The Anatomy of Collective Invention Processes: A Study of Early Nineteenth Century Steam Engineering*

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1. Introduction

According to T.S. Ashton, generations of schoolboys were accustomed to consider the industrial revolution as “a wave of gadgets [that] swept over England” (Ashton, 1948, p.48). Although admittedly crude, the definition of the industrial revolution as a cluster of key technological innovations (steam engine, textile machinery, iron production techniques, etc.) is still held to capture a good deal of historical truth. Traditionally, the history of these inventions has been told in terms of creative leaps of “technological” imagination made by individual inventors. Modern scholarship has qualified this view, but, in many respects, still regards the early phase of industrialization as the “heroic age” of independent inventors.

One of the main qualifications to what one might call the “heroic” account of the generation of new technologies during the early phases of industrialization is the acknowledgement of the central importance of incremental improvements. In fact, new technologies first appear in a rather rudimentary form and a long process of improvement is necessary before they could fully manifest their technical and economic potential. This process of incremental improvements, stemming from various learning processes occurring on both the producer’s and the user’s side, is, as argued by Rosenberg (1976), simultaneous with the diffusion of the innovation. It seems quite clear, then, that the dynamics of technological change exhibit both continuities and radical ruptures. Hence, a satisfactory theory of innovation must consider both aspects and the interconnections between them. In this respect, the adoption of evolutionary approaches has been particularly illuminating. Mokyr (1990) has argued that discontinuities in the evolution of a technology are the product of the introduction of “macroinventions”, that is inventions that open up entirely novel technological domains. After the emergence of a macroinvention, a technology progresses gradually by means of small incremental steps (“microinventions”).

Many modern empirical studies of innovation also highlight that technologies are developed through a continuous process of interactive learning in which a multitude of agents are involved (see Freeman, 1994 for a comprehensive overview). According to Mokyr, an appropriate “technological definition” of the industrial revolution is “a clustering of macroinventions leading to an acceleration in microinventions” (Mokyr, 1999, p.23).

The economic significance of these streams of incremental improvements during early industrialization has been stressed in several accounts (see among others Landes, 1969; Mathias, 1969; and David, 1975). Appropriately, Landes terms this type of innovations as “anonymous” technical change, to emphasize that their nature is markedly different from the most “visible” individual acts of invention, that have attracted the attention of historians of technology. Landes suggests that these “small anonymous gains were probably more important in the long run than the major inventions that have been remembered in history books” (Landes, 1969, p.92).

Given the central role that incremental technical change seems to have played during the industrial revolution, it is worth reflecting on the sources of this particular type of invention. According to Allen (1983), in capitalist economies four main sources of invention can be discerned: i) non-profit institutions (such as universities and publicly

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1 Mokyr’s conceptualisation of technical change has clearly many commonalities with the approach in terms of technological paradigms and trajectories originally proposed by Dosi (1982, 1988).
funded research centres), ii) private firms’ R&D laboratories, iii) individual inventors (such as James Watt and Richard Arkwright), iv) collective invention settings. In collective invention settings, competing firms freely release pertinent technical information on the construction details and the performance of the technologies they have just introduced to one another.

Allen has noticed this type of behaviour in the iron industry of Cleveland (UK) over the period 1850-1875. In the Cleveland district, iron producers freely disclosed to their competitors technical information concerning the construction details and the performance of the blast furnaces they had erected. In the words of Allen,

...if a firm constructed a new plant [more specifically, a blast furnace] of novel design and that plant proved to have lower costs than other plants, these facts were made available to other firms in the industry and to potential entrants. The next firm constructing a new plant build on the experience of the first by introducing and extending the design change that had proved profitable. The operating characteristics of the second plant would then also be made available to potential investors. In this way fruitful lines of technical advance were identified and pursued (Allen, 1983, p.2).

Information was normally released through both formal (presentations at meetings of engineering societies and publications of design details in technical journals) and informal channels (such as visits to plants, conversations, etc.). Additionally, new technical knowledge was normally not protected by patents, so that competing firms could liberally make use of the released information when they had to erect a new plant. As a consequence of the proliferation of these “voluntary” knowledge spillovers, in the period considered, the height of the furnaces and the blast temperature increased steadily by means of a series of small but continuous rises. Increases in furnace height and in the blast temperature brought about lower fuel consumption and lower production costs. On the basis of his findings, Allen suggests that the pattern of technical change emerging from collective invention settings is dominated by incremental innovations. One may indeed argue that the main thrust of Allen’s contribution is the identification of a specific institutional arrangement which constitutes one of the most favourable environments for micro-inventive activities.

The main contention of this paper is that together with individual inventors, collective invention settings were a crucial source of innovation during the early phases of industrialization. Until now, this has been very little considered in the literature. Furthermore, some recent contributions (Dutton, 1984; Lamoreaux, Sokoloff and Khan in a number of recent papers) have stressed the stimulating impact exerted by the patent system and, relatedly, by the development of a market for (patented) technologies on the rate of technical innovation. We argue that the importance of incremental innovations and of collective invention settings casts some doubt on the general validity of such a proposition. We shall develop our argument by means of a detailed case study of the Cornish mining district during the British industrial revolution. This case is particularly remarkable because the Cornish mining district was capable of generating a continuous and sustained flow of improvements in steam

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Note that Allen’s notion of “collective invention” does not refer to the exchange of information between users and producers studied by Lundvall (1988). In fact, Allen is describing an exchange of information among competing entities. “Collective invention” also differs from “know-how trading” described by von Hippel (1987). In “know-how trading”, engineers “trade” proprietary know-how in the sense the information is exchanged on a bilateral basis (non-participants to the transaction in question are excluded). In collective invention settings, all the competing firms of the industry have free access to the potentially proprietary know-how, see von Hippel (1987), pp. 296-297. Cowan and Jonard (2003) have recently proposed a model which analyzes the diffusion of knowledge in collective invention settings.
engineering which, in the end, greatly contributed to raising the thermodynamic efficiency of the steam engine. As we will see, innovations in Cornish steam engines originated from collective invention processes of the type described by Robert Allen. We will study in detail the specific economic and technical circumstances that led to the formation of this particular collective invention setting and we analyze its consequences for the rate of technological innovation. Our study will point out (once more) the historical significance of “anonymous” incremental technical advances, but it will also demonstrate that economic historians cannot rely simply on the emergence of an intellectual property rights regime to explain the acceleration of technical change in this historical phase.

2. Patent Institutions and Individual Inventors

Historians of technology have produced detailed accounts of the generation of new technologies during the industrial revolution. In many of these accounts, individual inventors are put centre stage (Cardwell, 1994, see especially the section on pp. 496-501 significantly entitled “In defence of Heroes”). One important reason that has motivated this focus on individual inventors is that historians of technology, such as Cardwell or Musson and Robinson, have been mainly interested in shedding light on the nature of the connections between science and technology in this critical period, and one relatively straightforward way to do so is to study in detail single inventions, trying to appraise how developments in science affected them (see among others Musson and Robinson, 1969; Cardwell, 1971; Musson 1972 contains an important critical overview of the studies dealing with connection between science and technology during the industrial revolution).

Economic historians, instead, have paid considerably less attention to the ways in which new technologies were drawn into play. In this respect, they seem to have accepted the view that ascribes the generation of new technologies to the actions of independent individual inventors. What is in need of explanation, then, is why Britain in this period was such a fertile soil for individual inventors, especially when compared to other European countries (Mokyr, 1999).

From a strictly economic point of view, the most straightforward explanation is that, in Britain, the rewards for inventive activities were high enough to attract a considerable amount of economic resources and human talents into this field. Following this line of reasoning, a number of scholars have turned their attention to the patent system. North (1981, pp. 164-166) has suggested that the acceleration in the rate of technological innovation in Britain during the eighteenth century should be considered as a direct consequence of the progressive development of a fully operational patent system.

Dutton (1984) has explicitly considered the connection between the patent system and inventive activities in Britain. The available evidence, according to Dutton, indicates that the British patent system, although granting an imperfect protection and requiring the fulfilment of cumbersome and costly bureaucratic procedures, was nevertheless capable of stimulating inventors’ efforts. Many inventors devoted time and resources to inventive activities with the perspective of appropriating economic returns through patent protection. It is also interesting to note that a fairly large number of patents were taken by “quasi-professional” inventors, that is to say individuals with several varied patents. Additional evidence shows that technological knowledge protected by patents, was the object of a robust “trade in
invention”. Hence, the development of the patent system in Britain led to the emergence of “an infant invention industry” (Dutton, 1984, p.104). Moreover, the imperfect protection granted by the patent system allowed for some imitation, and this, in many cases, facilitated a relatively quick diffusion of many innovations. All in all, Dutton’s conclusion is that the British patent system had a highly positive effect on the rate of technical change.

Christine MacLeod (1988) has instead suggested a more nuanced viewpoint. First, one has to take into account that the propensity to patent varied widely across industries and also across regions. Second, a great deal of inventive activities were carried out outside the patent system. Third, patents were taken for a variety of reasons, besides the aim of protecting inventions. All this makes it indeed very difficult to reach strong conclusions concerning the overall impact exerted by the British patent system on inventive activities.

We should take into account, however, that the first patent system working by what we might consider truly modern procedures was not the British, but the American one (Khan and Sokoloff, 1998; see MacLeod 1991 for an outline of the emergence of patent institutions in Britain, France and the United States). For this reason, one could argue that the validity of North’s hypothesis linking the acceleration in the rate of innovation and the emergence of patent institutions ought to be examined primarily in the case of the United States.

In a number of recent papers Sokoloff, Lamoreaux and Khan have tackled exactly this issue, examining the relationship between the patent system and inventive activities in the United States in the course of the nineteenth century. Their contributions are based on an extensive quantitative analysis of evidence collected from the patent records. Sokoloff (1988) and Khan and Sokoloff (1993) have examined the issue of the responsiveness of individual inventors to the economic inducements granted by the patent system over the period 1760-1865. They conclude that American inventors sought consistently to secure patent rights for their inventions and that patent protection permitted a quite effective appropriation of economic returns stemming from inventive activities. Furthermore, the attitude of the courts in litigation cases, by and large, reinforced the effectiveness of the patent system, providing patentees with reasonable perspectives of enforcing their intellectual property rights (Khan, 1995). In related contributions, using data on the licensing behaviour of a large number of patentees, Lamoreaux and Sokoloff (1996, 1999a, 1999b) argue that in the United States, in the course of the nineteenth century, a solid market for technical innovations structured around the institution of the patent system progressively emerged. Through this well functioning “market for technology”, individual inventors were able to sell the new technical knowledge they had discovered to firms. The existence of this type of market promoted a fruitful division of labour with “technologically creative individuals” (Lamoreaux and Sokoloff, 1999b, p.3) specializing in inventive activities, and firms in the production and commercialisation phases. Hence, the coupled development of the patent system and of the market for technology determined a steady acceleration in the rate of innovation.

More specifically, Sokoloff, Lamoreaux and Khan distinguish two phases characterizing the historical pattern of nineteenth century inventive activities in the United States (see, Lamoreaux and Sokoloff, pp. 12686-12687). The first phase covers approximately the period, 1790-1846. In this period, inventive activities are widely widespread across the entire population (“democratization of invention”). The rather simple nature of technology permitted to relatively ordinary citizens with common skills to be engaged in inventive activities. The second phase covers the period 1840-1920. In this period (due to the spread of mechanization and the increasing complexity of technology) inventions were primarily produced by individuals with technical
Lamoreaux and Sokoloff (2000) consider the case of the American glass industry. In this case too, they found evidence of the existence of a solid market for technologies operating through two channels: i) specialized trade journals disseminating general information and providing detailed descriptions of patent specifications; ii) specialized patent agents who were able to act as intermediaries in the sale of patented technologies. In the same study, Lamoreaux and Sokoloff also notice that a number of locations with high patenting activities were characterized by little glass production. In their view, this finding indicates that “learning by doing” and “localized knowledge spillovers” (two factors that have been prominently put forward to explain the connection between the localization of production and innovation) played a relatively minor role in the technological development of the industry. Geographical clusters of patenting in the American glass industry are instead accounted for by the existence of a more developed market for technologies in those areas. Although Lamoreaux and Sokoloff acknowledge that it is hard to draw robust generalizations, they contend that, by combining the evidence of the glass industry with their findings for the economy as a whole, the proposition that the development of the patent system produced a tidy and fruitful division of labour between innovation and production appears to be confirmed.

Finally, Khan and Sokoloff (1998) have compared the British patent system with the American one. Undoubtedly, the British patent system before the 1852 reform was far less effective than the American in protecting the intellectual property rights of the patentee. Furthermore, patent fees (and the other connected expenditures necessary to take out a patent) were considerably higher in Britain than in the United States, and this considerably restrained access to the system. On the basis of the previous discussion, Khan and Sokoloff suggest that the rate of innovation was probably lower in early industrial Britain than in the United States. In addition, high patent fees in Britain may have also induced a specialization of inventors in highly capital-intensive technologies (where it would have been easier to enforce patent rights and extract higher economic returns). In the end, this should have produced a more biased pattern of technical change in Britain (with more rapid technical change in capital-intensive industries).

As should be clear from this concise summary of their contributions, Lamoreaux, Sokoloff and Khan have elaborated a complex account of technical change in the course of the industrialization of the United States, which is in many respects similar to the one originally proposed for Britain by Dutton. It is worth stressing again that their interpretation, more or less explicitly, downplays the role of learning by doing and of knowledge spillovers in nineteenth-century technical advances.

On the other hand, as we have already pointed out in the previous section, many accounts of the industrial revolution have instead emphasized the crucial role of incremental innovation and learning by doing. This leads us to investigate the nature of the connection between processes of incremental innovation and patent institutions in the course of the industrial revolution. The Cornish mining district is a particularly interesting case for the purposes of the present discussion. In the first half of the nineteenth century, Cornwall was “one of the backgrounds that were strongly committed to inventive activities. The market for technology reinforced this process of specialization.
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 patent system.

3. Boulton and Watt in Cornwall

In Britain during the seventeenth and eighteenth centuries mining activities were severely hampered by flooding problems. Not surprisingly, some of the first attempts at employing steam power were aimed at finding a workable solution to mine draining problems. In 1712, after a prolonged period of experimentation, Thomas Newcomen developed a steam pumping engine that could be used effectively for mine drainage. Using steam at only atmospheric pressure, the Newcomen engine was well within the limits of the engineering capabilities of the time. Moreover, the Newcomen engine was robust, reliable and based on a quite simple working principle. As a consequence, once it was installed, it could work for a long period with almost negligible maintenance costs. Given these merits, it is not surprising that Newcomen types of engines soon became of widespread use in mining activities.

The Newcomen engine had the major shortcoming of a high fuel consumption, which was determined by the necessity of alternatively heating and cooling the cylinder at every stroke. In coal mining, where large supplies of cheap coal were available, high fuel consumption did not represent a major limitation, but in other mining areas fuel inefficiency did not permit a widespread diffusion of the engine (von Tunzelmann, 1978, chap. 4).

Since the early diffusion of the Newcomen engine, fuel consumption was considered as the main “metric” to be used in the evaluation of the overall performance of a steam engine. The most common measure of fuel efficiency was termed the “duty” and was calculated as the quantity of water (measured in lbs.) raised 1 foot high per 1 bushel (84 lbs.) of coal consumed. From an engineering viewpoint, the duty is a measure of the thermodynamic efficiency of the steam engine. However, ‘duty’ has also an important economic meaning because it is a measure of the productivity of a steam engine with respect to the largest variable input used in the production process (von Tunzelmann, 1970, pp.78-79).

In 1769 James Watt conceived an alteration to the basic design of the steam engine (the introduction of the separate condenser) that allowed for a drastic reduction in coal consumption. The Newcomen engine, as improved by John Smeaton in the early 1770s, was capable of a duty between 7 and 10 millions (lbs.). Watt initially raised the duty to 18 millions and later, when the engine design was fully refined, to 26 millions (Hills, 1989, p.131).

By virtue of their fuel economy, Watt engines became a particularly attractive proposition in locations where coal was expensive. Not surprisingly, the first important market for this type of engine was the Cornish copper and tin mining industry. In Cornwall, coal had to be imported from Wales by sea and was extremely expensive. Between 1777 and 1801, Boulton and Watt erected 49 pumping engines in the mines of Cornwall. Jennifer Tann has described the crucial role of the “Cornish business” for the fortunes of the two partners in these terms:

Whether the criterion is the number of engines, their size or the contribution to new capital, Cornish engines comprised a large proportion of Boulton & Watt’s business during the late 1770s to mid 1780s. From 1777 to 1782, Cornish engines accounted for more than 40% of Boulton & Watt’s total business and in some years the figure was significantly higher. In the early 1780s Cornish business was more fluctuating but with the exception
of 1784, Cornish engines accounted for between 28% and 80% of Boulton & Watt’s business (Tann, 1996, pp. 29-30).

The typical agreement that Boulton & Watt stipulated with the Cornish mine entrepreneurs (commonly termed “adventurers”) was that the two partners would provide the drawings and supervise the works of erection of the engine. They would also supply some particularly important components of the engine (such as some of the valves). These expenditures would have been charged to the mine adventurer at their cost (i.e. not including any profit for Boulton & Watt). In addition, the mine adventurer had to buy the other components of the engine not directly supplied by the two partners and to build the engine house. These were all elements of the total fixed cost associated with the erection of a Boulton & Watt engine.

The profits for Boulton & Watt resulted from the royalties they charged for the use of their engine. Watt’s invention was protected by the patent for the separate condenser he took out in 1769, which an Act of Parliament prolonged until 1800. The pricing policy of the two partners was to charge an annual premium equal to one-third of the savings of the fuel costs attained by the Watt engine in comparison to the Newcomen engine. This required a number of quite complicated calculations, aimed at identifying the hypothetical coal consumption of a Newcomen engine supplying the same power of that of the Watt engine installed in the mine.

At the beginning, this type of agreement was rather favourably accepted by Cornish mine adventurers. However, after some time, the pricing policy of Boulton and Watt was perceived as extremely oppressive. Firstly, the winter months during which most water had to be pumped out (and, consequently, the highest premiums had to be paid) were the ones in which mines were in general least productive. Secondly, mine adventurers knew the exact amount of payments they owed to Boulton and Watt only at the end of the month when these were actually due (Dickinson and Jenkins, 1927, p. 333). Finally and most importantly, in the late eighteenth century, several engineers in Cornwall had begun to work on further improvements to the steam engine, but their attempts were frustrated by Boulton and Watt’s interventions. Watt’s patent was very broad in scope (covering all engines making use of the separate condenser and all engines using steam as a “working substance”). The enforcement of almost absolute control on the evolution of steam technology, using the blocking power of the patent, was indeed a crucial component of Boulton & Watt’s business strategy. This strategy was motivated by the peculiar position of the company (as consulting engineers decentralizing the major part of engine production). All in all, it seems quite clear that Watt’s patent had a highly detrimental impact on the rate of innovation in steam technology (Kanefsky, 1978).

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The calculation system was cumbersome and the figures computed were frequently objected to, so that in a number of cases, Boulton and Watt decided to switch to an annual fix sum based on the general fuel saving potentialities of the engine they had installed, in the hope of avoiding the nuisances related with the computation of the actual coal savings, see Barton (1965), p. 31. However also the fixed annual sums were frequently disputed, especially when mines were not profitable. It must be remembered that from the early 1780s, the exploitation on large scale of the Parys Mountain copper mines in Anglesey determined a reduction in copper prices putting the profitability of many Cornish mining ventures under strain, see Rowe (1953, pp. 71-72 and p. 76).
The most famous case in this respect is that of Jonathan Hornblower, a Cornish engineer, who had taken a patent for the first compound engine in 1781 and who found the further development of his invention obstructed by the actions of Boulton and Watt. In 1782 a first engine of the Hornblower type was erected for the Radstock colliery near Bristol. Initially the performance of the engines was far from being satisfactory. After a period of experimentation, however, this engine was capable of delivering a performance comparable to the one of Watt engines. In 1791, Horblower began to erect engines in several Cornish mines, threatening Boulton and Watt’s monopoly position. Concomitantly, he applied to Parliament for an extension of his 1781 patent. The argument on which Hornblower based his petition to Parliament was the same underlying Watt’s petition of 1775: the engine had required a long and costly period of refinement after the patent was taken, so an extension was necessary to enable him to reap a fair profit from his invention. Boulton and Watt opposed the petition on the grounds that the salient features of the engine were a clear plagiarism of Watt’s invention. As in the case of the prolongation of Watt’s 1769 patent, Boulton’s powerful influence succeeded in gaining the consensus of Parliament and the bill requested by Hornblower was rejected.5

Yet, the conflict was far from being settled. After the Parliament’s decision, Hornblower went on erecting his engines in Cornish mines. Many Cornish adventurers saw in his engines the possibility of further curtailing their costs, by avoiding the payment of the high royalties claimed by Boulton and Watt. At the same time, another Cornish engineer, Edward Bull began to install steam engines for several Cornish mines. Bull’s engines were essentially a simplified version of Watt (they dispensed the beam, the piston rod acting directly the pumps) and thus a much clearer case of piracy than Hornblower’s, but at this point of time the majority of Cornish mine entrepreneurs were ready to explicitly challenge the validity of Watt’s patent monopoly.

Boulton and Watt had no other choice but to sue Bull for infringement. In his defence, Bull called explicitly in question the validity of Watt’s patent on the basis of the insufficiency of the specification. The dispute ended in 1799 with the courts confirming the legal validity of Watt’s patent and, in this way, attributing a complete victory to Boulton & Watt.

During the lawsuit, Watt published an insertion in the Bristol newspapers claiming that his 1769 patent covered all the following features: 1) cylinder with closed top, 2) piston pressed by steam (instead of atmospheric pressure as in the Newcomen engine, 3) steam case to cylinder, 4) separate condenser, 5) air pump, 6) piston kept tight by oil or grease (Dickinson and Jenkins, 1927, p. 305). In practice, it is impossible to move away from the design of the Newcomen engine, without making use of some of these features (Jenkins, 1931).

Hornblower, instead, considered Watt’s patent limited to the separate condenser. In his engine steam condensation took place in the lowest part of the second (low-pressure) cylinder and for this reason Hornblower was convinced that he was not infringing Watt’s patent. He later found out that the separate condenser could greatly improved the performance of his engine. Basically, Hornblower could not fully exploit his invention without infringing Watt. This was indeed the main motivation behind his decision to apply to Parliament for an extension (Hornblower patent of 1781 would have expired in 1795). In

5 On the conflict between Boulton and Watt and Jonathan Hornblower, see Rowe (1953), pp. 90-95.
this way, he could have enjoyed a period of protection after the expiration of Watt’s patent. As we have seen, Parliament turned down the request. At that point Hornblower decided to adopt the separate condenser in his engines relying on the insufficient specification of Watt’s patent. The performance of the Hornblower engine in its final form was roughly equal to a Watt engine in good conditions.\textsuperscript{6}

After the clash on the prolongation of patent, Boulton and Watt and Jonhatan Hornblower did not meet again in court. Boulton and Watt adopted the cautious strategy of starting their campaign of legal actions by suing makers of engines who were clearly infringing the patent. The first lawsuit was the one directed against Edward Bull; a second lawsuit was directed against Jabez Hornblower (brother of Jonathan) and Maberley who had started erecting pirate rotative engines in the London area. On the basis of the victory obtained in these two cases, Boulton and Watt sent injunctions to all the other users of “pirate” engines they could identify (including the owners of Jonathan Hornblower’s ones). At this point, none of them was available to fight further and so they all came to some form of settlement for the payment of the royalties. In Cornwall, the dispute also had other far-reaching consequences. Boulton and Watt, with their legal victory (pursued with relentless determination), completely alienated any residual sympathy towards them. After the expiration of Watt’s patent in 1800, steam engine orders to Boulton and Watt from Cornish mines ceased completely and the two partners had to call William Murdock, their engineer working in the county back to Birmingham. However, it is also important to mention that, at this stage, the market for industrial power had become the main focus of the company.

4. The Cornish engine as a case of collective invention

Following the departure of Boulton and Watt, the maintenance and the improvement of Cornish pumping engines underwent a period of “slackness”, as the mine adventurers were content with the financial relief coming from the cessation of the premia. This situation lasted until 1811, when a group of mine “captains” (mine managers) decided to begin the publication of a monthly journal reporting the salient technical characteristics, the operating procedures and the performance of each engine. The explicit intention was twofold. First the publication would permit the rapid identification and diffusion of best-practice techniques. Secondly, it would create a climate of competition among the engineers entrusted with the different pumping engines, with favourable effects on the rate of technical progress. Joel Lean, a highly respected mine captain, was appointed as the first “engine reporter”. The publication was called \textit{Lean’s Engine Reporter}. After his death, the publication of the reports was continued by his descendents and lasted until 1904.\textsuperscript{7}

\textsuperscript{6} Working at low pressures, the Hornblower engine could not exploit the advantages of compounding. Interestingly enough, about 1785, Hornblower discussed with Davies Gilbert (who would also engaged in a long correspondence with Richard Trevithick on the subject of the efficiency of steam engines) the possibility of adopting in his compound engines “the condensation of steam raised by quick fire” (i.e., high pressure steam and expansion), see, Todd (1967, p.94).

\textsuperscript{7} The first three reports were published on the \textit{West Briton}, a local newspaper. From 1812 \textit{Lean’s Engine Reporter} appeared as an independent publication. Joel Lean died in September 1812. After his death the reporter was continued by his two sons Thomas (I) and John for the years 1812-1827. In the period 1827-1831 the two brothers compiled two separate reports. The period 1831-1837 was covered by Thomas I alone and the period 1837-1847 by Thomas I in collaboration with his brother Joel (II). After that, Thomas II (Thomas I’s son) took charge of the reporter for the period 1847-1897. The final years 1897-1904 were covered by J. C. Keast.
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.

![Figure 1: Duty of Cornish Engines, 1769-1895](image_url)

**Sources:** 1769, 1772, 1776, 1778 (Lean, 1839); 1779, 1786, 1792 (Dickinson and Jenkins, 1927); 1798 Gilbert (1830); 1811-1872 (Lean II, 1872); 1873-1895 Trestrail (1896).

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:

Trevithick only regarded this engine as a small model designed to demonstrate what high-pressure could do. He claimed no patent rights for it; others were free to copy it if they would (Rowe, 1953, p.124).\(^8\)

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\(^8\) 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 explorations of the merits of the use of high-pressure steam used expansively.

Figure 1 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.

![Figure 1: Time series of Cornish steam engine efficiency](Image)

**Figure 2: Cornish copper ore production and duty of Cornish engines, 1771-1900**


The rate of innovation in Cornish engines appears to be rather tightly linked with the rate of capital formation. This is illustrated in figure 2 that shows that the period of increasing duty figures coincided with the rapid expansion of the Cornish copper mining industry (period 1810-1840), vice versa the phase of recession, beginning in the late 1840s, is coupled with a decline of average duty and best duty. A possible explanation for connection between the expansion of production and the growing efficiency of Cornish engines is that the installation of new productive capacity during the expansion phase permitted experimentation with design alterations prompting the discovery of new improvements. Conversely the phase of recession of the Cornish mining industry is characterized by a slow decline of average duty followed by a period of substantial stagnation. This link between capital accumulation and technical change has also been pointed out by Allen (1983) in his study of the Cleveland iron industry.

The case of the Cornish pumping engine seems to be indeed an “exemplar” case of collective invention in the sense of Allen. In his paper, Allen individuates three essential features of collective invention settings: i) the overall rate of technical change is dominated by incremental innovations; ii) firms make publicly available pertinent technical information
on the relative performance of various designs and operating practices; iii) firms employ this common pool of technological knowledge to further improve the technology in question. All these three propositions are amply corroborated in the case of the Cornish engine.

Almost every student of the technological history of the steam engine has pointed to the incremental nature of technical advances in the Cornish pumping engines (see e.g. Cardwell, 1971, pp.180-181). This is also apparent when looking at the contemporary engineering literature. For example, William Pole, author of a *Treatise on the Cornish Pumping Engine* noticed:

The alterations introduced since 1821 may be described as consisting principally in carrying out to a further extent the principle of expansion, by using steam of higher pressure, and cutting it off earlier in the stroke....in a considerable extension of boiler surface in proportion to the quantity of water evaporated; in improvements of minor details of the engine and of the construction of the working parts, particularly the pump work....and in the exercising of the most scrupulous care in guarding against waste or loss of heat by any means. All this has been done so gradually, that it becomes difficult to particularize the different improvements with minuteness, or to say precisely when, bow or by whom they have been respectively made. It must be remarked, however, that although the improvements have been minute, the aggregate result of increased duty produced by them has been most important. They have raised average duty from 28 to above 50 millions, and that of the best engines from 47 to upwards of 100 millions. (Pole, 1844, pp. 62-63, italics added).

In analogous terms, Caff remarked:

So many of the characteristics of the Cornish engine arise from a succession of improvements to details that it is impossible to credit them to any single person. Rather they belong to the whole school of Cornish engineers. The mining districts were sufficiently large and yet sufficiently compact for comparison and competition to be effective in a rapid spread of ideas. (Caff, 1937, pp.45-46).

The other two propositions are substantiated by the very publication of the *Lean's Engine Reporter*. As Cardwell has aptly noticed:

The publication of the monthly *Engine Reporter* seems to have been quite unprecedented, and in striking contrast to the furtive secrecy that had surrounded so many of the notable improvements to the steam engine. It was a cooperative endeavor to raise the standards of all engines everywhere by publishing the details of the performance of each one, so that everybody could see which models were performing best and by how much. (Cardwell, 1971, p.156)

What were the conditions that determined the emergence of this particular information disclosure regime? In our view, three main factors explained this case of transition from a regime of trade secrets and “proprietary” technology to collective invention.

The first condition has to do with the nature of the technology. Analogously with the blast furnace case, the design of a steam pumping engine was a rather risky undertaking from an engineering point of view. Furthermore, technology was much ahead of scientific understanding and complex – that is to say that the overall performance could be affected by a host of factors (boilers, steam pressure, engine, pitwork, etc.). Engineers could not rely on sound theoretical principles when they had to design a new engine. Vincenti (1990, chap. 5) has argued that engineers make use of systematic data collection and analysis to bypass the absence of an adequate theoretical understanding of the operative principles of a technology. Systematic collection and analysis of performance data 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.

Furthermore, Cornish engines like the Cleveland blast furnaces are a rather typical example of “complex capital goods”. Rosenberg (1982, pp. 120-140) has argued that for this type of products learning by using constitutes one of the main sources of improvement:

…[L]earning by using refers to a very different locus of learning than does learning by doing. There are various reasons why this should be so. Perhaps in most general terms, the performance characteristics of a durable capital good often cannot be understood until after prolonged experience with it. For a range of products involving complex, interdependent components or materials that will be subject to varied or prolonged stress in extreme environments, the outcome of the interaction of these parts cannot be precisely predicted. In this sense, we are dealing with performance characteristics that scientific knowledge or techniques cannot predict very accurately. The performance of these products therefore is very uncertain. Moreover many significant characteristics of the products are revealed only after intensive or, more significantly prolonged use (Rosenberg, 1982, p. 122).

Cornish engines were run 24 hours a day. The use of high pressure in such conditions put under considerable strain the pit-work and many components of the engine itself (e.g. valves, beam). In these circumstances, the proper evaluation of the merits and pitfalls of a design modification might have needed a prolonged phase of experience. Furthermore, interdependence between components often meant that the introduction of a design modification often required adjustments and modifications of other parts of the engine. Again, the type of modifications required very often became evident only after a period of experience with the new design. In the Cornish context, sharing of information relating to engine operating experiences reinforced the feedback loop from learning by using to the further development and refinement of the original invention outlined by Rosenberg (1982, p.125).

It is worth noting another important feature of the process of technical change in Cornish engines. Over time, a typical design emerged (single cylinder, high pressure, single-acting engine with plunger pump, basically the design of the engine erected by Trevithick at Wheal Prosper in 1812). Interestingly enough, however, alternative designs were never completely ruled out. For example in different periods, some engineers (like Arthur Woolf and James Sims) erected two-cylinder compound engines. The same goes for other engine components such as valves, pumps, etc. Thus, the design of the Cornish engine always remained in what we might call a fluid state, and this probably facilitated a more thorough exploration of the space of technological opportunities, avoiding the risk of remaining trapped in a local optimum configuration (see Barton, 1965, for a detailed technological history of the Cornish engine).

The second condition, instead, is related to the particular organisation of mining activities in Cornwall. Since the first systematic exploitation of copper and tin lodes, the Cornish mining economy was characterized by a peculiar form of industrial organization, centered around the so-called “cost book system” (Rowe, 1953). Under such a system, mine entrepreneurs or investors (“adventurers”) had first to obtain the grant for working the mine from the owner of the land. This was a normal renting contract (usually for a period of twenty-one years). The rent (called “dues”) was paid in terms of a proportion of the ore extracted. This
proportion varied according to the profitability of the mine. In deep and expensive mines, the lord’s dues comprised between 1/18 and 1/15 of the ore excavated. In more profitable mines this proportion could rise to between 1/12 and 1/10.

Before starting up the mining operations, adventurers met and each of them subscribed shares of the mine venture (normally the mine venture was divided into 64 shares). Shares were annotated in the mine cost book. One of the adventurers was appointed as the administrator of the venture (“purser”). At the same time, one or more mine captains were put in charge of the day-to-day management of the mine. Every two or three months, adventurers met and examined the accounts. If necessary a “call” was made and the adventurers had to contribute (in proportion to their share) to the coverage of mining costs until the next meeting. Failure to meet the call implied immediate forfeiture of the mine shares. Shares could be easily transferred, the only formality being notification to the purser. When the mine became productive and ore was sold, profits were divided in proportion to their shares. The “cost book” system had the advantage of allowing mine adventurers a limited financial liability (Rowe, 1953).

Adventurers were usually not tied to the fortunes of a single mine, but they often acquired shares of different mine ventures. Consequently, they tended to be more interested in the overall profitability of the district than in that of individual mines. Improvements in the average aggregate performance of the steam engines at work in Cornwall dictated an increase of the overall profitability of the district.9 Further, improvements in the average aggregate performance of Cornish engines also had the positive effect of increasing the value of the Cornish ore deposits (a similar mechanism was at work in Cleveland where improvements in the performance of the blast furnaces were also reflected in increases in the value of Cleveland iron mines). Thus, the particular structure of the Cornish mining industry seems to have permitted (at a sort of second stage) the “internalization” of a consistent part of the positive externalities generated by the free disclosure of innovations. Note that in several instances there were suggestions of implementing a similar system of reports for steam engines at work in textile areas, but nothing followed (Hills, 1989, p.131). A partial exception is the case of the Manchester Steam Users’ Association. This Association was founded in 1855 and its purpose was to provide its members with accurate reports on the safety and efficiency of the boilers they had in use.10 In defining the scope of the Association and the procedures for the compilation of the reports the example of Lean’s Engine Reporter was explicitly considered as a model (see, Manchester Steam Users’ Association, 1905, p. 24).11

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9 Besides the involvement of adventurers in different mining ventures, a long-lasting tradition of cooperation between neighboring mines was well established in the Cornish mining district: “Between the 16th and the 18th centuries a well-developed habit of cooperation had been created between the owners and managers of adjacent mines. Despite the impression of constant antagonism, litigation and even violence,...the general rule was for mutual cooperation for mutual profit...Examination of the 18th and 19th century cost books for mines in St. Just, St. Agnes and Redruth parishes show that cooperation over something as vital as mine drainage was the norm among mine owners, managers and landlords in Cornwall”(Buckley, 1989, pp.2-3).

10 The original name of the association was Association for the Prevention of Steam Boiler Explosions and for Effecting Economy in the Raising and Use of Steam. Article 18 of the Rules and Regulations of the Association stated: “[E]very member [can] have free access to the results recorded in the office of the secretary: but in all books and reports open to the inspection of the members each firm shall be designated by a number, and the names of firms shall only be given with their consent” (Manchester Steam Users’ Association, 1905, p. 22, italics added).

11 William Fairbairn one of the promoters of the initiative in the evidence given on boiler explosion at Stockport in 1851 said: “It seems to me that there should be some association...by which registers should be kept, not only with reference to the safety of the public, but also to show what duty engines and boilers
The initiative had only limited success, being capable of attracting only a small portion of steam engine users (Bartrip, 1980, p. 87).

The third important characteristic of the Cornish mining industry that is worth pointing out is that engineers were recruited by mine captains on a one-off basis (this was also the case in the Cleveland blast furnace industry described by Allen). Typically, engineers were in charge of the design of the engine and they supervised the erection works. They also provided directions for the day-to-day operation and maintenance of the engines they were entrusted with. The publication of technical information concerning the design and the performance of the various engines allowed the best engineers to signal their talents, hence improving their career prospects. Christine MacLeod has noted similar behaviour in other branches of civil engineering, where consulting engineers used to release detailed information on their works in order to enhance their reputation. Over time, this practice gave rise to a professional ethos favouring the sharing and the publication of previous experiences (MacLeod, 1988, pp.104-105).

To sum up, the peculiar organisation of the Cornish mining industry made mine entrepreneurs interested in improvements of the aggregate average performance of the pumping engines used and, at the same time, engineers in publicly signalling the above average performance of the engines they had erected. Thus, Lean’s Engine Reporter should be considered as attempt of reconciling the tensions between collaboration (among mine adventurers) and competition (among engineers) operating in the Cornish mining district in a fruitful way. It is worth to add a word of caution in this respect. In fact, it is possible that the fierce competition between engineers might have induced some of them to “cheat” and have, at least for some engines, an overestimated duty credited in the reporter. During the 1840s William West, one of the most active Cornish engineers, voiced several critiques to the procedures for reporting the duty adopted in Lean’s Engine Reporter complaining that they underestimated the duty delivered by his engines. In 1847 West withdrew all his engines from Lean’s Reporter and have them reported in a new monthly publication compiled by William Browne, that thereafter would be issued for 11 years. Although the majority of Cornish pumping engines continued to be reported in Lean’s Engine Reporter, a number of engineers (the majority of them entrusted with engines in the mines located East of Truro, which suggests that the split up of the reports had also a geographical dimension) joined the new publication (Barton, 1965, p. 54). This episode of defection towards Lean’s Engine Reporter well illustrates the difficulties of maintaining a stable context of cooperation among the engineers. The reporter was a powerful stimulus to competition and rivalry among engineers. However, (excessive) rivalry could undermine the very cooperation necessary for having the engines fairly reported on a useful comparative basis. It is our contention that, although with a number of difficulties, Lean’s Engine Reporter was indeed sustained by a remarkable sense of co-operative behaviour between Cornish engineers and that for these reasons it is to be considered a rather successful vehicle for the exchanges of information which form the basis of collective invention processes.  

perform. The best results have arisen from such regulations in Cornwall and it has led there to the greatest possible economy” (Fairbairn, 1877, p. 265).

12 This was the view of contemporary engineers such as Farey, Wicksteed and Pole who paid visits to Cornwall in order to gain some insights on the sources of the high duty performed by Cornish engines: “...the practice [of reporting the duty of the engines] is thought to have been attended with more benefit to the county than
Besides the three factors mentioned above, the transition to a collective invention regime in Cornwall was also motivated by the disappointing experience of the Boulton & Watt monopoly period. After the beginning of the publication of *Lean's Engine Reporter*, Cornish engineers followed the example of Trevithick with his Wheal Prosper engine and normally preferred not to take out patents for their inventions.

Table 1 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 there located. 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 centres.

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.

any other single event except the invention of the steam engine itself” (Pole, 1844, p.147). See also Barton (1965, p. 48 and pp. 54-57).
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Table 1: Geographical Distribution of British Steam Engine Patents, 1698-1852

* Cornwall including the patents taken by Arthur Woolf

**Source:** The list of steam engine patents is taken from *Abridgments of Specification 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.

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 commercialise 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). 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 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 which were not patented. The “Cornish water gauge”, an instrument which allow 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 of the society reveals that many inventions related to steam engineering. For the period 1833-1841, none of them was patented. 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).

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13 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).

14 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.
Passages in the contemporary engineering literature seems also to indicate some awareness of the advantages arising from keeping technical innovations in the public domain. For example, John Taylor wrote in 1830:

Under such a system [the Lean’s Engine Reporter] there is every kind of proof that the application of steam has been improved, so as to greatly economise fuel in Cornwall, and also the rate of improvement has been fairly expressed in the printed reports....[A]s since the time of Boulton and Watt, no one who has improved our engines has reaped pecuniary reward, it is at least fair, that they should have credit of their skill and exertion. We [adventurers] are not the partisans of any individual engineer or engine maker; we avail ourselves of the assistance of many; and the great scale upon which we have to experiment makes the result most interesting to us. (Taylor quoted in Farey, 1971, pp. 251-252)

To sum-up, in our interpretation, the realization of the three conditions outlined above (i.e., i) complex capital good technology, ii) dispersed and overlapping ownership of mining ventures, iii) existence of group of independent consulting engineers) combined with a rather widespread need of raising the efficiency of the steam engines after the period of “slackness” which had followed the expiration of Watt’s patent and led, in the early 1810s, to the emergence of a sustainable collective invention setting.

5. Patterns of technological change in Cornish steam engines

The availability of a data source tracing in quantitative detail the evolution of a technology such as Lean’s Engine Reporter is indeed a rather unique occurrence in the technological history of the industrial revolution. Furthermore, the Reporter portraits a particularly crucial phase in the overall development of steam power technology namely, the first systematic attempts of employing high pressure steam in combination with the “expansion principle”. In retrospect, it is not surprising that some of the most competent contemporary observers paid a great deal of attention to technological developments in Cornwall, as portrayed in the engine reports. For example, John Farey, changing quite drastically his initial publication plan, devoted the major part of the (unfinished) second volume of his opus magnum, to the Cornish engine, making extensive use of the data contained in Lean’s Engine Reporter. The superior fuel efficiency of the engines of the Cornish type was also widely discussed in France by scientists and engineers interested in the functioning of the steam engines. Sadi Carnot himself concluded his Réflexions sur la puissance motrice de feu mentioning the duty of 56 millions achieved by the engine erected by Arthur Woolf at the Wheal Abraham mine.

In this section we will make use of the data contained in Lean’s Engine Reporter to reconstruct the patterns of technical change characterizing the evolution of the Cornish pumping engine. The aim is to unravel the salient properties of the process of accumulation of technological knowledge in this collective invention setting.

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15 According to the original plan, the second volume should have comprised of two parts: the first describing the developments in engine design occurred in the early nineteenth century, the second one outlining a scientific analysis of the working of the steam engine, see Woolrich (2002).

16 In the 1810s the Cornish engine reports were reprinted regularly in Annales de Chemie et de Physique (see Cardwell 1971, p.157, also for other examples of early French inquiries on the performance of Cornish steam engines). In the same period, the Philosophical Magazine edited by Alexander Tilloc (one of the “patrons” of Arthur Woolf during his permanence in London) published summaries of Lean’s report.
Figure 1 (in particular the time series of the highest duty engine) suggests that the rate of technological progress was characterized by a succession of three relatively sharp bursts.

These three phases of rapid technological change which is possible to distinguish in figure 1 have a clear counterpart in more qualitative accounts of steam engineering in Cornwall. The first epoch of rapid technical change one can discern in figure 1 covers approximately the period 1811-1818. This period, which also corresponds to the start of Lean’s Engine Reporter, can be seen as one of experimentation aimed at finding the best design for implementing the use of high-pressure steam in an expansive way. The two pioneers of the time were Richard Trevithick and Arthur Woolf. The idea behind the adoption of the principle of expansion was that of fuel economy (i.e., allowing the ‘expansive force’ of steam to perform some of the work necessary to push the piston). This was done by cutting off the steam when the piston was at the beginning of the stroke and letting the expansion of the steam inside the cylinder complete the stroke. This idea was originally expounded in a patent taken by James Watt in 1782. However, in order to achieve some gain in fuel efficiency using steam expansion, higher pressures than atmospheric ones ought to be employed (at low pressures, the gain in efficiency was very limited). After the expiration of Watt’s key patent in 1800, however, Cornish engineers were free to begin the exploration of the high-pressure expansion trajectory.

Two distinctive engine designs emerged in this period, one associated with Trevithick, the other one with Woolf. Trevithick adopted a single-cylinder condensing design, which later on would become the definitive layout of the ‘Cornish engine’. Woolf, instead preferred a compound double-cylinder layout. A sort of ultimate test between the Trevithick single cylinder and the Woolf compound design was carried out in 1825 when two new engines (of comparable size) were installed at Wheal Alfred mine by Arthur Woolf. The duty of the two engines (Wheal Alfred Woolf 70” (compound 40” and 70”) and Wheal Alfred Taylor 90”) is given in figure 3. The monthly series of the duty of Cornish engines exhibit a short term fluctuating behaviour. This was due to the fact that operating conditions (amount of water to be pumped, quality of coal, etc.) were subjected to variation from one month to the other. In order to identify the “trend behaviour” of the duty series, we have filtered the series using the Hodrick-Prescott filter. As is apparent, during the year 1825, the two engines scored a similar duty (slightly above 40 millions). On the grounds of its reduced cost and easier of maintenance the single cylinder was favoured, becoming the predominant design in Cornwall.
Figure 3: Duty of Cornish engines (the test at Wheal Alfred mine)

In terms of the paradigm/trajectories view of technological evolution, this first period corresponds to the emerging phase of a new technological paradigm. Accordingly, this phase is characterized by experimentation and competition between different designs, culminating in the test at Wheal Alfred. The Wheal Alfred test established a common design framework (the single cylinder engine) where a steady flow of incremental improvements could take place.

The second epoch of rapid technological change comprises the years 1826-1834. Here the technological trajectory had already settled into the ‘dominant’ single cylinder design proposed by Threvithick. The flow of incremental innovation aimed at increasing the performance of this dominant design begins in this period.

The single cylinder design was further improved in the mid 1820s by Samuel Grose who took care of carefully “clothing” steam pipes, cylinders and boilers in order to avoid all possible heat losses. Figure 4 shows the duty of two engines designed by Grose and incorporating the new clothing system.

Figure 4: Duty of Cornish engines (engines designed by Samuel Grose)
Wheal Hope 60” was the first engine embodying these relatively minor modifications, which nevertheless, determined a drastic improvement in the duty (above 60 millions). Encouraged by the performance delivered by Wheal Hope 60”, Grose adopted similar practices of heat conservation in Wheal Towan 80” engine, achieving further gains in duty (above 80 millions).

In this respect, it is interesting to note the behaviour of Wheal Alfred Taylor 90” displayed in figure 3. This engine was originally installed at the Wheal Alfred (it was the single cylinder engine used in the test between the single and compound design). In October it was transferred at Consolidated Mines where it was renamed as “Woolf”. Woolf took the opportunity of the reinstallment of the engine for incorporating the clothing system ideated by Samuel Grose (Barton, 1965, pp. 46-47). This accounts for the sharp performance jump exhibited by the time series. This example also well illustrates the role played by Lean’s Engine Reporter in permitting the prompt individuation of the most fruitful pathways of technical advance. This example also shows, that, at least to some extent, a number of innovations could be “retrofitted” into existing engines. Thus, operations of maintenance or the transfer of a steam engine from one mine to another were occurrences that the engineers could exploit for “upgrading” existing machines.

Finally, the third epoch (approximately the period 1838-42) saw a revival of the compounding principle by means of the engines designed by James Sims (patented in 1841). These had to compete with engines erected by engineers such as Hocking and Loam according to the more traditional layout.

Note that the “convergence” phase in this final instance was probably due more to the deterioration of the best practice than from the “catching-up” of average practice. By the early 1840s the Cornish engine had probably reached its practical limits, so one can well speak of a maturity phase of the technological trajectory. Carried to the extreme the principle of expansion with steam pressures reaching about 50 p.s.i. produced an extremely powerful shock to the piston and to pitwork at each opening of the steam valve. Such an operating cycle was likely to increase the probability of breakages in the pitwork and to accelerate the wear and tear of the engine (Barton 1965, pp. 57-58). The main motivation behind James Sims’ elaboration of a new compound design was therefore not the search for further fuel economy, but the idea of finding a remedy for the strain that large engines were putting on the pitwork. Both Sims’ design and the competing solution proposed by Hocking & Loam (a circular protuberance in the piston which was fitted in a corresponding cavity in the cylinder top) did not encounter much success (Pole, 1844).

It is not surprising then that from the late 1840s, Cornish engineers preferred to give something up in terms of engine efficiency to reap gains on the maintenance and duration side:

all the coal saved above 70 millions duty is paid for at too dear price in the racking of the engine and pump-work and the increased liability to breakage (West Briton, cited in Barton (1965), p. 59, no date specified).

One can therefore interpret this phase as one in which decreasing returns to development along the established trajectory began to set in (in innovation studies, the phenomenon of diminishing returns to innovative efforts along a specific technological trajectory has been
frequently referred to as Wolff’s law). The single cylinder design had reached its practical limits, and in order to circumvent these, a new phase of experimentation was necessary. With hindsight, this phase appears largely unsuccessful, but this may be due as much to the changing economic circumstances (falling ore prices and the general decline of the Cornish mining industry) than to technological factors.

Unfortunately, Lean’s Engine Reporter does not cover a number of important technical characteristics and operating procedures that are intimately linked with the technological developments described above (e.g. steam pressure in boilers, rate of expansion or cut-off point). In this respect, we should take into account that much more information besides the tables of the reporter was shared by Cornish engineers, by means of informal contacts, visits paid to particular interesting engines, etc. (Farey, 1971).

After the crucial test in 1825 at Wheal Alfred between the Woolf and Threvithick engines, a major part of the energy of Cornish engineers was absorbed in the progressive exploration of the ‘optimal’ dimensions of the single cylinder design. In 1859, in a paper read to the South Wales Institution of Civil Engineers, James Sims presented a detailed description of dimensions, proportions, operating procedures of an ‘ideal’ Cornish engine (Sims, 1860). Note that the entire tone of the paper is such as if Sims was expounding what was to be considered fairly established common wisdom. In his paper he recommended 85” as the optimal size of cylinder diameter (if more power was needed, Sims suggested to install two engines, rather than erect one with larger diameter).

We can have a quantitative glimpse on this search process of the optimal dimensions of the engine by looking at the evolution of the cylinder diameters of the reported engine park. In figure 5 and figure 6 we have ordered the engines by cylinder diameter on the vertical axis, and we have charted the evolution of the shares in the total horsepower delivered each year (darker areas indicate higher levels of concentration).

Figure 5 shows that, in the 1810s, the major bulk of the horsepower was delivered by engines with cylinder diameters around 60”-70” (this was the typical size of the Boulton & Watt pumping engines). The ‘average engine’ in this period can be found inside the narrow black rim around 70”. After the emergence of the dominant design, i.e., the 1820s and 1830s, this ‘steady state’ dissipates, only to settle down at the higher level of 80” in the late 1830s and early 1840s. In the late 1840s and early 1850s we have a further movement upwards and we see another concentration peak around 90”.

Figure 6 shows the average duty delivered by classes of engines of given size. Interestingly the figure seems to indicate, for the period of the 1830s and early 1840s, the existence of scale economies in duty up to approximately 80”-85” cylinder size, with diseconomies taking place after that threshold. Contemporary engineers also noted this fact. The Leans contended that this behaviour ought to be regarded as a robust regularity:

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17 Boiler steam pressures began to be reported by the Leans in the late 1840s.
18 This is also confirmed by the accounts of Thomas Wicksteed (1838) and William Pole (1844) who in their visit to Cornwall had the possibility of having access to all the installed engines.
We are struck with the fact, that the duty performed advances with the size of the engine, till it reaches a certain point, (namely, 80” cylinder) and the recedes. (Lean, 1839, p.139).

Farey also made analogous remarks (Farey, 1971, p.243). This case illustrates quite well how Lean’s *Reporter* data were used to continuously refine the design of the Cornish engine (in this case the data permitted the identification of the “optimal” cylinder size of the engine).

![Figure 5: Distribution of the engines reported, cylinder size on the vertical axis, time on the horizontal axis, darker shades indicate a higher percentage of total HP delivered by the total population.](image)

*Source: Lean’s Engine Reporter (April)*

For the period 1811-1876 about 60 different names of engineers or engineering partnerships appear on the pages of *Lean’s Engine Reporter.*

Furthermore, we have to take into account that not all the engines at work in Cornish mines were reported. Unfortunately, we have little information on the total number of engines (and their relative size) at work in Cornish mines. At the end of 1834, Thomas Lean undertook a census of the pumping engines in operation in Cornish mines (Lean, 1839). Admittedly their list was not complete, but, nevertheless, it can be considered as representative of the major bulk of steam power employed at the time in Cornish mines. Another, probably more exhaustive, engine census was undertaken at the end of the year 1838 by W.J. Henwood, with the help of Rev. John Buller (Henwood, 1843).

Collateral evidence indicates that about twenty engines (or little more) were missing from this list (Barton, 1965, p. 252). Finally, another list of pumping engines at work in Cornish mines was compiled in 1864 by Thomas Spargo (1865). Also this list cannot be considered complete, but just as representative of the major bulk of steam power employed in Cornwall (some of the smallest mines not being included). Table 2 summarizes the results of these engine censuses (ordering the engines by size) and compares them with the engines contained in *Lean’s Reporter* in each corresponding year.
Figure 6: Distribution of the engines, cylinder size on the vertical axis, time on the horizontal axis, darker shades indicate a higher duty

Source: Lean’s Engine Reporter (April)

Table 2: Engines in Operation in Cornwall (by size)

<table>
<thead>
<tr>
<th>Cylinder size (diameter in inches)</th>
<th>1834 reported</th>
<th>1838 reported</th>
<th>1864 reported</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-20</td>
<td>1</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>20-30</td>
<td>16</td>
<td>16</td>
<td>26</td>
</tr>
<tr>
<td>30-40</td>
<td>25</td>
<td>30</td>
<td>53</td>
</tr>
<tr>
<td>40-50</td>
<td>11</td>
<td>25</td>
<td>48</td>
</tr>
<tr>
<td>50-60</td>
<td>16</td>
<td>26.32</td>
<td>35</td>
</tr>
<tr>
<td>60-70</td>
<td>23</td>
<td>47.83</td>
<td>42</td>
</tr>
<tr>
<td>70-80</td>
<td>17</td>
<td>41.18</td>
<td>28</td>
</tr>
<tr>
<td>80-90</td>
<td>18</td>
<td>66.67</td>
<td>16</td>
</tr>
<tr>
<td>90-100</td>
<td>4</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Total number of engines</td>
<td>105</td>
<td>153</td>
<td>253</td>
</tr>
</tbody>
</table>

Sources: for 1834, Lean (1839); for 1838, Henwood (1843); for 1864, Spargo (1865).

Table 2 clearly indicates that the practice of reporting engines declined over time, following the trend characterizing the growth of the industry. Thus from the late 1830s to the 1860s, not only the total number engines reported declined, but also the share of engines reported in the total number of engines at work shrunk.
Figure 7 and 8 give the share of engineers in the total number engines reported in each year. Considered together, figure 7 and figure 8 show that throughout the period 1811-1876 the bulk of the engines reported was highly concentrated on a restricted number of engineers.

Further evidence stemming from the contemporary engineering literature (see especially Pole, 1844) indicates that the Cornish engineering community was comprised of two different types of agents. On the one hand, we have what we might call the ‘inventors’, that is to say, engineers who were willing to take the risks of introducing modifications to existing designs. Engineers such as Richard Trevithick, Arthur Woolf, William Sims, James Sims, Hocking and Loam can be considered as typical representatives of this part of the Cornish engineering community. As shown in figures 7 and 8, this group of engineers controls the large bulk of the engines reported by the Leans. The engines designed by these group of engineers typically incorporated a certain degree of “design novelty” and this made of particular interest the monitoring of their performance (for the engineers that had designed them, but also for the wider community constituted by the other engineers and mine owners). On the other hand, we have other engineers who were more cautious and less willing, in the design of their engines, to depart from what was considered the accepted ‘best practice’. This group can by and large be considered as composed by “prudent imitators”: their general attitude was to adopt novel design features only when these had proven their potentialities. The names of these engineers tend to appear in the reporters only sporadically and the probably were entrusted of the large bulk of the non-reported engines.

The peculiar structure of the Cornish engineering community can be considered as a good illustration of the critical role played by “anomalous”, or “non conformist” behaviours (that is departures from what is considered as consolidated best practice) in the exploration of the space of technological opportunities. In this perspective, the rise of aggregate duty in over the period 1811-1841 can be seen as a series of waves of discovery-imitation between innovating and imitating engineers.  

19 Notably, in his case study of collective invention in the Cleveland blast industry, Allen also points to the existence of two attitudes towards the risks related with the introduction of new designs: “Suppose a firm had decided that construction of a new blast furnace was commercially justified and was considering building it a bit taller or hotter than the existing least cost design. As long as the furnace would have been built anyway, the cost of experimenting was the possibility that the production costs in the new design would exceed costs in the old design. Correspondingly, the benefit was the possibility that unit cost would be lower. Firms varied in their willingness to gamble. When it was realized in the Cleveland district that increasing height lowered full consumption, no firm was so risk prone as to build a ninety foot furnace. However, since height and temperature vary continuously, the increments in height and temperature could be made sufficiently small so that some firms found the gamble worthwhile. Those firms constituted the group of pioneers that leapfrogged each other increasing height and temperature. More risk averse firms copied the best existing design.” (Allen, 1983, pp. 11-12, italics added). Allen and McGlade (1986) describe a similar interaction between “innovators” and “imitators” in the case of Nova Scotian fishing fleets.

20 Allen (1988) and Dosi and Fagiolo (1998) have proposed two evolutionary models in which the interplay between the two class of agents (“innovators” and “imitators”) generates self-sustained growth in the overall performance of the system. One very interesting result emerging from these models is that a population composed only by “imitators” will perform poorly, exploring only a very limited part of the system’s evolutionary potential. On the other hand, a population composed exclusively by “innovators” will display the tendency to remain too dispersed and to jump too quickly on the space of technological opportunities, preventing a thorough exploitation of the discoveries they have made. The evolutionary potential of the system is best exploited by a mixed population of “innovators” and “imitators” with information flowing among the two
areas of the space of technological opportunities. In a second phase, these discoveries were integrated into average practice engines by the group of “imitators”.

In other words, the process of knowledge accumulation seems to be characterized by what Allen (1988) has defined as “evolutionary drift”. In general terms, the system, at least from the 1810s to the late 1840s seems to have an in-built tendency to generate novelties. If these novelties were proved to be performance-enhancing they became gradually incorporated in the average practice of the system, producing a rather effective collective dynamics of search and exploitation of the space of technological opportunities.

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*classes, so that “imitators” can refine and fully exploit the potential of the discoveries accomplished by the “innovators”.*
6. Concluding Remarks

Recent research in economic history has pointed to the patent system and, relatedly, to the market for (patented) technologies, as institutional arrangements that greatly stimulated innovative activities during the nineteenth century. The case study of the Cornish mining district presented in this chapter has illustrated the economic and technological significance of incremental and “anonymous” innovations in the development of one of the key technologies of this period, steam power. Notably, the institutional set-up supporting this stream of incremental innovations was one favouring practices of “technology sharing” rather than appropriability.

In his account of the development of the high pressure engine for the western steamboats in the United States (another fundamental branch of steam engineering) during the early nineteenth century, Louis Hunter has also emphasized that significance of various flows of incremental innovations (Hunter, 1949, pp. 121-180). In the light of the present discussion this passage from Hunter’s contribution is particularly intriguing:

Though the men who developed the machinery of the western steamboat possessed much ingenuity and inventive skill, the record shows that they had little awareness of or use for the patent system. Of more than six hundreds patents relating to steam engines issued in this country down to 1847 only some forty were taken out in the names of men living in towns and cities of the western rivers. Few even of this small number had any practical significance. In view of the marked western preference for steam over water power and the extensive development of steam-engine manufacturing in the West, these are surprising figures. How is this meagre showing to be explained and interpreted? Does it reflect a distaste for patents as a species of monopoly ungenial to the democratic ways of the West, an attitude sharpened by the attempts of Fulton and Evans to collect royalties from steamboatmen? Or, were western mechanics so accustomed to think in terms of mere utility that they failed to grasp the exploitative possibilities of the products of their ingenuity? Or, did
mechanical innovation in this field proceed by such small increments as to present few points which could readily be seized upon by a potential patentee? Perhaps each of these suggestions – and especially the last - holds a measure of the truth. At all events the fact remains that, so far as can be determined, no significant part of the engine, propelling mechanism, or boilers during the period the steamboat’s development to maturity was claimed and patented as a distinctive and original development (Hunter, 1949, pp. 175-176).

One might indeed tempted to see a close analogy with the Cornish case examined in this chapter, suggesting that the patenting behaviour of western steamboats “mechanics” perhaps reveals the existence of another collective invention setting. Interestingly enough, Hunter, suggests that the litigations related with the patents taken by Robert Fulton and Oliver Evans (mirroring the conflict between Boulton and Watt and the Cornish engineers) might well have been one of the reasons accounting for the negative attitude of western mechanics towards patents (see Hunter, 1949, p. 10 and pp. 124-126 for a short overview of these litigation cases). Of course, this is a rather speculatively explanatory hypothesis of the development of the western steamboat engine. More extensive research on the exchanges of information among western mechanics would be necessary to corroborate this interpretation.

In our view, the study presented in this paper also contains broader implications. Collective invention processes were probably a common feature of many local production systems during the nineteenth century. Indeed, in analogous terms with what Berg and Hudson (Berg and Hudson 1992, pp. 38-39; Hudson, 1989) have argued concerning patterns of economic and social change, one can suggest that a regional or local perspective on innovation during the industrial revolution is likely to be the most fruitful research approach. Aggregate analysis of trends in patents and in patenting behaviours such as those by Sullivan (1989) and the works by Lamoreaux, Sokoloff and Khan previously mentioned, can help us in shedding light on particular aspects of the innovation process, but it is crucial to take into account that the overall pattern is the result of an aggregation of fairly different regional and sectoral experiences. In order to gauge the volume, the intensity and the effectiveness of inventive activities in different contexts, it is necessary to look in detail also at what was undertaken outside the patent system (see Sullivan, 1995; O’Brien, Griffiths and Hunt, 1995 for a recent discussion on the merits and drawbacks of using patents as indicators of the volume of inventive activities).

In local production systems where technical advances were the product of collective endeavours like in Cornwall, the organization of innovative activities was governed by specific institutional arrangements, alternative to the patent system, that made sure that new technical knowledge remained in the public domain. These cases ought not to be considered as curious exceptions. In several instances, they exhibited a much higher degree of technological dynamism than locations which relied extensively on the patent system.

Another particularly interesting example is the case of the competition in the silk industry between Lyon and London (Foray and Hilaire Perez, 2000). In London, the organization of innovative activities was based on patents and secrecy, whereas in Lyon a sophisticated institutional architecture assured a rapid dissemination and an open use of technical innovations (Hilaire Perez, 2000, pp. 73-82). During the first half of the nineteenth century the two districts fiercely competed. The ultimate outcome was the complete demise of the London silk industry. Lyon instead proved to be one of the most flourishing industrial
districts of the nineteenth century, surviving successfully market crises and other adversities (Sabel and Zeitlin, 1985, pp 156-157). It is worth stressing, however, that it is very difficult to draw generalizations. In fact, one can mention other cases of local flexible production systems in which a patent and secrecy regime promoted a high rate of innovation. For example, Maxine Berg has noticed that in Birmingham, one of the leading inventive centres in metal industries, the institutional set-up underpinning innovative activities was based on patents and trade secrets (Berg 1991, p. 185; Berg 1993, p. 269).

In the United States, in a number of industries, processes of “collective invention” were implemented by means of patent pools. Note that in some cases, patent pools were created after having experienced phases of slow innovation due to the existence of blocking patents. In the 1870s, producers of Bessemer steel decided to share information on design plants and performances through the Bessemer Association (a patent pool holding control of the essential patents in the production of Bessemer steel). The creation of this patent pool was stimulated by the unsatisfactory innovative performance of the industry under the “pure” patent system regime. In that phase, the control of essential patents by different firms had determined an almost indissoluble technological deadlock (Morison, 1966, pp.162-205). Similar concerns over patent blockages led firms operating in the railway sector to adopt the same expedient of semi-automatic cross-licenses and knowledge sharing (Usselman, 1991, 1999).

Finally, the examples we have considered in this paper point to the variety of patterns of technological progress across industries. As Merges and Nelson (1994) have contended, the impact of the intellectual property rights regime on the rate of innovation is likely to depend very much on the nature of the technology in question. In the case of “cumulative systems technologies” (that is technologies consisting of a number of interconnected components and in which current improvements are tightly related to previous innovations), a strong enforcement of intellectual property rights might, in the end, hinder technological progress. In such cases, strong enforcement of intellectual property rights might either determine a case in which technical progress is stifled by a monopolist holding a particularly critical patent (this was the Cornish state of affairs at the end of the nineteenth century) or a situation in which the ownership of a critical body of knowledge is fragmented among different proprietors (so that each of them can exclude the others from making use of the bit of knowledge in her possession) and the final outcome is a delay of technical progress due to impossibility of fully exploiting the body of knowledge subjected to fragmented ownership. Heller and Eisenberg (1998) have labeled these instances as “tragedy of anticommons”. This was indeed the case of early Bessemer steel technology in the United States described by Morison (1966).

In “cumulative system technologies”, a better context for innovation is one in which a high degree of pluralism and rivalry in the exploration of technological opportunities is continuously rejuvenated. 21 As we have shown, in Cornwall in the case of steam pumping

21 Furthermore, one might add that a number of empirical studies have noticed that in some “high-tech” industries the proliferation of spillovers does not seem to significantly reduce the incentive for private investment in inventive activities (see Levin, 1988 for empirical evidence based on the Yale survey). Levin’s suggested interpretation of this finding is fully in line with the perspective set out in this paper: “[T]echnical advance in the electronics industries has been much more ‘cumulative’ than ‘discrete’. This period’s
engines (without doubt a cumulative technology), dissatisfaction over the innovative performance under Watt’s monopoly led to the creation of an “open” collective invention setting that produced a marked acceleration in the rate of technological advance. In other cases, the process of technical change tended to be more “discrete” and the dynamics of innovation less cumulative. Typically, this happens when technologies are relatively “simple”. In these situations, an institutional structure facilitating the appropriability and commercialisation of innovations is likely to be conducive to technological progress. The case of the American glass industry presented by Lamoreaux and Sokoloff (2000) seems indeed to fall into this category.

Note that all this does not mean that technologies will more or less automatically trigger transformations in the institutional structure which in the end will spur their own development. On the contrary, the examples discussed in this paper (see again Merges and Nelson, 1994, for additional evidence) indicate that practices of knowledge sharing were based on a set of preconditions that goes well beyond the mere nature of technological advance. Furthermore, the emergence of institutional arrangements underpinning collective technological learning appears to be the outcome of complex historical processes, deserving in most cases detailed study in their own right. For this reason, accounts of technical change in the early phases of industrialization which rely on simple and general causal mechanisms, such as those based on the emergence of intellectual property rights regimes and of the market for technologies, may be unwarranted. As Nelson (1990) has aptly put it, in capitalist economies, institutional arrangements presiding over the generation and development of technological opportunities exhibit an exceedingly wide degree of variety and of sophistication. Clearly, economic historians interested in discovering “how Prometheus got unbound” ought to take this consideration into account.

References


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