5 Industrialisation and technological change

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INTRODUCTION

Technological change was a central component in the industrialisation process of the late eighteenth and early nineteenth centuries, and thus in the making of the modern world economy. Nevertheless, more than two centuries after the beginnings of industrialisation, our understanding of the factors that impelled and shaped the development, diffusion and impact of the new technologies of early industrialisation remains far from complete. As a consequence, important questions concerning the place and interpretation of technological change in industrialisation remain unresolved.

The idea that we know relatively little about the sources and outcomes of innovation in the industrial revolution may seem strange, since there is a large historical literature organised explicitly or implicitly around the idea that technological change and industrialisation are intimately linked. Indeed there are many writers for whom new technologies *are* industrialisation, and so the emergence of new techniques is implicitly or explicitly a fundamental causal event. But the very size of the literature tends to obscure the fact that it actually tells us rather little about the dynamics of technological change in the industrial revolution, and particularly its impacts on growth. So although technological change is usually seen as a central element in the economics of industrialisation there is frequently no satisfactory account of the relationships between technological change and industrial growth. To put it differently, there are few comprehensive treatments of the technologies involved in the industrialisation process, in the sense of treatments that integrate economic, social and technological dynamics. Although such a task cannot be achieved within the space available here, nevertheless this chapter seeks to describe some broad patterns of technological change during the first industrial revolution, and to place them within an interpretative framework.

The core theme here is the need to understand innovation and technological change in the industrial revolution as an economy-wide process: that is, as a broad array of changes, across many activities, proceeding at uneven rates and with different degrees of 'visibility', but none the less wide in terms of developments and application. Technology – and hence technological change – in this context will be seen not just in terms of the technical performance characteristics of products or processes, but also in the broader sense of methods of organisation, co-ordination and management.

This chapter aims to do three things. First, it seeks to map some overall dimensions and distributions of technological change in British manufacturing during the period. The reason for this mapping exercise is that interpretation of the links between innovation and long-term growth should rest on an informed empirical understanding of the extent and character of innovation during the period in question. Second, it discusses questions related to the interpretation of this pattern of technological change – its sectoral composition, its radical or incremental character, its causality and so on. Finally, it discusses historiographical debates on the connections between technological change and economic growth in the British economy.

The first section addresses interpretative issues following from the question of whether the industrial revolution should be seen as a narrow or a broad phenomenon. Traditional histories of the period have focused on dramatic technological change and productivity growth, in relatively few industries, particularly textile processes. This literature tends to suggest the importance of radical change in what are here called 'critical technologies', concentrated in key industrial sectors. A critical technology can be thought of as one that plays an essential determining role, via direct or indirect effects on output and productivity growth, on the growth trajectory of any particular period. For many writers the critical technologies of British industrialisation were steam power and mechanised textile machines (particularly spinning machinery). Recent literature, however, stresses a much wider spectrum of change, and emphasises the importance of incremental innovation across industries. It is important to try to form some broad judgement about the balance and importance of these types of change, since this has implications for how we interpret impulses and incentives to technological change, and causality issues more generally. If, for example, a relatively small array of technologies drove change at that time, then we might want to look for sector-specific causal factors, perhaps related to the dynamics of specific technologies. A different approach would need to consider why it is that a broad-front process of advance was occurring, which – as we shall argue below – must lead us to economy-wide factors, such as general institutional change in legal frameworks, management systems, ownership and control patterns, for example. This broad approach need not assume that all technologies are advancing at the same rates or with the same impacts – it could be consistent with considerable heterogeneity across industries.

Any assessment of competing interpretations must rest on a reasonable understanding of the historical record of technological change. The second section therefore seeks to provide an empirical overview of the sectoral patterns and technical characteristics of technological change during the period, although a full account is of course far beyond the scope of this chapter. This draws on economic histories, histories of technology and business studies; the objective is to give a view of the diversity of technological change during the period. The intention is to look outside the areas of highly visible advance, such as textiles, and draw attention also to the widespread changes in such central areas of economic activity as agriculture, food processing, glass manufacture, machine tools and so on. The aim here is to emphasise the empirical fact that this was an economy with extensive technological change, change that was not confined to leading sectors or highly visible areas of activity. These less visible industries are frequently important when it comes to non-technological forms of innovation: pottery, for example, was a major field of organisational innovation. So we also emphasise the fact that these less glamorous sectors were often the site of major advances in organisational innovations – in vertical integration, in assembly line methods, in work organisation and in distribution, for example.

The conclusion will consider the implications of these contrasting views for general models of economic growth. At the present time, economists and others are increasingly using ideas about technological change during industrialisation as the basis for thinking about growth and change. Most notably we have a widely used Kondratievian–Schumpeterian position, basing models of long-run growth and change on the idea of radical technological discontinuities occurring in critical technologies. These models, and the literature which draws on them, often begin with stylised views of the nature of the industrial revolution, and this is one key area where discussions of the industrial revolution have contemporary resonance. Indeed it is quite common to see contemporary policy documents stressing the importance of innovation in information technology and biotechnology by referring directly to accounts of the role of steam power and machinery in the industrial revolution. If, however, much wider processes of change determine output and productivity growth, then we have before us important issues of principle in understanding productivity growth and indeed overall economic growth during the period.

COMPETING VIEWS OF INNOVATION AND INDUSTRIALISATION

In 1815 Patrick Colquhoun wrote that 'It is impossible to contemplate the progress of manufactures in Great Britain within the last thirty years without wonder and astonishment. Its rapidity, particularly since the commencement of the French revolutionary war, exceeds all credibility. The improvement of steam engines, but above all the facilities afforded to the great branches of the woollen and cotton manufactories by ingenious machinery, invigorated by capital and skill, are beyond all calculation' (Colquhoun 1815: 68). This view of the relation between technology and manufacturing growth was not uncommon: it focused on a number of highly visible techniques that began to be implemented from the later eighteenth century. Foremost among these were steam engines, cotton spinning machines, and metal working devices and products. These techniques were often associated with specific industries or activities, and it was a short and apparently natural step to link the techniques with the expansion of the industries concerned, and then see these industries as the driving forces of economic growth.

This kind of vision of the technology–industrialisation–growth link began with the first systematic work on the industrial revolution, Arnold Toynbee's *Lectures on the industrial revolution of the Eighteenth Century*. Toynbee (1969 [1884]) focused on five technologies, and argued that it was the intersection of these technologies and the emergence of free-market capitalism as described by Adam Smith that constituted the industrial revolution. The key technologies were the Watt steam engine and the 'four great inventions' which revolutionised the cotton textile industry between 1730 and 1830 – the spinning jenny, the water-frame, Crompton's mule and the automatic mule of Richard Roberts. Toynbee's work had a major impact on subsequent economic history, with its technological emphases being repeated in Paul Mantoux's classic *Industrial Revolution in the Eighteenth Century*, and in a wide range of later works up to and including Landes's *Unbound Prometheus*, which remains the main work on technological development in western Europe. Mantoux focused Part II of his work, 'Inventions and Factories', on exactly the same sequence of textile inventions to which Toynbee drew attention, adding Cort's iron process (Mantoux 1961: II, 193–348). Landes did likewise, adding a brief discussion of power tools and chemicals (Landes 1974: 82–114), although he also noted briefly that 'other branches of industry effected comparable advances' (1974: 41).

The approach based on critical technologies has fed through into contemporary analysis mainly through the ideas of Joseph Schumpeter. In *Business Cycles*, Schumpeter claims that innovations 'concentrate on certain sectors and their surroundings', and that there are discrepancies between the growth of sectors: 'some industries move on, others stay behind' (Schumpeter 1989: 75–6). The central idea is that innovations disrupt equilibria and cannot be smoothly absorbed into the system; however, 'those disturbances must be "big" in the sense that they will disrupt the existing system and enforce a distinct process of adaptation'. This process of adaptation is the so-called Kondratieff wave, a long period of growth and decline as the critical technologies are exploited and then exhausted. What 'big' means in this context turns out to be similar to the technological themes sketched above in the industrialisation literature based on critical technologies:

> Historically, the first Kondratieff covered by our material means the industrial revolution, including the protracted process of its absorption. We date it from the eighties of the eighteenth century to 1842. The second stretches over what has been called the age of steam and steel. It runs its course between 1842 and 1897. And the third, the Kondratieff of electricity, chemistry, and motors, we date from 1898 on. (Schumpeter 1989: 145)

These critical technology notions have been very influential, and it is only in recent years that a counter-emphasis has emerged in which other dimensions of industrialisation have been placed in the forefront of analysis. The reassessment has two elements. First, there has been increasing caution about how widespread technical innovation actually was. McCloskey, for example, emphasised that by 1860 only about 30 per cent of British employment was in 'activities that had been radically transformed in technique since 1780' and that innovations 'came more like a gentle (though unprecedented) rain, gathering here and there in puddles. By 1860 the ground was wet, but by no means soaked, even at the wetter spots. Looms run by hand and factories run by water survived in the cotton textile industry in 1860' (McCloskey 1981: 109). Samuel suggested that hand techniques and innovation were by no means exclusive. He rejected the idea that steam power in particular had economy-wide impacts, arguing that 'the industrial revolution rested on a broad handicraft basis . . . the handicraft sector of the economy was quite as dynamic as high technology industry, and just as much subject to technical development and change' (Samuel 1977: 60). Secondly, there is an emphasis on innovation outside these allegedly core sectors. Von Tunzelmann, for example, argued that 'the usual stress on a handful of dramatic breakthroughs is seriously open to question', and that what mattered was the variety and pervasiveness of innovation (von Tunzelmann 1981: 143). Maxine Berg and Pat Hudson have argued that most accounts of innovation in the industrial revolution in effect focus on process change, on innovation in capital goods (Berg and Hudson 1992). Berg has stressed the importance of a relatively unexamined part of innovation at that time, namely product innovation in consumer goods, especially in products that can be considered luxury goods. This was a key demand-side factor shaping innovation in Britain, and gave rise to major industries. Some of the evidence for this will be outlined below (Berg 2002; see also chapter 13 below).

What are the implications of these different views of industrialisation for understanding the process of change in the British economy from 1760 to 1830? The first view accords with an account in which industrialisation is driven by a small number of rapidly growing industries and by the inter-industry diffusion of a relatively small number of critical technologies that formed the basis of leading sectors. In this account the emphasis is on radical innovation, and an abrupt shift in leading sectors and technological methods (for a recent account, see Freeman and Louca 2001; for an economic history of industrialisation in this framework, see Lloyd-Jones and Lewis 1998). In such views technological change is a determining factor in growth. Within this first approach, technology tends to be seen as a *deus ex machina*; technological change has been treated as something that explains the industrialisation process, but is rarely itself seen as needing explanation. The second view implies a more complex story, in which innovation accelerates on an economy-wide basis, yet is usually incremental and small scale. In this approach, the problem is not so much one of using technology to explain growth, as explaining the wide disposition to innovation across a very broad set of activities: here technology plays no primary causal role, but rather is the phenomenon that needs explanation.

What types of evidence are relevant to deciding between these very different accounts of industrialisation? An obvious starting point is an examination of what we know about the actual processes of innovation and diffusion across the economic activities of Britain at that time. We turn now to this task, looking first at evidence from patenting behaviour, and then at the histories of specific technologies.

SECTORAL PATTERNS OF TECHNOLOGICAL ADVANCE: THE PATENTING EVIDENCE

One of the few available quantitative output indicators for technology is the patent series. A patent is the grant of monopoly rights of use for a new invention – at the time of the industrial revolution for a period of fourteen years – following an application to the Patent Office by an inventor (see also chapter 8 below). Patent applications must disclose details of the invention: these include details of the particular ways in which it is novel, its technical field, and areas of potential application. Patent applications and grants are published, and over time provide an insight into the extent and scope of inventive activity in society. In Britain the patent data map a definite acceleration of technological change from the mid-eighteenth century. Of course patents have obvious limitations as technology indicators: the propensity to patent is shaped by social and economic factors, and varies over time and between industries. Moreover the existence of a patent – which protects a new technical principle – does not imply a commercially viable product or process, since it does not necessarily lead to adoption of the technology. A patent therefore indicates nothing about the economic value of a new technique.

However, the patent series is linked – though in complex ways – to the evolution of industries, and gives us a reasonable guide to the pace and direction of technological advance in industry. Jacob Schmookler, for example, showed that patenting in a number of US industries was closely correlated with industry output (with patents lagging), and that a high proportion of patents within an industry were commercialised; his broad conclusion was that patenting was strongly associated with industrial activity, but more significantly that the lag relationship implied that invention was shaped by economic forces (Schmookler 1962, 1966).[1] Christine MacLeod, in the definitive study of the English patent system, emphasised the point that from its inception in the mid-sixteenth century – as a system of royal grants of monopoly rights in production of some commodities – the patent system was used for widely different purposes by different types of inventors. By the late eighteenth century, however, the system had changed along two dimensions. The first was 'the emergence . . . of two major patenting contexts': one in the mercantile and manufacturing community of London, the other in the manufacturing districts in the north-west of England.[2] The second dimension of change was in the scale of patenting, with a substantial increase occurring after 1750. The Bennet Woodcroft index compiled in the mid-nineteenth century showed a major increase in the gross totals of all patents registered annually after 1750.[3]

1 Nathan Rosenberg, while accepting this relationship, emphasised that it was not an encompassing theory and that invention also rested on independent scientific advance: Rosenberg 1974.

2 'One was firmly based in the London mercantile and manufacturing community, chiefly among the higher status crafts; the other in the manufacturing districts of the West Midlands and North-west. What both contexts shared was a highly competitive environment and a degree of capitalization unusual for that period. They also had in common the appearance of engine makers specializing in equipping and servicing workshops and factories. Between them they accounted for over three-quarters of all patents obtained between 1750 and 1800' (MacLeod 1988: 115).

3 Bennet Woodcroft (ed.), *Chronological Index of Patents of Inventions* (1854), cited in MacLeod 1988: 146.

Table 5.1 Patents for capital goods, 1750–99

Type of invention	1750–9	1760–9	1770–9	1780–9	1790–9	Total
Power sources	10	21	17	47	74	169
Textile machinery	5	6	19	23	53	106
Subtotal	*15*	*27*	*36*	*70*	*127*	*275*
Agricultural equpt	1	3	5	22	27	58
Brewing equpt	0	1	2	4	17	24
Machine tools	1	4	1	2	3	11
Salt making equpt	2	3	2	1	2	10
Sugar making equpt	0	1	7	1	1	10
General chemical equpt	0	3	2	9	9	23
Building tools and machinery	1	2	4	2	5	14
Mining machinery	1	5	3	7	5	21
Metallurgical equpt	6	9	11	18	19	63
Shipbuilding	4	14	7	17	37	79
Canal and road building	2	1	1	2	24	30
Other industrial	1	5	11	13	18	48
Total	34	78	92	168	294	666
% of all patents	37.0	38.0	31.3	35.2	45.2	38.3

Source: Derived from MacLeod 1988: 148.

MacLeod showed that growth was especially rapid in capital goods, which grew sharply in absolute terms but also as a proportion of all patents, making up 45.2 per cent of patents in the last decade of the century. The two fastest-growing categories were power sources and pumps (which of course include steam engines, with James Watt's engine being patented in 1775) and – fastest of all – textile machinery. The time paths of patenting in these categories are shown in Table 5.1. A sustained rise in patenting from 1750 is visible, and the rise is especially strong in the last decade of the eighteenth century: in both power sources and textile machinery about half of all patenting from 1750 occurred in the ten years 1790–9. So these technical categories are strongly present. However, it is important to keep their predominance in perspective. Over the whole period these two groups made up almost exactly 50 per cent of capital goods patents, which means that there was also substantial patenting in other areas. In fact exactly the same time path, with strong growth in the last decade of the eighteenth century, can be seen in agricultural equipment, brewing equipment, shipbuilding, canals, building equipment and metallurgical equipment. As we shall see below, these were large sectors where considerable technological advance was occurring.

Apart from the diversity of patenting, we should note that Table 5.1 refers to capital goods only. These made up just under 40 per cent of all patents during the period 1750–1800. So rapid growth in capital goods should not obscure the fact that innovation was also occurring

Table 5.2 Selected product and ornamenting patents, 1720–1800

	Birmingham	Total UK
Buckles and fastenings	11	36
Engraving, etching and chasing	1	12
Making and ornamenting frames for pictures and looking-glasses	2	7
Workboxes, music stands, dressing boxes and fire-screens	2	4
Castors, knobs and handles	6	10
Cabinets and other furniture	4	14
Metals and metallic substances		
Plating, tinning, lining and covering	11	35
Ornamenting, inlaying and polishing	3	9
Moulding and ornaments for buildings, coaches, and furniture	5	18
Paper mâché and japanned ware	2	5
Total	47	150

Source: Berg 1998a: 39.

across a wider spectrum of British economic activity (Sullivan 1990: 350). Maxine Berg's work on patents, focusing in particular on the Midlands metal trades, reveals some of the broadness of innovation activity during the early industrial revolution. Her work looks at consumption goods, showing that patents were taken out on a vast number of small, novel processes and products such as buckles and buttons. This suggests small-scale ingenuity, and a process of innovation and technological change involving a much larger number of people and of manufacturing processes and goods than suggested if we just look to the 'heroic' inventions stressed by Toynbee and those who followed his emphases. Table 5.2 shows some of the array of patents related to ornamentation and decoration, both personal and domestic.

These rather humble consumption goods may seem a good deal less exciting than new steam or textile technologies, but that of course does not mean that they have less economic impact. Taken together, there are a large number of them, and they are in areas of high demand and considerable economic significance in terms of the volume of employment and output; many of them rested on new types of production machinery and capital goods. So without far more detailed technological and economic analysis, we could not say that these were in some way less significant fields than those that comprise the textile process, for example.

What can we conclude from this brief look at patenting? The patent series suggests a technological dimension of industrialisation which was certainly apparent to contemporary observers, and which has played a central role in historical writing about the period ever since. However, during the period, the two largest groups of patents, power sources and textile machinery, constituted slightly less than 20 per cent of all patents. Within capital goods, relatively unglamorous activities such as brewing equipment, agricultural implements, machine tools, sugar making equipment and so on exhibit similar rises, although to smaller totals. Finally, there is a large set of consumption goods patents that indicate extensive inventive activity in a wide range of luxury and everyday products. So the patent evidence suggests a very broadly based process of technological change, with major capital goods inventions as important components, but with extensive inventive behaviour occurring across the whole spectrum of economic activity.

SECTORAL PATTERNS OF CHANGE: TECHNOLOGICAL HISTORIES

Beyond the patent record we have a wide variety of technological case studies that, taken together, provide a detailed overview of the range and scope of innovation during British industrialisation. In this section the evidence for a number of important economic sectors is reviewed in terms of the technological advances taking place over the period. We focus in detail on two broad, related types of activity – agriculture and food processing, the latter of which includes the brewing of beer which was a major scale-intensive activity at that time, and then on the glass industry, a prosaic activity perhaps but one with wide uses and impacts on the quality of life.

Agriculture

No account of the technological development of Britain can ignore agriculture, which was the largest economic sector at that time and one of the most significant in terms of technological change. Change within the sector encompassed a complex array of interacting institutional, organisational and technical shifts: 'the century from 1750 to 1850 saw considerable activity and expansion in British agriculture. The new interest in farming under the influence of the great improvers; the opportunity to adopt new ideas resulting from enclosure; the continually increasing population leading to additional demands for food; better means of communication; and the stimulus of the Napoleonic wars, all led to great developments in farming techniques' (Beaumont and Higgs 1958: 1–2).

Technological change in agriculture from 1750 encompassed a wide variety of technical functions within a complex set of agrarian production processes: farm tools, cultivation implements (ploughs, harrows, mowers, wheels for farm vehicles), sowing implements, harvesting equipment (reapers, rakes, hoes, scythes, winnowing and threshing devices, etc.), barn equipment, and drainage equipment. During the period 1750–1850 there was considerable change in the array of techniques, and technological progress occurred across a very broad front (Mathias 1983: 70).

The long and broad character of change had an important effect on the development of specialised equipment supply into the sector. By the 1830s,

> Many small engineering works and foundries had sprung up in the rural districts and market towns of England. Although these catered primarily for the farmer, their effect on farming methods was at first small, consisting mainly of the gradual substitution of cast and wrought iron for wood or stone in the construction of simple farm implements and appliances . . . [however] it was due to their influence that that basic farm implement, the plough, was transformed in the early years of the nineteenth century from a crude construction of wood and blacksmith's ironwork into a stronger, handier and far more efficient implement constructed entirely of cast and wrought iron.
> (Rolt 1980: 103–4)

Ploughing was then and now a time and energy consuming element in agriculture. The eighteenth century saw continuous change in ploughing techniques, beginning around 1750 with the Rotherham plough, a smaller and lighter swing plough derived from a Dutch model. This was primarily a design change rather than a change in materials, but it quickly led to materials substitution, with James Small introducing the 'Scotch swing plough' in 1763, involving the extensive use of wrought iron, and then in 1785 an important innovation, the self-sharpening ploughshare patented by Robert Ransome:

> The under surface of the share was cooled more quickly than the upper surface, thus making one side harder than the other and the share self-sharpening. Shares had previously been filed in the field or taken back to the forger for sharpening. When chilled cast iron shares came into use a permanently sharp edge was ensured. The principle of self-sharpening shares is still the same today. (Beaumont and Higgs 1958: 3)

This innovation, as Rolt remarked, was a case of a 'seemingly small innovation [that] had an immense effect on the speed and efficiency of arable cultivation' (Rolt 1980: 104). Ransome also took out a third very important patent in 1808, which involved nothing less than the introduction of standardised parts, a revolutionary step that is often held to have occurred much later (and then primarily in the USA). This was for a plough-frame to which components were bolted – new parts could be easily substituted for damaged or worn-out parts, a development that significantly reduced the cost and time involved in plough repair. These innovations were not necessarily small-scale trial and error processes; they certainly led to the formalisation and codification of the technologies used in agriculture, with publication of plans and books covering these techniques.[4] Both the development of standardised parts and the process of codification of

[4] These innovations 'inspired such as John Arbuthnot and James Small to consider principles of plough design and to discuss in books the relative merits of the various ploughs in use. They produced plans, tables, and detailed descriptions from which ploughs could subsequently be built' (Beaumont and Higgs 1958: 2–3).

technology are often regarded as watersheds in the evolution of technology as a whole, but the unglamorous origins of these in agriculture is often neglected.

This broad innovative effort around a particular farming function was replicated in other areas. For example, the drilling of seed was a problem approached in diverse ways. The major invention, Jethro Tull's seed-drill of the early eighteenth century, was the culmination of decades of attack on the problem by many inventors; it was invented in 1701, introduced (via a book) in 1731, and an improved geared version appeared fifty years later, in 1782. Its importance lay in the fact that it was 'the first important step towards the elimination of manual labour in farm operations in Britain' (Beaumont and Higgs 1958: 5–9; Rolt 1980: 671; Inkster 1991: 305). It should be emphasised that this was not an isolated innovation – it led to a trajectory of advance, with at least three further important seed-drill innovations by 1850, and a range of improved seed-drills being developed in a process of change that continued throughout the nineteenth century.

The innovative effort broadened to all the functions of farming. Tull himself developed a horse-hoe in the early eighteenth century that was progressively developed throughout the century (Derry and Williams 1979: 671). The problem of harvesting was also systematically addressed, at first through incremental improvements to such longstanding tools as the scythe (Daunton 1995: 46). This was followed with devices that attempted to replicate the hand actions of skilled farm workers (Balassa 1988: 151). These devices failed, yet between 1780 and 1850 a wide variety of reaping machines were invented and marketed in Britain and the USA. In Britain, the importance of this problem can be indicated by the fact that the Royal Society of Arts offered a prize for its solution in 1812. The defining solution to this technical problem came in 1831 in the USA, with the McCormick reaper of 1831, which rapidly became the standard technique for mechanical harvesting. But the noteworthy point is that this machine was not an isolated act of invention, but rather the culmination of a sustained inventive effort on both sides of the Atlantic; indeed it has been claimed that 'the seven essential elements of McCormick's reaper . . . had already appeared in English patents in the first quarter of the [nineteenth] century' (Giedion 1969: 152–3).

These examples can easily be multiplied. The mid-eighteenth to early nineteenth centuries saw the introduction of horse-rakes for haymaking, then Salmon's haymaking machine (the principles of which are still in use in haymaking), the threshing machine of Andrew Meikle, the winnowing machine of James Sharp, root and chaff slicers, and drainage equipment (such as mechanically made pipes) (Beaumont and Higgs 1958: 9–10; Mokyr 1990: 139; Inkster 1991: 306). This was an arena of technological advance with profound impacts on the extent and nature of labour inputs, and on output.

To what extent did technological change in agriculture depend on the use of advances from outside agriculture itself? Clearly the substitution of cast and wrought iron for wood, and the ability to design new metal-based technologies, relied to some extent on innovations deriving from the iron and steel industries. But the specific advances in casting that led to the self-sharpening plough were made within activities that were specifically focused on agriculture, and it does not therefore seem reasonable to see agriculture in terms of the spread of techniques from elsewhere. Where techniques diffused, it usually post-dated the acceleration of innovation in agriculture in the period discussed here.

This was particularly the case with steam power. Rolt remarked that 'Long after steam power had been successfully applied to manufacture and transport, the British farmer continued to rely solely upon the horse, while the most notable advance in agricultural mechanisation was the substitution of the threshing machine for the flail', and that as late as the early 1840s, 'aside from a few isolated experiments, there had been as yet no attempt to apply steam power on the farm' (Rolt 1980: 102, 104). Ultimately, steam powered technologies did appear: mobile threshing machines, winnowing machines, and cable-drawn ploughs for example. But 'There was little scope for new sources of power until well into the nineteenth century, when determined efforts were made to introduce steam engines into British farms. These were particularly successful in the large farms of the English lowlands such as Norfolk, where techniques of steam ploughing were perfected' (Buchanan 1992: 85).

It seems reasonable to conclude that agriculture was a self-sufficient arena of broad and significant technological innovation throughout the period considered here, and that any consideration of the technological trajectory of the British economy during the industrialisation period should incorporate this as a central component. Of course agriculture can be seen as producing inputs to other industries, such as textiles. But perhaps its most important contribution is to food production, and it is to this we now turn.

Food and food processing

Closely linked with agricultural change were the activities concerned with the processing, distribution and consumption of food. It is worth emphasising that during the industrial revolution these processes were the largest single complex of economic activity; moreover they remained so throughout the nineteenth century (and in fact the food cluster remains a core activity of advanced industrial economies today).

It is sometimes suggested that the 'food complex' was not an important field of technological change during the industrial revolution. For example Sidney Pollard suggested that:

> in the mid-nineteenth century the final stages in food-processing such as baking and meat preparation had not yet gone through an 'industrial revolution' as commonly understood. There had been no revolutions in technology there, manual skill or personal know-how were still predominant, there was no central motive power, no factory and no mass production. (Pollard 1994: 24)

In *The Lever of Riches*, Joel Mokyr concurred: 'Large sectors of the economy, employing the majority of the labour force and accounting for at least half of gross national product were, for all practical purposes, unaffected by innovation before the middle of the nineteenth century. In . . . food processing . . . techniques changed little or not at all before 1850' (Mokyr 1990: 83).

While Pollard and Mokyr are right to suggest that large parts of this major economic activity remained manual, domesticated and relatively static in their technical character, it is certainly not the case that food processing remained unaffected by technological change. (In fact, Mokyr in particular is a good guide to some of the major changes.) On the contrary, within food processing there were areas of change of deep importance, not only for the development and deployment of new techniques, but also for new forms of production organisation and enterprise structure. Certainly it was many years before these innovations diffused fully into the household sector, but the innovation effort in food processing was both widespread and sustained. In this section five areas of change are overviewed: food preservation, refrigeration, baking, brewing and grain milling.

Food preservation. The canning of food was an important achievement in early industrialisation, the basic technique being the vacuum sealing of cooked food. The technique was invented in France in 1795 by Nicolas Appert, using glass jars for storage. In 1810 Peter Durand, an Englishman, proposed the use of tin cans, a method that proved successful (Derry and Williams 1979: 695; Mokyr 1990: 140; Inkster 1991: 305). The early versions of this technique came rapidly into use – they were adopted by the Royal Navy, and canned soup and meat were being consumed by British sailors by 1814. This technology was incrementally improved throughout the nineteenth century, with changes in sterilisation processes, and the use of autoclaves for cooking (Derry and Williams 1979: 691–6). During the 1830s, preservation techniques for milk emerged, with 'condensed milk' being patented in 1835, although diffusion came much later.

Refrigeration. An important arena of technological change from early industrialisation to the present day has been the evolution of techniques for keeping food fresh. Early approaches all involved the use of ice. At first, both in Europe and the USA, this was based on the harvesting of natural ice, and its storage in insulated ice-houses. The main area of use was the fishing industry. Natural ice was being used by the late eighteenth century, with salmon being packed in ice for transport to London by 1786, and sea fish (from Harwich and Grimsby) by the end of the century. This rapidly ran into a supply constraint: 'Since demand clearly exceeded natural supply [of ice] . . . ice-making machines began to be patented in the 1830s and became numerous in the 1850s, the cooling effect depending either upon the expansion of compressed air or upon the evaporation of very volatile liquids such as liquefied ammonia' (Derry and Williams 1979: 698). The basic scientific and technological principle of refrigeration had been known since around 1755, and practical applications were driven by the needs of ice production. About a century of incremental development was necessary before James Harrison patented the first practical commercial refrigeration device in 1856 (Rolt 1980: 112). These changes had important impacts on the fishing industry – the development of large fishing boats ensued, with both refrigeration and onboard tanks for keeping fish alive. The extension of railways to the fishing ports, combined with the use of ice-based preservation, created new distribution possibilities and a large market, with fish being shipped fresh from the main fishing ports. Refrigeration contributed therefore not only to the growth of a new economic activity, but also to a significant shift in diet for urban populations.

Baking. Bread and biscuits were a long-term dietary staple. From the late eighteenth century a series of inventors had attempted to produce massively larger ovens that would permit the large-scale production of bread. Most of these involved either conveyor belts running through a large oven, or a process in which an oven rotated slowly over a fixed heat source (Giedion 1969: 176–7). As with food preservation by canning, the British navy was a lead customer:

> In the first decade of the nineteenth century, Admiral Sir Isaac Coffin (1759–1839) built for the British Navy an oven 'intended for baking sea-biscuits' . . . which he named the 'perpetual oven.' Coffin thus explains the name given to his oven: 'It is called a perpetual oven because the operation of baking may be continued for any length of time.' It was indirectly heated. An endless belt a yard wide and made of loose wire mesh ran the whole length of the baking chamber. At either end, outside of the oven, the belt ran around large cast-iron rollers, which kept it continually moving. (Giedion 1969: 176–7)

The production of biscuits for sea use was also associated with another epoch-making organisational innovation, namely the assembly line. The machines used for making biscuits were co-ordinated with each other, and with the accurately timed hand operations that were necessary to make biscuits. The principles of synchronisation are in many ways the key element of modern product assembly. Larger-scale ovens followed these innovations in the mid-nineteenth century, followed by automatic mixing and slicing, and by the use of carbonic acid in bread dough (patented in 1856). What we have here is the major technological upgrading of a traditional product – an important but neglected form of innovation during the industrialisation process and after.

Brewing. During the eighteenth century the brewing of beer shifted from small to large scale, although a diverse array of firm sizes persisted within it: 'brewing became a much more specialist activity as home brewing and inn-keeper brewing became less common. By the mid-1820s larger towns usually had several specialist brewers' (Timmins 1998: 108). This had important implications for scale and for the use of technology; as Daunton points out: 'In the course of the eighteenth century, the scale of brewing increased, and in most towns it was amongst the largest and most prosperous businesses . . . the brewers were amongst the first and largest users of steam power' (Daunton 1995: 324).

These firms not only used advanced technologies, they pioneered perhaps the most important organisational innovation of the modern economy, namely the professionally managed, vertically integrated, corporate enterprise. These were capital-intensive operations, and British brewers solved the problems of access to adequate fixed capital by extending ownership; the effect of this was to move away from the family firm as a mode of organisation, and to take an important step towards corporate capitalism. At the same time, the firms integrated backwards into the production of raw materials, and forwards into distribution and the ownership of networks of pubs (Landes 1969: 72; Daunton 1995: 324–5). This somewhat neglected industry has a genuine claim to being both the technological and organisational precursor of the modern economy.

Grain milling. As urban populations increased during the eighteenth century, the demand for flour grew sharply, and the scale of grain milling grew with it. On the one hand this had an important technological component: 'grain milling . . . turned increasingly to steam power in urban locations' (Timmins 1998: 108). On the other hand, as with brewing, there were integrated technological and organisational shifts. Increasingly, small-scale milling was replaced by:

> large, capital-intensive mills which purchased grain in order to supply long-distance markets; water-powered mills on the Thames were some of the largest industrial concerns of the eighteenth century, and steam-powered mills were erected in London . . . As the scale of firms increased, they integrated backward and forward. Large millers purchased their own supplies and cut out the factors, or they moved forward into the trade in flour and cut out the mealmen. The mealmen, in turn, integrated backwards and acquired mills. The whole pattern of supplying bread-stuffs, the basic necessity of life, had become a very different matter from a farmer pitching his wagon in the market-place: it had extended lines of distribution, involving capital-intensive plant and considerable amounts of working capital, with some of the largest concerns in the economy. (Daunton 1995: 324)

The examples offered here could readily be extended – into, say, sugar refining, jam manufacture, chocolate manufacture, coffee refining, tobacco processing and so on and so on. It is important to continue to stress the wider implications of this: it is reasonable to claim that the prosaic industries we have mentioned above were not merely adjuncts to industrialisation but leaders of it, and in fact were key bearers of technological change during the industrial revolution.

Glass manufacture

Glass is an important and differentiated industrial product, widely used across the early industrial economy and central to the development of industrialisation. Glass comprises both domestic products (bottles, glasses, lamps, mirrors, etc.) and important industrial inputs: containers, sheet glass and cast plate glass (of widely differing types, usually used for windows), and a complex specialised product, namely optical glass. As with the food industry, the rate and impact of technological change is subject to differences in interpretation. Derry and Williams suggested that the transformation of glass making into a machine industry was a slow process: 'It was, indeed, far from complete even in 1900 . . . in glassmaking the craftsman and the ancient, and often secret, traditional processes were not quickly swept aside by industrial change' (1979: 583, 592). Yet, reviewing the eighteenth century, Berg was able to conclude that the glass industry 'experienced major technological or organisational changes in the period [1700–1820]' (Berg 1994: 53). These views are not necessarily contradictory – although many hand processes remained, the period none the less also saw sustained innovation.

Glass was one of the few large-scale production activities in early industrialisation, along with textiles and iron manufacture (Mathias 1983: 185). It was a sector of steady innovation. In the seventeenth century an important innovation, the reverbatory furnace, had emerged; its basic principle was the separation of fuel and raw material, and this made possible the substitution of coal for wood and charcoal as a fuel (Landes 1969: 53–4; Mokyr 1990: 106; Timmins 1998: 43). In the late eighteenth century the production of plate glass was revived in Britain (where it had been produced on a small scale in the seventeenth and early eighteenth centuries) with the construction of a very large plant at Ravenhead, near St Helens, by the British Plate Glass Company (Timmins 1998: 109). In the 1830s cylinder processes were introduced for the manufacture of sheet glass, and in the 1840s machinery for grinding and polishing sheet glass was developed and diffused (Singer 1958: 367; Daunton 1995: 229). These innovations were important in the development of companies that have played a major long-term role in British manufacturing: for example, the cylinder process was introduced in the 1840s by the St Helens Crown Glass company, which became Pilkington Brothers, a firm that remains a major producer and innovator in glass (Timmins 1998: 201). Finally, 'from 1859 onwards there was a series of patents in various countries for bottle-making machines, and in 1887 the semi-automatic Ashley machine, used at Castleford in Yorkshire, provided the first commercial success' (Derry and Williams 1979: 698). In blown-glass products, some important innovations related to plant layout and organisation: 'manufacturers evolved a distinctive cone-shaped factory, with the furnace in the middle, together with the pots of molten glass, and plenty of space around it for the glass "blowers" to exercise their skill' (Buchanan 1992: 179). It should be noted that many of these innovations were in fact diffusions from western Europe, principally from Germany and France. The cylinder process came from Lorraine and the German states, although it probably originated in France (Singer 1958: 367; Mokyr 1990: 106).

The most knowledge-intensive component of glass production was however in optical glass:

> The closest link with the scientific advances of the period of the industrial revolution is in the steady progress of optical glass. It was in 1758 that John Dollond, a practical optician, was awarded a patent for the achromatic lenses that he had been constructing, contemporaneously with Moor Hall, for about a quarter of a century; they were made by cementing a convex lens of crown glass to a concave lens of flint glass. (Derry and Williams 1979: 592)

Many of the key developments in optical glass occurred in western Europe: glass manufacturing processes were developed in Switzerland by Pierre Guinand, in France by Bontemps and Lerebours, and in Germany by Franubhofer. These advances diffused to Britain via a Birmingham manufacturer, Lucas Chance, who purchased and patented the Bontemps technique in 1837. After the 1848 revolution Bontemps himself came to the UK and worked directly with Chance Brothers, who became major producers of optical, telescopic and camera lens glass. These developments became the object of specific research programmes in Britain, not only among manufacturers but among interested scientists such as Herschel and Faraday, who took charge of the Royal Society investigations into optical glass in 1824 (Singer 1958: 359–60; Derry and Williams 1979: 592–3).

The material in the sections above has been intended to demonstrate the extent of innovation in what are often thought to be rather stable, undynamic sectors of the economy. The kinds of experience represented by these activities could easily be expanded: in such activities as pottery and ceramics, machinery and machine tools, instruments and mining, important and persistent patterns of innovation can be found. Pottery, for example, was an important area of organisational innovation, particularly in the Wedgwood enterprise. McKendrick showed some years ago that Wedgwood's product innovations were accompanied by changes in plant layout and labour organisation and management that were in many respects the earliest important form of modern workplace organisation (McKendrick 1961). In machinery and machine tools there were numerous important innovations: the screw cutting lathes of Jesse Ramsden in the 1770s, the boring machines of John Wilkinson in the mid-1770s, specialist machines for making watches, the carriage lathes of

Henry Maudesley in the late eighteenth century, new woodworking lathes and planers (such as that built by Joseph Bramah in 1802), large-scale lathes and metal planing machines invented by Richard Roberts in 1817, Nasmyth's machines for accurate cutting of hexagonal nuts in 1829 and many others that were developed at that time (on these and related machine making technologies see Burstall 1963; Saul 1970; Derry and Williams 1979; Daumas 1980; Mathias 1983; Cantrell 1984; Inkster 1991; Buchanan 1992). Some of these developments, such as Wilkinson's accurate and large-scale boring machines, made possible such innovations as the Boulton and Watt steam engine, since all of the Watt engine cylinders were bored with Wilkinson's machinery. The growth in variety, scale and accuracy of machine tools (by 1830 Maudsley was using a bench micrometer accurate to 0.0001 inch) was of profound importance for production across many sectors).

The pervasiveness and extent of innovation across the industries outlined above give us reasonable grounds for a general conclusion, namely that innovation was not confined to alleged 'leading sectors' of the economy, but rather was present, often in an intense way, across virtually all economic activities. This does not of course mean that we can ignore the sectors such as textiles and steam power that have driven so much of the historiography of industrialisation; on the contrary, they deserve close examination.

THE 'MAJOR INNOVATIONS'

Textiles

Together with steam power, textile machinery has been the emblematic technology of the industrial revolution, to the extent – as we have seen – that many histories of the industrial revolution have seen textiles not only as the primary site of innovation but also as the driving force of economic growth. While we can contest both the singularity of the technological changes, and their impact on growth, it nevertheless remains the case that this was indeed a major sector of change, in which considerable explanatory challenges remain: 'This "story", endlessly narrated, has never been explained by historians, who lack a general theory able to account for the major breakthroughs in technology that occurred in textiles over the eighteenth century' (O'Brien *et al.* 1996: 155). The evolution of textiles equipment in the eighteenth century was in part a process of transition away from domestic manufacture to factory production. The first factory production of textiles began in the early eighteenth century in the production of silk thread and cloth, based on silk throwing machinery patented by Thomas Lombe and based on modifications of Italian technology. Lombe's patent expired in 1732, leading to entry in the industry:

by the 1770s there were about thirty silk mills in the Midlands, mainly supplying handloom weavers in London (Kirby and Rose 1994: 38).

The real expansion occurred however in cotton textiles. The major innovations began with the mechanisation of hand techniques, which then developed into new elements of mechanical technology (see Chapman 1972 for the best overview of the technical developments). The sequence is usually associated with four key technologies: Kay's flying shuttle, Arkwright's water-frame, Crompton's spinning mule and Cartwright's loom, but we could add into this such major developments as Roberts's automatic mule (a machine which introduced the principle of error-actuated servo-control, and which Marx claimed 'opened up a completely new area in the capitalist system'). The first development occurred in cotton spinning, with the spinning jenny design by the Lancashire spinner James Hargreaves coming into use in the 1760s. This was a hand powered device which made it possible for a strong and skilled operator to work with more than one spindle at once; it 'reproduced the actions of the hand spinner' utilising a system of spindles with a movable carriage (Mann 1958: 278). In the early 1770s this was followed by Arkwright's water-frame, which introduced two significant innovations: first a series of rollers which drew and spun the thread, and second, water power to drive the rollers. Shortly afterwards a new technology emerged, Samuel Crompton's spinning mule, so called because it was a hybrid, mixing elements of the Hargreaves and Arkwright approaches. This machine was working by 1779, and over the next fifty years was subjected to a great number of improvements which considerably increased its productive capacity; variants of this machine formed the staple device around which the development of the textile industry occurred. It was the dominant technology for almost a century. The mule permitted large increases in productivity: so much so that the technical development of the cotton sector as a whole is often written in terms of the imbalance between spinning and the other processes of cotton manufacture. It was not superseded until the Roberts automatic mule of 1825, a radical breakthrough that was, in effect, the first truly automatic machine in the world. What we have here is an interrelated series of 'macro-inventions' appearing over a relatively short time period. The technological history of the industry therefore involves questions concerning the impulses to these processes of discovery, combined with the impulses to diffusion, as well as a wide array of smaller-scale inventions and innovations in textiles. O'Brien *et al.* point out that between 1700 and 1850 there were 2,330 textile patents in the UK, and this extensive range of patents is far from encompassing all of the innovative activity of the period in this sector (O'Brien *et al.* 1996: 165–7).

These technological changes were associated with rapid industry growth. Between the late eighteenth century and the middle of the nineteenth century the cotton textile industry in Britain grew spectacularly, in the absolute size of output, in labour productivity, in the scale of enterprises, in capital employed, and in the proportion which it contributed to national income. The gross value of output grew from £0.6 million in 1760 to £30 million in 1815 (Deane and Cole 1967: 185–8). In spinning, the number of operative hours required to process 100 lb. of cotton declined from 2,000 in 1760 (using Crompton's mule) to 135 in 1825 (using Roberts's automatic mule) (Catling 1970: 60). Between 1797 and 1850 the average annual input of raw cotton per factory rose by over 1,000 per cent, which reflects an increase both in physical productivity and in the average size of enterprises (since the number of enterprises less than doubled during the same period) (Chapman 1972: 70).

These dramatic productivity shifts should not be seen simply as the result of technological change. First, it is important to remember that the textiles sector comprised more than cotton: it included flax, silk and woollen manufactures, plus the manufacture of such products as lace and hosiery. Hosiery and lace manufacture remained domestic hand technology tasks, and in spinning the input of human skills remained strong even after mechanisation (Samuel 1977: 19). Moreover it is important to remember the overall complexity of the textile processes: textile manufacture involved many differentiated products, with processes involving raw material preparation (cleaning, combing and so on), spinning (with many different types of output), various types of weaving, bleaching, dyeing and printing, plus the operations involved in working up cloth outputs into products. Within the textile production chain mechanisation was very uneven, and so cannot exclusively account for the productivity growth experienced by the industry.

Within textiles, production was shaped not only by technical change but also by major organisational innovations associated with the factory and changing managerial control. These organisational innovations should be borne in mind when considering the longer-term impacts of the industrial revolution, since the factory permitted not only the application of power and the adoption of new techniques, but also the organisation and intensification of labour. In fact such organisational and managerial elements were central problems in the early factory system (see chapter 2). These points lead to two broad explanatory problems: first, explaining the sequence of textile equipment innovations, and secondly, understanding and explaining the organisational innovations within which the new techniques were put to work.

There is no comprehensive historical explanation of the sequence and array of invention in textiles. O'Brien *et al.* (1996) offer perhaps the clearest steps towards an explanation. They stress contextual features of path dependence (Britain had been a major textile producer and exporter across the whole range of processes and fabrics for a very long period), and of changes in the political economy of the industry (particularly changes in the supply and price of cotton from the Americas, and the emergence of protection against Indian cotton fabrics and hence a process of import substitution). On the inventions themselves they strongly emphasise the importance of an eighteenth-century social milieu committed to technical improvement and invention – a critical mass of human capital based on 'widespread interest in natural philosophy, mechanics, automata, and even in technological fantasies, among the upper and middle ranks of British society, including members of the ruling elite' (O'Brien *et al.* 1996: 175).

The diffusion of the major innovations, however, depended critically on organisational change. The development of the factory involved the concentration and supervision of the process of production under one roof, but before this control could even be attempted a labour force had to be assembled. Once assembled it had to be maintained. There were here, as Pollard remarks, 'two distinct, though clearly overlapping difficulties; the aversion of workers to entering the new large enterprises with their unaccustomed rules and discipline and the shortage of skilled and reliable labour' (Pollard 1965: 160). Where the factory simply concentrated production, without changing the technical means of production and therefore without the opportunity to change the composition and skill requirements of the labour force, there was found to be great difficulty in maintaining a workforce. In weaving and hosiery, where it was possible for the domestic worker to produce outside the discipline of the factory, he often did so: as one hosier, Robert Cookson, reported to the Committee on Woollen Manufacture:

> I found the utmost distaste on the part of the men, to any regular hours or regular habits . . . The men themselves were considerably dissatisfied, because they could not go in and out as they pleased, and go on just as they had been used to do; and were subject, during after-hours, to the ill natured observations of other workmen, to such an extent as completely to disgust them with the whole system, and I was obliged to break it up.
>
> (*Committee on Woollen Manufacture*, evid. of R. Cookson, quoted in Pollard 1965: 162)

The second problem, that of skilled labour, was of a very different character. In the first place, the skilled labourers were not necessarily concerned to avoid the factory, for it formed a major market for their skills; indeed some could only be applied within industrial production. Rather they were concerned to exploit the increased demand for skilled labour that the growth of the factory system engendered. The industrialisation of the late eighteenth and early nineteenth centuries led to an extreme shortage of skilled labour in every important sector of the economy (Pollard 1965: 167–72); the textile sector was dependent on skilled wood and metal workers because most of its machinery was made within individual enterprises, until the arrival of standardised machinery in the second quarter of the nineteenth century:

> The early wooden textile machinery was made by the men who used it, or directly to their order by mechanics of many kinds – loom-makers, clock-makers, cabinet-makers, instrument-makers, and men with the mechanical hobby; the 'engineers' of that day being primarily pump-makers. Having learnt to make machines, the makers often set up as spinners, so that from both sides there was intermixture. McConnel and Kennedy of Manchester combined the two businesses in the early years of the firm. Henry Houldsworth, who, after six years at Manchester, went to Glasgow in 1799, still called himself a cotton-spinner and machine-maker in 1824. 'A great many manufacturers make their own machinery?' the Chairman of the parliamentary committee of that year said to one expert witness: 'they do', was the reply. Some of the largest firms long continued to do so – the Strutts at Belper, for example. But by 1820–30 the professional purveyor of machines made with the help of other machines, the true mechanical engineer of the modern world, was just coming into existence – in Lancashire and London where the demand was at its maximum.
> (Clapham 1926: 152)

Arkwright and Strutt were 'continually advertising' for woodturners, clockmakers, smiths etc., who were employed in machine making. A stern line was taken on apprentices in wood and metal trades who broke their contracts: Arkwright had one imprisoned, and offered a reward for the capture of another (Fitton and Wadsworth 1958: 105–6).

So there were problems in building a labour force. But there were also problems in maintaining that labour force in the face of a high labour turnover and continuing resistance to work in the factory. The problem of skilled labour was ameliorated in two ways: first, as industrialisation progressed, the education system and the apprenticeship system began to increase the supply of skilled workers (see chapter 12), and second, the growth of a specialised machine building industry based on highly paid skilled labour and producing more or less standardised cotton machinery displaced the problem away from the cotton mills themselves. It is probable that this specialised industry consolidated its labour force by differentiating it sharply in terms of skills, wages and status from that of the factory operative; John Foster, for example, in his study of Oldham, argues that the growth of machine building implied the development of a labour aristocracy (Foster 1974: 228–9).

In the mills the problem of labour turnover remained: 'one of the most enlightened firms, McConnel and Kennedy regularly replaced spinners who had not turned up within two or three hours after starting time on Mondays, on the reasonable presumption that they had left the firm: their average labour turnover was twenty a week, i.e. about 100 per cent a year' (Pollard 1965: 182). The Strutts' records from Belper and Milford show 1600 departures between 1805 and 1812, which with a total labour force of about 1,300 would indicate an annual turnover of 16 per cent (Fitton and Wadsworth 1958: ch. 9). But these records deal with those who gave notice, and not with those who ran away, left without notice or were dismissed. These are precisely the most important groups when considering turnover, so the true figure is probably much higher.

These turnover problems are associated with the control and intensity of work. An important aspect of the mechanisation of the cotton industry, and the continuous process of technological innovations, was its effect on the intensity of work. As Catling (1970: chs 9–11) showed, not only was unremitting attentiveness required, but the intensity of production was such that repair and maintenance tasks on the machines had to be performed while the machine was in motion, at considerable physical risk. Thus on a pair of typical late-period mules of 1,200 spindles each, about five or six threads would be breaking each minute. Clearly the work of repairing broken ends could never be neglected for more than a few minutes and was a most important staple task (Catling 1970: 156). In view of the fact that the machinery was powered from a central power source under the control of the master, we might expect to find evidence of an increase in the speed of operation of machinery; and indeed there is abundant evidence of this. The following is from a spinner's evidence to Factory Commission hearings in 1840:

> Q. Is 10 hours' labour now at cotton spinning in a factory any more intense than 10 hours' labour was within your recollection? – A great deal more so.
> Q. What does it arise from? – It arises from the extra quantity that is produced, and the extra speed; a great deal more yarn is produced than in former day: this is all taken from the spinner.
> Q. A greater quantity of yarn is turned off in a given time than formerly? – Yes.
> Q. That is brought about by the increased speed of the machinery? – Yes.
> Q. That requires increased exertions on the part of all engaged in that machinery, in order to effect that purpose? – Yes, another thing that helped it: the competition of the workmen with one another: those two circumstances combined have rendered that necessary.
> Q. It is your opinion that 10 hours' labour as a cotton spinner now involves a severer duty, and requires as much exertion, as 12 hours did when the speed of machinery was much slower than it is now? – Yes; 10 hours now would be sorer on the operative than 12 would have been in the year 1827, or 1828, or thereabouts.
>
> (Evidence of Henry Dunn, Factories I: 1840–1)

An important point here is that the technical innovations of cotton are associated with a new organisational form, the factory. Productivity grew not simply because of new techniques, but because of the intensification of work permitted by factory organisation. But the problems of intensification of work, labour turnover and labour resistance also played an important role in shaping the trajectory of technological innovation in the cotton industry. The most notable case of this was the Roberts self-acting (i.e. automatic) mule, patented in 1825.

Where workers possessed skills which were indispensable to the production process then they also possessed a certain power to resist managerial control, which in addition gave them an advantage in bargaining over pay rates, work speeds, and so on. In this context, technical innovation was not simply a process of increasing the technical capacity to produce output, but might also have had implications for the particular skill mix of a production process, hence for the kind of labour required, hence for the overall power of the cotton managers in the organisation of production. The development of engineering capabilities and mechanisation generally held out the possibility for managers to 'innovate around' labour problems.

In *The Philosophy of Manufactures* (1835), Andrew Ure gave a concrete example of this. He remarked that in cotton spinning, the mule spinners had 'abused their powers beyond endurance, domineering in the most arrogant manner . . . over their masters. High wages, instead of leading to thankfulness of temper and improvement of mind, have, in too many cases, cherished pride and supplied funds for supporting refractory spirits in strikes'. After a series of such strikes in Lancashire towns 'several of the capitalists . . . had resort to the celebrated machinist Messrs Sharp and Co. of Manchester, requesting them to direct the inventive talents of their partner, Mr. Roberts, to the construction of a self-acting mule, in order to emancipate the trade from galling slavery and impending ruin' (Ure 1967: 366–7). The result was Roberts' self-acting mule, a major breakthrough in factory automation. Its construction was no small undertaking, for Ure estimated its development costs at £12,000 (Ure 1967: 368; Catling 1970: 64). This was, perhaps, however a small price to pay, for as Baines remarked: 'One of the recommendations of this machine to the spinners is, that it renders them independent of the working spinners, whose combinations and stoppages of work have often been extremely annoying to the masters' (Baines 1966: 208).

There were many other examples of innovations aimed at reducing the power of labour – in calico printing machines, self-acting dyeing and rinsing apparatus, sizing machines for warp dressing in power loom weaving, and carding and combing machines (Bruland 1982). So the organisational problems of the cotton sector were also intricately linked to the innovations that are normally held to characterise it.

What can we conclude from the record of innovation in the textile sector? There is no question that this was a major growth industry, with immense productivity change, and a significant site for the development and adoption of new technologies. But it would be wrong to see this sector as being driven in its development by technical innovations, since many changes were the result of a complex interaction between technology, work organisation and managerial practices. It would be mistaken also to see textiles as a *sui generis* driver of growth in the economy as a whole.

It was one sector among many that were innovating at that time, and it was far from being the only sector to generate sustained productivity growth.

Steam power

The ‘critical technologies’ approach to British industrial growth ascribes the expansion to the effects of the deployment of new techniques as the primary agent of economic advance, and its strongest version is written around the steam engine: ‘If we were to try to single out the crucial inventions which made the industrial revolution possible and ensured a continuous process of industrialisation and technical change, and hence sustained economic growth, it seems that the choice would fall on the steam engine on one hand, and on the other Cort’s puddling process which made a cheap and acceptable British malleable iron’ (Deane 1965: 130). As I have argued above, this type of approach has a long history stretching back at least to the first systematic use of the term ‘industrial revolution’ in the work of Arnold Toynbee. However the strong emphasis on the primacy of steam power among the technologies of industrialisation goes back much further, into the nineteenth century itself. A classic statement of the alleged benefits of steam was made by Andrew Ure, writing in 1835. It is worth quoting this at some length, since the structure of the argument has been very important over the years, and continues to be reflected in the advocates of ‘critical technology’-based growth theories even today:

> There are many engines made by Boulton and Watt, forty years ago, which have continued in constant work all that time with very slight repairs. What a multitude of valuable horses would have been worn out in doing the service of these machines! And what a vast quantity of grain they would have consumed! Had British industry not been aided by Watt’s invention it must have done with a retarding pace in consequence of the increasing cost of motive power, and would, long ere now, have experienced in the price of horses, and scarcity of waterfalls, an insurmountable barrier to further advancement, could horses, even at the low prices to which their rival, steam, has kept them, be employed to drive a cotton mill at the present day, they would devour all the profits of the manufacturer.
>
> Steam engines furnish the means not only of their support but also of their multiplication. They create a vast demand for fuel; and while they lend their powerful arms to drain the pits and raise the coals, they call into employment multitudes of miners, engineers, shipbuilders and sailors, and cause the construction of canals and railways; and while they enable these rich fields of industry to be cultivated to the utmost, they leave thousands of fine arable fields free for the production of food to man, which must otherwise have been allotted to the food of horses. Steam engines, moreover, by the cheapness and steadiness of their action, fabricate cheap goods, and procure in their exchange a liberal supply of the necessaries and comforts of life, produced in foreign lands. (Ure, cited in Morgan 1999: 107)

Ure's arguments have been repeated many times since. On the one hand he is arguing that steam overcame a fundamental energy crisis for the British economy – alternative energy sources would have been so expensive as to slow down or stop industrialisation completely. On the other, there is an argument about backward and forward linkages. Steam produced a backward demand for coal (and, it is sometimes argued, iron and steel), and forward linkages into manufactures (usually argued to be textiles).

How valid are these ideas? A surprising feature of the literature on technology and industrialisation is that there are very few systematic studies of the impact of specific technologies. However, in the work of Nicholas von Tunzelmann (1978) we have a detailed assessment of the extent of use of steam power, and of its economic impact – in effect a quantitative assessment of the validity of ideas such as Ure's about steam. Von Tunzelmann's aim was 'to combine economics, engineering and history to reassess the contribution of the steam engine to British economic growth during the industrial revolution'.

The work draws on an influential approach to the assessment of large technology impacts, which has given rise to much debate, that of Robert Fogel (1964). The 'social savings' method pioneered by Fogel to assess the growth impacts can be described as follows. Any particular process innovation that displaces some prior process, either across sectors of the economy or by the effective creation of a new sector, diffuses essentially because it cuts total costs of production. Whether it diffuses slowly or quickly, via the replacement of worn-out equipment or by causing functional plant to be scrapped, will of course depend on the particular configuration of fixed and variable costs involved. These cost reductions can be represented as the difference between the resource costs involved in the old and new modes of fulfilment of some economic function. Such resource-cost differences, called the 'social savings', can be seen as the 'contribution' of the new process to national income at some specified time. The analysis is carried out via the formation of a 'counter-factual example': we know what the technical facts were at some point, so let us assume that they were otherwise, and attempt to quantify the costs of the counter-factual example. Fogel's counter-factual example assumed that the American railway network, which Schumpeter held to be the crucial sector of nineteenth-century American economic growth, was bombed out of existence in 1890. Fogel then calculated the costs of fulfilling the same transport functions through the canal system, coast-to-coast shipping around Cape Horn, etc. His conclusion is well known: the railways contributed less than 5 per cent to the US national income in 1890, a striking result which 'clashes with the notion that economic growth can be explained by leading sector concepts' (Fogel 1964: 236).

What about steam power in the UK? In fact, two principal techniques are deployed in von Tunzelmann's investigation. On the one hand there is an assessment of the social savings contributed to the economy by steam power. The second technique is a rather more empirical assessment of the backward and forward linkages of the steam engine in the economy.

Von Tunzelmann makes a very careful assessment of the number and utilisation of steam engines in Britain in the early nineteenth century – in effect he carries out an industrial census of steam engines in British industry. In terms of social savings, two cases are worked out: the first examines replacement of the Watt engine alone, while the second looks at all types of steam engines. The first case involves the supposition that all Watt engines are replaced by early atmospheric steam engines of the Newcomen/Savery types. Then the aggregate fixed and variable savings on the Boulton and Watt engine, and its pirate copies, on plausible patterns of use, are assessed at between £226,000 and £233,000 in 1800. A reasonable estimate of national income in that year is £210 million. This implies that

> the social saving estimated for 1800 is very low even by the normal standards of such reckonings. For Boulton and Watt engines alone (including their pirates) the social savings over atmospheric engines can be put at about 0.11 per cent of national income in 1800. If total real output was then growing at its average rate for the take-off years, the level of national income reached on 1 January 1801 would not have been attained much before 1 February 1801 without James Watt. (von Tunzelmann 1978: 286)

A similar, rather more intricate estimate for the replacement of *all* steam engines by animal and water power places the social savings at approximately 0.2 per cent of 1800 national income: 'If all steam engines, Watt and atmospheric alike, were hypothetically replaced with other means of motive power (a combination of water and wind would be optimal), the setback would have been about two months. These are upward-biased figures' (von Tunzelmann 1978: 287).

The other effects investigated in the text are possible backward linkages (into the development of the iron and coal industries) and forward linkages (especially to cotton, via the effects of steam power on the diffusion of automatic machinery in that sector). In opposition to those historians who allege a 'mutual sustenance of the steam engine . . . and the iron industry in the late eighteenth century', it is pointed out that, at the peak of production and sale of Boulton and Watt engines at this period, 'their consumption of iron would have amounted to under one-quarter of one per cent of annual output' (von Tunzelmann 1978: 286). He moreover points out that 'If all the engines operating in the textile industries had suddenly been swallowed up by the ground in the middle of 1838, and all blast furnace capacity in the country had then been set to work to smelt the iron required to rebuild them, it would have taken under a month to complete the task' (von Tunzelmann 1978: 109).

Backward linkages to coal were rather more substantial, though still arguably very small: possibly as much as 10 per cent of 1800 coal output was consumed in steam engine furnaces, though there are possible upward biases here, and anyway most historians have considered the technical development of coal to have taken place before the industrial revolution.

Nor do the forward linkages to cotton look much more impressive. These linkages came relatively late in the development of the cotton sector, 'when the cost of supplying power fell and this happened to influence the nature, extent, and mode of employment of machines driven by power', whereas – it could certainly be argued – the crucial period of cotton development came much earlier, in the acceleration of output which occurred between 1770 and 1800. The major technical innovations in cotton, until the development of Roberts's self-actor in 1825–30, were not developed for steam power; water power long dominated the power-intensive textile processes – 'rarely have I unearthed cost reductions from steam-powered inventions in textiles on the scale often intuitively supposed' (von Tunzelmann 1978: 294).

The method of social savings used by von Tunzelmann is certainly open to criticism on conceptual and methodological grounds (for an excellent critique of the social savings method, see O'Brien 1977). However the underlying empirical basis of his work, which demonstrates rather limited diffusion of steam relative to other power sources, has not been challenged, and his critique of the alleged backward and forward linkages of steam also remains unchallenged. What we can conclude here – in what is after all one of the very few detailed empirical examinations of a critical technology – is that the claims made for steam as a driving force for growth are seriously overdone. This does not mean that the impact of steam is non-existent – it would not have diffused or survived as a technology if it had no advantages. But those advantages do not necessarily add up to support for the extreme views of those who advocate a steam-driven view of industrialisation.

CONCLUSION: INTERPRETING THE PATTERN OF TECHNOLOGICAL CHANGE

This chapter opened with the suggestion that the technological aspects of early British industrialisation continue to present intellectual challenges; technological dimensions of industrialisation are far from fully researched, and are likely to remain a productive area for students in the future. The 'critical technologies' argument seems to obscure most of these problems, mainly because it rests on an implicit technological determinism in which a small number of innovations – whose provenance and trajectories are more or less unexplained – account for the basic growth dynamic of what was already a large and complex economy. While those who support these arguments often criticise the attempts to quantify the impacts of critical technologies (see for example Freeman and Louca 2001: 31–5), the proponents of the critical technologies arguments in general offer little evidence concerning the economic impacts of steam, railways and so on. Conceptual arguments as to precisely how the radical technological breakthroughs in textile machinery, steam power and the like fed through into economic outcomes are often absent, as is any form of quantitative evidence linking the industry concerned to the wider economy.

The alternative that has been explored here is that innovation was a broad process, pervasively embedded in many industries, even those that were essentially matters of hand technology. Samuel argued, in a chaotic but fascinating paper, that 'in speaking of the primacy of labour power one is referring not to single instances, or to curious survivals, but to a dominant pattern of growth', one that was 'quite as dynamic as high technology industry, and just as much subject to technical development and change' (Samuel 1977: 45, 61). There is in fact a wide array of evidence from business, technological and industrial histories to lead us to the firm conclusion that innovation in the industrial revolution was present across virtually all activities that comprised the British economy at that time. Clearing the ground on this issue is important in itself, but it also generates much wider questions. If we recognise that technological change during early industrialisation was not a matter just of steam, textiles or any other particular heroic breakthrough, but was rather a matter of extensive development across a very wide range of technologies, then we open up a new array of research issues. The wide scope of technological development in Britain after the early eighteenth century suggests a general social propensity to innovate. Exploring this propensity ought to lead us first to an adequate causal account of extensive technological change, secondly to a more satisfactory account of the relations between the different fields of technological and economic change, and finally to a better understanding of the economic causes and impacts of innovation.

6

Money, finance and capital markets

STEPHEN QUINN

Contents

INTRODUCTION: THE BRITISH FINANCIAL SYSTEM IN 1873

Walter Bagehot, editor of *The Economist*, published *Lombard Street* in 1873. Bagehot rejected the title 'Money Market' because he wanted to convey to readers that he was dealing 'with concrete realities' (Bagehot 1873: 1), and reality in 1873 was that the bricks-and-mortar components of the London money market around Lombard Street were banks: the Bank of England, private banks, joint-stock banks and discount houses. In Bagehot's words, these banks formed 'the greatest combination of economical power and economical delicacy that the world has ever seen' (Bagehot 1873: 2). However, the two centuries of financial development that produced Lombard Street also sheltered once-innovative, now-dated arrangements like England's decentralised regional banking system (Cottrell 1980: 16). In 1873, Britain had 376 private and joint-stock banks, of which ten were Scottish and 296 – 80 per cent – of the remaining 366 banks were English and Welsh banks outside of London (see Table 6.1). Similarly, two-thirds of England's £393 million of commercial bank deposits were outside of London, and most of Britain's 481 Trustee Savings Banks were also outside London (Table 6.1; Horne 1947: 379–85).

Regional banks were mostly local concerns, and London acted as the hub that integrated the regions into a larger financial system. On an