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"The Evolution of Useful Knowledge: Great Inventors, Science and Technology in British Economic Development, 1750-1930"

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> "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"
>
> --Sir Henry Sumner Maine (1885)

INTRODUCTION

This paper provides an empirical assessment of the contribution of different types of knowledge to British industrialization. Endogenous growth models are based on the premise that knowledge, ideas and induced innovation comprise a significant source of economic development. These theories raise fundamental questions about the nature of human capital, knowledge, skills, and other characteristics that are conducive to extraordinary creativity, and how those factors vary over time and field of endeavor. They imply that our understanding of economic progress requires an assessment of the types of knowledge inputs that are in elastic supply, and how they respond to economic incentives. Walt Rostow, for instance, contended that one of the preconditions for economic and social progress is an advance in scientific knowledge and applications, inputs which typically are scarce in many developing countries.[1] Nathan Rosenberg similarly highlights the determining role of science and specialized knowledge in economic advances.[2] Others regard scientists as disinterested individuals who are motivated by intangible rewards such as enhanced reputations and honour, the desire to benefit mankind, or the pursuit of timeless truths, rather than 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 policy measures.

These issues have been widely debated, especially in the context of industrialization in Britain and explanations for its subsequent loss of competitiveness. Still, little consensus has emerged from the plethora of contributions to this topic. A number of scholars support the Rostovian argument. According to some, the theoretical elitist biases of the European scientific establishment help to explain why Britain and not (say) France, was the first industrial nation. They point to examples of formal and informal links between scientific discoveries and technological change, and conclude that Britain's industrial lead depended on its scientific standing.[3] A classic but contested example of such ties is the influence of scientist Joseph Black on James Watt's improvement on the steam engine.[4] Similarly, John Roebuck and Charles Tennant applied chemical knowledge to produce sulphuric 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 over 1000 by the 1880s.[8] 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.[9]

David Landes produced a prominent exposition of a thesis in the equal but opposite direction, insisting that the industrial revolution "owed virtually nothing to science."[10] British innovations toward the end of the eighteenth century and at the start of the nineteenth century were largely produced by workers who had little formal education, and who benefited from apprenticeships and on-the-job learning. Significant problems such as measurement of longitude at sea were solved by relatively uneducated artisans rather than through the application of abstract or formal scientific observation. A number of other studies highlight the reciprocal nature of interactions between industry and academic science.[11] For instance, Neil McKendrick's guarded conclusion was that science "played a necessary but not sufficient role."[12] Many such researchers emphasize that until the middle of the nineteenth century science and engineering were closer to "organized common sense." More formal scientific endeavours 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.[13] Joel Mokyr highlights the rational scientific revolution of the seventeenth century, but his emphasis is on the general influence of the intellectual and methodological developments of Bacon, Hooke and Newton, rather than on specific applications of their scientific results to industry.[14] According to his 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.

As these diverse propositions suggest, significant aspects of the relationship between knowledge, science and technology in the industrial revolution still remain unresolved, in part because the discussion tends to be framed in terms that are not subject to falsification. This paper addresses these issues by defining knowledge inputs in terms of specialized inventive activity and in terms of inventive individuals with documented scientific credentials. Clearly this approach has its drawbacks and limitations, but it does allow us to present results that are explicitly measurable and comparable across time period, and I propose that these can illuminate the more detailed but untestable historical accounts.

The analysis employs a sample of "great inventors" who were included in biographical dictionaries because of their contributions to technological progress. I traced the inventors who were formally educated in science and engineering programmes. In addition, the data encompass broader dimensions of achievement such as membership in the Royal Society of Arts, scientific eminence, research activities, publications, and the receipt of prizes and nonmonetary rewards. These variables were supplemented with information from patent records on the numbers of patents filed over the individual's lifetime, the length of the inventor's career, the industry in which he was active, and the degree of specialization by sector.[15] Thus, we are able 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. More generally, the results have the potential to enhance our understanding of the shifts in the frontiers of technology during early economic growth.

The plan of the paper is as follows. Section 1 describes how the "great inventors" sample was compiled, and the birthplace and science backgrounds of the inventors. Section 2 examines the characteristics of the great inventors in terms of their social and educational backgrounds. Section 3 then presents the patterns of patenting of the great inventors, and compare the productivity of scientists and nonscientists, and their responsiveness to material incentives. In the final sections I discuss the results from multivariate analyses of inventors' commitment to patenting and scientific status, and also offer a conclusion.

I. THE GREAT INVENTORS SAMPLE

The set of "great inventors" was compiled from biographical dictionaries, including the 2004 *Oxford Dictionary of National Biography (DNB)*, and the *Biographical Dictionary of the History of Technology (BD*), among others.[16] My objective was to compile a sample of individuals who had made significant contributions to technological products and productivity. This accorded more with the intent of the BD, 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." 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.[17] A large fraction of the technological inventors are featured in the DNB as "engineers" even though the majority had no formal training. Other notable inventors are variously described as pioneers, developers, promoters or designers. Edward Sonsadt is omitted altogether although elsewhere he is regarded as an "inventive genius."[18] I therefore supplemented these two volumes with other biographical compilations, and numerous books that were based on the life of a specific inventor.[19] Although a few of the entries in any such sample would undoubtedly be debatable, this triangulation of sources minimizes the possibility of egregious error.[20]

The resulting British great inventors data set is comparable to the Khan and Sokoloff compilation of important inventors and their patenting activity in the United States during the same period.[21] The British sample comprises 434 men and one woman who made significant contributions to technological products and productivity, and who produced at least one invention between 1790 and 1930. These British inventors include 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.

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 technically trained inventors 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 localities outside of England. For instance, Isaac Holden, who is regarded as a prominent contributor to wool-combing technology, was born in 1807 near Glasgow, Scotland. Other such inventors include Lord Kelvin (Ireland), Richard Roberts (Wales), and Warren de la Rue (Guernsey). The famous Marc Isambard Brunel was born in Normandy, France, and 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 percent) relative to nonscientists (26 percent.)

Table 2 presents the distribution of inventors in terms of their science background and changes over the course of industrialization. There is some ambiguity about what a "scientist" connotes, so we examine three alternative measures of scientific orientation: formal education; eminence as gauged by listing in biographical dictionaries of scientists; and membership in the Royal Society. Of course, although even the university curricula of the day were fairly rudimentary, it is possible and likely that some may have acquired scientific knowledge from uncredited informal sources, but that is necessarily outside the scope of a systematic study. Approximately 20 percent of the great inventors were documented to have been educated at the post-secondary level in the sciences, mathematics or medicine. Similarly, 16.6 percent could be considered as scientists of sufficient eminence to be listed in a dictionary of scientists. A significant number (20.7 percent 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 a significantly higher proportion of inventors after this period possessed technical training in science and engineering. For instance, the percent of inventors with formal scientific training increased from 20 percent in 1852-1870 to 33.3 percent between 1871-1890, and the patterns are even more marked for great inventors with formal education in engineering, who comprised 11.1 percent of all inventors. Inventors with post-secondary engineering qualifications increased from a mere 1 percent before 1820, to 25.4 percent 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.

II. 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 key institutions. The epigraph by Sir Henry Sumner Maine suggests that Britain long remained an oligarchic society convinced that merit was causally related to inherited class. The United States arguably was ultimately able to assume global economic leadership in part because institutions such as its educational and political systems offered inducements to all classes of society to contribute to the growth process, and allocated rewards that were commensurate with individual productivity rather than social provenance. The elitist British educational system, in particular, failed to match up to institutes of higher learning in Germany and the United States, and has been portrayed as a hindrance to economic advancement.[23] 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 British great inventors by birth cohort in terms of their educational background. The great inventors were more educated than the general population, but it is clear that formal training was not a prerequisite for important invention in 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 cohort. Thus, these patterns refute the claim that "virtually all of the inventors" had exposure to scientific training, and is more consistent with the notion that the industrial revolution drew on traditional institutions that enhanced individual abilities such as apprenticeships and on the job training.[24] The route of 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. The skills that the inventor obtained could be combined with night-school or attendance at lectures offered by mechanics' institutes, or even a university degree later in life. Joseph Wilson Swan was apprenticed at 14 to a pharmacy store, but attended lectures at the Athenaeum in Sunderland that helped him to become a prominent chemist and electrical inventor. Both the Fairbairn brothers (Peter Fairbairn (1799-1861) and 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 training.

A fairly constant fraction of the great inventors obtained college degrees in general subjects such as divinity or the arts but it is noticeable that the importance of further education in science steadily increased over time. Engineering proficiency was more discontinuous, and was responsible for a jump in the technical orientation of the 1821-1845 birth cohort: 60 percent of all 27 inventors who received further education in engineering first produced inventions between 1871 and 1890. This is consistent with the earlier finding that scientific and technically-based inventions became more prevalent after 1870. By the beginning of the twentieth century, a science or technical educational background was typical of the majority of great inventors and many even received advanced and doctoral degrees in science. However, it is not clear whether university attendance or degrees in science and engineering prevailed among inventors because such qualifications enhanced their productivity at invention, or because a college degree was correlated with other arbitrary factors that gave these individuals preferment.

Donald Cardwell 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.[25] There might tend to be some differences in opinion about what comprises a humble beginning, but the data in Table 3 suggest that the common perception that the heroes of the 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 significantly 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 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 educated in the sciences were twice as likely to belong to these elite and professional families, and this pattern is invariant over the entire period, suggesting that such training might be associated more with the benefits of privilege rather than productivity.[26]

Another perspective on this finding is provided in Figure 2, which compares the social backgrounds of great inventors who attended college, across the two leading industrial nations of Britain and America. If it were true that elites prevailed because their privileged background and subsequent advantages in obtaining a college degree gave them an objective edge in technological creativity, we might expect little difference across countries. In the period before 1820 college attendees in both countries predominantly belonged to elite families. However, after 1820 the share of elites shrinks noticeably in the United States, and the vast majority of graduates come from nonelite backgrounds, whereas the pattern in Britain remains for the most part unchanged. The United States had set in place policies that facilitated human capital acquisition among the working class and led to social mobility through educational institutions, such as the Land Grant Act that subsidized universities. In Britain, and in England in particular, until the middle of the nineteenth century access to higher education was primarily available to the wealthy and those who adhered to the religious standards of the Establishment.[27]

An increasing fraction of inventors were educated at elite schools such as Oxford or Cambridge (Table 4), institutions which were unlikely to offer much in the way of knowledge or skills that would add to either scientific or technological prowess. Advancement at these institutions primarily depended on excellence in liberal classical subjects, and the engineer John Perry even declared that "Oxford fears and hates natural science."[28] Cambridge had offered the Natural Science Tripos since 1848, but for much of the nineteenth century the impact was nominal.[29] The anti-pragmatism of Oxbridge was reflected even 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 older schools.[30] 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 foreign postgraduate education were also correlated with a secure social and financial background.

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 distinguished in other ways. 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 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.[31] Although the Royal Society was associated with the foremost advances in science, many of its projects were absurd and impractical and it was widely criticized for its elitist and unmeritocratic policies.[32] 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 attributed a large part of the failure of British science to the Royal Society.[33] Even in 1860 more than 66 percent of its membership consisted of nonscientists and medical practitioners, whose inclusion was not altogether merited on the basis of their scientific contributions.[34] 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.

III. PATENTS, PRODUCTIVITY AND MARKET INCENTIVES

Rostow proposed the hypothesis that prospects for growth depended on the types of specialized knowledge that were inelastic and in scarce supply. The previous discussion of science and technology in early industrialization highlighted the role that an elite background played in promoting distinction among scientist-inventors in British society, which raises the possibility that such training did not necessarily increase productivity at invention relative to other inventors but merely comprised another index of privilege. Some researchers further suggest that, especially during the early stages of industrialization, scientists are not sensitive to market conditions. Others such as Crafts argue that major technological change was exogenous, and reject the notion that the growth process was characterized by endogenous responses to changes in market conditions. This section therefore uses patent records through 1890 to compare productivity at invention among scientists and nonscientists, and the extent to which these different groups of inventors were responsive to market incentives.

Patent records have well-known flaws as a gauge of invention and inventiveness, but they still have proved to be valuable in identifying the sources of variation over time and place in the rate, organization, and direction of inventive activity.[35] Table 5 shows that approximately 87 percent of the British great inventors were patentees (in the sense of having obtained at least one patent). 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.[36] In the United States, where patent institutions were extremely favourable to inventors of all classes, almost all (97 percent) great inventors were patentees, and very few of their patentable inventions remained unprotected. The British great inventors overall exhibit a somewhat lower propensity to patent, but this seems more related to institutional factors that affected all inventors, rather than to scientific disdain for material returns. In particular, there is a noticeable increase in the propensity to patent in the middle of the nineteenth century.

This period stands out because in 1852 the British patent system was reformed toward the American system in ways that increased access to patent institutions, and strengthened the security of property rights in patents. Significant aspects of the institutional overhaul included a reduction in 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. These reforms provide a natural experiment to determine the extent of supply elasticity of great inventions and their variation across knowledge inputs. 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, figures 3 and 4 support that view that great inventors -- scientists and nonscientists alike – quickly 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. 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, 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 groups 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 were also similar among all great inventors irrespective of their scientific orientation. Thus, 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.

The multivariate regressions reported in Tables 7 and 8 (estimated over patents) support these general conclusions. The regressions of industrial specialization in Table 7 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 gain specific knowledge, both scientists and nonscientists responded by increasing their specialization. The patent reforms in 1852 encouraged the nonscience-oriented inventors to increase their investments in sectoral specialization, but scientists lagged significantly. This supports the arguments of scholars such as Joel Mokyr, who argued that any comparative advantage from familiarity with science was based on broad unfocused capabilities such as rational methods of analysis that likely applied across all industries. Such conclusions are underlined by negative binomial regressions of career patenting (not reported here) indicating that the efforts of great inventors were rather evenly distributed across industries. Moreover, if specialized knowledge granted superior advantages, we would tend to expect that professional inventors (defined as those with higher numbers of patents over their career) would cluster in those industries with economies of scale in knowledge inputs. Instead, estimates of career patenting indicate that the degree of professionalization was fairly constant across all industries but, again, lower among the inventors with science backgrounds.

The regressions in Table 7 report the factors that influenced the proportion of patents that occurred in a single sector, as a proxy for industry-specific human capital investments. This is admittedly a rough gauge, but it is consistent that the amount of variation explained is higher for patents filed by those with science and technology education, as well as with the coefficients on the other, agricultural and construction industries. Inventors in the traditional building industry were significantly less specialized than even the agricultural sector (the excluded variable). Both technically-trained and untrained inventors specialized in the electrical and telecommunications technology, suggesting that innovation in this area required fewer knowledge inputs than improvements in engines.[37] It is noticeable that nontechnical inventors were directing greater attention to textiles and manufacturing technologies, indicating that they were able to acquire inventive skills through informal means, and that science and engineering backgrounds did not contribute as much to the technological capabilities in these industries. Indeed, inventors from elite schools and those who published or won prizes were more likely to be generalists. In sum, the results suggest that great inventors were able to acquire much of the knowledge that produced higher total factor productivity growth during the industrial revolution through specialization and on the job experience, rather than through insights gained from education in science and technology (the exception being innovations in engines).

The regression results 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.[38] Between 1826 to 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.[39] 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 scientific men, moreso for those who had gained recognition as famous scientists or Fellows of the Royal Society. The regressions further indicate that 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. It is not surprising that by 1900 the Council of the Royal Society decided to change its emphasis from the allocation of medals to the financing of research.[40]

Table 8 reports the results of logistic regressions that estimate the probability that a patent was filed by an inventor with a scientific education, technical education, or by a famous scientist. The time dummies show an increasing trend after the middle of the nineteenth century, but such variables only became significant after the 1870s. As perhaps might be expected, although both associated with elite schools, science and technology graduates differed in terms of their social backgrounds, and the latter were more likely to reside in the northern counties. Inventors with science training had smaller stocks of patents and were more likely to have engaged in research, unlike those with technical training. Key industries of the "industrial revolution" such as textiles, engines and transportation innovated without substantial benefits from specialized science or technical knowledge inputs.

IV. CONCLUSIONS

The generation of new technological knowledge is one of the most crucial processes of economic growth. What was the role of science, specialized knowledge and institutions in the creation of important technologies in this critical period? This paper takes advantage of biographical information and patent records to examine the characteristics of individuals and inventions credited with significantly expanding the frontiers of technology during the British industrialization. Among the great inventors of the period, formal science and engineering education increased over time, but did not play a significant role in accounting for technological innovations until towards the third quarter of the nineteenth century. Patents by formally-qualified great inventors were broadly distributed across sectors, rather than clustering in the key industries typifying productivity gains in the industrial revolution. As such, the results support the views of those who regard the sources of such productivity growth to be due to widespread incremental gains in common practice, and not to large investments in specialized human capital.

If we accept that the portfolio of patents filed by these great inventors represented important contributions to technological innovation, these results are more in keeping with a model of endogenous growth. The findings are also consistent with the notion that the course of British industrialization was significantly shaped by the nature of its rather elitist institutions that tended to funnel rewards toward rent-seekers and the already advantaged, rather than on the basis of potential abilities and productivity. The patent system manifestly favoured the wealthy and influential, and openly rejected the notion that useful knowledge could originate among the less distinguished members of society. Such bias was also evident in scientific and educational institutions. The paucity of scientific inputs owe in large part to the British educational system which restricted access to higher education to the already privileged.[41] Individuals with scientific qualifications were drawn from elite backgrounds, and it was likely that these connections furthered their advance as much as their inventive abilities. As a result, British science entered its golden age long after the advent of industrialization and, even as late as 1884, Francis Galton concluded that "an exhaustive list" of scientists in the British Isles "would amount to 300, but not to more."[42]

The evidence on educational institutions is particularly striking when one contrasts the British experience to the United States. College graduates from elite universities, especially those in science and technical fields, were generally better represented among great inventors in Britain than in the U.S. There were stark differences in the distribution of education attainments, as well as in the socioeconomic standing of those who were able to go to college. College educations were not so prevalent among the US inventors until quite late in the 19^{th} century, but 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 the UK actually overstates the importance of a science education for making a significant contribution to technological knowledge. Despite the advantages of their privileged backgrounds, it must be repeated that scientists were not all that well represented among the great British inventors until very late in the 19^{th} century. Instead, the evidence regarding technical knowledge of all kinds comported more with James Nasmyth's definition of engineering as "common sense applied to the use of materials."[43]

Economic historians of Britain have pointed out that its early economic growth was unbalanced and productivity advances were evident in only a few key capital-intensive sectors. Moreover, far from an "industrial revolution" 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, but the results we highlighted here regarding the generation of knowledge inputs are at least in accord with these findings. While it was true that Britain attained early technological leadership, these achievements arguably occurred in spite of, rather than because of, the elitist institutions that hampered their full attainment during the critical period of industrialization. The oligarchic nature of British society limited the potential size of the market, suppressed the universal acquisition of human capital through educational institutions, and encouraged rules and standards that disfavoured disadvantaged members of society. These deleterious incentives likely had a cumulative negative impact on the course of technological inventiveness, that ultimately contributed to Britain's loss of global cultural and economic leadership. Advocates of British economic policy might well argue that these statements are a function of ex post theorizing, but contemporary discussions along these lines proliferated in the American colonies, which chose to adopt a blueprint for institutions and policies that deliberately departed from their European predecessors. It does not seem coincidental that these institutional departures from the British model were associated with a trajectory that led to the advent of the "American century."

TABLE 1: BIRTHPLACE OF THE GREAT INVENTORS, BY BIRTH COHORT AND TECHNICAL ORIENTATION
(column percentages)

	BIRTH COHORT										
	Before 1780		1781-1820		1821-1845		After 1845		Total		
	S&T	Non	S&T	Non	S&T	Non	S&T	Non	S&T	Non	ALL
BIRTHPLACE											
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	25.0	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	2.0	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	31.0	31.8	18.1	26.9	12.7	28.6	18.4	28.6	20.1	**23.0**
Overseas	4.2	5.6	2.3	4.8	15.4	6.4	11.3	10.2	8.2	6.3	**6.9**
TOTAL NUMBER	**24**	**71**	**44**	**105**	**26**	**63**	**53**	**49**	**147**	**288**	**435**

Notes: S&T indicates post-secondary training in science and engineering or listing in a dictionary of scientific biography; Non 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.

TABLE 2
SCIENCE AND ENGINEERING BACKGROUND OF GREAT INVENTORS, BY YEAR OF FIRST INVENTION

	Science Training		Listed Scientist		Engineering Training	
Year	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

Notes: *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.

TABLE 3: SOCIAL BACKGROUNDS OF THE GREAT INVENTORS,
BY BIRTH COHORT AND TECHNICAL ORIENTATION
(column percentages)

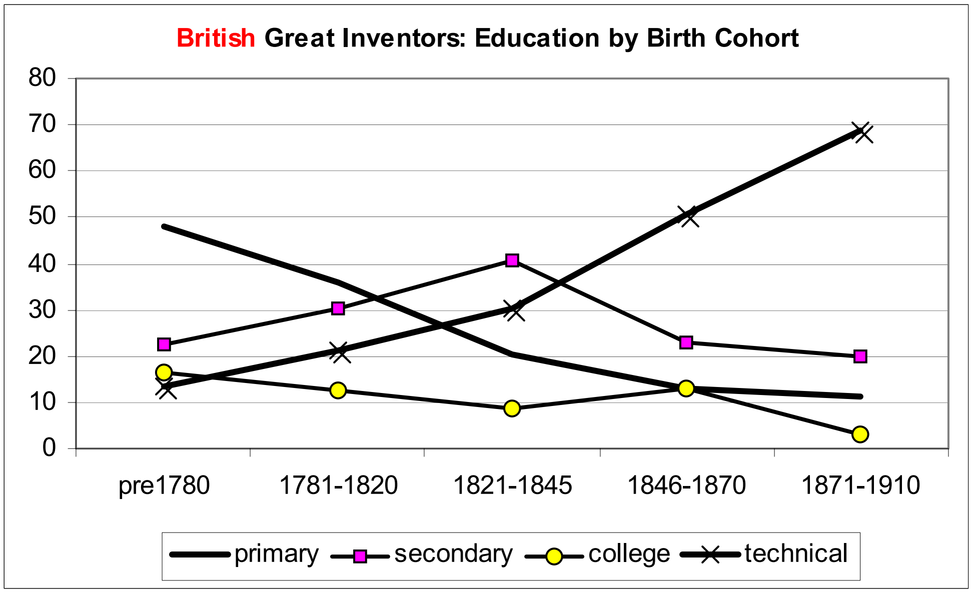
	BIRTH COHORT										
FATHER'S OCCUPATION	Before 1780		1781-1820		1821-1845		After 1845		Total		**ALL**
	S&T	Non	S&T	Non	S&T	Non	S&T	Non	S&T	Non	
Elite/Professional	58.3	25.4	50.0	21.0	46.2	28.6	60.4	26.5	54.4	24.6	**34.7**
White Collar	4.2	8.5	4.2	7.6	11.5	----	9.5	16.3	9.5	7.6	**8.3**
Skilled/Manufacturer	8.3	18.3	25.0	32.4	30.8	27.0	13.2	18.4	19.1	25.4	**23.2**
Farmer	8.3	7.0	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	31.0	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**

Notes: S&T indicates post secondary training in science and engineering or listing in a dictionary of scientific biography; Non indicates inventors who did not have such training and were not listed.

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

Notes: 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).


British Great Inventors: Education by Birth Cohort
80
70
60
50
40
30
20
10
0
pre1780
1781-1820
1821-1845
1846-1870
1871-1910
primary
secondary
college
technical

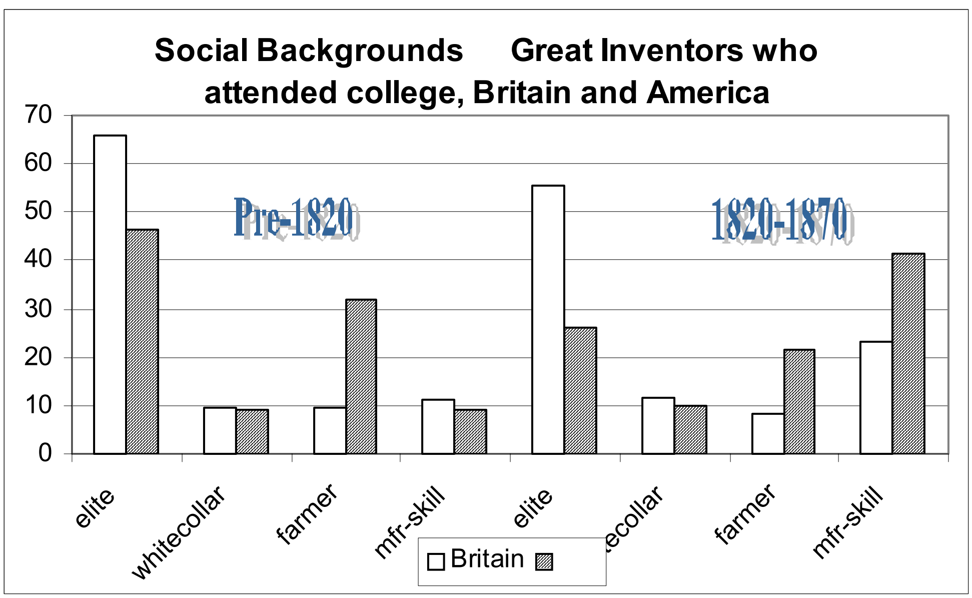

Social Backgrounds Great Inventors who attended college, Britain and America
70
60
50
40
30
20
10
0
Pre-1820
1820-1870
elite
whitecollar
farmer
mfr-skill
elite
ecollar
farmer
mfr-skill
Britain

FIGURE 3: PATENTING BY GREAT INVENTORS AND ALL PATENTEES, 1790-1890

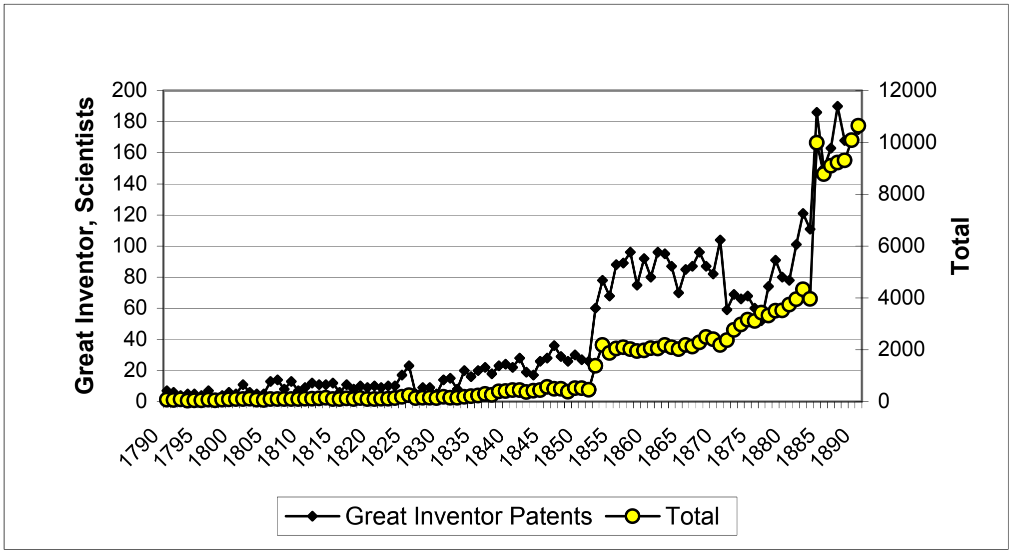
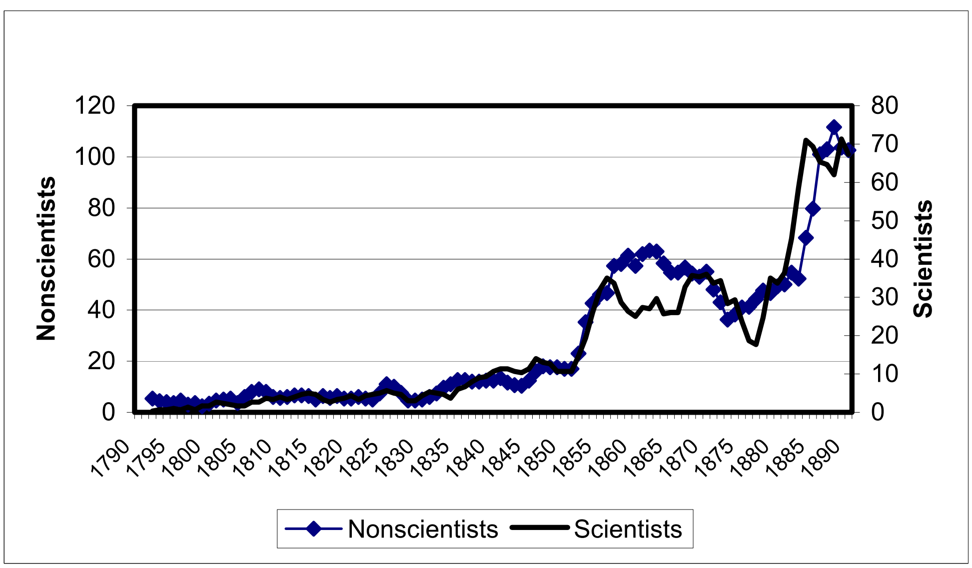


FIGURE 4: GREAT INVENTOR PATENTS BY SCIENTIFIC ORIENTATION
(3-Year Moving Average, 1790-1890)



Notes: Total patents filed before 1852 comprise patent applications, and patent grants after 1851. *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.

TABLE 5
THE PROPENSITY TO PATENT AMONG BRITISH GREAT INVENTORS,
BY YEAR OF FIRST INVENTION (THROUGH 1890)

Years	Before 1820	1821-1851	1852-1870	1871-1890	All
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	19.2	100.0	100.0	85.9

Notes: Patenting activities are traced through 1890, and will therefore underestimate the propensity to patent among inventors from the later cohorts. Science education refers to formal post-secondary schooling in science, whereas eminent scientists are those who have been listed in a biographical dictionary on account of their scientific achievements.

TABLE 6
PATENTS AND PRODUCTIVITY AMONG BRITISH GREAT INVENTORS,
BY SCIENTIFIC ORIENTATION AND YEAR OF FIRST INVENTION (THROUGH 1890)

	Before 1820	1821-1851	1852-1870	1871-1890	All
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 pats by specialized Inventors	57.5	45.4	69.3	73.9	60.3
Total No. of Patents	180	497	678	390	1776
Industrial distribution (select industries, % of patent by nonscientists)					
Engines	17.9	11.7	11.2	26.9	13.6
Electric-telecoms	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 pats by specialized inventors	63.5	31.0	48.7	85.4	54.0
No. of Patents	113	228	202	452	1012
Industrial distribution (select industries, % of patent by scientists)					
Engines	16.3	10.6	3.6	14.4	11.0
Electric-telecoms	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 No. of Patents	178	736	415	529	1875

Table 7
PATENTING BY GREAT INVENTORS: Sectoral Specialization

	Sectoral Specialization			
	(1) NonS&T	(2) S&T	(3) NonS&T	(4) S&T
Intercept	85.51	97.19	86.75	107.43
	(67.6)	(31.6)	(68.2)	(32.17)
Years				
Before 1800	-15.51	-15.98	-15.88	-17.87
	(11.91)	(2.54)	(12.11)	(2.96)
1800-1819	-5.11	0.35	-7.04	4.19
	(4.72)	(0.08)	(6.32)	(1.00)
1820-1839	-11.70	-6.27	-13.46	-2.17
	(15.77)	(3.46)	(17.18)	(1.14)
1840-1849	0.031	-12.90	0.81	-12.93
	(0.03)	(8.30)	(0.91)	(8.22)
1850-1859	-1.74	-4.78	-1.09	5.79
	(2.32)	(3.06)	(1.46)	(3.55)
Region				
London & Home Counties	0.37	-10.43	-0.86	-13.65
	(0.60)	(7.85)	(1.39)	(9.53)
Southern Counties	2.88	-8.18	4.83	-10.52
	(3.29)	(3.73)	(5.36)	(4.89)
Foreign & Other	1.27	-18.72	2.07	-24.55
	(1.04)	(8.52)	(1.73)	(10.42)
Industries				
Construction	-4.92	-7.98	-5.27	-9.44
	(3.39)	(2.61)	(3.69)	(3.16)
Electrical	12.37	15.71	10.64	14.15
	(10.65)	(6.11)	(9.04)	(5.72)
Engines	2.13	12.24	1.78	8.22
	(1.90)	(4.43)	(1.60)	(2.91)
Manufacturing	8.36	3.34	7.11	3.14
	(8.94)	(1.32)	(7.68)	(1.27)
Textiles	17.95	5.23	17.10	0.49
	(15.81)	(1.29)	(15.11)	(0.13)
Transportation	9.38	9.00	8.81	7.28
	(8.66)	(2.97)	(8.18)	(2.48)
Other	1.75	-4.06	2.68	-13.42
	(0.79)	(0.84)	(1.24)	(2.79)

Table 7 (Cont'd)
PATENTING BY GREAT INVENTORS: Specialization and Total Career Patents

	Sectoral Specialization			
	(1) NonS&T	(2) S&T	(3) NonS&T	(4) S&T
Log (No. of Patents)	-3.78	-5.43	-3.64	-6.81
	(15.04)	(9.78)	(14.16)	(11.09)
Education & Research				
Elite Schooling	----	---	-13.29	3.14
			(10.00)	(2.65)
Publications	---	---	-2.30	-7.10
			(4.03)	(2.48)
R&D	---	---	5.10	9.16
			(5.34)	(6.34)
Eminent Inventor				
Fellow of Royal Society	---	---	8.11	4.17
			(8.72)	(3.01)
Prize Winner	---	---	-1.84	-8.34
			(2.91)	(7.08)
	N=3444	N= 1326	N=3393	N=1317
	R^2=0.24	R^2=0.30	R^2=0.28	R^2=0.37
	F=67.12	F=35.50	F=61.42	F=36.91

Notes: The regressions are estimated according to OLS, with t-statistics in parentheses. The dependent variable in these regressions is patents weighted by sectoral specialization, measured in terms of multiple patentees with over 75 percent of their patents in the same sector. The log of all patents filed by great inventors through 1890 underestimates lifetime patenting for the later cohorts, and is computed over nonpatentees by adding a small number to zero. For information on the sample, see notes to previous tables and text.

Table 8
THE ROLE OF SCIENCE & TECHNOLOGY IN PATENTING BY GREAT INVENTORS:
Logistic regressions of the probability that a patent is by an inventor with S&T education

	Science Education		Famous Scientist	Technical Educn
	(1)	(2)	(3)	(4)
Intercept	-2.54	-4.54	-1.66	-2.59
	(138.7)	(203.60)	(110.42)	(62.09)
Years				
Before 1800	-2.11	-2.12	0.38	-14.53
	(35.24)	(29.92)	(7.37)	(317.8)
1800-1819	-1.56	-1.54	0.56	-4.11
	(36.51)	(26.34)	(34.68)	(16.42)
1820-1839	-0.54	-0.17	0.56	-3.14
	(20.09)	(1.45)	(34.68)	(99.05)
1840-1849	-0.65	-1.25	-0.02	-0.61
	(23.00)	(47.20)	(0.03)	(14.16)
1850-1859	-0.03	0.22	0.08	-0.86
	(0.10)	(3.09)	(0.74)	(28.86)
Region				
London & Home Counties	1.36	1.35	0.83	-1.10
	(160.57)	(102.50)	(116.80)	(62.43)
Southern Counties	0.56	0.58	0.24	-1.22
	(13.40)	(9.70)	(4.28)	(36.50)
Foreign & Other	1.59	1.94	0.22	-0.79
	(101.50)	(104.75)	(2.21)	(10.08)
Industries				
Agriculture	0.40	1.96	-0.15	-0.95
	(38.54)	(28.05)	(0.52)	(5.67)
Construction	1.55	2.65	0.27	0.41
	(38.54)	(54.97)	(1.84)	(1.35)
Electrical	0.89	1.75	1.63	-0.26
	(17.54)	(28.94)	(98.08)	(0.78)
Engines	0.64	2.17	-0.08	0.59
	(7.90)	(41.98)	(0.20)	(4.14)
Manufacturing	0.43	1.69	0.45	-0.03
	(4.23)	(28.25)	(8.60)	(0.01)
Textiles	0.34	2.20	-0.52	-3.25
	(1.48)	(30.08)	(7.00)	(9.66)
Transportation	0.26	2.01	-0.36	-1.71
	(1.24)	(34.59)	(3.95)	(20.58)

Table 8 (Cont'd)

THE ROLE OF SCIENCE & TECHNOLOGY IN PATENTING BY GREAT INVENTORS:
Logistic regressions of probability that a patent is by inventor with S&T education

	Science Education		Famous Sci	Technical Educn
	(1)	(2)	(3)	(4)
Prize Winner	---	-0.18 (2.67)	---	-0.45 (13.37)
Elite Family	---	0.53 (28.24)	---	-0.28 (5.70)
Oxbridge	---	1.82 (243.58)	---	2.33 (259.45)
President of Professional Org.	---	-0.56 (21.22)	---	---
Publications	---	1.22 (125.00)	---	1.06 (67.57)
R&D	---	1.36 (113.30)	---	-0.26 (3.14)
Log (No. of Patents)	---	-0.33 (44.97)	---	0.40 (34.57)
	N= 4827	N=4260	N=4820	N=4263
	LR=499.42	LR=1325.60	LR=666.16	LR=1120.55

Notes: The dependent variable in these binary logistic regressions comprise the probability that a patent is filed by (1) an inventor with post-secondary education in the sciences, (2) a famous scientist, defined as a Fellow of the Royal Society or an entry in a biographical dictionary of scientists, and (3) an inventor with post-secondary education in an applied technical field such as materials sciences or (mainly) engineering. Wald Chi-Square statistics are reported in parentheses. The regressions are estimated over patents filed by great inventors through 1890, and will therefore underestimate lifetime patenting for the later cohorts. For information on the sample, see text.

ENDNOTES

[1] W.W. Rostow, The Stages of Economic Growth, Cambridge: Cambridge University Press, 1960.
[2] Rosenberg emphasizes 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. Nathan Rosenberg, "Science, Invention and Economic Growth," Economic Journal, vol. 84 (333) 1974: 90-108 (p. 98, 104).
[3] "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 utilised applied science in their manufacturing processes." A.E Musson and E. Robinson, Science and Technology in the Industrial Revolution, Toronto: University of Toronto Press, 1969.
[4] See Robinson, Eric, and Douglas McKie (eds.), Partners in Science: the letters of James Watt & Joseph Black, Cambridge, Mass., Harvard University Press, 1970.
[5] See A. Clow and N. Clow, 1958.
[6] This Society met for monthly dinners in the Midlands and its roster included Erasmus Darwin, Matthew Boulton, Josiah Wedgwood, James Keir, Joseph Priestley, and James Watt, among others. See Robert Schofield, The Lunar Society Of Birmingham: A Social History of Provincial Science and Industry, Oxford: Clarendon, 1963.
[7] The influential members included Sir Joseph Hooker, Thomas Huxley, Sir Edward Frankland, John Tyndall, Herbert Spencer, and Thomas Hirst, among others, and three of them became 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." Roy M. MacLeod, "The X-Club a Social Network of Science in Late-Victorian England," *Notes and Records of the Royal Society of London*, Vol. 24, No. 2. (Apr., 1970), pp. 305-322.
[8] Ian Inkster, Science and Technology in History: An Approach to Industrial Development. New Brunswick: Rutgers University Press, 1991.
[9] Clifford Bekar and Richard Lipsey, "Science, Institutions, and the Industrial Revolution," Simon Fraser Working Paper, 2002, proclaim that "Virtually all of the [British] inventors were cultured and educated persons, in touch directly or indirectly with the latest scientific advances ... Science did matter" (p. 15).
[10] See A.R and M.B Hall, A Brief History of Science, Signet Library Books, 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."
[11] Donald Cardwell, The Development of Science and Technology in Britain, p. 483, refers to "the two-way relationship between science and technology," but implies that science benefited more from prior flows of technical insights. Paul Elliot, "The Birth of Public Science in the English Provinces: Natural Philosophy in Derby, c. 1690-1760," Annals of *Science*, Vol. 57 Issue 1, 2000: 61-100, considers such Derby luminaries as John Whitehurst FRS, Thomas Simpson FRS and Benjamin Parker. He concludes that their experience pointed to the possibility that technology likely influenced scientific discovery and education as much as the reverse.
[12] "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." N. McKendrick, "The Role of Science in the Industrial Revolution," p. 319.
[13] According to William Ashworth, An Economic History of England, 1870-1939, 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."
[14] Joel Mokyr, The Gifts of Athena: Historical Origins of the Knowledge Economy, Princeton, NJ: Princeton University Press, 2002, argues that useful knowledge comprises *proposition*al knowledge about natural regularities and *prescriptive* knowledge or techniques. Propositional knowledge refers to generalized principles such as natural laws and empirical observations obtained through measurement and classification. The concept is not limited to science per se, but also extends to mechanics, geography, engineering, and socially constructed beliefs that might be incorrect. Prescriptive knowledge consists of techniques, prescriptions, and instructions, which reside in human memory, artifacts or storage devices. Early on, the most important obstacle to self-sustaining growth was the narrow base of propositional knowledge in such areas as agriculture, transportation, power, and medicine. Thus, when the Industrial Revolution did occur, it was due to what Mokyr calls an "Industrial Enlightenment." Expansions in the base of propositional knowledge, and a positive feedback mechanism between the two types of knowledge, proved to be critical.

[15] The discussion of broad scientific culture is informative and yields insights into the role of social capital in economic development. However, we choose to focus here on the evolution of contributions to useful knowledge, which we define as additions to the social information set that have the potential to directly expand the production possibility frontier. We use patent counts 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, but they do offer the opportunity to adopt a more systematic approach to the relationship between science and technology in British economic growth.

[16] See the Oxford Dictionary of National Biography (online, September 2004), and Lance Day and Ian McNeil, Biographical Dictionary of the History of Technology, New York: Routledge, 1996.

[17] 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. Macleod and Nuvolari, (2006), The pitfalls of prosopography: inventors in the dictionary of national biography. Technology and Culture, 47, 757-776, have rightly pointed to flaws in the DNB. However, their criticism of the Khan and Sokoloff great inventor samples and of our results fails to acknowledge that our samples are not limited to any one source but were also drawn from an extensive array of other publications. The sample of British great inventors includes the names of almost all significant inventors that specialists in the area might cite. Moreover, the patenting records cover lifetime achievements, whereas Macleod and Nuvolari truncate their estimate in 1852, thus significantly underestimating the propensity to patent.

[18] Ian McNeil (ed), Encyclopaedia of the History of Technology, London: Routledge, 1990, p. 113.

[19] These include the Encyclopaedia Britannica; David Abbott (ed), Biographical Dictionary of Scientists: Engineers and Inventors, London: Blond Educational, 1985; Dictionnaire des Inventeurs et Inventions, Larousse: Paris, 1996; and other compilations. Approximately 15 percent of our sample from these sources were missing altogether from the DNB.

[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. We computed a simple logistic regression model where the dependent variable was the probability that an inventor from our sample was included in the DNB, and the independent variables included all characteristics that we intended to investigate in this study, such as birth cohort, occupation, education, science background, patenting and publications records, and so on. The response function Y| Xi (Xi= X_1, X_2, ... Xn) is assumed to have the form $E(Y|X_i) = \exp(ß_0 + ß_1 x + ...) / (1 + \exp(ß_0 + ß_1 x + ...))$, 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, $\log_e(p / 1 - p)$. We used maximum likelihood methods to estimate the parameters. We can reject the hypothesis of bias for almost all variables of interest, including time of first invention, educational status, science background, and occupation. 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.

[21] See B. Zorina Khan and Kenneth L. Sokoloff, “Institutions and Technological Innovation During Early Economic Growth: Evidence from the Great Inventors of the United States, 1790-1930,” in Institutions and Economic Growth, (eds) Theo Eicher and Cecilia Garcia-Penalosa, MIT Press (2006); B. Zorina Khan and Kenneth L. Sokoloff, “Institutions and Democratic Invention in 19th Century America,” American Economic Review, vol. 94 (May, Pap. And Proc.) 2004: 395-401; B. Zorina Khan and Kenneth L. Sokoloff, “Lives of Invention: Patenting and Productivity among Great Inventors in the United States, 1790-1930,” Les Archives D’Invention (ed) Liliane Hilaire-Perez (2005); B. Zorina Khan and Kenneth L. Sokoloff, "`Schemes of Practical Utility': Entrepreneurship and Innovation among `Great Inventors' During Early American Industrialization, 1790-1865," Journal of Economic History, vol. 53 (2) 1993: 289-307. Other economic historians have used biographical information to explore the patterns and sources of important and exceptional innovation. For example, in his studies of painters, novelists and Nobel prize winners in economics, David Galenson has proposed a life cycle approach to creativity, and discerns two different types of innovators : "conceptual artists" or theorists who primarily make their most significant discoveries early in their careers ; whereas "experimental artists" or empiricists are those whose "genius" emerges later in the life-cycle after a long gestation period during which they accumulate the skills and knowledge to realize better and better contributions or creations.

[22] A potential second candidate is Eleanor Coade (1733-1821), who is listed as 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.

[23] David 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 David Mitch, The Rise of Popular Literacy in Victorian England: The Influence of Private Choice and Public Policy, Philadelphia: University of Philadelphia Press, 1992.

[24] According to Bernard Cronin, p. 241, "throughout much of the 19th-century the craft-apprenticeship mode of training was the only form of technical education."

[25] Cardwell, The Development of Science and Technology in Nineteenth-Century Britain, Ashgate: Variorum, 2003. These specific claims are made in essays IV, p. 474; and VII, pp. 40-41.

[26] 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).

[27] Even though Dissenters were allowed to read for Oxbridge degrees after the 1850s, until 1873 they were precluded from holding fellowships at Cambridge.

[28] See Janet Howarth, "Science Education in Late-Victorian Oxford: A Curious Case of Failure?" *The English Historical Review*, Vol. 102, No. 403. (Apr., 1987), pp. 334-371. R. H. Tawney (Equality, 1931) wryly commented that the English "frisk into polite obsolescence on the playing fields of Eton." Along the same lines, Margaret Gowing (1978, p. 9) characterized English efforts at reforming its educational institutions at the end of the 19th century as "too little and too late." She attributes this to inadequate funding, the influence of social class and the Church, and poor administration.

[29] For an interesting analysis, see Roy Macleod and Russell Moseley, "The 'Naturals' and Victorian Cambridge: Reflections on the Anatomy of an Elite, 1851-1914," Oxford Review of Education, vol. 6 (2) 1980: 177-195. As late as 1880 only 4 percent of Cambridge undergraduates read for the NSTs and most were destined for occupations such as the clergy and medicine. 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 percent 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. Chairs in Engineering were created in Cambridge in 1875 and in Oxford in 1907, whereas MIT alone had seven engineering professors in 1891.

[30] Sarah V. Barnes, "England's Civic Universities and the Triumph of the Oxbridge Ideal," *History of Education Quarterly*, Vol. 36, No. 3. (Autumn, 1996), pp. 271-305, finds a tendency for the red-brick universities to be regarded as second-rate, and for the classical Oxbridge approach to be touted 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 meagre salaries. 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. See Report of the Royal Commissioners appointed to enquire into the Universities of Scotland: Returns and Documents, Parliamentary Papers xxxv (1878): 336-340.

[31] 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 Marie Boas Hall, All Scientists Now: The Royal Society in the nineteenth century, Cambridge: Cambridge University Press, 1984; and Michael Hunter, The Royal Society and its Fellows, 1669-1700, the morphology of an early scientific institution, Oxford: British Society for the History of Science, 1994.

[32] Charles Babbage, Reflections on the Decline of Science in England, and on Some of Its Causes, London : B. Fellowes, 1830. Babbage 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." The (London) Mechanics' Magazine, vol. 31, 1839, noted that:

"The time of the Committee is so generally taken up, and dwindled away, with projects and plans so evidently absurd, foolish, and puerile, that a really good thing stands little chance of having a fair consideration, especially if it stand second or third on the list." P. 118.

[33] Babbage 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." In 1831 disillusioned scientists founded the British Association for the Advancement of Science as a more open alternative to the Royal Society.

[34] According to Dorothy Stimson, Scientists and Amateurs: A History of the Royal Society, New York: H. Schuman, 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."

[35] For a pioneering study see Jacob Schmookler, *Invention and Economic Growth*, Cambridge, Mass.: Harvard University Press, 1966. Zvi Griliches, "Patent Statistics as Economic Indicators: A Survey," *Journal of Economic Literature,* Vol. 28, No. 4 (December 1990) :1661–1707, 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." For an excellent example of the way in which patent records can be adjusted to yield economically meaningful information, see Adam B. Jaffe and Manuel Trajtenberg, *Patents, Citations and Innovations: a Window on the Knowledge Economy,* Cambridge, Mass.: MIT Press (2002). An alternative approach is presented in Petra Moser, "How Do Patent Laws Influence Innovation? Evidence from 19th-Century World's Fairs," American Economic Review, vol. 95 (4) , September 2005, pp. 1215-1236.

[36] See William F. Cooke, The Electrical Telegraph: was it invented by Professor Wheatstone, p. 29 (II) London, 1857.

[37] 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 percent of all enrollment in engineering institutions) to 2100 (14.0 percent) in 1890 and 4000 (17.2 percent) 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 19th century. See Buchanan, 1985.

[38] This section is based on the empirical results from a study of prizes awarded to the great inventors. See Zorina Khan, "Of Patents and Prizes."

[39] Roy M. MacLeod, "Of Medals and Men: A Reward System in Victorian Science, 1826-1914," Notes and Records of the Royal Society of London, Vol. 26, No. 1. (Jun., 1971), pp. 81-105.

[40] The Council stated that its experience in the award of medals had revealed that adding to the number of such awards would be " neither to the advantage of the Society nor in the interests of the advancement of Natural Knowledge." Cited in Roy McLeod, 1971, p. 105.

[41] Donald Cardwell, The Development of Science and Technology in Nineteenth-Century Britain, Ashgate: Variorum 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)
Sir Eric Ashby, Technology and the Academics, p 7, considered British academic science to be "dogmatic and dessicated" until after the middle of the nineteenth century. Peter Alter, The Reluctant Patron: Science and the

State in Britain,1850-1920, New York: Berg, 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.

[42] See English Men of Science, London: Macmillan, 1874. Galton, p. 6, added that "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, Presidential Address of the British Association for the Advancement of Science, (Science, 34 (Sept) 1911: 289-304), "The middle of the nineteenth century will always be noted as the beginning of the golden age of science."

[43] James Naysmyth, Autobiography.

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