Collective Inventions: A Synthesis of Research Issues[*]

(very preliminary draft)

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1. Introduction

Patent systems have featured prominently in the most recent public policy debates. Underlying this new prominence is the widespread view that both *extending* patent rights (e.g., to life forms, software programs, designs, business processes, etc.) and *deepening* them (by increasing the "strength" of patent protection) will enhance rates of innovation. Such viewpoints have been highly controversial. Notwithstanding, these controversies and debates, however, it is clear that since the early 1980s, a generalized shift towards a strengthening of Intellectual Property Rights (IPR) regime has taken place in the global economy. As summarized, in the 1999 World Bank Report: "Stronger IPRs are a permanent feature of the new global economy" (World Bank, 1998, p. 3).[1]

The main support for this campaign for the implementation of stronger regimes of patent protection comes from the rationale proposed by standard economic reasoning for the creation of patent systems. Traditionally, economists have regarded technological knowledge as a public good, i.e. a good endowed with two fundamental features: (a) non-rivalry; and (b) non-excludability. Property (a) states that when one actor consumes or uses the good, this does not prevent other actors from consuming or using it. Property (b) refers to the fact that - when technological knowledge is in the public domain - it is no longer possible to prevent other actors from using it. The traditional economist's viewpoint contends that market economies are characterized by a systematic under-provision of public goods as their production is, due to the two properties described above, not profitable for private individuals or firms. In this perspective, the patent system provides a solution to the problem, by restoring private incentives in the creation of technological knowledge by means of the creation of a system of property rights.

Interestingly enough, this perspective ascribing a central role to patent systems in the creation of technological knowledge has also suggested, more or less explicitly, a rather peculiar reading of the economic history of Western world. For example, in a widely used undergraduate textbook on the theory of economic growth, Jones observes:

> It is the presence of patents and copyrights that enables inventors to earn profits to cover the initial costs of developing new ideas. In the last century (or two), the world economy has witnessed sustained, rapid growth in population, technology and per capita income never seen before in history. Consider how the….economy would behave in absence of property rights. In this case, innovators would be unable to earn the profits that encourage them to undertake research in the first place, so that no research would take place. With no research, no new ideas would be created, technology would be constant, and there would be no per capita growth in the economy. Broadly speaking, just such a situation prevailed in the world prior to the Industrial Revolution (Jones, 2002, p. 121)

It is interesting to note that Jones is essentially repeating an old assessment of Douglass North, who gave to the emergence and progressive operationalization of the patent system a critical role in origins of the Industrial Revolution. In their book, *The Rise of the Western World,* North and Thomas wrote:

> Innovation will be encouraged by modifying the institutional environment, so that the private rate of return approaches the social rate of return. Prizes and awards provide incentives for specific inventions, but do not provide a legal basis for ownership of intellectual property. The development of patent laws provides such protection....[B]y 1700...England had begun to protect private property in knowledge with its patent law. The stage was now set for the industrial revolution (North and Thomas, 1973, pp. 155-156). [2]

[1] In his appraisal of the long-term, historical evolution of IPR systems, Granstrand (2005) significantly labels the phase beginning in the early 1980s as "the pro-patent era".
[2] This assessment is repeated substantially unchanged also in North (1981), pp. 164-166.

Interestingly enough, North's assessment of the critical role of the patent system in Western industrialization, was not based on any systematic empirical research on the relationship between patent systems and innovation in England. It was essentially a "reasoned guess" formulated on the basis of theoretical speculations. It is not surprising then to discover that other authoritative works of synthesis on the industrialization of the Western world, put forward substantially different views. For example, David Landes argued:

> A number of writers have laid stress on the incentive effect of patent legislation. I am inclined to doubt its significance (Landes, 1969, p. 64). [3]

Some subsequent research has surely provided backing to North's views. For example, Harry Dutton's study of the English patent system in the century prior to its reform in 1852 seems to lend influential support to North's views (Dutton 1984: 202-5), while Zorina Khan's research suggests that North's argument is more applicable to the United States' patent system than to England's (Khan 2005). Indeed, Khan and Kenneth Sokoloff contend that deficiencies in the patent system were actively responsible for nineteenth-century Britain's relatively poor economic performance (Khan and Sokoloff 1998: 292-313). However we would contend that the majority of other historians have instead followed Landes and remained extremely skeptical of the existence of such direct relation between patent systems and the widespread acceleration of inventiveAshton, 1948. MacLeod, 1988; Clark, 2007, pp. 234-239, Mokyr 2009; MacLeod and Nuvolari, 2009 provide a survey of this literature).

The main difficulty facing North's argument is that more and more evidence is showing that the a very large bulk of inventive activities in industrial revolution England was carried out without resorting to patent protection. As noted by MacLeod (1988) throughout the eighteenth and early nineteenth century the coverage of the patent system remained highly restricted both sectorally (limited to the newly emerging capital-intensive sectors) and to commercially dynamic urban areas (chiefly, London, Birmingham, Bristol and Manchester). [4]

How can we account for such sizable bulk of innovation taking place completely outside the coverage of patent protection? The most obvious answer is that the standard economic argument predicting no investment or no efforts in inventive activities without patent protection is actually based on a number of very restrictive assumptions. In particular, on the critical assumption that, once in the public domain, new technological knowledge may be imitated almost without costs. It is easy to see that if we relax this assumption, innovators can easily profit from their inventions by exploiting a number of "first-mover" advantages. David Landes actually suggests that this was probably the most common way during the early industrial revolution for reaping the benefits of inventions (Landes, 1986, p. 614).

2. The role of collective invention

A complementary answer is that inventive activities may have been stimulated by the existence of institutional set-ups that were alternative to the patent system, such as for example prizes or

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[3] In another "classic" reference work on British industrialization, Mathias (1969, p.34) noted that the impact of patent laws on innovation "have proved particularly intractable to analyze or to asses" and refrained from formulating a final balance.

[4] Petra Moser (2005) research on the inventions presented at the Crystal Palace exhibition of 1851 provides an interesting snapshot on the large volume of inventive activities undertaken *outside* the patent systems in the first half of the nineteenth century. None of the British or American industries she considers had patenting rates (ie, the ratio between patented inventions and total inventions) higher than 50%. The highest value reported by Moser is 36.4% for the US machinery industry. Remarkably, differences in patenting rates across industries were similar in the US and Britain (countries that in 1851 were characterized by very different patent laws).

awards. In a seminal paper, Robert C. Allen (1983), has proposed that many nineteenth century inventive activities may have been organized by means of collective invention processes. In collective invention processes, competing firms or individual inventors freely release *pertinent* technical information on the construction details and the performance of the new 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.[5] In this environment, two fundamental innovation trajectories in blast furnaces were introduced and perfected. The first was a progressive increase in the height of the blast furnaces from 50 to 80 foot. The second was a steady increase in the blast temperature from 600 F to 1400 F. Both these inventions resulted in a dramatic increase in the fuel efficiency of the Clevand blast furnaces. These innovations had far-reaching economic consequences. In 1854 Cleveland's iron production was 275 thousands tons (9% of British production), by 1873 Cleveland's production was 2 millions tons (30% of British production) and Cleveland had become the largest producing district in Britain.[6]

Clearly, if inventive activities could be effectively organized by means of collective invention settings, the argument that the emergence of patent system represented a necessary pre-condition for onset of industrialization is seriously put into question. In what follows we shall explore the effectiveness of collective invention as a way for organizing inventive activities by means of a detailed case study of a critical invention in steam engineering, the Cornish pumping engine.

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[5] 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. Collective invention instead is clearly very similar to the contemporary phenomenon of user innovation studied by Von Hippel (2005).

[6] One of the most revealing contemporary assessments of the reasons behind the success of the Cleveland iron district was provided by Eugene Schneider: "Certain localities have had very restrictive habits in their industries; that is habits of secrecy. In those localities, every one hides what is doing, or takes out a patent. The localities in which this spirit prevails very seldom advance with great speed. They remain almost always at a very low industrial level. The localities, on the other hand, which have a very liberal spirit in matters of invention and in matters of patents, advance very rapidly. The entire locality profits greatly by it, and every one gets his share of the advantage…[O]ne of the most remarkable facts in the world is the immense progress which has been made by the locality of Middelsboro'…; 15 years ago, there was scarcely anything done there in the iron manufacture. At present it is the first district of the world for that manufacture, and I have found there is a most liberal spirit, everybody telling his neighbour, everybody telling any stranger who has had the honour of being admitted to those great manufacturers "This is what we do", "This is what succeeds with us", "This our invention". I have told you the result…." (Select Committee on Patent Laws, 1871, p.33)

After having done that we will try to formulate some general conclusions in terms of historical importance of the phenomenon.

3. The Cornish pumping engine as a case of collective invention[7]

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 most advanced engineering centres of the world" (Berg, 1994, p.112). However, as we will see, in Cornwall, inventive activities were mainly undertaken *outside* the coverage patent protection.

In 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 feet 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.

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

[7] This section is based on Nuvolari (2004)

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).[8] 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).

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

[8] 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).

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.[9]

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 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.[10]

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

[9] On the conflict between Boulton and Watt and Jonathan Hornblower, see Rowe (1953), pp. 90-95.
[10] 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).

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.

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 *Lean's Engine Reporter*. After his death, the publication of the reports was continued by his descendents and lasted until 1904.[11]

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

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

> 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).[12]

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.

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[11] The first three reports were published on the *West Briton*, a local newspaper. From 1812 *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.

[12] 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).

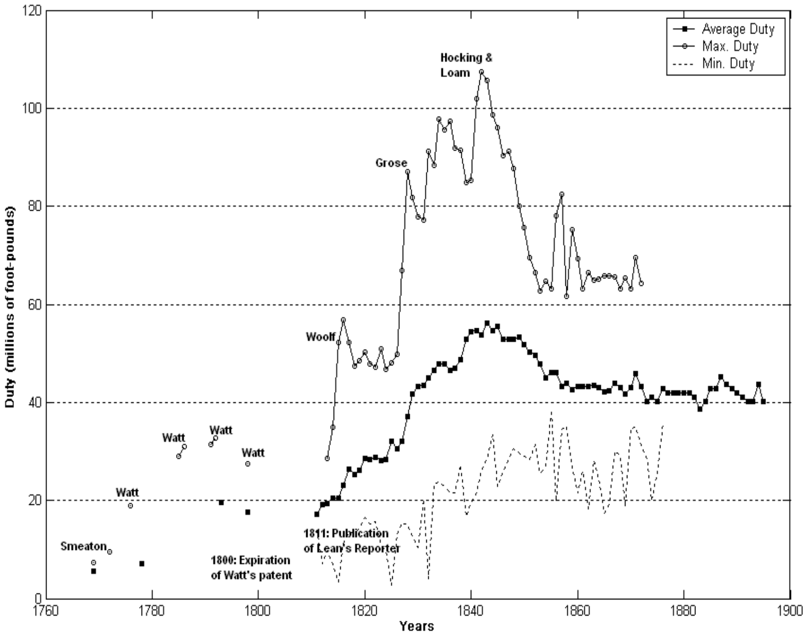

Figure 1: Duty of Cornish Engines, 1769- 1895

Source: Nuvolari and Verspagen (2007)

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.

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, how 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.

Unfortunately, *Lean's Engine Reporter* does not include information on a number of important technical characteristics and operating procedures that are intimately linked with the performance improvements described above (for example, 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 to particularly interesting engines, correspondence, and so on.

We can however surmise the role played by *Lean's Engine Reporter* in guiding the search for effective design principles by considering the development of the cylinder size of the engines (a more detailed discussion and other examples is in Nuvolari and Verspagen, 2007). In 1859, in a paper read to the South Wales Institution of Civil Engineers, James Sims presented a detailed description of dimensions, proportions, and operating procedures of an 'ideal' Cornish engine.

The overall tone of the paper suggests that Sims was expounding a fairly well-established conventional wisdom. Sims recommended 85" as the optimal size of cylinder diameter (if more power was needed, Sims suggested installing two engines, rather than erecting one with a larger cylinder diameter). It is likely that the definition of this optimal size was the result of the elaboration of the performance data of the *Reporter*. Writing in 1839, the Leans constructed tables containing the average duty of engines of different cylinder size, showing that 'the duty performed advances with the size of the engine, till it reaches a certain point (namely, 80'' cylinder) and then recedes'. Farey also made analogous remarks on the basis of a table constructed with the data for the year 1835. Figure 2 reports as histograms the tables constructed by the Leans illustrating the existence of scale economies in duty up to approximately 80–5'' cylinder size, with diseconomies of scale taking place beyond that point. It is interesting to note the abrupt transition to diseconomies of scale after 85". Speculatively, this was probably due either to problems of heat conservation in engines with the largest cylinders, or to difficulties in operating the largest engines with a rate of expansion that would optimize fuel consumption. Although noted by contemporaries, this peculiar 'scaling' behaviour of the Cornish engine has received very little attention from modern historians of technology.

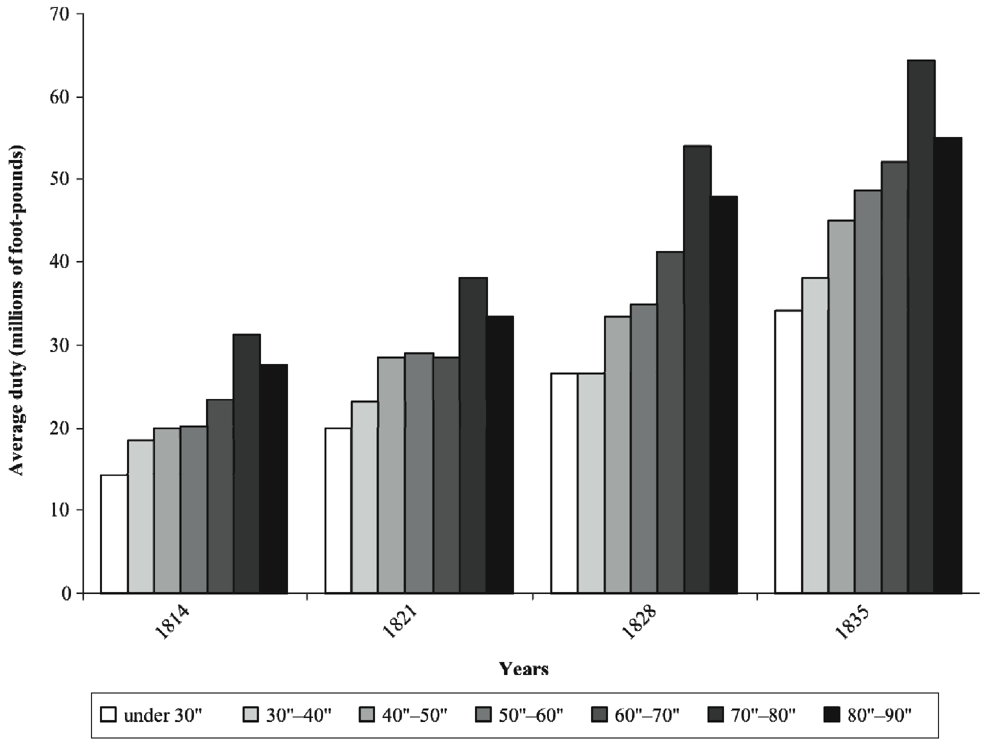

Figure 2: Average duty of Cornish Engines of various sizes

Source: Nuvolari and Verspagen (2009), based on data from Lean (1839).

This case provides a good illustration of how the data of the *Reporter* were employed to refine the design of the Cornish engine (in the example, the data permitted the identification of the optimal cylinder size). Table 1 shows the evolution of the distribution of the engines reported by cylinder size. The table indicates that in the initial period (the 1810s), the bulk of the reported engine park is constituted by engines with a cylinder diameter of 60–9''. Over time the share of engines of larger sizes (70–9'', 80–9'', and 90–9'') becomes predominant. This is not surprising, as the progressive deepening of mining operations required the use of larger engines. However, in the light of the evidence discussed here, the shift towards larger engines can, at least partially, be interpreted also as a reallocation of productive capacity towards better performing engines, following the extrapolation of the data published in the *Reporter*.

Table 2. *Distribution of cylinder sizes of the pumping engines reported*

Cylinder size (diameter in inches)	*1811 (%)*	*1821 (%)*	*1831 (%)*	*1841 (%)*	*1851 (%)*	*1861 (%)*	*1871 (%)*
20–9	0	4.65	0	1.72	0	0	0
30–9	8.33	11.63	14	15.52	25.81	17.86	0
40–9	25	16.28	12	10.34	3.23	10.71	9.09
50–9	16.67	20.93	12	8.62	6.45	10.71	4.55
60–9	50	34.88	30	18.97	12.90	25.00	13.64
70–9	0	6.98	14	15.52	22.58	21.43	40.91
80–9	0	0	8	24.14	22.58	10.71	27.27
90–9	0	4.65	10	5.17	6.45	3.57	4.55
Total	100	100	100	100	100	100	100
Number of engines	12	43	50	58	31	28	22

Table1: Distribution of cylinder sizes of the engines reported
Source: Nuvolari and Verspagen (2009)

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.[13] Further, improvements in the average aggregate performance

[13] 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

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.[14] 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).[15] 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

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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).

[14] 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).

[15] 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 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).

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. [16]

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.

[16] 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 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).

Table 1. *Geographical distribution of British steam engine patents, 1698–1852*

County/location	No. of patents 1698–1852	% 1698–1852	No. of patents 1698–1812	% 1698–1812	No. of patents 1813–1852	% 1813–1852
Cheshire	14	1·23	0	0	14	1·39
Cornwall	17	1·50	8	6·25	9	0·89
Cornwall[a]	21	1·85	12	9·38	9	0·89
Derby	11	0·97	1	0·78	10	0·99
Durham	13	1·15	0	0	13	1·29
Essex	6	0·53	0	0	6	0·60
France	21	1·85	0	0	21	2·09
Gloucester	20	1·76	8	6·25	12	1·19
Bristol	12	1·06	4	3·13	8	0·79
Hampshire	9	0·79	0	0	9	0·89
Ireland	13	1·15	1	0·78	12	1·19
Kent	31	2·73	1	0·78	30	2·98
Lancashire	145	12·78	5	3·91	140	13·90
—Liverpool	35	3·08	1	0·78	34	3·38
—Manchester	58	5·11	2	1·56	56	5·56
London and Middlesex	395	34·80	40	31·25	355	35·25
Northumberland	22	1·94	2	1·56	20	1·99
—Newcastle-upon-Tyne	11	0·97	1	0·78	10	0·99
Nottingham	13	1·15	1	0·78	12	1·19
Scotland	47	4·14	6	4·69	41	4·07
—Edinburgh	9	0·79	0	0	9	0·89
—Glasgow	22	1·94	3	2·34	19	1·89
Shropshire	6	0·53	3	2·34	3	0·30
Somerset	4	0·35	2	1·56	2	0·20
—Bath	2	0·18	1	0·78	1	0·10
Stafford	27	2·38	5	3·91	22	2·18
Suffolk	5	0·44	0	0	5	0·50
Surrey	88	7·75	10	7·81	78	7·75
USA	13	1·15	2	1·56	11	1·09
Wales	12	1·06	1	0·78	11	1·09
Warwick	58	5·11	8	6·25	50	4·97
—Birmingham	55	4·85	6	4·69	49	4·87
Worcester	11	0·97	1	0·78	10	0·99
York	63	5·55	11	8·59	52	5·16
—Bradford	11	0·97	0	0	11	1·09
—Kingston-upon-Hull	9	0·79	2	1·56	7	0.70
—Leeds	17	1·50	3	2·34	14	1·39
—Sheffield	6	0·53	0	0	6	0·60
Others	71	6·26	12	9·38	59	5·86
Total	1135	100	128	100	1007	100

[a] Cornwall including the patents taken by Arthur Woolf.

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

Table 2: Geographical distribution of English Steam Engineering Patents
Source: Nuvolari (2004)

Table 2 reports the geographical distribution (measured udsing 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.

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). [17] 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

[17] 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).

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 *Reports* of the society reveals that many inventions related to steam engineering. For the period 1833-1841, none of them was patented.[18] 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).

4. The historical significance of collective invention processes.

In his original paper Allen suggested that "under the conditions prevailing during the nineteenth century [collective invention]…was probably the most important source of inventions" (Allen, 1983, p.21). Allen's conjecture is essentially based on the idea that, before the establishment of corporate R&D laboratories, it is very likely that in many industries inventive activities may be essentially a by-product of investment processes. In these conditions, collective invention was likely to be a very effective method for organizing of identifying the most promising direction of improvements. On the other hand, in a recent assessment, Joel Mokyr has argued that collective invention ought instead to be considered as a relatively marginal phenomenon.

> Economic historians have found some examples of what Allen (1983) has termed collective invention, that is, the main actors in technological innovation freely sharing information and claiming no ownership to it. There are three reasonably well-documented cases of successful collective invention: the case documented by Allen (1983) of the Cleveland (UK) iron industry between 1850 and 1875; the case documented by MacLeod (1988, pp. 112-113, 188) of the English clock- and instrument makers, and the case documented by Nuvolari (2004) of the Cornish steam-engine makers after 1800. Examples of such cases are not many, and they required rather special circumstances that were not common, and collective invention in its more extreme form, to judge from its short lifespans, was vulnerable and ephemeral.

We think that this assessment may be premature. First of all, looking carefully it is possible to identify a number of instances in which inventive activities may be have organized by means of collective processes. These cases actually represent a challenging research agenda.

For example, it would be wrong to assume that collective invention was just a British phenomenon. In his account of the development of the high pressure engine for the western steamboats in the United States, during the early nineteenth century, Louis Hunter has also

[18] 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.

emphasized the 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 meager showing to be explained and interpreted ? Does it reflect a distaste for patents as a species of monopoly uncongenial 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 of the steamboat's development to maturity was claimed and patented as a distinctive and original development (Hunter, 1949, pp. 175-176).

This passage seems clearly to reveal the existence of another collective invention setting in early nineteenth-century steam engineering. Interestingly enough, Hunter suggests that the litigation of the patents taken by Robert Fulton and Oliver Evans (mirroring the conflict between Boulton and Watt and Cornish engineers) may help account 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). Again, the dynamics of technological change in western steamboats was characterized by the steady accumulation of many minor changes and alterations to the design of the physical characteristics of the steaming, which determined improvements in carrying capacity, increases of speed, reduction of cargo collection times, etc. The cumulative impact of these improvements led to a rate of productivity growth which was without parallel in the transport technology of the period (Mak and Walton, 1972). [19] The detailed study of paper-making in Berkshire (US) by McGaw (1987) seems also to point to the existence of another American collective invention setting. Note that, given the argument put forward by Khan and Sokoloff, on the critical role of the US patent system as the fundamental driver of innovation in nineteenth century America, it is would particularly interesting to document in detail cases of collective invention in the United States.

Other cases of collective invention have been identified in other countries, Foray and Hilaire-Perez (2006) suggest that it also characterized the highly successful silk industry of Lyon in France. Karel Davids (2009) argues that collective invention was also a common practice among the millwrights in the Zaankstreet in the Netherlands, during the seventeenth and eighteenth century. The Zaankstreet can be without doubt regarded as one of the cutting edge industrial districts in Europe of the time and it was the first location in which windpower was adopted on a massive scale. Kiriazidou and Pesendorfer (1999) propose that collective invention was also a characteristic of the Viennese bentwood furniture industry in the second half of the nineteenth century, which was very successful and that it was able to establish the Viennese chairs as a fashion item throughout Europe.

[19] "The available evidence suggests that the increase of steamboat productivity (on inland rivers), 1815-1860, exceeded that of any other major transportation medium for a period of similar length in the nineteenth century" (Mak and Walton, 1972, p.623).

Furthermore, Allen (2009) argues that collective invention was not limited to industry but it was also a feature of many fundamental improvements in agriculture practices that were introduced in England during the second half of the nineteenth century, such as the introduction of clover.

All in all, we would suggest that these cases indicate that collective invention was probably not such a marginal phenomenon as suggested by Mokyr. In our view, all these cases also suggest that an important research agenda that lies ahead would be indeed the systematic analysis and comparison of collective invention in different contexts, in a similar way to the approach adopted by Von Hippel and his associates for studying contemporary cases of "user innovation" (Von Hippel, 2005).

However, even if we would be able to establish that cases of collective invention were not so frequent, it is still important not to dismiss these cases of collective invention as "curious exceptions". It is worth stressing, once more, that key-technologies that lay at the heart of the industrialization process, such as high pressure steam engines, iron production techniques, and probably also steamboats, etc. were at times developed in a collective invention fashion, and consequently *outside* the coverage of the patent system. In other words, collective invention shows us clearly that inventive activities could be very effectively organized without patents. Hence, we should conclude, that the emergence of modern patent systems was not a necessary condition for the onset of the industrial revolution. The roots of Western industrialization were wider and deeper than the emergence of modern patent systems.

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