“Unravelling the Duty”: *Lean’s Engine Reporter and Cornish Steam Engineering*

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Summary

The development of the high pressure expansive engine marked a watershed in the evolution of steam power technology, allowing the attainment of major fuel economies. In Britain, Cornish engineers took the lead in the exploration of this specific technological trajectory. Notwithstanding its superior fuel efficiency was widely popularized, the high pressure expansive engine did not find widespread application in other steam-using regions (in particular in Lancashire), where the favourite option remained the Watt low pressure engine. In this paper, we provide a reassessment of the factors accounting for the precocious adoption of the high pressure steam engine in Cornwall and for its delayed fortune in the rest of Britain.

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* We would like to thank Nick von Tunzelmann for continuing discussions. We are also grateful to Kristine Bruland, Christine MacLeod, Geert Verbong and Joel Mokyr for very helpful comments on previous drafts of this paper.
One of the salient features of the industrial revolution was the transition from an economic system based on the exploitation of “organic” energy sources: animal, human and natural (chiefly, water and wind) to one structured around the intensive utilization of fossil fuels.¹ In this perspective the industrial revolution consisted in a dramatic increase of the potential energy susceptible of effective economic utilization. If we consider the cluster of technical innovations commonly associated with the early phase of the industrial revolution in this light, the steam engine allowing the transformation of thermal energy (heat) into kinetic energy (work) assumes paramount importance. Traditional accounts of the industrialization process have, more or less explicitly, assumed that a wide range of industrial sectors rapidly benefited from the development of steam power technology. In particular, Rostow's work can be considered as representative of this view of the British industrial revolution. Accordingly, Rostow dated the "take-off" of Britain in the years 1783-1802, linking it explicitly with the commercialization of the Boulton and Watt engine.² More recent research has suggested that such a direct link between steam power technology and the early phases of industrialization is indeed spurious. The available shreds of evidence on the diffusion of the steam engine suggest that the late eighteenth century and early nineteenth century British economy was still dominated by the widespread use of animal, wind and water power.³ Furthermore, the economy-wide repercussions of the progressive adoption of steam technology remained circumscribed until at least the 1840s.⁴ Therefore, it would seem that traditional accounts have improperly conflated the early development of the steam engine (in particular the invention of the Watt engine) with its economic significance. On the contrary, the studies of von Tunzelmann and Crafts point out that the diffusion of steam power was a particularly long and protracted process. In fact, the widespread adoption of the steam engine had to await a number of improvements that progressively reduced the power costs of the steam engine relative to other energy sources.

¹ Cipolla, Economic History; Wrigley, Continuity and Poverty, Progress and Population.
² Rostow, How It All Began, pp. 164-167. See also Rostow, Stages, p. 60 and, somewhat more cautiously, Landes, Unbound Prometheus, pp. 99-103.
³ Kanefsky, Diffusion especially pp. 188-233.
⁴ Von Tunzelmann, Steam Power, ch. 6 and Crafts, ‘Steam as a general purpose technology’.
To a major extent, the power costs of the steam engine were determined by the degree of fuel-efficiency of the machine. In the first half of the nineteenth century, major fuel economies were achieved by using to a greater extent the principle of "expansion" in combination with increasing steam pressures. Interestingly enough, these technological developments were introduced before the attainment of a consolidated theoretical understanding of the working principles of the steam engine. Cornish engineers took the lead in the exploration of the merits of the high pressure expansive engine design, whereas in rest of Britain, most remarkably in the manufacturing districts of the North and in the Midlands, the favorite option remained the Watt low pressure engine.

The Cornish mining district was endowed with very rich lodes of tin and copper, whose exploitation was severely hampered by flooding problems. The steam engine provided an effective solution to mine drainage problems. In comparison with other locations, one of the distinctive features of the Cornish mining economy was the high price of coal (coal was typically shipped into Cornwall overseas from Wales). As a result, Cornish mining entrepreneurs were keenly interested in improvements in the fuel efficiency of the steam engines that could curtail their costly fuel bill. Starting in 1811, they sponsored a monthly publication containing detailed reports on the performance (measured in millions of lbs. of water lifted one foot high per consumption of a bushel of coal, or, as it was termed by contemporary engineers, the "duty" of the engine), technical details and operating procedures of the steam engines at work in the county. Joel Lean, a highly respect mine "captain" was entrusted with the compilation of the reports and the publication was generally known as *Lean's Engine Reporter*.  

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5 The first three reports were published on *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 sons Thomas (I) and John for the years 1812-1827. In the period 1827-1831 the two brothers issued 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). Thereafter, 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. See Howard, *Mr. Lean* for biographical details of the various compilers of the reports. Also the name of the publication changed over time. In this paper, for sake of convenience, we shall follow the tradition of referring to the various reports compiled by the Lean family simply as *Lean's Engine Reporter*.  

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The availability of a rich data source such as *Lean's Engine Reporter* is a rather unique occurrence in the economic and technological history of the British industrial revolution. Furthermore, the *Reporter* portrays a particularly topical moment in the history of the steam engine, namely the first systematic attempts of using high pressure steam expansively. In this paper we make use of *Lean's Engine Reporter* for investigating the sources and the procedures of technical change in Cornish steam engineering in the first half of the nineteenth century. We will combine the quantitative information contained in the *Reporter*, with evidence of a more qualitative kind taken from contemporary engineering publications. Ultimately, our detailed case-study of innovation in Cornish steam engineering aims to shed light on the accumulation of "useful knowledge" during the early nineteenth century. As we shall see, the data contained in *Lean's Engine Reporter* will permit a more accurate characterization of technological learning than the one which is usually adopted by economists and economic historians, that, generally, limit themselves to describe the sustained improvement of a given "technological practice" by means of incremental improvements with broad concepts such as "learning by doing" and "learning by using", without venturing into the details of these cognitive processes. In this sense, our paper resonates with Joel Mokyr's recent plea that economic historians ought to pay due attention to the detail of the processes of generation and diffusion of "useful knowledge" which underpin the origins of modern economic growth.\(^6\)

I

A particularly suitable framework for the interpretation of historical patterns of technical change is provided by what may be called the paradigm/trajectory approach originally put forward by Dosi.\(^7\) Dosi defines a technological paradigm as a "‘model’ and a ‘pattern’ of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies".\(^8\) The term paradigm is clearly borrowed from Thomas Kuhn’s philosophy of science. In case of technologies, the

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\(^6\) See Mokyr, *Gifts of Athena*.

\(^7\) Dosi, “Technological paradigms” and “Sources”

\(^8\) Dosi, “Technological paradigms”, p. 152, italics in the text.
concept of paradigm refers to a cognitive framework, jointly adhered by a significant group of innovators, guiding the search for technical advances in a particular historical context. In this way, a technological paradigm defines the boundaries of the domain in which future technological developments will take place. Dosi suggests that it should be possible to “deconstruct” each technological paradigm in a set of “heuristics”. These represent the prevailing accepted rules prescribing the procedures to be adopted in the search for innovations (i.e., “in order to develop a more efficient engine, try to increase the rate of expansion”). It is interesting to note that the notions of technological paradigms and heuristics are intended to be broader in their scope than mere sets of engineering prescriptions. In Dosi’s view, technological heuristics are the product of the combination of what might be termed the “autonomous drift” of a technology (i.e., the “compulsive sequences” of technical challenges and solutions individuated by Rosenberg, which are typically insensitive to market signals\(^9\)) with “inducement factors” of a genuinely economic type (e.g., current and expected factor prices). This means that local circumstances can, to a certain extent, shape the pattern of technological development. In the case we are dealing with here, both the early development of high pressure in Cornwall and the various attempts of improving the low pressure engine in Lancashire, can be seen as a reflection of how the different economic needs of the various regions were incorporated in these engineering heuristics.

Very often, engineering heuristics are focused on the improvement or optimization of specific performance parameters. The classical example, in this respect, is Moore's law in micro-chips. As already mentioned, in the case of early steam engineering, one of the most common measure of the performance of a steam engine was called the “duty” and it was calculated as the quantity of water (measured in lbs) raised 1 feet high per 1 bushel of coal consumed. From an engineering viewpoint, duty provides an indication of the thermodynamic efficiency of a steam engine. However, this measure has also an important economic meaning because it is a measure of the productivity of an engine with respect to one of the most important variable inputs used the production process.\(^{10}\)

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\(^{10}\) Von Tunzelmann, “Technological diffusion”, pp. 78-79.
The heuristic search process practised by the inventors’ community, by channeling inventive activities in specific and finalised directions, generates relatively ordered patterns of technical change, called “technological trajectories”, which, at least in principle, can be mapped in both the space of input coefficients and that of product characteristics. In this way, the paradigm/trajectory view of technological evolution points to three essential features of the process of technical change:

i) the local nature of technical progress: inventive activities are paradigm-bounded and, for this reason, they are highly selective and focused in rather precise directions.

ii) along a specific technological trajectory, technical advances are strongly cumulative, that is to say, they are strongly related to previous attainments.

iii) technological development is likely to display strong irreversibility. This means that techniques developed along particular trajectories are likely to become superior to “old” ones at every relative factor price level. Once the movement along a particular technological trajectory has gained momentum, it becomes relatively irresponsible to changes in input prices.

The technological history of the steam engine suggests that the development of high pressure constituted a paradigmatic discontinuity in steam engineering, involving the emergence of a new set of heuristics guiding the search for innovations.11 This new paradigm involved both novel design features such as high pressure boilers and new components capable to withstand higher steam pressures and new procedures for the operation of the engine (mostly related to the application of the principle of expansion). In addition, in the course of time, these developments would lead to a complete reformulation of the body of knowledge concerning the understanding of the operation of the steam engine with the emergence of classical thermodynamics. In the remaining of this paper we shall contend that the paradigm/trajectory approach to technological evolution is capable of providing an intriguing historical interpretation, both of the

11 See Hills, Power
development of steam engineering practice in Cornwall and of the late adoption of the high-pressure engine in the rest of the country.

II

In a previous article, one of us has argued that the Cornish mining district in the first half of the nineteenth century may be regarded as a particular case of what Robert Allen has termed “collective invention settings”. Within “collective invention settings”, rival firms or independent individual inventors freely release to one another pertinent information concerning the solution of non trivial technical problems, rather than appropriating it. Each firm, in turn, makes use of the received information to incrementally improve on a basic common technological design. In Cornwall, the chief channel through which information concerning the technological characteristics and the performance of the steam pumping engine was released was clearly Lean’s Engine Reporter.

How representative was the sample of pumping engines 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 the Cornish mines. Admittedly his 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. Collateral evidence indicates that about twenty engines (or little more) were missing from this list.

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12 For the original paper by Allen, see Allen, “Collective invention”. For a detailed discussion of the operation of collective invention within the framework of the Cornish mining business, we refer the reader to Nuvolari, “Collective invention during the British industrial revolution”. As mentioned in the introduction, the current paper is focused primarily on the process of technological learning in Cornish steam engineering.
13 Lean, Historical Statement.
14 Henwood, “Metaliferous Deposits”
15 Barton, Cornish Beam Engine, p. 252.
Finally, another list of pumping engines at work in Cornish mines was compiled in 1864 by Thomas Spargo.\textsuperscript{16} 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 1 summarizes the results of these engine censuses (ordering the engines by size) and compares them with the engines contained in \textit{Lean’s Reporter} in each corresponding year.

Table 1 clearly indicates that the practice of reporting engines declined over time. Thus from the late 1830s to the 1860s, not only the total number of engines reported declined, but also the share of engines reported in the total number of engines at work shrunk.

\textbf{Table 1 about here.}

Table 1 also shows that other types of biases affected the reporting procedure. It is quite clear that large engines were more likely to be reported than smaller ones. The economy of fuel of large engines could play a major role in determining the overall profitability of some mines.\textsuperscript{17} For this reason, these engines tended to be reported \textit{continuously}. Small engines had a much lower fuel consumption, so the gains from increasing their fuel efficiency were proportionally limited, and for this reason they were more likely not to be reported. Casual perusal of \textit{Lean’s Reporter} also suggests that small engines had a higher tendency to be reported \textit{discontinuously}. Mine entrepreneurs could probably have small engines reported only once in a while to check their efficiency at particular “topical” moments of the engine lifetime (e.g., after erection, after a major reparation work or after the movement of the engine from one mine to another).

Figure 1 shows the evolution of the duty of the steam engines at work into Cornish mines over the period 1811-1890 as reported in \textit{Lean’s Engine Reporter}. The figure also contains some information on the duty performed by the engines at work in Cornish mines for earlier periods, collated from various sources. In this paper, in several

\textsuperscript{16} Spargo, \textit{Mines of Cornwall}

\textsuperscript{17} Von Tunzelmann, “Technological diffusion”, pp.83-85.
instances, we will make use of the duty reported in the month of April, as a general proxy for the duty performed in a given year. Figure 1 shows that the behaviour of the April series is indeed very similar to the corresponding series for the entire year as calculated by the Leans. In the Appendix we discuss the issue of the general reliability of the duty figures as measured in Lean’s Engine Reporter.

**Figure 1 about here**

The interest of fuel consumption by Cornish engineers renders duty a fairly good synthetic indicator of the technological performance of an engine. In terms of Dosi’s paradigm/trajectory approach, the historical evolution of duty may be regarded as a good representation of the specific technological trajectory characterizing the development of Cornish steam engineering. Figure 1 shows that the introduction of the practice of reporting the engines went hand-in-hand with a sustained improvement in performance. The series "weighted duty" represent the average duty weighted by the share of the engines in the total horsepower delivered by the reported engine-park. This series mirrors closely the simple average duty. Clearly, the fact that the weighted average slightly outperforms the simple average indicates that more efficient engines also tended to deliver more horsepower.

**Figure 2 about here**

Figure 2 shows the coefficient of variation of duty (for the April series), which we interpret as an indicator of convergence of the performance of the engines in the reported engine-park. Figure 2 suggests that there were three distinct "epochs" in which the rate of innovation underwent an acceleration (with best-practice escaping away from average practice, and hence the indicator going up). These phases correspond broadly to the late 1810s, the late 1820s-early 1830s and the early 1840s. These rather sharp bursts are also

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18 The series for the month of April have been constructed using the almost complete collection of Lean’s Engine Reporter conserved in the Cornish Studies Library (Cornwall Centre), Redruth, UK. We have integrated some missing or unreadable pages, retrieving the figures from the collection of Lean’s Engine Reporter conserved in the Science Museum Library in London.
clearly visible in the series of best duty in figure 1. Note that each of these phases is followed by a period of convergence, during which average-practice is "catching-up" with best practice. Figure 3 (a) and 3 (b) provide an overall view of the dynamics of the duty distribution of the engine park reported. In the figures the density of the duty distribution in a particular year has been estimated using an Epanenchinkov kernel.\textsuperscript{19}

**Figure 3(a) and 3(b) around here.**

In figure 3 (a) the duty performed is reported on the vertical axis. Darker (lighter) areas indicate higher (lower) concentration of engines. Initially the distribution of the engines is rather concentrated (around a duty of about 20 millions). Then we can distinguish a prolonged phase of increasing dispersion of the density coupled with a growth in average duty. From the 1840s the “width” of the distribution appears to narrow down and then remains stable. Figure 3 (b) is simply figure 3 (a) drawn in a three dimensional space.

The three phases of acceleration of technological change that are possible to distinguish in figure 2 have a clear counterpart in more qualitative accounts of steam engineering in Cornwall. The first epoch of rapid technical change that one can discern in figure 2 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 expansively. The two pioneers of this time were Richard Threvithick 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 achieved 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.

Two distinctive engine designs emerged in this period, one associated with Threvithick, the other one with Woolf. Threvithick adopted a single-cylinder condensing design, which later on would become the definitive layout of the ‘Cornish engine’. Woolf instead

\textsuperscript{19} See Silverman, *Density Estimation* for a general introduction to kernel density estimation techniques.
preferred a compound double-cylinder layout, where steam was expanded consecutively into two cylinders. In the same period, another Cornish engineer, William Sims also introduced a particular type of compound design. This consisted in the addition of a small high pressure cylinder to existing low pressure engines which could in this way be “upgraded” and operated using high pressure steam expansively. A sort of ultimate test between the Threvithick single cylinder and the Woolf compound design was carried out in 1825 with two new engines (of comparable size) at Wheal Alfred mine. The two engines performed the same duty (about 42 millions). This led to the abandonment of the Woolf design on grounds of his higher erection and maintenance costs.  

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

In the early 1820s there were very few “visible” technological developments. However, in this period, in many engines, the pitwork and other moving parts were considerably strengthened so that they could withstand the use of high pressure steam. It is likely that the familiarity acquired in this phase with the technical adjustments required by the use high pressure steam was of critical importance for the increasing use of steam expansion which characterizes the other two “spurts” of rapid technical change). This passage from a paper by James Sims describes the efforts made in 1820s to adapt the engines and the pitwork to the use of high pressure steam:

“[Woolf] having improved several Boulton and Watt engines, by causing them to work more expansively by using higher steam, awakened the whole of the Cornish engineers to a new era of steam power; and many sleepless night have I had with others in repairing the many breakages of engines and boilers, caused by the boilers being too weak for the steam attempted to be used, and the material of the engine not being

strong enough for the concussion given by the sudden admission of much higher steam on the piston than was originally intended”.  

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. In this period, one can indeed identify the mainspring of a steady flow of incremental innovation aimed at increasing the performance of this specific design. By and large, the central focus of this flow of incremental innovations was the careful thermal lagging of cylinders and pipes (in order to conserve heat) - as originally done by Samuel Grose at Wheal Hope mine in 1825. Woolf’s improved double beat valve (which greatly facilitated the operation of the engine working with high pressure steam) was also introduced in this period. 

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

Note that the “convergence” among of engine performance 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 with pressures reaching about 50 p.s.i., the expansion of steam produced an extremely powerful shock to the piston and to the pitwork. 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. In fact, the main motivation behind James Sims’ elaboration of a new compound design was not the search for further fuel economy, but the idea of finding a remedy for the strain that large engines working with a high rate of expansion were putting on the pitwork. Both Sims’ design and the competing

\[\text{\footnotesize 22} \text{ Sims, “Rise and progress”, pp. 170-171.} \]
\[\text{\footnotesize 23} \text{ Barton, Cornish Beam Engine, p. 46.}\]
\[\text{\footnotesize 24} \text{ Hills, Power, pp.109-110.}\]
\[\text{\footnotesize 25} \text{ Barton, Cornish Beam Engine, p. 57.}\]
\[\text{\footnotesize 26} \text{ Barton, Cornish Beam Engine, pp 57-58.}\]
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.27 In these conditions, 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 pumpwork and the increased liability to breakage.28

One can therefore interpret this phase as one in which decreasing returns to development along the established technological trajectory began to set in. 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 changing economic circumstances (falling ore prices and the general decline of the Cornish mining industry) than to technological factors.

Remarkably, figure 1 shows that after the maturity phase (early 1840s), the duty of Cornish engines began to decline, rather than to stagnate. This is quite startling because, at first sight, it might be interpreted as a curious form of “technological retrogression”. Contemporaries long debated on the possible factors accounting for the decline of the duty. One suggested explanation held that, over time, the number of diagonal, rather than perpendicular, pumping shafts increased. This meant that an increase amount of work was consumed by friction, possibly determining a deterioration of the duty. Table 2 shows that since the 1850s the share of the engines working “diagonal” shafts indeed began to increase steadily.

Table 2 around here

27 Pole, Treatise.
28 West Briton cited in Barton, Cornish Beam Engine, p.59 (no date specified).
An additional factor that probably contributed to a deterioration of duty was the lower quality of the coal employed in Cornwall since the early 1840s. This interpretation was also put forward in a number of contemporary accounts.²⁹

**Figure 4 about here.**

Finally, figure 4 displays the number of engines reported in each year. It is interesting to note that the number of engines grew steadily up to about 60 in the early 1840s and then began to decline, probably reflecting the widespread feeling that a sort of optimal design had been attained and there was little to be gained by means of systematic further exploration.

**III**

As suggested by Vincenti, engineers tend to make use of systematic data collection to bypass the absence of an adequate theoretical understanding of the operative principles of a technology.³⁰ This was exactly the situation in early nineteenth century steam power technology, when no full-fledged understanding of the working of the steam engine was available. Systematic collection and analysis of performance data allowed Cornish engineers to individuate a set of design principles that could successfully be used to project efficient steam engines.

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 technological developments described above (e.g. steam pressure in boilers,³¹ rate of expansion or cut-off point, etc.). In this respect, we should take into account that much more information besides the tables of the reporter was shared by Cornish

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³⁰ Vincenti, *What engineers*, ch. 5.

³¹ Boiler steam pressures began to be reported by the Leans in the late 1840s.
engineers, by means of informal contacts, visits paid to particular interesting engines, correspondence, etc.\textsuperscript{32}

However, we can have a quantitative glimpse at the role of the \textit{Reporter} in guiding the search for effective design principles, by considering the progressive refinement of the cylinder size of the engines.

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.\textsuperscript{33} 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 cylinder diameter).

It is highly likely that the definition of this optimal size was a product of the elaboration of the performance data of the Reporter. Writing in 1839, the Leans constructed tables containing the average duty of engine 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.”\textsuperscript{34} Farey also made analogous remarks on the basis of a table constructed with the data of year 1835.\textsuperscript{35} Figure 5 (a) and 5 (b) report as histograms the tables constructed by the Leans and Farey which illustrate the existence of scale economies in duty up to approximately 80-85” cylinder size, with diseconomies of scale taking place afterwards.

\textbf{Figure 5a and 5b}

\textsuperscript{32} Farey, \textit{Treatise}, vol II. This is also confirmed by the accounts of Thomas Wicksteed, “On the effective power” and William Pole, \textit{Treatise} who in their visit to Cornwall had the possibility of having free access to all the installed engines.
\textsuperscript{33} Sims, “On the Cornish engine”.
\textsuperscript{34} Lean, \textit{Historical Statement}, p.139.
\textsuperscript{35} Farey, \textit{Treatise}, vol II, p. 259.
This case provides a good illustration of how the data of the Reporter were employed to refine the design of Cornish engine (in the example, the data permitted the identification of the optimal cylinder size).

IV

The average growth of duty may be considered as an indicator of the overall rate of technical progress in Cornish steam engineering. Using the data of Lean’s Engine Reporter, it is possible to perform an accounting exercise that examines the behaviour of different segments of the engine population (more specifically we distinguish between existing and new engines) and estimates the relative contribution of each segment to average duty growth. In this way, it is possible to shed light on the various sources of duty growth. It is important to note that technical innovations could, to some extent, be retrofitted into existing engines. In his study of the Cornish pumping engine, von Tunzelmann has specifically argued that the continuous upgrading of installed capacity permitted a rapid diffusion of technical improvements and was one of the main factors responsible for sustained improvement of the average performance of Cornish engine in the first half of the nineteenth century.36

The analytical tool that we will use in our accounting exercise resembles the decomposition exercises that, in the industrial economics literature, are used to single out the contributing factors of productivity growth in “longitudinal” data sets.37 In our case, the weighted average duty in a given year is given by:

\[
\bar{D}_t = \sum_{i=1}^{N} S_{i,t} D_{i,t}
\]

37 Bartelsman and Doms, "Understanding productivity"
where \( N \) = number of engines in operation at time \( t \); \( S_{i,t} \) = share of horsepower delivered by engine \( i \) in year \( t \) on the total horsepower employed in the same year; \( D_{i,t} \) = duty performed by engine \( i \) in year \( t \).

Using the following decomposition formula\(^{38}\) it is possible to identify the main contributing factors underlying the rate of aggregate duty growth:

\[
\frac{\Delta D}{D_{t-1}} = \frac{\sum_{i \in C} (D_{i,t} - D_{i,t-1})S_{i,t-1} + \sum_{i \in C} (S_{i,t} - S_{i,t-1})(D_{i,t-1} - D_{i-1})}{D_{t-1}} + \\
\frac{\sum_{i \in C} (S_{i,t} - S_{i,t-1})(D_{i,t} - D_{i,t-1}) + \sum_{i \in N} (D_{i,t} - D_{i,t-1})S_{i,t} - \sum_{i \in X} (D_{i,t} - D_{i,t-1})S_{i,t}}{D_{t-1}}
\]

In the formula \( C \) represents the set of “continuing” engines, \( N \) the set of new engines (i.e., engines installed in year \( t \)) and \( X \) the set of “exiting” engines (i.e. engines active in year \( t - 1 \) that were scrapped in year \( t \)).

The first term on the right hand side represents a “within” engine component weighted for the initial share. The term captures the more efficient operation of installed productive capacity (arising from learning by using or from technical improvements that were retrofitted to existing engines, etc.). In other words, this term measures the change of performance of the “continuing” engines. So whenever the physical deterioration of the engines is not counterbalanced by maintenance and repairs and by the “disembodied” component of technical change, the term will assume a negative value.

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\(^{38}\) The formula we have adopted here is the “preferred” decomposition employed by Foster, Haltiwanger and Krizan, "Aggregate productivity growth". Other decompositions can be envisaged, but, as we shall see, in the present context, the formula proposed by Foster, Haltiwanger and Krizan seems to be particularly indicated.
The second term on the right hand side represents a “between” engine component (also called “static shift” effect). This term reflects the increase of the average duty due to the reallocation of the installed capacity from worse to better engines (or vice versa). Note that the term is expressed as deviation from the mean. Overall, this term can be considered to reflect the degree of efficiency in the management of the existing engine park (an effective management of installed productive capacity would require to the most efficient engines to deliver more horsepower).

The third term on the right hand side represents what might be called a “dynamic” shift effect and it captures the growth of the average duty determined by the reallocation of productive capacity towards more “dynamic” engines, that is engines endowed higher duty growth rates (note that the “between” engine component reflects the reallocation of capacity towards engines with higher duty levels). Also this term can be seen as representing a technology management aspect.

The fourth term on the right hand side measures the improvement of the average duty due to the installation of new capacity (introduction of new engines). Note that the term is expressed as a deviation from the mean, so, to give a positive contribution to average duty growth, a “new” engine should perform a higher duty than the average duty of the previous period. It should be noted that, because engines were often moved from one mine to another, in some cases, it is difficult to identify whether an engine that appears in the columns of the Reporter is new or an existing engine transferred from another mine. This can bias the results of the decomposition exercise, introducing an overestimation of the “entry effect” and an underestimation of the “within” effect.

Finally, the fifth term represents the effect due to the scrapping of existing capacity. Also in this case the term is expressed as a deviation from the mean. Accordingly, only the scrapping of engines with below average performance contributes positively to duty growth.
Figure 6 reports the results of the decomposition exercise. We have considered seven years intervals. In the figure the histograms indicate the magnitude of the different contributing factors in each interval. The total effect (equal to the rate of growth of average duty in each period) is indicated by the thick black line.

The first three intervals 1814-1821, 1821-1828, 1828-1835 cover the phase of duty growth. In this phase the predominant contribution to duty growth is given by the “entry” effect (installation of new engines). The “within” engine effect is also positive, indicating the existence of possibilities for improving (“upgrading”) existing engines.

In fact, our results indicate that - although the “upgrading” of installed engines, throughout the years 1814-1835, gave a positive contribution to duty growth - the major driving factor accounting for duty growth was represented by the installation of new engines. In this sense, it would seem that von Tunzelmann has probably overestimated the contribution of the “within” effect to the average improvement in performance.

It also should be noted that the within effect is particularly strong in the years 1814-1821, which is the period when William Sims converted to compounds a number of existing Watt engines. However, Farey noted that the comparisons of the performance of new high-pressure engines relative to the upgraded low-pressure ones induced most mine entrepreneurs to favour the installation of new engines:

The results of all altered engines, compared with those of the new engines at Wheal Abraham and at Dolcoath showed the miners that there would be far more advantage in having entire new engines, than in making any considerable alterations in their old engines.

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39 As noted above, our estimation of the “entry” effect can contain some upwards bias to the detriment of the “within” effect. However, for each of the three periods 1814-1821, 1821-1828, 1828-1835, the estimated magnitude of the “entry” effect is more than two times the “within” effect, leading us to conclude that, notwithstanding some possible overestimation, our decomposition is probably correct in the determining the relative contribution of the two effects. As we have seen, over the period 1810-1840 the development of the Cornish engine was characterized by three “big” spurts in which the distance between best practice and average practice grew considerably leading to a high dispersion of the performance across the installed pieces of capital equipment.

40 Farey, *Treatise*, vol. II, p. 188.
The static and dynamic shift effect, throughout all the period 1814-1870, appear to affect duty growth in a relatively minor way. This can be perhaps accounted for by the existence of “rigidities”. That is to say, there was rather narrow scope for adjusting the horsepower delivered by the engine, once this was installed.

The period 1835-1870 is the phase of “climacteric” in the historical evolution of the duty. Again, the major contributing factors to (negative) duty growth are the “within engine” effect, which shows a deterioration of installed capacity (this may well be a consequence both of the decline in the quality of coal used and of a diminished rate of expansion) and the “entry” effect. Note that since the entry effect is taken in deviation from the mean, this means that new engines tended to have lower duty than the average of the installed capacity.

All in all, it is clear that the main driver of technical progress in Cornish steam engineering was a powerful wave of “innovative investment” which took place throughout the first half of the nineteenth century. In the Cornish context, this expansion of productive capacity was coupled with a sustained experimentation with design modifications and with the discovery of a many improvements related with the use of high-pressure steam. Furthermore, in the Cornish context, the diffusion of these innovations was enhanced by an institutional set-up that enhanced the rapid dissemination of technological knowledge. Least, but not least, the accumulation of technological knowledge was further reinforced by “disembodied” processes of learning by doing and by using that allowed the improvement of installed capacity.

V

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. A large body of engineering literature on steam technology in the early nineteenth century was precisely informed by the debate on the different choice of
technique characterizing the use of steam power in Cornwall (where the high pressure expansive engine was adopted) versus the rest of Britain, especially the manufacturing districts of the North, where the favourite option remained the Watt low pressure engine.

The superior fuel efficiency of the Cornish practice led some contemporary observers to describe this situation as a manifestation of a “technology gap”, with Cornwall assuming the lead in steam engineering. For example, William Fairbairn, a highly influential character in the Lancashire engineering community, and one of the leading advocates of the technical merits of the high pressure expansive engine whose pleadings remained for a long period unfulfilled, wrote in 1849:

For a great number of years a strong prejudice existed against the use of high pressure steam and it required more than ordinary care in effecting the changes which have been introduced: it had to be done cautiously, almost insidiously, before it could be introduced. The author of this paper believes he was amongst the first in the Manufacturing Districts who pointed out the advantages of high pressure steam when worked expansively, and for many years he had to contend with the fears and prejudices of the manufacturers.41

Similarly, John Farey denounced a widespread and culpable “state of apathy as to consumption of fuel” in the “great manufacturing districts of the North”.42

According to James Nasmyth, the inventor of the steam hammer, the actual beginnings of the adoption of high pressure with expansion in Lancashire could be reasonably dated in the late 1840s when “timid and prejudiced traditions” had been finally dissipated. In a letter of 1852 which is quoted at length in the third volume of Marx’s Capital, Nasmyth wrote:

The engine power of this district (Lancashire) lay under the incubus of timid and prejudiced traditions for nearly forty years, but now we are happily emancipated. During the last fifteen years, but more especially in the course of the last four years (since 1848) some very important changes have taken place in the system of working condensing steam engines….The result has been to realize a much greater amount of duty or work performed by identical engines, and that again at a very considerable reduction of the expenditure of fuel…..43

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These passages suggest that, despite various solicitations, many engineers and practitioners had remained extremely skeptical, at least till the late 1830s, about the fuel advantages of using high pressure steam expansively. Several doubts were explicitly voiced on the actual levels of fuel efficiency achieved by Cornish engines, denying the existence of a Cornish technological lead. This was also due to the fact that the superior fuel efficiency of the high-pressure expansive engine remained theoretically unaccounted for. As a consequence, the dramatic early rise of the duty of the (best-practice) Cornish expansive engines (in the 1810s up to more than 40 millions and by the late 1820s to more than 80 millions) was not easily accepted outside Cornwall. In 1836 there was a heated debate in Mechanic’s Magazine on the general reliability of the reported duty figures of Cornish engines. Two years later, G. H. Palmer published an article on Transactions of the Institutions of Civil Engineers, in which he contended that the levels of fuel efficiency claimed for the Cornish engine were undoubtedly exaggerated (because in open contrast with the caloric theory of heat).44

If the statements given to the public by the Cornish engineers, whose sincerity I cannot doubt are correct, I dare not trust to call nature to account for the undue favouritism she confers upon our Cornish friends by enabling them to perform results that the London, Manchester and Birmingham engineers cannot approach......Upon what principle then, permit me to ask, can the Cornish engines perform so much more than all other engines. Strong, indeed, should be the evidence that ought to outweigh or cancel the....laws of nature, and induce this Institution to sanction statements of duty more than double of the best Watt engine, and still more, surpassing the limits Nature has assigned steam to perform.45

The most strenuous defender of Lancashire technical practice was perhaps Robert Armstrong. In his Essay on the Boilers of Steam Engines published in 1839, he declared that the Cornish duty figures were undoubtedly “gross exaggerations”, the real duty probably being equal to about 30 millions. He concluded that “there is nothing in the Cornish system of management that can be profitably imitated by…..Lancashire engineers”.46

It is frequently held that concerns about safety also contributed to delay the adoption of the high-pressure engine. The reluctance to shift to the high pressure engine outside

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44 In the same article Palmer, on the basis of the caloric theory of heat, fixed the maximum duty attainable by a steam engine to 44 millions (Palmer, 1838, p. 46)
46 Cited in Pole, Treatise, p. 59.
Cornwall, one could argue, was simply a manifestation of different propensities towards risk between Cornwall and other areas of Britain (with Cornish engineers more inclined to bear the risks of boiler explosions) and that this could explain the delayed shift to high pressure in counties such as Lancashire. In fact, the available data on the number of boiler explosions indicate that in Cornwall high-pressure steam was employed rather safely throughout the first half of the nineteenth century. On the other hand, if one considers that high-pressure steam engines began to be adopted in the rest of Britain from the 1840s, the evidence suggests that, when it occurred, the shift to high pressure in these areas was undertaken, notwithstanding the higher risks of explosions. In fact, in the 1840s, it was not infrequent to increase steam pressure by placing bricks on safety valves, with few concerns for the increased risks of explosions.

These considerations, in our judgment, greatly circumscribe the possible role that concerns on boiler explosions might have played in delaying the adoption of high-pressure steam outside the Cornish district. Hence, the search for the factors accounting for the lasting differences in technical practices between Cornwall and the rest of Britain cannot be resolved by invoking different concerns over safety in the two areas.

Instead, we would maintain that the model proposed by Paul David in his reassessment of the Rothbarth-Habakkuk debate can provide an interpretive framework that can be fruitfully applied to the case of differential rates of technical progress in steam engineering between Cornwall and the other manufacturing areas of Britain (say Lancashire) in the early nineteenth century. David abandons the idea of a neoclassical production function and adopts the suggestion of Atkinson and Stiglitz that technical progress is, to a large extent, “localized” (that is to say, improvements in one techniques do not “spill over” to other points of the unit isoquant). In case of localized technical change, different factor endowments can lead to persistent differential rates of technical progress between different environments (regions or countries).

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47 See Marten, “On boiler explosions”.
49 See also von Tunzelmann, Steam power, pp. 88-89.
50 David, Technical choice, ch. 1.
The available data indicate that coal prices were higher in Cornwall (the region could not rely on any local supply of coal and all the coal employed had to shipped from South Wales) than in Lancashire throughout the period in question. Figure 7 displays the behaviour of coal prices in various locations for the period 1800-1850. In this time span, the price of coal in Cornwall appears to have been higher than those prevailing in Lancashire (Manchester), Yorkshire (Leeds) and in the Midlands (Birmingham). Note that the price of coal in London, instead, was higher than in Cornwall.

We do not have information on the rental rate of capital in the two areas. Some evidence seems to suggest that interest rates were lower in the South West than in the North.\(^{51}\) At all events, here we will focus on differences in coal prices, assuming equal interest rates between the two regions.

Concerning the factor proportions of the two techniques, it is clear that many improvements introduced by Cornish engineers involved higher capital outlays (mainly because of the higher costs of the high-pressure boilers).\(^{52}\)

Given the foregoing assumptions, figures 8 (a) and 8 (b) illustrate the choice of technique for the entrepreneurs located in the two areas, Cornwall and Lancashire. The plan \((C, K)\) represents all the possible combinations of coal \((C)\) and capital \((K)\) per HP-hour. Only two techniques are available: the high-pressure expansive engine (point A) and the Watt low pressure engine (point B). The high-pressure engine has a higher fuel efficiency (i.e., lower \(C\), coal consumed per HP-hour), but involves a higher capital outlay (\(K\)). Note that in the first half of the nineteenth century, the fuel efficiency attained by using high-pressure steam expansive engine was lower for rotary engines than for pumping (i.e., reciprocating) ones (in reciprocating engines the early cut-off of steam in the cylinder could be exploited to a larger extent). Thus, the positions of the points representing the two high-pressure engines are different. The high-pressure reciprocating engine is

\(^{51}\) Von Tunzelmann, *Steam power*, p. 85.

\(^{52}\) Von Tunzelmann, *Steam power*, pp. 58-59
represented by a point like A, while the rotary engine by a point like H. However, in both cases, the positions of the high pressure expansive engine compared to the Watt low pressure engine (in terms of relative fuel consumption and capital outlays) are analogous (i.e., both points lay on the area “North West” of point B in the (C, K) plan). Thus, one can use diagrams such as 8(a) and 8 (b) to represent the choice of technique both in the case of a reciprocating and of a rotary engine, taking into account that rotary high pressure engines were characterized by lower levels of fuel efficiency.

The availability of only two techniques constraints the possibilities of factor substitution in response to changes in factor prices. In figure 8 (a), this is represented by the two Leontief type unit isoquants corresponding to the points A and B. At least in principle, entrepreneurs could also decide to produce employing a linear combination of the two techniques. Thus, the linear combination of the two techniques represents the “available process frontier” (APF). Note that all the other points (techniques) spanning the traditional unit isoquant FPF (which David calls “fundamental production function”) are not available. In a longer time span, entrepreneurs (perhaps responding to changes in factor prices) may be induced to attempt the development a new technique associated with new factor combination (i.e., a point of the FPF different from A and B), but this process (whose outcome is uncertain) ought to be conceived more properly as technical change and not factor substitution.

In figure 8 (b) we have depicted the relative factor prices prevailing in the two regions. According to the evidence mentioned above, the slope of the line cc’ (indicating the factor price ratio prevailing in Cornwall) is higher than the slope of the line ll’ (indicating the factor price ratio prevailing in Lancashire). In these conditions, the factor price ratio determines the adoption of the high-pressure expansive engine in Cornwall (point A) and of the Watt low-pressure engine in Lancashire (point B). Note that when the ratio of

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53 According to John Enys, “Remarks on the duty”, p. 458, the cost-book system used in Cornwall, not allowing a precise evaluation of annual capital costs, tended to favour the adoption of capital intensive techniques: “...the Cornish system of mining accounts, in which no reference is made to the capital expended, has afforded the mining engineer more liberty in the adoption of whatever proportions appeared to be advantageous in the boiler surface in the flues, or in the size of the cylinder for expansion, and in an increase of strength of the pitwork....”
factor prices is equal to the slope of the APF line, an entrepreneur will be indifferent between the two technologies (this value represent the "threshold" price used in diffusion studies literature).

In David’s interpretation, the critical point of the Rothbarth-Habakkuk thesis is the assumption that opportunities for further technical progress are unevenly distributed along the spectrum of the available techniques. This assumption combined with the hypothesis that the techniques currently in use tend to be improved by means of localized processes of technological learning leads to differential rates of technical progress in US and Britain. In our case, with the benefit of hindsight, it is clear that the higher potentialities for technical progress lay in the adoption of the Cornish practice of using high-pressure steam expansively. This is represented in figure 8 (c).\textsuperscript{54} Localized technical change along the ray $\alpha$, leads to the rapid improvements of the technique A (high pressure engine), whereas the movement from B (Watt low pressure engine) along the ray $\beta$ is much more difficult.\textsuperscript{55} David represents the movement along the $\alpha$ ray as constrained by the two “elastic barriers” b and b’. (Note that also the (slower) movement along the ray $\beta$ not shown in figure 8 (c) is also to be conceived as restricted by analogous barriers). The two barriers narrow the location in which the search for technical improvements takes place, so that the space (K, C) becomes fragmented into disconnected partitions. In this way, different choices of techniques in a specific historical instance may progressively “crystallise” into rather different courses of technical progress.

The notions of an uneven distribution of technological opportunities and of localized technological advances seem to be consistent with the available evidence of the nature of technical change in early nineteenth century steam engineering. For example, the first high-pressure pumping engine was erected in the London waterworks as late as 1838. The installation was preceded by a travel of Thomas Wicksteed to Cornwall where he conducted a detailed research on the merits of the Cornish engine.\textsuperscript{56} In one of his papers,

\textsuperscript{54} The figure is analogous to figure 4 in David, Technical choice, p. 66.
\textsuperscript{55} On the relative stagnation of technical progress in low pressure engines in the period 1800-1830, see Crafts, "Steam", p. 345.
\textsuperscript{56} Wickesteed, “On the effective power” and Experimental inquiry.
Wicksteed listed a number of technical features that characterized the Cornish high-pressure practice, which had no counterpart in London. In other words, in the period 1812-1838, a number of innovations had matured “locally” around the Cornish technique A (movement along the $\alpha$ ray), whereas the development of the low pressure engine (technique B) had stagnated. Although Wicksteed heartily encouraged the shift to the Cornish engine, the management of the waterworks was still rather reluctant and the engine was finally installed only under the condition that it would perform a duty of 90 millions over twelve consecutive months, otherwise a penalty had to be paid. 57

This episode can be seen as a manifestation of the existence of differential rates of technical progress between Cornwall and the rest of the country, leading to the emergence of a technology gap, at least as far as reciprocating engines are concerned.

Further technical problems hampered the adoption of high-pressure steam expansively in engines employed to power machinery. The Cornish practice of high-pressure expansive working could not be easily transferred to mill operations, where the application of the steam engine to industrial processes generally required a smooth piston movement. 58

Some of the problems created by the irregular power cycle could be solved by expanding the steam in two separate cylinders, reviving in this way, the Woolf compound design, which had not been crowned with much success in Cornwall. This involved some loss of fuel efficiency. As William Pole noted:

Th[e] principle...[of expansion] has hitherto been applied to the greatest advantage in engines with a single cylinder, used for pumping purposes, as in Cornwall. In these cases the peculiar nature of the motion admits of the steam being cut off after a small fraction of the stroke has been commenced, and allowed to expand during the remainder. When however the principle of expansion is applied in this mode to engines for producing rotary motion, some difficulties arise, which limit considerably the extent that the expansion may be carried to, and therefore reduce in a corresponding degree the economy of fuel. The Double Cylinder Engine offers a mode of applying the expansive principle to rotary motion, which removes or at least greatly mitigates the objections to the single cylinder... 59

57 Barton, Cornish beam engine, p. 258.
In terms of figure 8 (c), the discussion concerning the difficulties in extracting a uniform rotary motion from high pressure expansive engines amounts to say that the movement along the ray $\alpha$ towards the origin was slower in case of rotary engines than for reciprocating ones. Thus, while for pumping engines it seems rather clear from the writings of Wicksteed, Pole and Fairbairn, that at least since the early 1830s, technical progress had driven the high pressure engine to a point close A’ in figure 8 (c) (where it is the best technical choice for every conceivable level of relative factor prices), the issue remains unsettled for the case of rotary engines.

Von Tunzelmann has calculated the “threshold” coal price at which, it would have been economically worthwhile to switch from a Watt low-pressure engine to the high-pressure one for “rotary” applications in about 1835 as 12 s. per ton. As is apparent from the behaviour of the coal price series of figure 7 in the North (Lancashire and Yorkshire) coal prices were, at least since the early 1820s, below that level. In terms of figure 6.4, this means that, notwithstanding the progress achieved by technology A along the $\alpha$ ray, prevailing factor prices still dictated B as the best technology choice in Lancashire. In other words, the movement along the $\alpha$ had not reached yet the point A’, where the high-pressure engine had become the optimal choice for any configuration of factor prices. This result, according to von Tunzelmann, goes some way in the direction of rehabilitating Lancashire entrepreneurs from the “damnation” to which contemporaries, such as Farey, had condemned them:

The failure may have been one of the inventors rather than the businessmen: inventors were unable to come up with a satisfactory high-pressure rotative engine until about the mid 1830s.

By the early 1840s this situation had drastically changed. We can compute the threshold coal price between a low pressure condensing engine and a high pressure one for 1841

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60 In 1840 William Fairbairn published a paper Fairbairn, “On the economy” advocating the adoption of the Cornish engine to drain collieries in the North East.
61 Von Tunzelmann, *Steam power*, p. 91.
62 “From damnation to redemption: judgments on the late Victorian entrepreneur” is the title of a famous paper by McCloskey and Sandberg, in which the thesis of an entrepreneurial failure (i.e., technological conservatism) of late nineteenth century Britain put forward by historians such as Landes is rebutted.
63 von Tunzelmann, *Steam power*, p. 90.
using a list of prices referring to the steam engines produced by Benjamin Hick. Hick was one of the pioneers of the introduction of compound high pressure engine on the Woolf plan in the textile industries and his engines are probably to be considered as best-practice for the time.\(^{64}\)

In Table 3 we report Hick’s prices and our estimates of annual capital costs for engines of 40 and 50 horsepower (these were probably the most typical sizes for mill engines at the time).\(^{65}\)

In his price list, Hick also indicated figures for the fuel consumption of the engines: the low pressure engine consumed 14 lbs. of coal per HP-hour, whilst the Woolf compound, 5 lbs.\(^{66}\) Note that 5 lbs. of coal per HP-hour correspond to a duty of approximately 37 millions.\(^{67}\) The average duty of Cornish pumping engines (according to Lean’s reports) in the same period (early 1840s) was above 50 millions (see figure 1). This difference can be taken as a (rough) indication of the loss in fuel efficiency determined by the use of the high-pressure engine with a regular piston movement and not with the very irregular Cornish cycle.

With the level of fuel efficiencies stated by Hick, assuming that the engines worked on average 3800 hours a year,\(^{68}\) the threshold coal price for the engines (of both sizes) in table 3 is equal to about 1 s. 1 d a ton.\(^{69}\) This price is even lower than the cost of “slack” coal at the colliery pithead.\(^{70}\)

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\(^{64}\) A glowing appraisal of Hick’s compound engines was given in Farey, *Treatise*, vol II, p. 306.

\(^{65}\) See, for example, Hills, *Power*, p. 116.

\(^{66}\) Zachariah Allen estimated the average fuel consumption of the steam engines installed in Manchester in 1831 as 13 lbs. About ten years later in 1842, Fairbairn considered this to be about 10.5 lbs, see Hunter, *History*, p. 600. In the same year Josiah Parkes (Parkes, “On steam boilers”) considered 15 lbs to be more representative of the average coal consumption.

\(^{67}\) Pole, *Treatise*, p. 171,

\(^{68}\) This can be considered a reasonable estimate for the textile industries. In other industrial branches, engines normally worked slightly less, see von Tunzelmann, *Steam power*, p. 73.

\(^{69}\) The formula used is \( p_t \Delta C H = \Delta K \), where \( p_t \) is the threshold coal price, \( \Delta C \) the fuel saving (per HP-hour) deriving from the adoption of the high pressure engine, \( H \) the numbers of hours worked in the year, \( \Delta K \) the difference in capital cost per HP p.a.

\(^{70}\) Von Tunzelmann, *Some economic aspects*, p. 63 gives a price of 2s. 8d. for slack coal for a Staffordshire colliery in the period 1828-36. Our calculation suggests that threshold price computed by von Tunzelmann for 1835 is probably overrated. The source of this over-estimation is in the estimated increase in capital.
Our profitability calculation, thus, suggests that in the early 1840s the high pressure engine had become economically viable for any (conceivable) configuration of factor prices. In terms of figure 8 (c), also in the case of rotary engines, we are just above the point A’ along the α ray (note that the high pressure steam engine still demand higher capital outlays). In fact, from the late 1830s, manufacturing areas begun slowly to install high pressure engines.\textsuperscript{71}

These cases of early adoption did not amount to a slavish imitation of the Cornish practice. Lancashire engineers tried to “acclimatize” the high pressure engine to local circumstances and to strike a balance between gains in fuel efficiency and the higher capital costs involved in the use of high pressure. Accordingly, the shift to high pressures was coupled with the introduction of a number of adaptations/modifications, such as the “compounding” of existing low pressure engines with the addition of a high pressure cylinder (this practice was known as “McNaughting”),\textsuperscript{72} the employment of smaller versions of Cornish boilers, etc. James Nasmyth in the letter mentioned above described the early adoption of the high pressure condensing engines in Lancashire in these terms:

..[A]s the economic results of so increasing the pressure of steam….soon appeared in most unmistakable £ s. d. forms, the use of high-pressure steam boilers for working condensing engines became almost general. And those who desired to go to the full extent …soon adopted the employment of the Woolf engine in its full integrity, and most of our mills lately built are worked by the Woolf engines….By an ingenious arrangement, the Woolf system of double cylinder or combined low and high pressure engine has been

\textsuperscript{71} Von Tunzelmann, \textit{Steam power}, p.85.

\textsuperscript{72} As we have mentioned, a similar system for upgrading low pressure engines by means of a small cylinders was tried by William Sims during the 1810s.
introduced extensively to already existing engines, whereby their performance has been increased both to power and economy of fuel. The same result...has been in use these eight or ten years, by having a high-pressure engine so connected with a condensing engine as to enable the waste steam of the former to pass on to and work the latter. This system is in many cases very convenient.

In the interpretation we have sketched here, the localized nature of technical progress accounts for the prolonged resilience of technology gap between Cornwall and Lancashire. It is clear that this explanation relies on the role of the barriers such as b and b’ which constrain the search for technical improvements around specific techniques. In David’s original interpretation these barriers are generated by the “technological interrelatedness” existing among the various components of the technology in question. Improvements in one component, frequently require or induce modifications in other components. Thus the initial combination of factor proportions is preserved over time (i.e., technical change is “locally” neutral). In our case, one could argue that the adoption of higher and higher steam pressures in Cornwall demanded a proportionate strengthening of the pitwork, of the foundations of the engine house, etc. It is possible, however, also to give another interpretation of the localized nature of technical change which points to the role played by the cognitive dimensions of the inventive process.

The particular “topography” of localized technical change posited by David (which is alternative to the smooth movement of all points of the unit isoquant assumed by the traditional neoclassical view of technical change) appears to be fully consisted with Dosi’s paradigm/trajectory approach. By channeling inventive efforts in precise directions, the set of engineering heuristics of the prevailing technological paradigm act as the “elastic barriers” hypothesized by David. In this way, the existence of two distinct technological practices (low-pressure and high-pressure) in the first half of the nineteenth century may be seen as reflecting the competition between two distinct technological paradigms.

The existence of two distinct technological paradigms accounts for the disbelief with which information on the superior efficiency of the Cornish high-pressure engine was received outside Cornwall. Technological development within the high pressure

paradigm, proceeded following two (to a limited extent) overlapping sets of heuristics (which over time consolidated themselves in two distinct design traditions): the first one prescribed procedures for innovation in single cylinder pumping engines adopting the irregular Cornish power cycle, whereas the second was concerned with the compound engine and its application to manufacturing purposes. Technological opportunities determined a more rapid progress along the technological trajectory generated by the single cylinder set of heuristics, than along the compound mill engine one. Furthermore, many inventions matured along the single cylinder trajectory could not be readily transferred to the compound trajectory.

All this leads us to consider the “entrepreneurial failure” of Lancashire entrepreneurs and their delay in shifting to high-pressure steam in a rather different perspective. Clearly, the evidence presented above points to the technological conservatism of Lancashire industrialists. However, our interpretation stresses that one of the major stumbling blocks was represented by the deep entrenchment of the low-pressure technological paradigm in Lancashire. Hence, one could also note that authoritative contemporary advocates of the high pressure expansive engine such as John Farey and William Fairbairn were by and large ineffective in their timid efforts of instigating in the Lancashire engineering community the “revolutionary climate” needed for the successful and “timely” subversion of the low pressure paradigm and, precisely for this reason, indulge in the temptation of laying a non minor part of the responsibility at their doors.

VI

One of the features of the economic history of the steam engine that has attracted the attention of historians is the prolonged resilience of the low-pressure design in the first half of the nineteenth century. It seems likely that the initial choice between low pressure and high-pressure designs in various locations was dictated by specific economic conditions.74 Thereafter, due to the lack of a suitable theoretical framework that could guide the search for improvements, in each location technical progress proceeded

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74 Halsey, "The choice", p. 726.
"empirically" on the basis of highly specific sets of engineering heuristics. In the Cornish context, a peculiar institutional set-up promoted the creation and dissemination of a body of practical knowledge that led to the early development of high-pressure steam engines. However, notwithstanding these remarkable Cornish achievements in steam engineering had been popularized, the spatial diffusion of this new technological knowledge remained actually minimal. The evidence presented in this paper suggests that, besides economic circumstances, the highly idiosyncratic nature of the processes of technological learning taking place in each region constrained the spread of innovations in steam engineering.
Appendix: The performance of Cornish steam engines as measured in Lean’s Engine Reporter.

The main aim of the reporters was to ascertain the monthly duty performed by each engine. The duty was computed using the following formula:

\[
D = \frac{L \times l \times s}{C}
\]

In the formula \(D\) indicates the duty performed by the engine (expressed in millions of lbs lifted one foot high by consuming a bushel of coal), \(L\) the load of the water contained in the pumps (expressed in lbs.), \(l\) the length of the stroke in the pump (expressed in feet), \(s\) the number of strokes performed by the engine during the month, \(C\) the monthly consumption of coal (in bushels). Clearly, the reliability of the duty estimated depended on the reliability of the four observations used in the computation. Let us consider each of them separately:

1) \(L\) (the weight of water in the pumps): this was not measured directly but estimated on the basis of the volume of the pumps. Thus, when the pumps were not completely filled with water, (the Cornish term for such a behaviour was “working in fork”, this could happen when the mine was well drained or in periods of low rainfall), duty tended to be overestimated. Additionally, one has to notice that leakages in the pumps led also to overestimate the weight of water actually lifted and, as a consequence, the duty performed. On the other hand, the weight of water lifted was computed by multiplying the volume of pumps for a constant that represented the weight of a unit volume of spring water. Of course, the water pumped from Cornish mines, containing a non negligible amount of minerals in suspension, was in general heavier than pure spring water. This introduced an upward bias (going in the opposite directions of the foregoing downward biases) in the overall estimation of \(L\). During the 1830s, various experiments were carried out in order to measure directly the weight of water lifted. William Henwood and John Rennie measured the actual weight of the water pumped by the Wheal Towan engine and found that it was about 7.6 per cent lower than the one calculated using the
volume of the pumps. Thomas Wicksteed, during his experiment on the Holmbush engine, instead found a gap of about 13.5 per cent; finally, other experiments on the Eldon’s engine at United Mines found a gap of about 4 per cent. The conclusion that contemporaries such as William Pole and Thomas Wicksteed drawn from the results of these experiments was that the Reporter contained an inner tendency to slightly overestimate the water actually pumped by the engine. Overestimation could safely be considered to be between 4 and 10 per cent. Furthermore, no allowance was made for friction. The amount of friction to be overtaken depended on the specific circumstances of operation of each single engine (length of the pumps, their state, their inclination, etc.). This was an important factor to be taken into account when the performance of two engines was compared.

2) $l$ (the length of the stroke in the pumps): the length was calculated on the basis of the length of the piston stroke (multiplied by the proportion of the beam comprised between the pivot point and the attachment to the pump stroke). Accordingly, when the engine performed a shorter stroke, this method led to an overestimation of duty. The length of the stroke performed by the engine could be regulated quite easily by the engineer by properly adjusting the tappets which controlled that descent of the piston. In fact, making the engine perform a shorter stroke was considered as the easiest possible way of “cheating” (in the sense of having an engine credited for a higher duty than the one actually performed). According to Farey, the length of the stroke used in the reporter was the full length of the stroke in the cylinder. The actual stroke performed was about three of four inches shorter and this produced a difference between reported and actual length of about 1/25, as resulted from an experiment carried out in 1816. However, according to Pole (1844), the length of the stroke used in the reports was the mean length. This contrasting evidence probably indicates that some change occurred between 1816 and 1844 in the measurement of the stroke length. Pole also mentioned an experiment

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76 Pole, Treatise, p. 154.
77 Wicksteed, “On the effective power”, p. 121.
78 Von Tunzelmann, “Technological diffusion”, p. 81.
79 Farey, Treatise, vol II.
conducted on an engine at Consolidated Mines which showed that the difference between actual and reported stroke length did not exceed 1 per cent.  

3) $s$ (the number of strokes performed): the number of strokes was registered by a special counter that was installed by the “reporter”. The counter was protected by a Bramah’s lock and the key was entrusted exclusively to the engine reporter. An experiment of four months conducted in 1839 showed that the counter overestimated the number of strokes performed of about 2.5 per cent. 

4) $C$ (the bushels of coal consumed): this was measured on the basis of the coal purchased as resulting from the mining accounts. It is worth noting that bushel was a measure of volume, corresponding to a cylindrical vessel of 18.8 inches of diameter and 8 inches deep. This vessel was to be heaped up above the border to form a cone with the same base of the cylinder and at least 6 inches high. Typically the weight of the coal bushel was reckoned to be 84 lbs. This was a fairly good estimate for Newcastle coal. But, in Cornwall where Welsh coal was used, the weight of the bushel was normally higher. Rather surprisingly, early commentators of the Cornish engine reports such as Gilbert, Henwood and Taylor, did not take into account the greater weight of the Welsh coal compared to the Newcastle one and considered the bushel equal to 84 lbs., underestimating its actual weight. In 1831, Thomas Lean measured the weight of a bushel in 31 Cornish mines and found out that the average weight was equal to 92.43 lbs. (the maximum observation being 98 and the minimum 88 lbs, see Farey, 1971, p. 232). From 1835, in the engine reports the bushel was formally reckoned to be 94 lbs. Various criticisms were voiced against the use of a unit of volume rather than weight as a measure of the coal input. According to William Pole, these criticisms were wide off the mark. He

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81 Von Tunzelmann, “Technological diffusion”, p. 81
82 Farey, *Treatise*, vol II, p.181
84 Howard, “Was the bushel?”
85 Farey, *Treatise*, vol II, 232. In the same year William Henwood measured the weight of bushel at three mines and found an average of 93.6 lbs. The degree of wetness of the coal also influenced the weight of the bushel. When coals were dried the average weight of the bushel in the three mines was 87.1 lbs, see Farey, *Treatise*, vol II, p. 232-233).
noted that 1 bushel = 94 lbs could be used rather safely as a general conversion ratio, discrepancies from that value were likely to have only minor effects on the estimated duty. Additionally, one has to note that in Cornwall, until the end of 1836, coal was sold by the bushel (more precisely by the wey, corresponding to 64 bushels). Hence, the duty calculated in terms of bushel provided a measure of engine efficiency, endowed with a direct economic significance.

The upshot of all this is that the duty figures reported are to be considered as an approximate estimation of the fuel efficiency of the engines reported. However, being most of the engines reported for a number of consecutive months, it is likely that the possible influence of special circumstances on the estimated could duty have been easily individuated. In fact, it was common practice to perform special trials lasting one or two days, on the best-duty engines or on dubious cases. In these trials a number of independent observers took care of ascertaining properly the four observations necessary for calculating the duty of the engine in question. Furthermore, in some of the largest mining ventures, such as Consolidated Mines, the duty of the engines was calculated daily using another counter under the control of the mine captains. The average daily duty was compared with the one published in the monthly reporter when this was issued. The two measures were in most cases found to correspond very closely.

John Taylor, one of the leading mining entrepreneurs in the Cornish district, published several papers with the aim of dispelling the scepticism with which the duty figures

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86 Pole, Treatise, p. 155.
87 von Tunzelmann, “Technological diffusion”, p. 82.
88 See, for example, Lean, Historical statement.
89 Taylor, “On the duty”, pp. 54-55. Charles Babbage also mentioned the system of daily assessment of the duty in his On the Economy of Machinery and Manufacturing, pp. 284-285: “The advantage arising from registering the duty done by steam-engines in Cornwall has been so great that the proprietors of one of the largest mines, on which there are several engines, find it good economy to employ a man to measure the duty they perform every day. This daily report is fixed up at a particular hour, and the engine-men are always in waiting, anxious to know the state of their engines. As the general reports are made monthly, if accident should cause a partial stoppage in the flue of any of the boilers, it might without this daily check continue two or three weeks before it could be discovered by a falling off of the duty of the engine. In several of the mines a certain amount of duty is assigned to each engine; and if it does more, the proprietors give a premium to the engineers according to its amount. This is called million-money and is a great stimulus to the economy in working of the engine”
published in *Lean’s Engine Reporter* had been received outside Cornwall.\textsuperscript{90} In one of these papers published in *Quarterly Mining Review*, Taylor provided a detailed account of the reporting procedures noticing that there was very little room for fraud by the engineers and the workers entrusted with the engines. Furthermore, his position of mine entrepreneur gave him also the possibility of crosschecking the validity of the duty figures with the reduction of coal expenditure. He observed:

The evidence of progressive improvement….which the periodical reports of duty have gone on to exhibit, is corroborated by the unerring testimony of the account books of mines; and those savings which in the one [the monthly duty papers] appear in somewhat theoretic form are in the other apparent in the solid condition of money saved, and so in fact gained.\textsuperscript{91}

The overall conclusion of Taylor’s paper was that “the application of steam has been improved so as to economize fuel in Cornwall, and that the rate of improvement has been fairly expressed by the printed reports”. Taylor was without doubt one of the most convinced advocates of the accuracy of *Lean’s Reporter*. Other competent contemporary observers, such as Davies Gilbert, Thomas Wicksteed, John Farey, William Pole and William Henwood, who had first hand experience with the methods used to report the duty of the engines generally regarded the publication as providing reliable estimates. For our present purposes, it seems to us that the data contained in *Lean’s Engine Reporter* can provide a particularly useful picture of the development of steam power technology in Cornwall.

\textsuperscript{90} On John Taylor, see Burt, *John Taylor*.
\textsuperscript{91} Taylor, “On the duty”, pp. 51-52.
References


Lean (I), T. and brother (1839), *Historical Statement of the Improvements made in the Duty Performed by the Steam Engines in Cornwall* (London).


<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>1</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>8</td>
<td>19</td>
<td>23.33</td>
</tr>
<tr>
<td>60-70</td>
<td>18</td>
<td>23</td>
<td>42</td>
</tr>
<tr>
<td>70-80</td>
<td>13</td>
<td>17</td>
<td>28</td>
</tr>
<tr>
<td>80-90</td>
<td>9</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>90-100</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total number of engines</strong></td>
<td><strong>105</strong></td>
<td><strong>153</strong></td>
<td><strong>253</strong></td>
</tr>
</tbody>
</table>

Figure 1: Duty of Cornish Engines, 1769-1895

Figure 2: Coefficient of variation of duty

Sources: Lean’s Engine Reporter (April)

Figure 3 (a): Kernel density of duty (years on X axis, duty on Y axis, darker shades indicate a higher density)

Source: Lean’s Engine Reporter (April)
Figure 3 (b): Kernel density of duty (years on X axis, duty on Y axis, density on Z axis)

Source: Lean's Engine Reporter (April)

Table 2: Pitwork of the engines reported

<table>
<thead>
<tr>
<th>Year of Engines</th>
<th>Number of Engines</th>
<th>Pumping perpendicularly (%)</th>
<th>Pumping perpendicularly, then diagonally (%)</th>
<th>Pumping diagonally (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1812</td>
<td>16</td>
<td>7 (43.75)</td>
<td>8 (50)</td>
<td>1 (6.25)</td>
</tr>
<tr>
<td>1822</td>
<td>51</td>
<td>32 (62.75)</td>
<td>18 (35.29)</td>
<td>1 (1.96)</td>
</tr>
<tr>
<td>1828</td>
<td>59</td>
<td>40 (67.8)</td>
<td>19 (32.2)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>1834</td>
<td>62</td>
<td>44 (70.97)</td>
<td>17 (27.42)</td>
<td>1 (1.61)</td>
</tr>
<tr>
<td>1838</td>
<td>61</td>
<td>40 (65.57)</td>
<td>18 (29.51)</td>
<td>3 (4.92)</td>
</tr>
<tr>
<td>1840</td>
<td>62</td>
<td>35 (56.45)</td>
<td>24 (38.71)</td>
<td>3 (4.84)</td>
</tr>
<tr>
<td>1850</td>
<td>31</td>
<td>22 (70.97)</td>
<td>7 (22.58)</td>
<td>2 (6.45)</td>
</tr>
<tr>
<td>1855</td>
<td>22</td>
<td>11 (50)</td>
<td>10 (45.45)</td>
<td>1 (4.55)</td>
</tr>
<tr>
<td>1860</td>
<td>25</td>
<td>8 (32)</td>
<td>16 (64)</td>
<td>1 (4)</td>
</tr>
<tr>
<td>1868</td>
<td>24</td>
<td>7 (29.17)</td>
<td>16 (66.67)</td>
<td>1 (4.17)</td>
</tr>
<tr>
<td>1876</td>
<td>20</td>
<td>5 (25)</td>
<td>15 (75)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>

Source: Lean's Engine Reporter (April).
**Figure 4: Average number of engines reported**

Source: Henwood, “Presidential address”, p. lviii.

**Figure 5 (a): Average duty of steam engines of various sizes.**

Source: Lean, *Historical Statement*
Figure 5(b): Average duty of steam engines of various sizes, year 1835.

Figure 6: Decomposition of average duty growth.
Source: Lean’s Engine Reporter (April).
Figure 7: Coal prices, 1800-1850


Figure 8 (a): The main assumptions
Figure 8 (b): Choice of technique in Cornwall and in Lancashire

Figure 8 (c): Differential rates of technical progress between Cornwall and Lancashire
<table>
<thead>
<tr>
<th>Engine Type</th>
<th>40 HP (£)</th>
<th>50 HP (£)</th>
<th>40 HP (£)</th>
<th>50 HP (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low pressure condensing</td>
<td>960</td>
<td>1170</td>
<td>1130</td>
<td>1350</td>
</tr>
<tr>
<td>Woolf compound</td>
<td>240</td>
<td>280</td>
<td>320</td>
<td>400</td>
</tr>
<tr>
<td>Total</td>
<td>1200</td>
<td>1450</td>
<td>1450</td>
<td>1750</td>
</tr>
<tr>
<td>Cost p.a.</td>
<td>162</td>
<td>195.25</td>
<td>197.25</td>
<td>238.75</td>
</tr>
<tr>
<td>Cost per HP p.a.</td>
<td>4.05</td>
<td>3.905</td>
<td>4.931</td>
<td>4.775</td>
</tr>
</tbody>
</table>

Source: Hills, *Power*, p. 119. In calculating capital cost p.a., following von Tunzelmann, *Steam power*, p. 72, we have made the subsequent assumptions: depreciation rate set at 7.5% p.a. for the engine and at 12.5% p.a. for the boiler, interest rate set at 5%.
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