CHAPTER 4. TECHNOLOGICAL PROGRESS

Expansion of the market creates new opportunities for producers. Taking advantage of these opportunities requires a reorganization of production, and this reorganization is itself a major source of increased productivity. Market expansion and reorganization together also create new opportunities for the adoption of technology—for the application of practical knowledge to production.[1] The resulting technological progress—the improvement in the technology in use—further increases productivity.

We will examine the nature of technological progress in preindustrial Europe—first in agriculture and then in industry. From this evidence, we will identify some common patterns and draw some conclusions about the nature and causes of technological progress in general.

TECHNOLOGICAL PROGRESS IN AGRICULTURE

The conventional story of technological progress in agriculture is a tale of two 'agricultural revolutions'—the first in the Early Middle Ages and the second in the eighteenth century—with a millennium of technological stagnation in between. Recent research overturns this account.

The 'new' technology of the early Middle Ages had in fact been available since at least Roman times.[2] Similarly, the alleged breakthroughs of the eighteenth century fade under closer examination.[3] Indeed, George Grantham argues that there was no major breakthrough in the technology of agriculture between the Iron Age and the invention of artificial fertilizers and mechanical harvesters in the nineteenth century.[4]

For over two thousand years, therefore, the basic technology of agriculture remained the same. Farmers knew how to increase productivity by working the land more intensively—by applying more labor and by using more capital. So, if overall

---

[1](Smith 1976 [1776]) describes the connection between reorganization and technological progress.

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

[3](Kerridge 1967), (Slicher van Bath 1977), (Allen 2000), (Karakacili 2004), (Grantham 2007), ENREF_22" \o "Grantham, 2007 #4046" Grantham 2007), (Grantham 2007).

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

productivity remained low, it was not for lack of technology: it was because the best available technology—which was quite good—was not adopted more widely.

How widely the technology was adopted depended on the extent of commercialization: only in areas where agriculture was thoroughly commercialized did it make sense to apply intensive techniques. And, as we have seen, the spread of commercialization was slow and uneven. As a result, the diffusion of intensive techniques, and so technological progress, was also slow and uneven.[5]

Intensive agriculture

Technological progress in agriculture, therefore, was largely a matter of the gradual spread of intensive techniques, together with innumerable small improvements to these techniques.[6] The improvements were largely the consequence of trial and error, driven by the need to adapt techniques to different circumstances—to differing local conditions, to new forms of organization, and to changing prices. As a result of the accumulation of these numerous small improvements, the intensive agriculture of the seventeenth century was very different from that of the twelfth and far more productive.

How intensification raised productivity

Intensification raised productivity in agriculture enormously. It did not do so primarily by increasing grain yields.[7] Rather, its main contribution was making possible the cultivation of other, non-grain, crops that were more profitable.

In particular, a wide range of horticultural and industrial crops required intensive techniques for their cultivation. Such crops could be extremely profitable, but they were far more demanding than grain 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.[8]

---

[5](Allen 2000)

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

[7]Attempting to measure productivity gains by comparing grain yields over time, as many have done, is mistaken. Increasing productivity means producing greater value from given resources. The best way of doing this is not necessarily to produce more of the same output.

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

Intensive techniques were also necessary in later centuries for the cultivation of more exotic crops that were either new to Europe or had previously been no more than garden curiosities. New crops from the Levant and Asia included rice, sugar, citrus, mulberry (for silk), and cotton; those from the Americas included tobacco, maize, and potatoes.[9]

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

Developing the techniques of intensive agriculture

Intensive agriculture applies capital, labor, and purchased inputs to artificially improve growing conditions. The most important growing conditions is soil fertility. Cereals, the mainstay of European agriculture, depleted soil fertility; traditional, extensive agriculture restored fertility by letting the land lie fallow between crops. Intensive agriculture found alternative ways to restore fertility that reduced the need for unproductive periods of fallow—greatly increasing the productivity of the land in question.[10]

One way to do this was to alternate cereals with crops that regenerated the soil, such as legumes. The non-cereal crop in the rotation might be a food crop, a fodder crop, or an industrial crop. Fodder crops had the added advantage that they enabled animals to be fed in enclosures, which freed pasture for cultivation. The manure from the enclosures was, of course, returned to the soil as fertilizer.

The application of fertilizer was another important way of restoring fertility. As intensive agriculture developed, the use of fertilizers steadily increased. By the end of the sixteenth century, in the agriculturally more advanced regions, the use of fertilizers had completely eliminated the need for fallow.[11]

The use of fertilizers was greatly facilitated by the development of a market for fertilizers. The supply came partly from farms that specialized in raising animals. But cities and industries were also important suppliers. Cities supplied stable manure, night-soil, and street refuse: some cities in thirteenth-century Italy sold their horse manure at

---

[9](Jones 1997), (Epstein 1998)

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

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

auction.[12] Various forms of organic industrial waste were also used as fertilizers—for example, distillers' mash, oilseed cakes, and soap ashes.[13] In sixteenth-century England, farmers increased the effectiveness of fertilizers by adding marl and chalk to the soil to lower its acidity.

Another important condition for the growth of crops was the absence of competition from weeds. Intensive agriculture employed a variety of methods of weed control. Early on, these included denser seeding and frequent plowing, harrowing, and hoeing.[14] Later methods—used particularly by Dutch farmers cultivating high-value crops—included planting in beds and rows, which were cultivated by spade rather than plow, and then weeded carefully by hand.[15]

The implements used for cultivation improved steadily. They were initially made mainly of wood, with only the cutting edges made of iron. However, as the price of iron fell, it was used increasingly liberally.[16] Indeed, by the thirteenth century, almost every village had its own blacksmith.[17] The broader use of iron led, in turn, to significant improvements in the design and quality of the implements.[18]

Intensive methods were applied, too, to the raising of livestock. Subsistence agriculture had combined arable farming with the keeping of animals—primarily as a source of fertilizer. However, with commercialization, in some areas, animal husbandry became the primary activity.[19] In particular, some farms near cities came to specialize in dairying; others, in fattening beef cattle that had been driven in from outlying regions.

Dairy farms and feed lots kept their animals enclosed rather than putting them out to pasture. To feed them, they relied on fodder crops produced by intensive arable farming; this was also the main source of food for the large number of horses and mules employed

---

[12](Jones 1997)

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

[14](Grantham 1999)

[15](Toch 1997)

[16](Slicher van Bath 1977)

[17](Cipolla 1994)

[18](Jones 1997)

[19](de Vries 1974)

in transportation in city and country. As we have seen, intensive arable farming made use, in turn, of the manure produced by the dairy farms, feed lots, and stables. Thus, intensive methods of raising crops and of raising animals complemented one another.

The adoption and diffusion of intensive techniques

There were substantial obstacles to the adoption of intensive techniques. Intensive agriculture raised productivity, but it did so only by applying considerably more labor and purchased inputs: this increased the amount of working capital required.[20] Moreover, intensive agriculture required improvements to the land, new structures, and additional animals and equipment—increasing the necessary amount of fixed capital. These increases in working capital and fixed capital had to be financed. Financing was necessary, too, to help the farmer over the inevitable loss of income during the period of transition. And there was also, of course, the risk of failure.

Overcoming these obstacles was worthwhile only if the potential gains were substantial.[21] A major increase in agricultural prices could promise gains that were sufficiently large. Major price increases did occur during the Commercial Revolution and then again in the Long Sixteenth Century. In both cases, they were the result of rapidly growing urban demand for food and raw materials.[22] The rise in agricultural prices had the effect of raising the value of agricultural land, and this encouraged the adoption of intensive techniques to economize on its use and to boost its productivity.[23]

Of course, incentives to adopt intensive techniques were not enough: there also had to be the capacity to respond to those incentives. Capacity 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

---

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

[21]As was the case for the restructuring of land holdings, as we saw in Chapter 3.

[22] "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)

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

needed to do so. In particular, the market provided them with the additional financing they needed to transition to high-cost, intensive agriculture. So the adoption and diffusion of intensive techniques went hand in hand with reorganization.

The same considerations that applied to *when* the adoption of intensive techniques was worthwhile also applied to *where* it was worthwhile. Regions where land and labor were expensive were the first to adopt intensive methods. As we will see in Chapter 5, such regions were generally those that were closest to urban markets. In fact, intensive agriculture was long known as 'the Flemish husbandry' because so many of its techniques were developed in the comparatively highly urbanized region of Flanders during the Commercial Revolution.[24]

The meaning of 'close to urban markets' changed, however, with improvements in transportation. For example, these made possible a growing inter-regional trade in perishable produce—fresh vegetables, fruits, and flowers.[25] Improvements in the processing of agricultural products had a similar effect in that they made produce easier to ship. For example, improvements in 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.[26] Sometimes both effects worked together: beer—a form of processed grain—became an important item of inter-regional trade when urban breweries started using hops, a more effective preservative, and when improvements in shipping in the sixteenth century lowered the cost of transportation.[27] All of these examples involved intensive cultivation or intensive husbandry.

Other sources of technological progress in agriculture

However, not all technological progress in agriculture involved intensification. For example, improvements in processing also increased productivity directly. Since the final product of grain production was flour rather than grain, improvements in water-powered milling raised the effective net yield of output per hectare. Without the use of water

---

[24](Thoen 1997)

[25](de Vries 1974)

[26](Epstein 1998)

[27](Unger 2004)

power, a substantial part of the gross yield would have gone to feed the animals that ground the grain.[28]

Many examples of technological progress were motivated by rising input prices. In sixteenth-century England, for instance, the rising cost of pasture pushed farmers to raise more livestock on a given acreage. To this end, they adopted marling and chalking to neutralize the soil and increase the effectiveness of fertilizers; they also adopted rotations that would provide more fodder; and they flooded their meadows to improve pasture quality.[29]

Similarly, after the Black Death, the rising cost of labor encouraged the adoption of labor saving technology.[30] Threshing barns reduced the peak-load demand for labor by reducing the urgency of threshing in uncertain weather. Teams of specialized harvesters, skilled in the use of scythes, traveled from farm to farm replacing much larger numbers of part-time workers (mainly women) who had harvested with the easier-to-use sickle.

In general, rising labor costs promoted the use of more fixed capital—not only because of the rising cost of hired labor, but also because of the rising opportunity cost of the farmer himself. As we saw in Chapter 3, one way to raise the farmer's income is to increase the size of his farm: another way is to increase the amount of fixed capital he employs.[31]

Yet another type of technological progress was stimulated by the division of labor and specialization. Traditionally, beef production had been a subsidiary activity of dairy farmers. But in the sixteenth century it split off from dairying, with the establishment of commercial cattle ranches, particularly in eastern Europe.[32] These ranches developed, through selective breeding and the importation of better breeds, specialized types of beef

---

[28](Munro 2003). There were similar advances in water-powered pressing of olives for oil, with similar gains in net productivity.

[29][Clay, 1984 #1953]

[30][Toch, 1997 #2012]

[31][Kislev, 1982 #2367]

[32](Palliser 1983) Ch. 6

cattle that were larger and more sturdy than the dairy cattle that had until then been the primary source of beef.[33]

TECHNOLOGICAL PROGRESS IN INDUSTRY

In preindustrial Europe, the technology of industry like that of agriculture, was far from stagnant. And again, technological progress was largely incremental: innumerable small improvements to existing techniques and products gradually lowered costs and improved quality.[34]

The watermill, for example, was already widely used in Roman times. However, the technology improved steadily over the centuries. Medieval and early modern improvements included the overshot wheel, improved gearing, the use of cams and cranks, and better dams to control water flow. The watermill of the sixteenth century was, as a result, a far more powerful and efficient machine than that of classical antiquity.[35]

The principal form of technological progress in industry was, as this example illustrates, mechanization. We will begin by examining the economics of mechanization, and then apply it to understanding mechanization in the textile industry and in mining and metallurgy.

We will then look at some other examples of technological progress in industry. New types of fuel came into use, lowering the cost of energy. Metallurgists developed new techniques for extracting metals from ore. And the shipbuilding and armaments industries developed new products that ultimately enabled Europeans to dominate world trade and to conquer large parts of the world.

The economics of mechanization

Like intensification, mechanization, was not new to our period.[36] That the technology was indeed available is demonstrated by the widespread early mechanization of the

---

[33](Blanchard 1986)

[34](Persson 1988).

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

[36]There is evidence of water mills from the first century BCE and their use was widespread in the former Roman Empire by the fifth and sixth centuries.(Munro 2003)

milling of grain.[37] The Domesday Book lists over three thousand watermills in England in 1086, and there were over ten thousand by 1300.[38] Windmills first appeared in Europe in the late twelfth-century and were common by the end of the thirteenth.

Again like intensification, mechanization was not initially put to much use, because it was not profitable to do so.

Mechanization and scale

Mechanization was often not profitable, because it required a substantial and largely indivisible investment. Mechanization made sense only when the scale of production was sufficient to cover the associated costs. The mechanization of milling made sense, because the demand for milling, even in a single village, was large enough to justify the expense of a watermill or windmill.[39]

Most industrial production in preindustrial Europe, however, was at the relatively modest scale of the single family enterprise. While market expansion did increase overall production, this did not usually lead to an increase in the scale of individual establishments. As we saw in Chapter 3, there were significant organizational advantages to the family enterprise. Consequently, an increase in production tended to mean an increase in the number of enterprises rather than an increase in the size of each. In some industries, however, for reasons unrelated to the use of machinery, production did come to be concentrated in larger establishments. And it was in these industries that mechanization became attractive.[40]

The conventional theory tends to misinterpret this association between scale and mechanization. Seeing technological progress as the exogenous cause of growth, it

---

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

[38](Munro 2003)

[39]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.

[40]An interesting example of precocious mechanization is provided by the Cistercian monasteries of the twelfth century, which established large-scale industrial units using water-driven machinery. They did so, however, not for economic reasons but because their ideology of self-sufficiency precluded them from hiring outside labor.

assumes that production was organized on a larger scale to exploit the advantages of newly invented machinery. We will see, however, from numerous examples, that the causality generally ran in the opposite direction. Only when large establishments came into being—for other reasons—was machinery developed for their use.[41]

Other considerations

While large-scale production is necessary for mechanization, it is not sufficient. The profitability of mechanization depends as well on several other considerations.

One is relative costs. Machinery economizes on labor. However, if machinery is expensive to purchase and finance while labor is cheap, mechanization will remain unattractive. And a favorable relative cost is not sufficient by itself either—as the conventional theory would suggest. As we have seen, the scale of production has to be sufficiently large—both the extent of the market and the scale of the individual enterprise.[42] Both conditions need to be satisfied before mechanization became economical.

And that is not all. While mechanization saved labor—of man and beast—it tended to be wasteful of materials.[43] So when materials were expensive relative to labor, mechanization was uneconomical, even if the other conditions were satisfied.

Yet another consideration was quality. Mechanization, at least initially, tended to produce output of a quality inferior to that obtained by traditional, more labor-intensive methods.[44] As just one example, the spinning wheel produced woolen yarn that was decidedly inferior to that produced with distaff and spindle.[45]

The inferior quality associated with mechanization explains why guilds so often opposed it—an opposition that has often been wrongly attributed to 'innate

---

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

[42](Kaldor 1985)

[43](Masschaele 1997) Ch. 2; (Grantham 1999)

[44](Grantham 1999)

[45](Mazzaoui 1981) p 78

conservatism'.[46] As we saw in Chapter 3, a primary function of the guilds was to monitor quality—in this way protecting a city's brand name. When mechanization compromised quality, the guilds naturally opposed it. However, when mechanization did not compromise quality, they had no objection. For example, in twelfth-century Italy, guilds prohibited the use of the spinning wheel for woolen yarn but not for cotton, because for cotton yarn the spinning wheel actually improved quality.[47]

Mass-market goods and mechanization

Mechanization therefore made no sense for the production of luxury goods. Because materials were expensive, labor accounted for a only relatively small part of total cost. And anyhow, since demand was not very sensitive to price, cutting costs was not particularly important. However, demand was very sensitive to differences in quality. So any sacrifice of quality was unacceptable.

For mass-market 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 widespread mechanization had to await the development of a sufficiently large market for inexpensive goods, served by producers operating on a large enough scale. As we saw in Chapter 2, such markets developed only during the Long Sixteenth Century. Even then, however, scale varied significantly across industries.

Mechanization in textiles

The story of the textile industry illustrates the economic tradeoffs quite well.

Mechanization in the early woolen industry

The first significant mechanization in textiles came as a result of the emergence of the new manufacturing in the eleventh century.[48] Until then, unspecialized rural producers of woolens had relied on the cheap and simple vertical loom, in use since Roman times.

---

[46]An example of the classical view is (Pirenne 1937); it has been revived recently by (Ogilvie 2008). Among those who have questioned this interpretation are (Stabel 1997) (for Flanders), (Mola 2000) and (Epstein 1998; Epstein and Prak 2008).

[47](Mazzaoui 1981) Ch. 4

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

However, as we saw in Chapter 3, market expansion brought reorganization, which increasingly concentrated production in the towns.

Specialized urban weavers operated on a larger scale, and they found increasing mechanization worthwhile. In particular, they adopted the larger and more expensive horizontal pedal loom, which could produce longer and heavier cloths.[49] By the thirteenth century, this had evolved into the heavy horizontal broadloom, which required two or even three, usually male, operators.[50] Rural women continued to use the vertical loom to produce simple textiles for household use and for the local market.

After this, the organization and scale of spinning and weaving changed relatively little until the eighteenth century, and there was therefore no further mechanization. In particular, there was no use of water power. When a trade in cheaper woolens developed, it employed essentially the same organization and the same human-powered technology.

Silk and other luxury textiles

Some textile manufacturers, however, did operate on a larger scale. In particular, silk workshops became quite large: some in sixteenth-century Venice employed as many as twenty-five looms.[51] And royal workshops in France and elsewhere, producing silk and other luxury fabrics, were also quite large.

One reason for the size of such workshops was the need for quality control: close supervision required production to be concentrated in one place.[52] Silk manufacture also relied more on proprietary knowledge. With no protection of intellectual property, licensing was impossible; so the only way to profit from knowledge was to sell products that embodied it. Consequently, those—like silk producers—who possessed valuable

---

[49](Mazzaoui 1981)

[50](Nicholas 1992; Nicholas 1997). The broadloom not only increased productivity, but also improved quality (Munro 2003).

[51](Braudel 1972).

[52](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.

knowledge had an incentive to expand their scale of production to increase the returns to their knowledge.[53]

Scale did not, however, lead to greater mechanization in the case of silk workshops, or in the case of other large textile workshops, because they produced luxury fabrics and mechanization would have compromised quality.[54]

Mechanical fulling

Mechanization became quite common, however, in another part of the textile industry—the fulling of woolen cloth. Fulling is the process of compressing cloth to matt the fibers, making it 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 Italy. But mechanical fulling did not catch on, because it damaged the sort of luxury woolens then being produced.[55] Fulling mills did, however, become popular in the Low Countries in the thirteenth century when cheaper woolens were made there in large quantities.

In the fourteenth and early fifteenth centuries, however, Flemish producers were forced by rising trading costs to go back to producing luxury textiles. As a result, fulling mills disappeared. Then, in the late fifteenth century, when the large-scale production of cheaper woolens resumed, they reappeared all over the Low Countries.[56]

Mechanization in the Industrial Revolution

Spinning and weaving were to become fully mechanized only in the second half of the eighteenth century with the rise of factory production 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 the reverse.

Rick Szostak attributes the rise of the factory in England to the major improvements then taking place in inland transportation—particularly the extensive construction of

---

[53](Lane 1973) Ch. 12, (Kellenbenz 1977)

[54]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.

[55](Munro 2000)

[56](Van Uytven 1971)

turnpikes.[57] The new roads expanded the market. They also made it possible for manufacturers to sell by sample rather than, as had long been the practice, by sending out finished goods for inspection and sale. However, because the dominant form of organization was still the domestic system, it proved impossible to turn out goods of consistent quality that would reliably match the samples.

To solve this problem, manufacturers began to concentrate production in factories, so that they could supervise their workers and ensure consistency. To begin with, these factories employed the same technology as domestic producers, with scores of hand-looms standing side by side. However, the potential for mechanization was too obvious to ignore, and the result was rapid technological progress.

Mechanization relied initially on water power—steam came only later—and there was little in the new technology that was not available centuries earlier. But in the absence of factories, why would anyone want to invent machines for which there was no possible use?

Mechanization in mining and metallurgy

Mining and metallurgy provide additional examples that illustrate the principles underlying mechanization.

Increasing scale in silver mining and metallurgy

Initially, mining and metallurgy operated on a very small scale.[58] 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 near by. The technology was simple and the capital requirements 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.

By the thirteenth century, silver miners were having to dig deeper. As a result, they were forced to dig shafts to remove water and prevent flooding. The water was removed using pumps powered by horses or by water.

---

[57](Szostak 1991)

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

The princes who granted mining rights established large-scale facilities in the mining areas to process the ore. Their motive, no doubt, was to enforce their right of preemption and to ensure they received their royalties.[59] However, these facilities often handled a large enough volume of ore to justify considerable mechanization, including water-powered bellows and water-driven trip-hammers to crush the ore.[60]

A mass market for iron goods and the mechanization of the iron industry

The long sixteenth century saw significant progress in the extraction of iron and in the production of iron goods. The key advance here was the blast furnace. Once again, this was not a new invention: blast furnaces had been built in Europe occasionally since at least the thirteenth century.

However, the cast iron that blast furnaces produced was inferior in quality to the wrought iron produced by traditional, less-mechanized, methods.[61] So it was only with the development of a mass market for cheap iron goods that blast furnaces became economical.

Many blast furnaces were built in England and in the Low Countries because the development of mass markets there created the necessary conditions.[62] In contrast, none were built in the Hapsburg dominions or in France, neither of which developed significant markets for inexpensive iron goods: what mattered there continued to be quality rather than cost.[63]

With the expansion of the market for inexpensive iron goods, and consequently of iron production, iron fabrication too saw greater mechanization. Blast furnaces were often combined with forges where the cast iron ‘pigs’ produced by the furnaces were hammered into bars. Like the blast furnaces, these forges employed water-driven machinery, driving hammers that weighed as much as 200 pounds each.

---

[59](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)

[60](Hunt and Murray 1999) Ch. 2; (Munro 2003).

[61](Nef 1987)

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

[63](Nef 1964) Ch. 7

Water power was used as well in slitting mills and in plants that flattened the metal and drew wire. It was also used for grinding and sharpening by the edged-tool industry—then starting to develop around Birmingham.[64]

An energy crisis and new types of fuel

The sixteenth century also saw the beginning of a shift in industrial fuels from wood to peat and coal. The traditional explanation is that industry exhausted the supply of firewood and therefore had to seek alternatives. However, recent research on England reveals a story that is considerably more complex and interesting.[65]

Shortages of fuel were in fact not general but local. And they affected not industry but the cities. When industrial producers in the country exhausted local supplies of firewood, they could move to where wood was more abundant: cities could not do this. The development of the coal industry in England, therefore, was driven not by the needs of industry but by the need for fuel for residential heating and cooking in the cities—especially in rapidly-growing London. Similarly, the development of the peat industry in Flanders and later in Holland was driven by the fuel needs of Antwerp and Amsterdam respectively.[66]

The change in the fuel supply of the cities, however, did have consequences for industrial location, scale, and mechanization. The cost of transporting firewood was high relative to its value. So industries that were heavy users of fuel—such as metallurgy, glass, paper, and pottery—had located initially in rural areas where the supply of firewood was plentiful.[67] In all of these industries, a multitude of producers—mainly small—had been scattered throughout the woodlands of Europe.

This changed with the development of the coal and peat industries, and of the transportation infrastructure that they required. London, Antwerp, and Amsterdam were no longer places where fuel was costly; they became places where fuel was relatively

---

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

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

[66](de Vries 1974)

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

cheap. Cheap fuel attracted energy-intensive industries. By the mid-sixteenth century, for example, Antwerp had become Europe's major center for sugar refining.

Moreover, these new urban industries had a large local market and easy access to markets overseas. This meant that individual establishments could be set up on a large enough scale to justify considerable mechanization.[68]

Cheap fuel also attracted energy-intensive industries to the coal-producing areas themselves—industries such as salt production, soap-boiling, brewing, and lime-burning. With abundant local fuel and good transportation to urban markets, these establishments too operated on a larger scale. For example, in the production of salt, the casual workings of local peasants were replaced by large-scale enterprises, each employing several hundred men, and heating huge iron pans to produce salt.[69]

A new technique for extracting silver

The production of silver declined during the long fourteenth century—partly because of the general crisis and partly because of the exhaustion of most known deposits. However, when peace returned in the mid-fifteenth century, the economy revived, silver prices rose, and silver production recovered rapidly.

This recovery was facilitated by technological progress. A new process for extracting silver, the *Saigerprozess*, opened up for exploitation vast new deposits that had previously been uneconomical. The *Saigerprozess* had, in fact, been known since the late fourteenth century, when it had been developed by metal traders in Venice and Nürnberg. The new technique used lead to extract silver from silver-bearing copper ore. Its profitability depended, therefore, not only on the price of silver, but also on the price of copper, which it produced as a side-product. A fall in the price of copper at the time the technique was invented had led to its being shelved.

However, in the middle of the fifteenth century, major new deposits of zinc were discovered in Europe, and these 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.

68(Munro 2007)

69(Nef 1964) Ch. 3

With the price of silver rising too, the *Saigerprozess* now became profitable, and it began to see widespread adoption.[70] Plants employing the proprietary technique were large—each employing scores of workers—and also highly mechanized.[71]

So, here again we see that the pace of technological progress was not constrained by the creation of new knowledge. Rather it was constrained by the creation of economic circumstances in which the application of the new knowledge was profitable.

Technological progress in ship design

Preindustrial Europe saw enormous technological progress in ship design. In the eleventh century, European ships were small and of limited seaworthiness and sailability; voyages were mostly short, and routes generally hugged the coast. By 1600, European ships were regularly crossing the oceans to the Americas and the Indies, and the vessels that made those voyages bore little resemblance to the flimsy craft of the eleventh century.

An accumulation of small improvements

This transformation was not the result of any great breakthrough or revolutionary invention. The basic elements of ship design changed little, so that a shipbuilder from the eleventh century transported miraculously to the sixteenth would have seen little he did not recognize. However, the same basic elements were combined and recombined in new and creative ways that completely changed the characteristics of the ships that were built.

Here too, technological progress was a consequence of market expansion and of the resulting reorganization. The expansion in trade increased the demand for new ships, and as the pace of construction accelerated, so did experimentation and the pace of technological progress. Shipbuilders vied for orders in a highly competitive market by offering better products.

The organization of shipping and the size of ships

What was better was largely determined by the economics of shipping. The cost of carrying cargo by ship was mainly the cost of paying and feeding the crew.[72] Since the

---

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

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

size of the necessary crew increased less than proportionally with the size of the ship, larger ships were generally more cost-effective. However, labor was mostly a fixed cost, since the crew had to be paid whether the ship sailed full or half-empty and whether the ship was at sea on its way to its destination or stuck in port waiting for cargo. Because larger ships were harder to fill, small ships had the advantage until better organization made it easier to match ships and cargo.

Several different models of organization emerged in this period that addressed this problem. During the Commercial Revolution, the Venetians developed a system of government-sponsored galley fleets that departed on a regular schedule for a number of major destinations.[73] Knowing the date of departure in advance made planning easier and concentrated the volume of cargo. This helped ensure that the galleys sailed fully loaded.

The Genoese developed a different system, based on the idea of ‘hub and spoke’. The system relied on a number of strategically located trans-shipment centers.[74] Small ships gathered cargo and brought it to one of these ‘hubs’: small ships could enter the many small harbors more easily and sail up rivers in search of cargo; they were also easier to fill. At the hub, cargo was transferred to larger, more efficient ships for transportation over long distances to one of the other hubs. There, the cargo was transferred again to smaller ships for distribution.

Large ships suffered from another disadvantage—apart from the difficulty of filling them. Widespread piracy and the hazards of nature made the shipping of cargo a highly risky proposition.[75] Given the significant chance of losing a ship, merchants generally preferred to diversify by dividing their cargoes among a number of smaller ships.

This second disadvantage was overcome when improvements in organization facilitated the bearing of risk. Specifically, there developed a market for marine insurance that enabled a merchant to pay others to bear part of the risk of shipping a valuable

---

[72](Lane 1986). There was also a substantial labor cost of loading and unloading the ship.

[73](Lane 1973) Ch. 10; (Mazzaoui 1981). The scheduled loading periods also facilitated convoying, if this was considered necessary.

[74](Laven 1966) Ch. 3.

[75]The rate of loss before 1600 is largely unknown, but it was certainly high: even in the seventeenth and eighteenth centuries loss rates of 10-30% a year were not unusual. (Scammell 1972)

cargo.[76] The availability of insurance reduced the need for diversification, and this made larger ships more attractive.[77] The availability of insurance also made it possible for ships to take faster—but riskier—open-water routes to their destinations. In both of these ways, the availability of insurance brought about a reduction in the cost of shipping.

The importance of the bulk trade

Almost all the advances in ship design originated in the trade in bulk commodities.[78] For trade in high-value items, the cost of shipping was not that important. But it could make all the difference for trade in goods that were less valuable relative to their weight or bulk. Some illustrative numbers: the cost of carrying grain from Sicily to northern Italy around 1300 was about 40% of the original value of the cargo; the cost of carrying grain from the Baltic to the Low Countries in the fifteenth century was about 100%; the cost of carrying salt from Portugal to Bruges around the same time was about 600% of the cost of the salt at its point of origin.[79] Merchants trading in bulk commodities were therefore much more aware of shipping costs and much more eager to lower them to increase their margins and to expand their markets.[80]

The cog—the first major innovation in ship design in preindustrial Europe—was developed for the trade in bulk commodities. It evolved during the thirteenth and fourteenth centuries to meet the needs of northern merchants trading in wine, beer, and grain. It probably originated in the Anglo-Gascon wine trade, in which merchants needed ships big enough to enable large wine barrels to be rolled on, stored efficiently, and rolled off.

The cog lowered shipping costs significantly compared to earlier designs. Its use made it profitable to export beer from the Baltic to the Low Countries (beer, too, was shipped in barrels) and eventually to export grain. The introduction of the cog to the Mediterranean in the fourteenth century lowered the cost of shipping bulk goods there by

---

[76]For more on marine insurance, see Chapter 9.

[77](Unger 1998 [1979]) #2031}

[78]The following is mainly based on (Unger 1980).

[79](Unger 1980)

[80](Mazzaoui 1981), p 28; (Menard 1991) p 232

as much as 50%.[81] The fall in shipping rates stimulated Mediterranean trade in commodities such as alum, grain, salt, wine, and cotton.[82]

The full-rigged ship—the second major innovation in ship design—is known for its role in making possible the great voyages of discovery and the subsequent opening up of maritime trade with Asia and the Americas. It was not, however, created for that purpose. Rather, like the cog, it evolved to meet the needs of merchants trading in humble bulk commodities—specifically, those of Basque and Breton traders carrying iron and salt across the Bay of Biscay. Local shipbuilders developed the full-rigged ship to face the challenge of sailing condition in the Bay—among the worst in the world. Sailing the oceans turned out to be a breeze compared to navigating the Bay of Biscay,.[83]

An experiment in large-scale shipbuilding

On the whole, the techniques of building ships changed much less than the ships that were being built. However, there was one notable exception—the *Arsenale* of Venice—which employed remarkably modern methods of production.

The *Arsenale* was a huge state-owned shipyard covering some 60 acres and employing at its peak as many as 3,000 workers.[84] Anticipating Henry Ford, it manufactured standardized interchangeable parts and combined them on 'assembly lines'.[85] To coordinate such a huge and complex operation, the *Arsenale* employed a layer of specialized managers—much like a modern manufacturing plant.

Clearly, there is a connection between the scale of the *Arsenale* and the manufacturing methods it employed. However, the *Arsenale* did not grow large so that it could employ those methods. Rather—as with the connection between scale and mechanization—it came to employ those methods because it grew large for other reasons.

---

[81](Lane 1986)

[82]Imports of cotton to northern Italy, for example, increased threefold during the fifteenth century as shipping rates fell by 25%, despite rising wages. (Mazzaoui 1981) p 48-53

[83](Lane 1986); (Unger 1980).

[84](Steele 1994)

[85](Lane 1973) Ch. 25

The *Arsenale* was created by the Venetian government to produce galleys for its navy. It had to be large to produce the number of galleys the navy required. The seemingly modern methods of 'industrial engineering' that it employed emerged naturally as a consequence of its unusually large scale of production. Such methods were never employed by private shipyards, even in Venice, because private shipyards remained quite small.

Technological progress in armaments

Pre-industrial Europe saw unusually rapid technological progress in armaments.[86] Here too, technological progress was the result of expansion of the market and of reorganization. Expansion of the market was driven by increasing demand—the result of long periods of widespread warfare. Reorganization was driven, as in agriculture, by commercialization.

The commercialization of war

The wars of the Long Fourteenth Century soon revealed the inadequacies of the feudal military, and rulers came increasingly to rely on mercenaries. For different reasons, so did cities.[87] As a result, by the middle of the fourteenth century, mercenaries had become the core element of most armies.[88] Military entrepreneurs were putting together complete companies of mercenaries and contracting them out long term.[89] Navies too were commercialized, with contractors offering ships for hire or even complete war fleets.[90]

The commercialization of war accelerated technological progress in armaments. Military entrepreneurs had to compete for contracts, and they were eager to acquire the

---

[86](Hoffman 2011) finds, in the production of firearms, sustained rates of productivity growth of 0.6-1.4% per year from the fourteenth century onwards. This is far higher than general productivity growth in the period and comparable to modern rates of productivity growth.

[87]More on this in Chapter 10.

[88](Howard 1976) Ch. 1; (Nicholas 1997) Ch. 5; (Hall 1997).

[89](Redlich 1964) Ch. 1; (Ertman 1997) Ch. 2.

[90](Scammell 1981) Ch. 4. Genoese naval *condottieri* provided war fleets to rulers from France to Persia.

latest and best weapons. This created a lucrative and highly competitive market for arms.[91]

Before the Commercial Revolution, the manufacture of arms had largely been in the hands of hundreds of government-operated armories across Europe. Facing no competition, they turned out weapons that were neither innovative nor of particularly high quality.

But competition among commercial arms manufacturers changed the picture radically. A number of cities in Northern Italy, Southern Germany, and the Low Countries came to specialize in the large-scale manufacture of armaments with the resulting improvements in productivity and product quality one would expect.[92]

The gunpowder revolution

Technological progress in armaments, as elsewhere, largely took the form of the accumulation of small improvements. For example, cumulative improvement in arrow-making produced arrows that were able to penetrate chain mail; this made archers a serious threat to armored cavalry—as was demonstrated quite dramatically by English longbowmen at Agincourt in 1415.[93]

There was, nonetheless, one major 'revolution'—the emergence of gunpowder weapons. In the twelfth and thirteenth centuries, European foundries developed the technology of casting in bronze—primarily for the production of church bells. In the late thirteenth century, gunpowder arrived in Europe from China. Previously. In the early fourteenth century, the two technologies were brought together in Northern Italy to produce the first cannon.[94] The French were early adopters—using the new weapon to break up formations of English longbowmen.[95]

The first cannon were small and their effect mostly psychological. However, the usual process of gradual improvement led to the development of effective siege artillery by the

---

[91](McNeill 1982) p 79

[92](Hall 1997)

[93](Nef 1950) Ch., 2

[94](Nef 1950) Ch. 2

[95](Howard 1976) Ch. 1

fifteenth century.[96] The new larger cannon were able to destroy stone walls, giving the advantage to the offense for the first time in centuries.

The next innovation in armaments was small-arms. The demand of urban militias for missile weapons, which had long been satisfied by the cross-bow, created an obvious market for a smaller, more portable firearm that could be used by a single individual.[97] The first such weapon, the 'hook gun' was a mini-cannon that could be used in defending city walls. By the early sixteenth century, this had evolved into the musket. By then, gunmakers had also begun to produce various types of pistol.

The new gunpowder weapons changed the shape of armies. Instead of being built around armored cavalry, they were now built around a core of professional infantry, armed with pikes and muskets.[98] The infantry was supported by mobile, horse-drawn artillery and by light cavalry armed with sabers and pistols.[99]

The cannon revolutionized war at sea even more than it did war on land.[100] The first sea battles to be decided by gunfire rather than by boarding took place in the early sixteenth century in the Indian Ocean.[101]

The organization of war

The organization of war progressed too. Governments continued to contract with captains to provide companies of mercenaries. However, beginning in the sixteenth century, they also began to contract with 'military enterprisers' who could provide them with entire regiments and even complete armies.[102] These enterprisers depended on commercial dealers to provide them with arms and supplies they needed.[103]

---

[96](Rogers 1995)

[97](Hall 1997) The crossbow, easily mastered by the weekend warrior, was the 'equalizer' of the Middle Ages: knights tried to have it banned as unfair.

[98](Roberts 1995)

[99]On mobile artillery, see (Nef 1950) Ch. 2. On light cavalry, an Ottoman invention, see (Howard LINK \l "_ENREF_28" \o "Howard, 1976 #3213" Howard 1976) Ch. 1 and (Parker 1995).

[100](Unger 1980)

[101](Mallett 1994)

[102](Redlich 1964). In the 1630s where mere 400 military enterprisers active ((Parker 1996))

[103](Hale 1985)

At sea, navies were supplemented by free-lance privateers—private ships authorized by 'letters of marque' to prey on the commercial shipping of the enemy. Dutch and English privateers were particularly active in plundering the transoceanic trade of Spain and Portugal.

The key to success in privateering was to have a ship that was faster, more maneuverable, and better-armed than those of your adversaries and competitors. So privateers were willing to pay top gulden for the best ships and armament, and shipbuilders and gunmakers competed vigorously for their business.

This resulted in some major advances in technology. English, Breton, and Dutch shipbuilders produced smaller, faster and more maneuverable ships. English gunmakers solved the technological problems of casting cannon in iron to produce a much less expensive weapon than the brass cannon still favored by navy ships.[104]

CONCLUSION

Technological progress in preindustrial Europe exhibited several clear patterns, and these suggest some conclusions about the nature and causes of technological progress in general.[105]

Technological progress depends on the *adoption* of technology

The mere existence of a technology is of no economic significance if no-one uses it. For technology to affect productivity it must be adopted by producers and put to use.

Moreover, only when technology is actually put to use does it undergo the process of modification and adaptation that makes it really effective.[106] The improvement that results is not the result of any deliberate acts of invention but simply a by-product of the process of production itself.[107] While each individual modification may make only a small difference, their cumulative effect over time can be enormous. We saw this process at work in the intensification of agriculture, in the mechanization of industry, and in the design of ships.

---

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

[105] The following owes much to (Persson 1988).

[106] (Mokyr 1990) calls such modifications microinventions.

[107] (Persson 1988)

Adoption is driven by market expansion

The adoption of technology is driven by expansion of the market. In particular, expansion of the market makes adoption profitable, and expansion of the market induces the reorganization of production that is often a prerequisite for the adoption of new technology.

Overcoming the fixed costs of adoption

The adoption of new technology—new to the adopter—typically involves a large and uncertain fixed cost in the form of income foregone during the unavoidable period of experimentation and modification needed to get the best out of the technology. In addition, the adoption of technology often requires investment in new fixed capital. Together, these fixed costs constitute a significant obstacle to adoption. To overcome this obstacle, the potential profits from adoption have to be sufficiently large.[108]

Generally, it is market expansion that increases potential profitability enough to make adoption worthwhile. It does this primarily by increasing the total demand for the product, making it possible to sell enough product to cover the initial fixed costs. The greater volume of production also increases opportunities for experimentation, which accelerates the process of gradual improvement. For example, as incomes rose in the Middle Ages and population increased, the growing demand for bread led to the construction of many new mills; this resulted in increased experimentation which led to the improvements in mill design noted at the beginning of this chapter.

Market expansion can also make adoption profitable by changing relative prices. We saw an example of this in the case of the *Saigerprozess* for extracting silver.

The role of the reorganization of production

Often, the adoption of a new technology becomes feasible only after production is reorganized. For example, in preindustrial Europe, the intensification of agriculture would not have made sense before agriculture was commercialized and restructured into specialized family farms.

---

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

In industry, it was division of labor and production on a larger scale that created opportunities for mechanization. In shipbuilding, it was the improved organization of shipping that made it easier to fill large ships and so made larger ships economically viable. In armaments, too, technological progress was a consequence of the commercialization and reorganization of the military, which created the necessary market.

Other ways in which market expansion promotes technological progress

Market expansion also promotes technological progress by increasing competition in product markets. Increased competition puts pressure on producers to reduce their costs and to improve their products—as we saw in the case of ships and armaments.

Another way in which market expansion promotes technological progress is by accelerating the diffusion of technology. In preindustrial Europe, merchants were instrumental in bringing technology to new places where its adoption might prove profitable. For example, it was probably Flemish merchants trading in northern Italy who brought the horizontal loom and the spinning wheel to the Low Countries.

Market expansion also promoted diffusion by encouraging the migration of skilled craftsmen.[109] Practical knowledge was largely tacit—known to practitioners through experience and not written down or even easily expressed in words.[110] Practical knowledge, therefore, was largely embodied in those who possessed it.[111] As a result, its diffusion largely depended on migration.

Expansion of the market promoted migration by creating local shortages of skilled labor: the resulting higher wages attracted foreign craftsmen. Market expansion also promoted migration by creating new opportunities for those with valuable knowledge and

---

[109](Sella 1977). There was also considerable non-economic migration—driven by war, epidemic, and religious persecution. The wars and persecutions of the sixteenth and seventeenth centuries were a particularly fruitful source of technology transfer, with England and Holland being the chief beneficiaries.

[110](Epstein 2004), (Epstein 2005).

[111]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)

skills to sell their services. Pursuing such opportunities, German artisans spread the technology of mining and metallurgy all over Europe and into the Americas.[112]

The importance of mass-market goods

In all of this, an expanding market for mass-market goods is particularly important. In preindustrial Europe, the growing demand for non-grain foodstuffs was a major stimulus to technological progress in agriculture: intensification was largely a response to the expanding market for meat, dairy products, and fruit and vegetables. Similarly, as we have seen, the creation of a mass market for low-cost, lower-quality manufactures was a prerequisite for mechanization in textiles and iron goods. And it was not the inter-zone trade in luxuries that stimulated major improvements in ship design. It was, rather, the cost-sensitive inter-regional trade in bulk commodities.

The demand for technology and the supply

It is useful to think of technological progress in terms of the demand for technology and the supply. The demand is the desire or willingness to adopt technology. The supply is the stock of additional technology that is available for adoption. The supply has three components: technology that already exists but is not currently in use; technology that exists elsewhere and becomes available through diffusion; and completely new technology created by invention.

Historians of technology naturally focus on invention. But invention has no impact on technological progress unless the new technology is adopted—unless there is a demand for it. Invention increases the supply of technology available, but supply is not necessarily the limiting factor.

If invention is not sufficient for technological progress, neither is it necessary: there are other sources of supply. In preindustrial Europe, a great deal of technological progress was the result of adopting technology that had been around for decades or even centuries put had not been put to use because it was unprofitable. And much of the rest of the technological progress of the period was the result of adoption of technology invented elsewhere—in the Muslim world and in China—and brought to Europe by commerce.

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

Examples include cotton and silk cloth, the spinning wheel and the horizontal loom, the compass, porcelain, paper, and gunpowder.

So preindustrial Europe's technological progress was driven not by invention, but rather by its readiness to adopt and improve technology, whatever its source. That is, its technological progress was driven by demand. And, as we have seen, what created the demand was market expansion and the reorganization of production.

Without an economic environment conducive to the adoption of technology, the mere creation or acquisition of new technologies—increasing the supply—achieves nothing.[113] As an example, during the long sixteenth century, the Ottomans repeatedly imported skilled craftsmen from Italy, but the impact on technological progress in the Ottoman empire was minimal.[114]

Technology in the theory of economic progress

Distinguishing in this way between the supply of technology and the demand for it helps to clarify the very different ways in which the conventional theory and the new theory understand technological progress.

The conventional theory understands technological progress purely in terms of supply: it ignores demand. This is a consequence of its fundamental assumption that the economy is always at its full potential. If it is, then all useful existing technology must already be in use. Technological progress, therefore, must be entirely the result of an increase in the supply of technology—of invention. This view leads to a mistaken search for technological 'revolutions'. If invention is the cause of economic progress, then explaining economic progress means locating the critical breakthroughs.

The new theory, in contrast, does not assume the economy to be at its full potential. On the contrary, it sees economic progress as the process of exploiting potential. The new theory's understanding of technological progress is consistent with this: technological progress is largely a matter of exploiting potential through the adoption, diffusion, and

---

[113]"[T]he technological competence of Chinese was in no way inferior to that of Europeans; what was almost always absent was the intention of using their discoveries to obtain economic results." ((Baechler 1976) p 31) See (Bhidé 2006) for further development of this idea.

[114](Cipolla 1967) p 30-1

gradual improvement of technology. That is why the new theory focuses on the mechanisms that increase the demand for technology. It is the increased willingness and ability to make use of technology that leads to the exploitation of technological potential and so to technological progress.

Invention does, however, still have a place in the story. In the long run, invention is necessary if the pool of technologies available for adoption is not to run dry. So it is important to understand what drives invention. The conventional theory looks to factors outside the economy—for example, to a cultural predisposition for invention or to chance discovery.[115] In contrast, as we will see in Chapter 5, the new theory sees invention too as part of the self-generating process of economic progress.[116]

---

[115]There does exist a literature on 'endogenous growth', in the framework of the conventional theory, that allows for technological progress to be influenced by factors internal to the economy. For a summary, see (Howitt 2008).

[116]That technological progress is generated within the economic process was argued strongly, and famously, by (Schumpeter 1955 [1911]).

References

Allen, R. C. (2000). "Economic structure and agricultural productivity in Europe, 1300-1800." European Review of Economic History v4p1(April): 1-26.

Baechler, J. (1976). The Origins of Capitalism. New York, St. Martin's Press.

Bhidé, A. (2006). Venturesome consumption, innovation and globalization, Columbia University.

Blanchard, I. (1986). "The Continental European Cattle Trade, 1400-1600." Economic History Review, Second Series 39(3): 427-460.

Blanchard, I., A. Goodman, et al. (1992). Technological diffusion in the international mining and metallurgical industries: introduction. Industry and Finance in Early Modern History. I. Blanchard, A. Goodman and J. Newman. Stuttgart, Franz Steiner Verlag.

Braudel, F. (1972). The Mediterranean and the Mediterranean world in the age of Philip II. New York, Harper & Row.

Cipolla, C. M. (1967). Clocks and culture, 1300-1700. London, Collins.

Cipolla, C. M. (1994). Before the Industrial Revolution: European Society and Economy, 1000-1700. New York, W.W. Norton.

Clay, C. G. A. (1984). Economic expansion and social change: England 1500-1700. Cambridge, Cambridge University Press.

de Vries, J. (1974). The Dutch rural economy in the Golden Age, 1500-1700. New Haven, Yale University Press.

de Vries, J. and A. van der Woude (1997). The First Modern Economy: Success, Failure, and Perserverance of the Dutch Economy, 1500-1815. Cambridge, Cambridge University Press.

Epstein, S. R. (1998). "Craft Guilds, Apprenticeship, and Technological Change in Preindustrial Europe." Journal of Economic History 58(3): 684-713.

Epstein, S. R. (2001). The late medieval crisis as an 'integration crisis'. Early Modern Capitalism: Economic and Social Change in Europe, 1400-1800. M. Prak. London, Routledge.

Epstein, S. R. (2004). "Property Rights to Technical Knowledge in Premodern Europe, 1300 –1800." American Economic Review 94(2)(May): 382-387.

Epstein, S. R. (2005). Transferring technical knowledge and innovating in Europe, c.1200-c.1800, London School of Economics.

Epstein, S. R. and M. Prak (2008). Introduction. Guilds, innovation, and the European economy, 1400-1800. S. R. Epstein and M. Prak. Cambridge ; New York, Cambridge University Press: viii, 352.

Ertman, T. (1997). Birth of the leviathan: building states and regimes in medieval and early modern Europe. Cambridge, [Eng.], Cambridge University Press.

Glamann, K. (1977). The changing pattern of trade. The Economic Organization of Early Modern Europe. E. E. Rich and C. H. Wilson. Cambridge, Cambridge University Press: 185-289.

Grantham, G. (1999). "Contra Ricardo: On the macroeconomics of pre-industrial economies." European Review of Economic History 3: 199-232.

Grantham, G. (2003). The early medieval transition. On the origins of the manor and feudal government. Some problems of interpretation. McGill University, September.

Grantham, G. (2007). In search of an Agricultural Revolution, Department of Economics, McGill University.

Grantham, G. (2007). What's space got to do with it? Distance and agricultural productivity before the railway age, Department of Economics, McGill University.

Hale, J. R. (1985). War and society in Renaissance Europe, 1450-1620. New York, St. Martin's Press.

Hall, B. (1997). Weapons of war and late medieval cities: technological innovation and tactical changes. Technology and Resource Use in Medieval Europe: Cathedrals, Mills, and Mines. E. B. Smith and M. Wolfe. Brookfield, Vt, Ashgate.

Hammersley, G. (1973). "The charcoal iron industry and its fuel, 1540-1750." Economic History Review 26.

Hoffman, P. T. (2011). "Prices, the military revolution, and western Europe’s comparative advantage in violence." Economic History Review 64(S1): 39–59.

Holt, R. (1997). Mechanization and the medieval English economy. Technology and Resource Use in Medieval Europe: Cathedrals, Mills, and Mines. E. B. Smith and M. Wolfe. Brookfield, Vt, Ashgate.

Howard, M. E. (1976). War in European history. London New York, Oxford University Press.

Howitt, P. (2008). Endogenous growth. The New Palgrave Dictionary of Economics, 2nd Edition. S. Durlauf and L. Blume. New York, Palgrave Macmillan.

Hunt, E. S. and J. M. Murray (1999). A History of Business in Medieval Europe, 1200-1550. New York, Cambridge University Press.

Jones, P. J. (1997). The Italian city-state : from commune to signoria. Oxford ;, New York : Clarendon Press,.

Kaldor, N. (1985). Economics without Equilibrium. Armonk, NY, M.E. Sharpe.

Karakacili, E. (2004). "English agrarian labor productivity before the Black Death: a case study." The Journal of Economic History 64 (1)(March): 21-55.

Kellenbenz, H. (1977). The organization of industrial production. The Economic Organization of Early Modern Europe. E. E. Rich and C. H. Wilson. Cambridge, Cambridge University Press: 462-549.

Kerridge, E. (1967). The agricultural revolution. London,, Allen & Unwin.

Kerridge, E. (1985). Textile manufactures in early modern England. Manchester, Manchester University Press.

Lane, F. C. (1973). Venice, a maritime republic. Baltimore, Johns Hopkins University Press.

Lane, F. C. (1986). Technology and productivity in seaborne trasportation. Trasporti e sviluppo economico. Secolo XIII-XVIII,. A. V. Marx. Florence, Istituto Internazionale di Storia Economica 'F. Datini'. Pubblicazioni, 2nd ser., 5: 233-244.

Laven, P. (1966). Renaissance Italy, 1464-1534. London,, Batsford.

Mallett, M. E. (1994). The art of war. Handbook of European History 1400-1600. J. Thomas A. Brady, H. A. Oberman and J. D. Tracy. Leiden, E.J. Brill.

Masschaele, J. (1997). Peasants, merchants, and markets: inland trade in medieval England, 1150-1350. New York, St. Martin's Press.

Mazzaoui, M. F. (1981). The Italian cotton industry in the later Middle Ages, 1100-1600. Cambridge, Cambridge University Press.

McNeill, W. H. (1982). The Pursuit of Power: Technology, Armed Force, and Society. Chicago, University of Chicago Press.

Menard, R. R. (1991). Transport costs and long-range trade, 1300-1800: Was there a European 'transport revolution' in the early modern era? The Political Economy of Merchant Empires. J. D. Tracy. Cambridge, Cambridge University Press: 228-275.

Miskimin, H. (1977). The Economy of Later Renaissance Europe. Cambridge, Cambridge University Press.

Mokyr, J. (1990). The lever of riches : technological creativity and economic progress /. New York :, Oxford University Press,.

Mola, L. (2000). The Silk Industry of Renaissance Venice. Baltimore, Johns Hopkins University Press.

Munro, J. H. (2000). Flemish Woollens and German Commerce during the Later Middle Ages: Changing Trends in Cloth Prices and Markets, 1290 - 1550. Department of Economics, University of Toronto.

Munro, J. H. (2003). Industrial Energy from Water-Mills in the European Economy, Fifth to Eighteenth Centuries: the Limitations of Power. Economia ed energia, seccoli XIII - XVIII. S. Cavaciocchi. Florence, Le Monnier: 223–269.

Munro, J. H. (2007). Tawney's Century (1540-1640): the Roots of Modern Capitalist Entrepreneurship in England. June, University of Toronto, Department of Economics.

Nef, J. U. (1950). War and human progress; an essay on the rise of industrial civilization. Cambridge,, Harvard University Press.

Nef, J. U. (1964). The conquest of the material world. Chicago, University of Chicago Press.

Nef, J. U. (1987). Mining and metallurgy in medieval civilization. Cambridge Economic History of Europe: II, Trade and Industry in the Middles Ages. M. M. Postan and E. Miller. Cambridge, Cambridge University Press: 693-762.

Nicholas, D. (1992). Medieval Flanders. London, Longman.

Nicholas, D. (1997). The growth of the medieval city : from late antiquity to the early fourteenth century. London ; New York, Longman.

Nicholas, D. (1997). The later medieval city, 1300-1500. London ; New York, Longman.

Ogilvie, S. (2008). "Rehabilitating the Guilds: A Reply." The Economic History Review , New Serie Vol. 61, No. 1(Feb.): 175-182.

Palliser, D. M. (1983). The Age of Elizabeth : England under the later Tudors, 1547-1603. London ; New York :, Longman,.

Parker, G. (1995). The 'Military Revolution, 1560-1660'--A myth? The military revolution debate : readings on the military transformation of early modern Europe. C. J. Rogers. Boulder, Westview Press: xi, 387.

Parker, G. (1996). The military revolution : military innovation and the rise of the west, 1500-1800. New York, Cambridge University Press.

Persson, K. G. (1988). Pre-Industrial Economic Growth: Social Organization and Technological Progress in Europe. Oxford, Basil Blackwell.

Pirenne, H. (1937). Economic and Social History of Medieval Europe. New York, Harcourt Brace.

Redlich, F. (1964). The German military enterpriser and his work force; a study in European economic and social history. Wiesbaden,, F. Steiner.

Roberts, M. (1995). The Military Revolution, 1560-1660. The military revolution debate : readings on the military transformation of early modern Europe. C. J. Rogers. Boulder, Westview Press: xi, 387.

Rogers, C. J. (1995). The Military Revolutions of the Hundred Year War. The military revolution debate : readings on the military transformation of early modern Europe. C. J. Rogers. Boulder, Westview Press: xi, 387.

Scammell, G. V. (1972). "Shipowning in the economy and politics of early modern England." The Historical Journal 15: 385-407.

Scammell, G. V. (1981). The world encompassed: the first European maritime empires, c. 800-1650. Berkeley, University of California Press.

Schumpeter, J. A. (1955 [1911]). The theory of economic development; an inquiry into profits, capital, credit, interest, and the business cycle. Cambridge, Mass., Harvard University Press.

Sella, D. (1977). European Industries 1500-1700. The Sixteenth and Seventeenth Centuries. C. M. Cipolla. NY, Harper & Row: 354-426.

Slicher van Bath, B. H. (1977). Agriculture in the Vital Revolution. The Economic Organization of Early Modern Europe. E. E. Rich and C. H. Wilson. Cambridge, Cambridge University Press: 42-133.

Smith, A. (1976 [1776]). An Inquiry into the Nature and Causes of the Wealth of Nations. Chicago, University of Chicago Press.

Stabel, P. (1997). Dwarf among giants: The Flemish Urban Network in the Late Middle Ages. Leuven, Apeldoorn.

Steele, M. (1994). The state as entrepreneur in early modern Europe. Entrepreneurship and the transformation of the economy (10th-20th centuries): Essays in honor of Herman Van der Wee. P. Klep and E. v. Cauwenberghe. Leuven, Leuven University Press.

Szostak, R. (1991). The Role of Transportation in the Industrial Revolution: A Comparison of England and France. Montreal, McGill-Queen's University Press.

Thoen, E. (1997). The birth of 'the Flemish husbandry'. Medieval farming and technology : the impact of agricultural change in northwest Europe. G. G. Astill and J. Langdon. Leiden ; New York, Brill.

Toch, M. (1997). Agricultural progress and agricultural technology in medieval Germany: an alternative model. Technology and Resource Use in Medieval Europe: Cathedrals, Mills, and Mines. E. B. Smith and M. Wolfe. Brookfield, Vt, Ashgate.

Unger, R. W. (1980). The ship in the medieval economy, 600-1600. London, Croom Helm.

Unger, R. W. (1998 [1979]). Shipping in the Northern Netherlands 1490-1580. Ships and Shipping in the North Sea and Atlantic, 1400-1800. R. W. Unger. Aldershot, Ashgate Variorum.

Unger, R. W. (2004). Beer in the Middle Ages and the Renaissance. Philadelphia, University of Pennsylvania Press.

Van der Wee, H. (1963). The Growth of the Antwerp Market and the European Economy. The Hague, Martinus Nijhoff.

Van der Wee, H. (1993). The Low Countries in the Early Modern World. Aldershot, Variorum.

Van Uytven, R. (1971). "The fulling mill: dynamic of the revolution in industrial attitudes." Acta historiae Neerlandica v5: 1-14.