Technology, Innovation and Economic Growth in Britain Since 1870

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Abstract

This chapter examines technological change in Britain over the last 140 years. It analyzes the effects of patent laws and innovation prizes that were designed to promote technical progress. It explores the challenge associated with the changing organizational structure of innovation and the shift from independent invention to R&D activity taking place inside the boundaries of firms. And it also studies the development of British industrial science in universities and efforts to promote innovation through the formation of industry clusters. Overall, the evidence supports the traditional story of British failure in generating large payoffs from technological development. Although from the early 1970s Britain experienced a revival in the quality of innovation and improved productivity growth, structural weaknesses in the commercialization environment still remain.

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1. Introduction

Economic growth can be driven in the short run by factor accumulation or by utilizing factors more efficiently, but permanent increases can only result from technological innovation. Given Britain's loss of industrial preeminence from the late nineteenth century, an absence in new technology formation is as natural an explanation for British failure as cultural interpretations that emphasize a weakness of the industrial spirit (Weiner, 1981). While Britain was the first "workshop of the world" its lagging position behind the technology frontier during the drive to industrial maturity is a topic of some debate in economic history. Accounts of technological progress during industrialization emphasize that Britain's rise was defined by capabilities in a broad array of industries and by a culturally enlightened and technically competent stock of human capital that could translate new ideas from home, or abroad, into commercially viable innovations (Mokyr, 1999, 2002, 2010). What changed the trajectory of technological change in Britain from this high-point of early economic development?

This chapter examines the hypothesis that Britain has failed technologically. It provides a statistical portrait of innovation over the last 140 years and it then focuses on three main areas of explanation for Britain's historical innovation performance. First, it analyzes incentives for technological development, specifically British patent law and efforts to induce innovators using inducement prizes as an alternative or complementary mechanism. Second, it explores the organizational structure of innovation in Britain and R&D performance. Finally, it examines public policy efforts to promote industrial science and innovation clusters.

The data strongly support the argument that Britain has historically been lackluster technologically as other industrial nations began to catch up during the late nineteenth and early twentieth century. Some of this decline was inevitable given that advancing countries, especially the United States, had larger markets which promoted demand-induced innovation, larger populations leading to a greater supply of human capital for invention, or deeper capital markets to promote investment. But other aspects of decline were related to structural factors such as the lack of competition in product markets and the relative absence of creative destruction as disciplinary mechanisms to promote the efficiency of firms.

The data also reveal that Britain has experienced a renaissance in the quality of technological development from the early 1970s. This is consistent with the hypothesis that this period witnessed a positive change in the growth rate of productivity and the end of Britain's relative economic decline (Crafts, 2012). However, recent advances in productivity did not lead to performance gaps in the ability to manage innovation being fully overcome. In fact, managerial failures in small and large firms still act as a barrier to the widespread adoption of best-practice techniques (Bloom and Van Reenen, 2007; Bloom, Sadun and Van Reenen, 2012). Although Britain has a long tradition of excellence in the production of scientific knowledge, factors like weak management have stifled the rate at which new innovations have been commercialized.

2. Measuring Technological Change

A. Productivity Statistics

It is well-established in growth models that innovation is a main engine of economic development, but despite a glut of research in the area, technological change is still difficult to measure empirically. In growth accounting, the Solow residual is a measure of (among other things) technological progress, but as Abramovitz (1956, p.11) famously put it, it is really a "measure of our ignorance" and even more so if the inputs into TFP calculations are measured with error, as they tend to be historically. Yet, with advances in data and methodology, it is possible to make clear conclusions about Britain's productivity performance. Britain was outperformed by the United States and Germany during the early twentieth century; it fell behind European countries during the "golden age" of economic growth between 1950 and 1973; but a strong recovery occurred thereafter (Crafts, 2012). Because technology and productivity are inextricably intertwined, this implies a strong recent innovation performance. Consequently it is useful to analyze additional indicators to explore how productivity may be related to underlying measures of technological change.

B. Patents and Patent Citations

Innovation surveys offer new insights into the boundaries between "technology" and "innovation" and differences between product versus process innovation (e.g. Michie, 1998), but they are only available systematically for recent years. Patent and R&D data, by contrast, are more readily available over the long run and are commonly used as primary indicators of technological change (Griliches, 1990). Figure 1 shows the number of patents per thousand of population granted in Britain, the United States, Germany and France from the late nineteenth century up to the present. Much of the change in British patenting, and indeed patenting in other countries, can be explained by changes in patent laws. For example, the large drop in the number of patents granted in the late 1970s reflects more stringent novelty tests that were applied by the British Patent Office under the 1977 Patents Act, which represented a first step towards harmonizing patent standards across Europe. While the United States appears to have witnessed an increase in patents per capita in recent years, especially relative to European countries, measurement of this effect on a per capita basis is confounded by the fact that this period was also associated with a rise in the number of patents granted in the United States to inventors from overseas (Nicholas, 2011, p.801). Separating out domestic from foreign inventor patents, Khan (2011, p.774) finds that patent per capita for domestic inventors were far higher in the early twentieth century compared to at the end.

Figure 2 provides a more informative set of comparisons because it focuses on patenting activity by inventors in a single country – the United States – where the effects of patent laws remained largely the same for inventors from different countries. U.S. patent law required that the first true inventor be listed on the patent document. Accordingly, the data reflect the addresses of inventors *residing overseas* who were granted patents by the United States Patent and Trademark Office between 1870 and 2005. British inventors accounted for the highest share of foreign patentees up to 1900, but thereafter the share dropped and hovered at between 2 and 4 percent for the rest of the time period, with Britain's trajectory from the early 1980s up to the end of the period being closely synchronized with that of France. Noticeably, the share of patents accounted for by German inventors was severely disrupted by the First and the Second World Wars, but an equally pronounced feature of the data is the rise in the proportion of German inventors patenting in the United States from the 1950s up to the 1980s, which is consistent with a superior growth performance in this country induced by structural change during the "golden age" of European economic growth (Temin, 2002). From the 1980s all the countries shown in Figure 2 lost share as foreign inventors from countries such as Israel, Japan and Taiwan increasingly patented their inventions in the United States. Based on these comparisons, Britain's patenting performance over the long run appears weak. In 2004 the British share of foreign patents in the U.S. was 60 percent lower than it was in 1900.

Figure 3 shows the industry distribution of patents by the major time periods for inventions patented by British, German and French inventors in the United States, along with the distribution of patents by U.S. domiciled inventors. During the late nineteenth and early twentieth century British inventors patented disproportionately in mechanical-related areas, perhaps reflecting expertise in equipment used in British industry as revealed in an important study of the machine tools industry by Floud (1976). The relative dominance of patenting in German chemicals stands out across all the time periods and mechanical patents are another area of focus. France, like Britain, was heavily oriented towards mechanical patents prior to the First World War and even more so during the interwar years. Interestingly, the shape distribution of patents granted to British inventors is not dissimilar to that of patents granted to U.S. inventors over time. In recent years much has been written about the significance of information and communications technologies and the productivity benefits stemming from its interaction with organizational capital. From 1974 to 2004 approximately 10 percent of patents granted to inventors from the United States, Britain and France were in ICT.

But it is well-know that patents vary significantly by their quality and therefore insights based on raw patent counts, or their industry distribution, can be misleading. Even if inventors patented their best technologies in the United States, it is still possible that the quality of the inventions in the data in Figures 2 and 3 varied. A solution to this problem is to use citations that patents receive in subsequent patents granted as a measure of their technological significance (Trajtenberg, 1990; Nicholas, 2005) and then compare patents by citation frequency across inventors from different countries. U.S. patent law requires that all prior art (i.e., the knowledge on which the invention builds) is disclosed and this has been systematically recorded on patent documents in the form of patent citations going back to 1947. This method can be used to determine how highly cited were the U.S. patents of British inventors relative to otherwise equivalent patents granted in the U.S. to inventors from other countries.

Table 1 reports estimates of patent citation regressions, which take the following form where *i* indexes an individual patent, *j* a inventor's county, *k* a technology category and *t* a year:

$$\log(1+\text{CITS})_i = \alpha_j \text{COUNTRY} + \beta_k \text{TECHNOLOGY} + \gamma_t \text{YEAR} + \varepsilon.$$

Given the skewed nature of citations, the dependent variable is the natural logarithm of a count of patent citations to each patent granted in year *t* in all patents granted in the United States between 1947 and 2008. One is added to the citation count to rescale zero values to facilitate the log-transformation. This variable is regressed on a set of country dummies, with Britain as a baseline category. Technology dummies based on the United States Patent Office classification scheme, as developed by Hall, Jaffe and Trajtenberg (2002), are included because citations may reflect industry or factor endowment driven biases in the distribution of patents or citations. Year dummies control for time effects because earlier patents receive more citations *ceteris paribus* than later patents. Regressions are run using data on inventors from all countries that patented 10,000 or more inventions in the United States between 1870 and 2004. The data consist of 1.74 million patents from inventors residing in 17 countries.

Because countries enter into the data over time, it makes the most sense to examine patent citations during four separate sub-periods: up to the First World War (1870-1918); the interwar years (1919-1945); the Second World War and post-war years (1946-1973); and the period associated with the end of Britain's relative economic decline (1974-2004). The regressions are run in semi-logarithmic form so the coefficients measure the percentage change ($exp[\alpha_j^{BR}]-1\times100$) in citations to patent *i* granted in the United States to an inventor in country *j* relative to citations to patents by British inventors who also patented there.

Results in Table 1 for the period between 1870 to 1918 show that patents by British inventors tended to be, in relative terms, of a lower average quality. On a patent citations basis, inventors from Britain underperformed inventors from most countries in Europe, although it is important to note that in absolute terms the number of patents granted to British inventors was also much higher (Figure 2). During the interwar years, however, the share of patents granted in the United States to German inventors increased significantly (Figure 2) and the average quality of these inventions was also higher. Furthermore, at this time, patents by French inventors had approximately 4 percent higher citations than patents by British inventors. During the "golden age" of European economic growth, citations to patents by British inventors still slightly lagged average citations to patents by German inventors, but note that British inventors outperformed inventors from 8 out of the 13 countries on a citations basis from 1946 to 1973. Between 1974 and 2004 British inventors outperformed inventors from 13 out of 16 countries, including Germany, with only patents to inventors from Canada, Israel and Japan receiving significantly higher citations.[1] While this evidence suggests that from the early 1970s Britain experienced a relative increase in the quality of innovation, it is also worth pointing out that this coincided with

[1] Intellectual spillovers tend to be localized geographically. Hence it would be expected that the inventions of Canadian inventors would be highly cited by patents granted in the United States. The citation premium to inventors from Israel and Japan, on the other hand, is less likely to be confounded by the effect of geography and more likely to be consistent with their technological superiority.

a drop in the relative share of inventions by British inventors patented in the United States (Figure 2). In other words, the data suggest that the quality, but not the quantity, of patents was improving.

C. R&D Investment and Human Capital

Patents are an outcome measure of innovation whereas R&D is an input measure that informs our understanding of the scale of the resources devoted to technological change. Historical statistics on R&D are limited, but the scant data that are available suggest that at the turn of the twentieth century Britain was spending about 0.03 percent of GDP on R&D (Edgerton, 1996, p.32) and over time this share increased significantly as the complexity and capital requirements for innovation increased. During the 1990s Britain was spending about 2 percent of GDP on R&D and the share currently stands at approximately 1.8 percent.

Yet, the history of R&D investment in Britain is typically a story of underinvestment, or underperformance (or both) relative to international standards. Figure 4 shows that during the 1930s R&D output was less than half the level in the United States and a large gap between the two countries persists for all of the snapshot years, whether using net output or value added as denominators. While Britain looks better when using Germany as a benchmark, it seems reasonable to assume that Germany was far more productive per unit of R&D input, especially between 1945 and 1970 when the output from Britain's research effort was relatively weak (Horrocks, 1999). Data on research employment in Figure 5 show Britain in a more favorable light to Germany and the United States. But while the level and the quality of British human capital in R&D has always been high, firms have traditionally been weak at translating this knowledge into productivity performance (Nickell and Van Reenen, 2001).

It is clear from the statistics, and the historical evidence more generally, that over the long run competing countries had a much stronger tradition of productive R&D than did Britain. In Germany the exemplar case is knowledge and complementary capabilities in the chemicals industry (Murmann, 2003). Firms such as Badische Anilinund-Soda-Fabrik (BASF) and Bayer devoted large capital resources to R&D and to incentive mechanisms so that scientists developed the most appropriate types of new technical knowledge (Burhop and Lübbers, 2009). In the United States interactions between technology and organization led to the institutionalization of R&D (Mowery and Rosenberg, 1989). During the interwar period, Britain lagged even further behind Germany and the United States, as both countries heavily invested in industrial development. In the United States in-house R&D developed extensively as firms like General Electric, Eastman Kodak and Du Pont took basic and applied science seriously, leading to numerous breakthrough innovations such as electrical appliances, motion picture cameras and products like neoprene (Mowery and Rosenberg, 1989).

Although during the post-Second World War period, aggregate statistics suggest that Britain was devoting a large share of GDP to R&D this was unobservable in the growth statistics. One explanation would be scale effects, whereby higher levels of aggregate R&D investment in countries like the United States had a larger impact because externalities, which magnify the impact of innovation, grow with the size of the economy. Jones (1995), however, rejects the hypothesis of scale effects given that the number of scientists and engineers engaged in R&D in OECD countries increased substantially from the 1950s without a simultaneous boost to economic growth rates. Moreover, since the 1970s it is reasonable to assume that the effect of scale would not have shifted dramatically in Britain relative to other competing nations and yet British R&D has been particularly productive (Crafts, 2012). This implies factors other than scale may have been more influential determinants of British R&D performance.

3. Patent Laws, and Incentives

A. Patents

Among all the explanations for Britain's lackluster performance in the technical sphere patent laws should, on the face of it, be a good candidate. It is well-established that the institutional environment in which inventors and firms operate can powerfully influence both the rate and direction of technological change (Lerner and Stern, 2012). Patents provide a short run monopoly over the right to use an invention in order to compensate inventors for the expense incurred to develop the invention. Publication of the idea and codification of the underlying knowledge in a patent document is meant to encourage the diffusion of new ideas across inventors. British patent laws have traditionally been criticized for being expensive and cumbersome. In 1875 it was 19 times more expensive to hold a patent to full term in Britain than it was in the United States (Lerner, 2000).

According to one dominant theme in the literature, innovation in the United States flourished during the process of industrialization because patent laws provided cheap democratic access to intellectual property rights, whereas in Britain the high cost of obtaining a patent may have curtailed technological progress (Khan, 2005). On one level this argument is compelling because inventors in the United States were both able to access cheap patents and interact with intermediaries who created a market for ideas (Lamoreaux and Sokoloff, 1999, 2002). A challenge to the importance of patent laws in this account is that across countries the historical evidence shows changes in patent laws do not predict changes in innovation. Using data on patent reforms for 60 nations from 1850 to 1999, Lerner (2009) even finds a negative effect of reforms on subsequent patenting. He concludes that "the impact of strengthened patent protection may simply be far less on innovative activities than much of the economics and policy literature assumes" (p. 348).

More detailed evidence from a major patent reform in Britain also questions the significance of patent laws as a lever for innovation (Nicholas, 2011). The 1883 Patents Act represents one of the most significant reforms in patent law history as filing fees were reduced by 84 percent. The Act was passed against a long debate in European countries over the use of patents and whether knowledge should even be patentable (Machlup and Penrose, 1950), and in the late nineteenth century inventors in Britain protested that most governments in Europe and certainly the United States charged far less for patent protection. The most significant change associated with 1883 Patents Act was the substantial reduction in fees, although other administrative changes were also made such as the use of examiners to facilitate the patenting process. At the same time, Britain also ratified the Paris Convention for the Protection of Industrial Property, thereby providing full patent rights to foreign inventors from the signatory countries.

Despite the significance of the 1883 reform there is little evidence that it led to a shift in innovation. Although the number of patents granted increased by a factor of 2.5, there was not a step jump in the quality of technological development. In fact, while the propensity to patent increased as inventive activity migrated from outside to inside the patent system, the inventions that were patented were more likely to be those in the lower end of the patent value distribution. Moreover, for an event window around the 1883 reform, citations to patents by British inventors patenting in the United States did not increase after the reform relative to before. This suggests a limited role for British patent laws in inducing innovation.

After the 1883 Patents Act, British patent law grappled with the issue of how to balance the tradeoff between providing inventors with temporary monopolies and the public desire to limit the deadweight loss arising from inventors earning supernormal returns. In their influential assessment of the patent system, Boehm and Silberston (1967) argued that the balance was only partially resolved. They recommended replacing the fixed patent term (16 years when they were writing) with a flexible term based on patent extension principles, and they also suggested changing the scope of patent rights to take account of the relative merits of different inventions. These types of ideas form the basis of a large literature on the economics of patents, but they have not been implemented in policy, a problem that is often compounded by patent office mismanagement (Jaffe and Lerner, 2004). Furthermore, while patents have typically done a good job of protecting the rights of inventors (or at least those who are willing to defend their rights in the courts), they have done much less to achieve their second goal of diffusing knowledge across innovators. In the absence of strong incentives to share knowledge in a context where technology diffusion is a critical driver of economic growth, it is perhaps no surprise that patent laws have been largely indeterminate of the rate of technological change.

B. Prizes

Patents are a dominant mechanism for incentivizing inventors, but it is important to note that throughout British history alternative mechanisms have also been used. Science has long had a prominent place in British culture and the economy going back to the archetypal institutions that promoted learning during industrialization. By 1850 there were 1,020 scientific societies or associations in Britain with approximately 200,000 members (Mokyr, 2002, pp. 43-45, 66) and these helped to create an "enlightened economy" that was conducive to rapid technological progress. These institutions encouraged spillovers of technological knowledge in an environment where technical and practical knowledge was not only highly valued but also enthusiastically disseminated (Mokyr, 2010). To this end, scientific societies also used prizes in order to spur innovation where inventors could also protect their inventions using patents.

The basic theory behind prizes is long-standing. Polanvyi (1943) suggests that "[i]n order that inventions may be used freely by all, we must relieve inventors of the necessity of earning their rewards commercially and must grant them instead the right to be rewarded from the public purse." In a more recent theoretical contribution, Kremer's (1998) government funded patent-buyout mechanism establishes a price for the invention using a sealed bid auction, where the bidders have some small probability of winning the right to use the invention. If a bidder wins then the inventor receives a "prize" payment equivalent to the bid price plus some markup to reflect the social value of the invention. Otherwise the government pays the same amount to the inventor and it then owns the invention and places it in the public domain. The attractive property of the mechanism is that it avoids the deadweight loss associated with patents, but it does not need to replace the patent system altogether. Rather, it can be used to provide prize-based incentives in areas that have a particular appeal from the perspective of welfare. This type of intuition was behind the famous 1714 prize offered by the British government for an instrument measuring longitude (Sobel, 1996). It also applied in the acquisition of the Daguerreotype photography patent by the French government from Louis Jacques Mande Daguerre, and his partner. With public ownership of the patent, and therefore the underlying knowledge behind the invention, Daguerreotype photography diffused rapidly (Kremer, 1998).

The fact that prizes have worked to simulate invention is evident from a study by Brunt, Lerner and Nicholas (2010), which examines almost a century of data on prize competitions held annually by the Royal Agricultural Society of England (RASE). The RASE used medals and monetary prizes to spur technological development, sometimes in areas where British inventors lagged behind foreign competition, such as harvesting technology. Prizes were offered and awarded in these areas to promote innovation and medals in particular were effective at increasing the number of entrants into competition and both the number and the quality of patents. Furthermore, this boost to innovation did not come from substitution effects arising from inventors reallocating from non-prize areas to prizes areas. Instead, the overall level of aggregate innovation increased. This evidence shows the utility of British institutions of science in establishing pioneering mechanisms for promoting innovation. Of course, technology must interact with organization to create productivity improvements, and it is in the management and commercialization of new ideas that the British economy has been historically lacking.

4. The Organization of Invention and Managing R&D

A. Independent Inventors

The tension between Britain’s capacity for developing new ideas, but its relative inability to implement them successfully is evident from the careers of pivotal independent inventors. An often overlooked fact, given the large literature on the rise of the corporation, is that a significant share of innovative activity in Britain, and indeed other countries, during the late nineteenth and early twentieth century occurred outside the boundaries of firms. By 1930, approximately half of all patents in Britain, the United States and Japan were granted to independent inventors. Moreover, the average quality of these inventions was high (Nicholas, 2011).

Macleod's (2008) analysis of British culture from 1750 to 1914 shows that independents had a particularly prominent profile in cultural discourse going back to individuals like the steam engine pioneer, James Watt (1736-1819), who were celebrated for their creativity. Although their popularity in society diminished after the First World War, there is every bit as much evidence to suggest that they still mattered economically. In their extensive study of independents entitled *The Sources of Invention*, Jewkes, Sawers and Stillerman's (1958) conclude:

> The evidence of the continued survival of the individual inventor is simply that many men who have lived this century – numbers of whom are still, or were until recently, alive – fall into this category and by their genius have added enormously to the stock of useful ideas and to standards of living. (p.84)

In order to explain why these types of inventors developed such path-breaking innovations that changed everyday life, Jewkes, Sawers and Stillerman contend that "if invention ever became the prerogative of full-time professional employees, there are grounds for believing that it would be weakened in range, liveliness and fertility" (p.96). The purview of independent inventors was the pursuit of the unorthodox and the search for new ideas derived from original thinking. They could be more creative by being liberated from tradition, the boundaries of what was already known, or from what Joseph Schumpeter (1950) described as "routinization".

Jewkes, Sawers and Stillerman's assessment is based on the role of individuals such as Sidney G. Brown (1873-1948) who acquired 235 patents in his lifetime for inventions in the area of electrical engineering, the first of which he filed in 1899. Brown's career was typical of many independents in that he was motivated by the psychic rewards from discovery and only then by commercialization. Despite starting up a firm to facilitate commercialization of his inventions, expensive patent litigation meant that he made virtually no money from his most celebrated invention – the gyro-compass, a navigational device for determining geographical direction. Frederick W. Lanchester (1868-1946) was granted almost twice as many patents as Brown, and became a pioneer in aerodynamics and automotive engineering. Yet, although he acted as a consultant to B.S.A. motors and Daimler, his financial payoffs from invention were limited.

In many instances independents could neither commercialize themselves nor sell on their inventions to third parties and this has long been considered to be an inherently British problem. New technologies, by their very nature, are disruptive and are subject to commercial uncertainty, which may lead to technology trade working imperfectly (Arora and Gambardella, 2010). A well-known case is Frank J. Whittle (1907-96) who applied to the British patent office for protection on a turbo-jet engine in 1930, an invention which became one of the most significant discoveries of the twentieth century (Whittle, 1945). But when Whittle notified officials at the British Air Ministry of his idea and patent they rejected it as being infeasible and so did several private corporate entities. Eleven years later a prototype aircraft using a Whittle-style engine produced 800 pounds of thrust, reached 466 miles per hour and an elevation of 42,000 feet, far beyond anything that had been achieved prior to this point in time. Because of technology uncertainty and poor commercialization, the jet aircraft age was delayed.

On the other hand, payoffs could be achieved, both for inventors and society, by interactions between independents as sources of new ideas and firms that were in a position to commercialize. In the United States firms monitored the market for technology and there is strong evidence to suggest that this led to a division of labor in invention as firms selected complementary inventions from independents operating outside their formal R&D environments (Nicholas, 2009). There is also some evidence of this type of exchange in Britain, in contrast to the market failures mentioned above. For example, Cadbury, the confectionary manufacturer maintained a register of outside inventions. More generally, there was scope for the coexistence of independents and firms because they generally focused on different fields of technological development. That complementarity, plus the presence of intermediaries who could facilitate the sale of patents, meant that independents could play a crucially important role in the process of technological change even as the corporate economy developed (Nicholas, 2011).

B. Industrial Research and Management Practices

As technological progress depended on larger capital requirements, R&D inside the boundaries of firms became more important over time. The first corporate research laboratory is conventionally traced to 1868 when BASF opened a facility in Ludwigshafen, Germany. This lab was most prominently directed by Heinrich Caro, a leading chemist who synthesized the first indigo dye. Despite being a disorganized, idiosyncratic figure with a reputation for being a difficult collaborator, the in-house facility that Caro directed became a focal point of technological development in the German synthetic dyestuffs industry. Caro's path breaking innovations acted as a catalyst to the industrialization of chemistry. By hiring academically trained chemists and through links with noted professors in the field such as August Wilhelm

Hofmann from the University of Berlin and Adolf von Baeyer who won the Nobel Prize for chemistry in 1905, BASF created an auspicious foundation for the commercialization of basic scientific discoveries that became widely replicated in the industry (Murmann, 2003).

Mowery and Rosenberg (1989, pp.38-39) date the origins of industrial research in the U.S. to an 1863 facility in Wyandotte, Michigan that investigated the chemistry of Bessemer steel making, while prominent examples of corporate labs include those founded by Thomas Edison in Menlo Park, and Alexander Graham Bell in Boston, both in 1876. However, it was not until the early twentieth century that in-house R&D facilities assumed a prominence seen in the German dyestuffs industry. By the early 1900s the corporate sector had developed on such a scale that vertical integration and managerial hierarchies were necessary for the efficient functioning of American business (Chandler, 1990). Innovation was brought increasingly within enterprises because the market was no longer able to organize transactions to achieve efficient outcomes. By 1920 the National Research Council had noted a widespread demand for information on in-house research, and it conducted regular surveys of industrial establishments. Data from these surveys show that the number of scientists and engineers employed in industrial research laboratories grew at a rapid rate. Numbers more than doubled between 1921 and 1927 from 2,775 per 1,000 production workers to 6,274 (Mowery and Rosenberg, 1998, pp.21-22).

In an important study, Edgerton and Horrocks (1994) document the early history of R&D in Britain. They maintain that British firms invested quite heavily in in-house R&D, especially in the chemicals industry. Networks of technical experts facilitated spillovers of technological knowledge which were also promoted by inter-firm linkages. An early contributor to the British R&D effort was United Alkali which had centralized R&D as early as 1892. Firms like ICI (formed in 1926 as a merger of United Alkali and three other chemicals companies), GEC and Metropolitan-Vickers were R&D pioneers, a point noted in Hannah's (1976) work on the rise of the corporate economy. Edgerton and Horrocks' revisionist evidence represents a counter to Mowery's (1986) traditional argument that British R&D was weak and Chandler's (1990) implicit assertions that British firms also failed to generate large returns from R&D because they underinvested in the complementary capabilities of production, distribution and management.

In line with the revisionist view, there is anecdotal evidence to show that British R&D could be innovative and well-managed. Barker's (1977) study shows how Pilkington developed the Float Process after extensive R&D over a decade, which was facilitated by family ownership and control of the company and a commitment by the company to harnessing applied science and technology. Another prominent example of British success is the pharmaceuticals and biologics industry, where Glaxo-Wellcome, Smithkline-Beecham (these two companies merged in 2000 to form GlaxoSmithKline) and AstraZeneca have created a portfolio of some of the world's best known drug innovations such as Tagamet, Zantac and Nexium for the treatment of gastrointestinal problems. Equally there is anecdotal evidence of British R&D failure. Notably the British inventor Geoffrey Hounsfield, a scientist employed at the Central Research Laboratories of EMI, developed the profoundly significant CT Scanner, but EMI did not have the managerial capabilities to keep pace with demand. During the 1970s and 1980s it lost out to organizationally efficient U.S. companies like Technicare and General Electric.

Beyond individual case studies, Broadberry and Crafts (1992) argue that a critical set of drivers of firm performance are related to industry structure and the operating environment more generally, and these in turn influence incentives and management capabilities. For example, the British regulatory environment during the interwar years tolerated collusion between firms and provided subsidies for incumbents, so competition was absent as a disciplinary device in product markets. Furthermore, labor unions created an unproductive bargaining situation and constrained the reallocation of resources from poorly to better performing firms, which had a strongly depressing effect on productivity. It is well-known that if managers of incumbent firms do not face the threat of replacement then their preferences can tend towards the Hicksian "quiet life". On the other hand, competition can encourage innovation especially if firms are already close to the technological frontier. In this case, firms have more incentives to invest in R&D to capture the incremental profits deriving from innovating (Bloom et. al., 2005).

The notion that such factors were influential in Britain's more recent innovation performance is evidenced by the uptick in productivity as a consequence of more favorable competitive dynamics in British business. Deregulation, the liberalization of capital markets, better industrial relations standards and the strengthening of legislation with respect to product market competition all had positive effects (Crafts, 2012). At the same time, it is worth noting British weaknesses in the management and diffusion of technology still persist. Insofar as the main determinants of rapid TFP advance are the diffusion of innovations and the effectiveness of factors that affect the efficiency with which new technologies are used (Comin and Hobijn, 2010), the evidence suggests a large gap exists between Britain and the United States. Bloom and

Van Reenen (2007) find that competition in recent years is still relatively milder in Britain than in the United States and when combined with the preponderance of British family firms, this has led to a prominent and persistent tail of badly managed medium-sized firms. Among larger firms, Bloom, Sadun and Van Reenen (2011) find that U.S. multinationals operating in Europe were far more able to benefit from technology diffusion as manifested in the implementation of ICT advances compared to otherwise equivalent European firms. Weaker diffusion and inept management practice capabilities help to explain performance defects, although in a Europe-wide context, these are not uniquely British problems.

5. Efforts to Promote Science and Agglomeration

A. Science and Scientific Education

Another important set of influences on the determination of technological progress are public policy towards the promotion of basic science and education in technical capabilities. Scientific knowledge changed radically over time from the science of elementary mechanics during the Industrial Revolution to breakthroughs like complex polymer science that set the foundations for the Second Industrial Revolution. From electricity generation to nuclear power the growth of knowledge has been a defining characteristic of the modern world (David, 1990; Mokyr, 2002). Scientific and technical breakthroughs are critical inputs on the supply side. Where a fundamental connection exists between science and the growth of technology and invention, these inputs can be powerful drivers of the rate of economic development.

It has often been argued that Britain fostered high social status education institutions that were inimical to technological progress, with the traditional "cultural critique" suggesting that Britain did a good job of training gentlemen and not "practical men" (Wiener, 1981). By contrast, technical education was prioritized under the French education system as exemplified by the École Polytechnique in Paris, one of the most significant technical schools. It was also said to have been a priority in Germany where the integration of science and practice led to a productive type of knowledge. Summarizing this literature on Britain's education shortcomings, Edgerton (1996, p.19) quips "[s]cience is red-brick, not Oxbridge; it is Manchester not London; it is Harold Wilson and not Harold Macmillan; it is, furthermore, politically radical rather than conservative". With respect to science, Britain has always been culturally antithetical.

The alleged weaknesses of British education has been challenged by Sanderson (1988) who shows that scientific and technical instruction improved radically in Britain during the late nineteenth century, even at the high-prestige institutions. At Oxford and Cambridge, the number of students graduating annually in science and technical fields increased by more than one third between 1900 and 1914 (Edgerton, 1996, p.20). Moreover, the London and civic universities had never subordinated technical and scientific instruction to the classics. And, Berghoff and Möller's (1994) analysis prominently indicates that despite the alleged bias of the German education system to practice, the majority of German businessmen between 1870 and 1914 had actually received a classical education at a prestigious *Gymnasium*.

The data indicate a significant expansion over time in scientific education in Britain with noticeable growth after the Second World War. By the late 1920s, 30 percent of university students in Britain received a scientific or technical education rising to 52 percent during the late 1960s (Edgerton, 1996, p.22). The richness and importance of the science base has led to major breakthroughs. The 1953 DNA discovery by Francis Crick and James Watson at the Cavendish Laboratory at Cambridge University laid the foundation for the development of the bio-technology industry and furthermore there is general evidence of a disproportionately positive British influence on science. By the late twentieth century Britain produced 8 percent of the world's scientific research papers, yet it accounted for only about 1 percent of the world's population (Nickell and Van Reenen, 2001).

Britain's capabilities in science are evidenced in the developments associated with the Second World War and its geopolitical aftermath. Given that up to at least the 1960s approximately a quarter of R&D investment came from government-financed defense expenditure, the Cold War played an important role in the development of the British science base. Aviation, electronics and nuclear capabilities all received heavy levels of investment. In 1954 the Atomic Energy Authority was established with a view to managing the R&D process and creating collaborations and spillovers into private industry. And as Agar (2003, p. 352) points out "[w]ithout the Second World War the history of computing would have been radically different". The need to process and decipher large amounts of data for reasons of national security, led to an extensive research program. This culminated in the first programmable computer – "Collosus" – built at the Post Office Research Laboratory in North London, which was then used for code breaking at Bletchley Park.

Because Collosus was destroyed after the war, and the tacit knowledge cloaked in secrecy, it was not until the 1950s that Britain developed a computer mainframe industry. Hendry (1990) describes the formation of the National Research Development Corporation in 1949 as an institutional mechanism for government funded support of R&D efforts and a number of new computer manufacturers emerged such as International Computers and Tabulators, which later became ICL. But as the industry migrated to personal computers, Britain's main computer manufacturers – Acorn, Amstrad and Sinclair – enjoyed a limited period of success. And on the mainframe side the industry was soon surpassed by American manufacturers, specifically IBM. Furthermore, a new wave of semiconductor and micro-processing startups in Silicon Valley captured market share on the component manufacturing side. Britain's inability to compete in this area was an entrepreneurial problem that reflected a weakness at the intersection of science and technology. It was also caused by a lack of competition and new entry and the absence of creative destruction that was so dominant a force in the U.S. computer industry.

B. Clusters

Policy makers frequently cite Silicon Valley or clusters in Germany as optimal ecosystems for generating sustainable competitive advantage. Clusters have institutions and culture, industrial structure and corporate organizations that promote innovation and economic development (Saxanian, 1996). The idea that agglomeration creates positive externalities is a fundamental proposition in urban economics (Porter, 1990; Krugman, 1991), and the idea goes back to Alfred Marshall's famous quote in the *Principles of Economics*:

> The mysteries of the trade become no mysteries; but are as it were in the air, and children learn many of them unconsciously. Good work is rightly appreciated, inventions and improvements in machinery, in processes and the general organization of the business have their merits promptly discussed: if one man starts a new idea, it is taken up by others and combined with suggestions of their own; and thus it becomes the source of further new ideas (1890), p.271.

Marshall's insights have formed the basis of a large literature. Industry clustering it is commonly observed and yet it typically cannot be explained by exogenously determined natural advantages like resource endowments that would also lead to a close proximity between firms. In addition to the "mysteries of the trade" argument, which is essentially about social interactions spurring innovation spillovers, Marshall also recognized that clusters could be driven by a desire to save on transport costs between input suppliers and manufacturers or by firms and workers wanting to benefit from a pooled labor market.

Historical evidence provides a link between clusters and technology. Knowledge flows through informal contacts play a role in Allen's (1983) account of collective invention in the Cleveland blast furnace industry during industrialization where producers established the best height for the furnace through a process of information exchange. These mechanisms operated in steam technology according to Nuvolari's (2004) account of Cornish mining. Leunig's (2003) work shows that Lancashire cotton manufacturers were heavily clustered. In Blackburn, the average spinning mill had 7 weaving mills within 300 yards, and 28 within half a mile. Leunig contends that prior to 1914 Lancashire had high levels of human capital based on learning by doing, and world leading productivity. This contrasts with the traditional story of British backwardness and highlights how firms could efficiently operate in a vertically specialized setting characterized by the kind of strong external economies envisaged by Marshall.

The location of inventive activity informs our understanding about regional comparative advantage. Using patent data Cantwell and Spadavecchia (2011) investigate the regional concentration of inventive activity during the interwar years based on the locations of British inventors who patented over 8,000 inventions in the United States. They find a dominant spatial role for the South East, especially Greater London, which alone accounted for over 40 percent of all patents with the next largest regions in terms of patenting – the North West and the West Midlands falling some way behind. But while the London area has been an important center of inventive activity, it is not clear that innovation has been caused by cluster-based advantages. In fact, using an extensive 1996 survey of London businesses and examining inter-firm linkages and the geography of innovation, Gordon and McCann (2005) find "that the importance of specifically local informal information spillovers for successful innovation is very much more limited than has been suggested."

The absence of strong and sustainable agglomeration effects on a scale witnessed in Silicon Valley or in the industrial clusters in Germany can be illustrated with reference to Britain's best known cluster of Cambridge technology firms, or "Silicon Fen". Drawing on a strong university science base in scientific instruments, ICT and biotechnology, the number of firms there increased from 50 during the mid-1960s to more than 1,200 firms that employed 36,000 workers by the year 2000 (Garnsey and Heffernan, 2005). At the height of the ICT boom during the late 1990s, high tech firms in Cambridge had a combined turnover in excess of £3.5 billion, with a large number of acquisitions fuelling investment in entrepreneurship and new technology formation. Cambridge benefitted from government policy initiatives such as the 1998 University Challenge Fund, which established seed funding for turning scientific knowledge into commercial innovations. However, Drofiak and Garnsey (2009) show that the recent performance of the Cambridge cluster is less favorable, as fewer enterprises have received venture funding and firm survival rates have shortened. More generally, agglomeration effects may be more limited under policies designed to generate new innovation clusters in places characterized by old declining industries, especially if there is a mismatch between labor market pools. Relative to Silicon Valley, Britain has not created global innovation giants through cluster initiatives (perhaps with the exception of Silicon Fen's ARM Holdings a leader in mobile phone chip technology), which casts doubt on the long run success of British efforts designed to induce positive agglomeration externalities.

6. Conclusion

This chapter has surveyed the literature on technological development in Britain over the last 140 years in an effort to highlight major trends in the data and main patterns of causation. Technology is central to the growth process, and therefore the history of innovation should provide insights into why Britain lost its nineteenth century position as the dominant industrial nation and why Britain's decline up to the early 1970s was so relentless. To the extent that innovation and the diffusion of useful knowledge are main drivers of economic growth (Romer, 1990; Mokyr, 2002), an underlying hypothesis throughout this chapter has been that Britain's problem was fundamentally related to deficiencies in technology.

To be clear, Britain has not failed when considering the function of invention. Rather, Britain has a long tradition of excellence in invention and in basic science. The pioneer inventors during the era of industrialization were followed by path-breaking contributions to technological progress by both independent inventors and by corporations that pushed out the frontier of technological progress. The gyro-compass, jet engine, and the float glass process all stand out as examples of British success. Lancashire was a preeminent source of technological knowledge in cotton textile machinery, and the diffusion of this knowledge facilitated the growth of competing industries in the United States and Japan (Jeremy, 1981; Singleton, 1997). British academics discovered DNA, invented the CT Scanner and Tim Berners-Lee, a British computer scientist, is credited with the idea for the World Wide Web.

Furthermore, institutional mechanisms to support invention have flourished in Britain. Although the country's patent laws have been criticized because they were expensive and awkward to administer, this may not have represented a major drag on innovation, as historical evidence suggests that British (and indeed American) inventors did not frequently use patents to protect their intellectual property rights (Moser, 2005). Moreover, when patents did become cheaper – as indicated by the large drop in fees following the 1883 Patents Act – the propensity to patent increased, but very little else changed (Nicholas, 2011). Outside the patent system, British scientific societies contributed to the diffusion of knowledge during industrialization and they were frequently pioneers in using alternative or complementary mechanisms to incentivize inventors. From the early nineteenth century, the Royal Agricultural Society of England used inducement prizes to promote technological progress, and such exemplar historical cases are particularly relevant as policy makers in recent years have focused attention on the optimal design of public policies to promote innovation (Brunt, Lerner and Nicholas, 2012).

Despite these areas in which Britain displayed competence and distinctiveness, the management of technology has typically been weak. Organizational economists have long argued that a strong complementarity exists between technology, management practices and the demand for skilled labor, which creates a much more complex nexus through which invention contributes to productivity growth. Moreover, the economic environment in which firms operate is also central, including competition in product markets and the ecosystem to support R&D and a capacity to harness inventions developed domestically or diffused from abroad. In all areas Britain has failed to match the standards existing in the United States. Since the early 1970s constraints on growth, such as regulations that previously undermined competition and prevented reallocation to more efficient firms, have been progressively removed and there is strong evidence to suggest that the quality of innovation has improved, especially relative to other European countries. But, while the relentless phase of Britain's relative economic decline is now an artifact of the past, creating a foundation where technology continues to be an impetus to the acceleration in productivity growth is still a pressing issue of the present and the future.

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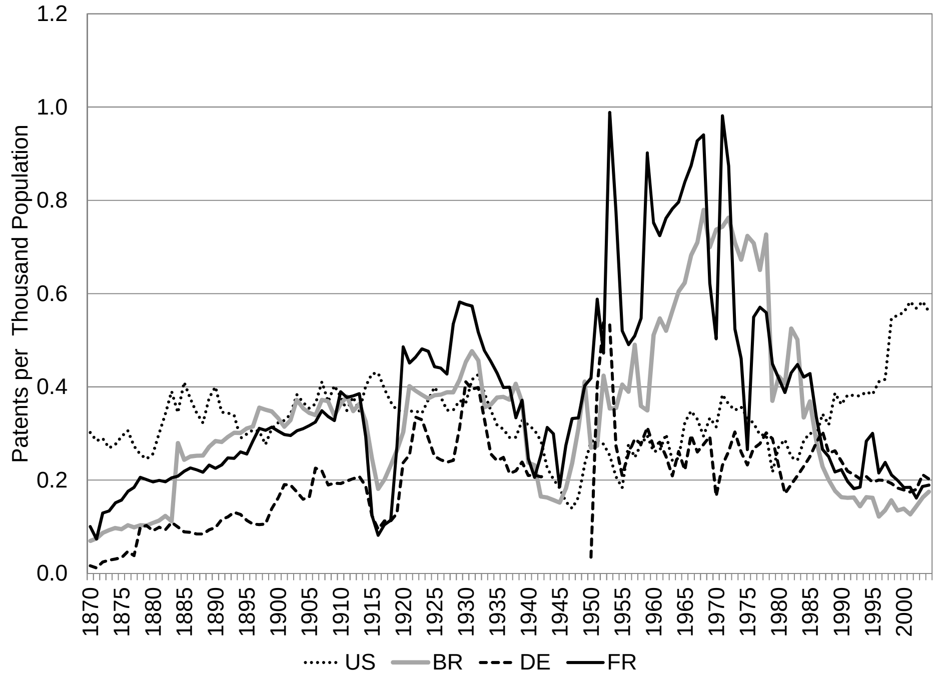
Table 1. Estimates of Historical Patent Citations
to Patents Granted to Foreign Inventors in the United States

	1870-1918	1919-1945	1946-1973	1974-2004
	Base Category is British Patents			
Austria	**0.041**	**0.023**	**-0.019**	**-0.221**
Austrailia	**-0.006**	**0.027**	**0.063**	-0.001
Belgium	0.003	**-0.075**	**-0.049**	**-0.060**
Canada	**-0.043**	**-0.040**	**0.054**	**0.117**
Switzerland	**0.023**	**0.008**	**-0.013**	**-0.114**
Germany	**0.024**	**0.030**	**0.010**	**-0.125**
Denmark	**0.035**	**-0.016**	0.002	**-0.082**
Finland	**0.103**	**-0.038**	**-0.040**	**-0.056**
France	**0.039**	**0.042**	**-0.007**	**-0.129**
Israel				**0.188**
Italy	**-0.013**	**-0.008**	**-0.057**	**-0.191**
Japan	**0.026**	**-0.038**	**0.059**	**0.054**
Korea (South)				**-0.081**
Netherlands	**-0.031**	**0.025**	**-0.048**	**-0.110**
Sweden		**0.030**	**-0.009**	**-0.082**
Taiwan				**-0.017**

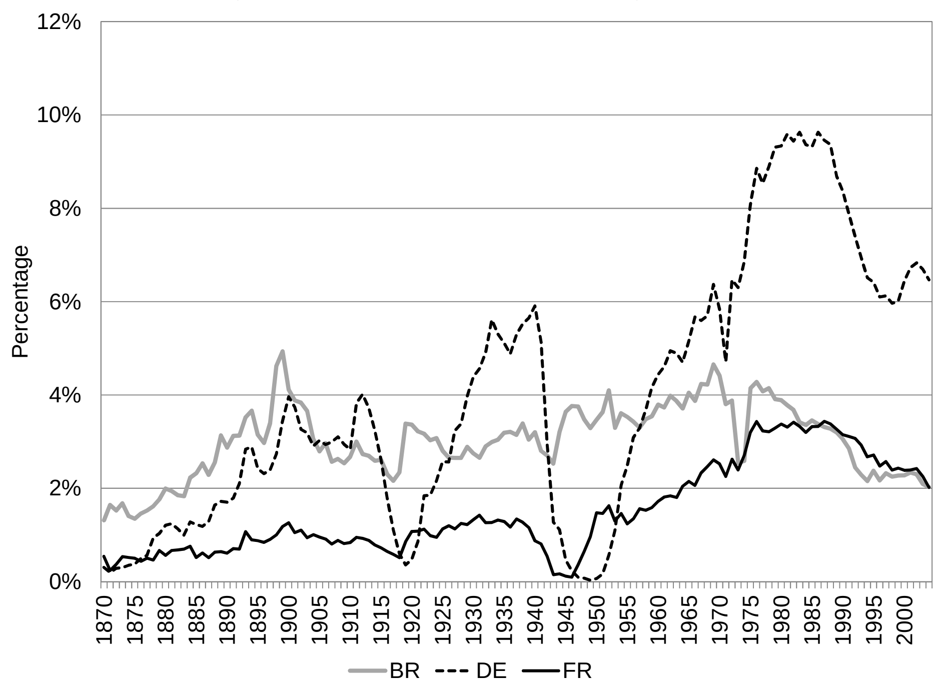
Notes: Coefficients are from historical patent citation regressions described in the text. Coefficients in bold are statistically significant at the 5 percent level and measure the percentage change i.e. [exp(α)-1×100] in citations for patents to inventors from each country relative to the baseline category of citations to patents by British inventors. Citations counts are derived from patents granted in the United States from 1947 to 2008.

Figure 1. Patents Scaled by Population, 1870-2004



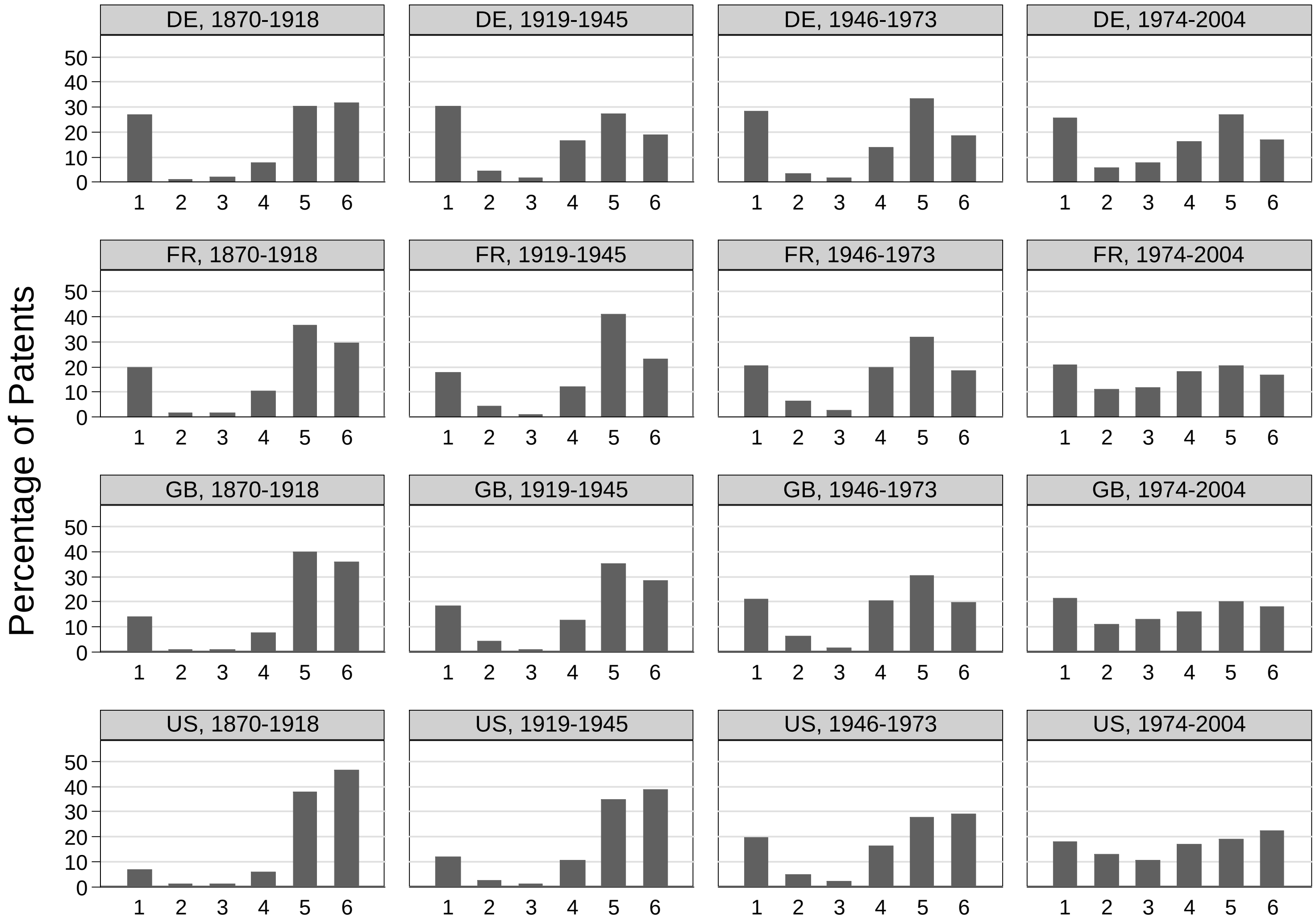
Notes: British and US patent data are from official statistics of each country's Patent Office. German and French data provided courtesy of Diebolt and Pellier (2010). Population data are from Maddison (2009).

Figure 2. Percentage of United States Patents Granted to British, German and French Inventors, 1870-2004



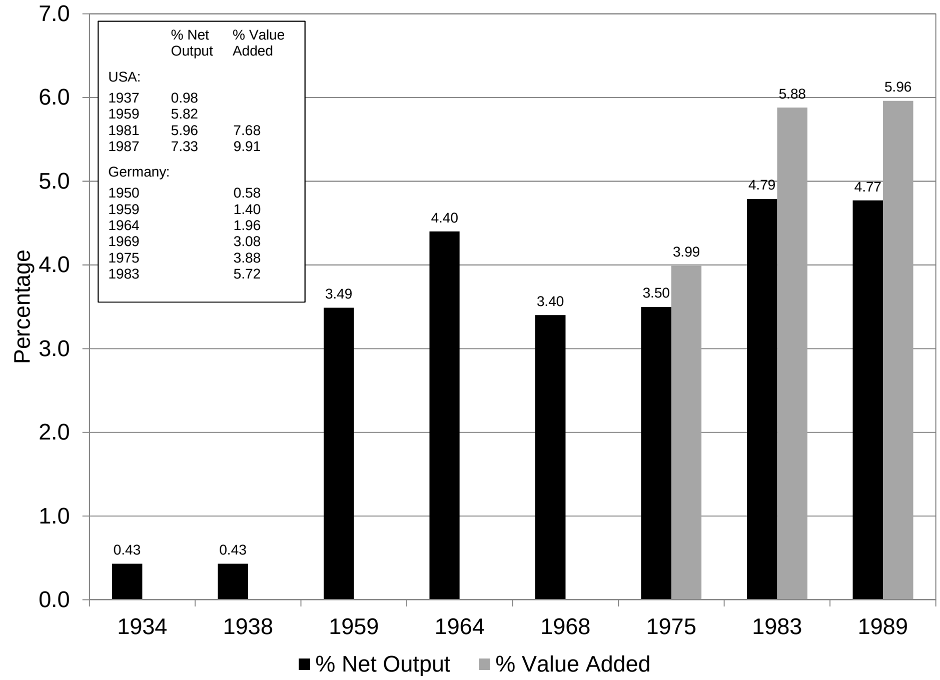
Notes: Data compiled by recording patent addresses of all patents granted in the United States from 1870 to 2004 and tabulating those British, German and French inventors.

Figure 3. Technology Category Distribution of Patents Granted to Inventors Patenting in the United States



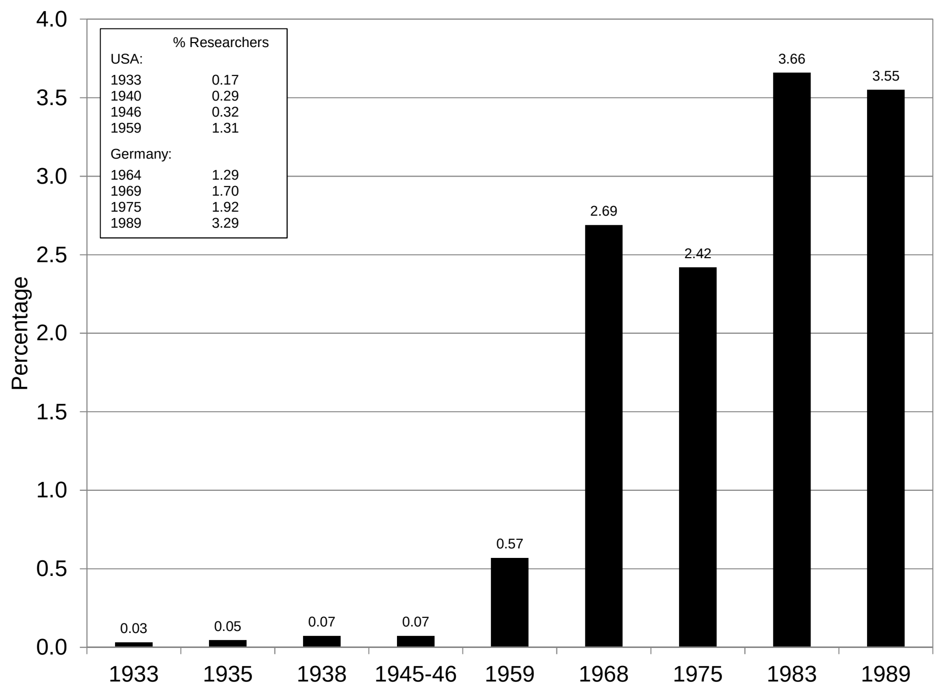
Notes: Data compiled by recording patent addresses of all patents granted in the United States from 1870 to 2004 and tabulating those British, German and French inventors. Patents were then categorized using the United States Patent Office scheme and then coded according to the categories used by Hall, Jaffe and Trajtenberg (2002). These are: 1=Chemicals; 2=Computers and Communications; 3=Drugs and Medical; 4=Electrical and Electronic; 5=Mechanical; 6=Miscellaneous.

Figure 4. Scaled R&D Expenditure in Manufacturing



Notes: Bars represent data for Britain and figures for comparison countries are given in the associated Table. Data are taken from Broadberry (2005), Table 8.14, p.122.

Figure 5. Scaled R&D Employment in Manufacturing



Notes: Percentage of manufacturing employment accounted for by "researchers". Bars represent data for Britain and figures for comparison countries are given in the associated Table. Data are taken from Broadberry (2005), Table 8.15, p.124.