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efficiency was increasing faster only if pig iron prices were falling faster in America relative to input prices.[4]

Three explanations of the slow productivity growth in British pig iron have been built on this narrow evidential base:

(1) The *technological* explanation, which I shall give the most attention, asserts that productivity grew slowly simply because the pig iron industry had exhausted the potential of the existing technology by the 1890's. In this view, slower productivity growth was not a peculiarly British phenomenon, but part of a worldwide "exhaustion on the innovations of steam and steel." [5] The technological explanation, in other words, stresses a slower growth in the world's supply of innovations.

(2) In contrast, the *economic* explanation stresses a slower growth in Britain's demand for innovations. As P. Temin has put the argument recently, the slower growth of iron and steel output in Britain than elsewhere led to less investment, and consequently, less modern capital equipment in Britain.[6] British productivity lagged behind an expanding supply of technological knowledge because Britian's demand for modern equipment embodying the knowledge was low.

(3) Finally, the *sociological* explanation stresses the low quality of the entrepreneurs in the industry. The entrepreneurs were mediators between technological supply and investment demand. Burn, for example, concludes that "attachment to routine and a lack of adequate training" caused Britain in the 1870's to adopt foreign innovations in iron and steel too slowly, and Burnham and Hoskins find that "the remaining factor of production in iron and steel is 'entrepreneurship' . . . ; our study has led us to suggest a weakness in this direction." [7]

A secondary purpose of this paper is to assess these three explanations, particularly the technological, by exploiting the available statistics on British and American pig iron. The primary purpose, however, is to establish beyond reasonable doubt the fact of

4. One measure of total productivity change in the British historical literature that does distinguish between movements along a fixed production function and movements of the production function itself is G. T. Jones' index of pig iron real costs in his *Increasing Returns* (Cambrdge England: Cambridge University Press, 1933). His index, however, covers only the Cleveland branch of the industry. See the first footnote in Section IV below.

5. E. H. Phelps-Brown and S. J. Handfield-Jones, "The Climacteric of the 1890's: A Study in the Expanding Economy," *Oxford Economic Papers, New Series*, Vol. 4 (Oct. 1952).

6. "The Relative Decline of the British Steel Industry, 1880–1913," in H. Rosovsky (ed.), *Industrialization in Two Systems* (New York: Wiley, 1966).

7. Burn, *op. cit.*, p. 65, and Burnham and Hoskins, *op. cit.*, p. 271.

stagnant total productivity in British pig iron. The discussion of the end of Britain's Victorian expansion has been founded on much too casual measurements of productivity: this paper tries to show what measurements are possible and necessary. The argument is as follows. From the late 1880's to the late 1939's productivity growth in British pig iron was nil. Despite this stagnation, however, British productivity was at least as high as American productivity before 1914. Therefore, before 1914 British productivity stagnated simply because Britain had exhausted the current technology: the technological explanation is adequate before 1914. After 1914 it is not and one must choose between a sociological and an economic explanation of the continued stagnation. I spend most of the paper proving these points, particularly that productivity did not grow from the late 1880's to the late 1930's. In the last section I show briefly how the argument of the main body of the paper affects the choice between a sociological and an economic explanation of the remaining years of stagnation from 1914 to 1935.

II

I have used the method developed by R. Solow [8] to measure total productivity change from 1870 to 1939 in British pig iron. Comparing estimates of the growth of pig iron output with estimates of the growth of the four significant inputs (coke, iron ore, blast furnace capital, and blast furnace labor) gives the picture of productivity in Figure I. (Ignore for the moment the line marked "Iron Content of Ore.") [9]

After a respectable rise [1] of about 1 per cent a year during the

8. Consult the first few pages of his article, "Technical Change and the Aggregate Production Function," *Review of Economics and Statistics*, XXXIX (Aug. 1957), for an explanation of the method. I shall summarize my use of the theory of this and other productivity measures in the footnotes. The formula for the proportional change in a productivity index, A, for pig iron is, in the Solow style,

$$\triangle A/A = \triangle Q/Q - (S_c \triangle C/C + S_o \triangle O/O + S_k \triangle K/K + S_l \triangle L/L).$$

Q is output of pig iron per year, C is coke, O ore, K capital, and L labor: s_c, s_o, s_k, s_l are the shares of each input in total costs. Under certain economic assumptions, A is the multiplier in the production function $Q = A.F\ (C,O,K,L)$. I shall mention these assumptions later in the text.

9. The Appendix, available from D. N. McCloskey, Economic History Workshop, 5 Linden Street, Cambridge, Massachusetts, is a description of the sources and methods used in making the estimates. The estimates are meant to be industry-wide and annual. The most important statistical sources are the *Statistical Yearbooks* of the British Iron and Steel Federation and the British government's annual *Mineral Statistics*.

1. It is respectable by comparison with, for example, the rate of growth of productivity that Solow (*op. cit.*) found in American manufacturing from 1909 to 1949, about 1½ per cent a year.

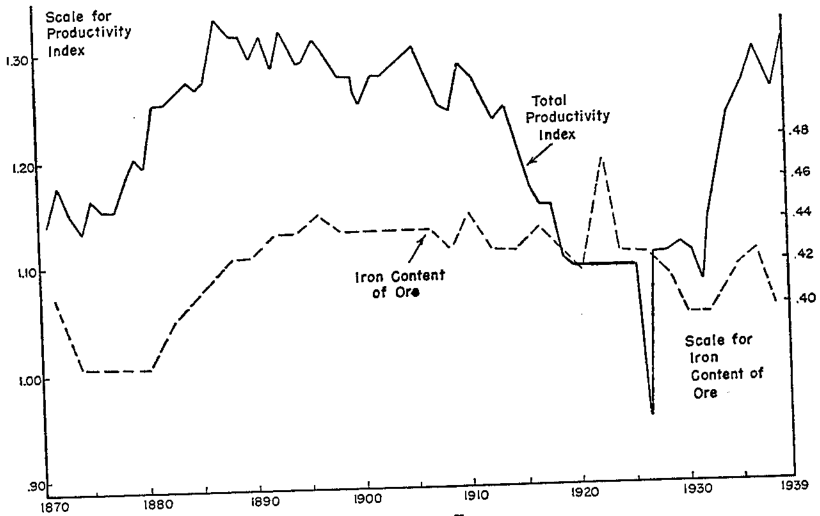

FIGURE I

The Total Productivity Index and Iron Content of Ore

1870's and 1880's productivity leveled off or, if anything, fell slightly until World War I. It fell sharply during the war, did not begin to rise until the late 1920's, and did not reach the level of the late 1880's until the late 1930's. The fall in productivity during and after the war is not significant: I show later that a good part of the fall is due to a temporary deterioration in the quality of coke used by the industry. The significant point is that by this measure the net growth of productivity in British pig iron from 1887 to 1939 was nil. This is a remarkable stagnation of productivity. For given inputs ironmasters got no more output in 1939 than they had in 1887.[2]

The assumptions underlying this measure of productivity change, of course, are not perfectly true. And estimating year-to-year productivity changes involves a good many compromises between the ideal and the available data. I should emphasize, however, that the argument requires only an approximate measure of productivity change: the important fact is that the measure did not rise significantly from the late 1880's to the 1930's.

Nonetheless, a theoretically-minded sceptic might argue that the apparent stagnation was simply a result of the violation of the economic assumptions underlying the measure. Although I can say

2. Preliminary calculations indicate that, though during World War II productivity fell, from the end of the war to 1960 it grew as fast as it did in the 1870's. By 1960 the level of productivity was far above its level in 1939.

little about one of the assumptions, profit maximization, I can give some support to the other four assumptions. The assumption that capital was freely variable seems reasonable, considering that the number of furnaces in blast varied from year to year. Likewise, the assumption that the size of the industry's output did not affect the technical conditions of production seems reasonable: it is unlikely that there were nonpecuniary diseconomies of industry scale in pig iron, and only these would produce a spuriously stagnant measure of productivity. The assumption that productivity change was neutral in its effect on the marginal products of every input is not necessary for a useful interpretation of the calculated productivity measure: when it is false the method no longer measures the proportional shift in the production function, but it does still measure the proportional change in output attributable to this shift. The last assumption, that firms lacked market power, is defensible on two grounds. First, until the company amalgamations of the 1920's and the iron and steel tariffs of the 1930's, the pig iron industry had a large number of firms and faced strong foreign competition. Second, I can make it plausible that competition is not necessary for the conclusion that productivity stagnated: even if firms *did* have market power it happens that the largest possible understatement of productivity growth would be quite small.[3]

An empirically-minded sceptic might worry more about the estimates embedded in the productivity measure. For example, a better estimate of capital per blast furnace than the volume estimate used here might be the surface area of blast furnaces, which would grow slower as furnace dimensions grew; a slower growing capital input would yield a faster growing productivity measure. But it happens that the choice between the two estimates is not crucial when one needs only an approximate measure of productivity change. Much of the movement in the capital estimate as it stands is due

3. A true measure of productivity would put the true elasticity of output with respect to each input in place of each input's share in total costs:

$$\triangle A^*/A = \triangle Q/Q - [E_{Q.C} \triangle C/C + \ldots + E_{Q.L} \triangle L/L].$$

The understatement of productivity growth would be, then,

$$\triangle A^*/A - \triangle A/A = (s_C - E_{Q.C}) \triangle C/C + \ldots + (s_L - E_{Q.L}) \triangle L/L.$$

Market power, whether on the product or factor market would tend to lower the share of the inputs other than capital (capital's share is calculated as a residual). To find an observable upper bound to the understatement, make the extreme assumption that *all* capital's share comes from the profits of market power, but that for the factors other than capital the terms such as $(s_C - E_{Q.C}) = 0$ (not < 0, as they logically should be, because allowing this would make the understatement smaller). The understatement reduces to $s_k \triangle K/K$, which is only about .06 from 1886–93 to 1912–20 and negative for the period after 1920 (in which capital in use was falling, so that $\triangle K/K$ was negative).

not to the volume correction but to the movement in the number of furnaces in blast. Moreover — and this point applies to the labor estimates as well — whatever the estimate of capital used, errors in it contribute little to over- or underestimation of productivity growth, because the share of capital in total costs is small.[4]

Finally, although it is possible that a change in the ratio of pig iron output to ore input — a component of the productivity measure — reflects productivity change within the industry, it is also possible that for the most part it reflects mere changes in the iron content of ore; and a change beyond the control of ironmasters in the quality of ore is not a change in the production function of pig iron.[5] But even if all the changes in the pig iron to ore ratio reflected mere changes in iron content, the conclusion that productivity was stagnant for most of the period would not be weakened; indeed, if anything it would be strengthened. The pattern of the curve marked "Tons of Pig Iron per Ton of Ore" in the diagram of the productivity measure shows that changes in the ratio explain only the rise of the measure in the 1870's. Removing ore's influence on the productivity measure would make it grow still more slowly than it does in the 1870's and 1880's and would not change it after the 1880's. By the Solow measure, then, productivity was stagnant for fifty years, from the 1880's to the 1930's.

III

Although the total productivity measure stands up well to criticism, it would be desirable to have some additional test of the stagnation in the pig iron production function. The average product

4. The data for the argument are the physical dimensions of blast furnaces presented in the Appendix. The period in which an underestimate of the rate of growth of productivity (arising from an overestimate of the rate of growth of capital) would alter the conclusions of this essay is that in which productivity did not grow, namely, after the late 1880's. From 1890 to 1940 the volume of a typical blast furnace grew at a compound rate of growth of .0181 per year, while its surface area grew at about .0125 per year. The difference between these two rates, .0056, is the amount by which capital growth per year would be overestimated if a volume estimate were used when surface area was, in fact, the correct estimate. But an error in the growth rate of an input, like its true value, enters the formula for $\Delta A/A$ weighted by its share in total costs. The shares of ore, coke, labor, and capital (capital is the residual share) averaged .45, .30, .10, and .15. Therefore, the underestimation of $\Delta A/A$ due to an incorrect choice of the volume measure is the overestimate of the growth rate of capital weighted by capital's share: (.0056) · (.15) = .00084. Correcting for this underestimate by compounding it over the fifty years would raise the index of the productivity level (the index of A) by only 4 per cent: (1.00084)50 = 1.042. That is, it happens that using a surface area index of capital per blast furnace would raise the productivity measure only 4 per cent in fifty years above its level using a volume index.

5. I treat coke quality later.

of coke, suitably adjusted, provides a test which avoids using the imperfect estimates of the quantities of labor and capital and the assumption that changes in the ratio of pig iron to ore reflect real productivity change in the industry. The pattern of the average product of coke from 1870 to 1939 was as follows (ignore for the moment the curve marked "Corrected Coke Productivity"): [6]

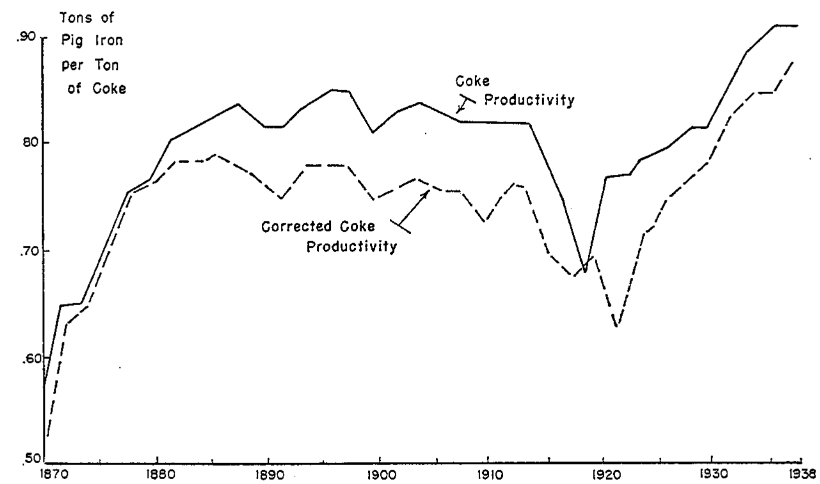

FIGURE II

Coke Productivity and Corrected Coke Productivity

The pattern of the average product of coke is similar to the pattern of the total productivity measure: it rises until the late 1880's, stays level from the late 1880's to 1914, falls during and immediately after World War I, and rises from the early 1920's to 1939. Since changes in the average product of coke play a large role in changes in the productivity measure (coke is 30 per cent of the cost of pig iron), the similarity is not surprising. Nor, without more evidence, is it a confirmation of the productivity measure: the average product of coke is influenced by the quality of the coke itself, the richness of the ores. and the amounts of the inputs of labor and capital rela-

6. There is one possible source of error in the series before 1915. I have used a .60 ratio of coke to coal to translate the "Coke used (including Coal converted into Coke)" of *Mineral Statistics* into coke. This appears to have been the official ratio, but from 1906 to 1919 detailed coking statistics for Britain in *Mineral Statistics* imply a lower ratio, about .54. If one used the lower ratio, however, the fall in average productivity during the war would be even greater than in the series using .60: using a lower coke to coal ratio would raise the average product of coke before the war; the average product after the war would not be raised correspondingly because it is based on returns of coke (not only coal) used.

tive to coke. But I can show easily that taking account of these influences keeps the similarity in pattern between the average product of coke and the total productivity measure.

Coke quality, for example, did not change from 1870 to 1939 except for a temporary deterioration during and after World War I. In these bad years the carbon content of British coke was about 82 per cent and the ash content about 11 per cent; before and after the war the typical carbon content was 88 per cent and the ash content 8 per cent. There is some evidence that this deterioration was the fault of the firms who made the pig iron.[7] But even if the quality of coke was a matter entirely external to the industry, in which case it should not be reflected in the productivity measure, the picture of stagnation is unchanged. Correcting for the change in coke quality removes the temporary fall in coke productivity after the war, but does not produce a rise.[8]

Iron ore quality did not change from the 1880's to the 1930's, so that the stagnation of coke productivity cannot be blamed on a falling quality of ore. The important measure of the quality of ore is its percentage iron content and, as I pointed out in Figure I earlier, this percentage changes little from the 1880's onward. The meaning of "little" in this context depends on the sensitivity of coke productivity to the iron content of the ore used. A cross section of British localities producing pig iron gives a rough idea of how much coke was saved or lost by using a richer or leaner ore.[9] The curve "Corrected Coke Productivity" in Figure II represents coke productivity corrected for the changes in ore quality: coke productivity would have moved in this fashion if the iron content of ore had stayed at its 1880 level (38 per cent) from 1870 to 1939. Aside from

7. Fifty-four per cent of the coke used in the pig iron industry was made by firms owned or controlled by the industry itself. About 80 per cent of the firms making their own coke owned coal mines as well: even the quality of the coal from the mines was controlled in these firms. *Royal Commission on the Coal Industry* (London: H. M. Stationery Office, 1926), Q1054.

8. Indeed, the deterioration in coke quality during 1914–28 would have to have been slightly greater than reported in the text (in terms of carbon and ash content) to explain all the fall in the average product of coke. Experiments in British blast furnaces during the 1920's showed that coke productivity fell by .015 (all the numbers here are proportions) for each rise in ash content of .010. On the basis of prewar performance, coke productivity fell by .009 for each fall in carbon content of .010. In fact, coke productivity fell by about .140. Ash content rose by about .030. Carbon content would have to have fallen by about .100 to explain the whole fall in coke productivity, whereas in fact it fell by about .060 or .080.

9. Assuming that the ratio of pig iron made to ore used is a measure of ore richness alone, in four years during 1870–1939 among seven pig iron districts a 1 per cent rise in ore richness was associated with, roughly, a 1 per cent rise in coke productivity. The coefficients are 1887, .7; 1897, 1.; 1912, 2.; and 1939, 1.

a somewhat lower level after 1880, the corrected coke productivity is very similar to the uncorrected productivity. If anything, it indicates an earlier beginning of the stagnation in productivity in Britain, 1880 rather than the late 1880's.

One important source of a spuriously stagnant coke productivity measure remains. Its stagnation from the 1880's to the 1930's may have been merely a result of diminishing amounts of capital and labor relative to coke. One can test this possibility, yet avoid using the estimates of the *quantities* of capital and labor, by observing the movement of the *prices* of capital and labor relative to coke. If both capital and labor had become cheaper relative to coke from the 1880's to the 1920's, ironmasters would have substituted capital and labor for coke, driving up the average product of coke. The failure of the average product of coke to rise despite the increases induced by the changes in the price ratios of capital and labor to coke would be evidence that the production function of pig iron had not risen over the period but, if anything, had fallen. History has been accommodating, for the prices of both capital and labor did fall relative to the price of coke from the 1880's to the 1920's.[1] That is, the growth of the average product of coke is an upper bound on the growth of the production function.

In short, the pattern of the total productivity measure and of the average productivity measure are the same. This is an important fact in itself. Obviously, the average product of coke is a good estimate of total productivity if and only if the impact of changes in the amounts of the other inputs, capital and labor, per ton of coke

1. The coke price per ton and the yearly wage that were used in the productivity measure are reliable indicators of trends. The wage fell relative to the price of coke from the 1880's to 1920, rose during the 1920's and fell again during the 1930's. All but the last movement would justify the use of the average product of coke as an indicator of the direction of productivity change. Since the price of capital that is implicit in the share of capital series used to construct the productivity measure is probably unreliable, one needs another estimate. The price index of capital goods implicit in C. H. Feinstein's real net investment series for the United Kingdom (B. R. Mitchell, *Abstract of British Historical Statistics* (Cambridge: Cambridge University Press, 1962), p. 373,) falls markedly relative to the price of coke from the decade 1885–94 to 1905–14. The slight rise in the yield on consols between the same decades is some offset. For one firm in the Cleveland district (Bell Bros.) the frequency of blast furnace relinings, a rough indicator of the rate of depreciation, did not change between the decades. In short, the price of capital fell relative to the price of coke from the 1880's to World War I (because there are no investment series for the war, it is difficult to go further). In view of the diminishing returns in British coal mining, it is not surprising that the price of coke rose disproportionately. Indeed, since coal is made with capital and labor, the rise of the price of coal (coal is 80 per cent of the cost of coke) relative to the prices of capital and labor is a measure of those diminishing returns.

can be ignored.[2] The similarity of the coke productivity measure to the total productivity measure in Britain suggests that, in fact, one *can* ignore the impact of other inputs, when their factor prices change by about the same amount as they did in Britain from the 1880's to the 1920's. This conclusion will prove useful when I come to compare British with American total productivity. For now, the similarity of the two measures reinforces the conclusion that productivity did not grow.

IV

It is reasonably clear that there was a long pause in the growth of productivity in British pig iron from the 1880's to the 1930's. By contrast, from 1885 to 1913 productivity in the American pig iron industry grew rapidly.[3] Before seeking explanations of this phenomenon in entrepreneurial negligence or slack demand, however, one must eliminate the possibility that productivity stagnated simply because the British industry had exploited fully and early the potential of the existing technology. There would be no need for sociological and economic explanations if the technological explanation applies from 1890 to 1930, that is, if British practice was touching on the limits of the world's knowledge of pig iron technology after the late 1880's, but the world's knowledge was not growing. I find, in fact, that the technological explanation *does* apply up to 1914.

Because it is difficult to measure directly the limits of the world's knowledge during seventy years, one must use the best actual world

2. Assume a constant returns, neutral technological change production function, $Q = A\,F\,(C, K, L)$.
Then: $Q/C = A\,f\,(K/C, L/C)$.
And, signifying proportional rates of change with stars,
$$(Q/C)^* = A^* + [f(K/C, L/C)]^*.$$
If the proportional change in f can be ignored, the average product is the same as the total productivity index.

3. A five year average of Jones's index of real costs in American pig iron falls from 164 in 1885 to 109 in 1913 (*Increasing Returns, op. cit.*, p. 296, column 4). In essence, Jones's index is the price dual of the quantity measure of productivity ($\triangle A/A$) used earlier. The formula for the dual price measure uses the rates of change of the *prices* of inputs and output in the places in which the quantity measure uses the rates of change of their *quantities*. The intuitive interpretation of the quantity measure is that there has been an increase in productivity when the quantity of output has risen faster than the quantities of inputs; analogously, the interpretation of the dual price measure is that there has been an increase (a fall in Jones's index of "real costs") when the price of output has fallen faster than the prices of inputs. The mathematical fact underlying the duality is that if $A = A.F\,(K, L)$, where F is homogeneous of degree one, then $P_q = a.f\,(P_k, P_l)$, where f is also homogeneous of degree one. By manipulating the analogous formulas for $\triangle A/A$ and $\triangle a/a$ it can be shown that, using the same data, $-\triangle A/A = \triangle a/a$ (which implies that the index of real costs, a, is the reciprocal of A). Using this equality, the fall in Jones's American index is equivalent to a growth rate of productivity of about 1 per cent per year from 1885 to 1913. This rate is the same as the growth rate of productivity in British pig iron during the 1870's.

productivity as the practical limit to British productivity. Actual American pig iron productivity is a convenient and reasonable standard of comparison, convenient because its record is full and in English, reasonable because the United States was usually regarded by critics of Britain in the decades around the turn of the century as the exemplar of advanced technique. The question is how to compare the levels of productivity in the two countries. The answer is to apply the measures developed earlier for comparing productivity between two dates to the new problem of comparing productivity between two countries. I use here the second of these measures, coke productivity corrected for the effects of differences in ore quality and differences in the prices of labor and capital relative to the price of coke.[4]

American coke productivity was not definitely higher than British until World War I. Indeed, before 1900 if the British industry had used ore as rich as American ore it probably would have had higher coke productivity than the American industry. Allowing for the temporary deterioration of British coke quality during and after World War I and assuming that ore productivity measures the iron content of ore, from 1880 to 1930 British coke productivity and iron content of ore were roughly constant at .81 and .41. During the same period, American iron content was constant at about .52. Assuming that a 1 per cent increase in the iron content of ore would have produced a roughly equal increase in coke productivity,[5] British coke productivity would have been .9 with American ores (.52 iron content) from 1880 to 1930. The estimate cannot be far off, considering that two important pig iron districts, the South Wales district (which used ore equal in iron content to American ore) and the Cleveland district (which used ore very much poorer than American) reached this level of coke productivity by the 1890's.

But according to data from the American Iron and Steel Institute and the *Census of Manufactures*, American coke productivities

4. Like the measure over time, this assumes unbiased differences in productivity, an absence of scale effects, perfect competition, and equilibrium. An alternative way to detect productivity differences would be to ask whether British pig iron would have cost less with American or Continental techniques. This has the advantage compared with the coke productivity approach that it drops the assumption of unbiased differences in productivity, but the disadvantage that it requires reliable data on both the quantity and price of capital (rather than *either* the price *or* the quantity alone as in the coke productivity approach). A quantity measure of total productivity differences between countries, by the way, would have a price dual as described in the last footnote.

5. This coefficient, 1, is roughly the average of the four coefficients used earlier to correct coke productivity for changes in the iron content of ore in Britain.

were below this .9 level until 1900 and definitely surpassed it only during World War I: [6]

TABLE I

AVERAGE COKE AND ORE PRODUCTIVITIES IN THE UNITED STATES

Year	Tons of Pig Iron per Ton of Coke	Tons of Pig Iron per Ton of Ore
1879	.70	.51
1889	.83	.53
1899	.89	.52
1904	.88	n.a.
1912	.92	.51
1917	.96	.51
1922	1.04	.52
1927	1.03	.51
1932	1.15	.57
1937	1.11	.53

Sources: 1879–1904: *Census of Manufactures*. In order to make use of the data it was necessary to estimate coke equivalents of the bituminous and anthracite coal used in blast furnaces. For the coke equivalent of bituminous coal I used the reported productivities in the manufacture of coke from bituminous coal (approximately .63 tons of coke for each ton of coal). For that of anthracite I used a higher figure to allow for the higher carbon content of anthracite (.75). Because most American blast furnaces were working with coke alone by 1899, these rough adjustments significantly affect only the 1879 and 1889 estimates. The low level of coke productivity in these two years compared with later years is consistent with the rapid growth of total productivity detected by Jones's index during the period. "Ore," as in the British data, includes a small amount of scrap, cinder, and sinter.
1912–1937: American Iron and Steel Institute, *Statistical Reports*.

Comparing coke productivities in an 1888–89 sample of eighty American coke blast furnaces with coke productivities in British districts in 1887 confirms one feature of the comparison: before 1900 American productivity was *lower* than British:

TABLE II

AMERICAN (1888–89) AND BRITISH (1887)
COKE PRODUCTIVITY AND ORE RICHNESS

Location	Number of Furnaces	Type of Pig Iron Produced	Tons of Pig Iron per Ton of Coke	Tons of Pig Iron per Ton of Ore Cinder and Scrap
		United States		
North	20	bessemer	.85	.60
North	10	forge and foundry	.81	.58
North	26	mixed	.83	.59
South	24	mixed	.69	.43
10 North, 1 South		mixed	.80	.55
		Great Britain		
South Wales	all furnaces	largely bessemer	.85	.53
Cumberland	"	"	.86	.55
Cleveland	"	mixed	.87	.35
All Great Britain	"	mixed	.84	.44

Sources: United States: C. Wright, *Sixth Report of the Commissioner of Labor* (2d ed.; Washington: Government Printing Office, 1891). Great Britain: *Mineral Statistics of the United Kingdom* for 1887.

6. The business cycle between census years would not have affected coke productivity greatly, as a glance at the British experience (Figure II) shows. These numbers plus or minus .03 would surely give a band containing the true trend.

The last line for the United States shows the average coke productivities of furnaces that used ores like those used in South Wales and Cumberland. The American furnaces had lower coke productivities. As in the Census data, at similar levels of ore richness (represented in the table by tons of pig iron output per ton of ore) America had definitely lower coke productivity before 1900.

The varying position of British relative to American coke productivity at equal iron content of ore — higher until 1900, equal until World War I, and lower in the 1920's and 1930's — was not due to relative variations in the quality of coke in the two countries. During and after the war, correcting for the effect of temporarily worse British coke does not bring British coke productivity up to the rising American standard. Before the war, when American coke productivity was equal or inferior to British coke productivity, the quality of the coke used in the two countries was the same: in both countries the carbon and ash content of the coke was about 88 and 8 per cent.

Until World War I, then, Britain had higher coke productivity (when the difference in ore richness was allowed for) than the United States. But if coke in America was cheap relative to capital and labor, the American pig iron industry would have used relatively more coke than the British industry. In this case, American coke productivity would have been lower even if the American pig iron production function was as high as the British production function.

Considering that British coal mining was facing diminishing returns and that coal was 80 per cent of the cost of coke, it is not surprising to find that coke was, in fact, cheaper in America relative to labor and capital than in Britain. In 1889 a ton of coke was half as expensive in America relative to a man year of labor as in

Britain.[7] Coke was also cheaper relative to capital. The relevant statistic for the comparison is $\frac{P_c}{(r+d)\,P_k}$. The interest rate r and the depreciation rate d were decidedly higher in America than in Britain during the 1880's and the price of capital goods P_k was higher relative to the price of coke P_c in America.[8]

I showed earlier that British coke became steadily more expensive relative to capital and labor. It is likely, therefore, that British coke continued to be relatively more expensive than American coke, as it was in the 1880's. British ironmasters would have substituted, if possible, cheap capital and labor for expensive coke, raising the average product of coke. Consequently, even if Britain and the United States had the same technology, British coke productivity would have been higher. That is, if labor and capital were good substitutes for coke, the United States surpassed Britain *earlier* than the inflated British coke productivities imply (1914). But, as I pointed out earlier, coke productivity and total productivity moved together in Britain and this suggests that labor and capital were poor substitutes for coke. Consequently, coke productivity was a good estimate of total productivity and the United States did surpass Britain around 1914, not before. The weight of evidence is that the technological explanation works until American coke productivity surpasses British coke productivity in 1914: world technology outran Britain only during and after World War I.[9]

7. American Connelsville coke sold at about \$1.40 a long ton in 1889. In the same year, daily wages of Northern pig iron workers were about \$1.50. Assuming 310 working days a year, a man-year of labor costs \$460. \$1.50/\$460 = .0033. Durham coke in 1889 sold at £.42 a long ton. According to my British pig iron wage series (which in 1889 is close to its reliable base year, 1886), a man-year of labor cost £77. £.42/£77 = .0055.

8. Comparing yields on safe bonds in the two countries in 1889, the American r was 4.5 per cent and the British 2.8 per cent. The linings of blast furnaces wore out in two and one half years in America and in seven years in Britain, implying that d was higher in America than in Britain. The yields on safe bonds are Macaulay's corporate unadjusted index number of yields of American railway bonds (U.S. Bureau of the Census, *Historical Statistics of the United States*, Washington, D.C.: 1960, p. 656) and the yield on consols B. R. Mitchell, *Abstract of British Historical Statistics* (p. 455). The commentator on the American series remarks on railways that "for many years no other industry had as high a credit rating" (p. 651). The lining wear data are from Wright, *Sixth Annual Report*, p. 38, and Greville Jones, "A Description of Messrs. Bell Brothers' Blast Furnaces from 1844–1908," in the British *Journal of the Iron and Steel Institute*, 1908, III, 59. The American comparison of P_k with P_c is for 1880–82 and is based on detailed costs of construction of blast furnaces in E. C. Potter, "The South Chicago Works of the North Chicago Rolling-Mill Company," British *Journal of the Iron and Steel Institutes*, 1887, I, 163–202. The British comparison is for 1887 and is based on B. Samuelson, "Notes on the Construction and Cost of Blast Furnaces in the Cleveland District in 1887," *ibid.*, pp. 91–119. I was able to compare the cost of coke with the cost of bricks, labor, iron hardware, blowing engines, boilers, and hoist engines.

V

As long as British productivity was not definitely inferior to foreign productivities, the technological explanation is adequate and one need not choose between the economic and sociological explanations. By World War I at the latest, however, British productivity *was* definitely inferior to American productivity and one does need to choose. In conclusion, I shall indicate briefly what the analysis earlier in the essay implies for this choice.

Given the long stagnation of British productivity from the 1880's to the 1930's, the choice between the sociological and economic explanations is affected by how early the technological explanation ceased to apply. The earlier this was, the longer is the period to be accounted for by other explanations; and the economic explanation by itself cannot easily account for long periods in which productivity did not grow at all. In the economic explanation, a slower growth of demand leads to a slower accumulation of capital equipment embodying new techniques. But so long as there is some fresh capital equipment entering the industry, even if only for replacement, productivity will grow, albeit slowly. The productivity index, however, did not grow. The iron and steel industry called the 1920's the "Black Decade," an appropriate description of a period in which pig iron output fell to its lowest levels since the 1850's: it is perhaps plausible that there was not even replacement investment in the pig iron industry from 1914 to 1930; and perhaps the rate of productivity growth was so small that it is lost in measurement errors. But the further back one sets the date when American overtook British productivity, the less plausible becomes an argument based on a total lack of replacement investment or on small measurement errors.

The economic explanation assumes that ironmasters adopted the best techniques available when they replaced old capital. If they did not, there appears to be no difficulty in explaining even a long lack of productivity growth: ironmasters were negligent. In this argument it is generally assumed that the negligence of the ironmasters was dependent on social rather than economic events. A

9. It is possible to make a few crude comparisons of coke and ore productivities with the Continent. Lacking measures of relative factor prices or coke quality, the point cannot be pressed, but it appears that though British was at no time superior to Continental practice, Continental was superior to British practice perhaps as early as 1900, and surely by the 1920's.

failure of the British educational system to adjust to the needs of the new technologies and a shift of occupational tastes away from business and towards politics and public service are two common explanations of growing negligence in British industry. It should be emphasized, however, that even if one admits the negligence of ironmasters as a contributing cause of the lack of productivity growth in pig iron, it is not necessary to abandon economic explanations of the negligence itself. In particular, a fall in the rate of growth for pig iron, just as it would tend to lower the rate of recruitment of fresh capital equipment into the industry, would also tend to lower the rate of recruitment of human talent. The rate of growth of pig iron output fell from about 4 per cent per year during 1858–80 to under ½ per cent per year during 1880–1918 and to a negative rate during 1918–38. If the successive falls in the growth rate lowered the quality of ironmasters as well as the quality of capital equipment, they could explain even a long pause in productivity growth.

A combination of this tentative hypothesis with the facts established earlier suggests the following sketch of the causes of productivity in British pig iron. A steadily falling rate of growth of demand from 1880 to the 1930's created a potential retardation of productivity growth. If technology had grown, productivity would have followed with less agility than before for two reasons: first, slower growing demand would require less investment and, therefore, would offer fewer opportunities for adopting new and better capital equipment; second, slower growing demand would attract to the industry a smaller number of men inclined to adopt the new equipment when it became available. For some time, the diminishing opportunity and inclination to adopt new equipment mattered little, because new equipment was no better than old: technology was not growing. But by World War I the technology of pig iron did begin to grow again. The potential became actual retardation of productivity growth.

Harvard University