of apprenticeship and learning on the job provided effective means to enable productivity and innovation. For developing countries today, the implications are that costly investments in specialized human capital resources might be less important than incentives for creativity, flexibility, and the ability to make incremental adjustments that can transform existing technologies into inventions and innovations that are appropriate for prevailing domestic conditions.

Keywords Technological change · Inventors · Human capital · Industrialization · Patents · Inventions

JEL Classification J24 · L26 · N13 · N73 · O31 · O33

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1 Introduction

Endogenous growth models are based on the premise that knowledge and ideas comprise a significant source of economic progress (Aghion et al. 1998; Jones 2005). These models raise fundamental questions about the nature of human creativity, what sorts of resources, skills, and other personal characteristics are conducive to extraordinary achievements, and how those factors vary over time and with the field of endeavor (Hanushek and Woessmann 2015; Galor and Moav 2004). They imply that our understanding of early economic progress requires an assessment of the types of knowledge inputs which were in elastic supply, and were responsive to economic incentives. Such concerns are longstanding, but are still debated today. Rostow (1960), for instance, contended that a precondition for economic and social advance was progress in scientific knowledge and technical applications, inputs which typically are scarce in many developing countries. Nathan Rosenberg (1974) and Margaret Jacob (1997, 2014) similarly highlighted the determining role of science and the growth of specialized knowledge.[1] Others regard scientists as disinterested individuals who are motivated by intangible rewards such as enhanced reputations and honor, the desire to benefit mankind, or the pursuit of timeless truths, rather than incentives associated with material benefits. If highly specialized skills and scientific knowledge are prerequisites for generating productivity gains, but such inputs are in scarce or inelastic supply, this has important implications for development strategies. The topic is also linked to an influential strand of research that indicates the extent to which guilds, apprenticeships and informal training institutions enabled and generated industrial change and technological innovation (Epstein 1998; Minns and Wallis 2013).[2] These issues bear on the general question of whether creativity is induced by expansions in market demand, or depends on investments in costly human capital that are largely unresponsive to perceived need.

Such concerns have been especially contentious in the context of industrialization in Britain and explanations for its subsequent loss of competitiveness (O'Grada 2016). The literature on the economic history of the British Industrial Revolution is exhaustive, and ranges from whether there was indeed a "revolution," through the factors that caused industrial advances, to the consequences of such changes.[3] Still,

[1] Rosenberg (1974, 97) emphasized that if we wish to understand economic progress "we must pay close attention to a special supply-side variable: the growing stock of useful knowledge," and further states that "a large part of the economic history of the past 200 years" was due to science and specialized knowledge. See also Rosenberg and Birdzell Jr. (1986).

[2] According to Minns and Wallis (2013), "Training through apprenticeship provided the main mechanism for occupational human capital formation in pre-industrial England."

[3] See, for instance, Crafts (1995, 2011), Broadberry et al. (2015), Kelly et al. (2014). Allen (2009) argues that observed patterns were due to induced innovation in response to factor prices and, in particular, relative wages; whereas Wrigley (2010) highlights endowments of coal. Allen (1983) and Nuvolari (2004) examined the role of collective invention or general access to knowledge. Sanderson (1999), Mitch (1992), and Floud (1982) have engaged in debates about the nature and consequences of literacy, numeracy, and different forms of education in the growth process during British industrialization. Sanderson, in particular, argues that British universities did not become fully engaged in the realm of practical science and engineering studies until late in the nineteenth/early twentieth century.

little consensus has emerged from the plethora of contributions to this topic, in part because of a lack of systematic evidence. According to some, the biases of the European scientific establishment toward abstract theory help to explain why Britain and not (say) France, was the first industrial nation. They point to anecdotal examples of formal and informal links between scientific discoveries and technological change in the former country and conclude that Britain's industrial lead depended on its scientific standing.[4] A classic but contested example of such ties is the influence of scientist Joseph Black on James Watt's improvement on the steam engine (Robinson and McKie 1970). Similarly, John Roebuck applied chemical knowledge to produce sulfuric acid through a lead-chamber process that increased output and reduced prices, and improved inputs into textile bleaching.[5] The eighteenth-century Lunar Society is consistently cited as proof-by-association of the relationship between natural philosophy and practical discoveries that increased industrial productivity.[6] Related institutions in the nineteenth century included the Surrey and London Institutions, as well as the "X-Club," a small number of influential scientists who attended social and professional monthly dinners.[7] More general enthusiasm for scientific studies was manifested in the rapid growth of less-eminent scientific and natural philosophy societies, whose number increased from fewer than fifty at the end of the eighteenth century, to some 1500 by the 1850s (Dowey 2014). Extreme versions of the "science matters" thesis go so far as to propose that "virtually all" inventors in Britain during the industrial revolution were influenced by scientific advances (Bekar and Lipsey 2004).

David Landes is the most prominent proponent of the opposing thesis that science did not influence early British advances in technology, and researchers in this tradition concur that the industrial revolution "owed virtually nothing to science."[8] British innovations toward the end of the eighteenth century and at the start of the nineteenth century were largely produced by artisans with little formal education,

[4] Musson and Robinson (1969, p. 7), early exponents of such views, declared that "Contrary to long accepted ideas, the Industrial Revolution was not simply a product of illiterate practical craftsmen, devoid of scientific training. In the development of steam power, in the growth of the chemical industry, and in various other industries, scientists made important contributions and industrialists with scientifically trained minds also utilized applied science in their manufacturing processes."

[5] See Clow and Clow (1952). For other developments in chemistry, see Donnelly (1986), Leicester (1965), Golinski (1999).

[6] This Society consisted of monthly dinners in the Midlands that included Erasmus Darwin, Matthew Boulton, Josiah Wedgwood, James Keir, Joseph Priestley, and James Watt, among others (Schofield 1963).

[7] The members included Sir Joseph Hooker, Thomas Huxley, Sir Edward Frankland, John Tyndall, Herbert Spencer, and Thomas Hirst, among others, and three of them would become Presidents of the Royal Society. "Anti-societies" such as the Red Lions rebelled against the "donnishness" of the British scientific establishment, and sought members among the "dregs of scientific society," MacLeod (1970). See also Orange (1972).

[8] See Hall and Hall (1964, p. 219): "The beginnings of modern technology in the so-called Industrial Revolution of the eighteenth and early nineteenth century owed virtually nothing to science, and everything to the fruition of the tradition of craft invention."

who benefited from apprenticeships and on-the-job learning.[9] Significant problems such as the mechanical measurement of longitude at sea were resolved by relatively uneducated artisans, rather than through the application of abstract or formal scientific observation (Sobel 1995). A number of other studies highlight the reciprocal nature of interactions between industry and academic science.[10] For instance, McKendrick's guarded conclusion was that science "played a necessary but not sufficient role."[11] Many such researchers emphasize that until the middle of the nineteenth century even the frontier of science and engineering was closer to organized intuition. More formal scientific endeavors of the day owed to skittish dons or aristocratic amateurs, whose efforts were directed to impractical pursuits and general principles in astronomy, magnetism, mathematics, botany and chemistry, rather than to useful knowledge that could enhance technological productivity.[12] Although Mokyr (2002, 2012, 2016) highlights the impact of the rational scientific revolution in the seventeenth century, and the market for ideas, his emphasis is on the general and untestable influence of the intellectual and methodological developments of Bacon, Hooke and Newton, rather than on specific applications of their scientific results to industry.[13]

The claim that scientific knowledge played an important role during industrialization in Europe primarily depends on qualitative arguments. Empirical evidence has been limited to potentially noncausal correlations between the presence of elites or inferred access to knowledge in particular locales and various proxies for technological innovation. Such authors acknowledge the extent to which geographical correlations between such variables might not indicate a causal connection, but their conclusions implicitly or explicitly tend to be based on causal inferences. Baten and van Zanden (2008) use book titles as a proxy for human capital and access to knowledge, and conclude that such variables were associated with early economic growth. Squicciarini and Voigtländer (2015) contend that city-level subscriptions to the Encyclopédie in mid-eighteenth century France provide evidence that scientifically-oriented elites increased

[9] Numerous research papers highlight the role of informal knowledge acquisition in such institutions as guilds and apprenticeship systems. See, for instance Epstein (1998), Humphries (2011), Feldman and van der Beek (2016). See also Wrigley (1982).

[10] Cardwell (2003) refers to "the two-way relationship between science and technology," but implies that science benefited more from prior flows of technical insights. Elliott (2000) considers such Derby luminaries as John Whitehurst FRS, Thomas Simpson FRS and Benjamin Parker. He concluded that their experience pointed to the possibility that technology likely influenced scientific discovery and education as much as the reverse.

[11] McKendrick (1973, p. 319) notes that "The major pull came from the demand side of the economy rather than from the push of scientifically induced advance on the supply side. Indeed, in the hierarchy of causal significance, science would not rank very high, but that does not mean that it would not rank at all as a dependent variable, the latent potential of which was released by more commanding variable, it played a necessary but not sufficient role in easing the path of industrial success and economic progress."

[12] According to Ashworth (1960, p. 27) "heroic inventions" were predominantly made by craftsmen, and the alleged scientists were "enthusiastic amateurs with, at best, a very modest knowledge of scientific theory."

[13] Mokyr (2002, 2012) argues that the Industrial Revolution was due to an "Industrial Enlightenment," whose major achievements owed to the abilities of an elite minority. According to this perspective, those who focus simply on pure scientific discoveries miss much of the point, since valuable knowledge was drawn from a combination of tâtonnement and conscious insight.

productivity in industrial technology and promoted economic progress. Dowey (2014) similarly correlates membership in scientific societies with exhibits at the Crystal Palace Exhibition and argues that elites were associated with technological innovation during the Industrial Revolution. By contrast, Khan (2017a) provides a more direct test of such hypotheses, using data from the Royal Society of Arts, and shows that the activities of the primary elite learned society in Britain between 1750 and 1850 had little or no impact on the course of technological innovation and industrialization. O'Grada (2016, p. 226) likewise surveys studies that support the conclusion that "such societies lent scientific knowledge respectability, [but] their role in spreading it was limited." As these diverse propositions suggest, significant aspects of the relationship between knowledge, science and technology in the industrial revolution still remain untested and unresolved.

This paper focuses on the role of different types of knowledge in British industrialization, and offers a systematic estimation that defines scientific inputs specifically in terms of individuals with demonstrable scientific credentials. This approach allows us to discover empirical patterns which can be compared to the plethora of more detailed and anecdotal historical accounts. The analysis is based on a sample of "great inventors" who were included in biographical dictionaries because of their contributions to technological progress. I traced the inventors who received formal training in science and engineering, as well as wider dimensions of achievement such as membership in the Royal Society, scientific eminence, publications, and the receipt of prizes and nonmonetary rewards. The variables from the biographical entries were further supplemented with information from patent records on the numbers of patents filed over the individual's lifetime, the length of the inventor's patenting career, the industry in which he was active, and the degree of specialization at invention.[14] This approach allows us to examine the backgrounds, education and inventive activity of the major contributors to technological advances in Britain during the crucial period between 1750 and 1930, and to determine the extent to which such advances owed to specialized human capital and knowledge. More generally, the results have the potential to enhance our understanding of the determinants of shifts in the frontiers of technology during early economic development.

2 The sample of inventors and inventions

The "great inventors" data set was compiled from biographical dictionaries, including the *Oxford Dictionary of National Biography* (DNB), and the *Biographical Dictionary of the History of Technology* (BD), among others.[15] I supplemented these two volumes with other biographical compilations, and numerous books that

[14] The discussion of broad scientific culture is informative and yields insights into the role of social capital in economic development. However, I chose to focus here on the evolution of contributions to useful knowledge, which are defined as additions to the social information set that have the potential to directly expand the production possibility frontier. Patent counts are used as a proxy for advances in such knowledge. Patents have well-known flaws that suggest that results should be interpreted with a sensitivity to their drawbacks (Griliches 1990); but they do offer the opportunity to adopt a more systematic approach to the relationship between science and technology in British economic growth.

[15] See Matthew and Harrison (eds.) (2004), McNeil (ed.) (1990), Day and McNeil (eds.) (1996).

were based on the life of a specific inventor.[16] The objective was to obtain a sample of individuals who had made significant contributions to technological products and productivity, matched with their lifetime patented and unpatented inventions, between 1750 and 1930.[17] It might be expected that such inventors would be associated with a portfolio of inventions with a higher average value than those of their peers.[18]

Khan and Sokoloff (1993, 2004a, b, 2006) first systematically investigated the contributions of "great inventors" in US economic history. Significant numbers of economists and historians have similarly used biographical information to obtain valuable insights regarding innovation in all realms of human endeavor (Khan 2011; Allen 2009; Nuvolari and Tartari 2011; Meisenzahl and Mokyr 2012; Galenson 2011).[19] Some observers might be concerned that biographical sources risk reinforcement of a myth of heroic inventors, with a corresponding underestimation of the importance of incremental inventions (Macleod and Nuvolari 2006). While it is true that any individual compilation will be based on somewhat subjective determinations about who should be included and who should be excluded as an

[16] These sources comprised compilations and individual biographies, including among others Williams (1982), Encyclopaedia Britannica, Crowther (1935), Abbott (1985), Nasmyth (1885), Schneider (1938), Gillispie (1970–1980), Daintith and Gjertsen (1999), Williams (1982), Dictionnaire des Inventeurs et Inventions, Larousse: Paris, 1996, Hilts (1975), Heilbron (2003), Hills (2002), McKendrick (1973). Only 15% of the sample from these records were missing altogether from the filtered data set obtained from DNB.

[17] This was more in accordance with the intent of the *Biographical Dictionary*, whose contributing authors were specialists in the particular technological field that they examined. The DNB's objective was somewhat different, for its editors intended to incorporate "not just the great and good, but people who have left a mark for any reason, good, bad, or bizarre." This statement is included in the description of the online subscription-restricted database. The volume employed inconsistent terminology in the occupational titles of its biographies, and the mention of inventors or inventions either in the title or text did not necessarily imply that the person in question had made a significant contribution to the course of technical change. For instance, their listings included Walter Wingfield ("inventor of lawn tennis"); Rowland Emett (cartoonist and "inventor of whimsical creations"); as well as the inventors of Plasticine, Pimm's cocktail, self-rising flour and Meccano play sets. At the same time, Henry Bessemer is described as a steel manufacturer, Henry Fourdrinier as a paper manufacturer, and Lord Kelvin as a mathematician and physicist. A large fraction of the technological inventors are featured in the DNB as engineers even though the majority had no formal training. Such non-technological entries were excluded from the data set. A number of inventors were variously described as pioneers, developers, promoters or designers, and Edward Sonsadt is omitted altogether although elsewhere (McNeil 1990, p. 113) he is regarded as an "inventive genius."

[18] Nuvolari and Tartari (2011, p. 12) tested the relationship between a proxy for patent value (WRI) and DNB inventions, for a limited number of DNB inventors through 1841, and conclude that "In all specifications, the variable "Great Inventor" (DNB) is positive and significant, indicating that patents with high WRI scores are consistently related with inventors that appear in the DNB."

[19] Nuvolari and Tartari (2011) included a "great inventor" dummy variable indicating if the patentees were included in the Dictionary of National Biography. A prominent example of biographical analysis comprises David Galenson's prolific studies of biographical information on painters, novelists, musicians, poets and Nobel prize winners in economics, among others [see, for instance, Galenson (2011)]. Allen (2009) employed a sample of 79 "great inventors" between 1660 and 1800.

important inventor, the use of numerous such sources reduces the probability of significant bias.[20] A heuristic approach suggests that, although a few of the entries in any such sample would undoubtedly be debatable, this triangulation of sources minimizes the possibility of egregious error.[21] Moreover, the central objective of the project was to obtain a sample, and not the entire universe, of important inventors of the era. In any event, even if these general concerns were valid, such factors are likely to produce a bias against the conclusion that relatively ordinary individuals without any particular formal training were initially responsible for the upper tails of technological productivity during early industrialization.

The resulting British great inventors sample is comparable to Khan and Sokoloff's (1993) data set of important inventors and inventions in the USA during the same period. The British sample is based on 438 men and one woman who produced at least one invention between 1790 and 1930, and who made significant contributions to technological innovations and productivity change. These British inventors include such well-known icons as Sir Humphry Davy, Sherard Osborn Cowper-Coles, John Dunlop, Charles Macintosh, Charles Babbage, Edmund Cartwright, Lord Kelvin, Guglielmo Marconi and George Stephenson. The lone woman inventor, Henrietta Vansittart (1833–1883), is referenced in the DNB as an engineer whose educational background is unknown.[22] She improved upon her father's screw propeller invention, for which she obtained two British patents and awards from a number of countries. Although one might be concerned about the absence of more women in these data, Khan (2017b) shows that feminine creativity

[20] One way to determine the extent of systematic sample bias is to estimate the probability that an inventor drawn from a particular biographical source (e.g. the DNB) was selected on different criteria relative to inventors from other sources. I computed a simple logistic regression model where the dependent variable was the probability that an inventor from my sample was included in the DNB, and the independent variables included all characteristics investigated in this study, such as birth cohort, occupation, education, science background, patenting and publications records, and so on. The response function Y| Xi (Xi = X1, X2, …, Xn) is assumed to have the form $E(Y|Xi) = \exp(ß0 + ß1x + \cdots)/(1 + \exp(ß0 + ß1x + \cdots))$, where ßi are regression coefficients that represent the intercept and slopes with respect to the particular independent variable. The resulting function is linear in the log of the odds, $\log_e(p/1 - p)$. Maximum likelihood methods were used to estimate the parameters. The entries from the DNB were significantly more likely to have earned prizes, and their residence at time of invention was more likely to have been in London and outside England. However, since this finding is not inconsistent with the secondary literature, the overall results from these regressions bolster one's confidence in the representativeness of the great inventors' sample. We can further reject the hypothesis of bias for almost all variables of interest, including time of first invention, educational status, science background, and occupation.

[21] Indeed, such data have provided demonstrably useful results regarding the very criticisms expressed by Nuvolari and Macleod. For instance, when Khan and Sokoloff (1993, 2004a, b, 2006) used a parallel sample of American "great inventors," their results *disproved* the claims about heroic inventors and "macroinventions," showing that these noted inventors tended to be drawn from relatively undistinguished backgrounds, and to behave very much like "ordinary inventors;" and that patterns for their inventive activity replicated those of incremental inventions. Moreover, the data on the "great inventors" were found to be significantly related to other measures of both economic and technical value, including patent assignments, litigation about inventions, and long-term patent citations.

[22] A potential second candidate is Eleanor Coade (1733–1821), the owner of an innovative stone-making factory. However, her status as an inventor is completely speculative: there is no evidence that she was responsible for the innovations her factory produced, and they might well have been the product of her employees.

Table 1 Birthplace of the great inventors, by birth cohort and technical orientation (percentage distribution)

Birthplace	Birth cohort										
	Before 1780		1781–1820		1821–1845		After 1845		All cohorts		Total
	S&T	None	S&T	None	S&T	None	S&T	None	S&T	None	
London	12.5	5.6	18.2	9.5	19.2	20.6	22.6	12.2	19.1	11.5	13.7
South	12.5	18.3	25	23.8	15.4	19.1	20.4	24.5	20.4	21.5	21.6
Midlands	12.5	11.3	6.8	13.3	3.9	15.9	7.5	2	7.5	11.5	10.1
North	12.5	22.5	15.9	22.9	19.2	19.1	15.7	30.6	15 7	23.3	20.7
Other Britain	41.7	31	31.8	18.1	26.9	12.7	28.6	18.4	28.6	20.1	23
Overseas	4.2	5.6	2.3	4.8	15.4	6.4	11.3	10.2	8.2	6.3	6.9
Number	24	71	44	105	26	63	53	49	147	288	435

"S&T" indicates post-secondary training in science and engineering or listing in a dictionary of scientific biography; "None" indicates inventors who did not have such training and were not listed. The "Home Counties" are included in the South; London includes Middlesex; Other Britain refers to Cornwall, Scotland, Ireland and Wales, the Isle of Wight and the Isle of Man. The "unknown" category is not reported, so percentages will not total to one hundred

during this period was primarily directed to incremental changes in consumer final goods and in designs, that enhanced allocative efficiency, but were less likely to result in significant outward shifts in production possibilities.

As Table 1 shows, the majority of great inventors were born in the South of England, and London stands out especially as the birthplace of a fairly constant share of the scientist–inventors who were born in the nineteenth century. The birth cohort before 1780 contributed to the onset of industrialization, and it is striking that almost a quarter of the great inventors during this critical period originated from Scotland and other locations outside of England.[23] For instance, Sir Isaac Holden, a prominent contributor to wool-combing technology, was born in 1807 near Glasgow, Scotland. Other noted inventors who were born in other areas outside England include Lord Kelvin (Ireland), Richard Roberts (Wales), and Warren de la Rue (Guernsey). The renowned Marc Isambard Brunel was born in Normandy, France, and such foreign-born inventors increased among the birth cohorts after 1820, including Gugliemo Marconi, Gisbert Johann Kapp, and Sir John Gustav Jarmay. It is noticeable that inventors who were born outside of England tended to be disproportionately trained in science, as indicated by the fraction of scientists (approximately 37%) relative to nonscientists (26%.)

Table 2 presents the distribution of inventors in terms of their science background and indicates the changes over the course of industrialization.[24] There is some ambiguity about what a "scientist" connotes, so the table examines three alternative measures of scientific orientation: formal post-secondary/college/university education; eminence as gauged by listing in biographical dictionaries of scientists; and membership in the Royal

[23] For general background see Bullough and Bullough (1973), Olson (1975, 1990), Elliott (2000), Kargon (1978), Mollan et al. (2002).

[24] The educational factors are all defined as categorical variables, since there is no systematic information on years of schooling for these individuals.

Table 2 Science and engineering background of great inventors, by year of first invention

Year	Science training		Listed scientist		Engineering training	
	N	%	*N*	%	*N*	%
Before 1820	10	10.0	18	16.8	1	1.0
1821–1851	21	18.8	24	19.5	3	2.7
1852–1870	14	20.0	8	9.6	7	10.0
1871–1890	21	33.3	14	18.2	16	25.4
After 1890	11	23.4	8	17.0	17	34.7
Total	78	19.8	75	16.6	44	11.1

Science training refers to post-secondary school education in the sciences, mathematics or medicine. A great inventor who is included in biographical dictionaries of scientists is denoted as a *listed scientist*. *Engineering training* indicates post-secondary school training in engineering. Columns may not sum to total owing to missing values

Society. Approximately 20% of the great inventors were educated at the post-secondary level in the sciences, mathematics or medicine. Similarly, 16.6% could be considered as eminent scientists. A significant number (20.7% of all inventors) were Fellows of the Royal Society. The data suggest that a change in the nature of important technological innovations occurred after 1870, since scientists accounted for a significantly higher proportion of inventors after this period. For instance, the percentage of inventors with scientific training in universities increased from 20% in 1852–1870 to 33.3% between 1871 and 1890. These patterns are even more marked for great inventors with technical training (as gauged by formal post-secondary-school education in engineering), who comprised 11.1% of all inventors. Inventors with such formal engineering qualifications increased from a mere 1% before 1820, to 25.4% of all great inventors by 1871–1890. Since part of our concern is with the contribution of this sort of specialized knowledge to innovation, the following section further explores the extent of formal training among the great inventors, and the role of education in science and engineering over the course of industrialization.

3 Characteristics of the great inventors

Economic studies have shown the importance of appropriate institutions in promoting self-sustaining growth and imply that the rate and direction of useful knowledge could be hampered, if not retarded, by flaws and inefficiencies in determinant institutions (Engerman and Sokoloff 2011). As Sir Henry Sumner Maine suggests, Britain long remained an oligarchic society whose governing premise was based on the conviction that merit was causally related to inherited social class.[25] The USA arguably was able to assume economic leadership in part

[25] According to Maine (1886, p. 98), “All that has made England famous, and all that has made England wealthy, has been the work of minorities, sometimes very small ones. It seems to me quite certain that, if for four centuries there had been a very widely extended franchise… the threshing machine, the power loom, the spinning jenny, and possibly the steam engine, would have been prohibited.”

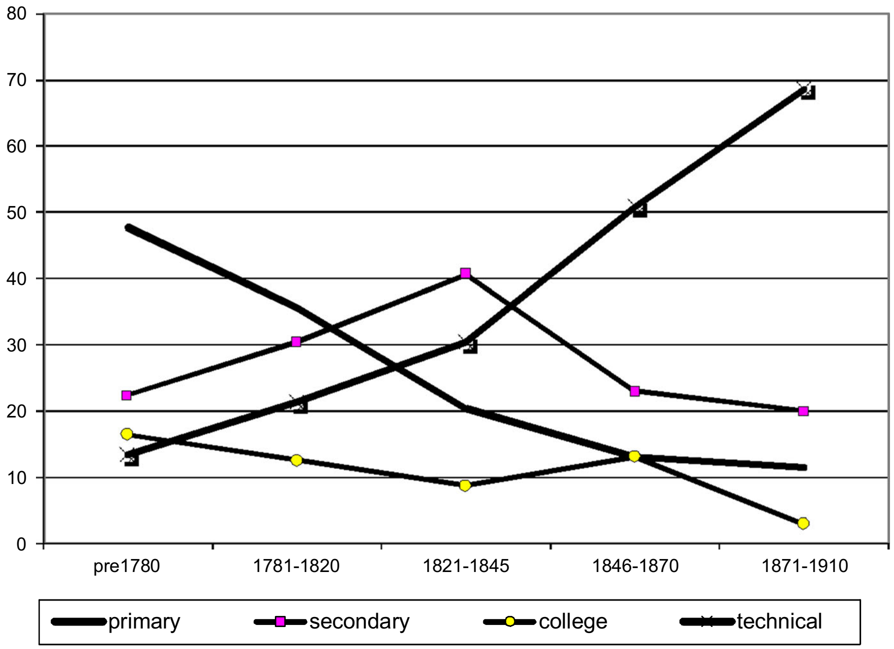

Fig. 1 British great inventors: education by birth cohort. *Notes* For information about the sample of "great inventors," see the text

because its institutions offered inducements to all classes of society to contribute to the growth process, and allocated rewards that were commensurate with an individual's productivity rather than his social provenance (Khan 2005). The British educational system, in particular, failed to match up to institutes of higher learning in Germany and the USA and has been portrayed as a hindrance to economic advancement.[26] However, the costs of such policies are a function of the degree to which productive economic activities depended on the acquisition of these sorts of human capital.

Figure 1 examines the distributions of great inventors by birth cohort in terms of their educational background. The great inventors were more educated than the general population, but these data make it clear that formal training in an educational institution was not a prerequisite for important invention during the early period of industrialization. The majority of great inventors had no formal education beyond the primary or secondary school levels, even as late as the 1821–1845 birth cohort. Thus, these patterns refute the claim that "virtually all of the inventors" had exposure to scientific training, and is more consistent with the

[26] Landes (1969) supports this position. The 1870 Elementary Education Act extended state support for education if private school funds were insufficient. Compulsory education was introduced in 1880 and limited free public education was made available in 1891. For an excellent study of the role of the state in promoting literacy, see Mitch (1992).

notion that the industrial revolution drew on traditional institutions that enhanced individual abilities, such as apprenticeships and on-the-job training.[27] The route of craft-apprenticeship was taken by an impressive roster of great inventors, including some who came from quite privileged backgrounds. Apprenticeship was a flexible source of human capital acquisition, which did not preclude social mobility or further education (Epstein 1998; Humphries 2011; Minns and Wallis 2013; Feldman and van der Beek 2016). The skills that the inventor obtained by apprenticeships could be combined with informal attendance at lectures offered by mechanics' institutes, and could even provide a route toward a university degree later in life. A prominent example, Sir Joseph Wilson Swan, was apprenticed at 14 to a pharmacy store, but attended lectures at the Athenaeum in Sunderland that helped him to become an internationally renowned chemist and electrical inventor. Both the Fairbairn brothers [Sir Peter Fairbairn (1799–1861) and Sir William Fairbairn (1789–1874)] were apprenticed as millwrights in a colliery at an early age, but were able to achieve distinction in a number of arenas. William Fairbairn, in particular, although he was self-taught, was appointed a member of the Academy of Science in France, a Fellow of the Royal Society, and President of the British Association. The military academies also allowed inventors to combine apprenticeships with more formal but somewhat diffuse training.

Over time, the importance of higher education in science steadily increased. Engineering proficiency was more discontinuous and was associated with a jump in the technical orientation of the 1821–1845 birth cohort; and 60% of all 27 inventors who received higher education in engineering first produced inventions between 1871 and 1890. This is consistent with the finding that scientific and technical invention became more prevalent after 1870. By the beginning of the twentieth century, a college degree in science or technical educational was typical of the majority of great inventors and many even received advanced doctoral degrees in science. However, it is not clear whether university attendance or degrees in science and engineering prevailed among inventors because these qualifications enhanced their skill at invention, or whether it was because a college degree was correlated with such other arbitrary factors as family income and connections that gave these individuals preferment.

Cardwell (2003) claimed that there were few institutional obstacles to innovation in England, for it was "a remarkably open society," and many of the inventive "heroes" in both science and technology were from humble origins.[28] These data suggest otherwise. Table 3 shows that the common perception that the heroes of the British industrial Revolution were primarily from modest backgrounds is somewhat overstated. Instead, an examination of the family backgrounds of the great inventors is more consistent with the notion that in the area of technological achievement elites were over-represented relative to the population. A third of the inventors did indeed come from farming, low-skilled or undistinguished (likely most of the unknown category) backgrounds. However, the majority of the great inventors were born to

[27] According to Cronin (2001, p. 241), "throughout much of the nineteenth-century the craft-apprenticeship mode of training was the only form of technical education."

[28] These specific claims are made in Cardwell (2003) essays IV, p. 474; and VII, pp. 40–41.

Table 3 Social backgrounds of the great inventors, by birth cohort and technical orientation (percentage distribution)

	Before 1780		1781–1820		1821–1845		After 1845		All Cohorts		Total
Father's Occupation	S&T	None	S&T	None	S&T	None	S&T	None	S&T	None	
Elite/professional	58.3	25.4	50	21	46.2	28.6	60.4	26.5	54.4	24.6	34.7
White collar	4.2	8.5	4.2	7.6	11.5	–	9.5	16.3	9.5	7.6	8.3
Manufacturer/ skilled	8.3	18.3	25	32.4	30.8	27	13.2	18.4	19.1	25.4	23.2
Farmer	8.3	7	4.6	6.7	7.7	6.4	3.8	8.2	5.4	6.9	6.4
Low-skilled worker	8.3	9.9	2.3	3.8	–	9.5	5.7	16.3	4.1	8.7	7.1
Unknown	12.5	31	6.8	28.6	3.9	28.6	7.6	14.3	7.5	26.7	20.2
Total	24	71	44	105	26	63	53	49	147	288	435

See notes to Table 1, and text

families headed by skilled artisans, manufacturers, white collar workers, or well-off families in the elite and professional classes. A striking feature of the table is that the inventors with education in science were twice as likely to belong to these elite and professional families, and this pattern is invariant over the entire period.[29]

Table 4 shows that an increasing fraction of inventors were educated at elite schools such as Oxford or Cambridge, which were unlikely to offer much in the way of direct knowledge or skills that would add to either scientific or technological productivity (Edgerton 1996; Wiener 1981).[30] Advancement at these institutions primarily depended on excellence in divinity and liberal classical subjects, and the engineer John Perry even declared that "Oxford fears and hates natural science."[31] Cambridge had offered the Natural Science Tripos since 1848, but for much of the nineteenth century the impact was nominal; as late as 1880 only four percent of Cambridge undergraduates read for the Natural Science Tripos.[32] The anti-

[29] Employers were averse to hiring college-educated workers. As the Times opined in 1897, "technical education is not needed for the masses of people. Indeed they are better without it… [it] only teaches the workman to think that he is as good as his master" (cited in Cronin, p. 222). See also Sanderson (1999).

[30] Edgerton (1996) contended that science was "not Oxbridge," and Wiener (1981) similarly faulted the elite universities for turning out gentlemen rather than productive individuals.

[31] See Howarth (1987). Tawney (1931, p. 37) wryly commented that the English "frisk into polite obsolescence on the playing fields of Eton." Along the same lines, Gowing (1978, p. 9) characterized English efforts at reforming its educational institutions at the end of the nineteenth century as "too little and too late." She attributes this deficiency to such causes as inadequate funding, and the influence of social class.

[32] For an illuminating analysis, see Macleod and Moseley (1980). Most Cambridge graduates were destined for occupations such as the clergy. The method of teaching eschewed practical laboratory work; and there was a general disdain among the Dons for the notion that science should be directed toward professional training; so it is not surprising that only 4% of the NST graduates entered industry. Students who did take the NSTs tended to perform poorly because of improper preparation and indifferent teaching, especially in colleges other than Trinity, Caius and St. John's. The contrast to the United States is striking: MIT alone had seven engineering professors in 1891, whereas a chaired position in Engineering was only created in Oxford in 1907.

Table 4 Elite background of great inventors, by year of first invention

Year	Family connections		Elite education		Fellows of the Royal Society	
	N	%	*N*	%	*N*	%
Before 1820	31	29.0	11	10.3	21	19.6
1821–1851	27	22.0	13	10.6	25	20.3
1852–1870	15	18.3	14	16.9	17	20.5
1871–1890	19	26.0	18	24.7	20	27.4
After 1890	6	12.8	9	19.2	7	14.9
Total	99	22.8	65	14.9	90	20.7

The percentages are within-period proportions, based on a total of 435 inventors. *Family connections* imply an elite family background or other family members being listed in the Oxford DNB. *Elite education* indicates the great inventor attended Oxford, Cambridge, Durham, or one of the Royal Colleges, or obtained a postgraduate degree overseas (mainly Germany)

pragmatism of Oxbridge was to be reflected in the "red-brick" institutions that were established toward the end of the nineteenth century to remedy the lapses in the scientific and technical curricula of the elite schools.[33] Even at the Scottish universities, which were widely regarded as leaders in science education in Britain, few nonmedical students had the opportunity to participate in laboratories or research.[34] It is not surprising that serious British students of science and technology chose to pursue graduate studies in the German academies which were acknowledged as the world leaders in higher education in such fields as chemistry, physics and engineering. However, it might be expected that opportunities for a foreign education were also correlated with a secure social and financial background.

Some might contend that programmes at elite universities like Cambridge and Oxford, while not directly addressing technological matters, nevertheless enhanced rational methods of thinking that facilitated innovation. This proposition is, of course, inherently untestable, but we can obtain some insights by comparing the social backgrounds of great inventors who attended college, across the two leading industrial nations of Britain and America (Khan 2011). If it were true that elites prevailed among inventors because their privileged background and subsequent advantages in obtaining a college degree gave them an objective edge in technological creativity, we might expect similar patterns across countries. In the period before 1820, college attendees in both Britain and the USA predominantly belonged to elite families. However, after 1820 the share of elites shrinks noticeably in the USA, and the vast majority of graduates come from nonelite backgrounds, whereas the pattern in Britain remains for the most part unchanged. These data are consistent with Sanderson (1999) who contended that the benefits of tertiary

[33] Barnes (1996) finds a tendency for the red-brick universities to be regarded as second-rate, and for the classical Oxbridge approach to be regarded as a superior model in a "triumph of tradition." Part of the problem was financial, since most professors had to pay for their research expenditures out of their meager salaries.

[34] See Report of the Royal Commissioners appointed to enquire into the Universities of Scotland: Returns and Documents, Parliamentary Papers xxxv (1878): 336–340.

education in Britain was due more to its association with elite privileges, rather than to the ability to acquire or apply useful knowledge.

Table 4 shows that the rather privileged background of many of the British great inventors is reflected in other dimensions of elite standing. Twenty-nine percent of the inventors who were active before 1820 had families who were connected to those in power or who were otherwise distinguished. An interesting facet of the relationship between privilege, science, and technological achievement in Britain is reflected in the ninety great inventors who were also appointed as Fellows of the Royal Society. The Royal Society was founded in 1660 as an "invisible college" of natural philosophers who included Isaac Newton, Christopher Wren, Robert Hooke and Robert Boyle. Fellows of the Society were elected and many of the members consisted of individuals who were not professional scientists but who were wealthy or well-connected.[35] The Royal Society was widely criticized for its elitist and unmeritocratic policies.[36] Great inventors Charles Babbage, William Sturgeon and William Robert Grove were representative of those who publicly assailed the nepotism and corruption of scientific institutions in the nineteenth century, and Babbage attributed a large part of the failure of British science to features typified by the Royal Society.[37] The Society long retained the character of a gentleman's club and, despite a series of reforms, did not become a genuine professional scientific organization until after the 1870s. Even in 1860 more than 66% of its membership consisted of nonscientists and medical practitioners, whose inclusion was not altogether merited on the basis of their scientific contributions.[38] Accordingly, although the Royal Society was associated with the foremost advances in science, many of its projects were absurd and impractical.[39] In short, these data suggest that scarce human capital was likely not a significant factor in important inventive activity during the period of early industrialization. Moreover, it is also possible that the prevalence of professional backgrounds at the start of the twentieth

[35] Sir Joseph Banks, the president during the critical years between 1778 and 1820, supported the election of wealthy patrons who might be persuaded to finance research efforts. See Hall (1984), and Hunter (1994).

[36] Babbage (1830, p. 52) noted that "those who are ambitious of scientific distinction, may, according to their fancy, render their name a kind of comet, carrying with it a tail of upwards of forty letters, at the average cost of 10£. 9s. 9d. per letter. It should be observed, that all members contribute equally, and that the sum now required is fifty pounds… The amount of this subscription is so large, that it is calculated to prevent many men of real science from entering the Society, and is a very severe tax on those who do so."

[37] Babbage (1830, p. 1) regretted that "in England, particularly with respect to the more difficult and abstract sciences, we are much below other nations, not merely of equal rank, but below several even of inferior power. That a country, eminently distinguished for its mechanical and manufacturing ingenuity, should be indifferent to the progress of inquiries which form the highest departments of that knowledge on whose more elementary truths its wealth and rank depend, is a fact which is well deserving the attention of those who shall inquire into the causes that influence the progress of nations."

[38] According to Stimson (1948, p. 236), "The change came by evolution rather than by revolution and took a good many years to become fully effective. As late as 1860 there were 330 Fellows who were scientists and 300 who were not. Also, in 1860, 117 of that group of 330 scientist Fellows were physicians and surgeons, an overwhelming proportion of medical men which had been characteristic of the Society's membership from the first."

[39] In Gulliver's Travels, Jonathan Swift satirized the Royal Society and some of its fantastical endeavors, as the "Grand Academy of Projectors" in the kingdom of Laputa.

century might owe to the privileges accorded to elites in British society, rather than to the contributions that specialized knowledge made to technological innovation.

4 Patents, productivity and market incentives

Numerous scholars since Rostow (1960) have contended that prospects for early growth depended on specialized knowledge inputs that were inelastic and in scarce supply. The data set of great inventors instead suggests that science was only weakly related to technology during the era of industrialization in Britain. A more speculative conclusion is that an elite background might have played some role in promoting distinction among scientist–inventors in British society, despite the possibility that such training did not necessarily increase productivity at invention relative to other great inventors. Some researchers further suggest that, especially during the early stages of industrialization, scientists were not sensitive to market factors, which would imply that they would tend to respond inelastically to economic conditions. This section therefore uses patent records through 1890 to compare productivity at invention among scientists and nonscientists, and the extent to which scientist inventors were responsive to market incentives.

Patent records have well-known flaws as a gauge of invention, but they have still proved to be valuable in identifying the sources of variation over time and place in the rate, organization, and direction of inventive activity.[40] Table 5 shows that approximately 87% of the British sample of great inventors were patentees. Charles Wheatstone reported that "some thought it not quite consistent with the habits of a scientific man to be concerned in a patent," but it is noticeable that the proportion of patentees is similar across all science classes, whether proxied by educational background, scientific eminence, or membership in the premier Royal Society.[41] In the case of the USA, where patent institutions were extremely favorable to inventors of all classes, almost all (97%) great inventors chose to obtain patent protection for their inventions. The British great inventors overall exhibit a somewhat lower propensity to patent, but Khan (2017a) shows this seems more related to institutional factors that affected all inventors, rather than to scientific disdain for material returns.

In particular, there is a marked increase in the propensity to patent after 1851 (Fig. 2). This period stands out because in 1852 the British patent laws were reformed in the direction of the American system in ways that increased access to patent institutions, and strengthened the security of property rights in patents (Khan

[40] Griliches (1990) discusses the costs and benefits of analyzing patents. The major problems with patent statistics as a measure of inventive activity and technological change are that not all inventions are patented or can be patented; the propensity to patent differs across time, industries and activities; patents vary in terms of intrinsic and commercial value; patents might not be directly comparable across countries or time because of differences in institutional features and enforcement; and patents are a better gauge of inputs than productivity or output. Griliches concludes (p. 43) that "In spite of all the difficulties, patent statistics remain a unique resource for the analysis of the process of technical change. Nothing else even comes close in the quantity of available data, accessibility, and the potential industrial, organizational, and technological detail."

[41] See Cooke (1857).

Table 5 The propensity to patent among British great inventors, by year of first invention (through 1890)

	Before 1820	1821–1851	1852–1870	1871–1890	All years
All great inventors					
N	89	105	78	65	337
%	83.2	85.4	94.0	89.0	86.9
All science (FRS, science education, eminence)					
N	28	37	23	28	116
%	80.0	82.2	95.8	90.3	85.3
Fellows of the Royal Society					
N	17	21	16	19	73
%	81.0	84.0	94.1	95.0	88.0
Science education					
N	7	17	13	19	56
%	70.0	81.0	92.9	90.5	83.6
Eminent scientists					
N	14	19	8	14	55
%	77.8	91.2	100.0	100.0	85.9

The figures indicate the number of inventors who had obtained at least one patent by the year 1890. For descriptions of the various categories, see the text and notes to prior tables

2005). Significant aspects of the institutional overhaul included lower patent fees, the administration was rationalized, and measures were undertaken to enhance the provision and dissemination of information. In 1883, further improvements in the rules and standards were introduced and the fees fell again. The reforms provide a natural experiment to determine the extent of supply elasticity of great inventions and their variation across knowledge inputs.[42] If great inventors in general, and scientists in particular, differed from ordinary patentees in terms of their responsiveness or commercial orientation, then we would expect their patterns of patenting to be largely unaffected by these institutional changes. Instead, Fig. 3 supports the view that the great inventors—scientists and nonscientists alike—responded to the decrease in monetary and transactions costs (and potential rise in net expected returns) by increasing their investments in patented invention.

The patent records also enable us to examine whether a science background increased productivity at invention (Table 6). Again, the patterns are consistent with the notion that at least until 1870 a background in science did not add a great deal to inventive productivity. If scientific knowledge gave inventors a marked advantage,

[42] Widespread dissatisfaction with the British patent system had existed more than a century before the reforms of 1852. The motivation for making changes in the patent rules came when the Crystal Palace exhibition in 1851 revealed that Britain was in danger of losing its industrial competitiveness to the United States. It was argued that part of the growing American advantage owed to its favorable patent institutions. As a result the British patent laws were explicitly revised in the direction of the U.S. system (Khan 2005). The motivation for the change therefore was exogenously driven by the perceived rise of American industrial superiority, and not to accommodate an increased propensity to patent in Britain.

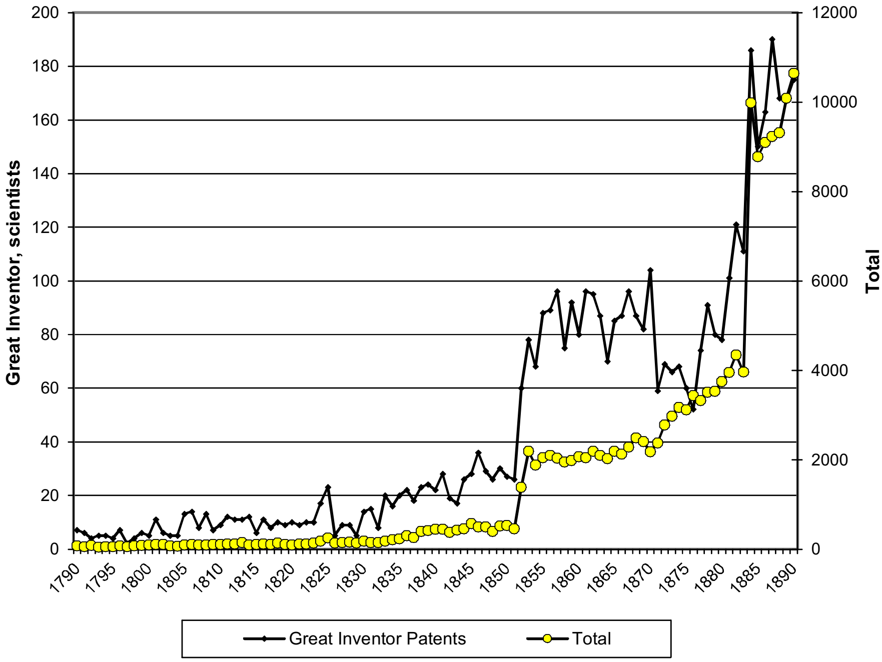

Fig. 2 Patenting by great inventors and by all patentees, 1790–1890. *Notes* The patent information was obtained from the Reports of the Commissioners of Patents, various years. For the "great inventors" sample, see the text

it might be expected that they would demonstrate greater creativity at an earlier age than those without such human capital. Inventor scientists were marginally younger than nonscientists, but both classes of inventors were primarily close to middle age by the time they obtained their first invention (and note that this variable tracks inventions rather than patents). Productivity in terms of average patents filed and career length are also similar among all great inventors irrespective of their scientific orientation. Thus, these data indicate that the kind of knowledge and ideas that produced significant technological contributions during British industrialization seem to have been rather general and available to all creative individuals, regardless of their scientific training.

Tables 7 and 8 show the relationship between inventive activity and different proxies for specialized human capital. Table 7 examines variation in industrial specialization, or the fraction of an inventor's patents that were filed in a particular industry. Since localities vary in terms of many unobservable factors, the regressions control for regional fixed effects. As one might expect, formal technical education in engineering and technology was associated with higher sectoral specialization. However, elite degrees from Oxford or Cambridge, degrees in science, or publications of books and articles, all indicated lower tendencies for specialization, and all of these variables added little to the overall explanatory power of the model. These results are bolstered by the finding that such industries as agriculture and construction were less likely to be specialized, whereas patents for

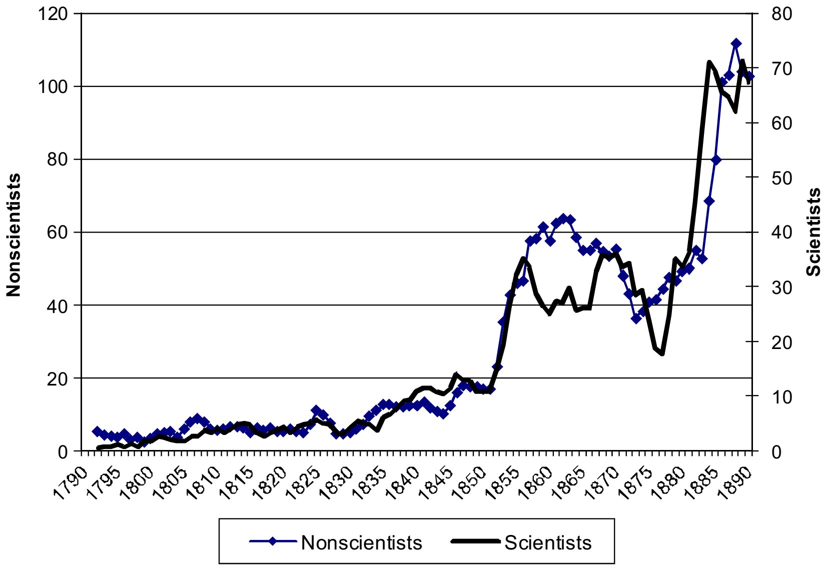

Fig. 3 Great inventor patents by scientific orientation (3-year moving average, 1790–1890). *Notes* The patent information was obtained from the Reports of the Commissioners of Patents, various years. For the great inventors' sample, see the text. *Scientists* include great inventors who were listed in a dictionary of scientific biography; received college training in medicine, mathematics or the natural Sciences; or were Fellows of the Royal Society

textiles and the electrical industries, as might be expected, went to inventors who were more specialized.

The final two regressions in Table 7 highlight the patterns over time in specialization and education. Regression (3) represents the results for the entire period and can be used as a baseline with which to compare the results in Regression (4). This final regression is estimated over the period after 1880 (inclusive). By this decade, elite education had become moderately more specialized than earlier on, but the activities of such graduates from elite schools did not differ significantly from individuals without any formal training. Similarly, the technological contributions of scientists remained diffuse and unspecialized throughout the entire period. However, after the 1880s, the inventive activity of those with formal technical education in such subjects as electrical and civil engineering was significantly more specialized than in the prior era. This finding suggests that, toward the final decades of the nineteenth century, inventive productivity was drawing on scarcer human capital that was enhanced by investments in technical skills; and this process was associated with greater specialization.

Total career patents comprise another measure of human capital in inventive activity, since inventors with greater numbers of patents would be more likely to have accumulated larger stocks of knowledge through learning by doing (Table 8). Career patents were higher in the South of England, where markets (as gauged by income and population) were more extensive (Floud and McCloskey 1994). The

Table 6 Patents and productivity among British great inventors, by year of first invention (through 1890)

	Before 1820	1821–1851	1852–1870	1871–1890	All Years
Nonscientists					
Age of first invention	35.1	35.2	33.9	29.5	33.6
Average patents	4.2	14.1	17.2	13.1	10.7
Career length	18.0	20.3	25.7	30.1	23.2
No. of inventors	72	78	59	42	286
Industrial specialization					
% of patents by specialized inventors	57.5	45.4	69.3	73.9	60.3
Total number of patents	180	497	678	390	1776
Industrial distribution (select industries, % of patents by nonscientists)					
Engines	17.9	11.7	11.2	26.9	13.6
Electric-telecommunications	2.2	2.6	13.9	9.5	7.5
Textiles	25.6	19.7	6.2	11.0	14.1
Manufacturing	25.4	31.4	36.1	28.6	31.5
No. of patents	313	1094	978	528	2945
All science (FRS, science education, eminence)					
Age of first invention	32.4	32.9	29.8	29.0	31.2
Average patents	4.9	16.2	17.2	16.8	12.8
Career length	21.2	25.6	24.5	34.2	26.9
No. of inventors	35	45	24	31	153
Industrial specialization					
% of patents by specialized inventors	63.5	31.0	48.7	85.4	54.0
Total number of patents	113	228	202	452	1012
Industrial distribution (select industries, % of patents by scientists)					
Engines	16.3	10.6	3.6	14.4	11.0
Electric-telecommunications	1.1	16.6	28.0	54.6	28.2
Textiles	15.2	3.7	4.8	1.1	4.3
Manufacturing	41.0	43.8	40.0	18.2	35.0
Total number of patents	178	736	415	529	1875

The patent information was obtained from the Reports of the Commissioners of Patents, and patents were categorized according to sector of final use. Career refers to lifetime career, defined as the difference between the first and last invention. See notes to prior tables and text

regression results for this proxy for the patentee's science and technology knowledge are consistent with those for industrial specialization. Elite education, science degrees, or research and development did not lead to higher patenting over an inventor's career. Career patents were higher for inventors who had engineering degrees but, as the descriptive statistics indicated, engineering qualifications were prevalent only later in the century.

Table 7 OLS regressions of specialization at invention

Variables	Parameter (1)	*T*-stat	Parameter (2)	*T*-stat	Parameter (3)	*T*-stat	Parameter (4)	*T*-stat
Dependent variable: industrial specialization								
Intercept	96.3	88.72***	98.42	49.52	87.63	62.54***	76.71	24.41
Before 1820	−17.61	−2.37***	−18.02	−8.95***	–	–	–	–
1821–1851	−6.97	−5.77***	−9.64	−5.16***	–	–	–	–
1852–1870	−11.97	−15.5***	−12.79	−8.15***	–	–	–	–
1871–1890	−4.16	−4.83***	−7.32	−4.45***	–	–	–	–
1891–1930	−3.69	−4.74***	−2.47	−2.85***	–	–	–	–
Residence								
London	−1.25	−1.58	−4.16	−5.29***	−5.42	−6.91***	−7.07	−5.31***
Northern England	1.38	1.63	−1.07	−1.26	−2.11	−2.51**	−5.60	−3.85***
Rest of Britain	−2.6	−2.06*	−4.62	−3.76***	−5.73	−4.65***	−12.44	−6.54***
S&T background								
Elite education	−2.96	−3.48***	−3.43	−4.09***	−4.30	−5.18***	0.3	0.26
Scientific education	−1.26	−1.64	−1.08	−1.45	−0.51	−0.68	−0.63	−0.56
Technical education	3.28	3.66***	4.56	5.24***	5.19	5.94***	7.83	6.80***
Prizewinner	−1.55	−2.61**	−1.28	−2.22*	−0.41	−0.71	−9.74	10.03***
Publications	−2.24	−3.87***	−2.51	−4.32***	−1.98	−3.45***	2.79	2.98**
Patents								
Log(number of patents)	−3.8	−16.5***	−4.09	−6.76***	−3.45	−15.0***	−0.62	−1.17
Post-patent reforms			−2.59	−1.84	6.76	11.88***	13.71	9.46***
Industry								
Construction	–	–	−10.56	−6.1***	−12.68	−7.31***	−12.16	−3.88***
Electrical	–	–	9.72	6.67***	8.96	6.10***	7.65	3.32***
Engines	–	–	0.23	0.16	−0.75	−0.51	2.44	0.98

Table 7 continued

Variables	Parameter (1)	T-stat	Parameter (2)	T-stat	Parameter (3)	T-stat	Parameter (4)	T-stat
Manufacturing	–	–	2.93	2.18*	1.57	1.16	−1.47	−0.64
Textiles	–	–	10.51	6.57***	9.35	5.84***	4.18	1.11
Transportation	–	–	2.59	1.76	1.91	1.28	2.91	1.17
	$N = 4827$		$N = 4827$		$N = 4268$		$N = 1423$	
	$F = 50.74$		$F = 54.64$		$F = 61.94$		$F = 34.15$	
	$R^2 = 0.14$		$R^2 = 0.22$		$R^2 = 0.20$		$R^2 = 0.29$	

The observations include all patents filed by the great inventors through 1930 and therefore understates the number of patents in the final period. The dependent variable represents the highest percentage of an inventor's patents that were filed in a single industry. The excluded region comprises the Southern counties of England. Prizes indicate whether or not the inventor received an award for technological achievements. Publications include academic articles and books. Post-patent reforms are a dummy variable for the period after 1852. The fourth regression is based on a subset of the data, limited to the period after 1880 (inclusive). For definitions of S&T background see text and prior tables

Table 8 Negative binomial regressions of total career patents

Variable	Parameter	Chi-square	Parameter	Chi-square
Dependent variable: total career patents				
Intercept	3.54	7935.13***	2.79	1817.74***
Before 1820	−1.45	487.87***	−1.39	442.81***
1821–1851	−0.98	330.12***	−0.95	297.31***
1852–1870	0.24	45.36***	0.22	39.78***
1871–1890	0.50	171.69***	0.49	156.72***
1891–1930	0.35	86.19***	0.31	66.29***
Residence				
London	−0.02	0.25	0.05	1.91
Northern England	−0.20	22.9***	−0.10	5.3*
Rest of Britain	−0.59	102.01***	−0.52	82.51***
S&T background				
Elite education	−0.03	0.59	0.01	0.08
Scientific education	−0.36	98.72***	−0.36	100.4***
Publications	0.10	12.02***	0.05	3.15
R&D	−0.06	2.47	−0.09	4.99*
Technical education	0.25	35.48***	0.24	31.56***
Industry				
Agriculture			1.06	203.64***
Construction			0.66	71.51***
Electrical			0.84	179.46***
Engines			0.67	111.4***
Manufacturing			0.70	144.66***
Textiles			0.69	96.04***
Transportation			0.65	102.8***
	$N = 4827$		$N = 4827$	
	−Log Likelihood = 18,843.2		−Log Likelihood = 18,736.3	

The dependent variable measures the total stock of patents filed by an inventor during his lifetime. The sample includes patents filed by the great inventors through 1930, and therefore understates the number of patents in the final period. The excluded region comprises the Southern counties of England. Prizes indicate whether or not the inventor received an award for technological achievements. Publications include academic articles and books. Post-patent reforms are a dummy variable for the period after 1852. For definitions of S&T background, see text and notes to prior tables

The overall empirical findings together suggest that, by focusing their efforts in a particular industry, relatively uneducated inventors were able to acquire sufficient knowledge that allowed them to make valuable additions to the available technology set. After 1820, as the market expanded and created incentives to move out of traditional industries such as textiles and engines, both scientists and nonscientists responded by decreasing their specialization. The patent reforms in 1852 in part may have encouraged the nonscience-oriented inventors to increase their investments in sectoral specialization, but industrial specialization among the scientists lagged significantly. This is consistent with the arguments of such scholars as Joel Mokyr, who argued that any comparative advantage from familiarity with science was likely based on broad unfocused capabilities such as rational methods of analysis that applied across all industries. The time path of specialization is especially informative in terms of electrical and telecommunications technology, which required more technical knowledge inputs than traditional areas such as textiles. Electrical innovation was also heavily specialized across region, and two-thirds of all related patented inventions were filed by residents of London. The expansion in this industry after the 1870s was associated with a greater marginal return for those with formal education, and this likely induced the substantive specialization in this industry among scientist–inventors, as well as college-educated engineers.[43]

The experience of the British great inventors also shed light on the reward systems that are frequently recommended as substitutes for patents. Prizes and medals, in particular, might be more effective inducements than patents if scientists were motivated by the desire simply for the recognition of their peers and not by financial incentives. Between 1826 and 1914, the Royal Society, for example, awarded 173 medals, 67 of which were given for work in mathematics, astronomy and experimental physics, and only two to engineers (MacLeod 1971). However, many were disillusioned with this award system, attributing outcomes to arbitrary factors such as personal influence, the persistence of one's recommenders, or the self-interest of the institution making the award. The timing also seemed ineffective, since the majority of premia were made later in life to those who had already attained eminence. The likelihood that an inventor had received prizes and medals was higher for unspecialized scientific men, more so for those who had gained recognition as famous scientists or those who had influential connections (Khan 2011). Prizes and medals tended to be awarded to the same individuals who had already received patents and, indeed, prizes were associated with higher numbers of patents. The incremental value of these awards was therefore likely to be somewhat low—not because scientists were unresponsive to incentives, but because their response was higher for financial motivations including the returns vested in patents. It is not surprising that, by 1900, key institutions had decided to change their emphasis from the allocation of medals to the financing of research.

5 Conclusions

The generation of new technological innovations is one of the most crucial processes of economic growth. What was the role of science, specialized knowledge and knowledge-generating institutions in the creation of important technological

[43] The Society of Telegraph Engineers (later the Institution of Electrical Engineers) was founded in London in 1871 by eight men, and rapidly became one of the largest societies in Britain. Its membership rose from 352 in 1871 (8.5% of all enrollment in engineering institutions) to 2100 (14.0%) in 1890 and 4000 (17.2%) in 1910. Even these professional institutions resisted formal education, and apprenticeships remained the favoured mode of human capital acquisition among the engineering class examinations until the end of the nineteenth century. See Buchanan (1985).

inventions during British industrialization? The evidence from the backgrounds and patenting of the great inventors in Britain suggest that the formal acquisition of human capital did not play a central role in the generation of new inventive activity, especially in the period before the second industrial revolution. Alexander Parkes (1813–1890), the creator of the first synthetic plastic, was trained as an apprentice to a firm of brass-founders in Birmingham, and initially described himself as a decorative artist, only later declaring himself as a chemist. Indeed, British science entered its golden age long after the advent of industrialization and, even as late as 1884, Francis Galton (1874) concluded that "an exhaustive list" of scientists in the British Isles "would amount to 300, but not to more."[44] Instead, during early industrialization, the evidence regarding technical knowledge of all kinds comported more with James Nasmyth's (1885) definition of engineering as "common sense applied to the use of materials."

These patterns may have owed in part to the character of the British educational system which largely restricted access to higher education to the privileged classes, in the nineteenth century and beyond.[45] The evidence on educational institutions is particularly striking when one contrasts the British experience to the USA. College graduates from elite universities, especially those in science and technical fields, were generally better represented among great inventors in Britain than in the USA. There were stark differences in the distribution of education attainments, as well as in the class backgrounds of those who were able to go to college, between the two countries. College education was not so prevalent among the US inventors until quite late in the nineteenth century, but even those graduates were drawn from a much broader range of social classes (judging from the occupations of the fathers). Thus, it is likely that the proportion of great inventors who were scientists in Britain actually overstates the importance of a science education for making a significant contribution to technological knowledge. Despite the advantages that people from elite backgrounds had at invention, scientists were not well-represented among the great British inventors nor among patentees during the height of industrial achievements. This is perhaps unsurprising since scientific efforts of the time were concerned "mostly about prisms and planets, and before the twentieth century … did not help much in worldly pursuits" (McCloskey 2011, p. 34). Instead, many of the most productive

[44] See Galton, who adds (1874, p. 6) "Some of my readers may feel surprise that so many as 300 persons are to be found in the United Kingdom who deserve the title of scientific men…" According to William Ramsay's 1911 Presidential Address of the British Association for the Advancement of Science, the true beginning of British science did not start until the middle of the nineteenth century.

[45] Cardwell (2003) attributes a scarcity of scientists to failures of the educational system. Reports from a number of Royal Commissions—including the Samuelson (1868 and 1882) and Devonshire (1878) Commissions—outlined the inadequacy of British science and its institutions of scientific and technical training. Enrollments in science classes at the secondary school level were "negligible;" and university science was "seriously deficient in quantity and quality." Despite the frequent investigations by Commissions of this sort, reform was "miserably slow." Gowing (1978), Ashby (1963, p. 7) considered British academic science to be "dogmatic and dessicated" until after the middle of the nineteenth century. Alter (1987) points to the equally limited role of the state in encouraging science. The state was involved in the establishment of the National Physical Laboratory, the Imperial College of Science and Technology, and the Medical Research Committee, but a significant role for state funding awaited the first World War.

inventors, such as Charles Tennant, were able to acquire or enhance their inventive capabilities through apprenticeships and informal learning, honed through trial and error experimentation.[46]

Economic historians of Britain have pointed out that its early economic growth was unbalanced and productivity advances were evident in only a few key sectors. Moreover, significant increases in total factor productivity growth were not experienced until the middle of the nineteenth century. The reasons for these patterns have not been fully elaborated on. Here, we highlighted the generation of knowledge inputs, and the elitist institutions that hampered their full attainment during the critical period of industrialization. The oligarchic nature of British society likely limited the size of the market, suppressed the widespread acquisition of human capital through educational institutions, and arguably encouraged rules and standards that discriminated against the efforts of disadvantaged members of society. Technological inventiveness and progress responded to incentives and were likely inhibited by such factors. Whatever the underlying reasons, the transformations that made science and technical backgrounds crucial to the creation of important inventions were not achieved until the end of the nineteenth century.

More generally, the experience of the First Industrial Nation indicates that creativity that enhances economic efficiency is somewhat different from additions to the most advanced technical discoveries. The sort of creativity that led to spurts in economic and social progress comprised insights that were motivated by perceived need and by institutional incentives, and could be achieved by drawing on practical abilities or informal education and skills. The acquisition of useful knowledge depended on transmission mechanisms within households, from fathers to children, and within crafts and guilds, from masters to apprentices. Apprenticeships, in particular, offered a particularly effective and flexible means of acquiring training and skills for creative individuals to engage in inventive activity and innovation. Elites and allegedly "upper-tail knowledge" were neither necessary nor sufficient for technological productivity and economic progress.

In the twenty-first century, specialized human capital and scientific knowledge undoubtedly enhance and precipitate economic growth in the developed economies. However, for developing countries with scarce resources, such inputs at the frontier of "high technology" might be less relevant than the ability to make incremental adjustments that can transform existing technologies into inventions and innovations that are appropriate for general domestic conditions. As Thomas Jefferson pointed out, a small innovation that can improve the lives of the mass of the population might be more economically important than a technically advanced discovery that benefits only the few. And, just as in the industrial revolution, improvements in informal training and institutions are quite likely to have significant returns at the margin that might exceed those from costly investments into tertiary education that typically subsidize elites at the expense of the general population.

[46] Charles Tennant (1768–1838), the son of a Scottish weaver, developed such inventions in chemistry as bleaching powder, and founded a firm that was the precursor of ICI.

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