Diffusing New Technology Without Dissipating Rents:

Some historical case studies of knowledge sharing

By

James Bessen
(Boston University School of Law)

Alessandro Nuvolari
(Sant'Anna School of Advanced Studies)

Preliminary version

ABSTRACT:

The diffusion of innovations is supposed to dissipate inventors' rents. Yet historical evidence documents many cases where inventors freely shared knowledge with rivals, including in steam engines, iron and steel production and textile machinery. In case studies examined here, each new technology coexisted with an alternative for one or more decades. This allowed inventors to earn high rents while sharing knowledge, making major productivity gains. In contrast, patents generated little value. The technology diffusion literature suggests that such circumstances might be common during the early stages of a technology. This has important implications for innovation policy.

Key words: technological change, technology diffusion, knowledge sharing, collective invention, patents

JEL codes: N70, O33, O34

I. Introduction

Economists have noted, with some surprise, that inventors sometimes freely exchange knowledge. Allen (1983) finds the sharing of knowledge of blast furnace technology "extremely puzzling." Von Hippel (1987) finds sharing of knowledge among steel mini-mills "novel." Lerner and Tirole (2002) find sharing of Open Source Software code "startling."

Knowledge sharing among inventors seems surprising because the uncompensated diffusion of technology—whether by imitation, "spillovers" or willful sharing—is supposed to dissipate innovators' rents. That is, standard theoretical models assume that diffusion allows rivals to drive down prices, reducing or completely eliminating the profits that the original innovator can make from the innovation. Willful sharing of technical knowledge — that is, facilitating free diffusion — would thus normally seem harmful to the innovator. While knowledge sharing can offer some benefits to innovators, especially with reciprocation, rent dissipation is typically assumed to outweigh any such benefits. Only, perhaps, in exceptional circumstances would knowledge sharing seem congruent with the pursuit of standard economic self-interest.

Yet an accumulating body of evidence (reviewed below) suggests that knowledge sharing between innovators is not at all exceptional. "Open Innovation" may be a recent management fad and Open Source Software may be a recent development, but innovators have shared knowledge of their inventions since the nineteenth century and before.[1] While episodes of knowledge sharing have been limited in time and geography, they have been responsible for major technological improvements in key technologies such as textile machinery, steam engines, iron and steel production. This is significant because it suggests that conventional notions about innovation incentives and diffusion might not be universally applicable. Critical features of the innovation landscape might appear under different conditions than those assumed in the standard models.

Using case studies of several nineteenth century episodes of knowledge sharing, this paper explores whether, in fact, free diffusion did dissipate rents during these episodes, and, if not, why. We find that during these episodes

- firms using new technologies continued to earn high profits for one or more decades despite knowledge sharing and diffusion,
- they also made dramatic productivity gains then, suggesting that innovation incentives remained strong and that knowledge sharing was important to technological advance,
- where inventors obtained patents, the patents generated relatively small rents, suggesting that market exclusion was not valuable then, and,
- the new technologies coexisted with alternative inferior technologies for extended periods of time, suggesting significant constraints on the implementation of the new technologies. A common constraint was the limited supply of people with the practical knowledge and skills to build, install, operate and maintain the new technologies.

---

[1] See Penin, 2007 and Powell and Giannella, 2010 for useful surveys. See Bessen and Nuvolari (2012) for a historical survey.

These findings allow us to identify some general conditions where free diffusion does not dissipate rents and where knowledge sharing is privately beneficial. These conditions might arise only at certain times, perhaps most significantly during the early stages of development of major new technologies. Indeed, the limited duration of these episodes suggests that diffusion might dissipate rents in the long term even in these cases. But, as we shall see, major productivity advances can occur before this happens and patents may be of little value then because they expire after limited terms. Thus these conditions have strong implications for innovation policy, economic growth and our understanding of the role of patents.

It is, of course, widely recognized that firms can protect their innovations against imitators without using patents. Trade secrecy, first mover advantages, and leverage from complementary goods and services might limit or slow diffusion (Levin et al. 1987). However, the puzzle posed by knowledge sharing raises a different issue, namely, that diffusion of knowledge itself does not necessarily dissipate the innovator's rents. That is, the historical episodes of knowledge sharing are not cases where innovators found ways to make their inventions excludable without patents; rather, excludability of the inventions was itself not particularly valuable to profiting from innovation.

Indeed, this distinction is important because there is a large empirical literature on technology diffusion that finds many cases where diffusion is slow even when appropriability is not an issue. Slow diffusion raises the possibility that early adopters might frequently earn rents even without substantial appropriability. Beginning with Griliches (1957), Salter (1960), Mansfield (1961) and Rogers (1962), researchers found that typically new technologies were only adopted gradually over a decade or two. Yet in many of these examples, the delay was not caused by restricted access to the innovation, which was available to all producers in the industry. The literature provides several explanations for the delays, including the nature of capital replacement (discussed further below), user heterogeneity, and user learning about the technology. Nevertheless, adoption took a long time and early adopters might well have had opportunities to earn substantial rents. Such rents might have made knowledge sharing advantageous in rather common circumstances.

More generally, the case studies highlight the diversity of conditions under which innovation occurs and, consequently, the need for analysis and policy that reflect specific conditions. Adaptable policy might be especially important during the highly critical early stages of new technologies, when major technological innovations are made. Such policy might involve more than patents and, perhaps, significant limitations on the use of patents.

A. Background

In order to analyze the case studies, we propose a general explanation for why knowledge exchange might be privately beneficial to innovators and why rents might not substantially dissipate during these episodes. We then compare observed behavior to the behavior predicted by our model.

Benefits

It is not hard to identify potential benefits that arise when innovators exchange knowledge. For example, some case studies below illustrate situations where different innovators have developed complementary improvements in different steps of a production process. Mutual exchange allows them to combine complementary innovations, improving productivity (see also Harhoff et al. 2003). Even the simple exchange of performance data can have benefits in identifying best practice. Other benefits include enhanced reputations of engineers and mechanics (Nuvolari 2004, Allen 1983, Lerner and Tirole 2002) or enhanced value of specialized assets (Allen 1983).

Mutual exchange of knowledge, as opposed to unilateral sharing, involves reciprocal knowledge flows. Often, unilateral knowledge sharing occurs only within a well-defined community of innovators, such as among the Bessemer patent licensees, where there might be a reasonable expectation of reciprocation. The distinction between unilateral sharing and mutual exchange might not be so sharp as is often supposed because frequently only a restricted community of innovators has the knowledge and skills to apply the knowledge being shared. In any case, our main focus here is on the other side of the cost-benefit calculation, namely, the dissipation of rents presumed to result from sharing information with rivals, with or without expectations of reciprocity.

Dissipation of rents

This dissipation of rents is typically assumed to be so harmful as to outweigh any benefits of sharing or mutual exchange. A standard assumption of almost the entire theoretical literature on innovation is that imitation dissipates rents, usually that imitation *completely* dissipates rents.[2] Thus Nordhaus (1969) assumes that an innovator earns zero rents after the patent expires. This is also a feature of the patent race models of Loury (1979), Lee and Wilde (1979) and the industrial structure investigation of Dasgupta and Stiglitz (1980). The assumption is that imitators add to industry output, driving down the equilibrium product price. In the worst case, imitators freely enter, driving the product price down until it equals marginal cost, eliminating all rents. Moreover, this argument applies not only to imitation, that is, to the intentional copying of technology, but also to other sorts of uncompensated diffusion, including inadvertent "spillovers" as well as intentional knowledge sharing.

The assumption that free diffusion dissipates rents seems highly plausible, but there is little actual evidence that this assertion is *universally* true, especially regarding the complete dissipation of rents. Certainly, there are many cases where diffusion does or could dissipate rents. But it is less obvious that this is generally true for all technologies at all stages of development.

Coexistence of new and old technologies

Indeed, the literature on technology diffusion and the replacement of obsolete equipment suggests that firms can earn rents even with freely available technology. Consider, for example, Salter's (1960) model of delay in the adoption of new techniques. Salter explored the lags in the adoption of blast furnace techniques and built a theoretical model to explain the phenomenon. In his model, producers using the new technology earn rents while other producers continue to use older, technologically inferior vintages. The market for pig iron is competitive so that the market price equals the marginal cost of production using the old technology.[3] Then producers using the new technology earn rents equal to the cost advantage of the new technology, that is, the difference between the marginal cost of production using the old and new technologies.

This model is at odds with the common assumption in the innovation literature of free entry with the new technology. If producers using the new technology could freely enter, they would drive producers using inferior technologies out of the market. Of course, this is what eventually happens, but the extensive empirical evidence of diffusion lags implies it can happen rather slowly. The

---

[2] An important exception is Boldrin and Levine (2008).

[3] Or, more precisely, since Salter considers multiple vintages at once, the market price equals the marginal cost of production of the oldest vintage still in use.

innovation literature often abstracts away from the coexistence of old and new technologies, assuming complete replacement instead.[4]

In Salter's model, the technology is embodied in capital equipment. Producers using old technology have sunk their investments in a particular capital vintage and will not switch to the new technology until they can earn enough profit to justify investment in new capital. In some models in this literature, this investment decision is shaded by expectations about the rate of technological improvement and the corresponding rate of technological obsolescence.[5] Economists have also realized that diffusion lags might involve investments in complementary assets in addition to investments in new capital goods, including investments in interrelated technologies (Frankel 1955), specific human capital (Chari and Hopenhayn, 1990), learning-by-doing (Parente, 1994; Jovanovic and Lach, 1989), and search (Jovanovic and MacDonald, 1994). Mokyr (1976) provides a "growing up" model of industrial development where a new technology sector coexists with an older technology, the pace of replacement determined by the rate of investment in new technology.

All of these models imply that the producers using new technology earn rents without restricting access to the technology. Under such conditions, knowledge sharing might be feasible. Braguinsky and Rose (2009) and Bessen (2011) develop specific models where knowledge sharing occurs when new and old technologies coexist. But we can identify some general conditions along these lines where diffusion would not substantially diminish innovators' rents, thus making knowledge sharing feasible:

1. A new technology coexists with an inferior substitute technology for some period of time. This coexistence might be temporary, perhaps lasting one or two decades.

2. In order to coexist, some constraint must limit the entry of producers using the new technology. Otherwise, in a competitive market, they would freely enter until the price fell so low that producers using the alternative technology would be driven from the market. What could impose such a constraint? One possibility is a limited supply of a critical input such as a specific iron ore for a new blast furnace technology (Allen 1983). Another, more general possibility arises when the knowledge needed to build, install, operate and maintain the new technology is in limited supply and cannot be easily replicated. Particularly during the early phases of a new technology, this technical knowledge and associated skills might be difficult to teach managers, mechanics and workers for a variety of reasons (see for example, Bessen 2012).

3. The alternative to the new technology produces an inferior substitute, for example, an alternative process that produces the same product, but at a higher marginal cost.[6] The innovator's rents derive from the difference in the marginal costs of the two technologies. Such a difference could arise from competition between new and old versions of the same

---

[4] For example, in Arrow (1962), a superior new technology immediately drives an incumbent technology from the market, even if the new technology is a minor "non-drastic" improvement. In this case, the producers of the old technology stop producing, but serve as a "competitive fringe."

[5] The literature considering expectations includes Brem (1968), Williamson (1971), Kamien and Schwartz (1972), and Rosenberg (1976). Bessen (1999) models expectations using real options.

[6] If it is a product innovation, the alternative product is equivalent, but of a lower quality.

basic technology; or it could arise from competition between domestic production and imports from countries with different factor prices; or it could arise from competition with an imperfect substitute, such as the competition between iron rail and steel rail.

4. The market for the final product is competitive. If, instead, incumbent producers have market power, rents might dissipate substantially. For example, in Reinganum (1983), a monopolist incumbent using inferior technology might coexist with a new technology, as long as the benefits of the new technology are not too great. In this case, the addition of an imitator using the new technology would affect prices and would diminish the innovator's rents. Thus only when the incumbent market is competitive, can we expect coexistence of old and new technologies to be a clear sign that diffusion does not dissipate innovator's rents.

The literature on diffusion lags and technological replacement suggests that these conditions might not be uncommon. Yet these conditions might thus make knowledge sharing feasible.

Patents

Conversely, under these conditions, the value of patents to innovators might be limited. When rivals do not dissipate rents, patents obviously do not provide value by excluding rivals from the market. Because the rents derive from use of the innovation rather than from exclusion, innovation under these conditions might be thought of as "user innovation" (von Hippel 1988). However, even under these conditions, patents might provide private value by restricting use of a particular innovative improvement. In this case, however, the value of the patent is only the incremental value of that improvement over the next best version of the technology, not the entire value of the technology. Moreover, innovators might be reluctant to assert patents in circumstances where it might undermine reciprocal exchange. This reasoning suggests that patents might be of relatively limited value under the conditions that give rise to knowledge sharing.

* * *

Summarizing these theoretical considerations, we examine cases of knowledge sharing below to see if, in fact, innovators earned substantial rents during the periods when knowledge was exchanged. We also look at whether productivity improved substantially during these periods, as evidence of healthy innovation incentives. We consider whether the new technology coexisted with an alternative, substitute technology and whether that substitute was competitively provided. We explore the circumstances leading to the end of "soft" competition between rivals using the new technology. And, in those cases where patents were obtained, we compare the royalties earned on patents to the rents earned from operations using the new technology. The findings are summarized in Table 1.

B. Survey of knowledge sharing episodes during the long 19th century

History textbooks and museums often depict inventors as jealously guarding their secrets to make sure that they are not copied. For example, the Wright brothers kept news of their first flight secret for several years so as to buy time to patent their invention and develop it further. Yet this view is one-sided. Significant evidence shows that inventors sometimes shared their knowledge. Indeed, before their successful experiment, the Wright brothers themselves actively shared knowledge in a vibrant international community of inventors and scientists that openly reported and discussed merits and limitations of different designs of flying machines (Meyer 2011). Such crucial activity is too often slighted in textbooks and museums. To be sure, it is much easier to find documentary evidence of patents than of shared designs. Perhaps, too, knowledge sharing that occurs during the early stages of a technology is ignored when the "winners write history." But economic historians are now developing a more complete picture of innovation where knowledge sharing plays a prominent role (see Bessen and Nuvolari 2012 for a more complete survey).

Allen (1983) was the first to identify knowledge sharing during the nineteenth century in the form of "collective invention," which he documented in the British iron industry in the Cleveland district. Allen (1983, p. 21) speculated that "under the conditions prevailing during the nineteenth century, [collective invention] was probably the most important source of inventions." Allen's conjecture rests on the idea that, before the establishment of corporate R&D laboratories, in many industries inventive activities were carried out as a by-product of investment processes without resorting to patent protection. This conjecture is supported by Moser's (2005, 2010) finding that most nineteenth century inventions were apparently not patented: only 11% of the British inventions and 15% of the American invention exhibited at the Crystal Palace World's Fair in 1851 were patented.

Prior to the nineteenth century and the Industrial Revolution, a strong tradition of innovation with knowledge sharing was supported by the guilds. Epstein argued that guilds actively promoted the sharing of technical knowledge in a period when its transmission by other means such as printed texts was inherently limited (Epstein, 2004).

Knowledge sharing practices survived the demise of the guilds, taking new forms during the nineteenth century. In the Cleveland iron district, systematic knowledge sharing among engineers and designers of blast furnaces revolutionized the iron industry (Allen 1983). More recently, Allen has documented earlier instances of collective invention during the Industrial Revolution (Allen, 2009). These include the development of coal-burning houses in London (Allen, 2009, pp. 92-93), the adoption of clover, sainfoin and turnips in crop rotations by open field farmers (Allen, 2009, pp. 68-74) and improvements to the spinning jenny, which was initially developed by James Hargreaves, but improved and refined by means of collective invention processes.

The best-documented case of collective invention during the Industrial Revolution is the early development of the high pressure steam engine in the Cornish mining district (Nuvolari, 2004; Nuvolari and Verspagen, 2007; see case study below). British civil engineers tended to share knowledge as well, with a view to enhancing their professional reputations (MacLeod, 1988, pp. 104-5).

During the early nineteenth century in the United States, knowledge sharing was seen in the cotton textile industry (see case study below), in the development of the high-pressure steam engine for western steamboats (Hunter 1949: 121-80, Mak and Walton, 1972), paper-making (McGaw 1987), and among mechanics generally (Wallace, 1978, pp. 211-239, Thomson 2009). Especially important was knowledge sharing among mechanics making firearms; they developed the techniques of using interchangeable parts, essential to the "American System" of manufactures (Thomson 2009, pp. 54-9). Later in the century, the Bessemer steel producers shared knowledge extensively (Meyer 2003; see case study below).

Nor was knowledge sharing restricted to manufacturing industries. In addition to the agricultural examples cited above, Moser and Rhode (2011) describe the existence of widespread knowledge sharing in the community of American rose breeders in the early 1900s. More generally, Olmstead and Rhode (2008) have demonstrated highly dynamic biological innovation in nineteenth and early twentieth century US agriculture in wheat, cotton, tobacco, alfalfa, corn and livestock. Individual farmers developed many of the improvements and they freely shared their varieties and knowledge with others.

This brief overview suggests that, contrary to the conventional view, knowledge sharing in the past was neither rare nor uncommon. To be sure, many of these episodes were short lived. Many involved rather mundane technical information, such as information on best practices conveyed through industry trade associations. Nevertheless, these episodes also involved major innovations in key technologies and, as we shall see in the case studies, critical productivity gains were sometimes achieved through shared knowledge.

II. Case studies

A. Power Weaving

Knowledge sharing

Automation of textile weaving, especially for cotton, was one of the most important technological advances of the Industrial Revolution. During the late 1790s, the first power looms were put into operation in Britain. Beginning no later than 1810, American inventors began developing power looms. These inventions were influenced to varying degrees by British designs. Although early US inventors of textile equipment imitated British technology, the two technologies diverged significantly as American inventors made distinct improvements and adaptations (Zevin 1971, Jeremy 1981). The design that eventually dominated the US cotton textile industry during the antebellum period was developed by William Gilmour, an immigrant mechanic who had experience with textile equipment in Scotland. Arriving in New England in 1815, Gilmour contracted to build weaving equipment for Judge Lyman of the Lyman Cotton Manufacturing Company in 1816 [Bagnall]. A year later, the loom was in operation.

But Gilmour did not patent this loom.[7] Instead, he freely shared the design with David Wilkinson, a prominent Rhode Island mechanic who had helped him, charging $10 for his drawings [Bagnall 1893]. And Judge Lyman encouraged the use of the loom by other manufacturers. Wilkinson and Gilmour went into the business of building textile equipment for these manufacturers. Gilmour also benefited from a $1500 subscription subsequently raised by cotton manufacturers to thank him for his important contribution.

Rents

Were Gilmour and Lyman irrational or foolhardy or acting on philanthropic motives to encourage rivals among mechanics and cotton manufacturers? Did these actions undermine their own self-interests by increasing competition and driving down the margins on looms and cotton cloth? Apparently not. Zevin [p. 144] provides evidence that both margins declined only slowly:

> In the years immediately before and after 1820 the Boston Manufacturing Company sold machinery at average prices 50 per cent above direct costs. By 1830 the successor, Locks and Canals Company, contracted to make machinery for a 30 to 35 per cent advance above costs.

---

[7] Gilmour later obtained a patent for a loom in 1820, although little is known about this design. Under patent law it had to be different than the model introduced in 1817.

By the late 1830s, it contracted to build the Massachusetts Cotton Mills for a profit of 5 to 10 per cent on direct costs.

Margins were high for two decades. But Gibb (1950, p. 78) notes that during the 1830s, Locks and Canals began the practice of frequently licensing improvements made by other manufacturers, implying that "no longer could a machine shop, however large, enjoy unchallenged local demand for all its products." By the mid-1830s, competition from outsiders had finally become significant. Zevin [p. 143] notes a similar or perhaps even slower decline in gross cloth margins, from 5.33 cents per yard in 1823-28, to 3.85 cents per yard in 1834-43, to 2.72 cents per yard in 1859-60 for coarse cloth at the Blackstone Manufacturing Company.[8]

The high margins earned by cotton manufacturers and by machine shops producing cotton textile equipment allowed them to earn supranormal profits despite diffusion of their technology. Why did the margins stay high for so long? Part of the reason was that the markets were in extended disequilibrium. Zevin finds that cotton cloth production in the US grew at a 42.1% per annum rate from 1815-24 and 17.1% per year from 1824-33. After that, growth slowed to 5.1% per year. Cotton cloth woven by power looms initially competed against several substitutes: cotton cloth woven on handlooms, wool and linen, and British imports, which were subject to heavy tariffs. Power woven cotton cloth initially coexisted with these substitutes, but unit costs were much lower than handloom rates, allowing high margins. By 1833, however, power weaving had completely replaced handloom weaving and British imports of coarse cloth (Zevin).[9]

Yet it took nearly two decades to largely replace these alternatives. Given freely available designs for looms and for other equipment, why did it take so long? What took so long for new machine shops to enter production, or for old ones to scale up production of textile equipment, supplying new entrants in cotton manufacture? Zevin [p. 144] attributes these rents to the relatively inelastic supply of people with ability to "build, install, operate, and maintain the new machinery." The design of the power loom was only one part of the total knowledge involved in the technology. Indeed, Gilmour was unable to make his own loom work until a weaver who had experience on English looms showed him how [Bagnall]. Bessen [2003, 2012b] argues that the new technology required weavers to acquire substantial new skills and few mill managers initially knew how to set up organizations to do this. Managers, furthermore, needed intimate knowledge of the technology. Zevin [p. 145] points out that almost none of the mills survived during the early years unless they had their own machine shops or a close relationship with an outside shop. The machine shops themselves faced a limited supply of mechanics who knew how to build and install this new equipment. As late as 1845, the Locks and Canals Company experienced production delays caused by skilled labor shortages, thanks to a scarcity of mechanics and the long training and experience needed [Gibb].

If Zevin's interpretation is correct, the machine shops and the mills earned substantial rents based on the skills and knowledge of their employees and managers, specific skills and knowledge associated with the new technology. These rents meant that diffusion had little if any effect on profits, at least in the near and medium terms. Hence, Gilmour and Lyman did not harm their own interests when they encouraged sharing of the new loom design.

[8] These estimates are calculated these from the figures in his Table 3. These differ slightly from the averages reported in Zevin's text.

[9] British imports of fancy cloths, a relatively small part of the market, was not entirely replaced by then, however.

On the other hand, there were well-known benefits to exchanging knowledge. Mechanics of this era widely shared knowledge with others in their networks [Wallace, Thomson, Meyer]. They generally visited each other's shops, learning from each other's techniques and shared inventions, sometimes even at an early stage.[10] Textile technology was highly complex and for each step in the process there were many different ways of proceeding and many different techniques to build the equipment. No one machine shop on its own could expect to develop the best equipment in all areas and build it using the best techniques. The Boston Manufacturing Company (BMC) developed the most complete product line, yet still actively sought to learn from others. For example, Francis Cabot Lowell, founder of BMC, proposed to the owner of another mill "that we might see your machinery and copy from it as far as we pleased provided we would permit you to have the use of our patent Looms and warping machine and permit you to copy our Dressing machine [Gibb 40]."

This sort of knowledge exchange could apparently be highly beneficial as suggested by the exceptionally strong productivity growth that accompanied it.[11] The labor time required to weave a yard of standardized coarse cloth fell from about 39.6 minutes on the handloom to 8.3 minutes on power looms at the Lawrence Company by 1835 (Bessen 2012a), a 79% reduction. The main inventions responsible for this reduction were either not patented or patents were not enforced.[12] Only about three minutes of the 31.3 minute reduction can be attributed to the patented loom temple. Even ignoring the initial power loom invention, which came substantially from England, the specifically American improvements in productivity were large during this period. From the BMC in 1819 to the Lawrence Company in 1835, the labor time required to produce a yard of cloth fell from 15.9 minutes to 8.3 minutes, a 48% reduction (Bessen 2012a). While later inventions, such as the Northrop loom, generated substantial *relative* decreases in labor time, the greatest absolute reductions occurred during this period of free knowledge exchange.

Thus knowledge exchange appeared to do little to dampen innovation incentives and may have done much to boost innovation itself. There was little downside from exchange thanks to the high rents that manufacturers earned.

Role of patents

Conversely, these conditions also meant that the mills had little to gain by using patents to exclude firms from the market. This is seen in the experience of the Boston Manufacturing Company, which began by patenting its inventions, but later reversed course. Francis Cabot Lowell of the BMC introduced the first commercially successful power loom in the US, two years before Gilmour. Gilmour's design later proved superior, but for a brief period, the BMC loom was the leading

---

[10] Wallace [1978, p. 216] writes, "They visited each other's shop constantly to exchange information, to stand silently watching a new machine or a new process, to speculate about the future of the mechanism. By and large, they knew each other's business and did not hesitate to show each other inventions in embryo, trusting their peers to honor their priority and the economic advantage it might mean. Their patents were often not taken out until years after the invention had become widely known in the fraternity; patents once taken were sometimes not announced or enforced, the patentee trusting his customers to honor his interest without reminder. To be sure, there were patent-infringement suits, like those levied by the embittered Oliver Evans, yet many of these were directed not against fellow mechanicians but rather against exploitive manufacturers.

[11] Of course, exchange could take place through negotiated patent cross-licenses, but this sort of exchange is likely to be incomplete because of transaction costs and asymmetric information about the technologies. Free exchange did not have such obstacles.

[12] This compares the handloom with production at the Lawrence Company in 1835.

technology. In contrast to Gilmour, Lowell and his agent Jackson patented their loom in 1815. Also, BMC's talented mechanic, Paul Moody, acquired eight additional patents on related equipment. In 1817, the BMC began offering patent licenses to its equipment designs and it began manufacturing patent looms and other cotton textile equipment then as well [Gibb 1950].

However, after a few years, the BMC reversed course. After 1821, Paul Moody did not obtain any more patents, despite making key innovations in such areas as power transmission within the mill [Burke, 1847, Gibb]. These innovations were not patented, but instead diffused rapidly through the industry, quickly becoming standard in all new mill construction. In 1823, the BMC ceased sales of equipment and patent licenses except to closely related companies [Gibb]. That year, the machine shop was sold to a related company and the following year it was moved to East Chelmsford, where it began producing equipment for new mills owned by closely related firms in Lowell, Massachusetts. For the next two decades, the continuing machine shop operation only sold to outsiders occasionally.

Why did Boston Manufacturing give up on patents? Because they could make more money putting the machine shop resources into building capacity for their own use. From 1817 through 1823, the BMC sold patent licenses on textile equipment worth $8,354 [Gibb]. In addition, they made gross profits on sales of manufactured textile equipment of $33,190, part of which can be considered patent rents. Thus they did make money on their patents. However, during the same period, profits on their own production of cotton cloth were much larger. Dividend payouts during this same period totaled $718,000 (on capital of $600,000).

To make the comparison more concrete, the one-time patent licensing fee on a single power loom was $15; the profit on each loom they built was $35. But each loom in cloth production earned profits of over $200 *each year* during the early 1820s.[13] The one-time patent royalty on a loom was less than one percent of the present value of expected profits from the operation of a loom. Thus it made far more sense to put the machine shop to work building equipment for BMC's own use or the use of closely-related companies. It only made sense to build textile equipment for other mills, perhaps, during temporary lulls in expansion plans. This appears to be the policy that the BMC machine shop and its successor companies followed through the 1830s as they built the equipment for the mills of Lowell, Massachusetts. And, while BMC could have continued to make some money selling a small number of patent licenses, it turned out that what customers really needed were licenses to BMC's entire technology, including their technical know-how and unpatented technology. From 1817 through 1823, BMC sold a few such complete technology licenses, making three times the royalties they earned from pure patent licenses [Gibb p. 47]. But the market for "naked" patent licenses was limited because these licenses would have been of little value without close access to a knowledgeable, skilled machine shop. But, as above, there were few such machine shops and, besides, these shops would likely have access to other loom designs, further limiting the market. In any case, complete technology licenses diverted the resources of BMC's machine shop

[13] The 1820 Census of Manufactures reports 1,350,000 yards of cloth produced on 175 looms at the mill in Waltham in 1819, or 7,714 yard per loom per year. During the early 1820s, BMC made about 9 cents per yard in profit [Ware, p. 114]. Assuming that one third of the profits earned on cloth production could be allocated to looms (looms comprised about one third of capital costs [Montgomery 1841]), the annual profit per loom would be $231.

away from producing their own equipment.[14] Profits were still far greater making equipment for their own use, and so the patent licensing program was dropped.

Nor was weakness of the patent system responsible for the relatively small magnitude of profits from patents. The BMC did have difficulty enforcing its patents for the double speeder (a machine used for winding cotton prior to spinning), in part because of faulty drafting of the patent [Jeremy 1981]. However, the power loom was the key invention, and it appears that the BMC had no difficulty getting $15 per loom for a patent license or $35 gross profit on manufactured looms through 1823 [Gibb , p 47].[15] Moreover, the patent royalty of $15 compares reasonably well with the $25 royalty that the powerful sewing machine patent pool was able to charge on a comparably priced piece of equipment [Lampe and Moser 2010].[16] Clearly, even if BMC had been able to charge a $25 or even a $50 royalty, the basic arithmetic still favored producing machines for their own use. Because the rents earned on technical knowledge were so much greater than the rents that could be earned on patents, under these conditions it made sense for mechanics and mill managers to exchange innovations. This did not harm them, they could gain access to improvements developed by others, and patents offered little in comparison.

Of course, patents were still valuable to independent inventors who did not necessarily possess the skills and experience to build equipment on a large scale and to manage production operations efficiently. Nevertheless, the same economics sometimes made it difficult for these inventors to capture much of the value of the technology. For example, Ira Draper was one of the more successful independent inventors during the 1820s and 1830s. He developed a successful loom temple, an attachment to the loom that kept the edges of the cloth straight. Draper patented this device in 1816 and he obtained a patent on an improved version in 1829 [Mass]. In 1830, Draper's successor licensed the patent and also sold his own manufactured version for $2. By comparison, the loom temple saved cloth manufacturers about $35 each year on each loom in labor costs.[17] Draper only captured a small part of the value of his invention because the textile manufacturers were in a strong bargaining position relative to independent inventors such as Draper.

There were at least two reasons for this strong bargaining position. First, the manufacturers' rents gave them bargaining power. In a more competitive market, if a competing textile manufacturer purchased superior loom temples, it could produce cloth at a lower cost and could gain an advantage by dropping prices. This would reduce the profits of any manufacturer who lacked the cost-reducing technology. But because competition between textile manufacturers was limited before the 1830s, they were not under the same pressure to acquire the latest technology.[18] Second, because there were

---

14 At least one of these licenses made claims on Moody's time when he was not occupied at Waltham [Gibb p. 43].

15 The persistence of this royalty through 1823 supports Gibb's analysis that the BMC did not experience significant price competition from Rhode Island mechanics using other designs, including Gilmour's.

16 BMC's cost for building a loom was $90; sewing machines cost about $75.

17 The loom temple reduced the labor required per yard of cloth by about three minutes [Bessen 2012]. A loom at the Lawrence Company in 1835 produced 14,465 yards per year [Bessen 2012], implying a savings of about 723 labor hours per loom per year. At a mean wage of 4.9 cents per hour [Layer 1950], this comes to a savings of $35.44 per year per loom.

18 Formally, if the textile manufacturers actively competed but the inventor did not have competition, the inventor would have all the bargaining power and, in a standard bargaining game, would get all of the rents. But when the textile

alternative loom temples already on the market, the effective value of Ira Draper's loom temple to a textile manufacturer was only its incremental value over the next best model.

Industry change

Thus during the first decade or two of power weaving in the US, both clothing manufacturers and machine shops earned large rents on their technical knowledge, allowing them to freely exchange knowledge without significantly dissipating their rents. Inventors could make money on their patents, as Ira Draper did, but the amounts were relatively small.

This changed, however, as the technology developed. As the markets for textile equipment and for cotton textiles became more competitive, bargaining power shifted towards independent inventors. Also, following with the sewing machine patent pool formed in 1856, inventors obtained greater bargaining power by creating patent pools or large portfolios of patents that covered multiple techniques for achieving a given result. In this way, they could limit competition from substitute techniques or devices. Draper's successors did just this, creating a pool of key patents on high speed spindles in the 1870s and acquiring over 400 patents on their own on spindles between 1871 and 1903 [Mass]. In 1895, when the Draper Company introduced the Northrop automatic loom, a major new weaving technology, they acquired a large portfolio of patents that gave them a dominant market position for decades [Mass].

Clearly, patents played a very different role in 1895 than during the first two decades of power weaving. Manufacturing could still provide profits beyond those achieved through patent licensing: the Draper Company chose to manufacture their looms after briefly licensing other manufacturers. And knowledge exchange between rival manufacturers continued: the New England Association of Cotton Manufacturers (later the National Association of Cotton Manufacturers) was founded in 1865 and its meetings featured sharing details of best technical and management practices. But the most important innovation after the Civil War was effectively and exclusively controlled thanks to Draper's patents.

When did behavior change? Did the growing competitiveness of markets during the mid to late 1830s spur innovators to patent more and share less? Some evidence suggests that this was the case. In Gilroy's review of US weaving technology published in 1847, some inventions were patented and some were not. As noted, Moody's improvements to power transmission in the mills (1828) were not patented. Nor was the most important invention of the 1830s, the weft fork.[19] But the significant inventions of the 1840s and 1850s were patented, by and large.[20] After 1860 there was a

manufacturers earned substantial rents themselves, the bargaining was more akin to a bilateral monopoly bargaining game where the parties split the rents.

[19] Gilroy himself claims to have invented the weft fork in 1831, but did not patent it (Gilroy 1847, p. 416). Ramsbottom and Holt patented a version in 1834 in England, but they did not patent it in the US, perhaps because of Gilroy's prior art. There was no US patent claiming a similar device in the US until Stillman in 1841. Even if one discounts Gilroy's claim, unpatented versions were in use in the US. The weft fork was used first in the manufacture of fine cloths and only later for coarse cloth production.

[20] Draper (1907) cites the automatic let-off (the Barlett motion patented in 1857) and parallel picker (patented 1851 and 1859) in addition to the weft fork as the most important inventions. Other important inventions include Bigelow's combination of weft fork and brake and let-off that "held at the beat" (both patented in 1856).

lot of patenting activity, but, in the view of George Draper (1907, p. 30), no significant improvements in the basic technology until the Northrop loom in 1895.[21]

The change in behavior occurring during the 1830s is also shown in Figure 1, which charts the number of loom patents in force. While patenting rates overall increased, especially after 1852, the number of patents on looms that were granted each year increased sharply during the mid-1830s and this was distinct from the general trend. A statistical test of grant rates for loom patents identifies 1833 as the year of a significant break, the same year that the industry stopped growing rapidly.[22]

In summary, the timing of this change in patenting behavior supports the view that knowledge sharing was valuable and patents were of little value when rents were high. Diffusion did not dissipate rents then. But when markets became more competitive during the 1830s—presumably because constraints on experienced personnel had eased—then patenting became more important and major inventions were no longer shared.

B. Bessemer Steel

Knowledge sharing

Patents played a much more central role in the development of Bessemer steel, making this example an interesting contrast to power weaving. In 1855, Henry Bessemer patented a process in Britain for refining steel by blowing oxygen through the molten metal. This process promised much cheaper steel, produced much more rapidly. But at that time, the technology was not well understood and the first attempts at commercial production failed, mainly because of difficulties in controlling the amount of phosphorus and carbon in the steel. Robert Mushet patented a technique in 1856 for controlling the carbon content and after much experimentation and the acquisition of low-phosphorus pig iron from Sweden, Bessemer began commercial production in 1858.

Although the original technology was developed in England, US innovators turned a somewhat crude technology into a true mass production tool. The largest market for steel produced using the original Bessemer process turned out to be steel rails for the booming American railroads. This market benefited from dramatic additional improvements in the scale, speed and cost of the technology realized by US innovators. By 1879, US production of Bessemer steel equaled and then exceeded British production (Bessemer 1905, p. 340). Most of the US improvements were realized through the free exchange of knowledge among competing Bessemer steel mills.

Railroads initially used rails made of iron, but in 1862 rails made of Bessemer steel were first used in Britain (Bessemer). Although steel rails were initially much more expensive than iron rails, they lasted much longer and, for that reason, were economical when used on the most heavily traveled sections of track despite high relative prices. Also in 1862, Alexander Holley visited Bessemer's British operation to learn about the process and with an eye to acquiring US rights to the technology (Bessemer). For his partners, Winslow and Griswold, Holley acquired rights to Bessemer's US patents in 1865, along with detailed plans for constructing a mill (Temin).

---

[21] Much of the inventive activity during this period was directed toward enhancements to deal with multiple colors, fancy weaves, carpets, patterns, etc. but not improvements in plain weaving.

[22] The "sup-Chow" test identifies this break as significant at the 1% level using the Quandt likelihood ratio test (Quandt 1960) with an F-statistic of 14.58. The data from 1816 through 1846 come from Burke (1847); we count patents described as looms, bobbins, cloth manufacture, and weaving.

At roughly the same time, another group acquired rights to Robert Mushet's US patent and to a US patent of William Kelly that read on the Bessemer process, although Kelly had not actually produced steel using this process (Gordon 1992). This gave rise to a situation of blocking patents where one group controlled Bessemer's patents on the equipment while the other group controlled patents on the process. In 1866, the two groups formed a patent pool to settle the conflict, with a share of the rights going to Winslow and Griswold (but not Holley) and the Kelly patent group.

The pool offered licenses to third parties for a modest flat fee plus running royalty (Temin).[23] Licensees received rights to the current patents plus rights to any future patents on steelmaking that the principles might obtain. But the license was also designed to encourage the transfer of knowledge (Temin 1964). Licensees received plans for a plant and detailed information on the process. To help transfer know-how, licensees could train two people at the Troy, NY plant run by Winslow, Griswold and Holley. And they were permitted to visit the Troy plant on an ongoing basis and were required to make their own plants open to the pool.

In addition to the formal communication requirements contained in the license agreement, the mills established several practices that ensured a high level of knowledge exchange. The top five or six engineers from the various mills met frequently to discuss technical issues (Temin).[24] One of the engineers, John Fritz, later wrote that "we met as a band of loving brothers…What each of us knew was common to all…This fraternal relationship was very important in the exchange of information in a new field (Fritz pp. 160-1)." Also, technical personnel rotated from one mill to another, learning the process under different conditions (Meyer). Usually, managers at the new mills had been trained at older mills (Temin). Also, from 1874 through 1877, Alexander Holley produced a series of fifteen to twenty technical reports for licensees (Temin 134). More generally, professional associations and publications for iron and steel professionals and engineers facilitated knowledge exchange. Several of the key Bessemer plant engineers published in the Transactions of the American Institute of Mining Engineers (Meyer).

Rents

Were the US mills hurt when their engineers provided information to competing US firms? During the first decade of Bessemer steel production in the US, the production of these mills had little effect on the price of steel rails because it was only a small part of the total production of rails. Most rails were made of iron, which at this time cost much less than steel rails. But steel increasingly substituted for iron as the relative price of steel rails came down. In addition, US steel rails had to compete against British imports, which were subject to a steep tariff. In 1872, seven years after Bessemer production began in the US, US Bessemer rails were only 6% of the total market. Prices that year for US steel rails were set to fall just below the price of British imports after taking into account tariff and transportation costs (Morison pp. 171-2). Consequently, the output of Bessemer steel producers in the US had little effect on prices at this time. Under these conditions, sharing a technical improvement that reduced a competitor's cost would cause little, if any, harm.

[23] The flat fee was $5,000 compared to an initial mill cost of $80,000 to $200,000 (2.5% - 6%). The running royalty was equivalent to about $5 per ton of steel at a time when the price of steel was initially $166 per ton, making the royalty 3%; the price fell to $106.75 by 1870, making the royalty roughly 5% (Temin).

[24] This included Alexander Holley, John Fritz of Bethlehem Iron Company, where the meetings were often held, George Fritz of Cambria Iron, R. W. Hunt from the Troy works, and William Jones of the Edgar Thomson Works.

Although profit data is fragmentary, the nature of the competition appears to have created opportunity for substantial profit margins, despite the large investments required to set up a new mill and the cyclical nature of demand.[25] It took the first mills several years to become fully productive. The Pennsylvania Steel Company began production in 1867 with barely over 1,000 tons produced (Morison pp. 168-9). It did not pay a dividend until 1873. But in 1878, it produced nearly 84,000 tons and made profits of nearly 80% of total capitalization, a profit margin on sales of about 45%. The Edgar Thomson Steel Works had a profit rate of 20 to 30% of capital during its first three full years of operation, from 1876 to 1878, years of depressed demand (Temin). But during the boom year of 1881, the Edgar Thomson Works earned a return of 130% of invested capital.

Assuming that these profit opportunities were anticipated, why did not more firms enter and drive rents down during the first decade of the industry? One reason was uncertainty about how well the technology would be able to perform and the large size of the investment required to establish a new mill. But it also seems likely that talented engineers and managers familiar with Bessemer technology were also in limited supply at that time. As noted above, managers of the new works were usually trained on-the-job at the mills already operating (Temin 133). Given the small number of operating mills during the early years, this could only have generated a supply rather slowly. Particularly, important were the talents and experience of Alexander Holley, who provided plans for six of the mills and consulted on two of the others. Indeed, the one mill that was not built to a Holley design, quickly turned out to be inefficient and failed (Temin). McHugh (1980, p. 200) writes that Holley was "one of three or four men in America who had the ability to construct and operate a Bessemer plant." Thus a limited supply of experienced engineers and managers constrained the growth of the industry even though the technology provided highly profitable opportunities to compete against older technology (iron) and tariff-burdened imports. In these circumstances, diffusion did not dissipate rents.

While the period of knowledge sharing among Bessemer steel producers lasted only a decade, the significance of this episode should not be underestimated. The technological progress achieved during that decade dramatically reduced the cost of production. The price of Bessemer steel rail minus the cost of pig iron (the primary input) fell from $122 in 1867 to $27 in 1877 (Temin), a reduction of 78%. Further progress was made after 1877, but clearly most of the productivity gain was realized during this first decade. These advances allowed the U.S. industry to produce the large quantity of rail needed by the booming railroads and to do so at prices less than could be offered by British producers.

Change in the market

Competitive conditions changed as the mills dramatically reduced production costs and increased output. The price of Bessemer rail was twice the price of iron rail in 1867 (Temin) and US Bessemer steel accounted for only a fraction of one percent of all rail produced or imported then; imports accounted for 26%. But by 1877 the price of Bessemer rail was only 29% higher than the price of iron rail and, for the first time, US Bessemer steel accounted for over half of all rail—57% of the total market. In that year, there were virtually no British imports. By 1884, US-produced steel rail cost less than iron rail and accounted for 97% of all rail.

---

[25] In addition, the patent pool held joint price discussions with the railroads and railroads held interests in the steel companies (Morison p. 173, Temin). However, based on Temin's analysis of subsequent developments (see below), it seems likely that any collusion would have had little effectiveness.

These changes motivated a sharp change in the nature of competition between Bessemer mills over time. During the first decade, an additional Bessemer mill would not have affected rail prices significantly. By 1877 and even moreso by 1884, the entry of rivals would likely have a negative impact on any one firm.

And so, the Bessemer mills changed their policies regarding entry into the industry. Prior to 1877, the patent pool actively advertised for new members (Temin). But in 1875, the eleven existing Bessemer mills attempted to form a new patent pool with a formal agreement to allot prearranged quotas to each mill. This attempt failed, but in 1877, they succeeded in forming a new patent pool based on the remaining patents still in force, including ten patents granted to Holley. The pool decided to restrict the use of these patents to mills currently making Bessemer steel and the pool ceased advertising for new members. Alexander Holley also ceased publishing technical bulletins in 1877. If we interpret these changes as evidence of the changing nature of competition, then knowledge sharing that would not have been at odds with profit-seeking self-interest prior to 1877, but might well have been harmful to it later.

Role of patents

In the case of Bessemer steel, patents clearly played a much more central role than they did with the power loom in the U.S. The pool was formed in order to prevent litigation over blocking patents. Moreover, Bessemer's original invention was a highly successful example of the rewards that patents could provide. Jeans wrote in 1884 that Bessemer had earned "the largest fortune perhaps that has ever been reaped from a single invention."

Nevertheless, the inventors of the original patents earned little in the US relative to the profits earned from operation of the steel mills, much as was the case with power weaving. A major reason for this was that it took so long to make the process commercially viable. Consequently, the patents largely expired before production ramped up in the US.[26] The Bessemer and Mushet patents expired in 1870. The Kelly patent expired in 1871, but Kelly successfully petitioned for an extension through 1878. In his petition, Kelly declared that he had only received $2,400 through 1871 (Temin, p. 176, fn. 15). Kelly is reported to have earned about $25,000 more in royalties during the patent extension.[27]

We can estimate an upper bound on the royalties from the original patents. Through 1870, the patent pool itself charged licensees $5 per ton on steel for rails (Holley 1866) and only 47,000 tons were produced through 1870. Considering that the pool might have kept some of these royalties itself, the inventors could not have received more than $260,000 in total, including Kelly's royalties

[26] Bessemer's profits largely came from Britain where 52 converters were producing steel by 1866, including his own Sheffield works (Jeans 1880, p. 86). Steelmakers were able to avoid paying royalties in many other countries (McHugh, p. 208-9, fn. 27).

[27] Reported by Dr. Rossiter Raymond (1896), the secretary of the American Institute of Mining Engineers. Casson (1907) contends instead that Kelly received $30,000 through 1870 and $450,000 during the extended term. However, this claim appears without citation in his book, "The Romance of Steel: the story of a thousand millionaires," which is dedicated to demonstrating the wealth generated by the new technology. Casson's claim appears to be dramatically at odds with Kelly's submission to the Commissioner of Patents.

after 1871. A single mill made greater profits than this in a single year.[28] Put another way, if we assume that the mills earned an average profit margin of 10% on sales through 1877—the Edgar Thomson Works earned this much in 1876, a depression year[29]—then the payments on the original patents were less than 3% of total profits through 1877.[30]

This number would surely have been larger had Bessemer's patent (and Mushet's) been extended. However, it still speaks to our main point: the value of the original invention itself was small without the additional knowledge needed to make the technology work efficiently at large scale. And this knowledge came through experience and experiment in a period of extensive knowledge exchange. These patents served to restrict the use of the Bessemer process to members of the pool, but admission to the pool was not costly and knowledge sharing within the pool served to make the process much more valuable.

After the original patents expired, the pool's subsequent patents proved to have only a limited ability to restrict entry. When the pool was reorganized in 1877, it sought to restrict entry by using patents that had been acquired since the first pool formed, most significantly eight patents obtained by Alexander Holley. But in Temin's analysis, these only restricted entry to a limited degree at most.[31] Perhaps because patents did not provide the desired degree of monopoly rents, the industry soon embarked on a consolidation spree, culminating in the formation of U.S. Steel ().

In summary, despite the prominent role of patents in this example, during the first decade of Bessemer steel production in the US, much more value was derived from rents associated with the use and operation of the technology than from patents. These rents were not dissipated by diffusion at that time and conditions permitted active knowledge exchange that facilitated dramatic productivity improvements.

C. The Cornish Mining and Cornish Engines

Knowledge Sharing

In the first half of the nineteenth century, Cornwall was "one of the most advanced engineering centres of the world" (Berg, 1994, p.112). However, as we will see, in Cornwall, inventive activities were mainly undertaken *outside* the coverage patent protection. In Cornwall, steam engines were used to pump water out of copper and tin mines. Since coal in Cornwall was relatively expensive, the Cornish mining district had been one of the early adopters of Boulton and Watt engines that

---

[28] The Edgar Thomson Steel Works, albeit one of the better-managed mills, made profits of $181,000 in 1876, $190,000 in 1877, $402,000 in 1878, all relatively depressed years. During the boom year of 1881, the mill made profits of $1.625 million (Temin p. 172).

[29] In 1876, its first complete year of operation, the Edgar Thomson Steel Works produced 32,000 tons of rail (Bennett 1995, p. 15). Given a market price of $59.25 per ton (Temin) and profits of $181,000 (Temin, p. 172), yields a net margin of 9.5%.

[30] Sales of steel rail were over $100 million through 1877, as estimated by multiplying the average price in Pennsylvania by total production for each year from Temin (??).

[31] "Restriction of entry by means of patents helped the existing steel firms to exploit the boom of 1879-1882 and it helped refuse entry to at least one new firm in the following years. Several other new firms were successful, however, and we may conclude that the use of Holley's patents for restrictive purposes was not very important for the industry as a whole. In any case, these patents expired in 1886, and entry was free as far as patent costs went." (Temin 182).

represented the best practice of the time in terms of fuel efficiency. Significantly, Watt patented his design for an engine with a separate steam condenser with a very broad specification. After Boulton and Watt's penetration in the Cornish market, several engineers began to develop further improvements, but were frustrated by Boulton and Watt's tight enforcement of Watt's patent (Nuvolari and Verspagen, 2007). The ultimate outcome was a period of stagnation in fuel efficiency.

In the wake of this disappointing experience, Cornish steam engineers typically preferred not to patent their inventions after Watt's patent expired in 1800. Accordingly, the share of Cornish patents in steam engineering for the period 1813-1852 fell to under one per cent of the national total (Nuvolari, 2004, p. 358). Furthermore, in 1811, Cornish mining engineers and entrepreneurs launched a monthly publication containing detailed reports on the performance, technical details and operating procedures of the steam engines at work in the county. The explicit intention was twofold. First, the publication would permit the rapid identification and diffusion of best-practice techniques. Second, it would create a climate of competition and emulation in the Cornish engineering community with favorable effects on the rate of technical progress. Joel Lean, a highly respected mine "captain" was entrusted with the compilation of the reports and the publication was known as *Lean's Engine Reporter*. It is exactly after the publication of *Lean's Engine Reporter* that Cornwall attained the world technological leadership in steam engineering with the introduction of a particularly successful high-pressure condensing engine that would become known as the "Cornish" engine (Barton, 1969).[32] It can be shown that the systematic comparison of technical features, operational procedures and performance of the engines allowed engineers to identify the best design configuration, for example in terms of cylinder size, for attaining economies of fuel (Nuvolari and Verspagen, 2009).

Interestingly enough, in the contemporary engineering literature, engines built on the basis of these design principles were not ascribed to this or that particular engineer, but simply known as "Cornish" engines, correctly acknowledging the cooperative and cumulative character of this particular form of technological development.

Concomitant with the beginning of the publication of *Lean's Engine Reporter*, Richard Trevithick and Arthur Woolf installed high-pressure engines in Cornish mines. The layout of the engine designed in 1812 by Richard Trevithick at the Wheal Prosper mine soon became the basic one for Cornish pumping engines. Interestingly enough, Trevithick did not patent this high pressure engine.[33]

---

[32] Notably, even though specific inventions introduced in Cornwall can be ascribed to individual inventors (eg, the tubular boiler to Richard Trevithick, the compound engine design and the double beat valve to Arthur Woolf), the high pressure condensing engine would become known as the "Cornish" engine, giving credit to the whole community of engineers.

[33] In fact, Trevithick had an ambiguous attitude towards patents (arising from an unsolved tension between appropriation and desire of the widest possible dissemination of his discoveries). Although he did not patent the Wheal Prosper design, he took five patents for other inventions in steam technology. It must also be noted that Trevithick's travel in South America in the topical period 1816-1827 prevented him for controlling the adoption of his inventions, leaving free ground to imitators and improvers. Another famous contemporary mining invention non patented was the miner's safety lamp contrived by Humphry Davy (another famous Cornishman) in 1815. Davy explicitly refused to take a patent for his invention in order to ensure its wide and quick diffusion, see Knight (1992, p. 112).

As a result of the publication of the engine reports, the thermodynamic efficiency of Cornish engines improved steadily. On strictly engineering grounds, this amounted to a very effective exploration of the merits of the use of high-pressure steam used expansively.

Figure 2 displays the evolution over time of the efficiency of Cornish steam engines (based on the collation of several sources). The figure clearly indicates that the practice of information sharing resulted in a marked acceleration in the rate of technical advance (measured in terms of "duty", millions of lbs of water lifted one foot high by the consumption of a bushel of coal).

Systematic collection and analysis of performance data published in *Lean's Engine Reporter* allowed to Cornish engineers to individuate a set of design principles that could successfully be used to project efficient steam engines, even in the absence of full-fledged theory of the functioning of the steam engine. By pooling together all the accumulated experience, it was possible to gain a deeper understanding of the connections between specific designs features and engine performance and, consequently, focus the search process in the most promising directions.

Rents

Figure 3 shows the production of copper and tin ore of the Camborne-Redruth district. As far as copper production is concerned the district was characterized by a continuous increase until the mid 1850s. After this peak, the copper mining industry exhibits a prolonged phase of the decline. It is interesting to note that the dynamics of copper ore production mirrors the dynamics of duty reported in Figure 2. In this case Salter's model seems to provide an adequate representation of the dynamics of technical change and investment in the Cornish mining industry. The opening and closing and mines produced waves of investment in different vintages of technology. Technical improvements were typically embodied in the most recent vintages (although some disembodied improvements could be also retrofitted in existing capacity). In this way, the dissipation of innovation rents took place gradually. Existing records permit some back of envelope calculations of the profitability of some Cornish mines (table 2). In the table we have also reported the intensity with which the mines in question published the performance of their pumping engines on the *Lean's Engine Reporter*. This is done in the second column using as measure the total number of engines-year reported (1 engine-year means that the mine in question published the performance of an engine in a given year). It is interesting to note that also mines that reported intensively their engines such as Dolcoath were able to gain very high rates of profit.

Patents

Table 3 reports the geographical distribution (measured using the stated addresses of the patentees) of patents in steam power technology over the period 1698-1852 (see Andrew et al. 2001 for a detailed quantitative analysis of the pattern of steam power patenting over the entire nineteenth century).

The London and Middlesex area holds the predominant position. In this respect the pattern of patenting in steam technology mirrors that for overall patenting outlined by Christine MacLeod (1988, pp.119-124), and it is likely that this high number is mainly explained both by the growth of the metropolis as a commercial and manufacturing centre and by the proximity to the patent office, which gave would-be patentees the possibility of following closely the administrative procedures related to the granting of the patent. Surrey also has a quite high concentration of steam patents. This case, besides by the proximity to the patent office, may also be accounted for by the presence in the area of a number of engineering firms specialized in the production of capital goods

(MacLeod, 1988, p. 124; Hilaire-Perez, 2000, p.111). Other notable locations with high numbers of steam patents are Warwickshire, Lancashire and Yorkshire, where patents were probably related to the increasing use of steam power by the industries located there. Again, one should take into account that in this case as well, patents were essentially an urban phenomenon (MacLeod, 1988, p. 125) and so they were concentrated in major towns such as Birmingham, Liverpool, Manchester and Leeds. The table also reports the number of patents in major urban centers.

Over the entire period 1698-1852, the share of Cornwall in total patenting is 1.85 per cent, which does not reflect at all the major contribution of the county to the development of steam power technology. Breaking down the period 1698-1852 into two sub-periods (1698-1812 and 1813-1852), in order to take into account the publication of *Lean's Engine Reporter* is even more revealing. In the first period, Cornwall (including in the count also the patents taken out by Arthur Woolf who, at the time, was working for the Meux & Reid brewery in London) is the county with highest number of patents after the London and Middlesex area, with a share of 9.38 per cent. In the second period, the share of Cornwall drops to a negligible 0.89 per cent and this is exactly the period during which the Cornish pumping engine was actually developed. In our view, this finding is indicative of the widely perceived awareness in the county of the benefits stemming from the adoption of a collective invention regime for the rate of innovation. After the unfortunate experience with the Boulton and Watt monopoly, it seems quite clear that in the Cornish engineering community, an *ethos* prescribing the full release of technical innovations into the public domain emerged and became progressively established.

The case of Arthur Woolf is particularly illustrative. Woolf was one of the leading figures in the Cornish engineering community (Jenkins, 1933; Harris, 1966). Born in Cornwall, he had an initial apprenticeship with steam engineering by working with Jonathan Hornblower. In the first decade of nineteenth century he moved to London, where he was entrusted with the steam engines of the Meux & Reid brewery. In this period Woolf took out four patents for innovations in steam engines (in particular his famous compound engine patented in 1804). In 1812 he moved back to Cornwall, where he tried to commercialize his compound engine by means of an agreement similar to the one proposed by Boulton & Watt (royalties paid as a proportion of fuel savings). His initiative was unsuccessful. Most mine adventurers awaited the expiration of the patent in 1818 before installing this type of engine (Farey, 1971, pp.188-189). [34] Later on, in 1823, Woolf invented a new valve for steam engines (the double-beat valve). The adoption of this type of valve greatly facilitated the operation of the engine (Hills, 1989, pp. 109-110). He did not claim any patent right for this invention. In the same period, he also introduced notable improvements in the cataract regulator, which he did not patent (Pole, 1844, p. 89). Similarly, Samuel Grose did not patent the system of thermal lagging that he introduced in 1826, even when Davies Gilbert had advised him to do so (Todd, 1967, p. 101).

Another example that confirms the negative attitude towards patents existing in the Cornish mining district is the limited diffusion of the two-cylinder compound engine patented by the Cornish

[34] This was also the fate of the circular calciner (which is considered an important step in the mechanization of the ore dressing processes) patented by William Brunton: "Although the advantages of the calciner were evident, very few mines used it until the patent had expired, and then it was found in operation throughout the length and breadth of the county" (Ferguson, 1873, p. 147, remark made by T. S. Bolitho in the discussion of the paper).

engineer, James Sims, in 1841. The first engine of this type erected at the Carn Brea mine performed particularly well in terms of duty (it was the second best engine in the *Reporter* in the early 1840s). However, being a patented design made the engine quite unpopular with other engineers and mine-owners, who, in the end, preferred not to adopt it (Barton, 1965, pp. 110-112).

One can point to other Cornish inventions in steam technology that were not patented. The "Cornish water gauge", an instrument that allows a prompt check of the height of water in the boiler, invented by Richard Hosking in 1833, is a noteworthy case. In his *Treatise*, Pole describes it as "a very ingenious apparatus...almost unknown out of the county" (Pole, 1844, p.109). The invention was awarded a prize by the *Royal Cornwall Polytechnic Society* and a detailed description was published in the Society's *Reports*. In fact, since its foundation the *Royal Cornwall Polytechnic Society*, a local learned society*,* in 1833 awarded a yearly prize for "Inventions and Workmanship". A perusal of the yearly reports *Reports* of the society reveals that many inventions related to steam engineering. For the period 1833-1841, none of them was patented.[35] It is also interesting to note that leading mine entrepreneurs, such as John Taylor, tried to steer the direction of inventive efforts by instituting prizes for inventions aimed at specific purposes (such as water meters for boilers, stroke counters, etc.). Overall, it is hard to tell the technological significance of these inventions. Remarkably, William Pole found some of them worthy to deserve a description in his *Treatise*, which indicates that they probably were not of trifling importance (see, Pole, 1844, p.122).

III. Conclusion

Perhaps some of the surprise that economists have expressed about knowledge sharing comes from a tendency to think of technology as consisting of inventions. Often technology is described as "ideas" or as information. But while information can be diffused very quickly, empirical evidence finds that technology diffuses much more slowly, often because technical knowledge is difficult to acquire and share, especially during the early phases of a technology's development.

Our case studies show that under these common circumstances, the free diffusion of ideas does not substantially dissipate rents. Then knowledge sharing is both privately valuable and critical for technological progress.

This distinction might help explain a bigger puzzle about the role of patents during the Industrial Revolution. Since North (1981), institutional economists have argued that stronger property rights were an essential precondition to the Industrial Revolution. Yet scholars studying the role of patents during the Industrial Revolution have had difficulty finding a central role for patent incentives (MacLeod 1988, Mokyr 1999). Many of the major inventors of the early Industrial Revolution did not benefit from patents, either because they failed to obtain them, the patents were invalidated or the inventors could not successfully enforce and profit from their patents (Mokyr 1999, pp. 42-3). Moser (2010) finds that most inventions shown at the 1851 Crystal Palace exhibition were not patented in the UK or in the US. On the other hand, most patents in the UK appear to have been obtained in fields with relatively little technological innovation (MacLeod et al. 2003). To explain why patents did not seem to play a more central role, Mokyr (2009) argues that formal institutions

[35] Again we have used Woodcroft (1854) to check that the inventions which were awarded a *Royal Cornwall Polytechnic Society* prize over the period 1833-1841 were not patented.

have been overemphasized and highlights, instead, private institutions that encouraged knowledge sharing. Our analysis suggests a complementary possibility: perhaps many of the new technologies of the Industrial Revolution were constrained by shortages of people with needed practical knowledge and skills, diminishing the importance of excludability while increasing the importance of knowledge exchange.

In any case, our analysis has a clear policy implication: innovation policy needs to adapt to different conditions, especially for early stage technologies. In this regard, patent doctrines such as enablement, which requires inventions to be reproducible, might be particularly important to enforce rigorously. On the other hand, the penchant of some judges to award broad scope to so-called "pioneer patents" might be particularly harmful (Love 2011). Also, policies that affect employee mobility, such as the enforcement of non-compete agreements, might also be important.

References

Allen, R. C. (1983), 'Collective invention', Journal of Economic Behaviour and Organization, 4: 1-24.

Allen, R. C. (2009), The British Industrial Revolution in Global Perspective, Cambridge: Cambridge University Press.

Allen, R. C. (2009b), 'The industrial revolution in miniature: the spinning jenny in Britain, France and India', Journal of Economic History, 69: 901-927.

Arrow, K. (1962). "Economic Welfare And The Allocation Of Resources For Invention," The Rate and Direction of Inventive Activity Economic and Social Factors, 1(P-1856-RC), 609--626.

Bagnall, William R. (1893), The textile industries of the United States: including sketches and notices of cotton, woolen, silk, and linen manufacturers in the colonial period, Volume 1, Cambridge: The Riverside Press.

Barton, D. B. (1969), The Cornish Beam Engine, Truro: D.B. Barton

Bennett, Michael G. (1995). "Us Steel Edgar Thomson Works," (HAER No. PA-384).

Bessen, James. 2003. "Technology and Learning by Factory Workers: The Stretch-Out at Lowell, 1842," Journal of Economic History, 63, pp. 33-64.

Bessen, J. (2011), 'The Two Faces of Innovation,' Boston University School of Law Working Paper 10-35 (previously titled 'Communicating Technical Knowledge'), http://ssrn.com/abstract=1698802,

Bessen, James. (2012a). "More Machines, Better Machines…Or Better Workers?" The Journal of Economic History, 72(01), 44-74.

Bessen, James. (2012b). "Was Mechanization Deskilling," working paper.

Bessen, James and Alessandro Nuvolari (2013). "Knowledge Sharing Among Inventors: Some Historical Perspectives," .

Boldrin, Michele and David Levine, (2008). Against Intellectual Monopoly, Cambridge University Press, Cambridge.

Braguinsky, S. and D.C. Rose (2009). "Competition, Cooperation, And The Neighboring Farmer Effect," Journal of Economic Behavior and Organization, 72(1), 361--376.

Brems, H. (1968). Quantitative Economic Theory: A Synthetic Approach, Wiley, .

Burke, 1876. Transactions of the National Association of Cotton Manufacturers, No. 21, p. 8-9.

Casson, Herbert N. (1907). The Romance Of Steel: The Story Of A Thousand Millionaires, A. S. Barnes & Co., US Steel, .

Chari, V.V. and H. Hopenhayn (1991). "Vintage Human Capital, Growth, And The Diffusion Of New Technology," Journal of Political Economy, 1142--1165.

Cotterau, A. (1997). 'The fate of collective manufactures in the industrial world: the silk industries of Lyons and London,1800-1850' in Sabel, C. and Zeitlin, J. (eds.), Worlds of Possibilities, Cambridge: Cambridge University Press.

Dasgupta, P. and J. Stiglitz (1980). "Industrial Structure And The Nature Of Innovative Activity," The Economic Journal, 266--293.

Davids, K. (2008), The Rise and Decline of Dutch Technological Leadership. Technology, Economy and Culture in the Netherlands, 1350-1800. Vol. I and II, Leiden: Brill.

Draper, George Otis. 1907. Labor Saving Looms, 3rd edition. Draper Corporation.

Epstein, S. (2004), 'Property rights to technical knowledge in premodern Europe, 1300-1800', American Economic Review, 94: 382-387.

Frankel, M. (1955). "Obsolescence And Technological Change In A Maturing Economy," The American Economic Review, 45(3), 296--319.

Fritz, John (1912). The Autobiography Of John Fritz, American Society of Mechanical Engineers, New York, .

Gibb, George. 1950. The Saco-Lowell Shops: Textile machinery building in New England 1813-1949. New York: Russell & Russell.

Gilroy, Clinton G. 1844. The Art of Weaving by Hand and by Power. New York: George D. Baldwin.

Gordon, R.B. (1992). "The" Kelly" Converter," Technology and Culture, 33(4), 769--779.

Griliches, Z. (1957). "Hybrid Corn: An Exploration In The Economics Of Technological Change," Econometrica, Journal of the Econometric Society, 501--522.

Harhoff, D. Henkel, J. and von Hippel, E. (2003), 'Profiting from voluntary information spillovers: how users benefit from free revealing their innovations', Research Policy, 32, 1753-1769.

Holley, Alexander Lyman. 1866. "The Bessemer Process in America," Engineering v. 2, p. 308.

Hunter, L. C. (1949), Steamboats on the Western Rivers. An Economic and Technological History, Cambridge (Mass.): Harvard University Press

Jeans, James Stephen (1880). *Steel: Its History, Manufacture, Properties, And Uses*, London: E & F. N. Spon.

Jeremy, David J. 1973. "Innovation in American Textile Technology during the Early 19th Century," Technology and Culture, 14, pp. 40-76.

Jeremy, David J. (1981). Transatlantic Industrial Revolution: The Diffusion Of Textile Technologies Between Britain And America, 1790-1830S, , .

Jovanovic, B. and S. Lach (1989). "Entry, Exit, And Diffusion With Learning By Doing," The American Economic Review, 690--699.

Jovanovic, B. and G. MacDonald (1994). "The Life-Cycle Of A Competitive Industry," .

Kamien, M.I. and N.L. Schwartz (1972). "Timing Of Innovations Under Rivalry," Econometrica: Journal of the Econometric Society, 43--60.

Lee, T. and L.L. Wilde (1980). "Market Structure And Innovation: A Reformulation," The Quarterly Journal of Economics, 429--436.

Lerner, J. and J. Tirole (2003). "Some Simple Economics Of Open Source," The journal of industrial economics, 50(2), 197--234.

Levin, R. C., Klevorick, A. K., Nelson, R. R., Winter, S. G., Gilbert, R., & Griliches, Z. (1987). Appropriating the returns from industrial research and development. Brookings papers on economic activity, 1987(3), 783-831.

Loury, G. C. (1979). Market structure and innovation. The Quarterly Journal of Economics, 395-410.

Love, Brian (2011). "Interring The Pioneer Invention Doctrine," North Carolina Law Review, 90, 102-175.

MacLeod, C. (1988), Inventing the Industrial Revolution. The English Patent System, 1660-1800, Cambridge: Cambridge University Press.

MacLeod, C., Tann, J., Andrew, J., & Stein, J. (2003). Evaluating inventive activity: the cost of nineteenth-century UK patents and the fallibility of renewal data. The Economic History Review, 56(3), 537-562.

Mak, J. and Walton, G. M. (1972), 'Steamboats and the great productivity surge in river transportation', Journal of Economic History, 32: 619-640.

Mansfield, E. (1961). "Technical Change And The Rate Of Imitation," Econometrica: Journal of the Econometric Society, 741--766.

Mass, William. 1989. "Mechanical and Organizational Innovation: The Drapers and the Automatic Loom," Business History Review, 63(4), pp. 876-929.

McGaw, J. A. (1987), Most Wonderful Machine. Mechanization and Social Change in Berkshire Paper Making, 1801-1885, Princeton: Princeton University Press.

McHugh, J. (1980). Alexander Holley And The Makers Of Steel, Johns Hopkins University Press, .

Meyer, D.R. (2006). Networked Machinists: High-Technology Industries In Antebellum America, Johns Hopkins University Press, .

Meyer, P. (2003), 'Episodes of Collective Invention', US Bureau of Labor Statistics Working Paper 368.

Meyer, P. (2011), 'Open sources in the invention of the airplane', Working Paper.

Mokyr, J. (1976). "Growing-Up And The Industrial Revolution In Europe," Explorations in economic history, 13(4), 371--396.

Mokyr, J. (1990), The Lever of Riches. Technological Creativity and Economic Progress, Oxford: Oxford University Press.

Mokyr, J. (1999). The British Industrial Revolution, Westview Press, .

Mokyr, J. (2008), 'The institutional origins of the industrial revolution' in Helpman, E. (ed.), Institutions and Economic Performance, Cambridge (Mass.): Harvard University Press.

Mokyr, J. (2009), The Enlightened Economy. An Economic History of Britain, 1700-1850, New Haven: Yale University Press.

Montgomery, James. 1840. A Practical Detail of the Cotton Manufacture of the United States of America, First Edition. Glasgow: John Niven.

Moser, P. (2005), 'How do patent laws influence innovation ? Evidence from nineteenth century world's fairs', American Economic Review, 95: 1214-1236.

Moser, P. (2010), 'Innovation without patents. Evidence from world fairs', Working Paper, Stanford University.

Moser, P. and Rhode, P. (2011), 'Did plant patents create the America rose ?', Working Paper, Stanford University.

North, D.C. (1981). Structure And Change In Economic History, Norton New York, .

Nuvolari, A. (2004), 'Collective invention during the British industrial revolution: the case of the Cornish pumping engine', Cambridge Journal of Economics, 28, 347-363.

Nuvolari, A. and Verspagen, B. (2007), 'Lean's Engine Reporter and the development of the Cornish engine: a reappraisal', Transactions of the Newcomen Society, 77: 167-189.

Nuvolari, A. and Verspagen, B. (2009), 'Technical choice, innovation and British steam engineering, 1800-1850', Economic History Review, 62: 685-710.

Olmstead, Alan L. and Paul W. Rhode (2008), Creating Abundance: Biological Innovation and American Agricultural Development, New York: Cambridge University Press.

Parente, S.L. (1994). "Technology Adoption, Learning-By-Doing, And Economic Growth," Journal of economic theory, 63(2), 346--369.

Pole, W. (1844), A Treatise on the Cornish Pumping Engine, London: Weale.

Penin, J. (2007), 'Open knowledge disclosure: an overview of the evidence and motivations', Journal of Economic Surveys, 326-348.

Powell, W. and Giannella, E. (2010), 'Collective invention and inventor networks' in Hall, B. and Rosenberg, N. (eds.), Handbook of Economics of Innovation, Vol. I, Amstersam: Elsevier: 575-605.

Quandt, R.E. (1960). "Tests of Hypotheses that a Linear System Obeys Two Separate Regimes," Journal of the American Statistical Association, 55, 324-330.

Reinganum, J.F. (1983). "Uncertain Innovation And The Persistence Of Monopoly," The American Economic Review, 741--748.

Rogers, E.M. (1962). Diffusion Of Innovations, Free Press of Glencoe.

Rosenberg, N. (1976). "On Technological Expectations," The Economic Journal, 86(343), 523--535.

Rossiter, Raymond (1896). "Pittsburg Meeting Of American Institute Of Mining Engineers," Engineering News and Railway Journal, 135.

Salter, W. E. G. 1960. Productivity and technical change, Cambridge: Cambridge University Press.

Temin, P. (1964). Iron And Steel In Nineteenth-Century America: An Economic Inquiry, MIT Press.

Thomson, R. (2009), Structures of Change in the Mechanical Age. Technological Innovation in the United States, 1790-1865, Baltimore: Johns Hopkins University Press.

Wallace, A. F. (1978), Rockdale: The Growth of an America Village in the Early Industrial Revolution, Knopf: New York.

Ware, Caroline. 1931. The Early New England Cotton Manufacture. Boston and New York: Houghton Mifflin.

Williamson, J.G. (1971). "Optimal Replacement Of Capital Goods: The Early New England And British Textile Firm," The Journal of Political Economy, 1320--1334.

von Hippel, E. (1987), 'Cooperation between rivals: informal know-how trading', Research Policy, 16: 291-302.

von Hippel, E. (1988). The Sources Of Innovation, Cambridge: MIT Press.

Zevin, R.B. (1971). "The Growth Of Cotton Textile Production After 1815," in Robert Fogel and Stanley Engerman, The Reinterpretation of American Economic History, New York: Harper and Row.

Table 1.

	Power weaving	**Bessemer steel**	**Cornish Engine**
Duration	1817 - 1833	1867 – 1877	1811-1904 (publication of *Lean's Reporter)*
Profits from operations	Textile mills, dividends to capital: 8.0%-27.5% (1817-26); 5.0%-13.8% (1827-36) Machine shop, sales margin: 23%-33% (1820-30)	Annual profits: 20% –130% of capital	See table 2
Coexisting products (initial)	Handloom weaving, British imports, wool, linen	Iron rail, British imported rail	Boulton and Watt low pressure engines
Replacement (end)	Replaces handloom, coarse imports	57% market share	100% share in Cornwall
Was incumbent market competitive?	Yes	Yes	Yes
Constraints on scale	Knowledge	Knowledge	Knowledge/Geological constraints on expansion
Productivity gain	79% less labor time/output	78% reduction in price of steel rail less price of pig iron	See figure 2
Patent royalties / profits from operations	< 1%	< 3% (original patents)	No patents

Table 2: Profitability of some Cornish mines (1811-1895)

Mine	Year-engine (reported,1811-1876)	Investments (£)	Dividends (£)	Return per £ invested
Dolcoath	90	45238	904641	19.997
Carn Brea	35	134525	392500	2.918
Cook's Kitchen	27	175379	28582	0.163
South Wheal Frances	26	80888	203164	2.512
North Roskear	24	50700	58800	1.160
Tincroft	23	92250	348900	3.782
Wheal Basset	19	78298	341709	4.364

Own computation based on Morrison (1980).

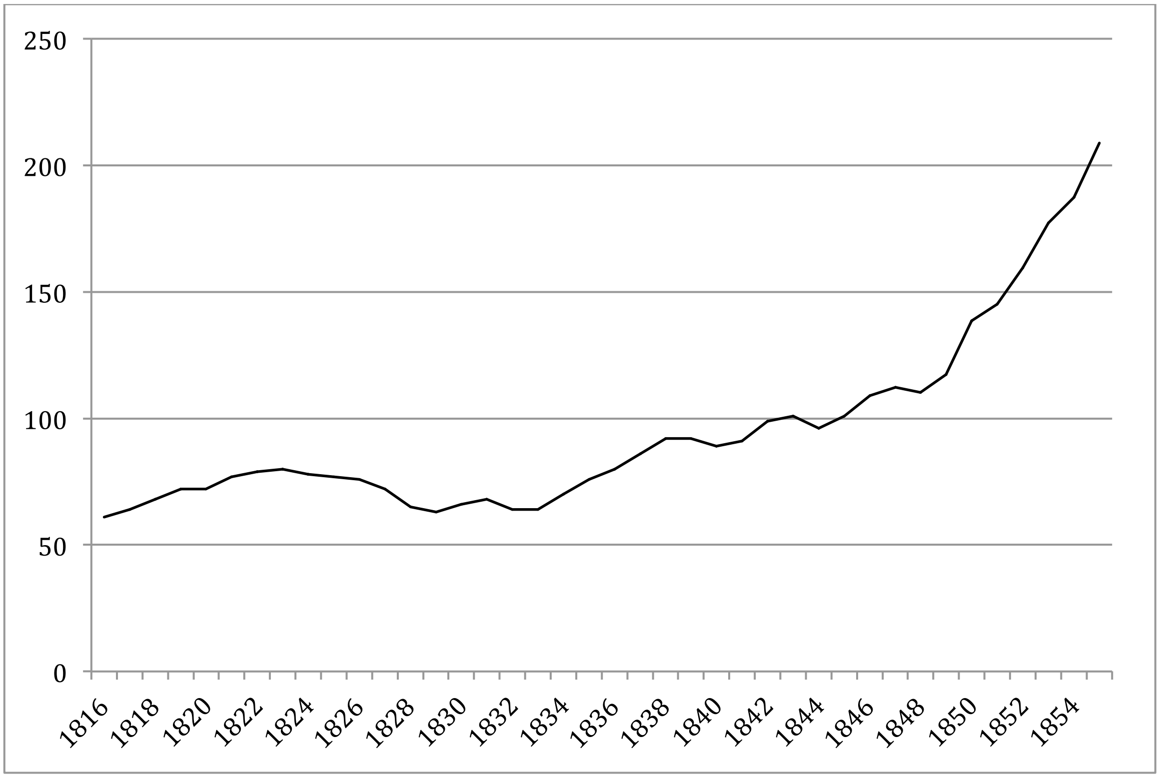
Table 3: Geographical Distribution of British Steam Engine Patents, 1698-1852

County	N.of Patents 1698-1852	% 1698-1852	N.of Patents 1698-1812	% 1698-1812	N.of Patents 1813-1852	% 1813-1852
Cheshire	14	1.23	0	0.00	14	1.39
Cornwall	17	1.50	8	6.25	9	0.89
Cornwall*	21	1.85	12	9.38	9	0.89
Derby	11	0.97	1	0.78	10	0.99
Durham	13	1.15	0	0.00	13	1.29
Essex	6	0.53	0	0.00	6	0.60
France	21	1.85	0	0.00	21	2.09
Gloucester	20	1.76	8	6.25	12	1.19
-Bristol	12	1.06	4	3.13	8	0.79
Hampshire	9	0.79	0	0.00	9	0.89
Ireland	13	1.15	1	0.78	12	1.19
Kent	31	2.73	1	0.78	30	2.98
Lancashire	145	12.78	5	3.91	140	13.90
-Liverpool	35	3.08	1	0.78	34	3.38
-Manchester	58	5.11	2	1.56	56	5.56
London & Middlesex	395	34.80	40	31.25	355	35.25
Northumberland	22	1.94	2	1.56	20	1.99
-Newcastle-up.-Tyne	11	0.97	1	0.78	10	0.99
Nottingham	13	1.15	1	0.78	12	1.19
Scotland	47	4.14	6	4.69	41	4.07
-Edinburgh	9	0.79	0	0.00	9	0.89
-Glasgow	22	1.94	3	2.34	22	2.18
Shropshire	6	0.53	3	2.34	3	0.30
Somerset	4	0.35	2	1.56	2	0.20
-Bath	2	0.18	1	0.78	1	0.10
Stafford	27	2.38	5	3.91	22	2.18
Suffolk	5	0.44	0	0.00	5	0.50
Surrey	88	7.75	10	7.81	78	7.75
USA	13	1.15	2	1.56	11	1.09
Wales	12	1.06	1	0.78	11	1.09
Warwick	58	5.11	8	6.25	50	4.97
-Birmingham	55	4.85	6	4.69	49	4.87
Worcester	11	0.97	1	0.78	10	0.99
York	63	5.55	11	8.59	52	5.16
-Bradford	11	0.97	0	0.00	11	1.09
-Kingston-up.-Hull	9	0.79	2	1.56	7	0.70
-Leeds	17	1.50	3	2.34	14	1.39
-Sheffield	6	0.53	0	0.00	6	0.60
Others	71	6.26	12	9.38	70	6.95
Total	1135	100.00	128	100.00	1007	100.00

* Cornwall including the patents taken by Arthur Woolf

Source: The list of steam engine patents is taken from *Abridgments of Specifications relative to the Steam Engine*, London, 1871. In order to retrieve the stated residence of the patentees, these patents have been matched with those contained in B. Woodcroft, *Titles of Patents of Invention Chronologically Arranged*, London, 1854.

Figure 1. US loom patents in force



Sources: Burke (1847) and USPTO. The data from 1816 through 1846 come from Burke (1847); we count patents described as looms, bobbins, cloth manufacture, and weaving and assume a 14 year term. After 1846, the patent counts come from the USPTO technology class database, dated December 2010. We include class 139, "Textiles: weaving," excluding subclasses less than 35 (Miscellaneous, Pile tufting, special-type looms), greater than 380 (mainly Fabrics), and 318-335 (Pattern Mechanisms). Because the classifications are different for the two data sources, we adjusted the counts after 1846 by the ratio of total patents granted in each database for the years 1836-46, when the two sources overlap.

Figure 2: Duty of Cornish Engines (source: Nuvolari & Verspagen 2009)

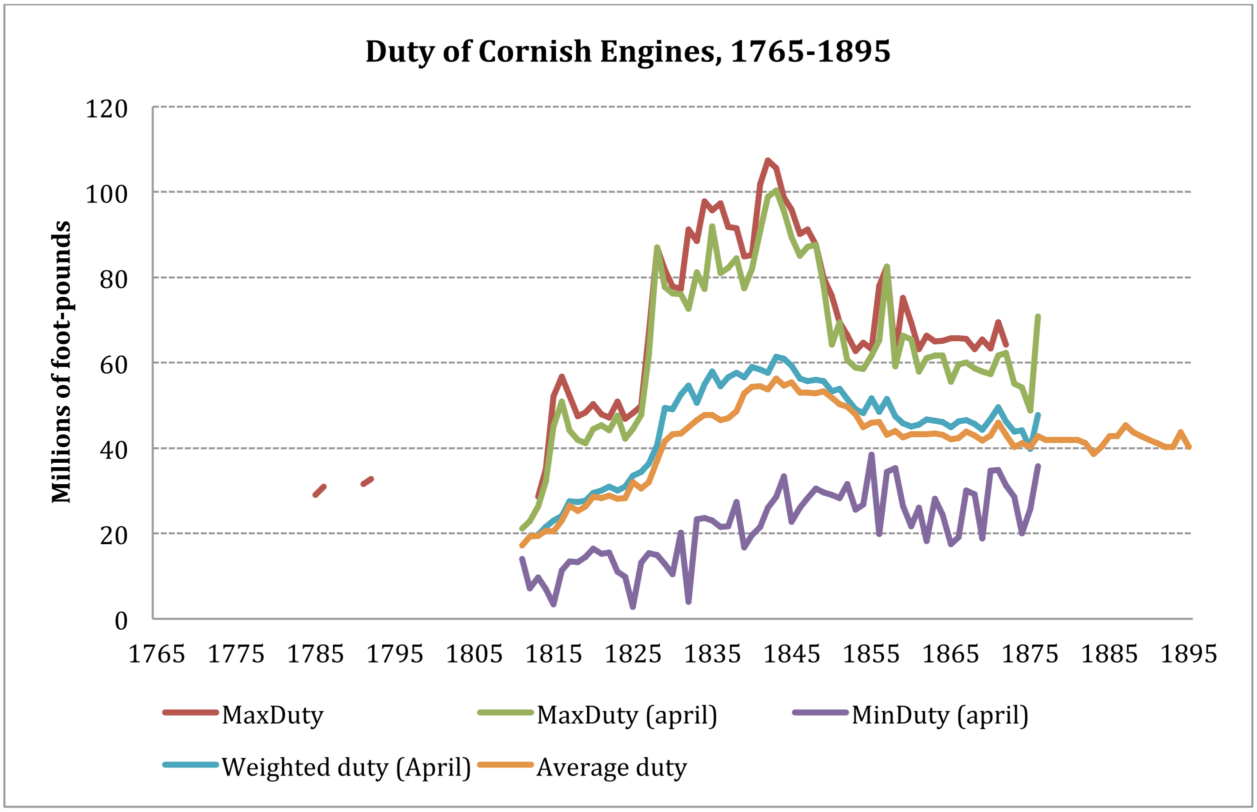


Figure 3: Production of the Camborne-Redruth Mines (1811-1895) (Source: Morrison, 1980).