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The Supply of Raw Materials in the Industrial Revolution

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Any great increase in the output of industry, such as began in England towards the end of the eighteenth century, must have as its counterpart an equally great increase in the input of industrial raw materials at the other end of the process of production.[1] The problem of providing an adequate raw material supply had been acute in many branches of industry in earlier centuries. The removal of these constrictions is intimately connected with several important aspects of the rapid growth which occurred, and its study affords a vantage point from which they can conveniently be surveyed.

The most important change in raw material provision which took place was the substitution of inorganic for organic sources of supply, of mineral for vegetable or animal raw materials. This was a *sine qua non* of sustained industrial growth on a large scale, for when industrial growth is based upon vegetable and animal raw materials present success can usually be obtained only at the cost of future difficulties. England in the sixteenth and seventeenth centuries provides some typical examples of the dilemma which confronts industries when they use animal or vegetable raw materials. The iron industry of the Weald was able to expand without prejudice to its future prosperity only up to the point at which the annual cut of timber equalled the yearly increment of new growth. Any expansion beyond this point could take place only at the cost of contraction in the future. Expansion without prejudice to future supplies could, of course, have been secured if more land had been devoted to the production of timber, but in a country where the area of unused land was small more woodland meant less ploughland or pasture. Competition for the use of scarce land was a perennial problem in these circumstances and a permanent, radical increase of industrial raw material supply was very difficult to obtain. Those Tudor pamphleteers who complained that the sheep were eating up men

[1] Except, of course, in so far as technological changes permit raw material saving.

were directing attention to the central problem of industrial raw material supply in an age when organic materials were essential for most industrial processes. More land devoted to the production of timber or wool meant less land available to produce food. The price of raw materials was sure to rise because of competition for the use of land and so inhibit industrial growth even where the government refrained from direct political action to guarantee the supply of food. If the government did not intervene to restrict pasture in the interest of tillage, the play of the market would ultimately produce the same result. Moreover, industrial growth not only provoked problems of this type directly by competing for the use of land, but also indirectly by encouraging a growth in population which in turn increased the demand for land upon which food could be grown. Once the spread of settlement had brought all available land into use, the only way in which the supply of food and of industrial raw materials of vegetable or animal origin could be increased simultaneously was by a general rise in the productivity of the land.[1]

The view that the productivity of the land controls the growth of industry no less than that of agriculture is a recurring theme in the *Wealth of Nations*. Adam Smith wrote just before the dramatic changes in industrial raw material supply had become fully apparent and did not recognize their importance. In his chapter *Of the natural Progress of Opulence* he began by defining the exchange of products manufactured in the towns for agricultural produce and raw materials as 'the great commerce of every civilised society'.[2] Later in the chapter he enlarged upon the nature of this exchange.

> It is this commerce which supplies the inhabitants of the town, both with the materials of their work, and the means of their subsistence. The quantity of the finished work which they sell to the inhabitants of the country, necessarily regulates the quantity of the materials and provisions which they buy. Neither their employment nor subsistence, therefore, can augment, but in proportion to the augmentation of the demand from the country for finished work; and this demand can augment only in proportion to the extension of improvement and cultivation. Had human institutions, therefore, never disturbed the natural course of things, the progressive wealth and increase of the towns would, in every political society, be consequential, and in proportion to the improvement and cultivation of the territory or country.[3]

If the productivity of the land in the last analysis governed the wealth of any country, it is hardly surprising that Adam Smith claimed of investment in agriculture that 'Of all the ways in which a capital can be employed, it is by far the most advantageous to society'.[4]

The supply of mineral raw materials forms an interesting contrast with the supply of vegetable and animal raw materials. In the very long run the mineral

[1] Within any one national market area, of course, it was possible to expand the supply of food and raw materials without increasing pressure on the land by import from abroad. Cheap sea transport enabled England to make good some of her shortage of timber, for example, in this fashion.

[2] A. Smith, *An Inquiry into the Nature and Causes of the Wealth of Nations*, ed. J. R. McCulloch (Edinburgh, 1828), II, 171.

[3] *Ibid.* 175–6.

[4] *Ibid.* 150.

supply problem is insoluble in a sense which is not true of organic raw materials, since every mine is a wasting asset. It cannot be made to give a sustained yield in the way which is possible with a forest or a farm. A forest can yield indefinitely: a mine cannot. Nevertheless, in any but the very long run the difficulty of obtaining a large increase in supply is less pronounced with mineral raw materials. Given an adequate mining technique and the existence of rich deposits production can rapidly be built up to high levels. As the individual mine nears exhaustion the price of extraction must rise, of course, but as long as it is possible to sink other pits to tap equally rich deposits the price of the product need not rise, and may well fall if increasing production encourages the creation of larger and more efficient production units. Moreover, an increase in the production of mineral raw materials does not take place at the expense of the supply of food or of other industrial raw materials. There is no equivalent in the production of inorganic raw materials to the competition for land which accompanies an expansion in the production of organic raw materials.[1] In the half century after the publication of the *Wealth of Nations* the vital importance of the new sources of industrial raw materials became clear. The passage which McCulloch in his edition found 'perhaps the most objectionable' [2] in the book was that which concluded that capital was best employed in agriculture from the point of view of society as a whole. Adam Smith had argued that rent is created by those 'powers of nature' which give an added productivity to agriculture, but had added that in manufacture nature does nothing for man; he must do everything for himself. McCulloch objected to this definition of rent, but he also denied that the powers of nature favoured agriculture alone. His was a world in which the importance of manufacture had ceased to be regulated solely by agricultural productivity. The amount of capital which could profitably be invested in manufacture was no longer controlled by the agricultural surplus in the manner suggested by Adam Smith.[3] Mineral sources of raw material had given another dimension to the discussion. To McCulloch the 'powers of nature' revealed in the steam-engine were as remarkable as any that Adam Smith had noticed in the fields.[4]

There is a second difference of great importance between mineral production on the one hand, and vegetable and animal production on the other. Production of the former is punctiform; of the latter areal. The transport problems involved in moving a million tons of coal from pitheads scattered over an area of only a few square miles are quite different from those involved in moving the same weight of grain or timber from an area of several thousands of square miles. The former implies heavy tonnages moving along a small number of routeways, whereas the latter implies the reverse. A heavy capital investment

[1] Open-cast mining forms a minor exception to this rule.

[2] Smith, *Wealth of Nations*, II, 150 n.

[3] See, for example, *Wealth of Nations*, II, 214–15, where his argument leads him to the conclusion that the manufactures of Leeds, Halifax, Sheffield, Birmingham and Wolverhampton are 'the offspring of agriculture'. The general argument of the chaper *Of the different Employment of Capitals* is also interesting in this connexion.

[4] '... are not the pressure of the atmosphere and the elasticity of steam, which enable us to work the most stupendous engines, the spontaneous gifts of nature?' *Wealth of Nations*, II, 150 n.

in improved communications is unlikely to give a good return when the raw materials of industry are organic since the traffic density along any one route is usually low. A large volume of mineral traffic, on the other hand, makes such an investment necessary to cope with physical difficulties, and financially attractive because the total possible savings are so much greater.[1]

I

The decisive technological change which freed so many industries from dependence upon organic raw materials was the discovery of a way of using coal where once wood had been essential. The timing of the change varied a great deal between the several industries. It came earliest in industries like the boiling of salt in which the use of coal presented no problem of undesired chemical change in the product because the source of heat was separated from the object by a sheet of metal. Industries like iron smelting and hop drying in which contact was more intimate presented greater problems in a period when chemical knowledge was slight. A long period of trial and error commonly elapsed before a successful method of substitution was developed. Coal-fired salt pans were a commonplace before the end of the sixteenth century: coke-fired blast furnaces were not successfully operated until the first quarter of the eighteenth, and in some branches of the iron industry it was near to the end of the century before charcoal could be dispensed with. In spite of the rather slow spread of coal use from one industry or process to another, however, it was already an industrial raw material of the first importance by the beginning of the eighteenth century. At that time coal production in England and Wales had reached a level of about three million tons per annum, or roughly half a ton per head of population. The production of coal both absolutely and *per caput* was already of quite a different order of magnitude in England from that obtaining on the continent; and by the end of the century production had tripled. Much of the coal was used for domestic rather than industrial purposes, but all helped to relieve the pressure on timber supplies. Wherever it could successfully be substituted for wood its effect was to liberate production from the physical limits upon output imposed on industries requiring a source of heat in a country where the timber resources were very limited. Unlike timber, a substantial increase in coal consumption in any one period did not prejudice supplies in the next, nor did an expansion in coal use in one industry affect others adversely. Moreover, once the initial period of prejudice against coal had passed and the difficulties involved in its use had been overcome, many industries discovered that coal was better suited to their purposes than wood had been.

In the absence of coal the timber requirements of a country whose industries were as large as those of England at the beginning of the nineteenth century

[1] Occasionally the older system had coped with quite heavy tonnages. The grain and timber trade, especially to the London market, was on a substantial scale and had meant large outlays on North Sea and coastal shipping and on river barges, but it was the new problems of mineral traffic on a large scale which produced the canals and the railways.

would have been enormous. Much heat was needed in a wide range of industrial processes, and to have provided it with wood must have denuded the forests of England, indeed the forests of Europe, in a few decades. The classic case is perhaps that of the iron industry. Benaerts quotes an estimate, for example, that the production of 10,000 tons of charcoal iron required the felling of 40,000 hectares of forest.[1] The pig which resulted from a coal or coke melt was for many years unsatisfactory and commanded only a very low price. The prejudice against it remained for some time even after Darby had overcome the main difficulties in smelting ore with coke, yet coke pig was to prove essential to the rapid progress of industrial growth. Without it there could have been no great expansion in the scale of iron output or fall in its price, and the physical properties of iron were so essential to the age of machines that it is difficult to believe that any great changes were possible without cheap and abundant iron. Many machines which were first constructed in wood could be greatly improved when made in metal, and many of the great engineering constructions after the turn of the century could not have been made at all without cheap iron. The physical properties of iron permit great precision of working: the steam engine and the machine tool depend on this. They and the iron ships, iron rails and iron bridges of the new age required the successful supplanting of vegetable by mineral fuels.

Coal could not be used as a direct substitute for wood in the building industry where timber was used not as a fuel but as a building material, but indirectly it was important because its use in the brick industry meant that the production of bricks could be expanded without unit costs of production rising, so that brick became the prime building material of the new age. The engineering and construction industries, as producer goods industries of central importance, are points of great sensitivity in any period of rapid industrial growth. The output of producer goods must necessarily expand faster than that of consumer goods at such a time, and it is vital that it should be easily expansible, and if possible that the costs of the raw materials involved should show a secular tendency to fall as the volume of production increases. In the past these industries had been heavily dependent on wood, which tended to induce a secular rise in the costs of the raw material when the scale of production grew. After the changeover to mineral raw materials the possibility of a much easier and unrestricted expansion was always present.

Those consumer goods industries, such as the Staffordshire pottery industry or the glass industry, which required much heat in their manufacturing processes also benefited from growing independence of vegetable fuel. Brewing, the paper industry, and some sections of the textile industry made use of coal too, though in their case the fuel was used to process organic rather than inorganic raw materials.

A part of the great increase in the productivity of industrial workers which began in the later part of the eighteenth century and has continued down to the present day arose in the manner which Adam Smith described and analysed.

[1] P. Benaerts, *Les Origines de la grande industrie alleman de* (Paris, 1933), p. 454. One hectare is equal to $2\frac{1}{2}$ acres.

Markets grew larger; production processes were subdivided; industrial skills became more specialized and workers nicer in their skills; new machinery was developed; real costs fell as productivity increased. But a part of the increase in productivity which took place, that part which became possible as a result of the rise to prominence of a class of industrial raw materials whose significance Adam Smith did not fully appreciate, that part which arose from cheaper and more abundant heat and mechanical power, could not take place as long as the land produced not merely the food of the nation but also its industrial raw materials. It is notable how frequently the industries in which expansion was marked in the years between Adam Smith and McCulloch were those which were gradually freeing themselves from dependence upon organic raw materials, especially wood. This is true of the industries making iron, non-ferrous metals, most types of machinery, glass, salt, pottery and bricks. The industry in which the most dramatic growth of all took place was, perhaps, cotton which provides an instructive contrast with most other quickly growing industries in that its raw material was vegetable. The cotton industry conformed quite closely to the picture of industrial growth envisaged by Adam Smith and will require further consideration at a later stage in this discussion.

II

Though the large-scale use of coal offered great opportunities, it also brought problems, in whose solution may be seen some of the most important economic and technological foundations of the Industrial Revolution. The prime difficulty was the great expense of transporting coal with the existing transport media. Coal could only come into general domestic and industrial use if it were cheap, and could only be cheap if it could be cheaply transported. As long as the price of coal taken overland doubled within five miles of the pithead it was not likely to be widely used. This, of course, is the reason why the first large-scale coal industry was on the Tyne in touch by sea with the London market and the smaller markets down the east coast. Sea transport had always been the cheapest form of transport, and moreover it had long been accustomed to dealing with the range of problems raised by punctiform production on a large scale. Large ports had for centuries concentrated a great bulk of goods at a single point and forwarded them to a limited number of similar points, often far away. The biggest ships were capable of moving hundreds of tons at a time, whereas on land loads measured by the hundredweight were normal. Exceptionally much larger weights might be moved (as with large building stones), but only over short distances and by making special arrangements. Before the era of large-scale mineral production there was little incentive to try to alter the capacity of overland transport systems since the areal production of vegetable and animal products seldom calls for the movement of a great bulk of material along a single route. Improvements to overland transport which are precluded when raw material production is areal may be both necessary and economically practicable when raw material production is punctiform. Once the Newcastle-London coal trade had shown the very real advantages of coal over wood for many purposes there was always latent the possibility that a radical improvement in overland communication might take place.

Prof. Nef has shown how important the growth of the coal trade was in developing more efficient methods of ship construction and working in this country.[1] By the end of the seventeenth century about half of the total British merchant fleet by tonnage was engaged in the coal trade. But the effect of the development of large-scale punctiform mineral production upon shipping was only to develop traits characteristic of the movement of goods by sea for a long time. Ports and pits had much in common as sources of cargo. It was otherwise with overland transport. When the production of the coal industry came to be measured in hundreds of thousands and even millions of tons annually a new solution was necessary if the coal was to reach inland centres of consumption. However inefficient to later eyes may have been the movement of grain, wood and wool on horseback or in carts along pitted roads, it was economically inevitable since the volume of the traffic was too small to warrant the investment needed to provide good roads or canals. Areal production meant poor communications. Minerals had, of course, also been moved on horseback before the eighteenth century in spite of the punctiform nature of their production, but they had moved in quite small absolute quantities and had not afforded any opportunity for substantial improvement. For a long time coal was moved in the same way whenever it was moved overland. It moved on pack animals from the Staffordshire coalfield to the Northwich salt pans and from the Yorkshire pits to the Bradford dyers, or on small river craft on the Severn and Thames. As long as the inland consumption of coal remained small, coal moved as other raw materials had moved for centuries. Large-scale consumption provided new opportunities. The demonstration that coal could be used so successfully where wood had been used in the past created a large potential demand for it which could not be met while communications were poor, but which provided a powerful incentive to improve them. The canalization of the Weaver to Northwich after 1720 in order to provide cheaper coal than could be brought overland from Staffordshire was an early example of the improvements in transport encouraged by the use of coal; and the work done on the Douglas from Wigan to the Ribble estuary dates from the same period. As coal consumption rose, more ambitious works became possible. Waterways were not merely improved; they were created. Forty years after the work on the Weaver and the Douglas the Worsley Canal was built, to be followed by many others in the next half century.

The art of building canals was not new to Europe. The Dutch had a long experience of making them, and several long canals were built in France in the seventeenth century, but the English canal network was constructed in response to an incentive of a new type. If mineral raw materials were to continue to grow in importance in English industry they required such a network. Canals are well suited to the movement of goods produced at a point, but not to areal production. The truth of this is well illustrated by the history of the many canals which were built in the first flush of enthusiasm for canals

[1] J. U. Nef, *The Rise of the British Coal Industry* (1932), I, 238–40, 390–4.

in purely agricultural areas of the country, and which were seldom successful financially.[1] The successful canals were those on which there was a heavy volume of mineral traffic, usually coal, but occasionally other minerals also: for example, the canal from the pottery district of Staffordshire to the Mersey carried a china clay traffic. Agricultural areas through which the canals passed benefited greatly from their presence, both because they made possible much cheaper movement of food to the market and because some of the essentials of good husbandry, such as lime and manure, were more easily obtainable after their construction. Agricultural traffic contributed significantly to the revenues of many canals built to cater chiefly for mineral traffic, but agricultural traffic was characteristically insufficient to sustain canal finances on its own, and canals which were built in agricultural areas in the hope that their presence would create sufficient traffic to make them profitable seldom fulfilled their promoters' expectations.

The development of railways, the other chief means of cheap internal transport created during the Industrial Revolution, was also closely connected with the switch to inorganic raw materials, and especially the transport of coal. From the seventeenth century there had been railways connecting pitheads with coal wharves on the Tyne, developed to deal with the problem of coal movement overland on a large scale. The laying of wooden planks along which the horse-drawn carts could move was a simple way of increasing the load which each horse could shift. When he no longer had to expend most of his energy in overcoming the mud in wet weather and the deep ruts in dry, a horse drawing a cart along planked ways was able to move two or three times as much coal. Once the volume of coal moving over the short roads to the wharves had become large the heavy expense of improving roads in this way proved well worthwhile. In time flanged wheels were introduced and it became profitable to cover the wooden tracks with metal plates in order to increase their life under constant heavy usage. Railways were peculiarly a mining development (even down to the track gauge), and were created to overcome the problems posed by large-scale punctiform mineral production, initially as feeders to waterways, but later as an independent network. Like canals, they also, of course, proved in time of great benefit to other forms of production and made easier the movement of the vegetable and animal raw materials. Moreover, they developed a great passenger traffic. Yet it is true of railways as of canals that most of those built in purely agricultural areas in England did not generate enough traffic to make them profitable.

As the eighteenth century progressed the volume of coal output rose steadily, from three million tons at the beginning to about ten millions at the end. The great coalfields near Newcastle no longer grew in output as quickly as some of the inland fields because the improvement in communications, especially the development of canals, made available to industrial and domestic consumers over a steadily increasing area the advantages which during the seventeenth century had been restricted to the east coast ports and to very small areas on

[1] Clapham noted this condition, though he cast his conclusions about it in a different form. J. H. Clapham, *An Economic History of Modern Britain* (2nd ed. Cambridge, 1950), I, 82.

the inland fields. Even at the beginning of the century probably no other mineral, vegetable or animal raw material approached coal in weight of production: by the end it had far outdistanced any rival. It was therefore peculiarly coal which provided at once the chief stimulus to the building of traffic arteries capable of dealing with the quantities of raw materials now used by the economy, and the main goods traffic on the canals and later the railways.[1]

III

Or the issue may be put in different terms. The importance of the changes in raw material supply and in the transport system can be illustrated from the writings of the economists of the period as well as traced in the narrative economic history, especially in the discussions of the limits of economic growth. The starkest discussion of the organization of economic life in a society bounded by the productivity of the land and the problems of transport is perhaps that of Thünen. When Thünen published his discussion of the pattern of land use which would be found upon a featureless plain surrounding a central city, he deliberately made a limited number of simple assumptions about the nature of its economic life. Upon these assumptions he was able to show that the steady rise in the cost of transporting produce as distance increased from the central market would cause the land to be divided up into a series of concentric rings each marked by a different type of land use. The innermost ring was devoted to the production of perishable commodities like milk and vegetables; the next ring to woodland to meet the city's need for fuel, charcoal, building materials, tools and furniture; and the remaining rings to agriculture of a gradually decreasing intensity, shelving off finally into pastoral activities at the point where the cost of transporting grain to the market made it unprofitable to plough and plant the land. Everything depended upon the demand in the central market, local changes in agricultural productivity, and the level of transport charges. As the price of raw materials and food rose in the central market, for example, or alternatively as the cost of transport fell, the whole system of rings would expand allowing a larger area of land to be used more intensively. Thünen himself illustrated the dramatic effect of falling transport costs on the intensity of land use by examining the effect of a river running across the series of rings to the central city along which transport costs were only a tenth of those overland. Thünen's model underlined many of the characteristics of the economic life of

[1] Paradoxically, although so many of the most important changes in transport and power were connected with the mining industry and specially coal, and although it was the adoption of mineral raw materials generally in industry which alone made possible the scale of expansion which occurred, the mining industry itself did not experience any revolutionary increase in manpower productivity. Output per man-year in a large coal pit in 1700 was about 150 tons (Nef, *The Rise of the British Coal Industry*, II, 136n.), a figure already about two-fifths as large as the peak figure in the 1880's. The coal industry, indeed, is sometimes referred to as an example of the impossibility of designing machines to perform all jobs previously done by hand, and is classed with, say, agriculture, in this respect. But the central difficulty of the production of coal has never been the winning of coal at the coal-face, hard and dangerous though this has always been, but its transport within the pit, up the pit shaft, and from the pithead to the point of consumption. The canal and the steam-engine solved the prime difficulties of the coal mines. Those at the coal-face were less pressing.

earlier centuries. His scheme makes it clear how crippling the high cost of transport can be; how, for example, local famine might well occur in a country enjoying a general sufficiency; how, though timber was essential to such an economy, its great bulk and weight made it difficult to deliver to a market at a reasonably low cost. When he published his book in 1826 his model still fitted the economic life of parts of Germany without excessive distortion, though by that date it was no longer appropriate to England. Thünen acknowledged Adam Smith as his chief mentor,[1] but his scheme embodied only a part of the world Adam Smith had studied. The *Wealth of Nations* describes a much more complicated world; it does not merely abstract from it some of its salient characteristics as *Der isolirte Staat* had done. Although Adam Smith maintained that a gradual rise in agricultural productivity alone made possible the development of cities and industry, and further maintained that in the last resort the size and wealth of cities must continue to be governed by the productivity of the land, he understood and entertained within his scheme of analysis the great modification and complication which arose out of the development of trade between city and city and nation and nation, not restricting himself simply to the consideration of trade between a city and its surrounding countryside. The wealth of nations could increase greatly when Thünen's limiting assumptions were relaxed in this way, and Adam Smith showed clearly how this might come about, and discussed which policies were likely to expedite the process or to frustrate it. The wealth of nations could not, however, increase without limit upon the assumptions within which Adam Smith worked since the productivity of the land set a ceiling to growth. In the half century following the course of events proved beyond doubt that the assumptions might be still further relaxed. The ceiling which Adam Smith had assumed to exist generally now applied only to food and to a limited range of organic industrial raw materials. The use of mineral raw materials removed the limit from industrial production in general, both directly by making it possible for an enormous increase in the physical volume of production to take place without prejudice to future supplies of raw materials, and indirectly by demonstrating that the 'powers of nature' were present just as abundantly in the mines as in the land, so that capital invested in industry could yield at least as good a return as investment in the land from the point of view of the community as a whole. There is thus a certain restricted sense in which Malthus has remained more relevant to the modern situation than Adam Smith, for in discussing the limitations imposed upon the growth of population by the size of the supply of food, Malthus was concentrating upon a part of the economy in which it has not been possible as yet to substitute inorganic for organic raw materials. He was mistaken about the rate at which the supply of food could be expanded, but the problem he posed still lives with us today. His argument in a modern setting appears wrong in degree, but right in kind. Adam Smith's discussion of the wealth of nations, on the other hand, appears wrong in the second sense because he was not aware of the new possibilities of increasing production just

[1] J. H. v. Thünen, *Der isolirte Staat in Beziehung auf Landwirtschaft und Nationalökonomie* (2nd ed. Rostock, 1842–50), pt. II, p. 1.

becoming apparent in his day when the substitution of mineral for vegetable and animal raw materials removed an ancient and important obstacle to industrial growth.

IV

The importance of minerals in general and coal in particular to the development of an industrial economy at the end of the eighteenth century extends beyond the improvement in communications and the possibility of escaping the close limits set to expansion as long as organic raw materials were essential to most industrial processes, for the development of the steam engine is peculiarly a product of the problems of the mining industry.

Although the expansion of mineral production was not subject to the same limitations as the expansion of the production of vegetable and animal materials, the technological problems of increasing production were nevertheless considerable. Perhaps the most intractable was that of draining pits when they were sunk to a depth which made impossible drainage by the cutting of adits to a point on the surface below the level of the seam. Horse gins were useful when the depths were moderate, but at the depths where some of the richest seams of coal and veins of tin and copper occurred a more powerful engine was required if the inflow of water to the workings was to be held in check.[1] The urgent difficulties of the mining industry were the means of turning the Newcomen from an ingenious but unpractical machine into a reliable piece of equipment without which the deeper pits could not have been maintained in production. The early engines of Savery and Newcomen were essentially pumping machines for which the only big market was the mining industry. A few Newcomen engines were used for pumping water from rivers to help with the supply of water to towns, but the majority were used in mines. They were at once essential to the continued expansion in coal production, and virtually unusable without a supply of coal. They are a product of a coal age rather than a wood age and could only be used extensively when mines rather than woodlands were their source of fuel. Otherwise they would have devastated an area of timber as quickly as the early iron industry had done, for the early engines were extremely inefficient and required very large quantities of fuel. Theoretical knowledge of the power of steam had long existed, but the coal industry's problems first provided the catalyst to convert this into workable machinery rather than engaging toys. The first use of steam engines in industries other than mining reflects their background as pumping engines in mines, for they were used initially simply to complete the cycle of water movement from tail-race to mill-pond and so to render water wheels independent of ordinary stream flow and prevent those interruptions to their operation which had previously been inevitable in prolonged dry weather. Watt's improvements to the steam engine (or rather his invention of a steam in place of an atmospheric engine) and his development of methods of gearing which gave rotatory rather than

[1] It has been claimed that three-quarters of the patents issued in England between 1561 and 1668 were connected with the coal industry, either directly or indirectly, and that a seventh were concerned with the drainage problem. S. F. Mason, *A History of the Sciences* (1953), p. 217.

reciprocating motion represent radical improvements upon the earlier Newcomen engines and gave the steam engine great importance in a wide range of industries as time passed. The steam engine more than any other single development, perhaps, made possible the vast increase in individual productivity which was so striking a feature of the Industrial Revolution by providing a source of power which dwarfed human, animal and even hydraulic sources. Yet the machine Watt improved was already widely used in the mining industry, which had fostered its development for several decades.

V

The cotton industry has attracted more attention than any other in discussions of the Industrial Revolution, and since it grew vastly while continuing to use a vegetable raw material, it merits further consideration in the context of this essay. No other major industry grew as quickly as cotton in the late eighteenth century. There was a series of inventions in both spinning and weaving which led to a marked rise in the output per worker. Cotton spinning was the first industrial activity to become organized in factories in the fashion which became normal during the next century. Lancashire became the area which first acquired the full range of features characteristic of the new industrial scene; large urban manufacturing populations living a life divorced from the rhythm of the countryside about them, working in factories, caught up in a web of exchange which connected their livelihood with events throughout the world. Cotton has for long been treated as the *type par excellence* of the new manufacturing industry, the lead-off industry in the take-off into sustained industrial growth.

The cotton industry fits well into the pattern of industrial growth which Adam Smith described. The decisive importance of the size of the market is well illustrated in its history. The attempt to expand production to keep pace with demand caused new mechanical devices to be seized upon eagerly and developed rapidly into reliable manufacturing machinery. There was a steep rise in productivity as workers became more specialized and turned to cotton manufacture as a full-time employment rather than a useful subsidiary source of income. The price of the finished article fell and still further enlarged the market. Once Whitney's gin had proved its worth, the demands of the industry for raw materials could be met by breaking in new land in the southern United States. There was no bottleneck in raw material supply and raw cotton tended to fall rather than rise in price. There is nothing in the story to call in question the assumptions of Adam Smith about the part played by the growth of industry in promoting the wealth of nations. Some coal was used in the preparatory and finishing sections of the industry, but only after a generation of expansion had caused the need for power to outstrip the capabilities of the human arm and the water wheel was the steam engine brought into use, so that the problem of raw material provision was very different in the cotton industry from those industries in which organic raw materials were replaced by inorganic. The example of the cotton industry makes it clear that industrial expansion could go far and fast in some directions without provoking difficulties in raw material supply.

For this very reason, however, the cotton industry, in spite of its importance in the Industrial Revolution, cannot be regarded as a microcosm of the whole process. In particular the great changes in inland transport and in power were not closely connected with the cotton industry. The movement of cotton presented no great difficulties to the methods of goods transport which had been in use for centuries. The movement of raw cotton was measured by the million pound rather than the million ton and bore a far higher value per unit weight than, say, coal. In consequence it was able to support relatively high transport charges without a crippling increase in price. The fact that many early mills were built in quite remote Pennine valleys close to a head of water underlines this point. Similarly, the well tried sources of industrial power, initially the worker's arms and later the water wheel, sufficed to move the machinery used in the cotton industry during the first two decades of rapid growth at the end of the eighteenth century. The cotton industry benefited substantially from the opening of canal communication between Manchester and Liverpool, both in that transport charges were lower than by river or on horseback and in that delivery was more reliable and quicker: but the cotton industry did not create a large enough tonnage of traffic to justify the construction of canals. 1800 was the first year in which the import of raw cotton exceeded fifty million pounds in weight, which is only some 23,000 tons, and no more than the annual output of perhaps 150 coal miners. Even though cotton might produce a much greater revenue per ton-mile than mineral freight it is clear that the cotton industry in itself could offer little inducement to spend capital on the scale necessary to build canals. In so far as the presence of the cotton industry in Lancashire did hasten the construction of canals it was perhaps rather as a consumer of coal and as an employer of labour which consumed coal domestically that it exerted an influence. Again, the cotton industry became an important market for Watt's new engines. Without them it might have lost impetus as the most suitable heads of water were harnessed one by one, leaving only the inaccessible or insufficient to be brought into use. But the history of the development of the steam engine lies outside the cotton industry.

It might indeed even be argued that there is a sense in which the cotton industry was exploiting old lines of development with a new intensity rather than striking out in a radically new direction. There had been periods of technological innovation in the textile industry in the past. When, for example, the spinning wheel superseded the distaff there had been a marked rise in the productivity of the individual spinner. The invention of the knitting machine and the introduction of the Dutch swivel-loom had also in their time brought about important changes in productivity and in the amount of fixed capital per worker. Water power had been used in the fulling of wool and the throwing of silk for centuries. Even the bringing together of many textile workers under one roof was not unknown before the eighteenth century. During the late eighteenth century the cotton industry brought development along old lines to a new pitch of perfection, evolving better machinery in both spinning and weaving and extending the use of water power into spinning. There was a vast increase in the quantity of cotton manufactured. It was produced more cheaply and, after early difficulties with the new machinery had been overcome, the quality of both yarn and cloth was higher than anything achieved in England in the past. In contrast with this the range of industries in which coal replaced wood as the main source of heat might be held to have struck out along a new line of development. The change from organic to inorganic sources of raw material supply led to no sudden or dramatic change in the quantity or quality of production in the industries concerned, yet latent in this change were new possibilities for improvement in the transport of goods and the supply of power to industrial processes. To borrow a biological analogy the raw material bottleneck produced a mutation in raw material supply which proved intensely favourable and led to changes which helped to transform industrial production and ultimately society as a whole.

The temptation to treat the cotton industry as a microcosm of the whole Industrial Revolution has proved difficult to resist. The signs of the new age were first readily apparent in cotton, but its history is not therefore typical of the whole. The fact that the cotton industry was singularly free from raw material supply problems marked it out from many others, at once facilitating its expansion at an early date and isolating it from a range of problems faced and solved by many other industries. Cotton benefited from the new sources of power and better transport facilities, but these were available because of the successful struggle against difficulties of raw material supply which had taken place in other sectors of the economy.

VI

It is natural that special attention should be paid by all those interested in the Industrial Revolution to any aspect of English life which was different from its continental equivalent. Hence the great interest shown in such questions as social mobility and capillarity, the organization of financial affairs and the capital market in England, English agriculture and systems of land tenure, the forms of English government and law, and in exploring any differences between English and continental demographic patterns. The supply of industrial raw materials may, of course, be treated in the same way. It is not difficult to show that the continent clung longer to the traditional types of organic industrial raw material, nor is it difficult to suggest reasons for this. Wiebe's price series,[1] for example, suggests that the supply of some types of timber was causing much less difficulty on the continent than in England in the seventeenth century. Yet it is perhaps more illuminating to dwell on the occasional similarities between England and the continent than on the general dissimilarity.

The area most like the new English industrial areas was central Belgium. This was the only area on the continent in which the production of coal in the

[1] G. Wiebe, *Zur Geschichte der Preisrevolution des XVI. und XVII. Jahrhunderts* (Leipzig, 1895). See esp. tables 522, 524 and 528.

eighteenth century reached a level at all comparable with that achieved in English coalfields at the same time. Both at Liège and near Charleroi the coal seams outcropped to the surface near the good water communication afforded by the Sambre-Meuse system, and this made possible the development of a wide market for coal at an early date. The Mons coalfield was not so well endowed with natural water communication, but the same problems and opportunities which produced a burst of canal building in England led to a similar development in Mons. The Mons-Condé canal, for example, was completed in 1814, linking the coalfield area with the industries of Nord. The history of the successful search for coal in the concealed Nord field which resulted in the sinking of the famous mine at Anzin is evidence of how useful even in the middle of the eighteenth century the discovery of coal was judged to be in this part of the continent. At that time traffic along the valley of the Sambre-Meuse resembled that along the valley of the Severn in England. The metal communes of Maubeuge and Valenciennes, for example, were dependent upon primary iron imported from the *pays de Liège* in the late eighteenth century. Belgian pits were quick to adopt British devices. Already before the turn of the century Belgian pits had reached considerable depths and were using Newcomen engines extensively. Soon after the turn of the century other British developments were absorbed into Belgian practice: the use of the steam engine for winding up coal and men as well as for pumping water, the Davy safety-lamp, and so on. There were independent local contributions to coal-mining and other industrial problems in Belgium at this time. Joseph Chaudron, for example, discovered an improved method of protecting main shafts by using a revetment of iron (the *cuvelage en fer*). Dony succeeded in extracting zinc from calamine. Gas lighting, a Belgian invention,[1] was in use in factories by 1810. The remarkable achievements of the Cockerill family in engineering and textiles at Seraing and Verviers during the first quarter of the nineteenth century form an industrial epic on a scale worthy of comparison with English equivalents of the period. John Cockerill constructed successful coke-fired blast furnaces at Seraing in the 1820's, and built excellent marine steam engines. The advance of central Belgium, in short, was very rapid, and it is perhaps symbolic of this that Neilson's hot blast was widely used there at a time when it was still a novelty in British iron centres outside Scotland.

The history of the rapid acceptance of British industrial advances in the valleys of the Meuse and Sambre is not vastly different from the history of their acceptance, say, in the valleys of South Wales. There was, it is true, usually a time lag, though not always longer in the case of Liège than in the case of the less active British areas. In view of the fact that Belgium during the eighteenth and early nineteenth centuries was ruled by other countries and was frequently disturbed by the passage of armies, it is striking how swiftly the areas whose problems and opportunities were similar to those of the new industrial areas of Britain followed the British lead and occasionally improved upon it.

Central Belgium was not unique among continental industrial areas. The

[1] Minckelers lighted his lecture room with gas in 1785, though it was William Murdoch who in the 1790's showed the commercial possibilities of this method of illumination.

supply with the rapid change in England. When Thünen published his book the Ruhr was still an area of agriculture and marshland. The example of central Belgium, however, where change came so rapidly on the heels of developments in similar English areas, stresses in the context of raw material supply two points which are perhaps true of the Industrial Revolution as a whole: first that western Europe was a single economic community within which like circumstances might give rise to similar results; and secondly that industrial growth was essentially a local rather than a national affair. In this regard it is perhaps unnecessarily inexact to talk of England and the continent rather than, say, of Lancashire and the valley of the Sambre-Meuse. Each country was made up of a number of regional economies. Within Belgium, for example, the Flemish domestic linen industry was in great straits because of its St. Etienne region, for example, showed some similar traits, but in the main it is fair to contrast the conservatism of the continent over industrial raw material failure to adopt English methods at just the period of brilliant advance on the Belgian coalfields.

Perhaps the chief advantage in looking at the Industrial Revolution from the standpoint of raw material supply is that it makes it easier to understand the nature of the gap which separates Adam Smith and his world from the world which McCulloch knew. The ordinary categories of economic analysis do not pick up the differences very well. In the world which Adam Smith described there could well exist a technically perfect capitalism, with a developed money market, extensive international trade, many intermediaries between the producer and the ultimate consumer, a divorce between the workers and the ownership of the means of production, and so on. But in this world there was a ceiling to the possible size of industrial production set by the difficulty of expanding raw material supply at constant or declining prices as long as most industrial raw materials were organic. When this was no longer true this ceiling disappeared. Adam Smith's world and that of his Physiocratic predecessors was a world bounded by the fertility of the soil. This was the backcloth to any examination of industrial development. Ninety years later when Jevons published his great work on the coal industry he was prepared to assert firmly that the greatest single factor governing the industrial prospects of any nation must be its wealth in coal.[1] If McCulloch was impatient with Adam Smith it was at least in part because the world in which he lived was different. The weaknesses in his argument would not have escaped Adam Smith if he had the benefit of being able to observe a further half century of economic history. If he had been privileged to do so, what he would have seen would have convinced him that the use of inorganic raw materials in industry on a vast scale had revealed the existence of 'powers of nature' whose potentialities he had not suspected.

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[1] 'Coal, in truth, stands not beside but entirely above all other commodities. It is the material energy of the country – the universal aid – the factor in everything we do. With coal almost any feat is possible or easy; without it we are thrown back into the laborious poverty of early times.' W. S. Jevons, *The Coal Question* (London and Cambridge, 1865), p. viii. See also the chapter *Of the Comparative Coal Resources of Different Countries.*

It is interesting to note that Jevons's main concern was that supplies of coal must soon run short in Britain; that mineral raw materials, being exhaustible, were a dangerous basis of national wealth and power.