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COLLECTIVE INVENTION

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This paper argues that many new production techniques have been developed by a process called 'collective invention'. When firms collectively invent, they make available to their competitors the results of new plant designs so that their competitors can incorporate extensions of those designs into new facilities they build. The paper analyses the implications of this behavior for the rate and bias of technical change and discusses reasons why this behavior might occur.

1. Introduction

Who invents? Why do they invent? In attempting to answer these questions, economists have identified and studied three kinds of institutions — non-profit institutions like universities and government agencies, firms that undertake research and development, and individual inventors.[1] In this paper, it is proposed that a fourth inventive institution be recognized. This institution is called collective invention. The pattern of behaviour which that phrase describes was first suggested to the author while studying the nineteenth century iron and steel industry, so examples from that industry are used to illustrate the phenomenon. However, it is contended that the principles involved have considerably broader application.

During the nineteenth century, non-profit institutions and firms undertaking R&D were of little importance as sources of invention for the iron industry. The British and American governments funded no research, and university faculty published scarcely any findings. Firms did not maintain research departments and seem rarely to have expended any appreciable quantity of resources with the main intent of advancing knowledge or improving products or processes. What is more remarkable is that the independent inventor was also not the major supplier of new inventions to the iron industry. Some major improvements can, of course, be

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[1]Jewkes et al. (1962), Nelson (1963), Nordhaus (1969, pp. 4, 17), and Schmookler (1957).

attributed to famous inventors — the hot blast to Neilson, the Bessemer converter to Bessemer, and the basic process to Thomas and Gilchrist. However, if one examines a sector like the blast furnace industry and determines the inventions whose diffusion were important for the growth in efficiency, it proves impossible to attribute their discovery to any single inventor. Certainly, no one received a patent for many of these advances. Thus, the increase in furnace height and blast temperature that were so important for productivity growth in England's Cleveland district evolved through the actions of many individuals over a twenty year period. The development of fast driving in the United States was similar.[2] Such experiences are usually dealt with by labelling them as 'the accumulation of minor improvements'. Since such accumulations explain most of the productivity growth in the pig iron industry, that explanation is hardly satisfactory. A close reading of the engineering literature of the nineteenth century indicates that many of the important changes in blast furnace practice were the result of a recurrent pattern of behaviour. Since these behavioural patterns were so pervasive and since they have important common characteristics and consequences, it seems worthwhile to identify them as a fourth institution of invention. The purpose of this paper is to identify the characteristics of collective invention, elaborate its consequences for the rate of invention, and explore the causes of its existence.

The essential precondition for collective invention is the free exchange of information about new techniques and plant designs among firms in an industry. This condition was generally satisfied in the iron industry. Thus, if a firm constructed a new plant 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 could build on the experience of the first by introducing and extending the design change that had proved profitable. The operating characteristics of this second plant would then also be made available to potential investors. In this way fruitful lines of technical advance were identified and pursued.

Collective invention was thus like modern research and development in that firms (and not individual inventors) generated the new technical knowledge. However, collective invention differs from R&D since the firms did not allocate resources to invention — the new technical knowledge was a by-product of normal business operation — and the technical information produced was exploited by agents other than the firms that discovered it.

From the point of view of the economic theory of invention, collective invention was an effective response to the structure of the iron industry and the legal environment in which it operated. The nineteenth century British and American iron industries were competitively organized. In addition, the

[2]Gjers (1871), and Allen (1977 and 1981).

inventions that were important for productivity growth were not 'novel' in the legal sense and hence not patentable. Under the circumstances of competition and non-appropriability, an individual inventor or a firm allocating resources to invention could expect an economic return far less than the social value of any invention. Consequently, the rate of invention — if left to individual inventors or firms undertaking R&D — would be much less than socially desirable. Collective invention provided a partial solution to that problem. Since firms did not allocate resources to invention but generated technical material as a by-product of their normal investments, the fact that they faced no incentive to invest in research was immaterial. As long as the rate of investment was high, the rate of experimentation and the discovery of new technical knowledge was also high. On the other hand, if the rate of investment fell for any reason, the rates of experimentation and invention fell with it. Under the circumstances of high investment, collective invention generated a high rate of productivity growth. When investment was low, however, the rate of invention was doubtless inadequate.

To provide an example of collective invention, section 2 discusses the history of technical advance in England's Cleveland district during the mid-nineteenth century. Section 3 discusses the nature of the costs of experimenting, the way in which collective invention spread costs among the firms in the industry, and the implication of these costs for the pattern of experimentation. Section 4 discusses the effect of the rate of capital formation on the rate of invention. The theory of collective invention is used to explain the decline in the rate of invention in the British iron and steel industry during the late nineteenth century. Section 5 argues that collective invention leads to biased technical progress. Section 6 explores the circumstances under which collective invention will occur. The decline of collective invention is linked with the emergence of the industrial research laboratory in the twentieth century.

2. Between 1850 and 1875 several important changes in blast furnace practice were developed in England's Cleveland district. The most dramatic were the increase in the height of the furnace from fifty feet — the previous norm — to eighty feet or more, and the increase in the temperature of the blast from 600°F to 1400°F. Together, these improvements reduced the fuel requirement for making pig iron enough to justify scrapping the original short, low temperature furnaces and replacing them with the new designs. These new techniques were developed through the operation of collective invention. In this section the invention of the tall blast furnace and the superheated blast will be considered in detail in order to illustrate the operation of that institution.

At the outset, it should be noted that the basic institutional arrangements did not conform to either the independent inventor or firm R&D model. I take it that both of these models imply that the agent in question devote appreciable resources to the solution of a technical problem and in the expectation of being financially rewarded, in most cases by the exploitation of the ensuing patent. It would be quite surprising if such behaviour were observed since neither a taller furnace stack nor a hotter blast was novel in the legal sense and hence patentable.[3] Consequently, no financial gain would follow from the commitment of resources to pursuing these possibilities. The only aspect of either invention that was patentable was the invention of particular designs of hot blast stoves; it is only in the invention of hot blast stoves that behaviour like that of the independent inventor or firm R&D model can be observed. Thus E.A. Cowper (an independent inventor) and C. Cochrane (the owner of the Ormesby Ironworks) jointly developed Cowper's patented hot blast stove.[4] T. Whitwell (the owner of the Thornaby Ironworks) also developed a patented, competing stove design.[5] As Whitwell's work shows, it was fairly easy to invent around a stove patent. As a result, the royalties for using a stove were very small,[6] and the behaviour of the stove inventors in practice was little different from collective invention. There can be no question that all of the increase in furnace height and the increase in blast temperature from 600°F to 1000°F were accomplished by collective invention. The experiments that showed these changes were beneficial consisted of a series of minor variations in the design of new plants. While their builders often hoped that the changes in design would lower costs, that consideration was not the decisive factor prompting the construction of the furnaces.

To show that collective invention occurred, it is necessary to establish the following propositions: First, the large overall increases in height and

[3]Neilson had patented the hot blast but the patent had expired by the mid-nineteenth century.

[4]Cochrane (1864 and 1870a), and Cowper (1869–1870).

[5]Whitwell (1869).

[6]Cochrane (1870a, pp. 69–74), presents the following figures which may be used to compute the present value of the cost savings of using Cowper stoves to heat the blast to 1400°F instead of using cast iron pipe stoves to heat the blast to 1000°F. Supposing the furnace to produce 500 tons of iron per week, the requisite Cowper stoves (including standby stoves) and gas purifying apparatus cost £7700 and lasted indefinitely if maintained and renewed. Pipe stoves cost £4000 but only last 10 years. The present value of a stream of costs of £4000 incurred every tenth year forever is £4000. $(1.05)^{10}/[(1.05)^{10}-1]=$£10,360, if the interest rate is 5%, which is the value Cochrane assumes. The reduction in capital costs attendant upon using Cowper stoves is £2260 = £10,360 − £7700. Maintenance and renewal costs of Cowper stoves are £140 per year higher than with pipe stoves. The present value of the additional maintenance costs if £2800 = £140/0.05. The major saving from using Cowper stoves was the reduction in blast furnace coke. Cochrane estimates the saving at 0.2 tons of coke per ton of iron, but a more reasonable estimate is 0.05 tons. [See Allen (1981).] Blast furnace coke cost £0.575 per ton so the present value of the fuel savings from using Cowper stoves with a furnace making 500 tons of iron per week forever was £0.575 · 0.05 · 500 · 52/0.05 = £14,950. Totalling these present values shows that the economic saving of the Cowper stoves was £14,810 = £14,950 + £2660 − £2800. The royalty for using a Cowper stove was a lump sum payment of £350 per furnace. Clearly, the royalty was much less than the economic value of the invention.

temperature were the culmination of a series of small increments. Second, firms made public the operating results of their new furnaces. Third, firms that built taller or higher temperature furnaces used the information generated by existing furnaces. Establishing these propositions illustrates in detail the way collective invention operated. Consider the three propositions in turn.

First, furnace height and blast temperature were increased in moderate steps.[7] The first furnaces built in Cleveland in the early 1850's were 45–50 feet tall. In 1858 Thomas Vaughan, and Hopkins, Gilkes and Co. and Jones, Dunning, and Co. blew in furnaces of 56–58 feet in height. This increase in size was prompted apparently by a desire to increase production but resulted in a noticeable fall in fuel consumption. As a result Bolckow–Vaughan rebuilt its short Witton Furnace to a height of 61 feet, which further reduced fuel consumption. Bolckow–Vaughan again led the way building in 1862 two 75 feet furnaces. These furnaces consumed even less fuel and their excellent records prompted Bell Brothers and Thomas Vaughan to build furnaces of 80 and 81 feet. Again Bolckow–Vaughan followed by building several 95 feet furnaces in 1865. At the same time Cochrane and Co. developed the technology in a slightly different direction. In 1867 C. Cochrane built two 76 feet furnaces and in 1870 two 90 feet furnaces. While they were not taller than Bolckow–Vaughan's, they were designed to have larger cross-sectional diameters and hence greater cubic capacity. Cochrane believed the lesson taught by the earlier furnaces was that fuel consumption declined with capacity rather than with height. The largest furnaces, in terms of both height and capacity were two 105 feet furnaces built subsequently by the Rosedale & Ferryhill Iron Co.

Not all furnaces built in Cleveland in the 1860's were taller than existing furnaces. Table 1 tabulates the height of new and rebuilt furnaces constructed in the vicinity of Middlesbrough during the 1850's and 1860's. It is apparent from the table that the average height of new furnaces did increase during the 1860's but, that most new furnaces were of the same height or slightly shorter than the tallest existing at the time. There were thus two types of firms operating in the district — the pioneers which leapfrogged each other in advancing the state of the art (the Schumpeterian innovators) and the followers that emulated the least cost design in use at the time they constructed their plant. The different in firm behaviour probably reflected a difference among the owners of the firms in *élan* or (in neo-classical terms) willingness to bear risks.

The increase in blast temperature cannot be followed as thoroughly, but the evidence that is available shows the same pattern of moderate but

[7]This paragraph is based on Gjers (1871, pp. 203–220), Jeans (1878, pp. 64–66), Bell (1871b, p. 324), and Cochrane (1869a, b, 1870a, 1875).

Table 1

The height of new or rebuilt furnaces in the vicinity of Middlesbrough.[a]

Height (feet)	1851	1856–1860	1861–1865	1866–1870	1871
41– 45	3				
46– 50	11	6			
51– 55	15		1		
56– 60		9	3		
61– 65		1			
66– 70			14	2	
71– 75			4	10	
76– 80			2	12	
81– 85			6	9	2
86– 90				2	2
91– 95					
96–100			2	3	2

[a]*Source:* Gjers (1871, pp. 203–207), and Jeans (1878, pp. 64–66).

continuous advance and the same difference between pioneers and followers.[8] When the first furnaces were built in Cleveland they were blown at 600°F, the standard in most furnaces in the world. By 1860, the average temperature in Cleveland had been raised to 750–800°F and some works, for instance Bell Brothers' Clarence Ironworks, were blown at 1000°F. In all of these cases, the blast was heated in cast iron pipe stoves. In 1857 E.A. Cowper had patented his regenerative firebrick stove, which applied the recently discovered regenerative principle to the problem of heating the blast. By 1860 Cowper and Cochrane had built such stoves at the Ormesby Ironworks and shortly after were employing blast temperatures up to 1400°F. In 1865 Whitwell patented an alternative design for a firebrick stove which could achieve similar temperatures. By the mid 1860's these experiments with high blast temperatures began to be emulated by other furnace companies. In 1869 Edward Williams (1869) could write that 'at nearly all the best and most carefully managed furnaces of the Cleveland district, the temperature of blast averages about 1000°', achieved with pipe stoves. A few works used firebrick stoves to heat the blast to 1400°. Several more decades were required before all furnaces in Cleveland converted to firebrick stoves and very high blast temperatures.

Increasing furnace height and blast temperature led to lower fuel consumption and costs. The first firms to build tall furnaces might have treated this knowledge as a trade secret, but they did not. This information

[8]This paragraph is based on Bell (1884, p. 23), Whitwell (1869), Jones (1871), Cowper (1869–1870), Cochrane (1864, 1869a, 1870a), Williams (1869), and Allen (1981, app. 2).

was made available to other parties through two channels — informal disclosure and publication in the engineering literature.

Informal disclosure was practiced throughout the 1850's and 1860's. In a history of Cleveland district, J. Gjers (1871, pp. 202–203), a prominent engineer and ironmaster, alluded to such information release in the 1850's:

> 'When, in 1851, the first blast furnace was built in Cleveland by the late Mr. John Vaughan, he followed the practice of the older districts, and made his furnaces 42 feet high by 15 feet diameter in the bosh; others soon followed in his steps without any decided increase in size, and Cleveland had thus, in its early days, although benefiting from the skill and experience of the older districts, also to suffer from their prejudices. Up to 1858 there was a small and gradual increase in size, but it cannot be said that the maximum then attained, viz., 56 feet in height by 16 feet bosh, materially exceeded those of other districts. The results, however, with these furnaces so far exceeded in economy those of the smaller kind, that it led Mr. Vaughan in that year to rebuild one of the Witton furnaces, and to increase the size from the original 42 feet by 13 feet, to one of 61 feet high by 16 feet 4 inches bosh.'

According to Gjer's account, Vaughan's rebuilding of the Witton furnace was prompted by his awareness of the reduction in fuel consumption occasioned by increasing height in previous furnaces. Bell (1872b, p. XIX) provides additional confirmation of information exchange among firms early in the districts' history when he writes,

> 'indeed, in the course of our constant communication on the subject, I made known to him [John Vaughan] the fact, that at the Wylam furnace, containing only 2,350 cubic feet, we were doing work as efficiently as in that at Walker, nearly one half large.'

After listing the furnaces built in Middlesbrough before 1859, Bell (1872b, p. XXI) adds that he had 'constant opportunities of ascertaining the duty performed by nearly the whole of the above named furnaces, in many cases from actual copies of their consumption sheets.' While Vaughan doubtless benefited from the knowledge he obtained from other firms' experience, he reciprocated in kind. Thus, Bell (1871a, p. 324) reports that Vaughan let him measure the thermal characteristics of the 75 feet furnaces built in 1862 in order to understand their low fuel consumption.

The owners of the sixty feet furnaces built around 1860 also made the designs and operating characteristics of their furnaces available to others. In 1864 Beckton (1864) published an engineering drawing of the Ormesby (57 feet), Jarrow (60 feet), and Thornaby (60 feet) furnaces, as well as data on their fuel consumption. That Beckton could assemble this information indicates firms were disclosing it.

Reference in the engineering literature of the late 1860's and 1870's allow the documentation of many instances in which firms released pertinent technical information to outsiders. Thus the discussions at two engineering society meetings in 1870 and 1872 establish that information was given away in the following instances:[9] Both C. Cochrane and I.L. Bell had taken thermal and fuel consumption measurements on the Ferryhill Furnaces. E.A. Cowper had had access to thirteen years of fuel consumption records from the Thornaby Ironworks. In addition, Bell had access to weekly fuel consumption and operating data of the Consett Ironworks. Bell's book, *Chemical Phenomena of Iron Smelting*, is a revelation in this regard, for in that book Bell summarizes and compares the size, temperature and coke rate of many blast furnaces in order to understand the determinants of fuel economy.[10] The ease with which Bell obtained this information was not unique. Whitwell (1872–3, p. 146), for instance, observed 'that he had visited the works of most of the ironmasters in Cleveland' obtaining information about their operations.

Formal presentations through papers presented to engineering societies was the second channel through which information was released. In mid-nineteenth century England there were both regional societies (e.g., the Institution of Cleveland Engineers and the South Wales Institution of Engineers) and national societies (e.g., the Institution of Mechanical Engineers). In 1869 the Iron and Steel Institute was established. It concentrated the presentation of much of the research for that industry. These societies served as forums for the presentation of technical material. Papers were presented which disclosed considerable detail about the design and efficiency of different plants. The papers and the subsequent discussion were printed in the proceedings of the society. By these means, engineering societies enhanced the dissemination of technical information.

Design and efficiency information appeared sporadically in the engineering literature during the mid-1860's. In 1863 Coulthard (1863) presented a paper to the Institution of Mechanical Engineers which described the Grosmont Ironworks and the fuel consumption of its 63 feet furnaces. In the next year Beckton (1864) presented a paper (previously referred to) to the same Institution which summarized the design and operating characteristics of 60 feet furnaces, and Cochrane (1864) reported to the same group on the fuel consumption of the blast furnace, at the Ormesby Ironworks. Of particular interest, were the results he obtained upon raising the blast temperature from 650°F to 1150°F.

There was a lull in publications for several years and then an explosive outpouring of technical information beginning in 1869. This material was published in the older journals — *The Proceedings of the Institution of*

[9]Bell (1870, p. 85, 1872–3b, p. 151), Cochrane (1870b, p. 105), Cowper (1870, p. 87).
[10]Bell (1871a, b and 1872b).

Mechanical Engineers and the *Minutes of the Proceedings of the Institution of Civil Engineers* — and in the new *Journal of the Iron and Steel Institute.* Some material was also published in the regional technical journals and some in the weekly trade press. Within the space of a few years papers were published revealing the design and operating results of furnaces at the Clarence, Consett, Thornaby, Ormesby, and Newport Ironworks, as well as at various ironworks owned by Bolckow–Vaughan.[11] Since most of these ironworks contained furnaces of several vintages and the authors of the papers tried to use the resulting data to estimate the impact of increasing height and temperature on fuel consumption, an impressive amount of useful information was made available to potential entrants. These investigations established unequivocally that eighty feet furnaces blown with air at 1000°F consumed much less fuel than fifty feet furnaces blown at 600°F. The investigations, however, failed to conclusively establish whether or not fuel consumption declined more if height and temperature were increased further.

The third requirement that must be satisfied to establish the existence of collective invention is to show that the builders of new furnaces used the information released by established producers. As long as the new entrants were cost minimizers, it would be surprising if they did not. The continuous increase in the heights of new furnaces tabulated in table 1 supports the proposition that new constructors learned from old. In two cases this learning can be documented explicitly. In 1865 Bell erected two 80 feet furnaces at the Clarence Ironworks because of the good performance of Vaughan's 75 feet furnaces and because of the expectation of further economy. Bell believed that changes in furnace design that lowered the temperature of the escaping gases resulted in lower fuel consumption. He wrote:

> 'In the neighborhood of Middlesbrough, we commenced with what Mr. Parry considered the maximum capacity a furnace ought to have, viz: 6,000 cubic feet, and in the year 1862, I undertook, with such pyrometers as we then possessed, to ascertain the quantity of heat escaping from our blast furnaces.... Furnaces were gradually enlarged up to 60 feet, when, in the year 1862, Messrs. Bolckow and Vaughan erected one at Middlesbrough 75 feet in height, with a capacity of between 10,000 and 11,000 cubic feet, the gases from which I immediately made the subject of inquiry. As might be expected, their temperature was found sensibly lower than that of those from the furnaces of 6,000 feet, but they still contained so much heat that, having occasion to erect two new furnaces at the Clarence Works, 80 feet was adopted, and boshes of 20 feet, with a capacity of nearly 15,500 cubic feet.' [Bell (1871a, p. 324).]

[11] Bell (1869, 1871a, b 1872a), Whitwell (1869 and 1871a, b), Cochrane (1869a, b, 1870a, 1875), Samuelson (1870–1), and Williams (1869).

Sir B. Samuelson's construction of two 85 feet furnaces at the Newport Ironworks in 1870 provides a second specific example of the use of technical information generated by previous construction. These furnaces replaced a plant of 50 feet furnaces built by Samuelson in 1854. In discussing the replacement decision, Samuelson (1870–1, pp. 367–368) asked rhetorically.

> 'What risk had he run by increasing the capacity of these blast furnaces very much beyond those which he had previously constructed? [He answered that] he did not run any great risk. He did not jump suddenly from a furnace with a capacity of 16,000 cubic feet to a furnace of 30,000 cubic feet, but he watched what had been going on in his neighborhood; and he found, somewhat in contradiction to the experience of Mr. Bell, that economy had, in every case, been derived from increased capacity.'

The most compelling evidence that ironmasters used the information generated by earlier construction when they built new furnaces is provided by firms smelting iron ore other than Cleveland ironstone. The owners of furnaces smelting hematite in Lancashire, Cumberland, and on the Northeast coast were aware of the developments in Cleveland and sought to emulate them to lower the fuel consumption of their furnaces. Thus, William Crossley (1871, p. 145) of the Furness Iron and Steel works at Askam, after reviewing the experience of several Cleveland ironworks, commented,

> 'With these results in the Cleveland district he [Mr. Crossley] was led to infer that larger hematite furnaces would similarly be attended with considerable advantages in increasing economy of fuel.'

The owners of the West Cumberland Hematite Iron Works, the Barrow Ironworks, and the Consett Ironworks made the same inference. All four companies erected furnaces of seventy or seventy-five feet.[12] Previously fifty-five feet had been the maximum height of a hematite furnace, so these firms were trying to accomplish in one step what the Cleveland industry had done in several. These tall furnaces proved to be disasters. Not only did fuel consumption not fall, but the quality of iron made by the furnaces deteriorated, they ran irregularly, and they scaffolded. In most cases the furnaces were cut down to a height of fifty-five feet, which greatly improved their performance. These circumstances were so anomalous that they provoked considerable discussion about the expectations of the builders and the reasons for the failures. Through the exchange of technical information, the hematite producers searched for the trick that would allow them, too, to build tall furnaces with low fuel consumption.

Showing that the increase in furnace height and temperature in Cleveland was accomplished in small steps, that the operating results of new furnaces

[12]Whitwell (1871b, p. 137), and Crossley (1871, p. 118).

were made available to potential entrants, and the new construction incorporated such information establishes the operation of collective invention for those technical advances. Many other important technical advances of the nineteenth century iron industry were also accomplished through collective invention. Thus, the technology of capping the blast furnace so the waste gases could be used for fuel was collectively invented.[13] Fast driving and the reduction in limestone charged into the furnace — the two techniques whose diffusion accounts for most of the productivity growth in American blast furnaces between 1870 and 1913 — were also the outcomes of collective invention. Neither change was patentable, the operating results of furnaces were made public, and new construction incorporated the results of the old. In the case of fast driving, it is clear that advance occurred in small steps.[14]

An intriguing example of collective invention is the licensing agreement for the Bessemer plant patent in the United States. In effect, the licensing agreement stipulated that the firms practice collective invention among themselves but exclude non-patent holders. The operating records of Bessemer plants were made available to other licensees,

> 'The technical personnel of these firms were involved in a continuing game of musical chairs, and the managers of the newer works usually had been trained at one of the earlier ones. Frequent meetings were held of the five or six top engineers of the industry to discuss common problems.'[15]

The 1870's were characterized by a vigorous contest among the Bessemer plants as each tried to break the existing production record, in the process increasing labour productivity. Successful lines of development could be discovered by one firm and carried forward by another. The incorporation of collective invention into the patent arrangement may have contributed to the high rate of invention in American Bessemer plants at this time.

3. In the nineteenth century there was no theory of the blast furnace that would have allowed an engineer to deduce the optimal design from general principles. As a result, building a furnace with a new design was an experiment whose result could not be predicted in advance. Suppose a firm had decided that the construction of a new blast furnace was commercially justified and was considering building it a bit taller or hotter than the existing least cost design. As long as the furnace would have been built anyway, the cost of experimenting was the possibility that production costs in the new design would exceed costs in the old design. Correspondingly, the

[13]Addenbrooke (1865), Blackwell (1852), Cochrane (1860 and 1869a), Lloyd (1860).
[14]Allen (1977), Gayley (1890–1), Grammar (1905), Gordon (1886), and Potter (1887).
[15]Temin (1964, p. 133). This paragraph is based on ibid., pp. 132–138.

benefit was the possibility that unit costs would be lower. Firms varied in their willingness to gamble. When it was first realized in the Cleveland district that increasing height lowered fuel consumption, no firm was so risk prone as to build a ninety foot furnace. However, since height and temperature vary continuously, the increments in height and temperature could be made sufficiently small so that some firms found the gamble worthwhile. Those firms constituted the group of pioneers that leapfrogged each other increasing height and temperature. More risk averse firms copied the best existing design.

When the operating characteristics of a novel design can only be forecast by extrapolating the behaviour of existing designs, two patterns of behaviour are to be expected. The first is overshooting. Overshooting refers to the construction of plants that exceed the optimal value of the relevant parameter. Bolckow–Vaughan's 96 feet Cleveland furnaces and the 105 feet furnaces of the Rosedale and Ferryhill Iron Co. are examples of overshooting.[16] Overshooting also occurred in the United States when fast driving was invented.[17] Overshooting is unavoidable when forecasting is done by extrapolation.

Replication of design is the second pattern of behaviour that is a consequence of the nature of the forecasting problem. As noted, the owners of risk averse firms simply copied the best existing design. While such replication does not extend the frontiers of knowledge in the same way building new designs does, some replication provides more observations so the technology can be more precisely ascertained.

One might naively regard a blast furnace as a deterministic chemical system, but, in fact, its behaviour is stochastic. Many aspects of a furnace — its interior lines, the placement of tuyeres, the quality of raw materials, the degree of scaffolding, etc. — exert an elusive but consequential effect on fuel consumption.[18] Consequently, if one builds a taller blast furnace, it is not immediately obvious whether its coke rate indicates the systematic effect of increasing height or is distorted by unusual random circumstances. Distinguishing the systematic effects from the random noise was a difficult problem for nineteenth century engineers since statistical theory and practice were so undeveloped. As a consequence, the engineering literature is replete with disputes revolving around doubtful inferences from small samples. Only the impressionistic inspection of very large bodies of data allowed those engineers to distinguish the systematic from the random.[19] These data would

[16]Furnaces built in the 1870's were generally between 80 and 90 feet and not any higher.

[17]Gayley (1890–1, p. 941), Potter (1890–1, p. 972), Grammar (1905, p. 134), Lutz (1904, pp. 418–419).

[18]Cochrane (1875, pp. 334–340 and 1883).

[19]For example, see Bell (1869, 1872b, p. xxi, 1872–3a, and 1872–3b, p. 152) and Cochrane (1870a and 1875). The protracted debate in the late 1860's and 1870's about the efficiency of increasing blast temperature from 1000°F to 1400°F reveals the weakness of nineteenth century

not have been generated without replication of design. Modern statistical methods have probably reduced the social utility of replication although some is doubtless still useful.

4. By spreading costs and risks among firms, collective invention meant that competitive industries could have high rates of invention even if the inventions were not patentable. But that inventiveness was a fickle spirit. One of the most important consequences of collective invention is that the rate of invention depends on the rate of gross capital formation. An increase in capital formation fosters inventions while a cessation of capital formation inhibits them. This synchronization follows from a consideration of the incentives a firm faces to build a new plant deviating from the existing best practice design. If the industry is sufficiently profitable so that the construction of a plant along the old lines would be commercially justified, then the cost the firm would bear in varying the design is the possibility that units costs in the new design would exceed those in the old. The benefit to the firm in varying the design is the possibility that production costs would be less. Now suppose that the industry is sufficiently unprofitable so that the construction of the old design would not be commercially justifiable. In that case, in order to compute the cost of the experiment in varying plant design, the capital cost of the plant must be added to the possibility that the new design will have higher unit costs than the old best practice plant. When an industry is profitable enough so that there is a high rate of capital formation, the cost of experimenting declines and the rates of experimentation and invention consequently rise.

This conclusion is reminiscent of Schmookler's (1954 and 1962) work. Schmookler presented voluminous evidence using patent statistics in order to establish that the rates of invention and gross capital formation were highly correlated. Schmookler explained the correlation by arguing that a high rate of capital formation implied a high demand for inventions embodied in capital equipment. Inventors then allocated their resources to inventing for that industry. A consideration of the operation of collective invention suggests a completely contrary explanation of such correlations. From the point of view of collective invention, a high rate of capital formation lowers the cost of experimenting and would thus increase the supply of inventions. To assess the relative importance of the supply and demand effects of capital formation on the rate of invention would require a detailed investigation for each industry of interest.

Schmookler did not include iron and steel among the industries he studied

statistical techniques. See Bell (1869, 1871a, b, 1872a, 1872–3a, 1872–3b, 1884), Cochrane (1864, 1869a, b, 1870a, 1875), Cowper (1869–1870), Samuelson (1870–1.), Whitwell (1869, 1871a), Jones (1908, p. 67). Modern statistical methods were first applied to blast furnaces in Clements (1920), Evans and Bailey (1928), and Evans et al. (1931).

closely, but its history appears to exhibit a correlation between rates of capital formation and rates of invention.[20] Thus, between 1850 and 1875, the Cleveland district had a high rate of capital formation and, as we have seen, a high rate of invention. Except for Britain's hematite district, capital formation was meagre elsewhere in Britain and in the United States. The regions of no capital formation were devoid of inventions. After 1870, the rate of capital formation in the American iron industry was very high, and so was the rate of invention (as, for instance, fast driving was perfected). At the same time capital formation ceased in the British. So did the rate of invention. The same story is repeated in steel. The British industry contributed important inventions (e.g., Gjers' soaking pit) to the world's stock of knowledge before 1890, i.e., when many new steel mills were built. After 1890 the construction of new steel mills in Britain ceased and with it inventive activity. During this period the rate of invention was very high in the United States, as is well known, and so was the rate of capital formation. There appears to have been a high correlation between capital formation and invention in iron and steel.

The operation of collective invention provides a better explanation for this correlation than the demand for invention argument propounded by Schmookler. Schmookler modelled the behaviour of independent inventors who choose the industry to which they would allocate their resources. As I have shown for some important instances, and as could be documented for others, collective invention — not the independent inventor — was the dominant inventive institution in the nineteenth century iron and steel industry.

When contemporaries discussed the decline in the rate of invention in the British iron and steel industry during the late nineteenth century, they often linked it to the decline in British capital formation. The proposed links are often evocative of collective invention. In 1890 the British Iron and Steel Institute took an excursion to the United States and visited many American iron and steel works. The journey impressed upon the British travellers the extent to which American technology had surpassed their own. C.J. Bagley (1890), a British engineer, explained the situation as follows:

> 'The American engineers have had magnificent opportunities to improve their practice, for during the past 20 years there have been hundreds of furnaces built in the United States.... The experience thus gained has shown them the possibility of increasing the output of the furnace enormously.... In fact, since 1875 not a single new furnace plant has been built in Cleveland, so that our engineers, who once held the proud position of being the leading blast furnace engineers, are now, from lack of opportunity, being outstripped in the race.'

[20]General accounts of the British and American iron and steel industries include Burn (1961) and Temin (1964).

Bagley's analysis makes good sense given the reliance on collective invention to generate technical progress.

The relationship between the rate of capital formation and the rate of invention implied by collective invention is also reminiscent of Arrow's (1962) model of learning by doing. Arrow's model postulates that the level of efficiency at any time depends on the sum of all investment that had taken place in the industry. Arrow does not consider the sort of inventive institutions that might produce that relationship. Collective invention is an obvious example.

Arrow was able to show that the rates of investment and invention in competitive industries were less than socially optimal. The result follows from the failure of firms to consider as benefits the increase in efficiency other firms would experience as a result of the learning associated with the act of investment. A similar problem arises in the case of collective invention as long as firms that contemplate building a plant of novel design do not recognize as a benefit the value to other firms of the information they produce. It is unlikely that this market failure is of any consequence when the rate of capital formation is high, but if investment slackens, the divergence between the private and social returns to invention might become very large. The British Steel industry after 1890 provides an important example. There would have been very large returns to the industry as a whole in developing the technology to make basic open hearth steel from Cleveland pig iron.[21] However, the costs of constructing experimental plants would have been so large that no firm undertook them. The necessary technology — the mixer and the tilting open hearth furnace — were invented collectively in the United States as solutions to other technical problems:[22] the mixer was a solution to the problem of conveying molten pig iron directly from the blast furnace to the Bessemer converter, and the tilting furnace was the solution to the problem of frothing that arose when open hearth furnaces were charged with pig iron but no scrap. Since the British steel industry (like the American) relied on collective invention for its new technology, the British had to wait until the Americans developed the mixer and the tilting open hearth furnace before moving into basic steel. This failure to invent a technology with a high social rate of return was a consequence of relying on collective invention.

5. The rate of invention is one aspect of invention which has been of interest. A second aspect is the bias of inventing. Bias has been variously defined. A common approach has been to represent the impact of a new technology on the production function with a set of factor augmentation

[21]Allen (1979).

[22]Campbell (1903, pp. 168–170, 205–211, 306–315), and Temin (1964, pp. 163–164).

coefficients. If the new technology augments the various inputs differentially, then the technological change is biased. Equivalently, an invention is biased if the decline in cost which its use entails depends on the prevailing input prices. For the past century, informed observers and economists have argued that invention has been biased towards augmenting relatively expensive inputs. In particular it has often been argued that the inventions produced in the United States, where wage rates have been high relative to other input prices, have tended to be labour augmenting. In other words, American technology lowers costs more if the wage rate is relatively high than if it is relatively low.

Developing a theoretical model to explain such a regularity has proved to be difficult. David (1975, pp. 58–85) has argued that the Atkinson–Stiglitz (1972) notion of localized technical change can account for this phenomenon. Indeed, if new technology is developed collectively, technical advance is of the sort hypothesized by David. In this case, design changes will be extended by the industry only if they lower costs in the environment in which the industry is operating. Thus, if a change in plant design causes a small inward shift in the isoquant in the vicinity of its tangency with the total cost line so that costs fall, other firms will elaborate the design change. On the other hand, if the change in plant design causes the isoquant to shift inward sufficiently far from the point of tangency so that costs do not fall, then the design change will not be pursued by other firms. Under these circumstances, the decline in costs associated with the new technology will depend on the prevailing set of factor prices. Inputs which are relatively expensive will be augmented. One would expect biased technical change when collective invention is practiced.

6. Collective invention is only one of the ways in which invention might be organized. What accounts for the appearance of collective invention rather than some other form? In answering this question it is useful to recognize that firms behave in two significant ways during collective invention. First, they release to their competitors information about the design and efficiency of their new plants. Second, firms do not devote appreciable resources to the discovery of new knowledge. I shall try to account for the appearance of collective invention by considering the circumstances under which firms would behave in these ways.

It is extremely puzzling why firms released design and cost information to potential entrants to the industry. If (as we continue to assume) the industry was competitively organized, it would appear that this action could only rebound to the disadvantage of the firm. To the degree that the information release accelerated technical progress, the price of the product would decline and so would the net income of the firm that released the information. There are three lines of argument that might account for the release of information.

The first reason that might account for firms' releasing information is that the owners and managers of the firm often had professional ambitions that could be advanced by releasing information about the operation of their firms. Under those circumstances the profits of the firm might be sacrificed and information released. On a less exalted level, firms seem often to have engaged in competitions in advancing size or output. Thus one of the reasons advanced by Gjers (1871, p. 203) to account for the increase in height of Cleveland blast furnaces was 'the natural ambition of one firm outstripping another in the race for size'. The continuous breaking of Bessemer converter and blast furnace production records in America in the 1870's and 1880's evince the same spirit.[23] Since you cannot win the contest unless you reveal valuable information, these competitions fostered information release.

The second reason that firms might release information is that so many people would know the relevant information that it would have been costly to keep it secret. In the case of blast furnaces and steelworks, the construction would have been done by contractors who would know the design. The designs themselves were often created by consulting engineers who shifted from firm to firm. Gjers' career was not atypical.[24] He was first employed by Cochrane in building the original Ormesby blast furnaces and was appointed blast furnace manager from 1855 to 1861. In 1862 he was made manager of Hopkins, Gilkes & Co.'s Tees-side Ironworks, and he constructed the Linthorpe Ironworks in 1864 for the same firm. In 1866 he designed the Tees-side blast furnaces. In 1868 and 1869 he was contracted to design or remodel four blast furnace works in other parts of England, and in 1870 he constructed the Ayresome Ironworks for his own firm, Gjers, Mills & Co., which he subsequently managed. Since the responsibilities of a consulting engineer like Gjers would not end until the furnace was actually functioning, he would also know its operating characteristics. Many people working in the plant would have some idea of these characteristics as well. Managers moved from firm to firm during their careers. Even top and bottom fillers would know the proportions of ore and coke in the furnace charge. From that one could easily compute the coke rate. Given the miserable wages of fillers, the coke rate would be a cheap piece of information to acquire. Since secrecy would be so hard to maintain, the release of information is not surprising.

The third reason that firms might have released technical information is that that behaviour might have been profitable. Hirschleifer (1971) has argued that inventors can be compensated for their efforts if they successfully speculate in assets that appreciate in value due to the invention. The owners of firms releasing technical information might be compensated in the same way. The following are three possibilities:

[23]Richards (1890–1, p. 969), Potter (1890–1, p. 972).
[24]Obituary: John Gjers (1898).

(a) If the production process involves a natural resource which commands a rent and if the invention lowers the costs of firms' processing only that portion of the resource with certain characteristics, then the owners of those firms might benefit from releasing technical information. The firms that raised the height of Cleveland blast furnaces benefited in this way. The taller furnaces lowered fuel consumption only for firms smelting Cleveland iron ore. Since Cleveland was only one of the North Atlantic market's producing centres, the main effect of the fall in blast furnace operating costs in Cleveland was to increase the value of the Cleveland ore deposit. Since the blast furnace firms either owned their ore mines or leased mining rights at fixed royalties, some of the rise in the value of the ore deposit accrued as a benefit to the firms that released technical information.

Rough calculations suggest that the rise in the value of the mines exceeded the decline in the value of the furnaces. The principal impact of increasing furnace height and blast temperature was to lower coke requirements by 0.6 tons per ton of pig iron. Coke cost £575 per ton. Sir. B. Samuelson owned ore mines and furnaces that produced 1000 tons of pig iron per week or 52,000 tons per year. In 1871 he rebuilt his ironworks, scrapping the small furnaces built in the 1850's and replacing them with 85 feet furnaces. The new furnace plant cost £56,331. Assuming a 10% interest rate and an infinite time horizon, the present value of fuel savings was £179,400. Since this figure exceeded the construction cost of the new furnaces, scrapping and rebuilding were in order. To put the matter differently, the tall furnaces fully depreciated the older furnaces rendering them worthless. By the same token, however, Sir B. Samuelson's wealth increased since the value of his ore deposit increased by the £179,400 he saved in fuel costs. Since all firms in the district, in particular the active propagators of information, faced similar conditions and replaced their original small furnaces with taller ones, one can conclude that all firms benefited in the same way.[25]

The characteristics of the situation that made collective invention profitable were the specificity of the resulting technical progress to local conditions and the fact that the Cleveland industry was only a small part of the world industry so that the price of iron could be regarded as exogenous. Under these circumstances, the owners of the natural resource would actively foster information propagation since they could not lose by it and might well gain.

(b) In possibility (a), it was the chemical composition of the iron ore that made the technical advance generated by collective invention in Cleveland specific to that district. Chemical composition is irrelevant, however, to many new techniques (such as those in which capital is substituted for labour)

[25]Allen (1981) reports the sources for the figures used in this paragraph and discusses the replacement decision in detail.

which were developed through collective invention. Differences in relative factor prices can, however, play analogous role to differences in chemical composition. In section 5, it was argued that collective invention tends to generate new techniques that are adapted to the localities that generate them in that the new techniques lower costs most when used by firms facing relative input prices like those prevailing in the locality of invention. Under those circumstances, if the world is characterized by competition among firms in different regions with different relative factor prices, each region can lower its costs and raise its resource rents relative to other regions by practicing collective invention and broadcasting technical information.

(c) The release of technical information can be justified even if there is only one region producing the product. In 1908 the Institute of Metals was founded in England. It was patterned after the Iron and Steel Institute, but dealt with the metallurgy of non-ferrous metals. Much of the early attention of the Institute was devoted to problems arising in the use of aluminium and copper alloys in marine engineering and shipbuilding. Since Britain produced most of the world's metal ships, the firms revealing their secrets at the Institute were competing only against each other and not against producing centres in other parts of the world. The early meetings of the Institute often debated the desirability of releasing trade secrets. Proponents of such behaviour justified it in the following terms:

> 'Each individual has some cherished bit of knowledge, some trade secret which he hoards carefully. Perhaps by sharing it with others, he *might* impart useful information; but by an open discussion and interchange he would, almost for certain, learn a dozen things in exchange for the one given away. General increase of knowledge would give general improved practice, most likely a larger use of the materials in which a manufacturer is interested.'[26]

And 'larger use' would yield larger profit.

In these discussions, it was not argued that every firm would always find it advantageous to reveal trade secrets [as was the case in possibilities (a) and (b)]. Instead, it was argued that output and profits would be greater if the existing regime of trade secrets was replaced by a new regime of free information exchange. Comparing the two regimes, it is not surprising that costs would be lower under the free information regime and, hence, that output would be greater. It is not obvious, however that profits would be higher. To explore whether they might be, consider the following circumstances: Suppose that production is characterized by constant returns to scale and that the supply curves of inputs to the industry rise. In that case, the industry supply curve rises and intra-marginal units of inputs earn

[26]Muntz (1909, p. 291).

rent. Suppose further that the consequence of reorganizing behaviour in accord with a free information regime is to increase efficiency in a Hicks neutral manner, i.e., all inputs are argumented equally. The supply curve characterizing the free information regime will be below the supply curve of the trade secret regime, and, if the demand curve slopes downward, output will be greater. The test for whether the free information regime is more profitable than the trade secret règime is whether the rents earned by intra-marginal units of owner supplied inputs under the trade secret regime are higher under the free information regime. Two sets of circumstances are individually sufficient to produce that result: If the production function is Leontief so factor substitution is impossible and if the product demand and supply curves are sufficiently elastic so that the induced proportional increase in output exceeds the proportional increase in efficiency, then the demand for all inputs will increase and all input prices and intra-marginal rents will consequently rise when the industry shifts to a free information regime. Alternatively, if all input supply curves are identical relative input prices will not change as the industry expands and all input prices will rise equally. Under these circumstances, the owners of existing firms will always benefit by shifting from a trade secret to a free information regime.

There are clearly circumstances under which this conclusion does not follow. For instance, suppose that technology is Leontief and that input supply curves are identical but the demand for the product is perfectly inelastic. In that case the shift to the free information regime lowers the demand for all inputs and hence lowers their prices and intra-marginal rents. In general, with a moderately elastic product demand curve, the possibility of factor substitution, and differences in the supply curves of inputs, the intra-marginal rents earned by owner supplied inputs might either rise or fall.

The purpose of possibilities (a), (b), and (c) is not to prove that the release of technical information is always profitable (since that is not true). Instead, the purpose is to suggest that such behaviour may be consistent with private profit maximization. It is interesting to note that this line of argument is consistent with explanations offered by economic anthropologists for analogous arrangements among primitive peoples. Herskovits (1952, pp. 99–108) presents examples from numerous cultures of the pooling of labour among households to accomplish large projects. His explanation is in terms of private self-interest: one family helps another clear a field today in the knowledge that the second family will be obliged to reciprocate in the future. If the activity must be executed quickly once it is begun, both families benefit from this arrangement. Collective invention can be similarly privately profitable.

The second behaviour pattern that characterized collective invention was that firms did not devote appreciable resources to invention. The resources a firm might allocate to that activity are limited by the benefits the firm expects to receive. As long as firms are small and industries competitive, the benefits firms can expect from research are also small. Suppose, however, that the industry be reorganized into a few large firms. The benefits each consolidated firm might expect to receive from any given expenditure on research would be greater than the benefits any of the small firms might have expected before the merger. Moreover, with fewer firms in the industry the costs of collusion would be less. The firms in the industry could decide to reap the benefits of lower costs as higher profits rather than passing those benefits on to consumers in the form of lower prices. For these reasons, one would predict that merger movements would encourage firms to undertake research and development programs. Collective invention would correspondingly be restricted. Twentieth century business history bears out this prediction since it has witnessed both the emergence of oligopoly in manufacturing and the widespread commitment of firms to R&D.

7. In this essay I have suggested that collective invention be recognized as an institution that produces inventions. Under the conditions prevailing during the nineteenth century, it was probably the most important source of inventions. Various consequences of generating new production methods by means of collective invention and the circumstances under which it would be expected to flourish have been explored.

Since 1900, collective invention has probably become less important, especially in comparison to research and development. Considering R&D from the perspective of collective invention, however, suggests that R&D (and other institutions producing inventions) be considered in a new way. An essential feature of collective invention was the release of technical information to actual and potential competitors. It was this behaviour which allowed cumulative advance. All of the factors that account for this behaviour apply to the other institutions as well. Hence, one would expect to observe the wilful dissemination of technical knowledge under a variety of circumstances. And, indeed, even a casual acquaintance with recent engineering literature indicates that such behaviour is rampant today. To the degree that economists have considered this behaviour at all, it has been regarded as an undesired 'leakage' that reduces the incentives to invent. That firms desire such behaviour and that it increases the rate of invention by allowing cumulative advance are possibilities not yet explored. They should be.

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