How and why economies develop and grow: lessons from preindustrial Europe and China

Chapter 4

Technological Progress

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ABSTRACT: Technological progress in agriculture consisted mainly of the refinement and diffusion of long-known methods of intensive cultivation. In industry, it consisted largely of mechanization. Both intensification and mechanization were driven by expansion of the market and the reorganization of production. Technological progress was, therefore, largely endogenous.

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Commerce promotes production through expansion of the market. Expansion of the market creates incentives, and the response to those incentives raises productivity. One part of that response, as we saw in Chapter 3, is a reorganization of production. The other part, the subject of this chapter, is technological progress.

Technological progress may be defined as an improvement in the practical knowledge that is applied to economic activity. Such an improvement may make it possible to produce existing goods with fewer resources (process innovation). Or it may make it possible to produce new or better goods (product innovation). Both raise productivity—the former by lowering cost, the latter by raising the value of output. The first stage of technological progress is invention—the generation of new knowledge that has the *potential* to increase productivity. The second stage is innovation—the realization of that potential in the actual commercial application of the new knowledge.

We will focus in this chapter on innovation and in particular on process innovation. We will have more to say about invention and about product innovation in Chapter 5. Since technological progress in agriculture and in industry differed in important respects, we will examine each separately. We begin, though, with some general observations on technological progress in preindustrial Europe that apply to both.

THE ECONOMICS OF TECHNOLOGICAL PROGRESS

Technological progress in preindustrial Europe largely took the form of small improvements to existing techniques and products.[1] These were not the result of any deliberate act of invention but rather an inevitable by-product of the process of production itself. While each individual improvement was small, their cumulative effect over time was significant.[2] For example, we saw in Chapter 1 that a host of minor improvements had transformed the ancient water mill, by the sixteenth century, into a far more powerful and efficient machine. Expansion of the market accelerated the pace of improvement. It did so by increasing the overall volume of production, and, through specialization and the division of labor, by increasing even more the volume of

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[1]Mokyr (1990) calls such inventions microinventions.

[2] Persson (1988)

production of particular processes.[3] The greater the volume of production, and the greater the number of producers, the more room there was for experimentation, and so the larger the number of small improvements.

In addition to the steady accretion of small improvements, there were occasionally major inventions that opened new technological frontiers. Although relatively infrequent, these fed the more basic incremental process of steady improvement and kept it going.[4] Often, such major inventions were the result of an idea being taken from one place to another or from one product or process to another—rather like a virus jumping from species to species.[5] Expansion of the market facilitated this sort of beneficial 'infection'. For example, the spinning wheel and the horizontal loom both came to Europe from the Levant as part of the technology of cotton production. Europeans then adapted them for use in the woolen industry, with enormous ultimate impact both on productivity and on the nature of the product. The reorganization of production also contributed to the promotion of major inventions. The division of labor focused attention on simpler specialized sub-processes that lent themselves to mechanization, and when one sub-process outpaced another it created bottlenecks that invited radical solutions.

While small improvements were generally implemented immediately, major inventions often had to wait for decades or even centuries before they were taken up. New technology did not generally work very well, and it therefore required a lengthy process of adaptation and modification to make it work. But this process could only begin once the new technology was actually put to use.[6] So the adoption of new technology involved an indivisible and uncertain fixed cost in the form of income lost during the necessary period of experimentation. Often, adoption also required an investment in new fixed capital. The indivisible fixed costs of adoption created a barrier that could be

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[3] Palliser (1983) Ch. 6 makes this point.

[4] Mokyr (1990) calls these macroinventions and emphasizes their role in stimulating microinvention.

[5] This aspect of technological progress is emphasized by Jacobs (1969).

[6] Persson (1988)

overcome only by a sufficiently strong incentive.[7] Generally, it was expansion of the market, and the resulting change in relative prices, that provided the incentive by generating a high enough expected return for the adoption of the new technology.

Incentives, however important, were not enough. There also had to be a readiness to innovate and a capacity for doing so. These, as we shall see, depended largely on the organization of production. So expansion of the market came first, then reorganization, and then—and only then—innovation.

Once a particular innovation had proven commercially successful, it was taken up by other producers and spread to other places. This required a diffusion both of the necessary knowledge and of the conditions required for its exploitation.

The diffusion of knowledge was constrained by the form that practical knowledge took in preindustrial Europe. Practical knowledge was almost entirely empirical: it consisted of specific results rather than general principles. Much of it was tacit—known to practitioners only unconsciously and not readily put by them into words.[8] As a result, practical knowledge was embodied in those who possessed it. It could be conveyed only person to person by example. This was generally accomplished through apprenticeship.[9]

Consequently, the diffusion of knowledge required the migration of those who possessed it. There was a great deal of non-economic migration—driven by war, epidemic, and religious persecution. For example, the secrets of silk production were brought to Lucca in northern Italy from Sicily by refugees, many of them Jewish, after Sicily was conquered by the French Angevins in 1266. Silk technology spread to other northern Italian cities, especially to Florence, when Lucca in its turn was conquered and sacked by Pisans and Florentines in the early fourteenth century.[10] The wars and

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7 There is a parallel here with the large potential gains necessary to offset the large and indivisible fixed costs of restructuring (see Chapter 3).

8 Epstein (2004), Epstein (2005).

9 As we saw in Chapter 3, the conditions of apprenticeship were often regulated by craft guilds. Guilds also provided a framework for the sharing of knowledge among their members. Epstein (2004)

10 Laven (1966); Mazzaoui (1981) p 65 et seq.

persecutions of the sixteenth and seventeenth centuries were a particularly fruitful source of technology transfer, with England and Holland being the chief beneficiaries.

Apart from the periodic waves of refugees, there was a constant flow of economic migration.[11] Much of this was spontaneous, the result of individuals seeking greater rewards for their skills. For this reason, German miners, metallurgists, and metalworkers carried their skills all over Europe and to the Americas.[12] Local shortages of skilled labor helped the diffusion of practical knowledge by attracting foreign craftsmen. Some economic migration was actively promoted by governments seeking to establish or to strengthen their own industries. In the thirteenth and fourteenth centuries, for example, Italian cities offered immigrants with valued skills a variety of inducements, including citizenship, tax exemptions, and monopoly rights.[13]

The diffusion of knowledge, however, was not by itself sufficient for the effective transfer of technology. During the long sixteenth century, for example, the Ottomans repeatedly imported skilled craftsmen from Italy, but the impact on their economy was minimal.[14] What they lacked was the capacity to make use of the new knowledge. In this respect, diffusion was much like innovation: the same obstacles stood in its way and it required the same incentives to overcome those obstacles. Diffusion—like innovation—was driven by expansion of the market and by the reorganization of production. In the absence of strong market incentives and appropriate forms of organization, acquisition of the necessary knowledge meant nothing.

Conversely, with the right incentives and the right organization, a lack of local inventions was no barrier to technological progress. Places having the incentive to innovate and the capacity to do so could adopt inventions made elsewhere. For example, during the Commercial Revolution, the Italian textile industry adopted and improved a number of important inventions from the Muslim world, including the spinning wheel

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[11] Sella (1977)

[12] Which is how the new technique of extracting silver from silver haloids reached the New World. Blanchard, et al. (1992)

[13] Mazzaoui (1981) p 71

[14] Cipolla (1967) p 30-1

and the horizontal loom.[15] And Europe as a whole adopted and improved a number of major inventions that originated in China—the compass, gunpowder, paper, and printing.[16]

So technological progress did not require new inventions. Indeed, in preindustrial Europe, most technical progress, as we shall see, came from the diffusion of better technology to more and more producers.[17] This raised overall productivity even when the technology in question had been around for centuries.[18] And it made no difference, as far as productivity was concerned, whether the technology was native or imported.

It is only natural that historians of technology focus on invention, but invention is not necessarily the limiting factor in technological progress. In preindustrial Europe, adoption rather than invention was the constraint. And adoption depended on incentives and on capacity. These, in turn, depended on expansion of the market and on the reorganization of production.

TECHNOLOGICAL PROGRESS IN AGRICULTURE

The conventional history of technological progress in agriculture is a tale of two 'agricultural revolutions'—one in the Early Middle Ages, the second in the eighteenth century—with a millennium of technological stagnation in between. Recent research challenges this account. As we saw in Chapter 1, the 'new' technology of the early Middle Ages had in fact been available since at least Roman times.[19] The alleged breakthroughs of the eighteenth century similarly fade under closer examination.[20] George Grantham has argued that there was in fact no major breakthrough in agriculture

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[15]Mazzaoui (1981)

[16]In Chapter 12 we will look at technological progress in China and at how it differed from technological progress in Europe.

[17]Mokyr (1990)

[18]Griliches (1987).

[19]Grantham (1999) p 205, Grantham (2003).

[20]Kerridge (1967), Slicher van Bath (1977), Allen (2000), Karakacili (2004), Grantham (2007), Grantham (2007).

between the Iron Age and the nineteenth century (when artificial fertilizers and mechanical harvesters were introduced).[21]

The true story of preindustrial agriculture is one of gradual, if uneven, advance.[22] For over two thousand years the basic technology remained the same: farmers knew how to increase yields by working the land more intensively—by applying more labor and using more capital. Technological progress consisted primarily of a slow diffusion of intensive agriculture, accompanied by innumerable small improvements.[23] These improvements were a result of the need to adapt the basic techniques to changing circumstances—to differing local conditions, to new forms of organization, and to changing prices.

If the overall productivity of agriculture was low, therefore, it was not for lack of technology. It was because the best available technology—which was quite good—was applied only in the few areas where agriculture was commercialized. And productivity rose only slowly and unevenly, because the process of commercialization was itself slow and uneven.

We will look first at the how the techniques of intensive agriculture developed and then at the factors that explain their adoption and diffusion.

Intensive agriculture

Despite the lack of major innovations, the intensive agriculture of the seventeenth century was very different from that of the twelfth century and far more productive. Grain yields per hectare were somewhat higher, but this seriously understates the increase in productivity. Most of it came not from producing the same output with fewer resources, but from switching to the production of different and more valuable types of output—made possible by the adoption and improvement of intensive techniques.[24]

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[21]Grantham (2007), Grantham (2007).

[22]Allen (2000)

[23]Slicher van Bath (1977), Grantham (2007), Grantham (2007)

[24]Gross grain yields per hectare are a problematic measure of productivity, even on their own terms. Kerridge (1967) argues that net yields or harvest/seed ratios, which increased much more, are a better measure. Munro (2003) makes the point that the final product was flour rather than grain. Consequently,

Intensive agriculture applies capital, labor, and purchased inputs to artificially improve growing conditions. Cereals, the mainstay of European agriculture, depleted soil fertility, one of the most important of those conditions. Traditional, extensive, agriculture restored fertility by letting the land lie fallow between crops. Intensive agriculture reduced the need for unproductive periods of fallow by alternating cereals with crops that regenerate the soil, such as legumes, and also by applying fertilizers.[25] The non-cereal element in the rotation could be a food crop, a fodder crop, or an industrial crop. Fodder crops allowed animals to be fed in enclosures, which freed up pasture for cultivation; the manure from the enclosures was, of course, returned to the soil as fertilizer.

As intensive agriculture developed, the use of fertilizers increased. In the more advanced regions, this had by the end of the sixteenth century completely eliminated the need for fallow.[26] The use of fertilizers was facilitated by the development of a market for fertilizers. Trade in fertilizers was partly a consequence of specialization, with some farmers growing crops and others raising animals. But towns and industry also became important suppliers. Towns supplied stable manure, night-soil, and street refuse. Some towns in thirteenth-century Italy, for example, auctioned their horse manure.[27] Industry supplied waste products, such as distillers' mash, oilseed cakes, and soap ashes.[28] In sixteenth-century England, farmers added marl and chalk to the soil to neutralize it, increasing fertilizer effectiveness.

In addition to boosting soil fertility, intensive agriculture employed various methods to control weeds. Early methods included denser seeding and frequent plowing, harrowing, and hoeing.[29] Later methods, used by Dutch farmers growing high-value crops, included planting in beds and rows, cultivating by spade rather than by plow, and

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water-powered milling increased the effective net yield per hectare, because, in its absence, a substantial part of the gross yield would have gone to feed the animals that ground the grain.

[25] Slicher van Bath (1977), Grantham (1999)

[26] Van der Wee (1963), Toch (1997)

[27] [Jones, 1997 #1684]

[28] de Vries and van der Woude (1997) Ch. 6; Clay (1984)

[29] Grantham (1999)

carefully weeding by hand.[30] The implements used for cultivation steadily improved. Initially, agricultural implements were made mainly of wood, with only the cutting edges of iron.[31] However, as the price of iron fell, it saw more liberal use, and by the thirteenth century almost every village had its blacksmith.[32] This, in turn, led to significant improvements in the design and quality of the implements themselves.[33]

Intensive methods were also applied to the raising of livestock. Animals were originally kept mainly as a source of fertilizer for arable farming. However, as agriculture developed, in some areas animal husbandry became the primary activity.[34] Some farmers specialized in dairying; others, in fattening cattle driven in from outlying regions. Dairy farms and feed lots relied on the fodder crops produced by intensive cultivation (as did the large number of horses and mules employed in transportation in town and country). Intensive cultivation in turn made use of the manure produced by the dairy farms, feed lots, and stables. Thus, intensive methods of raising crops and of raising animals were complementary. As pasture became increasingly scarce in some areas, it too became the object of intensification. Farmers used various forms of irrigation to increase the yields of grass or hay.[35] In the late sixteenth century, farmers in the Netherlands began to apply fertilizers to pasture as well as to arable.[36] Selective breeding and the importation of better breeds brought improvements in livestock.[37] For example, the highly commercial cattle ranches of sixteenth-century eastern Europe developed specialized breeds of beef

[30]Toch (1997)

[31]Slicher van Bath (1977)

[32]Cipolla (1994)

[33]Jones (1997)

[34]de Vries (1974)

[35]On the Po valley, see Jones (1997); on England, see Kerridge (1967) Ch. 6. Kerridge argues that most of the English agricultural innovations of the sixteenth century were motivated by the increasing shortage of pasture.

[36]de Vries (1974)

[37]Palliser (1983) Ch. 6

cattle, larger and sturdier than the dairy cattle that had until then been the primary source of beef.[38]

Intensive techniques were indispensable for the cultivation of a wide range of horticultural and industrial crops. Such crops were highly profitable, but they were more demanding in terms of growing conditions. Early examples included flax and hemp for textile fibers; woad, saffron, and madder for dyes; and coleseed, turnips, and olives for oil.[39] Later, intensive agriculture permitted the commercial cultivation of more exotic crops that were either new to Europe or had previously been no more than garden curiosities. New crops brought from the Levant and Asia included rice, sugar, citrus, mulberry (silk), and cotton; those from the Americas included maize, potatoes, and tobacco.[40]

There were also advances in activities complementary to agriculture—particularly in food processing and transportation. There was steady improvement in the mechanical milling of grain and pressing of olives. Better butter churns and the invention of hard cheese opened up long-distance trade to dairy farmers by enabling them to ship their output in less bulky and less perishable forms.[41] Similarly, beer—and the grain it embodied—became an important item of inter-regional trade when urban breweries started using hops, a more effective preservative, and when improvements in shipping lowered the cost of transportation.[42]. In the sixteenth century, better transportation made possible a growing inter-regional trade in perishable produce—fresh vegetables, fruit, and flowers.[43] These improvements in processing and transportation effectively extended the market for agricultural produce to more distant regions. This promoted intensification there and made possible the production of more valuable forms of agricultural output.

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[38] Blanchard (1986)

[39] de Vries (1974), Jones (1997)

[40] Jones (1997), Epstein (2001)

[41] Epstein (2001)

[42] Unger (2004)

[43] de Vries (1974)

The adoption and diffusion of intensive techniques

As we have seen, the adoption and diffusion of new technology depended on incentives and capacity. The obstacles to the adoption of intensive techniques were substantial. Intensive agriculture raised productivity, but it required considerably more labor and purchased inputs. This increased the need for working capital.[44] Moreover, the transition to intensive agriculture usually required significant investment in improvements to the land, in structures, and in animals and equipment. The increases in working capital and in fixed capital had to be financed. In addition, there was the loss of income during the period of transition and the risk of failure. The expected gains from intensification had to be significant to make it worthwhile.

A major rise in agricultural prices could promise gains large enough to tip the balance. There was such a rise during the Commercial Revolution and again in the long sixteenth century. In both cases, the rise was fueled by a growing urban demand for food and raw materials.[45] The rise in agricultural prices increased the value of land, encouraging the adoption of techniques that raised its productivity.[46] Another change that could trigger intensification was a significant rise in the cost of labor—as occurred following the Black Death. In this case, the incentive was to raise the productivity of labor by employing more capital.[47]

The same considerations that determined *when* intensive techniques were worthwhile also determined *where* they were worthwhile. Regions where land and labor were expensive were the first to adopt intensive methods. As we shall see in Chapter 5, such regions were those closest to urban markets. In fact, intensive agriculture was long known as 'the Flemish husbandry' because so many of its techniques were developed in Flanders during the Commercial Revolution.[48]

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[44] Grantham (1999), Epstein (2001), Slicher van Bath (1977)

[45] "The key to the 'escape from Malthus' before the technological innovations of the 1840s was greater agricultural investment induced by high demand prices for farm produce." Grantham (2007)

[46] Slicher van Bath (1977), Miskimin (1977) Ch. 3

[47] Toch (1997)

[48] Thoen (1997)

The capacity to adopt intensive techniques was largely a function of organization. As we saw in Chapter 3, the subsistence-tribute agriculture of the early Middle Ages was reorganized over the centuries into an agriculture of family farms, served by markets for land, labor, finance, and inputs. Family farmers had the motivation to respond to changing incentives, and the market provided them with the resources they needed to do so. In particular, the market provided the additional financing needed for high-cost, intensive agriculture. So the adoption and diffusion of intensive techniques went hand in hand with reorganization.

TECHNOLOGICAL PROGRESS IN INDUSTRY

In industry, as in agriculture, technological progress was gradual. Here too we find that 'revolution' fades on closer examination. In particular, the Industrial Revolution of the eighteenth century proves to be less dramatic than once thought: many of the changes once attributed to that period have much earlier origins.[49] Moreover, industrial technology, like agricultural technology, was far from stagnant in the preindustrial period: we see both process innovation and product innovation. We begin with the former.

Mechanization

Process innovation in industry primarily meant the increasing use of machinery. The pace of mechanization, like that of intensification, was limited by the economics rather than by invention. That invention was not the constraint is clearly shown by the precocious mechanization of the Cistercian monasteries in the twelfth century. The Cistercians had an ideological commitment to self-sufficiency and therefore wished to avoid hiring outside workers. To reduce their need for labor, they developed large-scale industrial units, employing water-driven machinery. So mechanization was clearly feasible technologically as early as the twelfth century. But for most commercial producers at the time, it made no sense economically.

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[49] Persson (1988)

An early exception was the milling of grain.[50] Local demand, even in a single village, was large enough to justify investment in a watermill or windmill.[51] The Domesday Book lists over five thousand watermills in England in 1086, or roughly one for every fifty households. Windmills appeared in Europe in the late twelfth-century and were common by the end of the thirteenth.

As these examples show, scale was essential. Investment in machinery was indivisible, so it took a certain minimum level of output to justify it. The typical industrial establishment, a small family enterprise, was generally not large enough.

Expansion of the market increased output overall, but this did not necessarily imply an increase in the scale of production for the individual establishment. As we saw in Chapter 3, the organizational advantages of the family enterprise meant that an increase in output was usually accomplished by an increase in the number of producers rather than by an increase in the size of each. In some industries, for various reasons, individual establishments did increase in size. It was in these that mechanization became an option.

It is easy to misunderstand the nature of the relationship between scale and mechanization. A technological determinist might assume that scale was the consequence of technology—that production was organized on a larger scale to exploit the advantages of newly invented machinery. We shall see, however, that causality ran in the other direction. In some industries, for a variety of reasons unrelated to the use of machinery, production became concentrated in larger establishments. These large establishments found it worthwhile to employ machinery, and machinery was developed for their use.[52]

Large-scale production could result not only in mechanization but also in remarkably modern techniques of industrial engineering. The *Arsenale* in Venice was a huge state-owned enterprise covering some 60 acres and employing at its peak as many as 3,000

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[50] Mokyr (1990), Holt (1997)

[51] There was also a fiscal motivation. Lords generally required their peasants to use the official mill, because it facilitated taxation. Private hand- or animal-powered mills were prohibited and were destroyed if found.

[52] "Simply put, people are much likelier to develop technology suited only to factories after factories have come into being." Szostak (1991) p 9

workers.[53] Anticipating Henry Ford, it produced standardized interchangeable parts and assembled them on 'assembly lines'.[54] To coordinate such a huge and complex operation, it employed—much like a modern manufacturer—a layer of specialized managers. However, it is clear that the *Arsenale* did not grow large to be able to exploit these advanced industrial techniques. Commercial shipyards, even in Venice, were quite small, but the *Arsenale* was not a commercial enterprise. It was created by the Venetian state to produce galleys for its fleets. It grew large to meet the state's considerable military needs. The seemingly modern techniques emerged naturally as a consequence of its scale of production.

While mechanization required a sufficient scale of production, scale alone was not enough. Whether or not mechanization was worthwhile also depended on the relative cost of materials and labor. Mechanization saved labor, but it tended to be wasteful of materials.[55] So when materials were expensive relative to labor, mechanization made no sense.

Yet another consideration was quality. Mechanization, at least initially, often produced output inferior to that obtained from more labor-intensive traditional methods. For example, the spinning wheel produced woolen yarn of a quality inferior to that produced with distaff and spindle.[56]

The inferior quality associated with mechanization explains why guilds were often opposed to it—an opposition that has often been wrongly attributed to the guilds' 'innate conservatism'.[57] As we saw in Chapter 3, a primary function of the guilds was to monitor quality, protecting a town's 'brand name'. When mechanization compromised quality, the guilds naturally opposed it. However, when mechanization did not compromise

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[53] Steele (1994)

[54] Lane (1973) Ch. 25

[55] Masschaele (1997) Ch. 2

[56] Mazzaoui (1981) p 78

[57] An example of the classical view is Pirenne (1937): "Technological progress took on the appearance of disloyalty. The ideal was stable conditions in a stable industry." p 186. Among those who have questioned this interpretation are Stabel (1997) (for Flanders) and Epstein (1998).

quality, they had no objection. For example, in twelfth-century Italy, they prohibited the use of the spinning wheel for woolen yarn but not for cotton, because the spinning wheel actually improved the quality of cotton yarn.[58]

Considerations of cost and quality militated against mechanization in the production of luxury goods. The potential savings in labor held little appeal: because materials were expensive, labor made up only a small part of total cast. Moreover, demand for luxury goods was not very sensitive to price. It was, on the other hand, extremely sensitive to quality, so that any sacrifice in quality was unacceptable. For cheaper goods, the tradeoffs were very different. Quality was less important, and because materials were less expensive, labor cost weighed more heavily. Moreover, cost reduction mattered more, because demand was highly sensitive to price.

So extensive mechanization had to await the development of sufficiently large markets for cheap goods, served by producers operating on a large enough scale. As we saw in Chapter 2, large markets for cheap goods developed only during the long sixteenth century—in inter-regional trade in the northern zone and in the large internal markets of England and the Netherlands. Scale varied across industries. To understand the factors involved, we examine two of the most important industries—textiles and metals.

Textiles

It was the emergence of the new manufacturing in the eleventh century that gave rise to the first significant increase in the mechanization of textile production.[59] Until then, unspecialized producers of woolens in rural Flanders had relied on the cheap and simple vertical loom that had been in use since Roman times. As we saw in Chapter 3, market expansion brought reorganization, and production became increasingly concentrated in the towns. With the resulting division of labor, specialized urban weavers, operating on a greater scale than rural households, adopted the larger and more expensive horizontal

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[58] Mazzaoui (1981) Ch. 4

[59] Van der Wee (1993) Ch. 11; Nicholas (1992); Nicholas (1997)

pedal loom, which produced longer, heavier cloths.[60] Rural households continued to use the vertical loom to produce simple textiles for their own use and for the local market.

The organization and scale of spinning and weaving changed little until the eighteenth century, and consequently no further mechanization took place until then. When a trade in cheaper woolens developed, it employed essentially the same organization and technology.

A few textile manufacturers did operate on a larger scale. Silk workshops in particular reached a considerable size: some in sixteenth-century Venice employed as many as twenty-five looms.[61] One reason for their size was the need for quality control: close supervision required production to be concentrated in one place.[62] Silk manufacture also relied more on proprietary knowledge. With no protection of intellectual property rights, licensing was not possible: the only way to profit from knowledge was to sell products that embodied it. So those, like silk producers, who possessed valuable knowledge had an incentive to expand their scale of production to increase the return to their knowledge.[63] However, scale did not lead to greater mechanization in the case of silk, or of other large textile workshops, because they produced luxury cloths and mechanization would have compromised their quality.[64]

Mechanization did take place in one part of the textile industry—the fulling of woolen cloth. Fulling is the process of compressing the cloth to matt the fibers, making the cloth thicker and heavier. It was traditionally done by workers pounding the cloth with their feet. Water-driven mills were first employed for this purpose in tenth-century

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[60] The horizontal treadle-loom, which allowed the utilization of very long warps originated in China where it was used to produce silk. It was later modified in Iran and Syria for the production of wool and introduced in Europe in the eleventh century. Mazzaoui (1981)

[61] Braudel (1972).

[62] Kerridge (1985) argues that whether or not the domestic system was employed in the woolen industry of early modern England depended mainly on whether it "had to be done under the master's eye". Fine cloths needed close oversight, cheap cloths did not.

[63] Lane (1973) ch. 12, Kellenbenz (1977)

[64] In other knowledge-based industries, particularly various 'chemical' industries, such as glass, soap, dyes, and metallurgy, scale did lead to increasing mechanization because quality did not suffer as a result.

Italy, but mechanical fulling did not catch on. The reason was that mechanical fulling would have damaged the luxury woolens then being produced.[65] However, fulling mills became popular in the Low Countries in the thirteenth century when cheaper woolens were being manufactured there in large quantities. However, they disappeared in the fourteenth and early fifteenth centuries as Flemish producers went back to producing luxury textiles. They then reappeared in the Low Countries in the late fifteenth century, with the resumption of large-scale production of cheaper woolens.[66]

Spinning and weaving were to become fully mechanized only in the second half of the eighteenth century with the rise of the factory in England. While the eighteenth century is well beyond our period, the example is irresistible, because it illustrates so clearly that organization drives technology and not vice versa. Rick Szostak attributes the rise of the factory to the major improvements then taking place in inland transportation—particularly the extensive construction of turnpikes.[67] The new roads expanded the internal market. They also made it possible for manufacturers to sell by sample rather than by sending out the finished goods for inspection and sale. However, the domestic system, still the dominant form of organization, proved incapable of producing goods that reliably matched the samples. So manufacturers concentrated production in factories to permit supervision and ensure consistency. Factories initially employed the same technology as domestic producers, with scores of hand-looms standing side by side. However, the opportunity for mechanization was too obvious to miss, and rapid technological progress followed. Mechanization relied initially on water power—steam came later—and there was little in the new technology that could not have been invented centuries before. But in the absence of factories, why would anyone invent machines for which there was no possible use?

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[65] Munro (2000)

[66] Van Uytven (1971)

[67] Szostak (1991)

Metals

Mining and metallurgy operated initially on a very small scale.[68] Through the twelfth century, mine workings were close to the surface—typically quarries or shallow caves; and smelting was carried out in small hearths and forges located close by. The technology was simple, and the capital requirements were modest. Peasants often engaged in mining and smelting as part-time occupations. While the extraction of iron continued in this manner for centuries, the extraction of silver began to change.

In the thirteenth century, silver miners were having to dig deeper, and this required organization and capital. Shafts had to be dug and water removed to prevent flooding, using pumps driven by horses or water. Since the necessary investment exceeded the means of a single miner, groups of miners banded together in partnerships. The partnership owned and operated the mine, and, after paying royalties to landowner and prince, divided the residual earnings among its members.[69] Princes established large-scale facilities in the mining areas to process the ore, partly no doubt to enforce their right of preemption and to ensure they received their royalties.[70] These facilities often handled a volume of ore large enough to justify considerable mechanization, including water-powered bellows and water-driven hammers to crush the ore.[71]

During the long fourteenth century, war and economic downturn, together with the exhaustion of most known deposits, caused a decline in silver production. However, with the return of peace in mid-fifteenth century, the economy revived, silver prices rose, and silver production experienced a rapid recovery. As mines continued to get deeper and more expensive, miners needed more capital. To this end, they expanded the traditional mining partnership to include purely financial partners. These provided financing and received a share of the profits, but were not themselves involved in the work. Strong

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[68] Nef (1987), Hunt and Murray (1999) Ch 2

[69] Spufford (1988)

[70] Glamann (1977). They usually leased these facilities, often to the metal traders to whom they sold the output. The metal traders also provided the miners with working capital. Nef (1987)

[71] Hunt and Murray (1999) Ch 2. The

market incentives and the challenges of deeper mining gave rise to significant technological progress.

One of the most important advances was adoption of the *Saigerprozess*, a technique that used lead to extract silver from silver-bearing copper ore. This technique had, in fact, been known since the late fourteenth century, when it was developed by metal traders from Venice and Nürnberg. However, its profitability depended not only on the price of silver, but also on the price of copper, a joint product. A fall in the price of copper at the time led to the technique being shelved. However, in the middle of the fifteenth century, major new deposits of zinc were discovered that made possible the renewed production of brass, a zinc-copper alloy. The strong demand for brass, particularly for the manufacture of cannon, sent the price of copper soaring. With the price of silver rising too, the *Saigerprozess* became profitable, and it began to see widespread application.[72] Plants employing the (proprietary) technique were large—each employed scores of workers—and highly mechanized.[73]

The long sixteenth century also saw significant technological progress in the extraction of iron and the production of iron goods. The key advance here was the blast furnace. Like the *Saigerprozess*, it was not a new invention: a few blast furnaces had been built in Europe since at least the thirteenth century. However, the cast iron they produced was inferior in quality to the wrought iron produced by traditional, less-mechanized, methods.[74] Only with the development of a large market for cheap iron goods did the technology become economically attractive. The growth of internal markets in England and in the Low Countries created the necessary conditions and led to the construction of a large number of blast-furnaces in both places.[75] In contrast, no blast furnaces were built in the Hapsburg dominions or in France, both of which lacked

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[72] Blanchard, et al. (1992); Nef (1987)

[73] Nef (1987), Nef (1964)

[74] Nef (1987)

[75] Nef (1950) The Dutch were responsible for developing the iron industry in Sweden, where iron ore and fuel were plentiful.

significant markets for inexpensive goods; the focus there continued to be quality rather than cost.[76]

With the expansion of their production of iron, England and the Low Countries became leaders in iron technology. One example was the role of English gunmakers in pioneering the casting of iron cannon.[77] Iron cannon were much cheaper than brass cannon, but initially they were much inferior in quality: indeed, if fired repeatedly they tended to overheat and explode. This made them completely useless for warships, which continued to rely exclusively on brass cannon until the middle of the seventeenth century, when the problems of casting iron cannon were solved.[78] However, iron cannon found a large and ready market among the merchant fleets of England and the Netherlands. An armed merchantman needed only to get off a couple of rounds to make its escape or—if it was a privateer—to capture its prey. The lower cost meant that more ships could be armed and that each could carry more cannon.[79]

With the expanding production of inexpensive iron goods, fabrication too saw greater mechanization. Blast furnaces were often combined with forges where the cast iron 'pigs' produced by the furnace were hammered into bars. These forges, like the blast furnace, employed water-driven machinery, with hammers as heavy as 200 pounds. Water power was used too by slitting mills, by plants that flattened the metal and drew wire, and by the edged-tool industry—then developing in the vicinity of Birmingham—for grinding and sharpening.[80]

New types of fuel

The sixteenth century saw the beginning of a shift in industrial fuels from wood to peat and coal—another significant step towards the Industrial Revolution. The traditional explanation is that industry exhausted the supply of firewood and so was forced to seek

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[76]Nef (1964) Ch. 7

[77]Unger (1980) Ch. 6. The Dutch and Swedes soon followed.

[78]Glete (1999) Ch. 2

[79]"…battery guns had ceased to be the status symbol of the powerful, and became a workaday commodity within the pocket of any pirate or privateer." Rodger (1998) Ch. 16

[80]Nef (1964), Holt (1997)

alternatives. However, recent research on England reveals a story that is more complex and interesting.[81] Shortages of fuel were not general but local. And they affected not industry but the cities. When local supplies of firewood were exhausted industrial producers could relocate, but cities could not. The development of the coal industry in England was not driven by the needs of industry but rather by the demand for fuel for residential heating and cooking, especially in the rapidly growing metropolis of London. The development of the peat industry in Flanders and later in Holland was similarly driven by the needs of Antwerp and Amsterdam.[82]

The change in fuels had consequences for industrial concentration and scale and so for mechanization. Since the cost of transporting firewood was high relative to its value, heavy users of fuel—industries such as metallurgy, glass, paper, and pottery—had been scattered in rural areas where the supply of firewood was plentiful.[83] A host of small producers were to be found scattered throughout the woodlands of Europe, with none operating at a scale large enough to warrant much mechanization.

The development of the coal and peat industries, and of the transportation infrastructure that they required, converted London, Antwerp, and Amsterdam from being areas of expensive fuel to being areas of relatively cheap fuel. The availability of cheap fuel attracted energy-intensive industries. For example, by mid-sixteenth century Antwerp had become Europe’s major center for sugar refining. Because of the large local market and easy access to markets overseas, these new urban industries could be established on a scale large enough to justify considerable mechanization. Cheap fuel also attracted energy-intensive industries to the coal-producing areas themselves—industries such as salt, soap-boiling, brewing, and lime-burning. With abundant local fuel and good transportation links with urban markets, these establishments also operated on a larger scale. In the production of salt for example, the casual workings of local peasants

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[81] Hammersley (1973), quoted in Palliser (1983) Ch. 8.

[82] de Vries (1974)

[83] Nef (1964); Palliser (1983) Ch. 8

were replaced by large-scale producers using huge iron pans and each employing as many as three hundred men.[84]

CONCLUSION

Our examination of technological progress in preindustrial Europe sheds some light on the proper place of technological progress in a theory of economic growth.

As we saw in Chapter 1, the standard Ricardian theory regards technological progress as being the primary cause of growth. Indeed, since it assumes the economy to be always at its full technological potential, no other cause is possible. Moreover, if the economy is at its full potential, technological progress can only be the result of new technology—of invention. One consequence of this view is the search for 'revolutions': if growth is the result of new technology, then explaining growth means locating the critical breakthroughs. Although technological progress is at the center of the Ricardian theory, there is no economic explanation of why it occurs. Instead, it is explained in terms of non-economic causes such as a cultural predisposition for invention or chance discovery.

In Chapter 3, we saw that the fundamental Ricardian assumption is wrong: the economy of preindustrial Europe was far from being at its full potential. We saw too that productivity depended not only on technology but also on organization. Expansion of the market induced a productivity-enhancing reorganization of production. This raised productivity and brought the economy closer to its technological potential.

In this chapter, we have seen that technological progress too was a consequence of expansion of the market and of the resulting reorganization of production. Contrary to the Ricardian view, there were no revolutions. Also contrary to the Ricardian view, technological progress did not consist primarily of the invention of new technology but rather of the adoption and diffusion of technology that already existed. New technology did play a role, but its emergence is explained not by cultural predisposition or chance but, as we shall see in Chapter 5, by economic incentives created by the expansion of the market.

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[84] Nef (1964) Ch. 3

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