MEN,
MACHINES AND HISTORY

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A SHORT HISTORY OF TOOLS AND MACHINES IN RELATION TO SOCIAL PROGRESS

BY

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(NOTE: The dates in brackets indicate only very roughly the periods covered by the chapters. Almost every chapter includes material belonging chronologically to an earlier or later one.)

LIST OF ILLUSTRATIONS

PREFACE

I HAVE aimed to write this book in such a way that it can be read by young people in their last years at school and at Universities, Technical Colleges, Continuation Schools, etc. But, as I felt that the subject is of interest to people who in the course of time have become more knowledgeable, I have not hesitated to include here and there a sentence or a paragraph specially for their benefit.

Since my aim was to consider the history of tools and machines in relation to all aspects of life, I have necessarily included many references to social conditions at various epochs. I was able to make these brief, because this book is part of a series, other volumes of which will fill in the background at greater length and correct any distortions that may arise from my brevity.

I have chosen to interpret the word 'machine' somewhat widely. In particular, I include in its scope the many electronic devices (radio, sound films, photo-electric cells in the control of machinery, etc.) which have been so prominent in this century—for I feel that, though these are not 'mechanical' in the strict sense of the word, their development does represent the modern form of that trend towards greater control over nature which was earlier expressed in strictly mechanical form.

The work had to be done almost entirely in spare time while carrying on a war job, and though a final revision was made during the first year of peace, there was not time for as full an investigation of sources as might be desired. These circumstances, coupled with the breadth of the field, compelled me to rely to a considerable extent on secondary sources. However, I have cross-checked my information wherever possible, and though some factual errors may remain, these are not likely to be ones of major importance. Responsibility on matters of interpretation is, of course, entirely my own.

My thanks and acknowledgements are due to the following, who helped in various ways, from giving advice on particular topics to reading and commenting on the typescript: Mr. C. E. Allen, editor of *Machinery*; Mr. E. Bramhill, of the Shorter Process Company Ltd.; Messrs. Buck and Hickman Ltd.; Mr. P. V. Daley; Mr. C. Davies; Mr. W. E. Dick, editor of *Discovery*; Mr. R. E. Doré, of the British Oxygen Company; Mr. R. H. Heindel, Director of the American Library in London; Mr. A. F. P. Parker-Rhodes; the late Mr. John Wilton; the Secretary of the Institution of British Agricultural Engineers and, last but not least, the editors of the series.

Cambridge, August 1946. S. L.

CHAPTER I

THE FIRST INDUSTRIAL REVOLUTION (TILL 3000 B.C.)

THE earliest men we know of made and used tools. In fact, man as we know him probably could not have survived without tools—he is too weak and puny a creature to fight nature with only his hands and his teeth. The first men were of a species very different from our own. Perhaps they could have managed to live without tools. But only with the aid of the tools that these more primitive species learnt to use was it possible for the man of today to evolve, losing much in bodily strength and speed, but more than compensating for this loss by developing a brain and hands and eyes that enabled him to call to his aid his many tools and machines that made him master of the world.

For the earliest tool-using men we have no space here. We begin with men of the late Palæolithic Age, men now of our own species, living by hunting and food-gathering. Already at this stage men had acquired a vast variety of tools. They had axes, knives, saws, spokeshaves, and scrapers of chipped stone, mallets, awls and piercing tools, needles of ivory, spears and harpoons. They had even tools for making tools. They used two very important machines: the bow and the spear-thrower. The former is the first machine which stores energy; the bowman puts his energy gradually into the bow as he draws it, storing it up ready to be released in concentrated form at the moment of shooting. And the spear-thrower is an application of the lever as an extension of a man's arm, giving the spear a greater range.

The transitional mesolithic societies that followed the Old Stone Age advanced yet further, developing in particular fishing tackle, a fine range of carpenter's tools, including the adze, gouge and chisel, and learning to make and use the sledge and the dugout canoe with its paddles.

But it is with the introduction of agriculture and the whole series of techniques associated with it that this history must really begin. This was the first great Industrial Revolution in man's history, the neolithic revolution, which took place not much more than 7,000 years ago. Formerly man gathered the food that nature unaided provided. Now he learnt to make nature provide what he wanted. All his previous advances seem insignificant beside this leap forward. The story of this first Industrial Revolution has already been told in Volume I of this series; here we shall only re-emphasize those aspects that have direct bearing on the subsequent history of tools and machines.

For agricultural purposes, men had to invent special tools: the wooden hoe to till the ground, the sickle of wood set with flint to reap the corn (Figure 1), the flail to thresh it, the quern to grind it.[1] But a full change from hunting and food-gathering to agriculture as the basis of life could not take place without a whole series of auxiliary changes. The wooden hoe and sickle required tools to shape them; sometimes plots had to be cleared before sowing. For these and other purposes neolithic man developed further the carpenter's tools that had appeared in the Neolithic Age, using ground and polished stone instead of the cruder

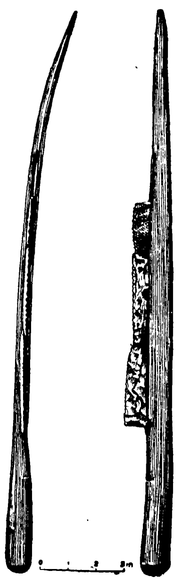


Fig. 1. Flint sickle from Fayum in Egypt.

[1] A primitive form of sickle, the straight reaping knife, appeared a little before the development of agriculture, for cutting down edible grasses not sown by man. Similarly the hoe has an ancestor in the digging-stick of mesolithic times; while pestles and mortars, which had been used for other purposes by palæolithic man, were used as well as the quern for early corn-grinding.

chipped stone of his predecessors. He also added the bow-drill, in which the drill is rapidly driven by a string wrapped round it, attached at each end to a sort of bow which is moved back and forth. Cereals required storage and new ways of cooking. The game caught by the hunter can be roasted on a spit before an open fire, but cereals need slow, gentle cooking in some sort of vessel. Neolithic man solved this problem with pottery.

The skins of hunted animals provided the few clothes of palæolithic man. The agriculturalist had to find a substitute and he found it in textiles. But to master textiles he required two new machines: a spinning machine and a loom. The early spinning machine was very simple—a short stick with a hook or notch on one end to which the thread was attached and a flywheel (whorl) of stone or pottery at the other to ensure continuous spinning motion; and a distaff or forked stick to hold the unspun fibres. The spindle is given a twist and hangs spinning in the air while the operator feeds fibres from the distaff on to the end of the thread, where they are twisted into yet more thread. It is a simple mechanism by modern standards, yet a tremendous complication compared to any previous machine. And no fundamental improvement took place in the process of spinning till the Middle Ages.

The loom, even in its simplest form of a frame on which the warp is stretched while the weaver's fingers push the woof alternately over and under the warp threads, is a complicated piece of apparatus. And it did not stay long at that simple stage, but was soon improved with the heddle for separating the alternate warp threads, and other devices.[1]

Thus, almost from the beginning of the Neolithic Age, man had vastly increased the number of tools and machines that he used. But a very rapid advance was to follow. The

[1] Textile machinery is difficult to describe and its early history is often obscure. We shall therefore deal with it only in very general terms till medieval times.

change in man's way of life was propitious to invention. He had more security than ever before. The periods of leisure that intersperse agricultural activity gave time for invention. The comparatively permanent life that agriculture (at least in its more advanced stages) made possible allowed him to construct, accumulate and use equipment that the hunter would usually see only as an encumbrance. And lastly, man had learnt that nature could be controlled for his own benefit and had therefore acquired a degree of self-confidence that encouraged him to try new methods of increasing that control.

Conditions were particularly favourable in Mesopotamia and the valleys of the Nile and the Indus, where the periodically flooding rivers, soon to be controlled by irrigation, watered the crops and spread a new layer of mud each year which prevented the exhaustion of the soil. In these countries we find a great spate of invention in the couple of millennia before 3000 B.C. In this period man learned to smelt and use metals, to harness animals; he invented the plough and the wheeled cart and the sailing ship. These, and many similar inventions, laid the basis for great social changes which we shall mention later.

Copper and iron sometimes occur naturally as metals, and men at an early stage learned to make some use of them. But they used them as a superior sort of 'stone'—a 'stone' which was much less brittle than those commonly used for tools and which could be hammered into shape, instead of requiring chipping or grinding like the common stones. The great step forward came when men made two great discoveries. First, that heating certain types of stone with charcoal produced copper—the process of smelting. Second, that copper could be melted in a suitable furnace, run into a mould where it would solidify to reproduce the shape of the mould—the process of casting. These discoveries were probably made in or near Mesopotamia about 4000 B.C. Smelting was an important step, because the supplies of natural metals in the world are so tiny that their use could have no important effect on men's lives. And without casting, the most valuable and important properties of copper would be left unused.

Though there were in some places 'factories' for making them, in general the stone tools could be made by the man who used them, as and when he needed them. Not so with metal; it required a highly organized system of production. Quarrying (and later, underground mining) required a host of techniques for dealing with hard rocks, such as cracking them by lighting fires against them and throwing water on the hot surface, or splitting them by inserting wooden wedges in cracks and then soaking them in water so that they expand and prise the rocks apart.

Then the ore must be smelted. That required furnaces capable of giving temperatures so high as to need some sort of blast. The best way to produce the blast would be by bellows, but these were not discovered till about 3000 B.C., so that the earlier workers had to use blowpipes or tunnels arranged to catch the prevailing wind.

Then the smith had to turn the crude lump of copper into useful tools or weapons. The first process was casting, which like smelting requires a high-temperature furnace, as well as crucibles in which to melt the metal. There must be moulds of sand, clay or pottery to run it into, and means of shaping these moulds as required. For anything but the simplest product the mould must be made in two or more pieces which can fit together to receive the molten metal. After casting, the tool must be finished in various ways, by hammering, smoothing with files, grinding to a sharp edge on a stone, and so on.

So it will be seen that the use of copper required many auxiliary inventions to make it practicable, and many specialized craftsmen to do the work—specialists who would not be producing food but must be fed by the community.

How men discovered the smelting of metal we do not know. It has been suggested that perhaps somebody accidentally dropped some malachite (a copper-bearing mineral commonly used to paint the eyes, partly as a cosmetic, partly as a protection against certain fly-borne infections) into a charcoal brazier, and observed a few beads of copper running out at the bottom. Perhaps the discovery was made many times, and many times forgotten as useless. For we must remember that the usefulness of an invention depends on the structure of society. The use of copper, as we have seen, requires specialist miners and smiths, who shall devote their whole time to that work and therefore must be fed, clothed and housed from a surplus produced by other members of the community. Until the technical level was high enough to provide this surplus, it would be impossible to keep these specialists, and therefore impossible to use metals. Thus, even if the smelting of copper was discovered accidentally in some early neolithic society, it would have been brushed aside as useless and soon forgotten. But eventually with the gradual advance of neolithic technique the time arrived when the community could afford to keep specialists who produced no food—and then any further accidental discovery of copper smelting would soon be developed as a useful asset.

The miners and smiths were not by any means the only specialists required to make metals socially usable. Copper ore was not found in the lands occupied by the advanced neolithic farmers, who could support the smiths and use their products. The ore or the copper had to be transported over long distances. This required traders and transport workers. Early neolithic communities had been more or less self-supporting, trade being confined to a few luxuries, ornaments and charms. But as the societies became capable of producing a surplus over their immediate needs, they tended more and more to exchange this surplus for products obtainable only from a distance, the most important of which were copper and its ores. At the same time the villages tended to grow into towns containing craftsmen like smiths and carpenters, and later entirely unproductive classes like priests, kings, nobles. All these had to be supported by food and other basic necessities carried in from the surrounding countryside. Thus the transport industry grew, and as it grew it developed better methods of transportation.

The sledge, we have seen, was invented in mesolithic times. The agricultural peoples enormously extended its use. Then, perhaps through first using rollers to ease the work, they invented the wheeled cart—next to agriculture and metallurgy, perhaps the most important invention ever made. Wheeled vehicles were in use in Sumeria as early as 3500 B.C., in North Syria perhaps earlier. By 3000 B.C. they were in general use in Mesopotamia, Elam and Syria; they reached the Indus by 2500 B.C. But in Egypt they were unknown till very much later.

The wheeled cart would not have been nearly so great an advance, were it not combined with another invention—the harnessing of animals (Figure 4). This invention is connected partly with the expansion of transport that we are discussing, and partly with another great invention of this period: the plough—a tremendous improvement over the hoe which had earlier been used to till the ground. Animals were soon widely used both for ploughing and for drawing vehicles.

The harnessing of animals was the first instance of men using some force other than human muscles to do their work for them. At about the same time they also first learned to use an inorganic force—the wind, to drive sailing ships (Figure 2). Sailing ships were in use in Egypt soon after 3500 B.C., and by 3000 B.C. they were freely navigating the eastern Mediterranean, and probably also the Arabian Sea. Today the comparative comfort and safety in which we can live is based largely on our use of non-animal power—wind, water, coal and oil. Here in the East, before the dawn of civilization, we see the first step being taken towards our modern age of power.

To describe all the inventions of these thousand or two fruitful years before 3000 B.C. would take too much space. Here we shall mention only one more, the potter's wheel, which not only made possible the production of much better pottery at the cost of much less labour, but also made pottery the first mechanized production industry, the first step on the way to the mass production factory of today.

Finally, let us note how closely these inventions were interconnected. Metals, for example, could not have been used without improvements in transport to carry the ore or metal from mine to user, nor without the agricultural improvements which gave sufficient yields to allow the supporting of specialists withdrawn from primary production. And conversely the wheeled cart, the plough, the sailing ship, or the potter's wheel, requiring, as they do, quite advanced carpentry, probably could not have been used on any extensive scale without metal tools to make them.

CHAPTER II

THE FIRST CIVILIZATIONS
(3000–1100 B.C.)

ALONG with the advances in the field of tools and machines that we described in the last chapter, there occurred equally important advances in other techniques. For example, in the river valleys of Mesopotamia, Egypt and the Indus systems of controlled irrigation were evolved, which enormously increased the productivity of the land. In all spheres of activity men were able to produce much more than before, because they had better tools and better methods. The savage hunter, or the early neolithic farmer, could make ends meet in good seasons—and in bad, part of the tribe died from under-nourishment. Now it was possible to produce an assured sufficiency for all, and beyond that a

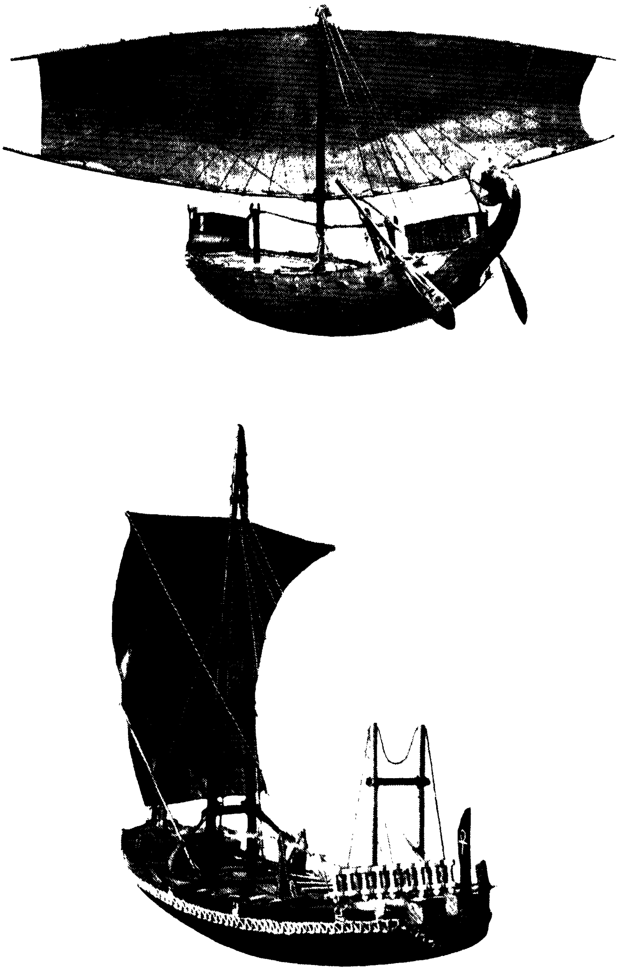


Fig. 2. Egyptian sea-going ships. The upper ship belongs to the middle of the third millennium B.C. The lower one, a thousand years later, shows many detailed improvements in construction, but note that the steering gear remains fundamentally unchanged.

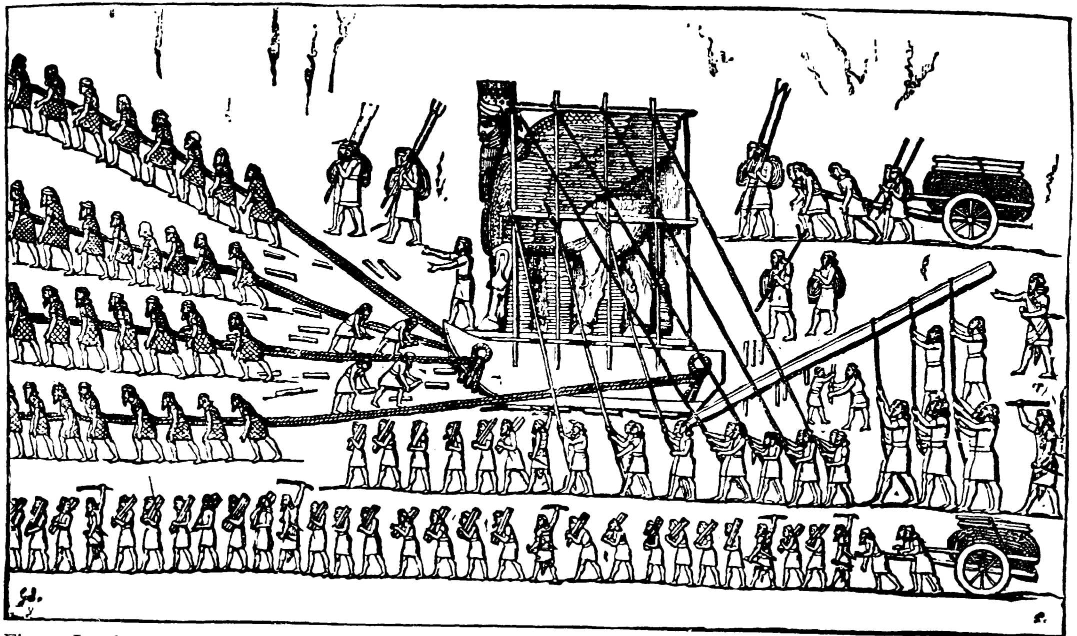


Fig. 3. Land transport in the late Bronze Age. Assyrians hauling a giant statue on a sledge—an example of the capacity of the Bronze Age civilizations for organizing large labour forces. Note also the wheeled carts for lighter loads.

small surplus, available to increase the comfort and luxury of life. But social progress did not take place along the simple lines of a continually improving standard of living for the whole population; the technical developments themselves decreed a different form of development.

The tools and machines we have described could only be made at the cost of a considerable amount of labour. Only the few men or families who had been more than usually successful with their crops could spare the time to make them, or alternatively barter a part of their surplus crop with a specialist in exchange for an advanced tool. But once acquired, the new tool gave its possessor a great advantage. With a plough his crops would be yet better, and he would in future have a further surplus available to barter for yet more specialized tools. This was especially true of copper. It provided more serviceable tools than stone; it could be cast into forms which could not be produced from stone; copper tools lasted much longer than stone tools; when the edge was dulled, it could more easily be resharpened. But more than that, if copper is superior to stone for tools, it is much more so for weapons. If a chisel breaks, it means only a delay to make a new one. If a dagger breaks in battle, it means death or captivity. So the owner of copper weapons had a tremendous advantage in warfare. Again, copper is a much more costly commodity than stone. In the period we are speaking of, only a few could possess it. For centuries the tools of the peasant remained of stone and wood.[1]

There resulted a tendency to the accumulation of wealth in the hands of the few. He who was already moderately well-to-do could obtain copper implements or other advanced tools. Using these, he (or his family, or later his slaves or serfs) could work more efficiently than others and gather yet more wealth, which gave him a further advantage over his neighbours—and so on, in snowball fashion. Or,

[1] This is especially true of Egypt; in Mesopotamia sickles were often made of bronze after 2500 B.C.

if he wished to gain wealth by force of arms, or to make others work for him, his advantages with copper weapons were even greater.

From this (and many other factors tending in the same direction) there resulted a complete social revolution. The hunters and food-gatherers of the Palæolithic Age had lived in an equalitarian society of the type called 'primitive communism'.[1] Their wealth was the property of the whole tribe and the welfare of every member of the tribe was the responsibility of all. Some might accumulate more personal possessions (ornaments, for example) than others, but differences in wealth were usually small. Government was by the meeting of the whole tribe, with possibly an elected chief in times of stress. The tribe was held together in this communistic society by the necessity of presenting an unbroken front in the hard struggle against nature; internal rivalry meant failure in the struggle, and death. The change-over from hunting to agriculture weakened the basis of this type of society; for the family, tilling its own fields, was capable of becoming a self-sufficient unit, and therefore the tribe as a unit became less important. The neolithic societies remained essentially equalitarian, in that land was communally owned and the fields redistributed from year to year among the different families. Nevertheless, it became possible for one family by greater skill or greater luck to prosper more than another. At first these differences would not be great, nor would they have any strong tendency to grow.

But with the use of copper and the other inventions described towards the end of the last chapter, the situation (as we have seen) became such that any person who had

[1] We have no direct knowledge of the structure of any society before about 3000 B.C., but these descriptions, based on reconstruction from the houses, tools, etc., left behind by these peoples and on the structure of apparently similar societies existing in modern times in backward parts, must be somewhere near the truth. They are, however, much over-simplified and schematized, as are the descriptions of the changes which followed.

accumulated a small surplus had a great advantage in accumulating more. Differences in wealth and power between different members of the community increased apace. Men used the advantage given them by copper weapons to force others to pay them tribute or rent for the land or to become their serfs. Having dominated local communities in this way, they built armies from them and went on to conquer surrounding districts—till great empires were built up.

The process was probably a gradual one in which the inequalities grew slowly, but by 3000 B.C. it had produced a decisive change in the structure of society. The simple communities of more or less equal farmers had been replaced by states in which the vast majority of the inhabitants lived at subsistence level, often as slaves or serfs, while all the surplus product of their labours was used to provide a luxurious existence for a small class of kings, nobles and priests, as well as supporting the civil services and armies which formed the mechanism for extracting from the masses the products of their work. Class-divisions had become the basis of social structure.

From the point of view of the oppressed peasant, serf or slave, this change would seem an unqualified catastrophe. But from the point of view of the human race as a whole, and especially from the point of view of people living today on the verge of another transformation of equal magnitude, it was a necessary step forward. Though factors arising from the new social structure sometimes held back advance for centuries, nevertheless the technical developments that had to come, in order to carry forward the progress described in the last chapter, would have been impossible without the form of organization that class-divisions produced. This arose, for example, from the mere costliness of producing copper tools. If the surplus above subsistence level that neolithic society produced had remained equally divided among all the members of the village, then only rarely would a family have sufficient surplus to exchange with a smith for even one tool. But the increasing concentration of wealth in the hands of a few at the expense of the many enabled these few to barter their surplus food (or other necessities) for the smith's tools, and thus provided the basis for the existence of the smith (or the miner, or any other specialized craftsman). And some of the technical advances that we shall describe in the rest of this book required much larger numbers of craftsmen, or the organization of large labour forces, withdrawn from the direct production of necessities, and consequently they were only possible because a few individuals possessed sufficient wealth (or, what it really amounts to, sufficient power to make others work for them) to be able to support these large numbers of specialists.

Thus the many technical advances of the millennia before 3000 B.C., not only caused the social changes, but probably also depended on the gradual increase of class-divisions to provide the concentrations of wealth necessary for their use. And the full establishment of the great class-divided states in Egypt, Mesopotamia and the Indus valley shortly before 3000 B.C. was followed by several centuries of a great flowering of the various techniques. This was not such a period of radical innovation as that which we described in the last chapter; rather it was one in which men built on these innovations, refining the skill with which they were used and increasing enormously the scale on which they were applied.

But there were several important inventions. About 3000 B.C., or within a century or so after, several important developments in metal-working took place in and around Mesopotamia. Tweezers were enlarged into tongs (not hinged, however, but depending on the spring of the metal) with which the smith could efficiently handle the smaller pieces of hot metal. But large objects and crucibles containing metal had to be lifted between two stones or between green twigs. The introduction of bellows improved metallurgical processes. The extremely ingenious *cire perdu* process of casting was developed. In this a wax model of the shape required is made. This is then coated with clay and placed in a furnace, where the wax melts and runs away, while the clay is baked hard to form a mould. Molten metal is then run into the mould and, after cooling, the clay is broken away. Most important of all metallurgical advances of this period was the introduction of bronze, an alloy of copper and tin, which was a radical improvement on copper. It gave harder and more durable tools, and it made possible really fine casting, which is impossible with unalloyed copper. None of these new techniques spread to Egypt till over a thousand years later.

Already the craftsmen of Egypt and Mesopotamia produced a wide variety of articles of high quality. The coppersmith of about 3000 B.C. made axes, adzes, chisels, gouges, drills, knives, saws, nails, clamps, needles, razors, tweezers, and so on. The carpenter made boats, chariots, furniture, harps and lyres; by about 2800 B.C. he was using plywood of six layers.

The Egyptian pyramids constitute the supreme example of the enormous scale on which the rulers of this time could organize labour and the high degree of accuracy that could be achieved. The Great Pyramid of Cheops was built of about 2,300,000 blocks of stone, totalling some 5,750,000 tons in weight, while the larger blocks weighed up to 350 tons. Merely to reach the site, they had to be dragged up 100 feet. According to a tradition reported by Herodotus, 100,000 men were engaged in moving blocks three months of each year for ten years. With a base of 775¾ feet square, the error in any side was less than one inch in length or level. As a contribution to the progress of mankind, the pyramids are of negligible value, but the techniques evolved for building them to such size and accuracy must have had a profound effect on all subsequent building. Only soft rocks could be cut with bronze tools. Hard rocks were pounded with balls of dolerite (a hard resilient stone). The craftsman could do this in such a way as to detach a block as required from the mass in the quarry—a task of no mean skill, since either too hard or too soft a blow will fail. Metal wedges or wooden wedges expanded by wetting them were also used to detach blocks. These were modifications of the techniques of the copper miners. The block was pounded into shape with dolerite balls or pointed hammers, then dragged into position on a sledge (the wheel was still unknown in Egypt). There the shaping was continued with picks and lastly, at the fine stage, with tubular drills, probably bow-driven, using some abrasive. The implements used in building the pyramids were the lever, the sled, ropes, rollers and sleepers (the pulley was a much later invention), measuring rods and cords, the plumb line and water for levelling. The method of levelling was to run a watercourse round the work, banking it up with mud, and to measure down from it at many points to the level required.

Our first reaction is amazement that such magnificent results should be achieved with such meagre technical equipment. Yet meagre as the equipment seems to us, it was the final product of a great advance in the mason's technique, and not for many centuries was it improved upon. The increased scale of application showed itself in other fields. Ships, for example, had reached 170 feet in length by 2700 B.C.

Yet before 2500 B.C., what can be termed the first industrial revolution of human history had come to an end. It was a revolution that began with the invention of agriculture and the techniques that came with it, continued through that great period of invention in the couple of millennia before 3000 B.C., and then, with advances in skill and scale rather than fundamental innovations, till about 2500 B.C. But after that date stagnation set in, and for many centuries only slight advances took place. Not only did fundamental advances cease for a long period, but even in many techniques where the basic ideas had been evolved earlier, but remained

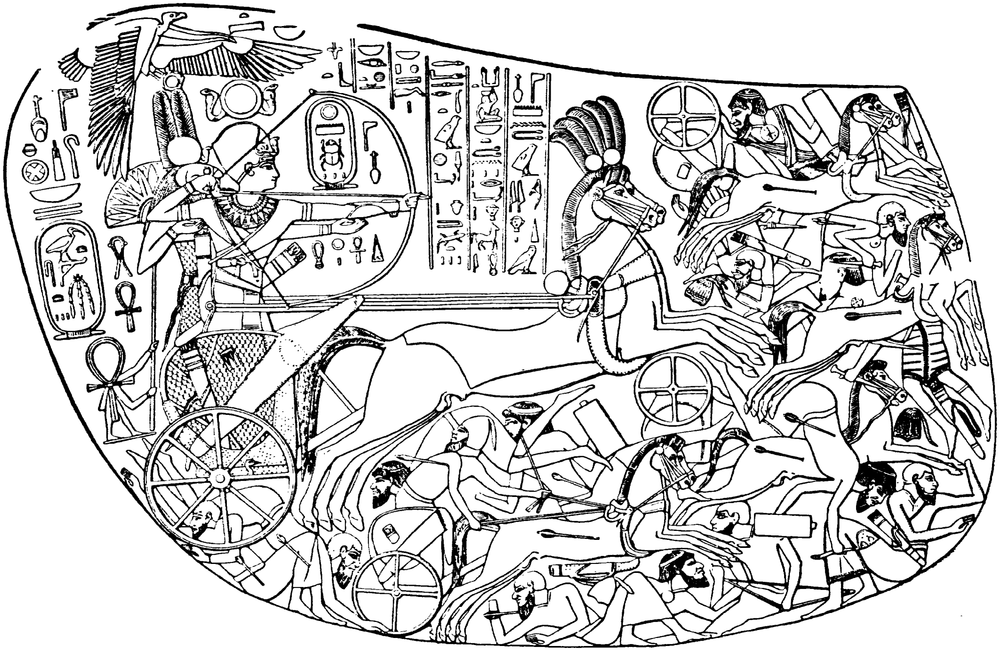


Fig. 4. The ancient harness for horses. Note how the band round the horse's throat forces its head back into a position which reduces its pulling power.

imperfect, and where it seems obvious to us that a little extra effort could have produced great improvements, no further progress took place till the Middle Ages.

The ancient harness, for example, had been developed for use with oxen. Its main element was the yoke resting on the back of the necks of a pair of oxen, and the shape of the ox's neck made this a quite efficient harness. It was not, however, efficient as a harness for the ass or more especially for the horse. Yet, when these were introduced, it was applied to them with only minor modifications. As the horse's neck is not correctly shaped to take the yoke, a band or collar was attached to the yoke at the back of the horse's neck and passed round its throat (Figure 4). Compared with a modern harness, in which the collar rests on the shoulder blades, this was a very inefficient arrangement. When the horse pulled, the pressure of the band choked it, and forced it to throw its head back into a position ineffective for exerting its strength (or even to rear on its hind legs). Further, animals were not shod (leather sandals were probably used to protect injured feet). The result was that two-thirds, at least, of the power of the horse was lost. Again, no really effective harness for one horse or for more than two was evolved. Not till the Middle Ages did a sensible harness come into use. Till then horse traction was suitable only for the lighter loads, and heavy loads were pulled by human labour, at the cost of unnecessary suffering.

The ancient plough was a swing plough; that is, it had no wheels, but was held at the correct height and angle by the ploughman. It ploughed an irregular furrow and the ploughman had to use an excessive amount of energy even to do this. It was ineffectively designed, so that it merely scratched the ground, instead of cutting the sod and turning it over, as does a modern plough. It does not seem that much ingenuity would have been required to fit a pair of wheels and improve the shape of the ploughshare—yet this again did not happen for millennia.

And so also with other techniques. Until the Middle Ages, the spindle described in Chapter I remained in use without radical improvement; the steering mechanism of ships, which was very imperfect (Figure 2), remained unaltered. Until the Iron Age, the smith's only hammer was a ball of stone held in his hand. To quote Engelbach,[1] 'Apart from architectural forms, it can almost be said that, after the Great Pyramid, the masonic craft remained static as regards mechanical and technical processes until the advent of the Greeks and Romans'.

The examples given will make it clear that this stagnation of technique was not caused by a lack of problems to be solved, or lack of obvious deficiencies to be rectified. Some of the problems may have been too difficult at that particular stage of progress—we do not expect men familiar with no more complicated means of transport than carts and sailing ships to create an aeroplane—but improvements to the harness, or the application of the *already familiar* wheel to improve the *already familiar* plough, were steps by no means beyond the capabilities of men's minds at that time. Some deeper explanation must be found. The most probable explanation lies in the nature of the social system which dominated the advanced part of the world in this period of stagnation. We have already remarked that the appearance of class-divided society was necessary for the development of man's technical equipment beyond a certain stage. We also hinted that this social structure did not ensure uninterrupted progress, but at times retarded technical advance for long periods. It is now time to see how this came about.

The societies of the period we are discussing, when the great social changes were complete and the class-divisions fixed and hardened, were divided, broadly speaking, into two classes. The great mass of the people, belonging to the oppressed classes of peasants, slaves and serfs, did all the productive work of the community, but received in return

[1] In *The Legacy of Egypt*, edited by S. R. K. Granville (Oxford, 1942), p. 148.

only the bare necessities of life. The small ruling class of priests, nobles and kings did no productive work, but lived luxuriously on the products of the work of others. The labouring classes were familiar with the techniques already in existence, and they had the practical experience from which it would have been possible to learn how they could be improved. But they had no incentive to make improvements, since any resulting increase of production would be taken from them and used merely to increase the well-being of their masters. Nor, worked to the utmost night and day, did they have the leisure required for invention. The ruling class, on the other hand, saw the world only from the point of view of consumers. Ignorant of the actual methods of production, they could not usually be aware of technical deficiencies, nor had they the practical knowledge to effect improvements. They *were* familiar with the art of exploitation, of government, of extracting the last available grain of corn from the peasant, and in these arts they produced many improvements. But they were incapable of advancing the technical methods of society. Thus, with one class possessing the requisite knowledge and experience, but lacking incentive and leisure, and the other class lacking the knowledge and experience, there was no means by which technical progress could be achieved.

Evidence that it was the form of society that caused this cessation of invention comes in a variety of ways. The wheeled cart, for example, had spread over Mesopotamia, Elam and Syria by 3000 B.C., that is by about the date at which the new social structure reached a stabilized form. But it had not by then reached Egypt and, in spite of the fact that the countries are so close together that news of it must have reached Egypt, it was not in fact used there till about 1650 B.C., and even then only as a result of invasion by peoples from lands where it was already common. It is true that Egypt, with its convenient internal water transport, had less urgent need of the wheel than other countries, but even to the Egyptians it would have been a great saver of labour, especially on such tasks as pyramid building. We are thus forced to the conclusion that the wheel was not adopted in Egypt because it failed to reach there before the structure of society became so unfavourable to innovation as to prevent its introduction. In the same way, bronze (as opposed to unalloyed copper) bellows and tongs were not employed in Egypt till about 1600 B.C., though they had been in use over a thousand years earlier in Mesopotamia.

Yet even in this period of stagnation, progress did not entirely cease. The spoked wheel, a considerable advance on the earlier solid wooden wheel, appeared before 1800 B.C. (Figure 3). Light horse-drawn chariots came into use for military purposes. By 1600 B.C. the Cretans were using rapiers. After 1500 B.C. unexplained causes made bronze considerably cheaper. In Egypt its use had formerly been confined to ornaments, weapons and the tools of the finer crafts; now occasional metal hoe blades and ploughshares appeared. In barbarian Europe bronze came to be used for heavy and rough work—from about 1300 B.C. copper miners in the Austrian Alps had sledge hammers and gads with bronze tips. It is significant, too, that it was among these barbarians, and not in the great empires, that the only really fundamental invention definitely known to belong to the later Bronze Age was made—the windlass, used to raise ore from the mine-shaft.

But more important than this comparatively small progress was the diffusion of Bronze Age techniques over large parts of Europe and Asia, which went on continually after 3000 B.C., and made it possible for the further advances that we shall be discussing to take place on a far wider basis than ever before.

CHAPTER III

IRON, THE DEMOCRATIC METAL

(1100 B.C.–A.D. 500)

BECAUSE of its rarity and costliness, bronze had not very greatly extended man's control over nature. It never provided any important proportion of the tools for agriculture, which thus remained at a level not very much above that of the later neolithic period (though it is possible that bronze *indirectly* raised the agricultural level by providing better tools for making ploughs, carts, and so on). While agriculture remained at this level, there could be no general increase in living standards, and surplus agricultural production must remain so small that only a tiny number of workers could be spared to specialize in other crafts. Thus, apart from weapons, bronze provided mainly tools with which a small number of craftsmen produced luxuries for a small wealthy class. Production in general remained basically neolithic. Even the great irrigation works of Egypt and Mesopotamia were for the most part carried out with stone and wooden equipment.[1]

But when men learned to smelt iron, as they had formerly done for copper, great new possibilities were opened up. Iron is not only a superior metal to bronze for most purposes (expecially when the tricks of varying its properties by different methods of smelting and subsequent treatment are known), but also it is far more widely distributed over the earth's surface, so that far more people could obtain it for tools without having to organize elaborate transport and exchange. And, finally, iron is a much cheaper metal than bronze. Copper

[1] The Mayas of Yucatan (Central America) independently reached a civilization in many ways like that of the eastern Bronze Age, but without the use of metals. This shows that metal is not essential to some sort of low-level civilization.

in 1800 B.C., in the middle of the Bronze Age, cost nearly twice as much as did iron a thousand years later, while tin, the other essential constituent of bronze, was still more expensive.

Just when a generally applicable technique of iron-smelting was discovered is not clear. It may have been known to, and kept secret by, an Armenian tribe even before 2000 B.C. But it is from about 1100 B.C. that iron tools and weapons began to be used widely, in Palestine, Syria, Asia Minor and Greece, spreading thence to other countries.

The cheapness and wide distribution of iron had profound effects on man's way of life. At last metal tools became generally available to the farmer and enormously increased the productivity of agriculture. Before 1000 B.C. iron hoe-blades, ploughshares, sickles and knives were in use in Palestine. From about 700 B.C. iron axes permitted the clearing of forests and allowed a great expansion of agriculture in Europe. Soon Greek and Roman farmers were using a wide variety of iron implements, including shovels and spades, forks, pickaxes, mattocks, scythes and bill-hooks. Shears for shearing sheep (which had previously been plucked) were invented about 500 B.C.—and were also applied to barbering and cloth-cutting. The greatly increased productivity of agriculture yielded a surplus which could support a large number of specialized craftsmen. The product of the craftsman became generally available instead of being the monopoly of the wealthy. In particular the craftsman provided for the farmer those same tools with which the latter increased the productivity of his work. And thus, for the first time, there arose a balanced relationship between industry and agriculture, instead of the former one-sided relationship by which agriculture provided the food for the craftsman, but the craftsman's product went only to a select few.

Iron also provided the craftsman with a variety of tools—and better tools at that. By 500 B.C. carpenters had frame-saws and cross-cut saws, as well as a greater variety in iron of tools they had formerly possessed in bronze or stone, such as gouges, chisels, adzes, axes, drills, hammers and mallets; augers and planes were added to this equipment before 50 B.C. Smiths, by 500 B.C., had hinged tongs, bits, rymers, chisels and improved bellows. They had several kinds of specialized hammers, in sharp contrast to their Bronze Age predecessors, whose only hammers were balls of stone held in the bare hand. After 200 B.C. specialized nail-making anvils and blocks for wire-drawing came into use. Many of these, perhaps, do not imply great inventiveness, merely a logical working out of the possibilities which easily available metal provided. But in other trades there were notable new inventions.

The pulley, for example, appears to have been invented in the early Iron Age. The pulley seems an obviously useful invention and a simple step for peoples acquainted with the wheel. Yet there is fairly strong evidence that, for example, the Bronze Age Egyptians did not have it for the obvious use of hoisting sails, and it was certainly not used in their great building operations. The first definite evidence of its existence is in an Assyrian relief of the eighth century B.C. (Figure 5). Perhaps this is yet another example of how the social structure of the earlier civilizations retarded technical progress; or perhaps it merely indicates that, simple though it is, the pulley could not be made cheaply enough for practical use until iron became available both for materials and tools. Be that as it may, the pulley soon revolutionized the building industry. It provided a far better method of hauling stones into position than the Bronze Age method of pulling them up an earthen ramp, and then dropping them into position. It was developed into a rudimentary crane, which was used by the Greeks by 450 B.C. Capstans were also in use by that time, while by the beginning of our era sheers with block-and-tackle had appeared.

The possibility of using metal parts in machines and the use of iron tools for working in stone and wood, gave new potentialities for the making of various types of machine, and so opened up possibilities for new inventions. Most

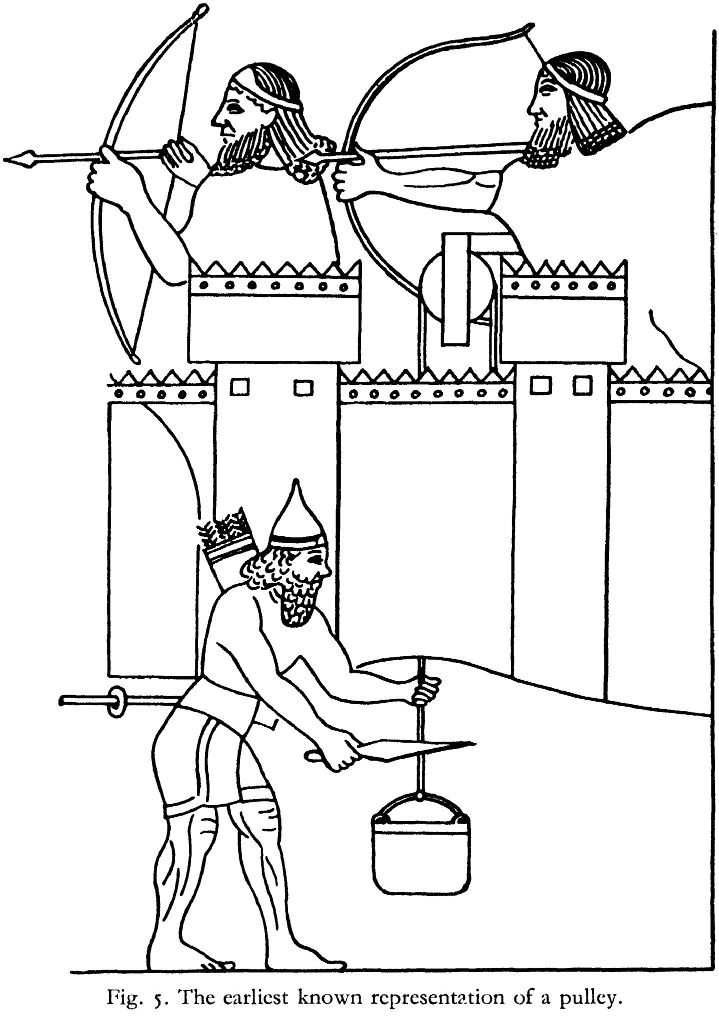


Fig. 5. The earliest known representation of a pulley.

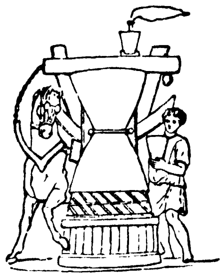


Fig. 6. A Roman horse-driven quern. In fact asses were more commonly used than horses.

notable is the mechanization of corn-grinding. The Bronze Age method was to pound the grain in a mortar or rub it on a slightly hollowed stone (the 'saddle quern') with a roller-like stone held in the hand and pushed to and fro. Every household did its own grinding. About 600 B.C. there appeared the rotary quern, in which the corn is ground between two circular stones, the upper revolving on an iron pivot projecting from the centre of the lower. Even in its simple form, turned by hand, the rotary quern saved much labour, besides giving a better flour. By the fifth century B.C. the further step had been taken of increasing the size of the quern, now installed in a commercial bakery, and working it by a donkey attached to a shaft projecting from the upper stone and walking round and round (Figure 6). This was the first extension of the use of non-human power to do man's work since the first harnessing of animals to carts and ploughs before 3000 B.C. It opened up great possibilities for the easing of human toil. But these, as we shall see, were not fully utilized. The same sort of principle was also applied about the same time to the grinding of ore (for instance, in the Athenian silver mines at Laurion), and another animal-driven machine was used for crushing olives to produce olive oil.

The general availability of iron tools also made possible the cutting of tunnels and building of aqueducts to bring water to towns and made many other such amenities available. It made possible considerable advances in the sphere of transportation (though there were no fundamental inventions here), by providing the means for building more, larger and better ships and waggons, and for road-making on an increased scale (for which purpose iron picks were in use by 850 B.C.).

In all these ways the use of iron brought about great changes in the life of mankind. The total capacity to produce

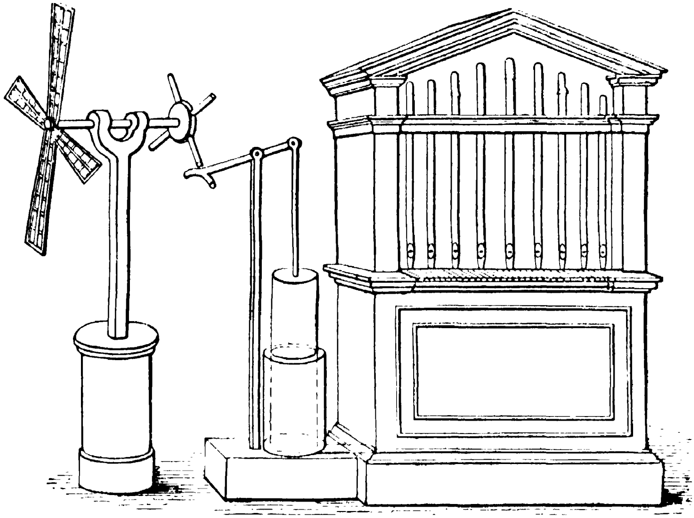


Fig. 7. A reconstruction of Hero's windmill driving a hydraulic organ. It is not certain that this reconstruction is substantially correct.

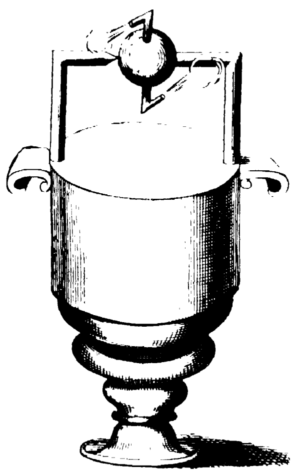


Fig. 8. A reconstruction of Hero's primitive steam turbine. The reaction of the steam issuing from the nozzles causes the sphere to rotate.

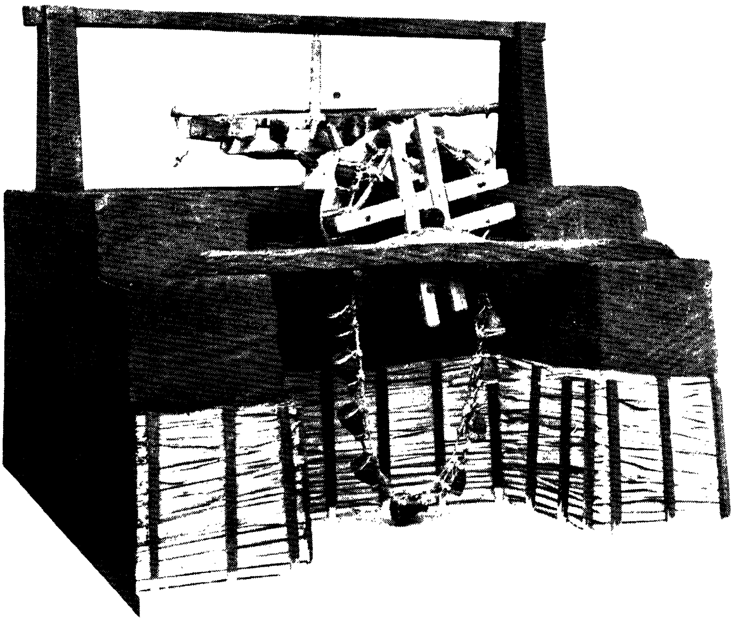


Fig. 9. Animal-driven chain of pots. This is a model of a primitive modern Egyptian version, but it probably differs very little from those used in the second century B.C. The ox is harnessed to the beam attached to the horizontal wheel; his circular path takes him over part of the ground that has been cut away in the model.

both necessities and luxuries greatly increased. The Bronze Age condemned the vast majority to live at a subsistence level, a very few being supported in luxury on the tiny surplus that the many produced. In the Iron Age a much larger proportion of the people could have a comfortable standard of living, and correspondingly the class of really wealthy could also grow considerably. The craftsman and trader could now work for a general market, in which even the peasants could afford their goods, instead of being condemned, as in the Bronze Age, to remain dependent on the nobles and temples. At first they produced to order, but to orders coming from a much wider section of the community than before. Later, it even became possible to produce their goods for sale on a general market, not knowing who the eventual purchaser would be—as the factory worker of today does not know who will eventually use his products. With improvements in transport the market for which they produced could be a very distant one, though these potentialities could only be fully realized in countries like Greece, well situated for marine transport. Even by 650 B.C. Greek exports were sold all over the eastern Mediterranean and the Black Sea. And as this tendency increased, some states became more and more dependent on trade, till eventually, around 450 B.C., Athens was incapable of providing herself with the basic necessity of corn and depended on importing it in exchange for exports of her specialized agriculture (olives, olive oil and wines)[1] and her mining and manufacturing industries (pottery, arms, etc.).

[1] The working up of this agricultural produce had a big influence on the development of machinery in classical times. An olive-crushing machine has already been mentioned. Again, in earlier societies which produced wine chiefly for immediate household use, the pressing of grapes had been done by such crude means as compressing them in a bag by twisting the ends. But for their extensive wine trade the Greeks developed special presses. The beam press, after a long evolution, reached a stabilized form about 200 B.C. The more advanced screw press (like the book press of today) appeared in the first century B.C.

Such an economy, then, had in it far more economically independent people than in the Bronze Age. Bronze, as we have seen, had implied the centralization of economic power, and therefore also a political power in the hands of an aristocratic few. Iron, with its consequence of good tools and weapons for a much greater number, and with the large classes of craftsmen and traders, independent of the patronage of noble families, led to a greater economic equality and a decentralization of economic power. Inevitably, this must produce political changes of a corresponding nature. The first few centuries of the Iron Age show a gradual democratization of society (not without bitter resistance from the aristocrats) till by 450 B.C., concurrently with its transformation into a state depending entirely on trade, Athens had a constitution in which there were virtually no legal differences between the rights of *citizens*. The word 'citizens' is italicized here because this democracy was limited by the exclusion of women, slaves and foreigners from citizenship.

Athens led the world in this change to a more democratic form of society, largely because she also led the world in making use of the new industrial possibilities opened up by iron tools. Besides contributing her share to the technical advances that we have mentioned earlier in the chapter, she was the first state to live by producing specialized goods for export. In order to be able to do this she also made fundamental innovations in the organization of industrial production. At first, production, even for the export market, was carried on by a host of independent craftsmen. But production for the market can be carried on better by the concentration of several workmen within a factory, each specializing in one aspect of the job and all together mass-producing the articles to be sold. A pottery factory, from the sixth century B.C. on, would often have separate specialists for throwing (i.e., shaping the vessel on the wheel), painting, and baking in the furnace. And, as Athenian industry grew, the size of the factories grew too. At the end of the fifth century B.C.

we hear of a bedstead workshop employing twenty slaves, an arms factory with thirty-two, a shield factory with 120. Perhaps twelve to fifteen slaves constituted a largish factory, but in mining the numbers ran up to 1,000, and perhaps beyond.

Note that in these later factories the workers were slaves. This was another new development, industrial slavery on a huge scale, largely replacing the former free craftsmen. It provided the labour for the great expansion of the export industry mentioned above, but at the same time it introduced new factors which were soon to put an end to Athenian progressiveness. Slave labour, while triumphant Athenian armies and successful pirates made it generally and cheaply available, was a convenient solution to all problems of heavy labour. It was usually simpler and cheaper to put slaves on to heavy work (even if it wore them out in a few years) than to design and construct a machine to do it. Thus, after about 450 B.C., the growth of slavery very greatly inhibited the spread of the animal-driven machines that we described above. At the same time, since manual work and even the management and supervision of it was the lot of these slaves, it came to be despised by citizens. And so the type of contradiction that we described near the end of Chapter II was revived in a new form. The slave, with no education, no leisure and no hope of reward, was not in a position to invent better productive methods; the citizen despised manual labour, and even despised the process of invention as being connected therewith.

A second great factor which greatly inhibited technical advance in this period was the division of the Mediterranean world between a large number of tiny city states, almost continuously at war with one another. On the one hand this division greatly restricted the markets available for manufacture of goods; on the other it diverted to warfare the energies of many men (perhaps many geniuses) who might otherwise have contributed something to human progress.

The Greek world, especially Athens, had made enormous advances by 450 B.C. But now, as a result of these contradictions, the creative impetus waned, and after 400 industry went into decline. The contradictions were partially solved when Alexander the Great made his series of conquests which forcibly united the Greek world and then expanded it into a vast empire embracing Egypt, most of hither Asia, and even parts of India. On Alexander's death this empire disintegrated, not however into city states, but into three or four empires of considerable size. And a new economic and cultural unity held all this territory together. Many of the restrictions arising from the former divisions were removed. Commerce expanded five times in a few years. Formerly Greek trade was more or less confined to the eastern Mediterranean; now it reached from the Danube in the north to Ethiopia in the south, from India and even China in the east to the Atlantic coasts. Ships increased in speed and size, reaching even 5,000 tons, though that was an exception, most ships being well under 100 tons. Great harbours were built and canals dug, for example between the Mediterranean and the Red Sea. Lighthouses were built, beginning with the famous one at Alexandria. Alexandria, capital of the empire of the Ptolemys, centred on Egypt, became the commercial centre of the world.

Industry expanded along with commerce. Division of labour was carried much further till, for example, the stonemason did not sharpen his own tools, and the quarryman who cut the stone did not sweep away the sand. Industrial slavery decreased, though only for a time, and the factories were run either by free wage-labour, or the temporarily conscripted labour of men who otherwise were free (a method adapted from the Bronze Age). Such conditions once more encouraged mechanical inventiveness, and the three centuries after 330 B.C. produced a crop of inventions greater than in any comparable period between 3000 B.C. and the later Middle Ages.

For the first time we begin to find fairly comprehensive written descriptions of some mechanical matters to supplement the archæological evidence and occasional literary evidence on which our story of previous periods is based. The educated classes, who could leave a record of their work, were at last beginning to take some interest in mechanical matters. In theory the upper classes still despised everything connected with the crafts, but in practice, apparently, industry now held such an important place in the general economy that a few of them at least applied their theoretical training to industrial matters. Some crafts or professions had become respectable, too: for example, surveying. The division between the worker and the man of the leisured classes who had time and education at his disposal, which had frustrated advance in the Bronze Age, and again after 450 B.C. in the Iron Age, was less clear than before. It did, however, remain and it tended to grow again; so that gradually the interests of the educated in mechanical matters was diverted from the invention or improvement of useful machines to the construction of ingenious mechanical toys. And, in point of fact, the most important inventions of the period were still the work of unknown craftsmen.

Among those of the educated classes who tackled serious mechanical problems, the most outstanding was Archimedes (287–212 B.C.), one of the greatest mathematicians of all times. By developing the theory of the lever he virtually initiated the science of theoretical mechanics (though but little use was made of it in antiquity and it did not prove of much practical value till its study was once more taken up at the end of the Middle Ages). He may have invented the screw pump which bears his name, and which at any rate came into use about that time for irrigation and for pumping water from mines and the holds of ships. And he invented and constructed various military devices for the defence of Syracuse, with such success (according to the tradition) that the attacking Romans fled in fear when any strange apparatus appeared on the walls of the town. The chief military machine of Greek times was a sort of artillery using, not explosives, but the elastic power of twisted ropes, capable of throwing a sixty-pound stone 200 yards. Archimedes is said to have greatly improved these machines. Other attempts to improve this 'artillery' were made by Ctesibius (second century B.C.) and Philo of Byzantium (third or second century B.C.), the latter in particular suggesting the use of the power of bronze springs or compressed air instead of twisted ropes. Neither of these attempts was successful; those of Philo certainly could not have been carried out with the technical equipment of the times. Ctesibius is also generally considered to have invented the force-pump. It was not, however, used very widely, though it was apparently used in fire engines and for driving hydraulic organs (which were invented in the second century B.C., possibly by Ctesibius himself).

Hero, a later Alexandrian writer who lived somewhere between 100 B.C. and A.D. 100, left treatises which described a large number of mechanical devices then in use. He was probably a surveyor and it is therefore interesting that two of the most useful of them were a sort of theodolite and an instrument for measuring distances by counting mechanically the rotation of a wheel, as a cyclometer does today. The latter contains a train of gearing—the first literary record of gearing in existence. He also describes pumps, a syringe, a fire engine, and gadgets for automatically adjusting the wick, oil level, etc., of lamps. But by far the greater part of the devices he describes 'resemble the equipment of the temporary fun-fairs opened in shops on short leases in modern cities' (as Crowther puts it).[1] They include, for example, a slot machine for delivering holy water, puppet theatres worked by falling weights, a device whereby a fire lit on an altar causes the temple gates to open (these had their 'use' for overawing the superstitious masses as a part of technique

[1] *The Social Relations of Science* (London, 1941), p. 99.

of government), and things like 'an automaton, the head of which continues attached to the body after a knife has entered the neck at one side, passed completely through and out of the other; which animal will drink immediately after the operation'. This illustrates well enough what happened when the first impetus of the expanding industry after the Alexandrian conquests had petered out and increasing class distinctions had once more cut the theoretician adrift from the practical problems of the craftsman.

Two of Hero's devices are worth special note. One is apparently (though there is some doubt about the meaning of a vital word in his description) a windmill arranged to drive the bellows of an organ by means of a trip-hammer action (Figure 7). The other is a primitive reaction turbine, whose mode of action can be seen from Figure 8. The significant point is that here we have two devices capable of being developed into effective prime movers.[1] But to Hero they were merely toys. The turbine merely turns; it does not turn anything. The windmill drives the organ merely as an exhibition of ingenuity. No attempt, apparently, was made to apply either of them to useful work in order to lighten toil. True, the turbine could not, at the current technical level, have been made into an effective machine, but the windmill probably could. However, the significant fact is that no attempt was made, for only by trial could they have been proved impossible. This can only be attributed to the general availability of slave labour for all work requiring great power—while this apparently inexhaustible supply of human power remained, inventors saw little reason to apply themselves to the task of harnessing natural power.

While human ingenuity was thus being wasted in constructing elaborate toys, unknown craftsmen were in fact making inventions of far more lasting importance; and among

[1] A prime mover is an apparatus (water-wheel, steam-engine, petrol-engine, etc.) which converts some natural source of energy into mechanical power capable of driving machinery.

these were important steps towards the production of really useful power-driven machinery. The water-raising wheel (for irrigation and much later for draining mines), a wheel fitted with pots which lift the water as it turns and pour it into a trough, was known in the Bronze Age, as was also, probably, the chain of pots, an extension of the same principle by fitting the pots to a rope which passes over the wheel but hangs to any desired depth below. They were originally driven by treadmills or windlasses. Sometime after 200 B.C. the step was taken of arranging them to be driven by oxen (Figure 9). The oxen walked round a vertical shaft, as in the rotary quern described earlier, and this was geared to the horizontal shaft of the wheel. This represents another important extension of the use of animal power and is also probably the first use of gearing to transmit power.

Sometime after 100 B.C. a far more revolutionary development took place somewhere in the Near East—the invention of the water-wheel. Men, it will be remembered, had first harnessed the power of inorganic nature by their use of sailing ships before 3000 B.C. This was the first further use of such power and also the first application of inorganic power to stationary machinery. For centuries its use was confined to flour-milling.[1] One of the earliest references is in a poem by Antipater of Thessalonica (about 65 B.C. or possibly a few years later):

> Cease from grinding, Oh you toilers. Women, slumber still,
> even if the crowing rooster calls the morning star.
> For Demeter has appointed Nymphs to turn your mill
> and upon the water-wheel alighting here they are.

[1] This may not be strictly true. Philo of Byzantium, referring to a chain of pots, as mentioned above, says 'the apparatus is to be installed at such a level below the stream that the force of the water will drive the whole mechanism'. It is not clear whether Philo is referring to actual practice or merely to an idea of his own and, if the latter, whether the idea was put into practice. There is thus the possibility that water-power was occasionally used to drive the chain of pots even as early as the third century. Nevertheless all the specific references to water-power before the fourth century A.D. are concerned with flour-milling.

See how quick they twirl the axle whose revolving rays
spin the heavy rollers quarried overseas.
So again we savour the delights of ancient days,
taught to eat the fruits of Mother Earth in ease.[1]

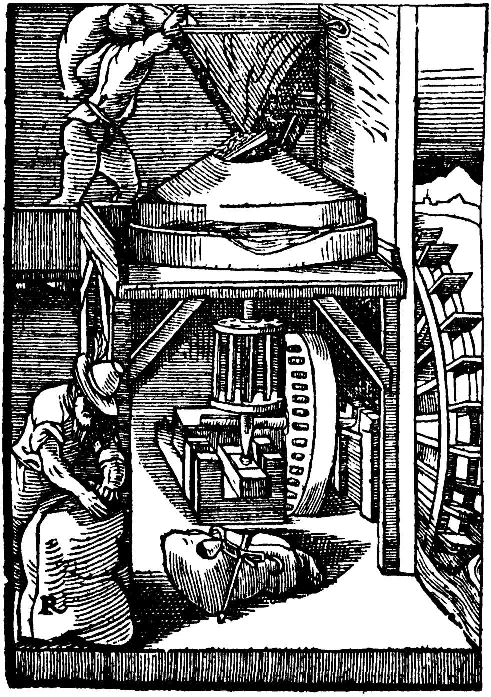


Fig. 10. Reconstruction of Vitruvius' water-mill.

The Roman Vitruvius about 16 B.C. gives a description of a water-mill in which the power is transmitted from wheel to grindstone through a pair of gears, as in Figure 10. This type of gearing was already in use for the water-raising wheel described above. There is a more primitive type of mill, with the wheel revolving horizontally on a vertical

[1]Translated by Sir W. Marris in *The Oxford Book of Greek Verse in Translation.*

shaft, which needs no gearing, but it is not clear whether this type preceded the geared mill.

This invention came at the time when the Romans were acquiring their domination over the whole civilized world. The Roman economy, more even than the Greek, was based on slave labour. While the Empire expanded, the supply of captured slaves was apparently inexhaustible. Slavery was a more convenient way of dealing with heavy power problems than the development of power-driven machinery. Thus during the period of the Roman expansion there was little development of the use of the water-wheel. Even the driving of querns by animal-power considerably decreased, slaves doing the work instead. (This is probably connected with the inefficiency of the ancient harness, referred to in Chapter II. So little of the potential power of the animal was actually effective that it was but a poor competitor of the slave.) Thus slavery, as always in the ancient economy, prevented the full application of non-human power.

The contradictions and antagonisms that had retarded technical progress at various times in the Greek world applied with redoubled force to the Roman Empire. Also it is probable that the Greeks had carried technology about as far as could be done in an economy based on slave labour. The Romans, living with the same basic social organization, could do no more therefore than exploit, sometimes on a larger scale, the technique they had learnt from the Greeks. The whole period of Roman greatness produced not one single mechanical invention of importance.

When Roman power began to decline, when successful armies no longer brought in victims as slaves, a serious labour shortage began to appear. In these circumstances at last some notable development began to take place in power machinery. The fourth and fifth centuries saw a considerable spread of water-mills in various parts of the Empire. In the mid-fourth century they appear near Rome and before the end of the century in Rome itself. Thus, haltingly, began the trend, not to be fully expressed till the Middle Ages brought new social conditions, towards the widespread use of water-power to lighten toil. Still the wheel was used only for corn-milling. One solitary exception is on record—a water-driven sawmill for cutting marble in the fourth century—but it was the role of the Middle Ages to generalize the use of the water-wheel and apply it to a whole series of new tasks.

CHAPTER IV

THE SECOND INDUSTRIAL REVOLUTION: EMBRYO (500–1440)

THE decay and final collapse of the Roman Empire meant that for a time some of the higher peaks of civilization were lost. Art, literature and the more formal and theoretical aspects of science were forgotten (except in small areas where they were preserved in a petrified condition until a later age found a use for them). Many historians of culture have been concerned only or mainly with these particular aspects of civilization and have therefore seen the Middle Ages as the 'Dark Ages' in which 'civilization' had perished, in which no progress was made till, in a rather magical 'Renaissance', men rediscovered the arts and sciences of Greece and Rome and thereupon began a return to 'civilization'.

But it must be remembered that art, literature and theoretical science in the ancient world were the prerogative of a few rich and leisured men. They were not true indexes of the level of civilization. If we look beyond them to consider the way in which mankind in general lived, we find a different picture of the Middle Ages as an era of renewed advance after the long period of comparative stagnation. The level of civilization is to be measured, not only by its peaks of intellectual culture, but also by the standard of living of its *whole people*. And the latter in turn depends on improvements in the means by which men wrest their living from nature—on technical invention and its application. We have seen that the period from 2500 B.C. to the end of the Roman Empire produced comparatively few inventions—so far as the subject of this book is concerned, the only real outstanding ones were a process of smelting which made iron generally available and had therefore a very considerable effect on living standards, the application on a small scale of animal power to certain types of machinery, and the use—on a very limited scale—of water-power. The Middle Ages began by applying very widely those techniques which had previously been restricted by the availability of slave labour and, after a few centuries, began to produce a series of new inventions which laid the foundations of the modern world.

The reasons for this renewed technical progress are too complex to discuss in full here (even if they were now fully understood), but some indication must be given. The collapse of the Roman Empire brought also the collapse of that particular social structure, based on slave labour, which had effectively inhibited progress during the greater part of Græco-Roman times. Slavery did not suddenly and abruptly disappear; it progressively diminished in scale throughout the last few centuries of the Roman Empire and the first few of the Middle Ages. In fact the slave supply could only be maintained while Rome was a strong and expanding military power. As her power declined, the supply dwindled and that, until a new basis of production was found, could only mean a return to a more primitive life.

Later Roman society returned, in fact, to a form of organization that had existed before the slave societies emerged—a system of local self-sufficient units, based on their own agricultural production, doing their own simple manufactures on the spot with little trade except in a few essentials like iron and salt. But such a change meant a reduction in the severity of class-divisions; instead of ranging from a 'divine' Emperor to a 'sub-human' slave, the strata ranged only from a serf who, while bound to the soil he worked, had very definite rights to a certain proportion of the products of his own labour, to a lord of the manor who was sufficiently closely in touch with his serfs to have some real knowledge of the processes of production. The barbarians who invaded Europe as Roman frontiers receded and mingled with the former Rome-ruled population, bringing with them recent memories of a more nearly classless society, helped to complete the transition to a society in which the relative status of the worker was much higher than in antiquity. The craftsman, who never entirely disappeared and in the coming centuries became gradually a more and more important element of society, was in a position to benefit from the results of his inventiveness to a far greater extent than his counterpart in antiquity. Such changes encouraged inventiveness.

The supply of slaves having failed, the early Middle Ages was faced with a severe shortage of labour. For tasks of heavy labour the answer of antiquity had been simple—many slaves. The Middle Ages had to find another answer and this answer had to be the development and application of sources of power other than human muscles.

First the water-wheel, whose use had been so greatly restricted till late in Roman times by the easy availability of slave labour, was applied on a greatly increased scale. At first it was applied as previously to the grinding of corn, and the number of corn mills grew till, for example, in England in 1086 there were over 5,000 mills (probably mostly water-driven). That is about one to every 400 of the population, certainly enough to make a profound difference to the people's way of living. Later water-power was applied to a great diversity of industries, beginning with the fulling of woollen cloth. Fulling is the process of beating the cloth in water to shrink it and so increase its density and durability. Formerly this was done with the hands or feet or with clubs,

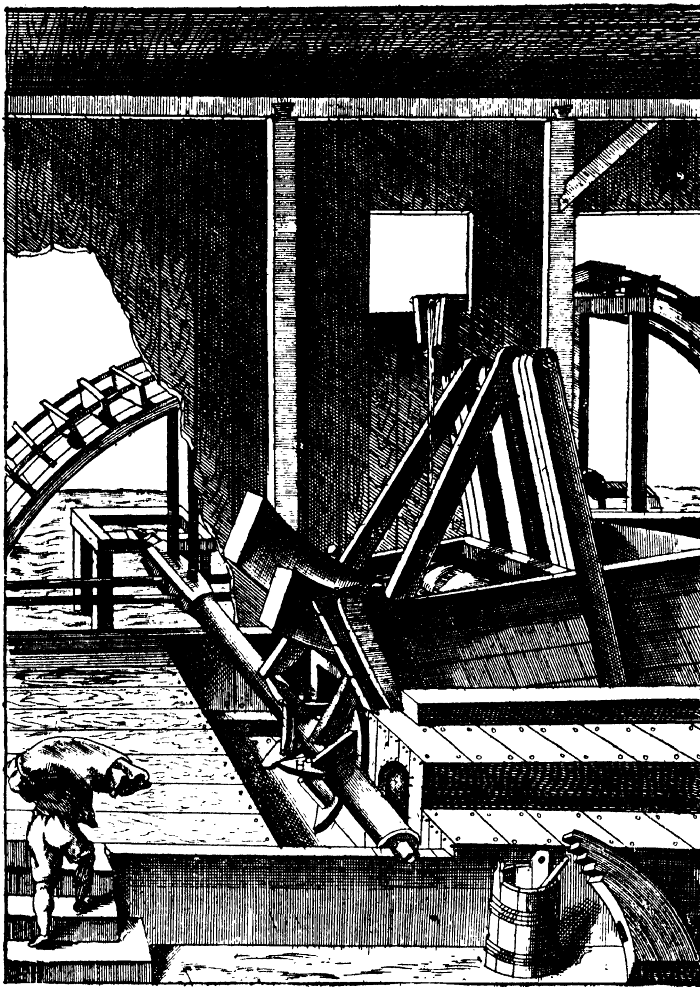


Fig. 11. An advanced form of the water-driven fulling mill, from the sixteenth century.

but from the second half of the twelfth century water-power was applied to the process, using the trip-hammer principle (Figure 11). About the same time trip-hammers were also applied for crushing woad, tan bark and similar materials and by the fourteenth century for forge-hammers. However, a different principle was applied earlier (in the twelfth century) for heavy forging—that of the tilt-hammer, in which a heavy hammer at one end of a beam is counter-balanced by a vessel which can be filled with water from a duct, thus raising the hammer; then the vessel is suddenly emptied by opening a valve, allowing the hammer to fall quickly. Water-power was used to drive forge bellows in 1295, saw-mills also in the thirteenth century and grind-stones in the fourteenth. And by about 1450 it was in use in pumping[1] for mines and salt-pits, winding in mines, and driving iron rolling-mills and wire-drawing machines.

In the twelfth century the appearance of windmills made another source of power available in Europe. (It is not certain whether this windmill—more or less the type we know today—is an independent European invention or is derived from a different type which was in use some centuries earlier in the East.)

Besides wind and water, the only other source of power available before the steam-engine was that of animals. It will be recalled that the harness at the stage it had reached before 3000 B.C. was such as to waste most of the power of the animal (Figure 4). Throughout the Bronze Age and Græco-Roman times no improvement was made. In the second half of the tenth century a decisive change is noticeable in the harnessing of animals in Europe and by the twelfth century a completely modern harness had been developed, eliminating the defects that we described in Chapter II. Meanwhile horseshoes appeared almost simultaneously in Byzantium

[1]The pump, as opposed to other devices, such as chains of pots and Archimedean screws, was first applied to mine drainage sometime in the Middle Ages, though it had been used for other purposes in late Greek times.

and N.W. Europe about A.D. 900. Thus at last it was possible to make full use of the tractive power of animals. This meant more than improved transport. Animal power was also used widely for driving machinery, on lines which had been opened by inventions of Greek and Roman times, but little developed because of the inefficient harness and the availability of slave labour.

These three sources of power, at last rationally used, made a tremendous difference to the world. Before their arrival a high level of civilization could only be provided for a few, on the basis of huge numbers of slaves, used not as workers, but as sources of power, as engines. But a horse driving a machine with the now efficient harness was the equivalent of ten slaves, while a good water-wheel or windmill gave the work of up to 100 slaves. Athens had had about one slave to every two freemen. England's cornmills alone in 1086 already represented one slave to every four or five of the population and that was before the use of water-power had been anything like fully developed. These new sources of power, therefore, provided the basis for the development of a high level of civilization without slavery, and as they were developed slavery died out.

The devising of an efficient harness was by no means the only major improvement in transport machinery in medieval times. From the fourth millennium B.C. to the later Middle Ages the steering mechanism of ships had remained basically unchanged. It was, in fact, little more than an oar, such as was used in propulsion, somewhat specialized for steering (Figure 2). In the larger ships it was lashed to the stern and fitted with a lever, not unlike a tiller, to give more purchase. All this was little more than an extension of the method of steering a canoe by a paddle held by a man sitting in the stern. It was not an effective method. Little purchase could be brought to bear on it and it was too easily deflected by the battering of the waves. For the small coasting ships of 3000 B.C. these disadvantages mattered little, but as ships grew in size the inadequacy of the steering mechanism became more and more important and in fact limited the size to which ships could be built. Attempts were made to overcome the difficulty by fitting several steering oars, but these were never really effective. Also, with such a poor steering mechanism ships could not sail close against the wind. With sailing so inefficient, galley slaves had to be used for many purposes, and so the poor steering mechanism was another factor in maintaining slavery. In the thirteenth century there appeared the modern type of rudder, fixed firmly to the stern-post, itself an extension of the keel and therefore an integral part of the ship. It was well under water, free from the effects of the waves, and so its size could be greatly increased, permitting in turn a corresponding increase in the size of the ship. And it gave sufficient control for ships to be able to sail close to the wind. In the next two centuries shipping made more progress than in the previous four millennia. From the first sailing ships to the end of the ancient world navigation merely developed from sailing on rivers to coasting round parts of continents (with the one very special exception of crossing the Indian Ocean with the aid of the reliable monsoons). But in 1492, only two or three centuries after the invention of the modern rudder, the Atlantic was crossed. A further important improvement in navigational instruments was the invention of the ship's compass in the twelfth century, while inland water transport was greatly improved by the appearance of canal lock-gates in the fourteenth century. A minor, yet significant, invention affecting local transport 'on the job' was that of the wheel-barrow in the thirteenth century.

Naturally these tremendous changes in transportation had very great social effects. One of them, not obvious at first sight, was to make possible the wider application of water-, wind-, and animal-power that we discussed above. For power-driven machinery can only be used if there is sufficient work to do to make it economical; and that usually implies bringing the work over considerable distances to the machine. The improved transport facilities of the Middle Ages made it possible to carry the corn to a central water-mill or the tree trunks to a central saw-mill. With its inferior transport the ancient world had to be content with more localized industry on too small a scale to use much power-driven machinery. Thus the development of power machinery, the improvement of transport and (as we have seen) the abolition of slavery were all closely interlinked.

Again the new transport facilities paved the way for what is often called 'the commercial revolution', the era of great commercial expansion which began in the later Middle Ages. Within a few centuries the countries of Europe were no longer self-sufficient, but imported raw materials and products (luxuries at first, later necessities) from all over the world. And this was an important factor in the growth of industry and with it of more and more powerful machinery that we shall describe in later chapters.

Changes in the plough revolutionized agriculture. In Chapter II we described the plough as it was at the beginning of the Bronze Age. This inefficient form, improved only by the addition of an iron ploughshare, remained in use in the Mediterranean countries till the Middle Ages. Though it merely scratched the surface, it was not hopelessly inadequate for light soils, but for the heavy soils of N.W. Europe it was useless. Before 100 B.C. (perhaps as early as 400) the barbarians who lived there invented a much more adequate heavy plough. This had a coulter to cut the sod, a mouldboard to turn it over, and wheels which enabled a more even furrow to be cut and lightened the work of the ploughman by relieving him of the task of keeping the plough at the proper level. Successive refinements during the Middle Ages brought the plough by the thirteenth century to an essentially modern form. Another important new tool of agriculture was the hinged flail for threshing. Hitherto threshing had been done by driving cattle over the stalks, dragging sledges fitted with stones in the bottom over them, or beating them with straight sticks. The hinged flail was a big advance which came probably about the eleventh century.

Clothing is second only to food as a necessity of life: so it is natural that in this era of progress textile machinery should also undergo fundamental changes. Progressive improvements had taken place in the loom with the addition, at dates that are ill-defined, of better heddles, pedals and reeds. In the fourteenth century a further improvement arrived in the form of a reed set in a runway for the shuttle, which guided it and took its weight off the warp threads. Medieval Europe also received from China an important new type of loom, the draw-loom, which allowed the weaving of complex patterns through an arrangement for selecting the set of warp threads to be raised or lowered at each passage of the shuttle. This type of loom first appeared in China between the ninth and third centuries B.C., reached the Near East by the fourth century A.D. and in the Middle Ages spread to Europe.

The spindle at the beginning of the Middle Ages had not advanced beyond that of the earliest spinners. Now fundamental changes took place, leading to the invention of the spinning machine. Silk, which is provided as a continuous thread by the silk-worm, is easier to deal with mechanically than fibres like linen, cotton and wool which have to be spun in the true sense to join many short fibres into a continuous thread. Silk requires only the firm twisting together of two or more threads to give

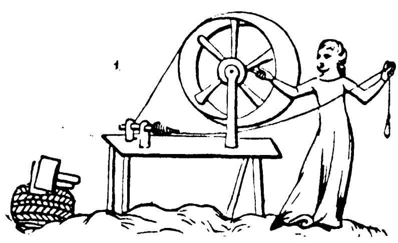


Fig. 12. A fourteenth-century quilling wheel. The thread is being wound on to the bobbin from a primitive spindle hanging from the spinster's left hand. By that date, this type of wheel was also in use for spinning, but the quilling and spinning had to be done alternately.

strength and the winding of these on to reels. These processes were mechanized at Bologna in 1272. The development towards the spinning wheel which was to be found in every cottage until a couple of centuries ago and which still figures largely in our museums, began about the same time. In this a large wheel is turned by hand (and later by treadle, see Chapter V) and a band from this to a small wheel attached to the spindle causes the latter to rotate quickly (Figure 12). At first the wheel was apparently used merely for the process of quilling, that is winding on to a bobbin or quill a thread that had already been spun on a primitive spindle. But by 1298 at the latest the wheel was used for the spinning itself and in the fourteenth century such spinning wheels spread widely. We have already mentioned another important advance in textiles—the application of water-power to fulling.

The most complex machines produced by the Middle Ages were mechanical clocks. Water-clocks, measuring time by the amount of water dripping out of a vessel through a small hole, had been in use from the Bronze Age. They were improved in Greek times by the addition of various regulating devices and mechanical connections to show the time by means of a pointer on a scale. And, possibly in Greek or Roman times, certainly among the Arabs from the sixth century on, there were added elaborate devices to work puppet shows at each hour. But the water-clock was never a reliable time-keeper. Mechanical clocks first appeared in the thirteenth century. It is not clear what regulating devices were first used in them, but by 1348 at the latest the foliot balance and verge escapement, a quite efficient regulator, had been perfected. It appeared in the Dover Castle clock (Figure 13) of that date, which is now to be seen in South Kensington Museum. There are records of thirty-nine clocks built between 1232 and 1370 (though some of them were not full clocks exhibiting a continuous record of the time). Most of them were public clocks in large towns, often attached to the cathedral or monastery which still remained largely the centre of town life. By 1500 most towns had a tower clock. This growth of public timepieces is perhaps an indication that medieval town life was already becoming so highly organized socially that some convenient time standard was essential by which all citizens could regulate their actions.

Clock-making, even though the early clocks were large and crude, demanded a much higher standard of accurate workmanship than did any previous machine. Subsequent mechanical advances owe much to the skill in fine workmanship which was developed by clock-makers, allied to the techniques of heavy engineering that were used by millwrights and builders of other power-driven machinery.

One of the latest and most revolutionary developments of medieval times was that of printing. China had printing several centuries before Europe, but it is not clear whether Europe learnt from China or invented printing independently. Europe certainly owes to China one of the fundamental materials for printing—namely paper, the only material with properties suitable for printing that could be produced cheaply enough. It appeared in China about A.D. 100, and until the end of the seventh century it was confined to the Chinese Empire. Thereafter it appeared in Samarkand, on the route from China to the then flourishing empire of the Arabs, in 751. We can then trace its spread through the countries dominated by Islam, through Baghdad (793), Egypt (900), Morocco (1100), till about 1150 it reached Spain, the main point of contact of the Arab and European civilizations. Thence it spread to South France by 1189, Italy in the thirteenth century, Germany in the fourteenth and so on.

Three main stages may be distinguished in the invention of printing. First came printing from wooden blocks, so that a separate block had to be cut for every page. The next stage was printing from movable wooden characters, so that by having several hundred copies of each character the printer could combine them in a frame to set up the type for each page in turn; but each of the several hundred copies of each character had to be cut separately. Finally came the use of movable metal type, all the copies of each character being mass-produced by casting from a single mould.

In China wood-block printing appeared in the sixth century, movable wooden characters in the eleventh and movable metal type (in Korea) about 1390. The European developments are all considerably later. The techniques used in Europe are distinctly different from those of China, so that it is fairly certain that the invention was not simply imported to Europe from China. But that does not exclude the possibility that, with more frequent trading contacts between the two civilizations, news of Chinese printing may have reached Europe and stimulated some individuals to see if they could produce a similar process.

The first sign of printing in Europe is the use of woodcuts to print the elaborate capital letters for books that were otherwise still copied by scribes in manuscript. This appears in a monastery at Engelberg in 1147. Block-printing is found at Ravenna in 1289 and in the fifteenth century it appears as a common process in several places, for example Brussels, Ulm, Nordlingen, Venice. The transition to movable and metal type seems to have followed quickly and in several places simultaneously. We find it at Limoges in 1381, Antwerp in 1417, Haarlem in 1435 and Avignon in 1444 (it was apparently a well-established process there by that time). But it was in Mainz that the process was brought to perfection by Gutenberg between 1436 and 1450. We can take the last date as ushering in the era of modern printing.

Printing has had as profound effects on human life as the inventions in power machinery and transport that we discussed above. The reader can think out those effects for himself by pausing to consider the role of printing in the modern world or its influence on the history by which the modern world developed from that of the fifteenth century. But let us note here that it played an important part in breaking down one of the major contradictions that had hitherto prevented the best application of human ingenuity to technical invention—the separation between the practical craftsman and the man with education. We have seen how changes in social structure reduced this separation by reducing class distinction and making practical affairs more important and more 'respectable'. Printing also helped by bringing books, which had hitherto been valuable treasures because of the costly process of hand copying, within the range of wider classes of people. Within a century or two the ambitious craftsman had the means to study in books the accumulated experience of others and to apply it to his own problems. This was a revolution comparable to that brought about by the introduction of iron. Iron democratized physical tools; printing did the same for the tools of thought. This was an important factor in the increasing rate of invention that came in the following centuries.

The primary kit of carpenter's tools with which these many new machines were produced was, on the whole, not greatly changed since ancient times, but some significant advances were made. The brace and bit replaced the bow-drill which had been in use since neolithic times. The lathe was almost certainly a medieval invention, though some writers have put it as early as the Bronze Age. Lathes in the Middle Ages and for some time to come were usually of the pole-lathe type, the spindle being driven by a cord wound round it as in the bow-drill, attached at the bottom to a treadle and at the top to a flexible pole. The late Middle Ages saw the appearance of the method of driving that was later to become the commonest for lathes and many other machines—the treadle and crank motion. Nuts, bolts and spanners were also of medieval origin.

Though the machines we have mentioned were constructed largely of wood, they did require metals for certain bearing parts and cutting edges. A much greater demand for metals came from medieval warfare, with its complex armour and its crude cannon added to earlier types of armaments. Thus in metal working we find the beginnings of methods that in the next century or two were to revolutionize the industry. For example a wire-drawing machine appears in Nuremberg in 1350, rolling-mills in early fifteenth-century Germany. But the most important advances in metal-working were those arising from the application of water-power to its heavier aspects, as described above. It was the application of water-power to produce blast that made possible in the late Middle Ages the production of *cast* iron. Previously, with the lower furnace temperatures available, the iron was obtained as a spongy solid mass, mixed with slag, which had to be beaten laboriously to expel the slag and reduce the metal to solid wrought iron. The metal could not be melted in the earlier forges, but must be beaten into shape at temperatures high enough to make it plastic. Power-driven blast enabled molten metal to be obtained, which could be run into moulds to produce the required articles much more quickly and cheaply by casting. Blast-furnaces first appear in the fourteenth century but only in the late fifteenth do they become common. Cast iron has a different composition and therefore different properties from wrought iron (in particular it is more brittle) and therefore could not be used in all the places where wrought iron had previously prevailed. Nevertheless by producing cheaper iron, eminently suitable for some purposes, it contributed greatly to the industrial changes of the succeeding century.

Thus the Middle Ages changed the face of industry. The Power Age had begun and, though it was still a long road to the general application of power that we know today, yet already water-, wind-, and animal-power were doing many things for which previously only human muscles were available. Machines entered into many phases of life. They had become familiar objects. What is more, they had been successful—obviously so—in solving many problems of living. Men began to have a new faith. The spirit of the

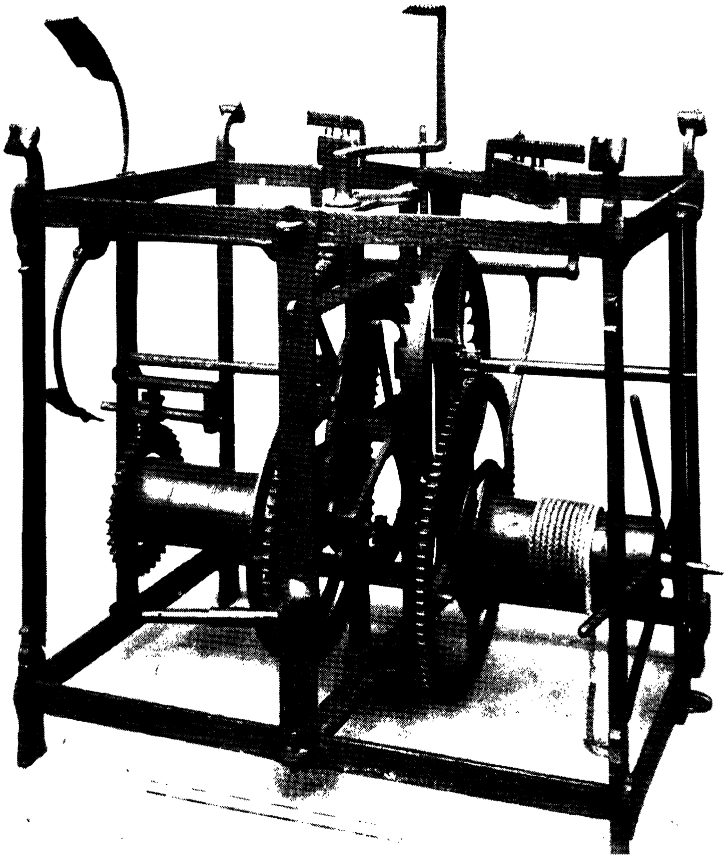


Fig. 13. The Dover Castle Clock.

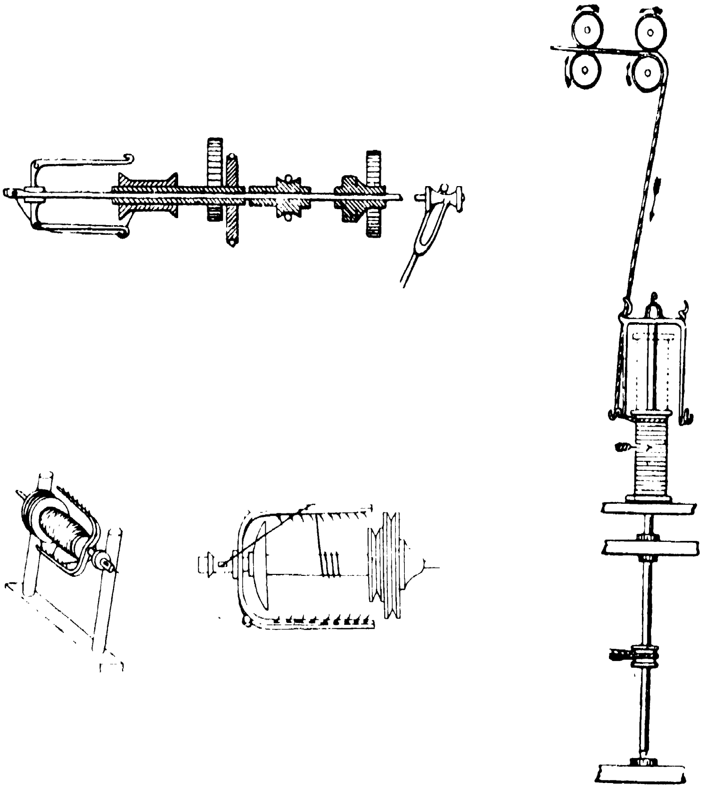


Fig. 14. Various forms of the spindle with flyer, which allowed spinning and quilling to be carried on continuously and simultaneously.

Leonardo's design (top) contains not only arrangements for rotating the spindle and flyer at different speeds, but also a mechanism (worked by the fork on the right) for causing the flyer to reciprocate bodily from left to right and thus build the thread evenly on the bobbin. Jürgen's simplified version (bottom, left and centre), which came into general use on the domestic spinning wheel, has no building mechanism. In the system (right) developed by Wyatt, Paul and Arkwright, the right-hand pair of rollers rotates faster than those on the left, thus drawing out the bundles of fibres before passing them to the spindle and flyer below.

times was expressed, as early as the mid-thirteenth century, by the English monk and scientist, Roger Bacon:

'I will tell first, therefore, of the wonderful works of Art and Nature, in order to assign to them afterwards their causes and means; in these there is nothing of a magical nature. Hence it may be seen that all magic power is inferior to these achievements and unworthy of them. . . For first machines of navigation can be constructed, without rowers, as great ships for river or ocean, which are borne under the guidance of one man at a greater speed than if they were full of men. Also a chariot can be constructed that will move with incalculable speed without any draught animal. . . Also flying machines may be constructed so that a man may sit in the midst of the machine turning a certain instrument, by means of which wings artificially constructed would beat the air after the manner of a bird flying. Also a machine of small size may be made for raising and lowering weights of almost infinite amount—a machine of the utmost utility. . . Machines may also be made for going in sea or river down to the bed without bodily danger. . . And there are countless other things that can be constructed, such as bridges over rivers without pillars or any such supports. . .'

The possibilities Bacon speaks of were not to be realized for many centuries,[1] yet these were well-founded speculations—founded on the observation that machines had in fact succeeded in giving men many of their desires, where hopes misplaced in magic had been dashed. They epitomized the new faith, by which man was in the next seven centuries to make more progress toward a fuller life than in the whole of his previous history. While Bacon wrote of great things far ahead, other men were tackling the practical immediate problems in terms of the new faith—a faith based on experience—that these problems *could* be solved by mechanical inventions.[2]

[1] Some of them were not so very distant. A successful submarine was built in 1624, though of course it was not till modern times that submarines could be anything other than curiosities.

[2] Magical beliefs, of course, lingered for centuries, but we are concerned here to emphasize the new positive and progressive trend.

CHAPTER V

THE SECOND INDUSTRIAL REVOLUTION: CHILDHOOD (1440–1660)

THE period with which we deal in this chapter is one that acted in the spirit of the quotation from Bacon given on p.49. In it the use of machines already known was greatly extended and many new types of machinery were invented. But more significantly it was a period of first attempts on many mechanical problems, some of which were not to be successfully solved for centuries. From the conscious strivings of this period, unsuccessful though they were at the time, arose many of the successes of later times. Thus, as we shall see below, it was in these two centuries that men began to realize the enormous potential power of steam and to seek for some way of harnessing it for driving machinery; they did not succeed, but building on their experience, others at last produced practical steam-engines. And if the reader will watch carefully in subsequent chapters, he will see that many machines which reached success only in the nineteenth century were first attempted in the period we are now discussing.

The striving to improve old machines and invent new ones became far more conscious than ever before. Men who were interested in technical progress began to form scientific societies, the first being the *Academia Secretorum Naturæ* (Academy of the Secrets of Nature) founded at Naples in 1560. These societies had, of course, many interests besides machinery, but they did devote a good deal of attention to gathering and systematizing knowledge about machines, promoting their wider use and encouraging invention. This period also saw the publication of the first great treatises on machinery and applied mechanics, like Agricola's great work on mining and metallurgy in all its aspects, *De Re Metallica* (1556), from which several of the illustrations for this chapter are taken, or the treatises of Ramelli (1588) or Zonca (1607). And in the latter part of the period began the development of scientific theories of mechanics, providing a general basis for the solution of the various problems concerned with machinery—but this more theoretical aspect we shall have to omit here.

All this took place against the background of that vast expansion of trading which is called the Commercial Revolution. With growing transport and commerce, the tendency of each district to produce its own essential requirements progressively disappeared. It became possible for a district to specialize in the production of commodities for which it was naturally best suited, obtaining its other requirements by exchanging its own products for those of other districts or other countries. This allowed the growth of concentrated, comparatively large-scale industry, which in turn permitted mechanization on an ever greater scale.

The outstanding mechanical genius of the times was Leonardo da Vinci (1452–1519). Throughout his life, alongside many other interests, he was continually inventing and improving machinery. He meticulously recorded his ideas, whether complete designs or mere tentative suggestions. He left 5,000 pages of notebooks on various scientific and technical subjects, a very great part of which was devoted to machinery. It is difficult to evaluate exactly his influence on contemporary industrial practice. Some of the machines sketched in his notebooks may represent contemporary practice which had not previously been recorded. Others he may have introduced into Italian industry by direct contact with the manufacturers concerned. His notebooks were not published till long after his death, but they were read by quite a number of people, who almost certainly used Leonardo's ideas and introduced them into practice without acknowledging their debt. On the other hand, the fact that an invention is sketched by Leonardo and some time later appears in practice does not prove that the idea was taken from Leonardo—for the same industrial problems that caused him to work on any particular invention would also cause others to do the same and they might then arrive at the same results independently. Be that as it may, it is certainly true that within some fifty years of his death, many of the machines he sketched are to be found in actual practice. The most important of these are some of his textile machinery and his turret windmill, which will be mentioned below. And, choosing examples more or less at random from a long list, his wheel-lock pistol is paralleled by the wheel-lock musket that appeared in Germany about 1500; his roller bearings appeared in practice in the sixteenth century; his use of the pendulum to drive pumps more evenly is recorded again in the treatises of Ramelli and Besson, which almost certainly owe a lot to Leonardo; and his dredges are mentioned by Besson. On the other hand, many of his inventions did not appear in practice for a very long time. Sometimes this was because his schemes were based on entirely wrong principles—his flying-machine or his power loom, for example. Often it was because, though fundamentally sound, they would have required standards of workmanship or materials that were not available in his time—such are his centrifugal pump, hydraulic press, rifled fire-arms, breech-loading cannon. In these cases it is reasonably safe to assume that the later practical device was created independently of Leonardo. Even when Leonardo's schemes were for the time being impracticable, they do typify the spirit of invention that permeated the age and was shared by many lesser geniuses. Let us now turn to some of the dominant trends of the times.

Public clocks, as we have seen, had become commonplace by 1500. The next step in the evolution of the clock was to drive it by a spring instead of weights. This was first done by Peter Henlein of Nuremberg between 1490 and 1500. Portable watches appeared soon after. But the spring brought new problems. The old foliot balance and verge escapement kept remarkably good time in weight-driven clocks, where the force exerted by the weights was constant. Not so, however, with the variable force of a spring. A partial and temporary solution of this problem was reached with the invention of the fusee (a device for equalizing the force) by the Swiss, Jacob Zech, between 1525 and 1540. But the complete solution had to await the invention of the pendulum clock and improved escapements.

Before we come to that it is necessary to describe a commercial problem that concentrated much attention on the improvement of clocks. The great expansion of sea-going commerce called for more accurate methods of navigation. When ships sailed the Mediterranean or north-south along the coasts of Europe and Africa, a determination of latitude, supplemented by dead reckoning, would fix the ship's position accurately enough for most purposes. And latitude could easily be found by astronomical methods familiar to the Phœnicians, if not earlier. But when, in the fifteenth and subsequent centuries, vessels began to cross open oceans east to west, the accurate determination of longitude became very desirable. An error in estimating longitude meant at the least a delay, perhaps shipwreck on an unexpected coast. Now the determination of longitude amounts in essence to the comparison of the time (by the sun) on the ship with the time at some fixed point, such as Greenwich. To find the time on the ship needs only a simple astronomical observation, but to find for comparison the time at Greenwich is much more difficult. Two methods were possible; first, an astronomical one which required astronomical prediction so accurate that even after centuries of effort it was never fully satisfactory, and which need not concern us here; and second, by carrying an accurate mechanical clock aboard ship.

As early as 1520 the mechanical clock was suggested as a possible method. But many difficulties stood in the way. They were not overcome till well beyond the period covered by this chapter, but it will be well if we complete the story here, for it will give one specific example of how painstaking research in this period led to success in a later one. The foliot balance and verge escapement was not sufficiently accurate. The first step towards the production of an adequate clock was the introduction of the pendulum. In 1593 Galileo (Italy) discovered that a pendulum swinging in small arcs made its swings at constant intervals of time, irrespective of the exact length of swing. With the possibility of its use in navigation in mind, Galileo designed towards the end of his life a clock using this property of the pendulum, and it was partly built after his death in 1642 by his son. (It is claimed on very doubtful evidence that a pendulum clock was built by Jost Burgi in 1612.) Huygens (Holland) spent some twenty years of his life trying to make the pendulum clock reliable at sea, adding many important new inventions and building two clocks in 1657 and 1661. But these, like the many subsequent attempts that continued till 1726, failed to overcome the difficulty of making the pendulum behave regularly under the irregular motion of the ship.

A more promising method of control was the balance-wheel and hair-spring, invented about 1658 by the Englishman, Hooke, who again had navigational uses in mind. Hooke, Huygens and others strove hard to make adequate marine clocks with this new device, but still success was elusive (though meanwhile the balance spring served usefully in pocket watches). The longitude problem was becoming more and more desperately important. Various governments and individuals offered prizes for its solution, the last and largest being the offer by the British Government in 1714 of from £10,000 to £20,000 according to the accuracy achieved. These prizes greatly encouraged further work. The escapement was greatly improved by the introduction of the anchor escapement by Clement in 1680 and further by its modification to the dead-beat escapement by Graham in 1715. Among the outstanding problems the chief was that of temperature compensation, to ensure that the clock kept the same time in all seasons and weathers. Not till the middle of the eighteenth century was this solved, independently and within a few years of one another by Harrison (England), Le Roy (France) and Berthoud (Switzerland). Harrison, who had built four increasingly successful chronometers (as these accurate clocks came to be called) by 1759, was awarded the British Government prize, but it is on Le Roy's chronometer of 1766 that actual subsequent developments were based. By 1780-90 stabilized designs had been reached and navigation entered a new era of reliability and safety.

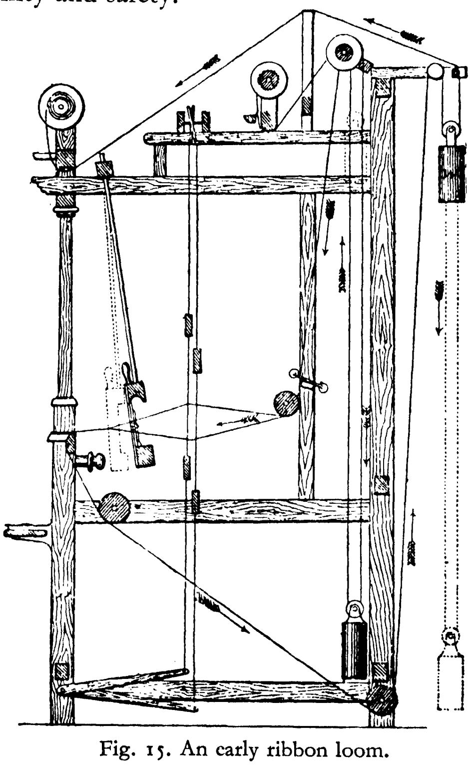


Fig. 15. An early ribbon loom.

The progress in textiles that we recorded in the last chapter was also carried further. The spinning wheel, as we left it there, was such that the two processes of spinning and quilling (winding the thread on to a bobbin) had to be done alternately. The addition of the flyer (Figure 14), which

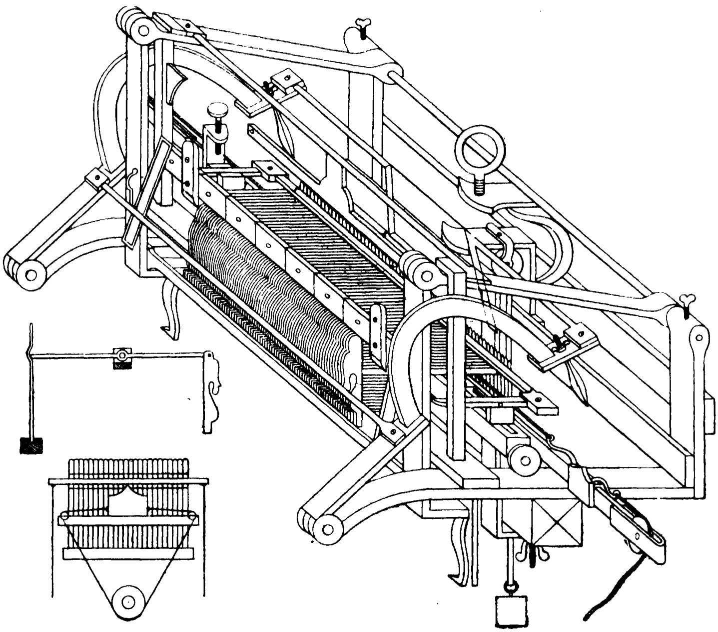


Fig. 16. An early knitting machine (stocking frame).

revolved round the spindle at a different speed, enabled the two processes to be done simultaneously. The flyer appears in Leonardo's sketches, but there are the usual doubts as to how much his ideas actually affected practice. It was put into actual use about 1530 by Johann Jürgen, whose wheel contained another innovation, the drive by treadle and crank, which left both hands free for manipulation. Such wheels were in general use by the end of the century.

The ribbon loom is an adaptation of the loom to weave several ribbons simultaneously, a single movement of the operator causing each operation to be performed on the several ribbons. It is a fairly complex piece of machinery, as a glance at Figure 15 will show, and represents a considerable inventive achievement. According to a Venetian writer of 1629 it was invented at Danzig in 1579, but the City Council, fearing unemployment among the weavers, suppressed the invention and had the inventor secretly strangled. It appeared again at Leyden in 1621, and by end of the century was in use in Holland, Germany, Switzerland, England and France.

The knitting machine (Figure 16) also belongs to this period. Knitting itself is a surprisingly recent invention—apparently no older than the late fifteenth century. Yet a knitting machine was invented in 1589 by the Rev. William Lee, curate of a village near Nottingham. This is a very remarkable achievement, considering the short time that had elapsed since the introduction of hand knitting and the great complexity (compared with, say, weaving) of the operations the machine must perform. Though by no means completely automatic, the knitting machine, even in its earliest form, was considerably more so than any other machine of the times performing an equally complicated job. Together with the ribbon loom, it represents a very significant step on the way to the machines which today perform very complex operations with no human interference except in feeding and maintenance.

Considerable progress also took place in the various auxiliary textile machines. Water-driven fulling machines were more widely used. Leonardo sketched power-driven machinery for silk reeling and twisting (perhaps owing something to the machines of 1272 at Bologna, mentioned in the last chapter), but the machines that appear in actual use in the late sixteenth century are substantially different from Leonardo's designs. Leonardo also designed a power-driven gig-mill (for raising nap on the cloth). Such machines are found in actual practice in the mid-sixteenth century (whether derived from Leonardo or not). The earliest full description of gig-mills as used in practice comes from Zonca (1607); they are better in general design than Leonardo's, but are hand-driven.

In all these ways the basis was being laid for the spectacular mechanization of the textile industry which was to be one of the main elements of Britain's rise to industrial supremacy in the eighteenth century.

The developments of the period in heavy engineering took place mainly in mining and metallurgy. All the commercial and industrial developments had increased the demand for metals, so that these two industries expanded more rapidly than any other. To meet this expansion, especially to meet the requirements of much deeper mining, heavy power-driven machinery had to be used. The illustrations included in this chapter (mostly from Agricola's *De Re Metallica*, 1556) will give a far better idea of this machinery than any verbal description. But in considering them it should be noted that some of them do not represent new inventions, rather increases in scale of application; also that development was very uneven, so that simultaneously with these advanced machines, much cruder methods were in use.

Figure 17 shows the application of the horse-whim for winding. This derives from the use of animal-power for corn-milling (fifth century B.C.), but with the improved harness of the Middle Ages, and from the gearing of the water-raising wheel (after 200 B.C.) and water-mill (first century B.C.). But the whole apparatus is so much increased in size that it represents the solution of much greater problems of engineering construction. Note the brake acting on the drum (centre). Figure 18, of a hoist driven by a water-wheel 36 feet in diameter, probably represents the most powerful machinery that could be produced with the materials of the age. It was used here for hoisting water, as a substitute for pumping, but it could, of course, be applied equally to the hoisting of ore. Note the two sets of buckets on the water-wheel, providing a reversing mechanism

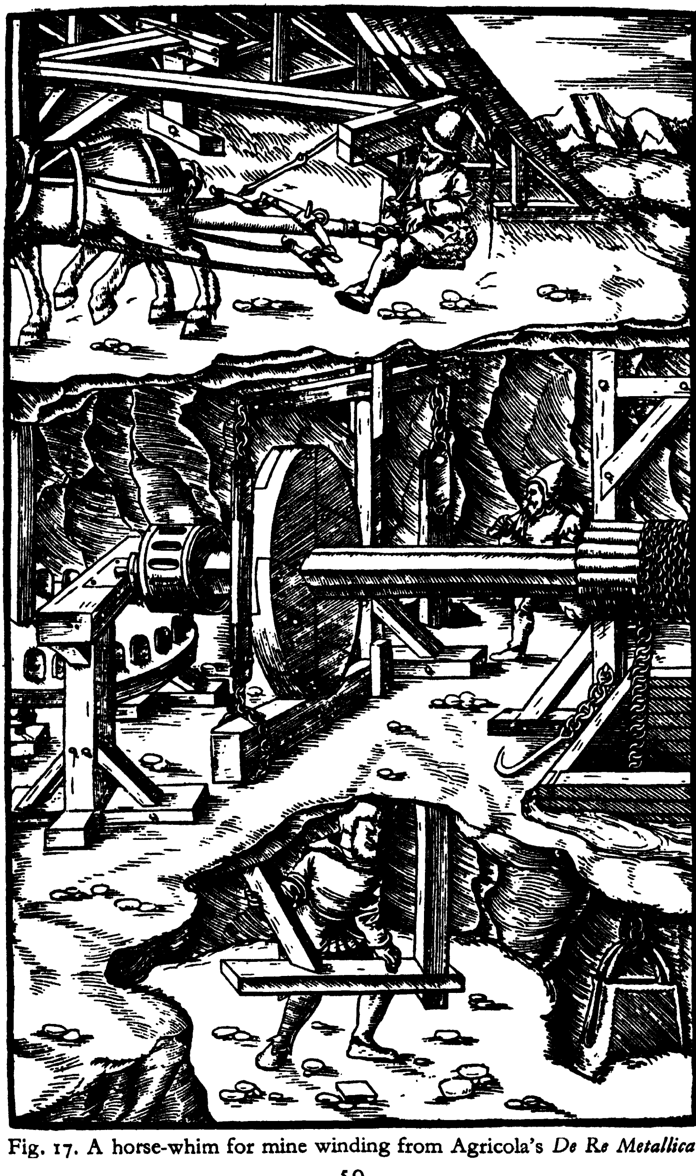


Fig. 17. A horse-whim for mine winding from Agricola's *De Re Metallica*.

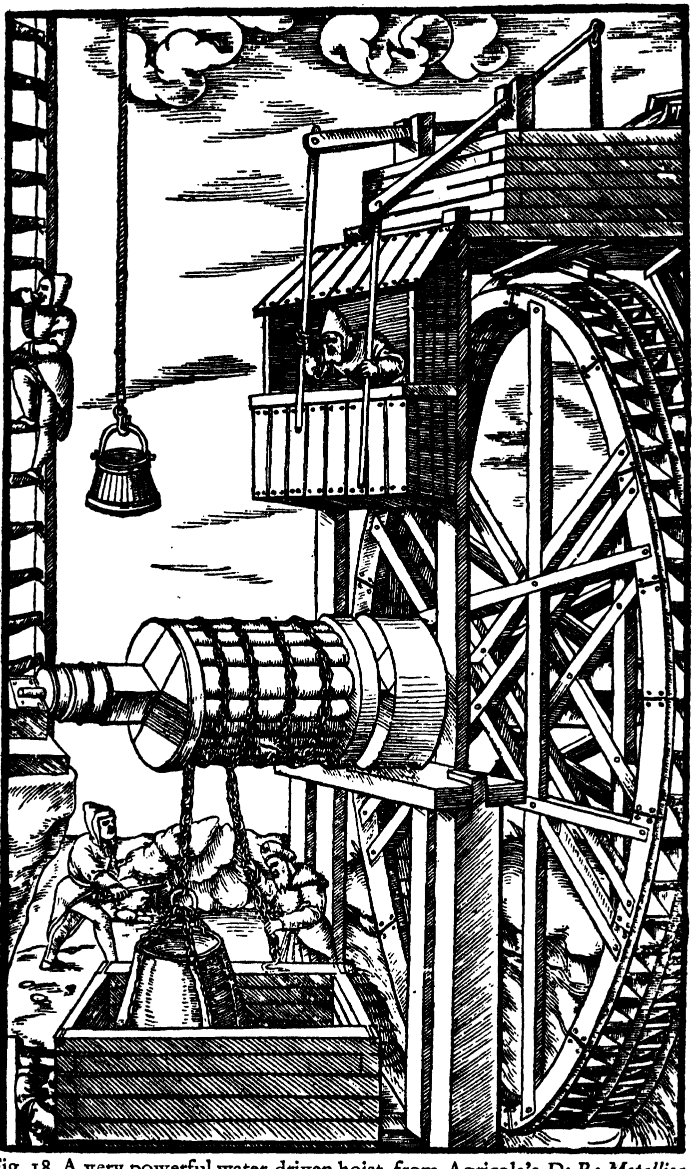


Fig. 18. A very powerful water-driven hoist from Agricola's *De Re Metallica.*

controlled by the workman, who pulls one or other lever to open the appropriate sluice to give the required direction of rotation. For transporting the ore from the minehead crude railways, such as those shown in Figure 19, were in use in Germany by the mid-sixteenth century at the latest. After about 1500 water-power was applied to crushing ore, through water-driven stamp-mills like that shown in Figure 20.

The most difficult problem of mining, however, was that of pumping away the water that always threatened to drown the workings—a threat that increased rapidly with the depth of the mine. The most advanced heavy engineering of the times is concerned with mine drainage. One such machine, described by Agricola, we have already noted (Figure 18). Agricola also describes the use of force-pumps, suction-pumps, chains of pots (like those used for irrigation purposes as described in Chapter III, but with the important change from ropes and earthenware pots to iron chains and iron buckets), and the rag-and-chain pump portrayed in Figure 21. This last is a compromise, with many advantages at the current level of technique, between the force-pump and the chain of pots. The balls (made of horsehair) fill the vertical tube, whose top can be seen in the picture and whose bottom lies in the sump, and, as the chain moves up, they carry the water to the top. In the force-pump the bottom of the pipe has to stand the pressure of the whole column of water, and it is no easy task to make such strong pipes, but with the rag-and-chain much of this pressure is taken away from the pipe and transferred to a force on the chain. Note that the pump is worked by human power through a tread-mill. Human power was still often used, sometimes through the cruder mechanism of the capstan or windlass. On the other hand Agricola describes a plant at Chemnitz consisting of three rag-and-chain pumps working in series, the lowest being 660 feet below ground; the whole plant was worked by four shifts of twenty-four horses—a quite considerable use of power. The suction pump suffers from the great disadvantage that it will only lift water through some thirty feet. Figure 22 shows a device for overcoming this difficulty by coupling in series a number of suction pumps all driven by the same water-wheel; Agricola says this was invented about 1546.

The increasing commerce and industry resulted in a notable growth of the towns.[1] This brought with it new problems of water-supply, which resulted in the introduction of heavy pumping machinery for this purpose also. Germany led the way in this, as in the mine engineering we have just discussed. Several German cities probably had notable water-pumping plant by 1500, though the earliest known description is for Augsburg in 1550, by which time a very complex system had grown up there. The plant was driven by water-wheels and it used the screw of Archimedes (see Chapter III) repeated several times in series to raise the water to the tops of towers, from which it was distributed in pipes; force-pumps may also have been used. Several very ambitious schemes were attempted at Toledo from 1526 on, but without success. A windmill was used in 1542 at Gloucester to feed the town reservoir. London's first pumped supply came from a machine, driven by a tide-mill, erected in 1582 near London Bridge by a German engineer named Peter Morice.[2] Other London schemes followed. Paris had its first water-works erected in 1608, and so on.

As well as the power-driven machinery we have just been describing and a great expansion in the use of the other power-driven machines we mentioned in the last chapter, water-power was now being used in many other industries, such as paper-making, gunpowder manufacture, nail-making, sword-making and most branches of metallurgy. There was thus a constant and increasing demand for more and larger

[1] In the fifteenth-century some typical population figures are Paris, 300,000; Venice, 190,000; Bruges and Prague, 100,000 each; London, 35,000.

[2] The people of London, through the Metropolitan Water Board, still pay £3,750 a year to Morice's heirs and executors, though the pumps were scrapped over 150 years ago.

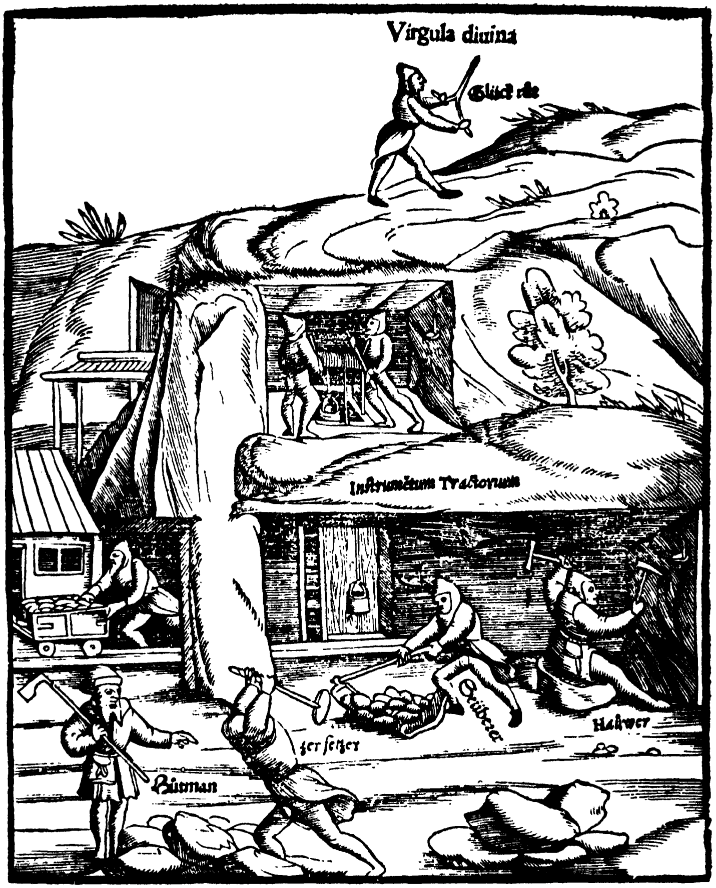


Fig. 19. A sixteenth-century minehead railway. Note also the crude winding by winch in this case.

sources of power. Many and determined attempts were made to produce new prime-movers or improve old ones—yet the problem was so difficult that notable successes did not, on

Fig. 20. A sixteenth-century water-driven stamp-mill for crushing ore.

the whole, arrive till the period covered by our next chapter. Water-wheels increased in size, as materials and constructional methods improved, till in the early seventeenth century wheels yielding twenty h.p. were in use. Various modifications of design were tried, which began the evolution of the water-turbine (see Chapter VII). Windmills also increased in size, and one fundamental innovation took place that permitted great increases in power. In the earlier type, the post-windmill, the whole mechanism revolved on a pivot to face the wind (Figure 24a). This greatly restricted the size of

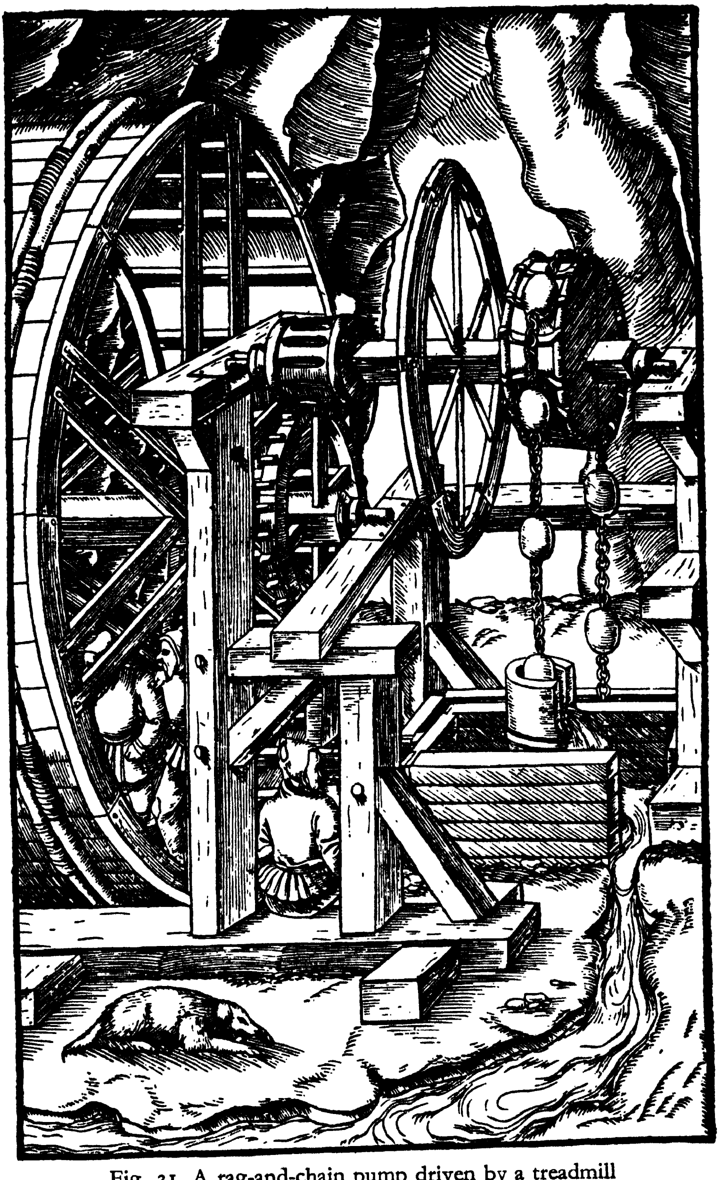


Fig. 21. A rag-and-chain pump driven by a treadmill from Agricola's *De Re Metallica*.

the mill. In the turret windmill the machinery is all housed in a fixed tower, except for the sails and connecting gearing which are placed in a revolving turret at the top (Figure 24b). With this arrangement 6–14 h.p. could be obtained, as against 2–8 h.p. for the post-mill. The source of the invention is obscure. Perhaps it had several independent inventors. Sketches of it appear in Leonardo's notebooks and a complete drawing was given by Ramelli (1588), but the general development of turret-mills was carried out by Dutch engineers of the late sixteenth century.

The demand for power was slowly but surely outrunning even these sources and men began to look for new sources of power. The great power of steam may have been realized vaguely for some centuries, but till the middle of the sixteenth century, no serious attempts were made to harness it and there was no clear conception of its nature or properties—it was not clearly distinguished from air, for example. From 1550 on, however, and increasingly in the seventeenth century, men began to investigate the properties of steam and to seek for methods of using its power. The earlier attempts were of no practical value, but they do demonstrate a conscious search for a way of harnessing steam, and it is on the experience thus gained that the successful steam-engine was eventually built. Baptista Porta in 1560 described a method of raising water by the condensation of steam—a method which forms the basis of the Worcester and Savery engines, to be mentioned later. De Caus in 1615 described a steam-driven fountain, which works in much the same way as when a boiling kettle with a tight-fitting lid forces water from the spout. In 1629 Branca suggested the impulse turbine shown in Figure 23. This was not a practical proposal, but the picture seems to indicate that he had hopes of steam as a source of industrial power. The Marquis of Worcester in his *Century of Inventions* (written 1655, published 1663) describes, in language intentionally vague for purposes of secrecy, a steam-engine for driving fountains. It is not certain

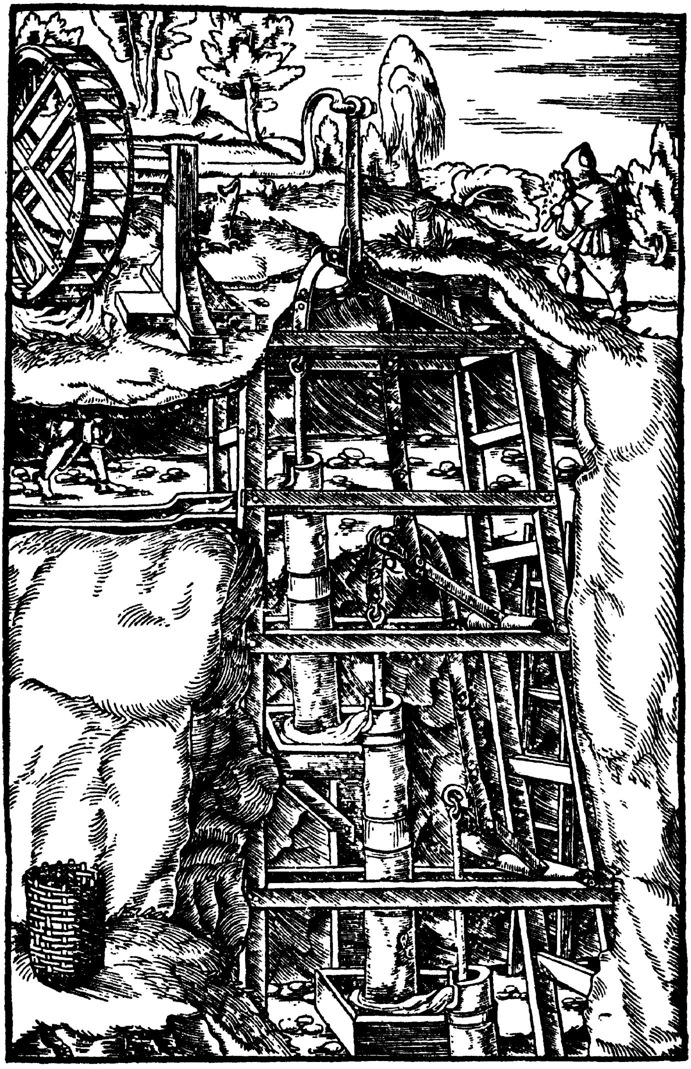


Fig. 22. Suction pumps in series, driven by a single water wheel, from Agricola's *De Re Metallica*.

whether the engine was built or not, but the design was, for this limited purpose at least, fundamentally sound—that is, if it was anything like the reconstructions that have been based on his vague descriptions. It seems to have been somewhat like the Savery engine discussed in the next chapter. Though these attempts show increasing approximation to it, the workable steam-engine was not to appear for several decades, and only after social changes in England had given a new impetus to the search.

Meanwhile the technical advances that have been described in this and the previous chapter were once more affecting social structure. Throughout the Middle Ages, industry had been subservient to agriculture; correspondingly political and economic power was chiefly in the hands of the feudal lords, who maintained it through their control of the land and of the workers thereon. In industry the typical unit of production was the independent craftsman owning his own tools and workshop. The master craftsman would be helped by a few apprentices and perhaps one or two journeymen working for wages, but these were merely preparing for the not very distant date when they would themselves become masters. Where industry was concentrated on any scale, the master craftsmen were organized in Guilds, which established craft standards, ensured that apprentices were properly trained before becoming journeymen or masters, protected the trade from the invasion of outsiders, and generally protected the conditions of the trade. This form of industrial organization remained dominant in most trades till long after the end of the Middle Ages.

But before the end of the Middle Ages a new form of industry had begun to appear, timidly as it were, and on a restricted scale; and during the period covered by this chapter it made great strides towards eventual domination of the whole economic system. The heavier machinery that we have described can only be used properly by a number of men working together. This provided the basis for the

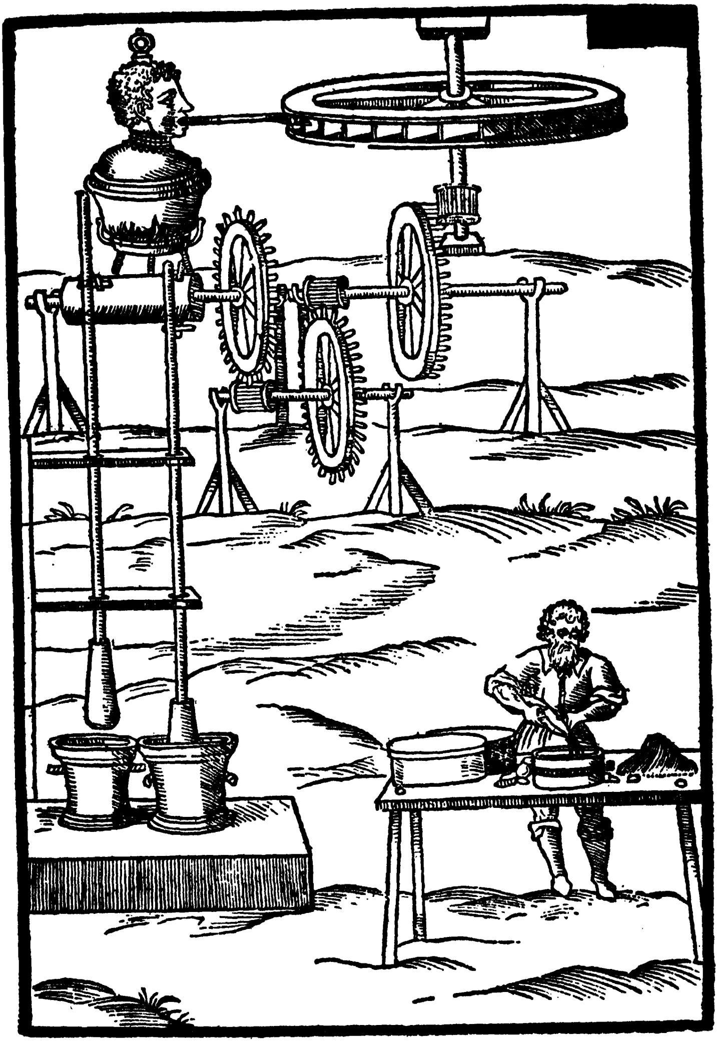


Fig. 23. Branca's suggestion for an impulse turbine.

growth of the factory system, in which the necessary machines are gathered in a factory, owned by one man (the 'capitalist', who, by saving or otherwise, provided the capital required to construct machines and factory), or by a group of such men. The work in the factory was carried out by employees working for wages and, in contrast to the journeymen of the Guild system, unlikely ever themselves to become employers.

This capitalist type of industry naturally appeared first in those trades where heavy machinery is most necessary—chiefly mining and metallurgy. But even before the end of the Middle Ages we find occasional examples in other industries—for instance, a factory of 120 weavers at Amiens in 1371, one of as many printers in Nuremberg about 1450. In the early sixteenth century the famous Jack of Newbury built a weaving factory with more than 200 looms, employing about 600 workers. Before 1660 such large-scale enterprise, requiring the accumulation of considerable capital, became more common, especially in England. The capital required for mining rose from £100 or so in early Elizabethan times to several thousands under the Stuarts. Blast-furnaces involving several thousand pounds of capital appeared in the mid-seventeenth century. In 1649 two capitalists spent £6,000 on a copper-wire mill at Esher. A London brewery under Charles I had a capital of £10,000. All these, however, are but hints of the great change-over to the factory system that took place in the eighteenth and nineteenth centuries.

With such enterprises the old-fashioned guild craftsmen could not compete. They were in grave danger at least of losing their independence and becoming mere employees, at the worst of losing their livelihood altogether, when a failure of markets to keep pace with more efficient production caused unemployment. Naturally they opposed the new capitalist type of industry, using the very great political power of the Guilds to prevent the introduction of the factory system. They saw, too, that the growth of machinery favoured capitalist industry at the expense of their own crafts and therefore they sought to prevent the use of machines. One such case, the suppression of the ribbon loom at Danzig in 1579, has already been mentioned. Similarly, Cologne tailors were forbidden to use machines for pressing pinheads in 1397; the English Parliament under Guild pressure prohibited in 1553 the use of the power-driven gig-mill; in 1623–4 Charles I ordered the destruction of needle-making machines. Such opposition could never be successful in stopping technical progress—but it did hinder progress sufficiently to be an important factor in making necessary the social changes that are described in the next chapter.

CHAPTER VI

THE SECOND INDUSTRIAL REVOLUTION: YOUTH (1660–1815)

IN all that has gone before the names of British inventors are few. Some crept in because we carried the history of chronometers well beyond the period covered by the last chapter. The others, like Lee (whose knitting machine of 1589 was the *first* English mechanical invention of note), Hooke and Worcester, occur only towards the end of the period in question. But in the present chapter British names occur almost to the exclusion of all others. This sudden change reflects great social changes which took place first in England.

Though England had not been conspicuous hitherto in mechanical invention, she had from the mid-sixteenth century on made outstandingly rapid strides in the industrial application and use of such inventions. Already we have noted some of the large industrial enterprises set up in England in the early seventeenth century. Similarly, between 1540 and 1600 there were introduced into England from abroad the first paper and gunpowder mills, cannon factories, alum and copperas factories and sugar refineries (some of these industries existed earlier on a small non-factory basis). The average annual production of coal rose from 210,000 tons in the decade 1551–60 to 2,982,000 tons in 1681-90. The number of merchant ships over 100 tons rose from 35 in 1545 to 183 in 1588 and 350 in 1629. The new English ships were technically superior, too, to those of the older mercantile countries—this was one of the principal reasons for the crushing defeat of the Spanish Armada in 1588. With their new and excellent ships, British merchant sailors traded with the whole world and provided the commercial activity which was a necessary parallel to the expansion of industry.

Thus, in the century before 1640, England was transformed from one of the most backward to one of the most rapidly advancing commercial and industrial countries of Europe. This brought to a head contradictions, which have already been hinted at, between the new forms of industry required to use advanced mechanical methods and the political structure. By this time England had already moved politically beyond strict feudalism. Yet the feudal basis remained and tended always to restrict industrial and technical progress. Besides the types of restrictions mentioned in the last chapter, there was, for example, the growing practice of granting monopolies for the manufacture or sale of this or that article, sometimes as an encouragement to individuals to promote some backward industry, more often as rewards to court favourites (this being, in fact, an attempt to divert the profits of new industry to the benefit of the feudal upper classes). Local tolls and taxes hindered commerce, whose free growth was essential for the full use of the new industrial methods; feudal restrictions prevented the creation of a free market; and so on. Round these and other issues, great political struggles raged in early seventeenth-century England, culminating in that Revolution which began in 1640 and in a few years had replaced the old

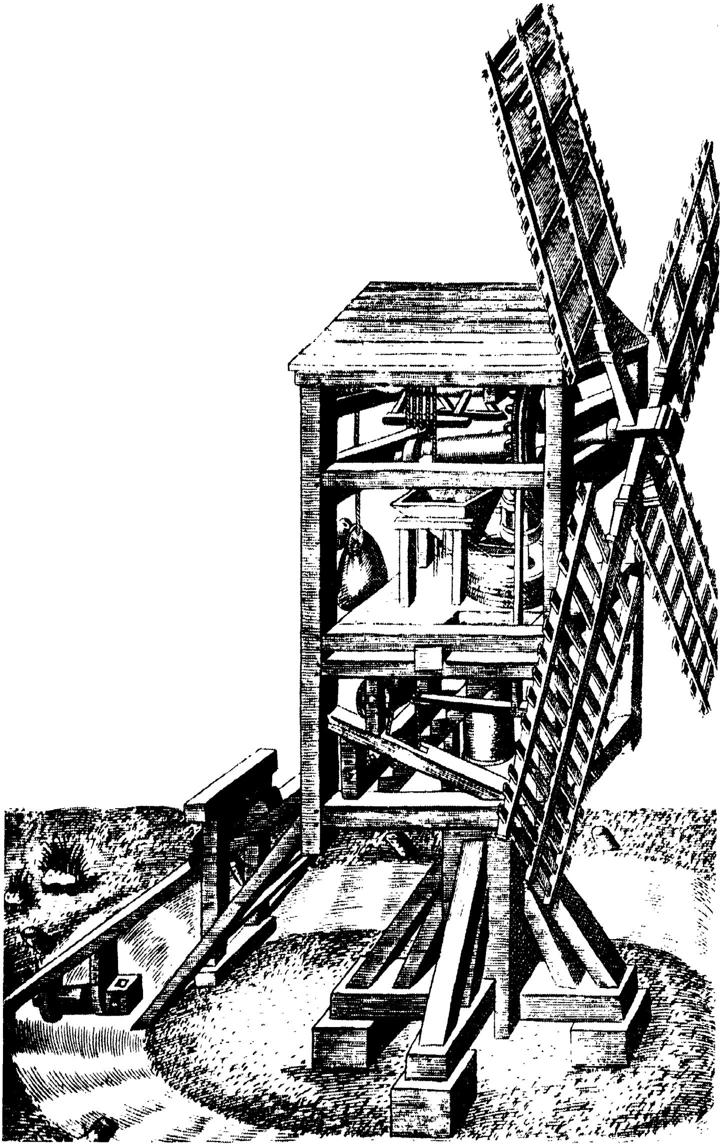


Fig. 24a. Post windmill.

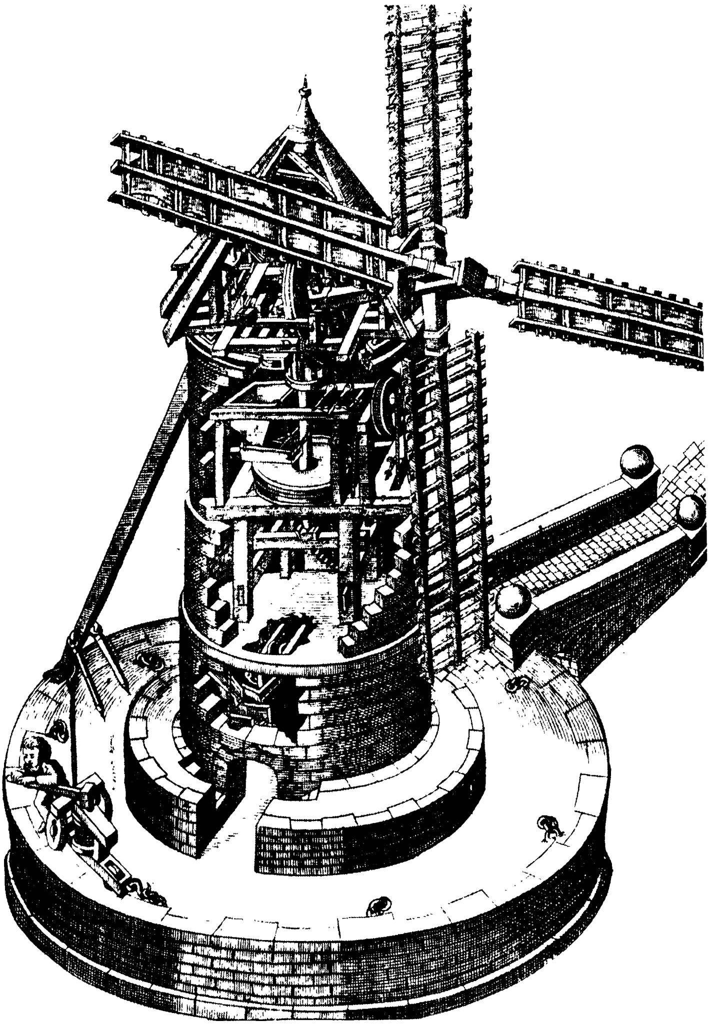


Fig. 24b. Turret windmill.

political structure by a new one from which most of the old restrictions were gone. Political power now passed mainly into the hands of the new class of capitalists or 'bourgeoisie' (for which reason this is referred to as the 'bourgeois revolution'). The description given here is greatly over-simplified. For one thing, the revolution was not completed in a few years in England, as it was later in other countries, but required further changes, particularly in 1688, but covering in all a period of nearly 200 years, for its completion. The reader will be in danger of acquiring a distorted view of it (in particular he will miss the many other factors besides industrial mechanization that went to make it), unless he reads more complete descriptions of it.

In the new social structure, free in the main from feudal restrictions and with power in the hands of the manufacturers, British industry forged ahead on an unprecedented scale. Since Britain was by over a century the first country to take this step, she was without serious rival throughout that period. And with expanding industry came increasing invention to cope with the many new problems that arose. That is why for over a century the names on the roll of inventors are almost entirely British.

The outstanding mechanical problem still remained that of pumping, both for draining mines and for water supply. Coal-mines reached 400 feet deep by 1700 and 600 feet by 1750—and with every increase of depth the problem of pumping became more acute. One English mine operator in 1702 was using 500 horses to give power for pumping. Many improvements in pumps were made to meet this trouble, but these do not concern us so much as does the role of the pumping problem in bringing to fruition at last the attempt to make use of the power of steam.

The first engine to achieve even partial practical success was that of Savery, patented 1698, which is shown diagrammatically in Figure 25. He intended it as a solution of the mine drainage problem, as is made clear by his

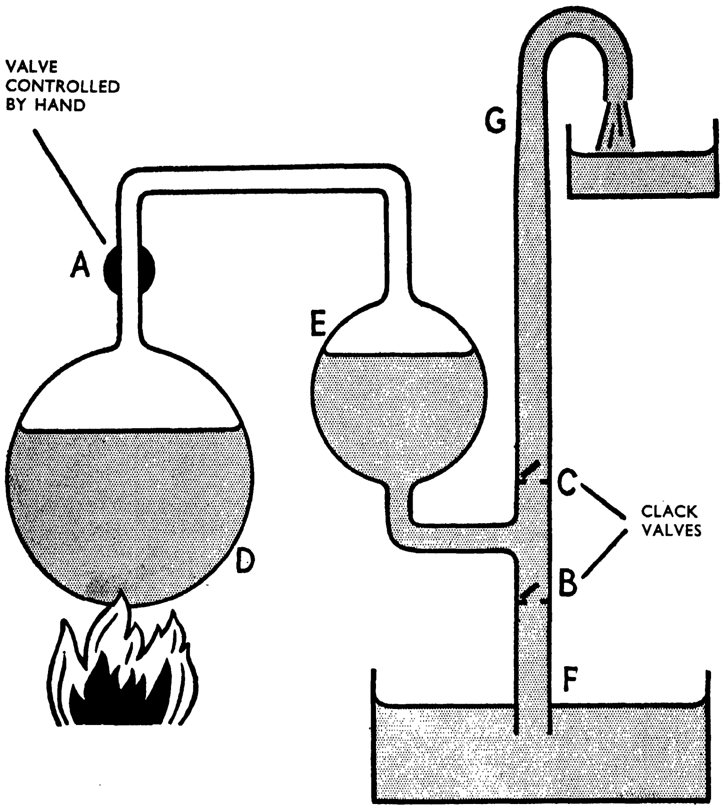


Fig. 25. The principle of Savery's steam-engine. With the vessel (E) full, the valve (A) is opened; steam from the boiler (D) drives the water out of (E); the pressure closes the clack-valve (B) and opens (C), so that the water is driven up the pipe (G). When (E) is empty, the valve (A) is closed and cold water is poured over the outside of (E); the steam condenses and creates a vacuum; this closes valve (C) and opens (B), so that water is sucked up from (F) into (E); after which the first process is repeated.

pamphlet of 1702, *The Miner's Friend.* It was, however, inadequate and there is no record of its use in more than one mine, though several were made to pump water for country houses.

The Worcester and Savery engines had shown an appreciation of the harnessing of steam-power, both through using it to create a vacuum and through using its expansive force. But before really adequate steam-engines could be produced another vital component was needed—the piston and cylinder. It is interesting to note here how much the steam-engine owes to pumping problems. Not only was pumping the main urge to create it, but also the piston and cylinder as a piece of mechanism had become familiar through its widespread and increasing use in the pump, while the necessary knowledge of vacuums and atmospheric pressure, which had been worked out by various scientists from the mid-sixteenth century on, was itself originally a product of investigation of the working of suction pumps. As early as 1680, Huygens (who has already been mentioned in connection with the chronometer) had attempted to make a piston and cylinder engine using the explosion of gunpowder as the source of power. The attempt was naturally unsuccessful, but it led Papin to try the use of a similar mechanism with steam. His rudimentary 'engine', produced about 1690, made use of the expansion of steam to drive up a piston in a vertical cylinder and its condensation to create a vacuum and draw it down again. But there was no boiler; apparently water lay in the bottom of the cylinder, and the evaporation was done by placing the fire under the cylinder and the condensation by removing it again. It was not, therefore, a practical engine.

Success came when Newcomen discovered how to combine this piston and cylinder with the separate boiler of Savery's engine and with suitable valves to control the admission and exhaustion of the steam, on lines indicated in Figure 26. It is not clear how much Newcomen knew of

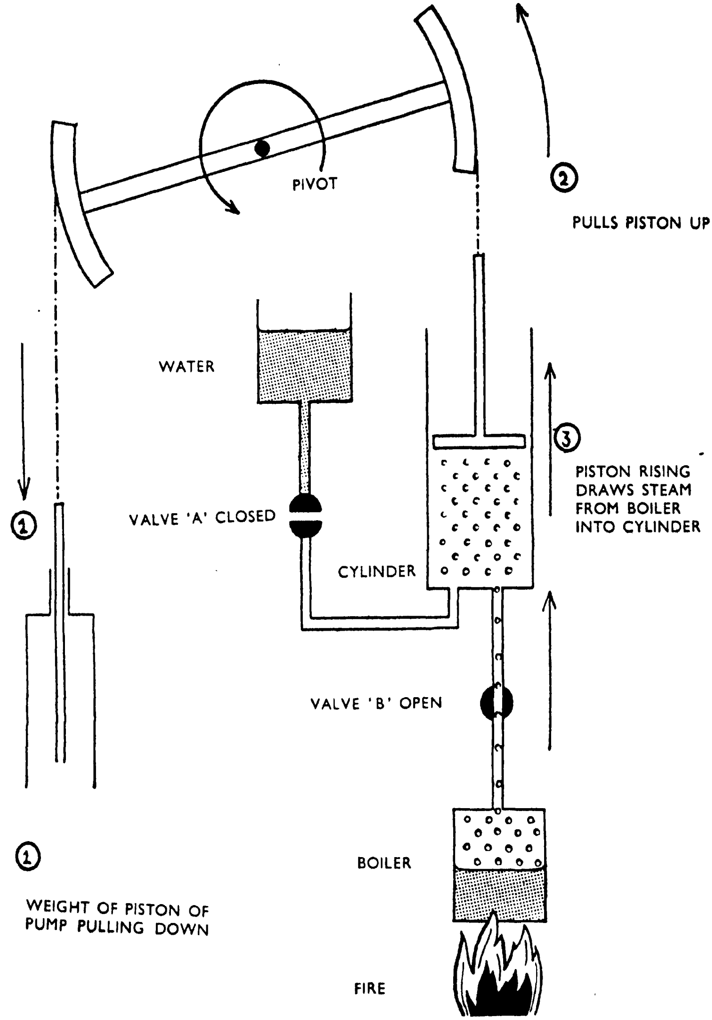
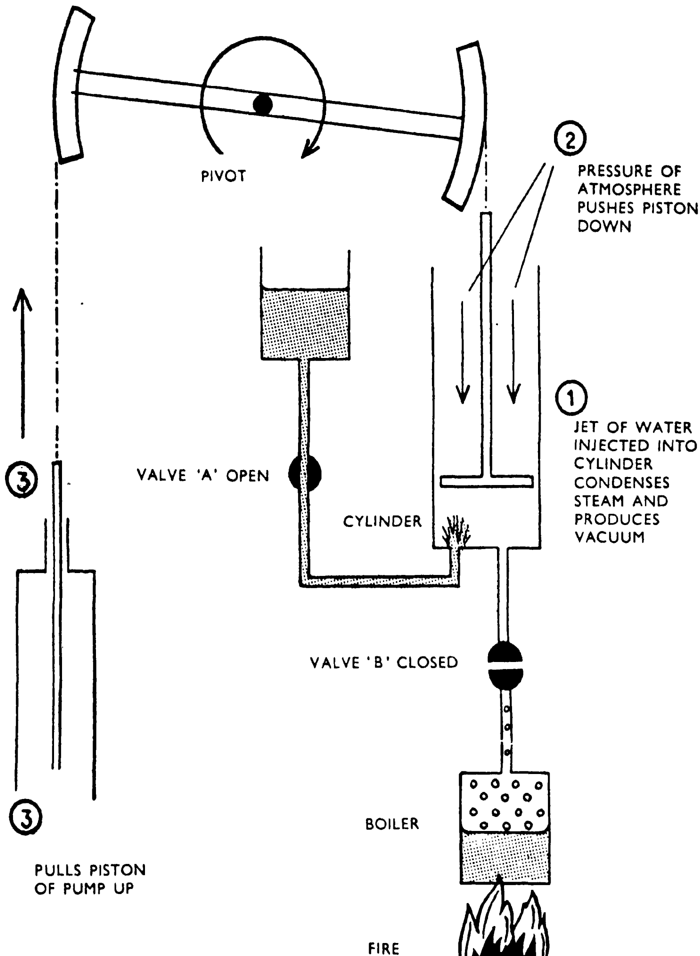


Fig. 26. Diagrammatic drawing of Newcomen's pumping engine. To understand its working, follow in each diagram the numbers in circles and the



attached legends. Note that the work is done by the pressure of the atmosphere during the working stroke (second picture). For this reason the engine is called an atmospheric engine.

Papin's 'engine' or of other experiments that he and others had made with pistons and cylinders and vacuums, but there is probably some connection. Newcomen was working on his invention before 1705, but the first engine whose construction we definitely know dates from 1712.

The Newcomen engine really was a success. In spite of the disadvantage of a high fuel consumption, it did provide an effective means of pumping from mines. Its use spread rapidly. In 1714 three more engines were built. After 1720 it was widely used in Cornish tin mines. In 1769 100 engines were in use in the north of England, fifty-seven being in the Newcastle (coal-mining) district. Even in 1830, sixty years after the invention of Watt's much more efficient engine, Newcomen engines remained in use—though only at coal-mines, where waste low-grade fuel was available.

Meanwhile the eighteenth century saw the transformation of several of England's main industries from local craft or cottage industries to mechanized factory industries. The most startling changes took place in textiles. Early in the century the Lancashire textile industry was worked by hundreds of weavers and spinners working in their own homes, buying raw materials from 'factors' and selling their finished products back to them. They used the equipment described in previous chapters. The first great change came with John Kay's invention of the flying shuttle in 1733. Formerly the shuttle was passed from hand to hand through the web. The flying shuttle, as its name implies, flew freely through the web, being driven from a box on one side to a box on the other by a mechanism controlled by cords which the weaver held in one hand. To use it required considerable skill, but given that, it allowed the weaving of wider cloth, left one hand free for other operations and roughly doubled the weaver's output. It was adopted only slowly; in some parts of the country it was little used even in 1820. In Lancashire, however, it had come into general use by about 1760, and it had the immediate effect of making it very difficult for the spinners to keep up with the requirements of the weavers. Thus in the decade after 1760 we find a series of inventions designed to improve the productivity of the cottage spinning-wheels.

But more radical changes were required in spinning, and the first of these came considerably earlier. The first steps in spinning are to arrange the fibres parallel and then draw them out till they form a loose thread of appropriate thickness, which is then twisted on the spindle. The drawing out was formerly done by hand. In 1738 Lewis Paul obtained a patent for spinning by rollers (on somewhat doubtful evidence it is said that a similar idea occurred to Wyatt in 1730 and a machine was constructed in 1733). This machine drew out the fibres by passing them between pairs of rollers. In 1741 Wyatt and Paul had a spinning mill working on this principle, employing ten girls and using power from a capstan driven by two asses.

However, the most rapid advances came after the general use of the flying shuttle had greatly raised the demand for yarn. First came Hargreaves' 'spinning jenny', which allowed one operator to control at first eight spindles, later eighty or more. This machine contained the essentials of the modern 'mule', except that certain operations were manually controlled instead of being automatic. It was without rollers and flyer, so that the processes of drawing out, twisting and winding on were performed intermittently. It was probably conceived about 1764 and was perfected by 1768. In 1769 Arkwright introduced his 'throstle' or 'water frame', a machine for spinning by the use of animal or water-power. It used rollers and flyer (Figure 14) and, after various improvements, produced a much firmer thread than was hitherto possible. Formerly cotton thread was so imperfect that it could only be used for the weft, linen being used for the warp. Arkwright's machine made possible the production of all-cotton fabrics. Crompton, after five years of work, had by 1779 completed his invention of a machine (Figure 27) combining the best features of Hargreaves' and Arkwright's. He took Arkwright's rollers and Hargreaves' spindles without flyers and with this combination it was possible to produce a much finer thread than formerly. Because it was a cross of the two earlier machines, this was known as the spinning 'mule'. From 1790 attempts were made to make the mule automatic, though they were not successful till 1825. Between 1830 and 1833 Thorpe and Mason introduced ring spinning, which is now the main system except for fine, soft yarns.

The greatly increased productivity of these machines soon transformed the spinning industry, especially after the introduction of steam-power. The cottage industry gave way to the factory where hundreds of spinners worked as wage-earners for the factory owner. Factories sprang up in dozens alongside streams which provided water-power. By 1811 there were 310,500 spindles in Great Britain working on Arkwright's frames, 4,600,000 on Crompton's mules and 156,000 on Hargreaves' jennies. In 1761 the Manchester cotton industry had been so unimportant that there were no cotton workers in a procession representing the principal trades of the city; by 1774 there were 30,000 people in the industry in or near Manchester.

As the efficiency of spinning increased by leaps and bounds, it was the turn of the weavers to find they could not keep pace. Renewed attention was given to the problem of producing a power-driven loom. It will be remembered that Leonardo had designed a power-loom, though his conception was inherently impracticable. Other attempts were made in the seventeenth century, but the various mechanical elements that had to be combined to make an efficient machine were lacking. Improvements to the ribbon loom by Kay and others made it substantially automatic by 1745 and a decade or so later it incorporated most of the essentials of automatic weaving. The outstanding remaining problem was that of the control of the shuttle in wide webs, and Kay's

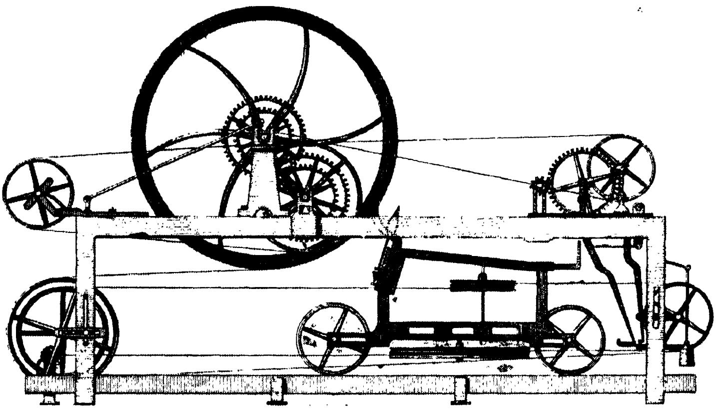


Fig. 27. Crompton's 'mule'.

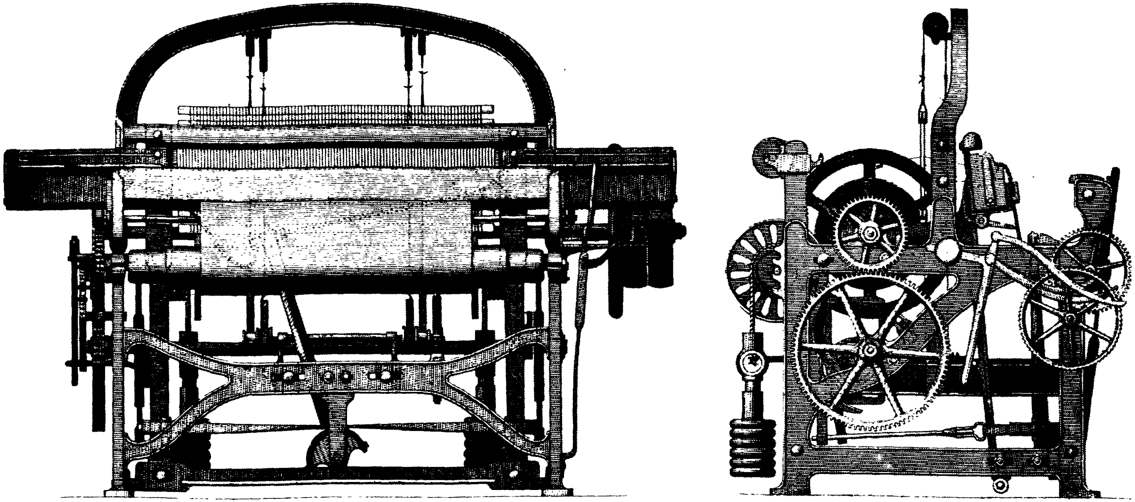


Fig. 28. Cartwright's power loom.

flying shuttle of 1733 provided the basis for its solution. With these elements available renewed attempts were made. Some progress was made by Barber in 1774 and the main steps forward were taken about 1787 by the Rev. Edmund Cartwright, whose loom (Figure 28) embodies the main principles in use for power-weaving today. His machine was used to some extent, but the power-loom was not sufficiently perfected for general use till after the improvements introduced by such men as Radcliffe (1802), Johnson (1803–5), Austen (1789 and subsequently) and Horrocks (from about 1810 onwards).

Horrocks' improvements represented the decisive advance to a machine of general practical use; his loom was put into regular manufacture after 1822. The number of power looms in England was only 2,400 in 1813 and 12,150 in 1820, but after the appearance of these improved looms it rose to 45,500 in 1829 and 85,000 in 1833. The Northrop loom, in which empty shuttles are automatically replaced, appeared in 1892.

All this refers to the ordinary loom for plain weaving. Meanwhile the draw loom (for various patterns) had elsewhere been undergoing a long evolution, culminating in the perfection about 1804 of the Jacquard loom (so called after its inventor, a Frenchman). In this the raising and lowering of the various selections of warp threads to produce complicated patterns were automatically controlled by cards punched with appropriate holes.

At the same time the auxiliary stages of textile production were being rapidly mechanized. A carding machine was patented by Paul in 1748, while Kay produced another. Bell invented a cotton-printing machine about 1783. In America modern types of shearing machines were patented in 1792 and 1793. The combing machine was invented by Heilman in 1850.

With the aid of these machines the British textile industry expanded several hundredfold between the middle of the eighteenth and the end of the nineteenth century. It captured the markets of the whole world, as is shown very clearly by the following table:

Year	Value of exports of cotton goods, yarn, etc.
1701	£23,253
1751	£45,986
1780	£355,000
1790	£1,662,369
1800	£5,406,501
1820	£20,509,926
1860	£52,012,430
1870	£71,416,345

after which the figure remained stable and then slowly declined. The decline was partly caused by the rise in industrial strength of other countries, which broke Britain's world monopoly; but it was also partly due to the technical backwardness of the British industry compared with its new rivals—in recent years only five per cent of the looms in Lancashire were automatic, against ninety-five per cent in the U.S.A., while over half of the cotton-making machinery in Lancashire was installed before 1910.

Though we have carried the story well beyond that point, it will be clear that by the 1770s the mechanization of the cotton industry was such as to put a serious strain on existing sources of power. It was the same in other industries. Most of them, however, saw no such spectacular pageant of invention as in textiles; rather there was an increase in the size and capacity of machines already well known, an increasing use of power to drive them and a growth of factories in place of craft or cottage industry. Thus the eighteenth-century pottery industry used increasing amounts of wind- and water-power for such purposes as grinding and crushing flints, grinding enamel colours and mixing clays. With growing towns, flour mills increased in size. And so through the whole range of industry. Only in metallurgy and heavy engineering (and at the end of the century in light engineering also) was progress as spectacular as in textiles. All the aspects of industrial progress that have been mentioned, together with growing shipping, bridge building, and the continued progress of the steam-engine made heavy demands on metallurgy and engineering, calling for larger furnaces and therefore larger bellows for blast, heavier rolling mills, boring machines, and so on—all in their turn requiring more and more power to drive them.

In such an atmosphere men turned in the mid-eighteenth century to serious attempts to improve the known sources of power—water, wind, animal and the Newcomen steam-engine (which, it must be remembered, would not drive rotary machinery). All these prime-movers had been pushed as far as empirical work could push them. The intuitive approach of the skilled craftsman could carry them no further. To produce further increases in efficiency required careful comparative measurement, in controlled conditions, of all the factors involved and the power output obtained. In other words, further progress depended on the application of scientific analysis. Among those who tackled water-wheels scientifically was Smeaton, one of the outstanding engineers of all time. In 1752–9 he built laboratory models of water-wheels and, by carefully measuring their output of power while he varied the shapes and relations of their various parts, was able to redesign water-wheels to a greatly increased efficiency. With the introduction of the breast-wheel in the late eighteenth century, the plain water-wheel (as opposed to the turbine) reached the end of its evolution. Meanwhile, on the Continent various workers were pursuing theoretical investigations which, though producing little of practical value at the time, prepared the way for the creation of the water-turbine in the nineteenth century. Smeaton also scientifically investigated and greatly improved windmills. In 1750 Andrew Meikle made several improvements in windmill construction, adding, for example, the fantail mechanism—the small auxiliary windmill at the back which automatically turns the main sail into the wind. Sails which automatically adjusted themselves to the wind speed were introduced by William Cubitt in 1807. In 1769 Smeaton again embarked on a scientific investigation of the Newcomen engine and as a result of his experiments was able to tabulate the best cylinder diameter, stroke, rate of working, boiler size, water injection and coal consumption for a given power. With this data he was able to build bigger and better engines—for example, one at Chasewater with a 6-foot cylinder, 9½-foot stroke, yielding 76½ h.p. It can be said that after Smeaton's work, the Newcomen engine reached the limit of its development and further progress depended on the fundamental changes introduced by Watt.

Water-wheels had the disadvantage that the factory had to be placed by a stream. Windmills suffered from irregularity of working. The Newcomen engine was free from these disadvantages but it would drive only pumps, not rotary machinery. Hence attempts were made to adapt it for the latter purpose. Since the engine would pump water and since water-wheels would drive machinery, the most obvious method was to use the engine to pump water to supply a wheel which drove the machinery. Between 1732 and 1734 the firm of Darby, the ironfounders who took such a prominent part in eighteenth-century progress, built a Newcomen engine which pumped water for ten water-wheels to drive their machinery. A similar device was in use in the Potteries in the years 1750–60. In the second half of the century this method was commonly used for haulage in mine shafts; the pumping engine, required in any case for drainage, pumped water over a wheel operating the haulage. In 1779 Pickard was granted a patent for producing rotary motion from a Newcomen engine, using the crank; the attempt produced little success, but the patent later obstructed Watt's work.

Such was the drive to produce better sources of power. Such was the atmosphere in which James Watt was urged to do the work which transformed the crude Newcomen engine

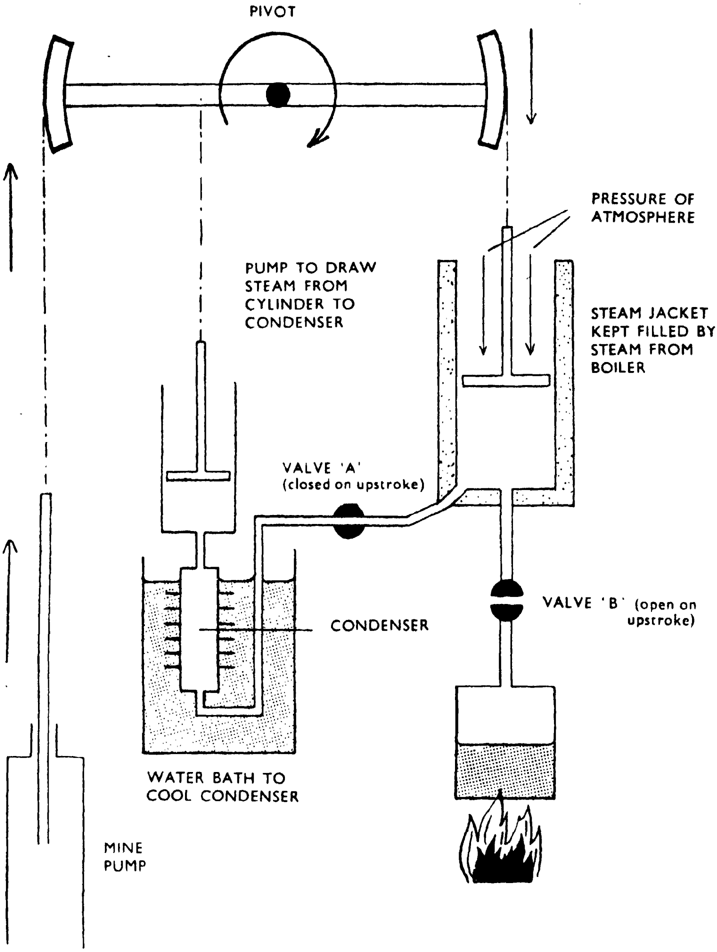


Fig. 29. Diagrammatic representation of Watt's pumping engine (working stroke). Compare with Figure 26. This is still an atmospheric engine, working on the same principle as Newcomen's, except that (a) the steam jacket keeps the cylinder constantly hot, and (b) the condensing is done in a separate condenser, kept constantly cool by cooling water and exhausted by a pump.

into a really efficient machine. Watt was not the father of the industrial revolution. It was not his engine that started the great drive of mechanization. The mechanization started first, based chiefly on water-power, but soon outran it and produced demands for power such that men sought to improve the steam-engine. Watt was outstandingly the most successful. He answered the problem of power and on his work industrialization could go forward assured of adequate power sources.

Mine drainage still presented the largest single power problem, while the Newcomen engine was a basis from which to start; so it is natural that Watt's first steps were to improve the pumping engine out of all recognition. In 1763 he was called to repair a model Newcomen engine and noted its inefficiencies, but so difficult was the problem of eliminating them that it was not till 1765, after much thought, consultation with scientists and scientific experimenting of his own, that he saw the solution. He observed that the main source of inefficiency in the Newcomen engine arose from the condensing of the steam in the cylinder; the cylinder was cooled at every stroke and a great part of the steam was wasted in reheating it. His main improvements were therefore to keep the cylinder permanently hot by enclosing it in a steam jacket and to do the condensing in a separate condenser, kept permanently cold (see Figure 29). He built a model in 1765, but it took him till 1769 to solve the problems of full-scale working, and obtain his patent.

The first Watt engine (1776) was installed to drive the bellows of the blast furnaces in the ironworks of John Wilkinson, who was responsible, along with the firm of Darby, for many of the great advances in heavy engineering and whose improved boring machine had made possible the production of Watt's cylinders. In 1777 came the first order for a pumping engine for a Cornish tin mine and thereafter Cornwall was the best field for these engines, forty being installed by 1800.

By the time the pumping engines were in regular production, the demand of the textile and other industries for improved sources of power had grown fully effective and Watt, at the request of his partner, Boulton, turned his attention to the production of an engine for driving rotary machinery (Figure 30). His rotative patent was taken out in 1781 and the following year he developed the double-acting engine and expansive working. In 1788 he added the centrifugal governor (to right of cylinder in Figure 30), and in 1796 the steam-engine indicator.

In 1782 a Watt rotative engine was installed in Wilkinson's works for driving a forge-hammer and another at Wedgwood's pottery (the first of several there). The first for winding at a coal-mine was at Newcastle in 1784, and by 1800 thirty Watt engines of both types were being used at collieries and twenty-two at copper mines. In 1785 it was used to drive a flour mill. In 1787 came the first application to cotton-spinning and by 1800 there were eighty-four Watt engines in cotton mills, after which date steam-power became common in the industry. By 1850 cotton mills were using 71,000 horse-power of steam, against 11,000 horse-power of water-power. If the reader will glance back at the export figures already quoted, he will see that the general introduction of steam allowed an even greater expansion of the industry than did the original inventions of the sixties and seventies. Wool-spinning was more backward and was only using nine of the engines by 1800. Large-scale power weaving belongs to the nineteenth century, but by 1789 a Cartwright loom was driven by steam. In 1796 Wilkinson ordered another engine to drive a rolling-mill and by the end of the century there were twenty-eight Watt engines in foundries and forges. In 1802 appeared a steam-driven threshing machine. In 1811 power was first used in printing. These examples will show how great the need for power was and how much the further progress of industry was helped by the satisfaction of that demand by Watt's engines.

The subsequent history to and beyond the rise of the modern high-speed reciprocating engine after 1870 would require a book to itself. Here we can only note the beginnings of two important developments. The compound engine was first used by Hornblower in 1781, but it had to be abandoned because it infringed Watt's patent. After the expiry of the patent in 1798 compounding was reintroduced by Woolf in 1804. Watt's engines were still primarily atmospheric engines, working at little above atmospheric pressure. The transition to the modern engine working at high pressure depended on improvements in iron-working towards the end of the century. Murdock, a workman of Watt's, made a successful model in 1784, but the significant development of high-pressure engines begins with the work of Trevithick in England and Evans in the U.S.A. about the turn of the century.

In all the applications of the steam-engine mentioned above, the method of driving was obvious—the machines were previously driven by some rotary mechanism, such as a water-wheel, and it was only necessary to attach a rotative engine instead. But with one other application which reached considerable success before 1815 the method was less obvious—the application to shipping. Ships were driven by sails, oars or paddles, and none of these are in any obvious way adaptable to a steam-engine drive. It is therefore not surprising that many weird devices were used. John Fitch of the U.S.A., for example, in 1785 designed a steamboat driven by an endless chain of floating boards—a sort of naval tank-track—and later adopted a set of paddles moving like those used in canoeing. He also suggested jet-propulsion in 1790 and the same system was proposed on numerous occasions and even tried out by Rumsey, who in 1793 succeeded in driving a jet-propelled boat on the Potomac at four m.p.h. These more fantastic experiments were soon eliminated (though jet-propulsion was to reach limited success for ships in our times, apart from its recent application

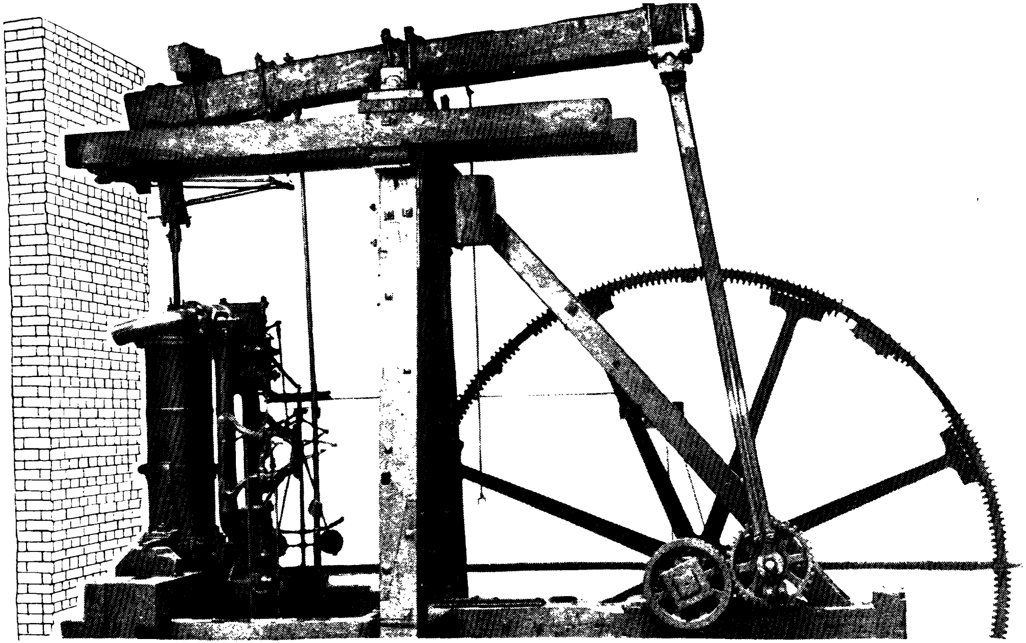


Fig. 30. One of Watt's rotative engines. Apart from the 'sun-and-planet' mechanism, which adapts it to drive rotary machinery, this is the same in principle as the engine of Figure 29.

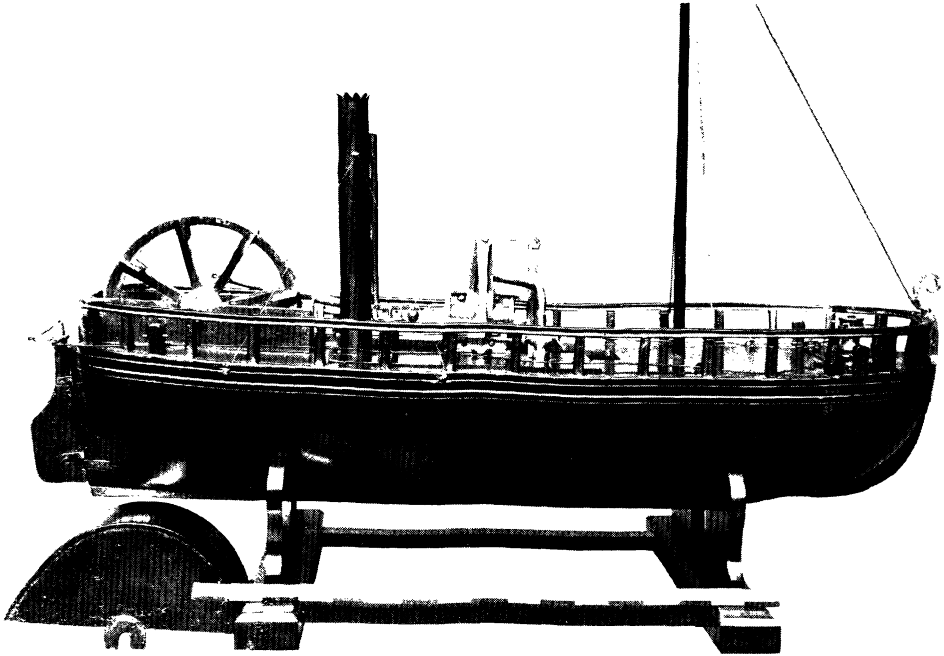


Fig. 31. A model of the *Charlotte Dundas.*

in the air) and only two remained—the paddle-wheel and the screw.

The paddle-wheel was occasionally used for propulsion even before the advent of steam, being driven by human power through cranks or capstans. Various proposals and attempts were made at paddle-boats driven by engines of the Newcomen and Watt types, but without notable success until 1788, when Miller and Symington built a paddle-boat, which on trial on Dalvinston Loch reached a speed of five m.p.h. Symington carried on the work and built the *Charlotte Dundas* (Figure 31), which in 1802 towed two 70-ton barges 19½ miles in six hours against a headwind so strong that no other vessel on the canal dared to move. The greatest of the pioneers, however, was Robert Fulton, an American citizen who worked in France and England, but achieved his successes after returning to the U.S.A. He used a very scientific approach, making experiments on water resistance and similar topics. His *Clermont* of 1807 created a sensation by steaming 150 miles from New York to Albany in thirty-two hours. Thereafter steam navigation on rivers in the U.S.A. made rapid progress and was thoroughly established by 1815. In Britain progress was slower till about 1830, and in 1815 the country had only twenty steamers. Incidentally the first American steam-driven warship was launched in 1814; Britain did not follow suit till 1833.

Britain regained the lead as steam conquered the oceans. The first steamer to cross the Atlantic was the *Savannah* in 1819, but she was primarily a sailing vessel using steam as an auxiliary, and the same applies to several later crossings. It was commonly held that steamers were useless for long voyages, because the coal they would have to carry would reduce the payload too much. These ideas were dispelled when the British *Great Western* in 1838 created a transatlantic record of fifteen days in a race with another vessel for the honour of establishing the first regular transatlantic service. Thereafter the position of steam was secured; large shipping companies with steam vessels came into being—the Cunard Line, for example, was established in 1840.

These vessels were of wood and paddle-driven, but about the same time the screw and iron construction were beginning to appear. The screw had been tried at various times since 1796 (and indeed had been proposed even earlier). Only towards the middle of the nineteenth century did it come into regular use and there is much doubt as to which of the many claimants should be given credit for making it a practical mechanism. The critical step forward is usually taken as the patents of Ericsson and Smith in 1836 and the first really successful use as that by Smith on the *Archimedes* in 1839. Perhaps it would be more just to give the credit to the designers of engines working at higher speeds, for undoubtedly with the slower engines of earlier years the screw was bound to be less efficient than the paddle-wheel. After experiments dating from 1787, iron construction became common about the middle of the nineteenth century. The first steel ship was launched in 1863, and from 1874 steel has completely replaced iron. The use of turbines and diesels as power units completed the transition to the modern ship, which binds the world into a single unit in which national divisions become more and more artificial.

While these great industrial changes were going on, an equally important agricultural revolution was taking place—indeed the growing industrial population could not have been fed without great agricultural changes. The more important agricultural advances were in such things as the introduction of new crops, new methods of rotation of crops and so on, but mechanical matters also played their part. The form and construction of ploughs improved rapidly from the invention of the Rotherham plough in 1730, and about the turn of the century ploughs made wholly of iron began to appear, coming into common use about 1820. The seed-drill, which opens a furrow, inserts the seed and covers it, is a great improvement upon the traditional broadcast sowing. Various forms of drills had been tried in the sixteenth and seventeenth centuries, but its real development began when Jethro Tull (famous for his part in all aspects of the agricultural revolution) strongly advocated its use in the decade 1730-40. Tull's drill bore little resemblance to a modern machine, but an essentially modern drill was invented by Cooke in 1782, after which the drill developed rapidly. Threshing was the only aspect of agriculture to which power, other than that of animals, was applied until near our own times. In 1636 Van Berg patented a thresher consisting of several flails operated by cranks. In 1732 Michael Menzies invented a water-driven thresher, which according to his advertisement would 'give more strokes in a day than forty men and with as much strength'. This had some success, but the first really useful thresher was that of Andrew Meikle, working on the rotating drum principle, invented in 1786. Threshers were adopted widely in the early nineteenth century and from 1802 began to be steam-driven. A rotary chaff-cutter was invented by James Cooke in 1794, and about the same time a machine was used in Germany for slicing potatoes for cattle.

All the developments we have described in this chapter depended, of course, on improved methods of producing and working metals, but this subject we shall leave for special discussion in Chapter VIII. Besides, there were many minor inventions, such as the modern water-closet (Bramah, 1778), paper-making machinery (1798), and a most ingenious tumbler lock by Bramah in 1784, so secure that despite a substantial reward it was not picked till 1851 and even then took fifty-one hours' work, but even more significant because its fineness and intricacy played a key part in the development of more accurate machining methods. Printing with rollers was developed by Koenig, and in 1814 his presses began to print *The Times* at the rate of 800 sheets an hour—the beginning of the cheap and plentiful newspapers (now printed at 20,000 copies an hour[1]), so essential on the one hand for an informed democracy, so amenable on the other to use by interested parties to mislead the public. And in addition this period saw the first significant achievements in various lines that were to be fully developed in the nineteenth and twentieth centuries; the beginnings of balloon and even dirigible flight, of electrical devices, the first steps in the mechanization of agriculture, in coal-cutting machines for the mines and the first achievements in mass-production methods.

The social effects of these industrial changes are probably better known to the reader than any previous ones. The most obvious are evil. The superior efficiency of machines drove hand-workers out of employment. When they sought work again in factories, their wages were continually depressed; so much so that all the family had to work and even toddlers worked long shifts in cotton mills. Working conditions were foul. Hours of work were long—twelve or even sixteen a day—perhaps no longer than they had worked as spinners in their own cottages, but then they had worked freely, choosing their own periods of rest, while now they were subject to the relentless discipline of the factory which waited for no man. Housing conditions in the new towns that sprang up round the mills were as bad as working conditions. Individual houses were, perhaps, no worse than the cottages they had lived in before, but sanitary conditions that will do for a village are of no use for a crowded town, and housing methods utterly failed to cope with the new problems.

Perhaps most obvious of all was the mass unemployment of displaced craft workers, only slowly absorbed by the expanding factories. Such unemployment (at this period) was only temporary, but it was nevertheless serious to those displaced. Machines, it seemed, were the cause of that unemployment. They did work formerly requiring many

[1] The modern rotary press, however, developed from that invented by Hoe in 1845.

hands. Small wonder that the craftsmen turned against these machines. In 1663 and again in 1767 they wrecked mechanical sawmills which had been erected in London. There were riots against the ribbon loom in 1676 and stocking frames in 1710. John Kay had his home wrecked in 1753 and was forced to leave the country. In 1768 the Blackburn spinners destroyed Hargreaves' jennies. In 1776 and subsequent years systematic attacks were made on Arkwright's machines. The introduction of power-weaving in Nottingham was followed by riots in 1811–12. Crompton had to go into hiding. And so all over the country, wherever the new machinery was introduced. Such methods could not, however, solve the problem, and it was not until the nineteenth century that the workers found the real way forward.

But behind all this open misery, the machinery and the factory system were also bringing immense benefits. They made available far greater quantities of all commodities. The workers, of course, did not automatically get their share of these goods—they had to learn how to fight for it—but they did get some share, and living conditions on the whole did improve, after the black period of the first few decades. The best index is perhaps population, which in England and Wales rose from 6½ millions in 1750 to over 10 millions in 1811.[1] Part of the rise was due to a rise in the birth-rate, but more to a fall in the death-rate, which was a sign of better health and a rising standard of living. These in turn came partly from the increased productivity of the machines, though it must not be forgotten that the parallel revolution in agricultural methods was equally important. In a London lying-in hospital between 1749 and 1758 one mother in every forty-two and one child in fifteen died; in 1799–1800 deaths

[1] The effect of industrial changes on the size of population is better brought out by comparing the average annual increase over various periods. Between 1483 and 1700 the average annual increase per thousand of population was 0.7; between 1700 and 1750 it was 3.3 per thousand; then as the effects of the Industrial Revolution became more marked, it rose quickly to 8.5 in 1750–1811 and 12.8 in 1811–51.

had been reduced to one mother in 914 and one child in 115. Partly, this shows that the mothers coming in were healthier and better fed. Partly, that medical knowledge and medical service had improved—but that in turn owes something to the fact that increased industrial and agricultural productivity allowed a greater number of men to withdraw from the production of essentials and devote themselves instead to the study and practice of medicine.

Thus, in spite of their black side, the industrial changes of the seventeenth and eighteenth centuries did mean a tremendous step forward for mankind, a step towards the position in which we find ourselves today with the prospect of eliminating poverty for ever and providing for all the material essentials on which to base a full and happy life.

CHAPTER VII

THE SECOND INDUSTRIAL REVOLUTION: MATURITY (1815–1918)

In the eighteenth century Britain was the only highly industrialized country. That is why almost all the inventions described in the last chapter were of British origin. But by the end of the century other countries were developing industrially. The French Revolution of 1789 swept away the hindrance of feudal structure, as the English one of 1640 had done, and did it more suddenly and completely. The people of the American colonies gained their independence from Britain in 1783 and the United States was soon on the way to industrialization. Other countries followed at various times.

Once free of restriction, the industries of these countries began to grow as that of England had done. And as industry grew, so also did their citizens turn to science and invention to provide better industrial methods. Already we have noticed how the U.S.A. took the lead in steam navigation within a few years of winning their independence. France and the U.S.A. figure as prominently as England in the present chapter and towards the end of it Germany also comes to the fore. In France in particular, the complete and uncompromising revolution was followed at the beginning of the century by very conscious efforts to encourage inventions and raise the level of industrialization. Napoleon on hearing of a project by Fulton for steam navigation, wrote to his Minister of the Interior in July 1804: 'I have just read Citizen Fulton's project, which you have delayed sending much too long, for it seems capable of changing the face of the world. In any case, I request you to have the matter enquired into at once by a committee composed of members of the Academy who are authorities on European science. A great physical truth is here disclosed to me; it is for these gentlemen to see it and make it serviceable. Send me the report if possible within a week, as I am burning to hear the result.—N.'[1] Such direct interest of political leaders in invention, because it was 'capable of changing the face of the world', was a quite new phenomenon and indeed was not to be paralleled until after 1917 in the U.S.S.R. The *Société d'Encouragement pour l'Industrie Nationale* subsidized inventors, offered prizes for important inventions (their prize offered for the construction of a practical water-turbine was largely responsible for the early lead of France in that field) and compiled critical reports on inventions with respect to both their technical excellence and their economic and social effects. In the U.S.A. the interest of political leaders in technology was nearly as great. Thomas Jefferson was interested in mass production methods and also applied mathematical methods to working out the best shape for plough mouldboards. Benjamin Franklin was at once America's first noted scientist and one of her greatest diplomats. George Washington himself experimented with the mechanical sowing of grain. In

[1] The Academy turned down the proposal.

Britain the inventor was left to take care of himself, though voluntary organizations like the Royal Society of Arts did something to help; but Britain's lead by the beginning of the nineteenth century was such that she was able to maintain her place almost unchallenged until near the end of it.

The period 1815–1918 saw the development of steam navigation on an ocean scale (see Chapter VI), the growth of the railway, the completion of the mechanization of textiles, the development of several prime-movers—the water-turbine, the steam-turbine, and the internal combustion engine—the appearance of the motor car and the aeroplane, the development of electric power, the telegraph, telephone and radio, much progress towards the effective mechanization of agriculture and of coal-mining, besides many hundreds of minor advances. It was so fruitful a period that in this book we can do no more than skim over its surface—a full history of the mechanical inventions of the period would require volumes to itself.

Few innovations have had more far-reaching effects than the railway—that is, the steam-driven public railway, for railways as such are of much older origin. We have already noted in Chapter V (see especially Figure 19) that railways were used at German mines in the sixteenth century. The railway provided a cheaper and more efficient mode of transport at mines than the ordinary cart running on a necessarily very imperfect road. As industry grew, the number of such railways grew too. Gradually they were improved, by covering the original wooden rails with iron plates (hence the term 'platelayer'), and eventually by the total substitution of iron for wood. By the end of the eighteenth century such railways were common at British mines and also at foundries, where transport was equally heavy. The Darbys' ironworks at Colebrookdale, for example, had about twenty miles of railways. All these were horse-drawn.

Fig. 32. Stephenson's 'Rocket'.

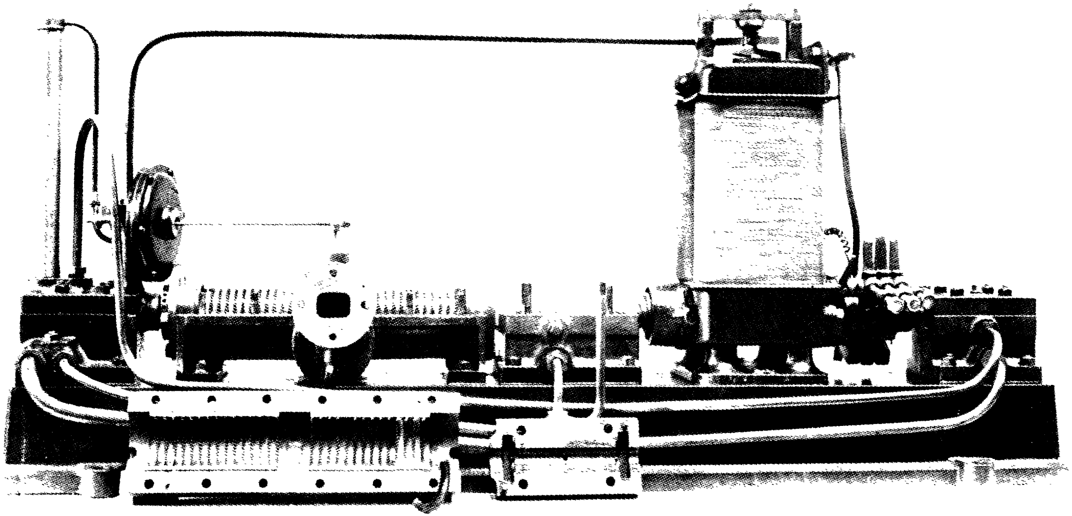


Fig. 33. Parsons' first turbo-generator.

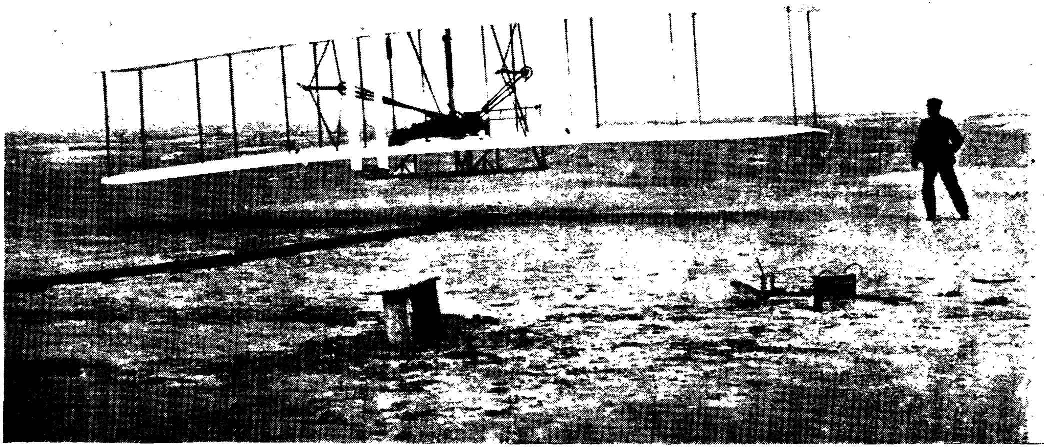


Fig. 34. The Wright brothers' first flight. Orville Wright is piloting (lying flat on the lower plane); Wilbur is on foot.

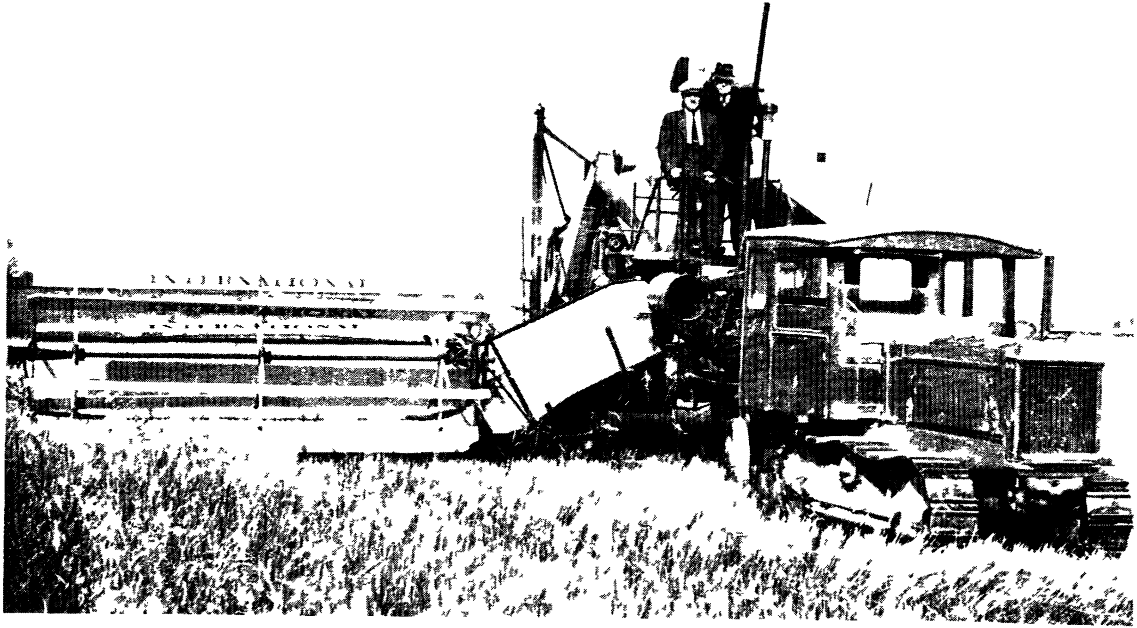


Fig 35 A modern version of the combine harvester

The next great innovation was the driving of railways by steam. The earliest steam locomotives were not intended for use on railways, but as road carriages. Proposals for steam carriages go back to the late seventeenth century, but the first steam carriage to achieve even limited practical success seems to have been that of Cugnot in 1770. It was sound in conception but defective in proportions, so that it ran at 2½ m.p.h., but stopped every thirty yards or so to get up more steam. Murdock made a highly successful model in 1784. But the real pioneer was Richard Trevithick, who worked on the problem from about 1797, produced moderately successful road carriages, and then conceived the idea of applying this new method of haulage to the railway. He probably did not envisage the public railway we know today, merely the idea of using a new and better method of haulage for the railways that connected with the mines and ironworks. In 1803 he built a locomotive for the ironworks at Colebrookdale and in 1804 another for the Pen-y-Darran ironworks, which pulled ten tons of ore and seventy passengers at five m.p.h. These early locomotives were not very successful, but the need for a better haulage system on the railways became generally felt in the next few years and many men worked on the problem. Of these George Stephenson was outstandingly successful and it was he who established the railway system as we know it today. He built his first locomotive (for a colliery) in 1814; shortly afterwards he made the important innovation of chimney blast. Thereafter by careful analysis and brilliant workmanship he rapidly improved the efficiency of his engines.

At the same time a new idea was developing—that of the public railway. One such was in use carrying merchandise between Wandsworth and Croydon in 1801. It used horses for traction; the idea of steam traction was then little known and the railway was merely a method of using horse traction to better effect than was possible on the roads. Transport problems in the new, more highly industrialized England were becoming acute—the roads were poor, road transport costly, and though canal transport was cheap the canals were seriously overburdened. That was the background against which a Bill was put before Parliament in 1821 for a railway between Stockton and Darlington to be worked 'with men and horses or otherwise'. There was still general doubt as to whether the steam locomotive could do the job. But Stephenson convincingly demonstrated that it could and the railway was opened in 1825 with locomotives of his manufacture.

Meanwhile the cotton manufacturers of Manchester had been finding that the Liverpool-Manchester canal was inadequate to carry the enormously expanded export trade that we noted in the last chapter. A Bill was put before Parliament in 1825 to sanction a railway between those towns—*and was defeated!* It was defeated by organized opposition of the landowners, who objected to this spoiling of their estates, and the canal owners and turnpike owners, who saw only its potential effects on their own interests. A campaign of vilification was started, in the Press and by special leaflets; cows, frightened by the trains, would yield no milk; smoke from the funnels would kill the birds; sparks would fire houses; boilers would burst and kill the travellers, and so on. By such tales and by much lobbying, the vested interests defeated the Bill. At the same time they organized sabotage and even armed attacks on the men who were surveying the line. Then came the success of the Stockton-Darlington line and that, aided by an expenditure of £27,000 by the railway interests, got a second Bill for the railways passed in 1826.

A competition was held in 1829 to decide whose locomotives should be used for the line. Stephenson's 'Rocket' (Figure 32) was the only one that satisfied the conditions. On the second day of the trial it pulled thirty passengers at 30 m.p.h. The line was opened in 1830 and the steam railway was established as the primary mode of inland transport for nearly a century. Yet opposition continued to hold back development and by 1838 only 490 miles had been laid in Britain. Then came the railway boom, and the milage reached 1,900 in 1843 and 5,000 in 1848.

The railways opened up possibilities of travel to wider classes than ever before. But far more important were their effects in relation to further industrial developments. The railways became the arteries of industry. The industrial trend that we shall discuss in subsequent pages, demanded more and more the centralization of production in large units. The benefits of industrialization depended on a transport system which could carry raw materials and finished products where they were wanted. The railway on land and the steamship at sea provided this transport.

The water-turbine has a longer and more complicated evolution than most previous inventions. Its evolution can be traced back to a primitive form of horizontal water-wheel, which appeared in the fifth century or possibly much earlier. With the earliest rise of modern mechanical methods various improvements took place in the design of such wheels all leading gradually in the direction of the turbine. One of the earlier modified wheels was proposed by Leonardo and in the seventeenth and eighteenth centuries many more followed, some of them being used fairly widely in practice. But though the general idea of the turbine, in which the water would act on blades in a close-fitting casing, was simple and though the obvious possibilities of greater efficiency than the comparatively crude water-wheel provided an incentive, yet there were many difficulties to be overcome. The details of the correct shaping of blades and casing were very far from obvious, and unless these were correctly designed, the turbine could not fulfil its promise. Thus, ultimate progress depended very greatly on theoretical investigations in the light of the rising science of hydro-dynamics which were made by a number of men in the second half of the eighteenth century. These led gradually towards a sound grasp of the essentials of turbine design. Indeed Euler, as a result of his theoretical work (1750-4), was able to produce a crude form of turbine, which did find some commercial application, though it was not yet good enough to be of general significance.

The other great difficulty was an engineering one—a close fit of comparatively fast-moving parts was necessary if the turbine was to be reasonably efficient. The engineering experience of the eighteenth century provided at last the possibility of sufficiently accurate workmanship and so it is in the early nineteenth century that we find the turbine fast becoming a practicable proposition, as a result of the efforts of many workers, almost all in France. Then in 1823 came the offer by the *Société d'Encouragement pour l'Industrie Nationale* of a prize for a perfected turbine and with this added incentive the efforts of inventors were redoubled. Part of the prize was awarded to Burdin in 1827, but the real credit for the perfected turbine belongs to Fourneyron. His first turbine, of 6 h.p., was produced also in 1827. By 1832 he had produced a perfected version (the actual turbine was of 50 h.p. and was used to drive a forge-hammer), and was awarded the prize of 6000 francs. The turbine thereafter expanded very rapidly in size, reaching 800 h.p. by 1855. It later found its main application in electric power generation.

The story of electricity, whose application to many uses is one of the greatest achievements of the nineteenth century, is likewise one of long evolution, the result of the efforts of many men. Here we must skip the early developments and begin with the discovery of the Voltaic cell in 1800. This cell gave for the first time a continuous current, the first essential for practical application and the basis on which scientists could discover the important properties of electric currents and then learn how to apply that knowledge. Thereafter development was extremely rapid. The principle of the arc lamp was discovered by Davy in 1808; Faraday discovered the fundamental principles of the electric motor in 1822 and of the dynamo in 1831. Also in those years were discovered the fundamental properties on which the telegraph, the telephone and many other applications were to be based. But electricity was no easy tool to master and decades passed before really practical results were obtained.

The first important application to be brought to success was the telegraph—partly because the practical problems here were simpler than, say, for electric lighting, partly because the need was more obvious and insistent. With the growing commerce of the times, speedy means of communication were much to be desired and after the advent of railways the need for some method of informing the signalman ahead of the train's progress was a very pressing one. Various methods of rapid communication were in use—carrier pigeons, or 'telegraphs' based on the sending of visual signals along relays of stations, but none was satisfactory. From the beginning of the century and, in a desultory way, even before, many men sought for an electric telegraph but it was not till 1837 that success was achieved independently in the U.S.A. by Samuel Morse and in England by Cooke and Wheatstone. In 1838 Morse telegraphed ten miles while the Cooke and Wheatstone system was installed on the London-Blackwall railway. In 1851 the Dover-Calais submarine cable was laid; and with the establishment of a transatlantic service in 1866 after many tribulations, the telegraph became a means of communication on world scale.

If men could communicate signs over long distances by electricity, it was natural that they should seek the more convenient method of transmitting actual speech. The first to succeed was Phillipp Reis in 1861, but his apparatus, though it worked in a limited way, was little more than a curious toy. And it was not till 1876 that a practical telephone was invented by Alexander Graham Bell of the U.S.A. Within a few years his telephones were in use in all the advanced countries of the world. Improvements came hard on each other's heels: improved microphones by Edison and Berliner in 1877 and again by Blake in 1880, and the automatic exchange in 1887 (though this came but slowly into use). By 1876 Bell had transmitted over two miles; by 1880, forty-five miles was reached and by 1892 the New York to Chicago line of 900 miles represented the economic limit that could be achieved until the use of inductive loading in 1900 and later of relays depending on thermionic valves (developed in connection with radio) practically removed all limits of distance, so that by 1913 a line of 2,600 miles joined New York to Salt Lake City.

If the telegraph and telephone changed the world by making possible instantaneous communication over the whole globe, even more revolutionary possibilities were implied in the transmission of power by electricity. It makes power available for small units—household appliances, for instance, or individual drives for factory machines, eliminating the cumbersome, inefficient and noisy shafting, ending the need to concentrate machines round the steam-engine. It provides the possibility of moving the factory out of the crowded towns, away from the coal wharf to which it was formerly tied, and into the countryside, where, in healthier conditions, it can still get its power from electricity. Or alternatively, if the factories must for other reasons remain concentrated in cities, it gives the opportunity to burn fuel elsewhere, transmit electric power to the city and so keep the city clean and healthy. These possibilities have not yet been fully utilized, though a beginning has been made; but the opportunity is there for future generations to grasp.

In point of fact the pioneers of electrical transmission of energy were not thinking of such possibilities; they were not to any great extent concerned with the transmission of power at all. Their main concern was electric lighting, perhaps partly because that problem was somewhat simpler, partly because gas lighting (London's Gas Light and Coke Company, for example, was founded in 1812) provided an obvious precedent. The dynamo, whose principle was discovered by Faraday in 1831, was developed by a whole series of workers over the next fifty years. Davy's arc lamp was turned into a practicable commercial possibility by Foucault in 1844 and others after him. Arc lighting came into use for special purposes. It was installed at Dungeness lighthouse in 1862. In the years 1870–80 it was widely used and in 1878–80 it had a definite boom, being used to light railway stations, docks, theatres and even streets.

But it was in just those boom years, no doubt partly because of the boom, that the more efficient and convenient system of incandescent lighting was established. Like many other electrical developments it had its beginning in the early nineteenth century; De La Rue produced an incandescent lamp of platinum in 1820. But it was the work of Swan and especially Edison between 1878 and 1880 that made a practical proposition of the incandescent lamp with carbon filaments. Edison's contribution was much more than a lamp. He put almost the final touches to the generator, so that by 1882 the generators in use were essentially those of today, apart from the carbon brush introduced in 1883 and certain improvements in winding and, of course, vast changes in size. Edison also worked out the by no means obvious system of distribution by cable and wiring circuits. After his work the industry expanded, possibly more rapidly than any industry had ever done before. The first commercial installation was made in 1880 on a ship, the first on land (a private installation) in 1881. The first public lighting supply was opened at Appleton, Wisconsin, in the same year, with an output of about 1 h.p.! The first station in England was opened in 1881 at Godalming in Surrey. Then in 1882 came the opening of the famous Pearl Street Station, New York, which finally established the method of electric supply to any consumer in a district, followed rapidly by several others. By the end of the year nearly eighty electricity companies were founded in England, though few had yet begun to operate.

In 1883 the first public electric railway was opened—between Portrush and Giant's Causeway in Ireland.

Hydro-electric generation had been used at some of the earliest stations in 1881–2, but the station which established its value was that at Niagara, begun in 1891 and put into operation in 1897–8. Soon the generation of electricity became the principal application of the water-turbine.

Until about 1890 very little use was made of electricity for power. Thereafter the improvement of the electric motor and more especially the use of the polyphase system (developed by Tesla from 1887 on and first applied on a large scale at Niagara in 1897–8) brought about the rapidly increasing use of electric power.

The early central stations, working on direct current at low voltage, could distribute over a radius of only a few hundred yards. The station had to be in the centre of the area served. To gain the full advantages of electric power it should be generated at some convenient point where fuel or water-power is easily accessible and thence transmitted to the area where it is required. This requires alternating current, generated at a high voltage. A lead was given by Ferranti in 1889 with his 10,000-volt generators at Deptford, whence power was transmitted to Central London. But small local stations remained common for decades. Indeed it took Government action, in the form of the Act of 1926 which set up the Grid, to secure anything like general adoption of Ferranti's policy in Britain, while other countries showed little if any more progress. The greatest benefits of all arise when the electricity can be transmitted over really long distances—up to about 200 miles in present general practice. Marcel Duprez experimented very early on long-distance transmission and in 1882 covered nearly forty miles. The system was adopted in such cases as the Niagara power station, but its general use belongs to the inter-war period.

One of the most important elements in electric power technique is the steam-turbine. It will be recalled that two of

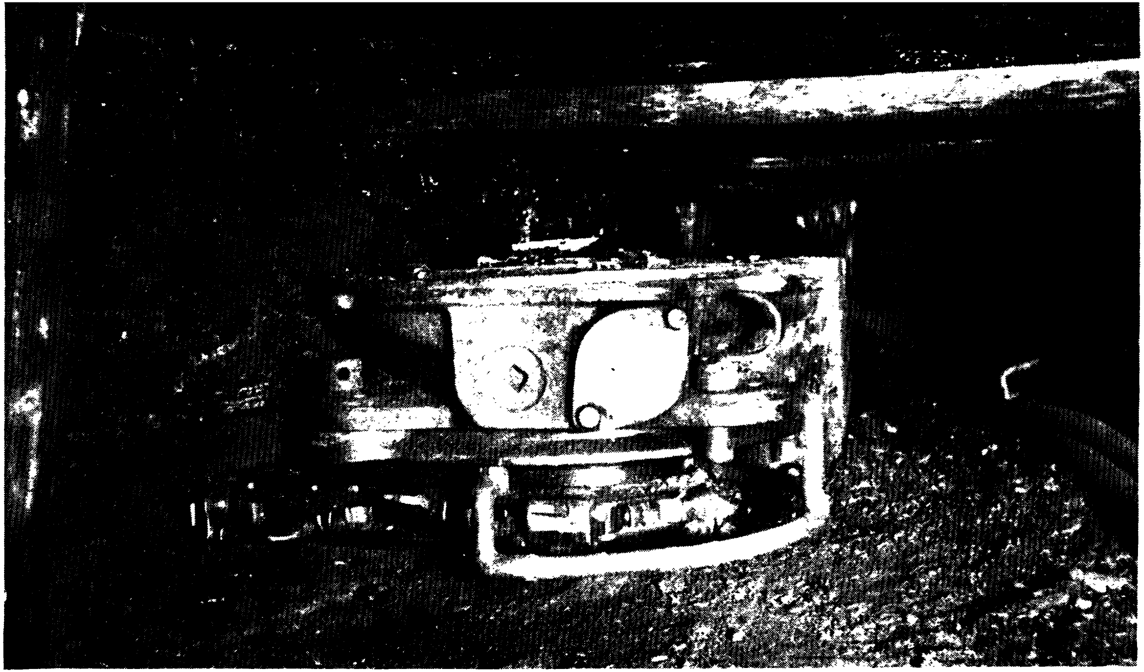


Fig. 36. A chain-type coal-cutter.

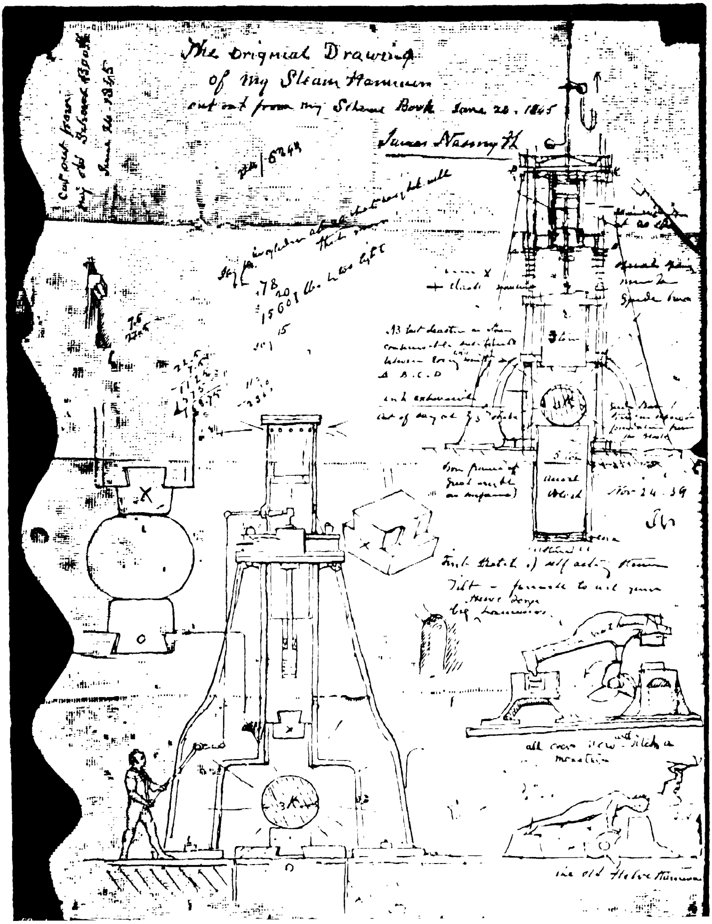


Fig. 37. Nasmyth's own first sketch of his steam-hammer, made 24 November 1839.

the earliest schemes for steam-engines (neither of any practical significance) were for turbines—those of Hero and of Branca. With the success of the reciprocating engine, attention was diverted from the turbine, and by the same time good engineers, with their increasing knowledge, had come to realize the tremendous difficulties of making any workable turbine. Speeds would have to be enormously beyond anything then practicable and the engineering difficulties of ensuring a close fit at such speeds remained beyond practical possibilities until the late nineteenth century. James Watt put the matter neatly when he replied to fears expressed by Boulton concerning the effect of a proposed turbine on their business; after a few calculations he remarked 'without God make it possible for things to move 1,000 feet per second, it cannot do much harm'.[1]

Nevertheless, the turbine, if it could be made practicable, had certain obvious advantages—it promised higher efficiency and greater power, it would eliminate the rather round-about process of converting the energy of steam into rotary motion via reciprocating motion. Thus several attempts were made in the latter half of the nineteenth century to produce workable turbines, but none was successful until that patented by Charles Parsons in 1884. Parsons developed the turbine chiefly in relation to electricity generation (though his patent shows that he had other purposes also in mind from the beginning). The first turbine (Figure 33) was used to drive a small generator and gave satisfactory results. Many turbo-generators were built for small installations in factories, ships, and so on. After the incorporation of condensers in 1892 and other improvements, the turbine rivalled the reciprocating engine in efficiency and was rapidly adopted for central generation of electricity. Thereafter it soon surpassed in both size and efficiency the

[1] The gearing in Branca's proposal (Figure 23) may indicate that even he had some vague idea that high speeds were involved.

utmost limit possible with the reciprocating engine. By 1912, turbo-generators of 25,000 kW. (about 33,000 h.p.) had been reached, whereas the maximum power obtainable from a reciprocating engine is about 8,000 h.p.—and that only in the special conditions of the triple-expansion marine engine.

It was to marine engines that Parsons next turned his attention, for this was the only other large field that could make use of the full potentialities of the turbine, especially in regard to size. He constructed a small launch, the *Turbinia*, which created a sensation at the Naval Review of 1897 by reaching a speed of thirty-four knots, against the twenty-seven knots of the fastest destroyers in existence. In the following years the turbine was tried in various vessels of the Navy, with such success that in 1905 the Admiralty took the decision that turbines should be used exclusively on all classes of warships. Meanwhile the first merchant vessel with a turbine was built in 1901 and soon turbines were accepted as the best drive for all fast ships—the *Lusitania* and the *Mauretania* were launched in 1906, each with four turbines totalling 70,000 h.p. From 1909 onwards Parsons developed the system of driving the propellers through reduction gearing and thereby made possible the use of turbines in slow cargo vessels.

To use fuel directly in a cylinder is a simpler idea than the more complex cycle of fire, boiler and cylinder involved in the steam-engine, so that the earliest attempts at internal combustion engines occurred in the period just before the practical steam-engine arose. Huygens' attempts to produce a gunpowder engine about 1680, followed up by Papin about 1690, have already been referred to in Chapter VI. But if the concept of an internal combustion engine is simpler than that of a steam-engine the practical problems of making it work are much greater; thus the arrival of the practical steam-engine put an end for a time to work on the internal combustion engine.

Nevertheless the internal combustion engine presents certain features which were bound to be attractive to inventors—its greater simplicity in principle, the possibilities of lightness and smallness arising from the elimination of fire-grate and boiler, the promise (not to be so easily realized) of greater efficiency through eliminating the loss in the chimney, boiler and steam-pipe system, and the possibility of conveniently producing engines in smaller units, suitable for the small factory or workshop (whereas the economical use of steam was confined to larger establishments). For these reasons renewed attempts were made from the last decade of the eighteenth century onwards to construct internal combustion engines of various types. The coming of coal-gas provided a suitable and readily available fuel and from the twenties the gas-engine became more and more practicable, attaining gradually increasing commercial success from 1860 on, till the Otto 'Silent' gas-engine of 1876 completed its main evolution. The gas-engine, with its adaptability to small-scale use, allowed power mechanization of many smaller industries, just as the steam-engine had done for the larger ones a century before. However, the growing use of electric power around the turn of the century largely replaced it in this important field and, although very large units using blast-furnace gas were developed with efficiencies greater than steam in suitable circumstances, yet from the point of view of present-day machinery the gas-engine is chiefly important as a step on the way to the petrol and oil engines. All its principles were embodied in the latter, which have thus a more rapid evolution. Petroleum in large quantities had been discovered in 1858 in Pennsylvania and from 1873 onwards petrol engines were attempted and Daimler's engine of 1885 marks the beginning of the modern petrol engine—though many essentials, like electric ignition, were still to be added.

Almost concurrently attempts were made to use heavier and heavier oils. The Priestman brothers of Hull were successful with refined medium oils about 1885 and about 1890 the Ackroyd Stuart engine for the lighter crude oils was developed. Diesel's main patent was dated 1892, though it was several years before a workable engine was produced. The Diesel engine used the crudest of crude oils. It realized at last the dream of an oil engine which should be more efficient than steam, and was soon expanded to sizes where it could rival steam in electricity generation and ship propulsion except in the very largest units. By 1930 a considerably greater tonnage of new shipping was being powered with Diesel engines than with steam.

The effects of the petrol engine were most revolutionary in the field of transport, first on the roads and later in the air; its lightness in relation to power made it pre-eminently suitable for this field. Mechanical road transport does not, however, begin with the petrol engine. The steam-carriages which we mentioned above in connection with the railways began almost concurrently with the effective establishment of the railways to reach a reasonable degree of practicability. By 1831 there were twenty such carriages operating for public transport in or near London with speeds from five to thirty miles per hour. The growth of the railways, however, made such transport uneconomic. And when, about the middle of the century, steam-carriages had been sufficiently improved to become once more a rival, the combined opposition of railway and coaching interests succeeded in obtaining restrictive legislation in England which made steam transport by road well nigh impossible. The Act of 1861 required that each vehicle should carry at least two drivers and restricted speeds to ten miles per hour in the country and five miles per hour in towns. The Red Flag Act of 1865 reduced these speed limits to four and two miles per hour respectively and required that a man carrying a red flag or a red lantern should walk sixty yards ahead of the vehicle. In this way the interests of the railway companies were protected. A hardly surprising result was that the main initial inventions connected with the motor car were made outside England. England could not compete till the Red Flag Act was repealed in 1896.

The first petrol-driven car was that of Benz in 1878, but the really significant achievement was Daimler's car, about 1889, using his engine of 1885 already mentioned. Other inventors soon followed with other cars. Petrol buses and lorries appeared about 1904. The rest of the story of the motor car is not so much a tale of invention as the tale of the application of mass production methods to make widely available machines; it is therefore postponed to Chapter VIII.

With many of the inventions we have described it is clear that they were achieved at some particular period because general social conditions had fairly suddenly established a great need for them; many inventors responded with their efforts to satisfy this need and one or a few of them were successful. The history of flight is different. It is, of course, true that there was more practical gain to be achieved from flight in the industrial era of A.D. 1900 than at any previous time. Nevertheless, man's desire to fly has been in most periods so great that we have to say that the reason why practical flight arrived no earlier than it did was not a lack of general desire, implying lack of incentive for the inventor, but lack of ability. The technical problems of flight, more than any previous mechanical achievement, were such that their solution could only be built on the results of centuries of engineering experience and scientific analysis.

Mankind first sought to fly by magical means. Then the great change from faith in magic to faith in machines that took place in the Middle Ages and early modern times brought about a change of tactics. Thereafter men tried to construct suitable machines. They worked logically, though their attempts remained very inadequate, for lack of the requisite knowledge. Thus even as early as 1030 Oliver of Malmesbury attempted to fly with wings attached to his hands and legs. Thus Leonardo at the close of the Middle Ages carried out thorough and penetrating studies of the flight of birds and attempted to construct a flying machine on this basis. But, as scientific analysis progressed, it was realized (and stated by Borelli in 1680) that human muscles were inadequate and heavier-than-air flight had to await the coming of a suitable motor.

Lighter-than-air flight came much sooner. After many proposals and experiments, from the early seventeenth century onwards, flight in hot-air balloons was achieved by the Montgolfier brothers in France in 1783; and in the same year the first flight in a hydrogen balloon was made. Immediately ballooning became a craze. Many flights of considerable daring were made. The Channel was crossed in 1785. Balloons were used by the French Army for observation in 1794. The year after the first successful balloon flight, a proposal was made for a dirigible balloon, i.e. an airship, but the first successful airship did not come till 1852, when Henri Giffard's machine with a three h.p. steam-engine covered seventeen miles at four or five miles per hour. This was far from a practical airship—it had not got sufficient power to fly against the wind—and practical development begins from about 1884. Zeppelin began building his first ship in 1898 and made his first flight in 1900. His ships were rapidly successful. His fourth in 1908 crossed the Alps. Between 1910 and 1914 Zeppelins carried 35,000 passengers and covered 170,000 miles without serious mishap. In the 1914-18 war airships were widely used for military purposes, but not long after a succession of catastrophic disasters, which stood out in sharp relief because a practical alternative, the aeroplane, was being developed, put an end to airship construction, except for very special purposes.

A critical step towards the creation of the aeroplane was taken in 1809 when Sir George Cayley formulated accurately the principles that must govern heavier-than-air flight. He made it clear that the main problem was to obtain a suitable engine and that the steam-engine was not likely to be suitable. It would serve, however, for models and from about 1840 there was considerable experiment with power-driven model planes, the first model to rise under its own power and land safely being constructed in 1857.

Further developments now depended on a thorough scientific analysis, of which the basis was the study and practice of gliding flight carried out by the Lilienthal brothers in Germany from 1877 on and by others after them. Then in the nineties came renewed attempts at power flight on a more rational basis, many of them almost achieving success—machines that rose a little from the ground, others that flew a few hundred yards but were clearly not under full control and ended by crashing.

In 1900 the Wright brothers began extensive gliding experiments coupled with painstaking scientific and mathematical analysis of the problems involved. They developed a system of lateral control by independent flexing of the wings, a system which, in the form of the aileron, eventually proved to be the key to successful flight. Then they turned their attention to power flight. The recently developed automobile engine provided the basis for a suitable motor, but the brothers took equal pains in designing their particular motor and propeller. Their thoroughness was rewarded on 17 December 1903, when their machine flew for twelve seconds and covered twenty-five yards (Figure 34). Larger distances had been covered before, but the point was that this time the machine was fully under control. Progress thereafter was rapid. Their fourth flight lasted fifty-nine seconds; in 1904 they flew five minutes four seconds; in 1905 they covered twenty and three-quarter miles in thirty-three minutes seventeen seconds. By 1908, when many others besides the Wrights were flying successfully, the duration record was just over three hours; the distance 112 miles; and the speed record fifty miles per hour. In 1909 Blériot flew the Channel.

Till 1914, nevertheless, flying remained something of an adventurous sport. The forcing house of war, with technicians, factories and Government funds all made available, turned the plane into a reliable machine. Between 1914 and 1918 maximum speeds rose from 70–80 m.p.h. to 140–155 m.p.h.; air-cooled engines developed from weights of 4 lb. per h.p. to 1.9 lb. per h.p. and water-cooled from 4.05 to 2.2; the average ceiling rose from 7,000 feet to 30,000 feet. The crossing of the Atlantic in 1919 by Alcock and Brown demonstrated what a reliable and useful machine had emerged from the war. Regular air services were quickly established and even in 1920 they flew a total of nearly three million miles.

Wireless communication, which also came into being about the turn of the century, arose from two main sources. The incentive to attack the problem came from the same social needs for rapid communication that earlier gave birth to the telegraph and telephone, plus the promise that wireless would provide one great advantage that these two never could—communication with ships. The basis for the solution was provided by the theoretical work of Clerk Maxwell about 1862 and the experimental work of Hertz from 1887 on, which demonstrated the existence of electro-magnetic waves, the basis of radio. In the nineties this problem interested a number of inventors, several of whom were partially successful. But the only outstandingly successful system was that of Marconi, who arrived in England from Italy in 1896, transmitted radio signals over three miles and patented his invention the same year. Rapid development followed. In 1899 the British Navy on manœuvres used radio telegraphy over seventy-five miles and in 1901 Marconi bridged the Atlantic, while only seven years later a regular trans-atlantic telegraph was established.

Experiments in radio telephony started almost immediately on the success of telegraphy. By 1900 Fessenden of the U.S.A. had achieved some success. In 1906 he claimed to have transmitted speech across the Atlantic. In 1909 de Forest, also of the U.S.A., transmitted Caruso's voice from the Metropolitan Opera House.

But progress was slow, because the transmission of speech depended on ability to radiate *continuous* waves and the systems then available for doing so were of very limited value. Ultimate success of radio telephony depended on the 'valve' or thermionic tube. The two-electrode tube, which would act as a detector but not for other purposes, was invented by the English physicist, Fleming, in 1904. The three-electrode tube, the real key to modern radio, was the invention of de Forest in 1906 and of others elsewhere independently. Nevertheless, it was not till 1913 that the radio valve and associated circuits were advanced enough to be ready for general use.

As in the case of flying, it was the war of 1914–18 that gave the incentives and means for the rapid mastery of the critical problems. Radio telephony was used widely by the fighting forces. Valve techniques were developed rapidly, especially for aircraft, in which they were used for both transmission and reception. Sets of less than ten pounds in weight in reconnaissance planes transmitted speech up to 200 miles. The development and perfection of radio techniques during the war was such that it took only two further years of systematic experiment by scores of workers all over the world (among whom Marconi remained one of the most successful) to pave the way for the beginning of regular broadcasting in 1920. Radio direction-finding began about 1907 and again was greatly developed during the war.

Aeroplanes and radio were perhaps the most startling and romantic developments of the century before 1918. But the standards of human life were much more greatly affected by the mechanization of agriculture. The change-over from hand methods to machine methods of farming, which began to be marked in the second quarter of the nineteenth century, provided for the first time in the world's history the possibility of abundant food for all. More than that, it was the essential basis for the growth of a highly industrialized civilization.

In the early nineteenth century the advanced countries completed the change-over to the all-iron plough. This in itself meant a notable increase in productivity. Steam-power was applied to ploughing after 1850 when John Fowler introduced the system of cable-ploughing—in which steam-engines at either end of the field dragged the plough across by means of cables. This remained the main system of power ploughing until 1918 and even after that it was only slowly displaced by the tractor.

Whereas ploughing had used animal-power from the early Bronze Age, reaping until the nineteenth century remained a job entirely for human muscles. One exception to this is an extremely crude ox-power reaper described by Pliny as being in use in Gaul in Roman times, but this hardly reduced the human toil involved and does not seem at any stage to have been widely used. From 1799 onwards attempts were made to construct reaping machines. The first to achieve any success was that of Patrick Bell, in 1826, which was widely used in Scotland for some years. But south of the Border mechanical reaping made no progress till after the introduction of the superior machines developed in America. The great fields of the U.S.A. provided the ideal conditions for mechanization and it was there that the modern reaping machine developed. Several reapers were invented in the thirties, the most successful being that of McCormick in 1834, which cut the labour involved in reaping to one-third. By 1851 McCormick was making a thousand machines a year. From then on more and more automatic machines appeared. The American Civil War of 1861–5 created a great man-power shortage and thus gave a boost to mechanization. After several steps the completely automatic sheaf-binding harvester appeared about 1878, cutting the labour required to one-half or one-third again. In 1880 four-fifths of the U.S. wheat harvest was cut by this machine.

The next step was the combine harvester (Figure 35)—a machine to reap the corn and thresh it at the same time. Two such machines were patented in 1836, but the practical development of the combine does not begin till about 1860. By the eighties combines drawn by twenty to forty horses were reaping twenty-five to forty-five acres a day in California. In the nineties combines drawn by steam tractors had an even greater capacity. By 1930 a combine required 3·3 man-hours of labour to produce 20 bushels of wheat, compared with 57·7 man-hours with a sickle and flail in 1830. Nevertheless, the combine did not spread outside California till after 1914, when man-power problems caused its introduction east of the Rockies. It did not appear in Great Britain till 1928 and even then spread but slowly.

Meanwhile other aspects of agriculture were being mechanized. A grass tedder was invented in 1814, but haymaking was largely done by hand until about 1850, when machines and horse-rakes spread rapidly. By the end of the century essentially modern haymaking machines had been developed. By then the potato-plough and spinner types of potato harvesters were in use. The latter throws the potatoes clear of the soil, but scatters them widely, after which they must be picked up by hand. The elevator-lifter type of harvester, which does not eliminate hand-picking, but does lay the potatoes conveniently in narrow rows, began to develop in the early twentieth century. Potato-planting machinery was developed about the same period. However, machinery for crops other than cereals and grass was not sufficiently perfected for general use till after 1918.

Apart from threshing (see Chapter VI), cable-ploughing, the use of steam tractors with combines in the nineties, and a few experiments in other directions, the horse remained the main source of power in agriculture till the end of the nineteenth century. But about 1890 in the U.S.A. and a few years later in Great Britain the first attempts to use tractors with internal combustion engines were made. The caterpillar track was improved in the early twentieth century and the arrival of the light petrol tractor about 1910 paved the way for the displacement of the horse. In the U.S.A. the transition began just before 1914, but in Great Britain the horse was not seriously challenged until the introduction of the Ford tractor in 1917.

These machines, with other advances in agricultural technique, provided, as we have remarked, the possibility of a highly industrialized civilization. In 1787 it took the surplus food produced by nineteen farmers (these are U.S.A. figures) to feed one city-dweller. In recent years these same nineteen farmworkers produced enough surplus to feed sixty-six other people. At the first level it was impossible to spare sufficient workers from the land to create a large-scale industry; at the latter, for every worker on food production there can be 3½ producing manufactured goods, transport services, etc., all of which contribute to a high standard of living.

Equally important for feeding industrial populations was the development of refrigeration, which permits food to be brought right across the world or stored for long periods, to supply industrial districts which cannot be self-supporting. After some forty years' development, mechanical refrigeration became a practical proposition in the seventies, the most important step being Linde's ammonia compression refrigerator of 1873. Frozen meat was first imported from America in 1877 and from Australia in 1880. Refrigeration has many other industrial applications. For example, oxygen, used for a variety of purposes from oxy-acetylene cutting to chemical synthesis, is best obtained by distilling it from air that has been liquefied by cooling. Linde produced an economically practical method of liquefying air in 1895. His process depended on cooling the air by compressing it and then expanding it through a valve, making use of a property of gases known as the Joule-Thompson effect, which is, however, quite small. It was early realized that better results could be obtained if the air were made to do external work, that is to drive an engine. This was technically difficult but by 1902 Claude succeeded in producing a liquid air machine in which the air was cooled by driving a reciprocating engine. The process was later improved by Heylandt.

Just as agriculture provides the food for the industrial worker, so does coal-mining provide the food for the industrial machine. It was during the nineteenth century and still remains the main source of power. Naturally, therefore, much attention was given to the problem of mechanization of coal-mining. Under-cutting the coal face prior to breaking it down with explosives or other means, is one of the most laborious of all tasks, and attention was first devoted to the substitution of machines for men at this work. In 1761 Michael Menzies (who has already been mentioned in regard to threshing) invented a coal-cutting machine, with a swinging pick imitating the miner's action, driven by a horse and a man. In 1768 appeared 'Willie Brown's Iron Man' operated by the power of two miners. A patent of 1843 for a cutter based on a circular saw action foreshadowed the modern disc-type cutter. During all this period the main difficulty was to find a suitable power source. Steam-engines were both too cumbersome and too dangerous. Various proposals were made for drives using man-power, animal-power, or even water- or steam-power at the pithead connected to the machine by ropes. Compressed air was first used in a British colliery in 1849 and quickly became the power source on which further attempts at mechanization were based. In the next forty years all the types of coal-cutters in use today, except the percussive cutter (1901) were developed. This was an experimental and pioneering stage, not one of wide practical use. In it the main problems of mechanized coal-cutting were solved, and by 1890 the stage was set for rapid development. In the U.S.A. the percentage of bituminous coal mechanically cut rose from about 4 per cent in 1890 to 51 per cent in 1913. Great Britain, in spite of the fact that most of the pioneering had been done there, was much slower and in 1913 only 8 per cent of British coal was cut by machine and only 676 mines out of 3,267 used coal-cutters. Meanwhile electricity, proposed as a source of power in 1863, was used in practice from about 1885 on and by 1918 was almost as much used as compressed air.

Mechanization of other mining processes was slower. The face-conveyor first appeared about 1902 and all the various types now in use had been developed by 1913. But the spread of their use was even slower than with cutters and in 1913 Britain had only 359 of them. The loading of coal at the face involves lifting two to five feet and casting horizontally six to twelve feet—no light task; yet serious attempts to mechanize it came surprisingly late. The first loader to attract general attention appeared in 1903, but was not adopted in practice. A few loaders of various design were in use in the U.S.A. by 1918, but the general use of loaders did not begin until some years later.

In all the above we have only mentioned some of the outstanding lines of mechanical development in the century before 1918. But in point of fact machinery came to enter into almost every branch of industry in this period. To recount all the inventions of those years would alone take several volumes, and we can do no more than list a few examples. If the reader, as he notes each date, will pause to think what life would be like without that particular machine or without its cheap and plentiful products, he will gain some idea of the changes that machinery brought in the nineteenth century. Many branches of manufacturing were mechanized: steel-pen making, 1828; match-making, 1848; shoe-making, by McKay's shoe-sewing machine of 1861 and Goodyear's welt shoe-sewing machine in 1871. A cigarette-making machine appeared in 1876, a glass-blowing machine in 1886 and Owen's famous automatic bottle-machine in 1907. After many attempts at mechanical type-setting from 1822 onwards, Mergenthaler's linotype appeared about 1886. Workable sewing-machines were invented from 1829 on, but the machine from which are descended the sewing-machines that are used in the home today was that of Elias Howe, 1846. Calculating machines, after an evolution starting from 1642, became practicable and began to be regularly manufactured in the nineties. A typewriter was invented by Charles Thurber in 1843, but the first successful model was that of Sholes, 1868. The first typewriters produced for sale appeared in 1874 at a cost of $125 (about £25). Pope invented his safety bicycle, the culmination of a long line of evolution, in 1886; Dunlop added the pneumatic tyre in 1889. By 1896 there were four million cyclists on the road. Edison invented the phonograph in 1877 and Berliner developed it into the gramophone by 1887, as well as inventing most of the essentials of the multiple reproduction of gramophone discs. Cinematograph pictures became practicable during the nineties. The time-lock was invented in 1847 and Yale's now familiar lock in 1855. E. G. Otis invented his passenger lift with safety devices in 1862. The steam-roller appeared in 1867. X-rays were discovered in 1895. Sperry invented his gyroscopic compass, which has now largely replaced the magnetic, in 1905. These are but a selection. They do not include the many further machines which were invented in principle before 1918, but not widely used until after.

Machinery now entered into almost every aspect of production. The material wealth available for the good of mankind was enormously increased, at least in the advanced countries. Wealth had become better distributed too, though this had taken a bitter struggle to achieve. The machine-wrecking tactics by which the workers had formerly hoped to alleviate their distress were abandoned, though there were still occasional outbursts up to the middle of the century. This was not the way forward, for the machines did create more abundant wealth. It was the uneven distribution of wealth that had caused the misery of the factory workers—that and the concentration of the ownership of the factories, tools and machines in the hands of a comparatively small number of employers, giving them the power to decide on what terms the workers shall work. To this power the workers found a partial answer in Trade Unionism, which grew in strength throughout the nineteenth century and from about 1850 became thoroughly established. The workers as individuals had been powerless to prevent the degradation of their working and living conditions. But united in the Trade Union they could challenge the power of the industrial magnates and wrest from them a greater share in the wealth that the new machinery had brought. They learned also to take political action to protect themselves. The political pressure of the factory workers, with the help of the more humanitarian of the richer classes, produced the passing of the Factory Acts between 1802 and 1847, which abolished the worst features of the early factory exploitation. Here we cannot go into details, but merely note that the period covered by this chapter sees a general rise in the living and working conditions of the common people, but a rise that was only achieved by continual vigilance and struggle.

Since the capitalist type of economy had first appeared, there had been an era of tremendous technical progress. New inventions had almost yearly increased the efficiency with which men wrested a living from nature and these inventions had been used almost to their maximum to provide an ever-expanding flow of commodities. In the middle of the nineteenth century it might have seemed as if this unparalleled progress was destined to go on uninterrupted for ever. But towards the end of the century interruptions did take place. Slumps or depressions of unprecedented severity occurred, in which apparently the goods produced could not be sold, though there were still millions in need of them. The manufacturer, unable to sell his products, closed (or partly closed) his works. Workers became unemployed. And only after a lapse of some years did the economic machine begin to work properly again—only to slow down once more in a new slump a few years later. After 1918 these things became more or less permanent. Alternations of slumps with periods of comparative prosperity continued, but unemployment and the difficulty of selling goods became permanent features—so much so that some came to believe that too much was being produced (in spite of the fact that most people obviously could not get the things they wanted) and coined the phrase 'over-production' to account for the troubles.

Connected with these difficulties was the growth of two new features in the economic system: monopoly and imperialism. A monopoly was formed when one firm succeeded in gaining control of a large part of the production in one industry; or when all the firms in an industry came to an agreement covering the amounts they would produce and the prices they would sell at (in this case the combination of the firms is called a cartel). Often they sought to avoid the effects of economic depression by restricting production below the level that was possible and by artificially high prices. Formerly, any industry was composed of hundreds of small firms and free competition between these, by giving a great advantage to the producer who used the most advanced methods, had been the main stimulant of invention. Monopoly did not eliminate the stimulant of competition, but it did reduce it, with effects that will be apparent later.

Nevertheless, this development of monopoly was inevitable and could not be reversed. It was brought about by many forces, most of them economic, and so outside the scope of this volume. But one cause lay in the development of the machines themselves. In the early nineteenth century or before, when the cost of building and equipping a factory with adequate machinery would be only a few thousand pounds, any monopoly would have been quickly broken by some new entrant into the industry. But after all the mechanical developments described in this chapter and the next, the cost of setting up a business to compete with already existing firms would in many industries be hundreds of thousands of pounds. No small man, on the basis of his life's savings, could hope to enter the industry. Many spheres of industry became closed shops, in which only those already established could exist. And even among these the increasing cost of the most advanced equipment gave tremendous advantages to the largest firms, putting them in a position to squeeze out or absorb their smaller competitors.

It is outside the scope of this volume to discuss the effect of monopolies on the growth of imperialistic rivalries and the consequent drift to war. War, however, had been a growing phenomenon all through the nineteenth century. As the various powers grew in industrial strength without any over-riding plan and sought for markets, as political forms failed to keep pace with improvements in transport and communication which were making the world more and more an indissoluble whole, so clashes became inevitable. There were other types of war too—the American Civil War, for instance, to decide whether America should be an industrial capitalist country or an agricultural slave-owning one. But all these are as nothing compared with the colonial wars at the end of the nineteenth and the beginning of the twentieth centuries, and the culminating struggle of 1914–18. It is therefore fitting that we should end this chapter with a note on a few of the many military inventions that mark the period.

The resources of nineteenth-century science and industry were used to make practicable many weapons, like the breech-loading cannon, which had been conceived earlier but had remained mere ideas for lack of suitable production methods, or to make suitable for general use weapons like the rifle (as opposed to the smooth-bore musket) which had been in use in the late eighteenth century, but only in the hands of expert marksmen. Many new military inventions were added: the revolver by Samuel Colt in 1835, the machine-gun by Gatling in 1861, the torpedo by Whitehead in 1866 (though because of many practical difficulties it did not become important till the Russo-Japanese war of 1904-5). The submarine as a military weapon was the object of many inventors. A submarine, propelled by man-power and intended to fix mines to ships, was constructed during the American War of Independence; it succeeded in 1776 in travelling under water, but failed in its main object. The idea was revived during the American Civil War and, after many failures, a submarine did succeed in fixing a mine and sinking a ship. The modern submarine was developed competitively in several countries during the eighties and nineties. In 1916 appeared the tank, which takes so prominent a place in warfare today. These are but a few of the more outstanding military inventions. We have already noted, also, how the needs of war gave a tremendous impetus to the development of aeroplanes and of radio, which had previously been advancing comparatively slowly. Only after the aeroplane had served its purpose as an agent of destruction and had been made efficient for that purpose, was it used to any notable extent for peaceful purposes. In the next chapter, which deals with the fundamental industries on which all mechanical development is based, we shall again note that much progress has been in response to the call of war.

CHAPTER VIII

MATERIALS, MACHINE TOOLS AND PRODUCTION METHODS BEFORE 1918

In the last two chapters we have almost completely ignored three very important aspects of machines: the materials from which they are made and the tools and methods used in making them. These are so vital that they deserve a special chapter.

If the reader will look back at the illustrations to Chapter V he will note that most of the machinery of that period was made of wood and until almost the end of the eighteenth century wood remained the chief material for industrial machinery, metals being usually confined to bearing parts, cutting edges and other positions where their special properties were absolutely essential. During the eighteenth century the steam-engine had, of course, to be constructed mainly of metal (though boilers, for example, were at first often made of wood bound with iron hoops on the lines of a barrel, and brass was used more than iron in the early engines). Iron remained a costly material to be used only where it was essential. This was largely because no major technical improvements had taken place in iron-smelting since the first production of cast iron towards the end of the Middle Ages.

Iron-smelting, since its earliest days had been carried out by means of charcoal, that is, carbon produced by the controlled combustion of wood. The scale of iron production was therefore limited by the size of the forests. When industry entered the period of comparatively rapid advance from the sixteenth century onwards, this factor severely limited the expansion of the iron industry and therefore limited the progress of machinery in general. England especially, being but poorly wooded, felt the shortage. Between 1540 and 1640 the price of firewood rose nearly three times as fast as general prices. At one time it seemed as if the British iron industry was doomed to extinction, and with it the, by then, very promising growth of British industry in general.

It was early realized that coal was a possible alternative and in the sixteenth century many industries learned to use coal instead of wood. The problem of using coal for iron-smelting was, however, a more difficult one. Patents for such processes were obtained by Simon Sturtevant, 1612, and Dud Dudley, 1619, and other attempts were made. But little success was achieved till Abraham Darby, about 1717, though the date is not very certain, succeeded in using coal for smelting, by the process of first turning it into coke. When this process became generally adopted—not, in fact, till towards the end of the century—and when it was combined with various other improvements to furnaces, such as a more powerful blast, the British iron industry was set for a great expansion. The production of pig-iron rose from 62,000 tons in 1788 to 125,000 tons in 1796, 250,000 tons in 1806 and, after the introduction of hot blast by Neilson in 1828, by leaps and bounds to figures of about 3 million tons a year in the middle of the century and about 8 million tons near the end of it. Iron became available in quantities sufficient for the construction of machinery wholly of iron and so paved the way for such developments as railways, iron ships and the many machines which we discussed in the last chapter.

All this refers to pig-iron or cast iron, which, because of its high carbon content, is comparatively brittle and therefore unsuitable for many purposes. Wrought or malleable iron, which is tougher, is, of course, much older than cast iron, being produced as a spongy mass in the old bloomeries. But this method of production was suitable only for very small quantities. The later Middle Ages developed a process of obtaining wrought iron from cast iron by 'puddling' (roughly, stirring it in a furnace lined with iron oxide to take up the carbon and other impurities). This process required great skill, gave only a small production and still required charcoal as fuel. Large-scale production of malleable iron only became possible in 1784, when Cort, building on the partial achievements of earlier workers, perfected the method of puddling in a reverberatory furnace, using coal but so arranged that only the flames came into contact with the iron.

The late eighteenth century saw also considerable development in the machinery for working up wrought iron by hammering and rolling. The water-powered forge-hammer, dating from medieval times, was rapidly increased in size and in 1782 John Wilkinson first used steam to work a tilt-hammer of 7½ tons. The powerful, but very delicate, modern steam hammer was invented by Nasmyth in 1839. (Figure 37). The hydraulic press, invented by Bramah in 1796 was applied by Whitworth about 1850 to get an even more powerful forge hammer. Small water-driven rolling-mills, for finishing iron sheets already hammered roughly into shape, were in use in Germany in the early fifteenth century. They were much developed by Polhem and others in Sweden before 1750, but to Cort in England belongs the credit of devising, in 1784, a rolling-mill in which the sheets or bars were rolled directly from the bloom without previous hammering. Wilkinson was once more the first to use steam-power, in 1796.

An essential material for the construction of machines involving great stresses like the electric generator, the steam-turbine, the internal combustion engine, motor-cars, and so on, which came into use near the end of the nineteenth century, was steel—a metal whose special properties arise from the fact that it contains an amount of carbon intermediate between that of cast and wrought iron. In the Middle Ages methods of production were such that steel was almost a precious metal. Even after Huntsman's development of a process for making cast or crucible steel in the years

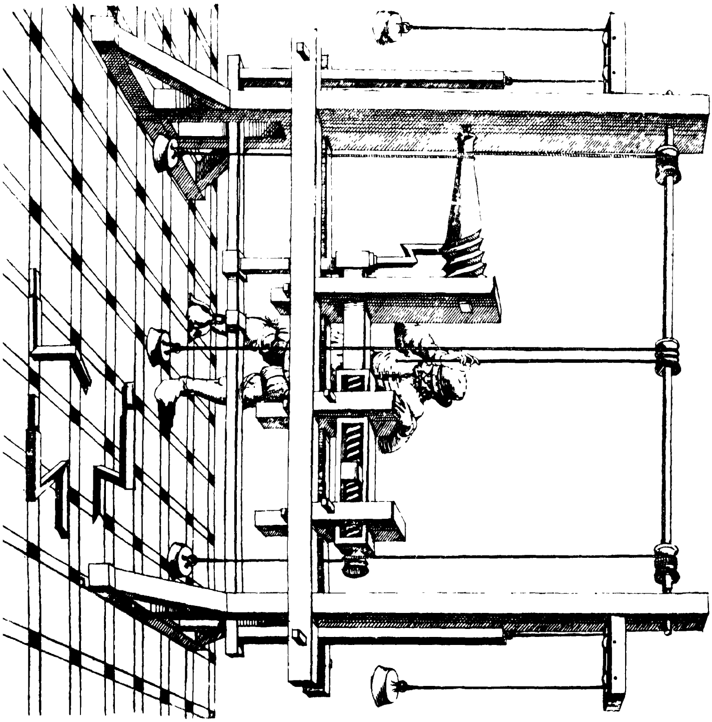
1740–70, it remained too costly for use except in very special circumstances, such as cutting edges. The crucial step towards the production of steel in sufficient quantities for its general use in all parts of machinery where its tensile strength, toughness, etc. make it desirable, was taken by Bessemer about 1856. In 1854 he had invented a new form of shell for use in rifled cannon, but could find no iron strong enough to make a gun to use it in. Investigating this problem, he invented his method of producing steel from pig-iron by burning away the impurities with a blast of air in a vessel now called the Bessemer converter. About 1867 Siemens followed with his open-hearth method of steel-making, which is slower, but gives more control over the final product. In 1877 came the basic Bessemer process and soon after the basic open-hearth, both of which permitted the use for steel making of the more common ores containing phosphorus, which had previously proved unsuitable.

The properties of steel are vastly improved and a much greater variety of properties made available by alloying it with small quantities of other metals. Although Faraday in 1822 had made systematic experiments with various alloys, these did not affect industrial practice and the practical history of alloy steels begins with the invention by Mushet in 1871 of a tool-steel containing tungsten and chromium, which allowed cutting at much higher speeds. Other alloys followed, such as manganese steel by Hadfield in 1882, and nickel steel by Schneider in 1889. With the exception of Mushet's tool-steel, these were intended for use in armaments and were only later applied to more constructive purposes. Then in 1898 came the invention of high-speed tool-steel by Taylor and White, of which we shall have more to say below.

The end of the nineteenth century is also marked by the introduction of various light non-ferrous alloys based on aluminium. Aluminium did not become a commercial proposition until its production in the electric furnace from 1886. Thereafter it was used for special purposes where lightness was of prime importance—for example, in airships from 1895. Duralumin, an alloy of aluminium and copper, remarkable for its high strength-weights ratio appeared in 1909, and thereafter various alloys of aluminium and later of magnesium have been playing an ever-increasing part in engineering. The later nineteenth century also saw the beginnings of the plastics industry, though plastics did not have much effect on engineering practice till the inter-war years.

The pioneer engineers of the eighteenth century met the utmost difficulty in getting their machines constructed with adequate accuracy. Smeaton had to tolerate errors of about half-an-inch on twenty-eight-inch cylinders for Newcomen engines which he made. The engines were made to work only by the device of using a layer of water on top of the piston as a seal. This trick was not applicable to the Watt engine and so Smeaton was led to remark that 'neither the tools nor the workmen existed that could manufacture so complex a machine with sufficient precision'. Perhaps the Watt engine could not have been a success if it were not for Wilkinson's timely invention of an adequate cylinder-boring machine. As late as 1830, it is said, a fitter who could work to one-sixteenth of an inch was a good workman.

Machines for boring pump-barrels from solid tree trunks date back at least well into the Middle Ages. In the early fifteenth century the same principle was applied to the boring of cannon, though only for finishing off hollow castings. An improved borer designed by the Swiss, Maritz, in 1713, was capable of boring cannon from the solid. When the Newcomen engine arrived, it was natural that the cylinders should be bored by such machines. But the diameters involved were much greater than in the case of cannon. The heavy drill-head worked effectively only on the bottom of the cylinder and very great inaccuracies resulted. Various methods were tried to improve the state of affairs, but none was successful until John Wilkinson, having invented an



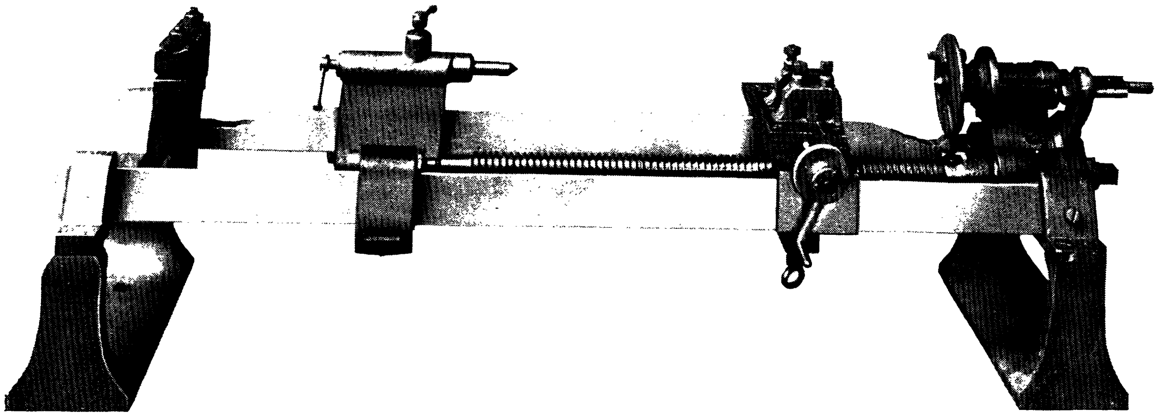


Fig. 39. Maudslay's screw-cutting lathe of 1797.

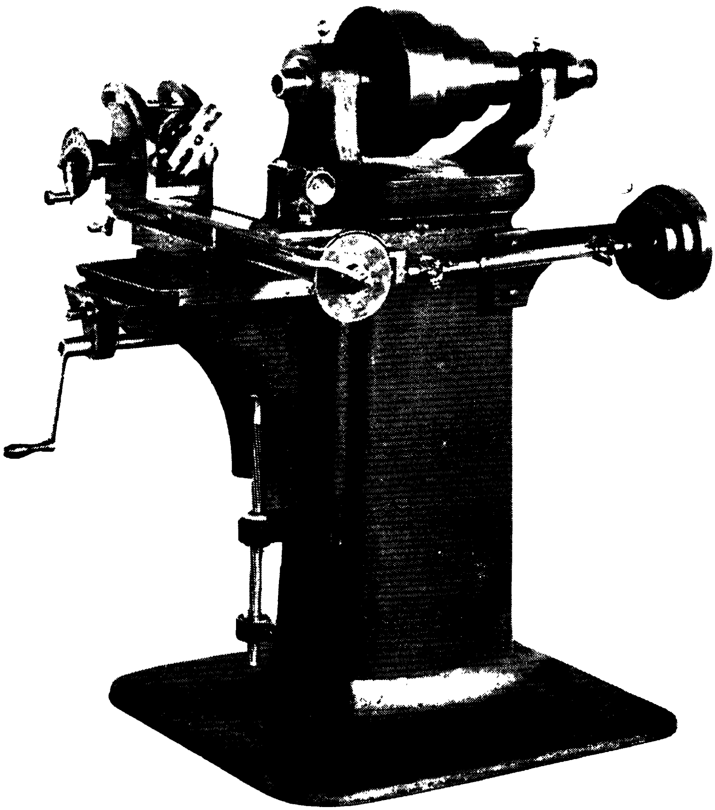


Fig. 40. The first universal milling machine.

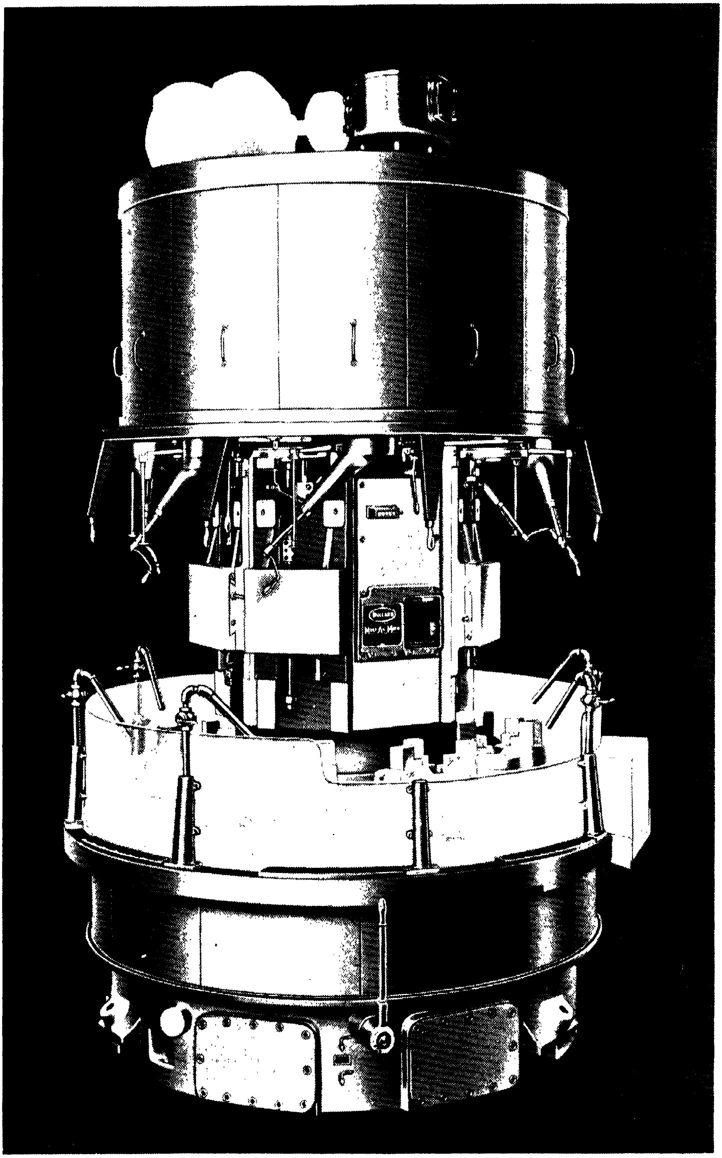


Fig. 41. The Bullard 'Mult-Au-Matic'.

improved cannon borer in 1774, followed this up with an improved cylinder borer in 1775. In this the drill-head was carried on a long stiff bar passing right through the cylinder and supported at both ends. This machine solved Watt's cylinder troubles, and in 1776 Watt wrote to Smeaton, 'Mr. Wilkinson has improved the art of boring cylinders so that I promise upon a seventy-two-inch cylinder being not further from absolute truth than the thickness of a thin sixpence in the worst part'. Others gradually improved on Wilkinson's machine and by about 1830 the cylinder-boring machine had reached an essentially modern form.

The lathe, with its many variant forms, is the most important of the machine tools and the possibility of most of the nineteenth-century advances was closely tied up with its development into a machine of high precision. Before the middle of the sixteenth century, the only form was the plain centre-lathe, on which the work was turned between fixed centres, the drive being applied to the work itself through a cord wound round the work and usually attached to a treadle below and a flexible beam above. The earliest known illustration of the mandrel lathe, in which the work is fixed in a chuck to which power is applied, appeared in 1568; and a little earlier Besson gave an illustration of a crude screw-cutting lathe (Figure 38). Lathes with screw-guides in the mandrel, for screw-cutting, appeared before the end of the seventeenth century and this method, in which the work traverses and the tool is stationary, was widely employed in the eighteenth century. Meanwhile clock-makers had made approaches on a small scale to the modern lathe in which the work merely rotates and the tool traverses; these embodied the elements of the slide-rest but only in a form suitable for light work, such as that involved in clock-making.

The critical steps in the transformation from the crude eighteenth-century lathe to the modern high-precision machine were the work of Henry Maudslay. The highly ingenious lock invented by Bramah in 1784, to which we referred in Chapter VI, required standards of accuracy far higher than those then current but was nevertheless to be produced in large numbers. Bramah employed Maudslay and it was while working on the problem of producing the lock that Maudslay began his work on the lathe, which he carried on after 1797 in his own workshop. His lathe of 1797 (Figure 39) and more especially the improved version of 1800 mark the beginning of a new era in engineering.

Maudslay is commonly said to have invented the slide-rest. That statement greatly distorts and undervalues his work. A rudimentary slide-rest was already in existence, but it was used only for light work such as clock-making, and the construction of large lathes was too crude to accommodate it. Maudslay greatly improved the slide-rest and made it suitable for heavier work. But his really important contributions to the development of the lathe were two improvements which greatly increased its accuracy and, as it were, turned the lathe as a whole into a fit vehicle for the slide-rest. These two critical improvements were: all-metal construction, and the technique of cutting accurate lead-screws of sufficient length to allow the use of the traversing tool on large work. The construction of an all-metal lathe, instead of the former method of mounting metal working parts on a wooden base, may not seem at first sight to be of great importance; yet the rigidity it gave was the foundation of all further progress in accuracy. And Maudslay's constant and painstaking work on methods of screw-cutting after 1800 entirely changed current practice. Further great advances in screw-cutting and other aspects of high-precision work were made from about 1833 onwards by Joseph Whitworth, who began as one of Maudslay's workmen. Meanwhile the planer, the other basic tool of precise engineering, was developed from its crude ancestors by a number of British workers between 1815 and 1840. But the rise of precision work as a general practice was largely associated with mass-production on the principle of interchangeability, to which we now turn.

Mass-production is the basis on which today we can have many machines (and other conveniences) manufactured and sold in large quantities and for reasonable prices. If 10,000 Ford cars only were produced, they would cost £2,000 each; one Ford, of its present standard of workmanship, might cost tens of thousands. But in fact hundreds of thousands are produced, all identical (apart from minor variations of colour or finish). Every process in the manufacture has to be repeated hundreds of thousands of times. Thus it is economical to build a special machine, even one costing many thousands, to do each process efficiently, and as a result Fords cost £100 or so (pre-war prices!). The same goes for most things we use today: pen nibs, vacuum cleaners, radio sets.

There are two types of mass-production to be considered. The first is for things consisting of only a single part like a nail, or a pen nib, or a pin. In such cases there is no need for two samples of the product to resemble each other very closely—so long as they are near enough to standard to satisfy the customer. It is not very difficult to arrange for the mass-production of such articles, provided the demand is large enough to justify either the cost of building special machines, or the wage bill for a factory of many workmen each specializing in one small part of the process. And indeed there are very early examples of mass-production of this kind. The casting of metal type at the close of the Middle Ages is perhaps the earliest. Another is a special stamping machine, worked by a treadle used at Nuremberg about 1680 for fixing heads on pins. Christopher Polhem, of Sweden, ran a factory for mass-production of many articles on these lines from about 1700 onwards. He employed about 100 men and used water-power at every possible stage of manufacture. He had special machines for nail-making, for cutting iron bars or metal sheets, presses, rolling-mills, and so on. And he turned out in mass quantities such articles as ploughshares, harrow teeth, hammer heads, tin plates and vessels. Another very remarkable example of this type of mass-production was the factory for producing pulley blocks for the Admiralty, which began work in England about 1808. This scheme was the joint product of Marc Brunel and Samuel Bentham. Henry Maudslay executed the machinery, which was divided up into specialized groups for each of the processes involved. There were forty-four machines in all, of thoroughly modern design, and so good was the production method that ten unskilled men did the work of 110 skilled by previous methods. The output was about 130,000 blocks a year, greater than the previous output of the six largest dockyards.

The example of Brunel and Benton was not followed in England, and for the next 100 years, though Britain continued to lead the world in heavy engineering and the machines required by it (such as forging machinery, large lathes and the planing machine), the pioneering on mass-production methods and the types of machinery required by it was done elsewhere.

The mass-production of pulley blocks begins to approximate to the second, more refined type of mass-production. All the blocks and all the sheaves must be so close to one another in size that any sheaf will fit any block—otherwise all the advantages of mass-production would be lost in searching for pairs to fit one another, or in re-working those that do not fit. In this case the fit need only be a rough one, but in many other cases it must be extremely close indeed, if mass-production methods are to be used at all. When the article being made consists of several parts, each one of them must conform to standard sizes, so that any set of parts chosen at random can be assembled into the finished article. The parts, in fact, must be interchangeable—for which reason this second type is called mass-production on the principle of interchangeability, or interchangeable manufacture. In future, when we refer to mass-production, it is this type that we shall mean.

Very few machines of types in which very fine workmanship and close fitting are required were needed at the beginning of the nineteenth century in quantities sufficient to justify interchangeable manufacture. The one great exception was firearms. The lock, especially, of the musket or pistol is an extremely delicate mechanism which will only work if it is accurately adjusted. Gun-making was a highly skilled job and the demand for arms was very great. England, with more skilled workmen than any other country, had in 1811 a stock of 200,000 musket barrels, which were useless for want of gunsmiths to repair the locks. As early as 1717 and again in 1785 attempts were made in France to produce firearms by interchangeable manufacture. Thomas Jefferson, while U.S. Minister in France, wrote home that Le Blanc, the author of this last attempt, presented him with parts of fifty locks taken to pieces. 'I put several of them together myself,' he said, 'taking pieces haphazard, as they came to hand, and they fitted in the most perfect manner. The advantages of this, when firearms need repair, are evident.' Ultimately the French attempt seems to have failed and it is in the U.S.A. itself that the method was first successfully applied.

Eli Whitney in 1800 began the manufacture of muskets by mass-production methods, and Simeon North did the same for pistols a little later. They used water-driven machinery on a large scale for such purposes as forging, rolling, boring, grinding and polishing. But the accurate finishing to precise measurements was at this stage done by specialized workmanship and filing in special jigs rather than by special machinery. Soon, however, special machinery capable of working at high speed and with great and unvarying accuracy was developed for the purpose. Whitney invented the milling machine in 1818, and Blanchard a lathe for irregular turning in the same year. The capstan or turret lathe appeared about 1845. By about 1835 great advances had been made in drop-forging, die-stamping, and pattern turning. In 1855

Samuel Colt, whose revolver had hitherto been manufactured by Whitney under contract, opened his own works. He employed Elisha K. Root, a brilliant organizer and mechanic, who designed many new tools (including a much improved form of drop hammer). Root also used all the best tools already available and thus indirectly gave a new impetus to others to create yet better. The next few decades produced the universal milling machine (1861–2) (Figure 40), the cylindrical grinder (first commercially produced in 1864), the automatic lathe (in which several tools in succession are automatically brought to bear on the work, and the operator has only to feed the raw material in the form of rods, see Figures 42 and 43) and the multi-spindle lathe (in which the work is passed automatically to several spindles in succession and subjected to one or more different processes at each). The multi-spindle lathe in turn gave birth to highly automatic machine tools, such as the 'Mult-Au-Matic' (Figure 41), which appeared just before the first World War, and in which the work is moved through a series of six or eight stations at each of which it can be subjected to such operations as boring, turning, facing, threading, grooving or drilling.

The arms-makers for a long time led the field in mass-production techniques, but clock-makers were not far behind. Eli Terry of Connecticut began mass-production of wooden clocks in 1809 and by 1814 had reduced their price from $25 to $5. Mass-production of brass clocks started a little later, and by 1855 these were being produced at the rate of 400,000 a year, the price coming down eventually to 50 cents apiece. Mass-production of watches was first tried in 1848 and was successful in the fifties.

By 1850 mass-production methods were fully established. They were fundamental in making a success, in the fifties, of the sewing-machine, which was mass-produced almost from the beginning. A little later they made possible the widespread use of agricultural machinery. In this last case, like that of firearms, the property of interchangeability was important to the user as well as the producer—repairing agricultural machinery was beyond the powers of a village blacksmith, so that the availability of replacements which could be fitted into place without any skilled adjustment was an essential condition for the use of the machines. This contrasts with the position in clock-making, where interchangeability is only of importance to the manufacturer—because it simplifies his production problems. Mass-production was applied to typewriters in the eighties and to bicycles in the nineties, making possible the production of cycles at a rate of several hundred thousand a year.

Then came the motor-car. All the early cars were *built*, in the same sense that an early steam-engine was built. Then about 1902 some firms started using interchangeable manufacture. Olds produced about 2,500 of his little runabouts in 1902, 4,000 in 1903, 5,000 in 1904. Ford's production passed 10,000 a year by 1909. By 1913 there were about 200,000 motor vehicles in Britain and 600,000 in the U.S.A. The car industry carried the technique of mass-production a stage further. It was mainly responsible for introducing another vital feature of modern quantity production—the straight line or conveyor belt system. In this the whole factory is highly organized in such a way that each piece of work passes successively through a series of stations, at each of which one or a few operations are performed on it. The whole factory becomes a single highly organized entity, in which raw materials flow in at several points and the work in various stages of manufacture flows along several streams which gradually come together, until the finished car (for example) is driven off the end of the main conveyor, ready for testing and the road. The germs of this system are to be found in methods used in the nineties for making freight wagons for the American railways. The Chicago stockyards further developed it. An overhead conveyor picked up the pig by one leg. Moving along this conveyor the pig was killed and every necessary operation performed on it, without handling, until the carcass was finally released. The system was organized to make use of everything the pig could provide—it is even said in jest that the pig's dying squeal was piped off to work the factory whistle. The application of these methods to engineering was begun, and largely carried through, by the American car industry. Ford gave the lead from about 1913 on, but the modern straight-line production system was not fully developed till after the first World War. Since then the method has been applied to the production of many other articles which are required in large quantities.

The motor-car industry in its turn promoted the development of a host of new machine tools: precision gear-cutters, precision grinders of many types, a great variety of presses for stamping and forming the chassis, fenders, bodies, etc., broaching machines, precision die-casters, drilling and tapping machines. Some of these had existed before, but the mass-production of cars led to their perfection and their use on a much greater scale. The tendency towards automatic machines was intensified.

Two advances in the production of materials contributed greatly to the progress of precision machining about this time. One was the production of artificial abrasives—carborundum for example, synthesized in the electric furnace, from about 1893 on. These could be made much harder and finer than the natural emery previously used. They allowed grinding as a machining process to spread greatly and, for many purposes, to supersede cutting almost completely. Grinding, which gives greater accuracy and a much smoother finish than cutting, is now indispensable for the manufacture of internal combustion engines. The other new material was high-speed tool-steel, to which we referred earlier. It allowed cutting speeds to be increased four or five times. It has been estimated that as a result of its introduction the annual production of all industries in the U.S.A. increased by about eight billion dollars (say £1,600 million) and this

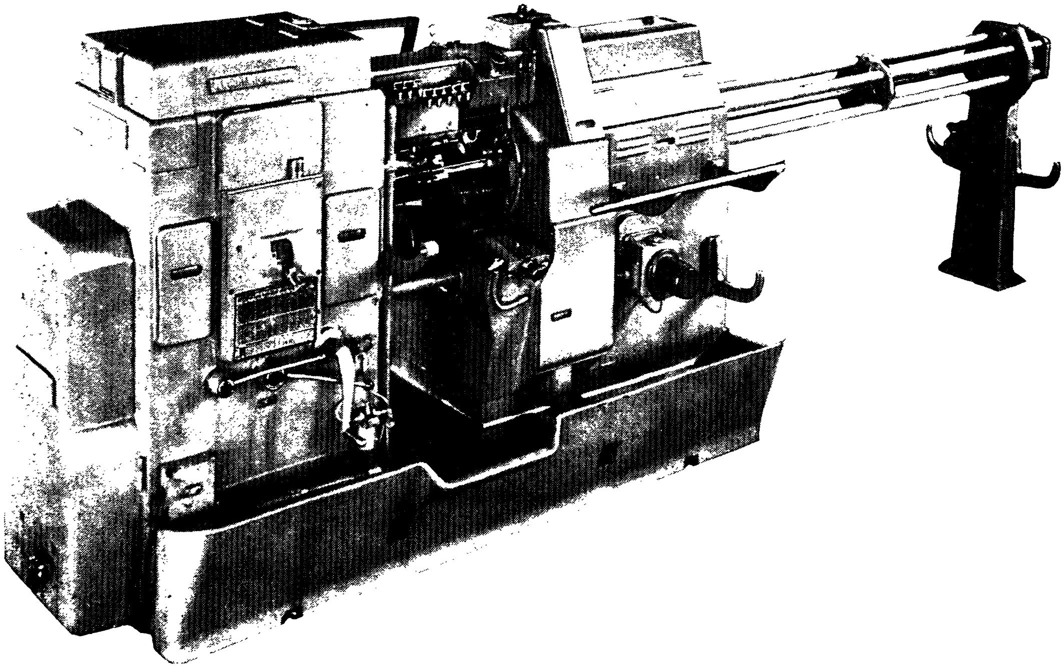


Fig. 42. An automatic lathe.

Fig. 43. Samples of work produced by the automatic lathe.

by the use of only about twenty million dollars' worth (£4 million) of the new steel per year, plus, of course, the new machine tools to use it.

All these improvements in machining methods were necessarily accompanied by parallel improvements in methods of measurement. We have no space here for a full discussion of this problem. Whitworth, who was mentioned above, played a very great part in the development of precise methods of measurement (for though America ran away with mass-production, Britain still led in many types of high-precision construction of machines only required in comparatively small numbers). The rise of interchangeable production in America was necessarily accompanied at every stage by the progressive refinement of measuring methods and the various types of gauges used.

Other processes of great importance that must be mentioned are electric welding (1886) and thermit welding (1908), which have played an increasing part in construction ever since and in many cases have done away with the clumsier methods of riveting or bolting. Oxygen cutting (oxy-acetylene and similar combinations) came into use about the turn of the century.

American manufacturers on the whole maintained a clear lead till 1914 in mass-production methods and the corresponding machine tools. Even in Britain manufacturers were slow to use the new methods. A beginning was made only after 1863, when a British Small Arms Commission recommended the adoption of what they called the 'American system'. And in 1914 shops could still be found where lengthy and laborious hand filing was used on processes admirably adapted to milling or machine grinding. The war of 1914-18, with its unprecedented demand for huge quantities of accurately produced armaments and other products, changed all this. As Cressy puts it: 'Hundreds of shops in which high-speed tool-steel was little more than a name began to use it regularly. Many automatic machines, and especially millers and grinders, crept into small and obscure engineering works and came to be regarded as essential elements of equipment. The use of jigs for machining or drilling objects of awkward shape, and of gauges for the production of interchangeable parts, spread to an enormous extent under the stress of military necessity.'[1]

CHAPTER IX

BETWEEN TWO WARS (1918–39)

THE years between the two wars were marked not so much by startling new inventions as by remarkable advances in the efficiency of already familiar machines. This resulted from a multitude of small inventions and detailed improvements, the work of thousands of engineers, inventors and scientists. In 1918, for example, the best power stations required about 1½ lb. of coal to generate one unit of electricity; by 1939 the best stations had reduced this figure to about ¾ lb. In the same period improvements in ship design reduced the power required to carry a given cargo by some 15–20 per cent, while the fuel consumption of engines of the same power was reduced by 50-60 per cent; so that the overall fuel consumption on the most up-to-date ships was reduced to one-third of its former value. Improvements over industry as a whole were such that the productivity of labour (i.e. the output per man-hour) in the U.S.A. increased by 39 per cent between 1920 and 1935.

But at the same time these improved techniques were not always used to the best effect. The *average* amount of coal used to generate a unit of electricity in Great Britain or the U.S.A. was about 3 lb. in 1918 and a little under 1½ lb. in 1939. In other words the average efficiency of power stations

[1] *A Hundred Years of Mechanical Engineering* (London, 1937), p.212.

in 1939 was only about half of the best possible and was just about equal to the best in existence in 1918; average efficiency lagged twenty years behind the best. The advance of 39 per cent in productivity, referred to above, was not used to provide 39 per cent more goods and services. Actual production rose only 14 per cent in the same period and the remainder of the increased efficiency was offset by increases in unemployment. And similarly (as we shall see below) it was frequently the case that various industries failed to use the best machinery available.

It must be remembered in this connection that it is not possible to introduce each new technique instantaneously over the whole industry. The new machines have to be constructed and installed. Whether this can be done or not depends, in the last analysis, on whether hands are available to do the work. In the mid-nineteenth century also efficiency lagged somewhat behind the best possible, but that was inevitable, since the number of unemployed was negligible. The lag in raising efficiency after 1918 would have been equally justified if there had been a scarcity of labour. But there were millions of unemployed and the fact that these available workers were not set to work in bringing efficiency up to the best possible indicates a failure of social organization.

One exception must be made to these remarks. The U.S.S.R. had no unemployment (at least after its initial disturbed period). The efficiency of industry there was by no means the best that was technically possible, but at least it was the best that was possible in practice, since the whole of the available man-power was used to advance it. The U.S.S.R. began as a very backward country. It had a few islands of advanced industry, but in general pre-revolutionary Russia was an agricultural country and a very backward one at that, with medieval equipment. In 1910 there were ten million wooden ploughs and eighteen million wooden harrows in use in Russia; and only 4½ million iron ploughs, to say nothing of the almost complete absence of the more modern agricultural equipment, which elsewhere had come into use since about 1800. The war of 1914-18 and the destructive wars of intervention greatly worsened the situation. It took till 1928 to restore production even to its pre-war level, and then began the struggle of the Soviet people to raise their technique to a level comparable with the advanced countries. In 1931 Stalin said, 'We are now one hundred years behind the advanced countries. We must make good this distance in ten years, or they will crush us.'

There followed the most rapid and the most conscious industrialization known in history. From 1913 to 1938, the volume of industrial production in the U.S.A. increased by 20 per cent, in Great Britain by 13 per cent, in Germany by 32 per cent. But in the U.S.S.R. industrial production in 1938 was *nine times* the 1913 level, in spite of the fact that the advance only really began from 1928. In output of electric power the U.S.S.R. moved from fifteenth place in the world in 1913 to third in 1936; in coal production from sixth to fourth; in the production of agricultural machinery from fifth to first. Tractors and combine harvesters were not made at all in Tsarist Russia; by 1936, Soviet production led the world in both.

These results were achieved by a conscious approach to the problem of mechanization. The objective of plenty for all could be reached only through raising production by the most advanced techniques. The raising of the technical level was not left to individuals, but was undertaken by the State and became one of its main political tasks. Inventors were given every possible encouragement; apparatus, laboratories, and so on, were lavishly provided. Education was directed to providing a maximum of skilled engineers, scientists and inventors. Workers were given facilities to enable them to use their intimate knowledge of the job for the purpose of inventing improvements. Hundreds of thousands of inventions came from workers. The Stakhanovite movement epitomized the conscious struggle to make the best possible use of the best possible machines.

The figures given, however, can be misleading. Though its total output was by 1939 on a par with any other country, the output of the U.S.S.R. in relation to its population was still low. In 1937 its output *per head* of pig iron (which can be taken as a rough index of industrial strength) was 86 kilograms, against 292 for the U.S.A., 234 for Germany and 183 for Great Britain. Although the U.S.S.R. was being industrialized at a more rapid pace than any other country at any time, the Soviet industrial and political leaders still reckoned that some fifteen further years were required to catch up with the most advanced countries of the world.

It will be impossible, in the space available here, to do more than describe some of the general trends of machinery in the period 1918–39 and choose some of the more interesting examples for more detailed discussion; a complete survey would occupy several volumes. Let us turn first to the basic machines and methods of production, the successors of those we discussed in the previous chapter. We referred there to the revolution in industry that was brought about by the introduction of high-speed tool-steel. The coming of tungsten carbide, second in hardness only to diamond, as a tool material about 1926 began a similar revolution, which received further impetus from the introduction of mixtures such as tungsten and tantalum carbide about 1939. As a result cutting speeds have increased once again by six or seven times, implying vast increases in production potential. Unfortunately, this material, of German origin, came under the control of international cartels which greatly restricted its production and use outside Germany.[1] To the people of

[1] For details see *Germany's Master Plan* by J. Borkin and C. A. Welsh and the U.S. Government publication, *Economic and Political Aspects of Cartels*, by C. D. Edwards (Washington, 1944), which shows how the cartel raised the price per pound of tungsten carbide from its 1927–8 level of $50 to $453 and kept it above $200 till, after an anti-trust indictment in 1942, it fell again to between $27 and $45.

other countries this meant loss of potential wealth. To the monopolies involved it doubtless meant no more than the protection of vested interests and the maintenance of high prices, but to Germany it meant the ability to rearm quickly with efficient tools, while ensuring that the peace-loving nations would be comparatively unprepared for war.

Grinding, as a substitute for cutting in producing high-precision finish, continued to spread rapidly. Centreless grinding, which first appeared (though not in its modern form) in 1916, came increasingly into use from the twenties on.

Another notable trend in metal cutting was the increasing use of oxygen flame cutting. It made possible the cutting of thicknesses of steel well beyond the possibilities of mechanical methods. At the same time the flame began to take over some of the work of cutting tools in operations equivalent to planing and boring. Its precision increased greatly, till, for example, it could be used for certain types of gear-cutting, and fairly automatic flame-cutting machines were developed. Just before the war the flame began to be used instead of a cutting tool for some types of turning operations —only on a limited scale and for coarse work, but implying considerable possibilities for the future.

But the most interesting development was in the great increase of highly automatic machines. Instruments for automatic control of machines and processes formed 8 per cent of the total sales of machines in the U.S.A. in 1923; by 1939 they formed 35 per cent. On the small scale there was the development of lathes and similar equipment with devices to measure the work and stop the machine automatically when the right size was reached. On a larger scale is the plant for making car frames, belonging to A. O. Smith and Co., Milwaukee, which turns out one completed frame every eight seconds, or about 10,000 a day, virtually untouched by human hand. It is run by a staff of 120, mostly supervisory or maintenance, so that one car frame is the product of about sixteen man-minutes of work. This machine makes seventy-five per cent of the car frames used in the U.S.A., other than those used by Ford, who has a similar plant of his own.

One of the most useful automatic machines is the automatic die-caster, a development of the die-casters which the automobile industry brought into being early in the century. In such machines objects are cast in permanent metal moulds with great rapidity. The machine is not highly specialized—mere changing of the die or mould converts it to the production of a new object—and, because of its simplicity, can be made highly automatic. A typical example cost about £1,000 before the war and, attended by one man can cast eight pieces per minute or over four million a year, if it runs all the time. Of course, it has to stop for repairs, but two such machines running only half time could produce radiator caps for the entire motor-car industry of the world. Such machines naturally prompt consideration as to whether full use can be made of modern technique when industry is run in several competing units. Die-casting is restricted to certain alloys, but automatic moulding machines of a rather different type, larger and more complicated, will cast almost any metal. A remarkable example is the automatic moulding machine at Klimovsk, U.S.S.R., for iron castings. Its output is 10,000 in a two-shift day. It cuts labour requirements by 60 per cent, auxiliary metal cutting machines, which would otherwise be used for finishing, by 75 per cent, and the cost of production by 50 per cent.

The simplest processes to make automatic are those in which the raw material is uniform (casting for instance), so that the machine has to exercise no function comparable to judgement. Next come those in which 'judgement' is required, but this can be exercised through contacts of moving parts comparable to the sense of touch. However, human judgement in production is almost always used through the sense of sight. For that reason probably the most revolutionary development of the period under review is the application to a wide variety of processes of the photo-electric cell or 'electric eye', which transmutes variations in light into variations of electric current and thence, through amplifiers and relays, into mechanical action. The earliest type of photo-cell depended on the discovery in 1873 that the electric conductivity of selenium varied with the amount of light falling on it. But cells based on this principle are slow in response, and the modern extremely sensitive photo-cell, based on the fact that certain substances emit electrons when light falls on them, is mainly a post-1918 development, though again it depends on fundamental discoveries made from the eighties onwards.

Photo-cells have already found a wide application in such processes as grading and sorting commodities like rice, beans and cigars, detecting and rejecting tins with labels missing as they come from an automatic labelling machine, reading a drawing and controlling the tool making a copper engraving of it for printing. But the biggest potentialities undoubtedly lie in their application to the basic production processes of metallurgy and engineering—reversing the rollers in steam rolling-mills, removing metal bars from the furnace at a given temperature, automatic inspection of the articles coming off machine tools, and so on. One such inspecting machine for camshafts is reported from the U.S.A. to have enabled four men to do the work formerly requiring eighteen. A British example of about 1939 was an automatic machine for drilling and reaming crankshafts, controlled by a beam of light acting on a photo-cell through slotted discs, instead of the usual cam mechanism. An even more revolutionary development reported from the U.S.S.R. in 1940, though details do not appear to be available here yet, is a photo-electric lathe, in which the photo-cell reads the blue-print and controls the actions of the tools on one or many lathes to cut accordingly. A similar application, made during the last war in the U.S.A., is to the control of an oxygen cutting machine by a photo-cell reading a scale drawing.

Such applications of the photo-cell, and of other similar devices for measuring temperature, chemical composition, etc., promise the possibility of entirely eliminating all those monotonous forms of labour in which human judgement is used merely to decide whether or not an article conforms to a given standard. The ill-effects of such monotonous work, repeated endlessly day after day, form one of the most serious problems of mass-production methods. The developments discussed provide the means of solving it, but, to quote C. C. Furnas, 'as a first guess I would say that there are at least a million workers in America doing routine tasks of sorting, inspecting or controlling, who could be cheaply and successfully replaced by devices actuated by photo-cells'.[1] The present author is inclined to believe that the amount of such unnecessary repetition work is even higher in Britain, and this must certainly be the case if the developments foreshadowed by such inventions as the photo-electric lathe are taken into account.

Concurrently with these advances in basic production methods, of which we have merely sketched a few samples, came equally important additions to the range of raw materials available—a rapid development of plastics, superior for some engineering purposes to metals; the appearance of a wide variety of new alloys, particularly the light alloys based on aluminium and magnesium. Parallel with this came improvements in methods of heat treatment of metals (though mostly based on techniques in use in cruder forms before 1918)—one example of many is the Shorter process for local hardening by heating by a blow-pipe followed immediately by a quenching jet, a process which can be finely controlled and made substantially automatic.

To give more than a brief account of the development of electrification between the wars would fall outside the scope

[1] *The Next Hundred Years* (London, 1936), pp. 179-80.

of this volume. But some mention of it must be made here, since the enormously increased use of electricity for such purposes as replacing cumbersome shafting and belting connecting machine to steam-engine by small and economic individual motors, or by providing new electrolytic methods for producing metals, has revolutionized industry; while equally, electrical appliances have changed the face of home life. The output of electricity in Great Britain, for example, rose from about 125 million units a year at the beginning of the century to 9,927 million in 1928 and 26,409 million in 1939. Efficiency improved enormously, as we have already noted. Large power stations, generating at high voltages and transmitting their power in high-tension cables over distances up to 200 or 300 miles, replaced the tiny local direct-current stations of the early part of the century. Nevertheless, this progress did not come easily. Mr. S. B. Donkin, then President of the Institution of Civil Engineers, said in 1938: 'The earlier technical developments were accompanied by no commensurate improvement in the organization of the supply industry as a whole, nor is there any evidence which might be put before an impartial observer to suggest that the undertakings had any broad policy for the future or conception of the part which might be played by electricity in national life'.[1] The electric supply industry, in fact, was almost the first[2] in which the forms of organization of industry, which had played so great a part in developing world resources for more than two centuries, clearly proved themselves inadequate to carry that development further. The strain of the 1914–18 war showed great weaknesses in the industry and after some years of investigation the Government decided that the industry could only

[1] *Transactions of the International Engineering Congress, Glasgow*, 1938, p. 49.

[2] A much earlier example, of course, was the electric telegraph, which in Britain had to be nationalized in 1870, because of the poor and inefficient service given by the telegraph companies and the high prices charged. When the Post Office took over, the number of messages sent trebled in five years, while the technical efficiency of the equipment improved by leaps and bounds.

be properly organized by nationalizing the transmitting section of it and co-ordinating the generating section. This was done by the Electricity Act of 1926, which provided for the setting up of the 'Grid', one of the greatest engineering achievements of our time. The result was a very remarkable improvement in the efficiency of the industry. Previously each individual station had to maintain sufficient plant to cope with its peak load (though that operates for but an hour or two a day), besides a considerable amount of reserve plant to allow for breakdowns. Now a station on peak load could be helped out by another which was slack; the best plant could be kept running continuously and the older plant used only at the peak, thus lowering the overall cost of power; and the linking up enabled one set of reserve plant to deal with emergencies in several stations. In 1928, when construction of the Grid was just beginning, generators as a whole ran on an average only 1,127 hours in the year; by 1939 they ran 2,701 hours. Each generator, therefore, was lying idle for a much shorter time, so that a truly enormous saving was made in the capital cost of generators. By 1937, this amounted to £27 million and had paid—in less than ten years—for the original cost of the Grid.

Similar trends occurred elsewhere. In the U.S.A. much of the electricity industry remains in private hands, but the most outstanding advances have been made in Federal schemes like the Tennessee Valley Authority, which formed the central pivot for the development of a backward area into one of the more advanced industrial districts in the U.S.A., and which raised the average domestic consumption of electricity in the Valley by 146 per cent in two years.

Planning is the key to an efficient electricity supply. The U.S.S.R. with its fully planned industry had therefore a special advantage—though this had to be set against the disadvantage of an extremely backward industry to start from. Though the U.S.S.R. had still a long way to go before overtaking the other major powers in the *per capita* consumption of electricity, nevertheless the advances made were truly amazing—from 500 million units generated in 1920 to 4,205 million in 1927, 13,540 million in 1932 and 36,400 million in 1937. The planning of the whole of industry allowed a much more efficient use of the plant than elsewhere. Thus the generators in district power stations in the U.S.S.R. were able to work 4,300 hours in 1935, against 2,300 hours, for example, in Great Britain.

The technical progress of the electricity industry since 1918 is mostly a matter of gradual improvement, increases in efficiency, higher transmission voltages and so on, the details of which would be out of place here. Apart from some experimental progress towards the realization of high-tension *direct-current* transmission, which would allow transmission over much longer distances, the only outstandingly new technical development was that of combined heat and power generation. In this the heat which necessarily emerges from the condensers of the steam-turbines and which was formerly wasted, is transmitted as hot water or steam through pipes to factories or blocks of flats to be used there instead of local heating apparatus. This method leads to a fuel economy of some 30 per cent. The U.S.S.R. has led the world in this particular development, though district heat distribution unconnected with electricity supply is not uncommon in the U.S.A.

By 1918 machines had been developed which mechanized the agricultural processes of ploughing, cultivating, sowing, reaping and threshing cereals, the various hay-making processes, and some of the processes connected with root crops, besides various miscellaneous machines which we have not mentioned. The tractor was already beginning to replace the horse. It was subsequently greatly improved, while about 1924 appeared tractors with high clearances suitable for cultivation between rows of young plants. The use that was made of tractors and other machinery varied enormously from country to country. In the U.S.A., where the development was most rapid, the number of tractors in use rose from 80,000 in 1918 to 1,600,000 in 1939. That amounts to somewhere about fifteen per hundred workers on the land.[1] But in Great Britain the number in 1939 was only 55,000 or about eight per hundred workers. The U.S.S.R., starting from the very primitive agriculture we have already described, had only 700 tractors in 1920 and from this developed to 483,000 in 1938 and 523,000 in 1940. In relation to land workers this still remains very small—rather less than one tractor per hundred workers. On the other hand, the organization of agriculture in collective farms permitted a much more efficient use of the machinery than elsewhere. Expressing the work done by a tractor in terms of the equivalent of ploughing an acre, the average output of a Soviet tractor in 1936 was 1,210 acres, against 225 in U.S.A. That meant that, although the U.S.A. had four times as many tractors as the U.S.S.R. the actual work got out of them was only the equivalent of some 350 million acres of ploughing, against nearly 600 million in the U.S.S.R. Similarly it has been estimated[2] that the output of British tractors could easily be trebled. Some 90 per cent of Soviet ploughing and sowing was done by machine and 50 per cent of the grain harvested by combine in 1940. This last figure was also reached in the U.S.A. in 1938.

Among the new agricultural machines that came into use in this period one of the most notable was the gyrotiller which cultivates the ground by blades rotating beneath it, as it travels along on a caterpillar tread. The principle was tried in California as early as 1868 and in Britain in the seventies and eighties, but the lack of caterpillar tread and the great weight of the steam-power units prevented its successful use. Successful machines were developed shortly

[1] These figures, however, fail to show the extreme unevenness of development. The large mass of small farms did not have the benefit of machinery. Only about one farm in six had a tractor, while one in five was without even animal-power.

[2] D. N. McHardy, *Power Farming for Crops and Stock* (Reading, 1938), p. 9.

after 1930. The same principle has also been successfully applied on a smaller scale to give machines suitable even for market-gardening work.

In other aspects of agriculture mechanization was still at the pioneering stage. Ditching and drainage were successfully mechanized in this period. Machinery for vegetable and root crops developed notably. The potato-harvesting machines referred to in the last chapter were considerably improved, though even by 1939 the elevator-lifter required favourable soil conditions. Attempts were made to mechanize beet lifting, with a degree of success which is well estimated by the comment in the *Journal of the Ministry of Agriculture:*[1] 'Several beet harvesters are available, and some of them, at any rate, are worth serious attention'. Machines for transplanting young vegetables were successfully developed. Attempts to pull flax mechanically were not in general successful, though reports from the U.S.S.R. about 1940 indicate the favourable development of a combine which pulls, cleans and binds three acres of flax an hour. In the U.S.S.R. machines were also in the experimental stage for some jobs hitherto done entirely by hand, such as picking and pressing tea leaves and pruning tea bushes.

Mechanical cotton-picking has had a singularly unfortunate history. The first patent for a mechanical cotton-picker, in the U.S.A., dates from 1850, and by 1937 over 900 patents had been filed. Yet cotton was still picked almost entirely by hand. Concerning a recent machine which can pick in 7½ hours as much as a good hand picker in five weeks and which could reduce the labour required by 75 per cent, the U.S. Government report *Technological Trends* comment (page 58): 'Fear of over-production with consequent shattering of existing price levels, and of dramatic displacement of cotton pickers, is deterring the introduction of the automatic cotton picker invented by the Rust brothers. . . The inventors, cognizant of the revolutionary consequences

[1] Volume 45 (1938–9), pp. 593–4.

attending their invention, are themselves withholding its application, except for its trial use on a co-operative farm in Mississippi and in the Soviet Union, where the problem of unemployment does not exist and the introduction of the machines can be regulated.' In the last analysis the root cause of the trouble was the cheapness of hand-picking labour arising from the low standard of living at which the Negro population of the Southern States is forced to exist. It is doubtful if this or any other cotton-picker is yet in a fully satisfactory state; but even if that be the case, the blame must still rest to some extent with the cheapness of labour and consequent diminished incentive to replace it by machine.

From all these examples it will be clear that the possibilities of mechanization in agriculture still lie largely in the future.

In Chapter VII we noted that mechanization had become established by 1918 in two important aspects of coal-mining, namely undercutting and conveying the coal from the face. Here again the relative rates of progress in various countries are of interest. In the U.S.A. the percentage of bituminous coal cut by machine rose from 51 per cent in 1913 to 79 per cent in 1935. Britain on the other hand reached the American 1913 level of 51 per cent only in 1935, and even in 1939 reached only 61 per cent. Similarly in 1939 only 58 per cent of Britain's coal was carried from the coal-face in conveyors. In the U.S.S.R., where the backward Tsarist régime cut only 1·7 per cent of its coal mechanically in 1913, the rate of mechanization of the industry was truly remarkable. By 1940 over 95 per cent was cut by machine and the industry was said to be more highly mechanized than in any other country in the world (though the figure was higher in particular coalfields elsewhere, for example, the Ruhr with over 97 per cent).

The serious lag in the mechanization of British mines naturally meant that the productivity of labour remained low and prices high, and, since almost the whole of British industry depends on coal for its power, this was a very *serious drag* on British industrial progress. The events of the second World War brought these facts home to the British people, and the Government set up a Technical Advisory Committee on the Coal Industry under the chairmanship of Mr. C. C. Reid. Its report (1945) was illuminating. Different natural conditions, it said, invalidate any comparison of the British and American industries, but natural conditions in Britain are 'comparable with those of the Ruhr and Holland, and, therefore, afford no explanation of the much lower O.M.S. in Britain'. (O.M.S. is the Report's abbreviation for 'output per man-shift', which in 1936 was only 23.54 cwt. in Britain, compared with 35.94 cwt. in Holland and 33.66 in the Ruhr—in spite of the fact that in 1913 Britain was slightly ahead of both these.) The explanation of this low O.M.S., said the Committee, lay not only in the failure to mechanize the mining processes, but more fundamentally in the poor general planning of mine layout and systems of underground transport (which depends largely on layout). Questions of general mine planning are beyond the scope of this book, but we have to note the fact of the British industry's backwardness in this respect, because, as the Reid Report stresses, the outdated layout and haulage systems were unable to deal with the greater potential output of mechanized methods at the face, and were therefore an important factor in retarding the introduction of machine-cutting and conveying. The report made recommendations for a drastic technical reorganization of the industry, and said, '. . . we have come to the conclusion that it is not enough simply to recommend technical changes which we believe to be fully practicable, when it is evident to us, as mining engineers, that they cannot be satisfactorily carried through by the Industry organized as it is today'. Thus, other considerations apart, the recent nationalization of the coal-mining industry is an elementary step towards its urgently required technical rehabilitation.

We turn now to more recent developments in mining machinery, whose value could not be regarded as fully established in this period. By 1918, we have seen, some preliminary attempts had been made at power loading on to the conveyor at the coal-face. But the real beginning of power loading dates from J. F. Joy's design of 1922. It cannot be said, however, that the problem of loading has yet been solved in a way that is satisfactory in all circumstances and even by 1937 only 17 per cent of American bituminous coal was loaded mechanically, while Britain had only about twenty power loaders in 1939. A modern loader is shown in Figure 44. Machines which cut the coal, break it down and load it as one process are a more recent development of some promise in all the advanced countries, though they have yet to prove their worth.

The idea of breaking the coal down, after undercutting, by machines using hydraulic power, was tried out before 1914, but little use was made of them till about 1936, when they gave excellent results in at least one British colliery. A cylinder with pistons in its side is pushed into a hole specially drilled and hydraulic power pushes the pistons out and breaks the coal down. The method gives a smaller proportion of 'smalls' than shot-firing and is very much safer.

In 1937 a mine at Sverdlovsk in the U.S.S.R. tried out the new method of hydro-mechanical mining. The coal is smashed up and carried away by high-pressure jets of water directed at the coal-face. The water not only wins the coal, but also transports it in troughs and the smaller particles are even pumped to the surface in the water. It was estimated that the method increased the productivity of labour threefold and cut production costs by one-half. By 1940 it was being applied in several other mines.

The greatest Soviet innovation, however, was the underground gasification of coal. It is not strictly a 'tool' or 'machine', but because of its potential effects on power production it must have some discussion here. It eliminates mining altogether and turns the coal seam into an underground gasworks. Air or steam or a combination or alternation of the two is pumped down one shaft to the burning coal seam and up another comes the gas, which can be varied in composition at will. The idea of this method was suggested early in the century by William Ramsay, an English chemist, but it was not tried out till Soviet experiments began about 1933. Many difficulties had to be overcome, but by 1940 the first full-scale industrial station was established and several more followed it. The method shows several advantages over mining, at least for some types of seams. It abolishes the dangers of underground work. It extracts 80–90 per cent of the coal, as against 60 per cent by mining methods. It makes economical the exploitation of seams which are too thin and of too low quality for ordinary methods (it is to these that it has so far been applied, and it may prove to be less advantageous for rich seams). Although the method is still in its infancy, it is claimed that it has already reduced the cost of power production from coal to one-third of the usual. The gas which emerges is used for electric power generation and as the basis for synthetic chemical industries, besides being distributed to consumers in the same way as ordinary town gas.

The synthetic chemical industries just referred to, or indeed any synthetic chemical industries and a large variety of other industries, require a cheap and abundant supply of oxygen. Special interest therefore attaches to another recent invention emanating from the U.S.S.R. Oxygen is obtained by distilling liquid air, and we have noted in Chapter VII the Linde and Claude processes for liquefying air. Just as the steam-turbine is a more efficient engine than the reciprocating engine, so also a turbine should be more efficient for liquefying air than Claude's reciprocating engine. This fact was early realized, but the difficulties of design were so great that no progress was made till Kapitza produced a practical machine in 1939, in which the liquefying is done in a turbine rotating at 40,000 revolutions per minute. The Linde and Claude processes require compression of the air to 200 atmospheres; Kapitza's needs only 5 atmospheres, thus reducing the size and cost of compressor plant. Early models equalled the efficiency of the established processes, and though no details are yet available of the results of the large-scale development of the process which has since gone on in the U.S.S.R., it appears that the efficiency should be raised by some 20 per cent.

One of the most remarkable inventions since 1918 was in connection with the less violent refrigeration for food preservation (as in the domestic refrigerator). All the early refrigerators required a pump as part of the mechanism. The invention (patented 1923 by a Swedish firm) of a refrigerator driven entirely by heat and using no pump was a piece of outstanding ingenuity. The heat which a refrigerator withdraws from the object it is cooling is given out into its surroundings. In other words, a refrigerator will act as a heater, and in this form it is called a 'heat-pump'. When using electricity it is much more efficient than the familiar resistance heater. All this was realized by Kelvin in 1852, but only in recent years has the idea been put to practical use. It has already proved successful in heating for certain industrial processes and heating public buildings, and it appears very likely to become important for domestic heating in the future—because of its high efficiency and the fact that it can be used in reverse for cooling in hot weather.

Compared with, say, the period 1875–95, which saw the perfection of the gas-engine, the development of the main types of petrol and oil engines, including the Diesel, and the development of the steam-turbine, the twenty years between the two wars were not remarkable for the invention of prime movers. There were great increases in efficiency, of course, such as those we mentioned at the beginning of the chapter, and one fundamentally new form of prime mover appears to have passed through the critical stages of its development shortly before the second World War—namely the internal-combustion turbine, which uses the expansion of burning gas (or atomized liquid fuels) directly to drive a turbine. There are obvious advantages to be hoped for from such an engine—chiefly low initial cost, small size and weight for a given power output, quick starting (compared with steam), independence of water supply and simplicity of construction. The chief disadvantage is that in order to attain reasonable efficiency the turbine has to work at a very high temperature which implies very high demands on the materials of construction.

Curiously enough, the first known proposal for an oil engine, that of John Barber in 1791, was for a crude type of turbine. This, of course, was a freak, of no practical importance, but towards the end of the nineteenth century more practical attempts were made. The first to reach any success was that of Holzwarth, designed in 1905, which after trials and improvements was used industrially to a limited extent. This, however, was an explosion turbine, the burning of the gas taking place intermittently. It thus avoided many of the problems associated with a continuous turbine, but in doing so it sacrificed the advantage of simplicity—it was, in fact, a highly complicated machine. The development of the continuous turbine belongs largely to the inter-war period and was done chiefly by a Swiss firm. It was first used for auxiliary purposes, where waste gaseous fuel was available, so that efficiency was less important: for example, exhaust gas-turbines to supercharge Diesel engines and later for charging Velox boilers and other processes. But as its efficiency increased (to some 17–20 per cent, compared with 30–35 per cent for the best steam cycles), it became feasible to use the turbine for the primary production of power in certain cases where its special advantages outweighed its comparatively low efficiency. For taking the peak load in electricity generation, where the engine may only run for some three or four hundred hours a year, so that low capital cost and quick starting are more important than efficiency, it appears to be an economic proposition. The first[1] installation (4,000 kW.) for this purpose was made just before the war at Neuchâtel in Switzerland. Again, it has obvious advantages for use on railways where lightness is important and where the efficiency of the steam locomotive is very low (8–12 per cent). The first locomotive of this type, of 2,000 h.p., with an overall efficiency of some 15–18 per cent, was ordered for the Swiss Federal Railways just before the war and has since been put into commission. Very considerable attention has also been devoted to the gas-turbine in the Soviet Union. Details do not seem to be available here yet, but apparently a beginning was being made about 1940 of large-scale installations for the production of electric power from underground gasification stations. It is too early yet to estimate the place that the gas-turbine will take in future power production. The difficulties of producing materials to withstand the high temperatures required for efficiencies comparable with steam are very great. But there is no reason to believe them insuperable, and the gas-turbine may within a few years become one of our principal prime movers. It will certainly have great advantages wherever underground gasification is developed.[2] (See Figure 49.)

The war of 1914–18, as we have seen, found the aeroplane at little more than an experimental stage and left it as a

[1] Gas turbine generating sets up to 6000 kW. had been used for some years before the war in American oilfields; but this is not a parallel case, since cheap fuel was available.

[2] While the book was in the press I learnt of the Escher Wyss 'aerodynamic' turbine, a Swiss wartime development of the closed-cycle gas turbine, which appears to give very satisfactory results. It promises in large plants to yield efficiencies of the order of 45 per cent. As a provisional judgement it would seem very likely that this type of turbine may in a few years largely displace the steam turbine.

reliable machine capable of development as a useful servant. In 1919, the year the Atlantic was first flown, regular air services were first established covering 3,200 miles of route. By the next year the figure had risen to 9,700 miles and nearly three million miles were flown. By 1938 there were 349,100 miles of regular air services in operation, and the mileage flown was nearly 234 millions, an expansion of seventy-eight times in eighteen years! In May 1939, Pan-American Airways began the first regular transatlantic air mail. The expansion is an indicator of the increased efficiency and safety of aircraft, brought about by a multitude of detailed improvements as well as some outstanding inventions such as the Handley-Page slot (1919), flaps, the application of the super-charger (earlier used on racing cars) and the variable-pitch propeller (developed by a series of inventors between 1924 and 1934). The last two enabled aeroplanes to fly at great heights, thus reducing air resistance and greatly increasing speed. The auto-gyro, which made some approach to the solution of the awkward problem of the large aerodromes required for air travel, appeared about 1925. Many attempts were made to produce practical helicopters, which would completely solve this problem by allowing take-off and landing on a few square yards. Limited success was obtained from about 1937 on, but the really practical development of the helicopter is one of the important by-products of the second World War.

Radio, like the aeroplane, had passed its most critical barriers in the 1914–18 war and thereafter it too developed with extreme rapidity. The advance from the first tentative broadcasts in 1920 to the important part that broadcasting plays in life today and the great reliability with which it plays that part is a reflection of the great improvements in technical efficiency. Ideas for beam transmission had been put forward from 1905 onwards. But its practical achievement dates from 1924, when work by Marconi and Franklin culminated in the setting up in Britain of a radio telegraph station for communication with the Dominions and India, using short-wave beams. Beam transmission provided the basis for much wider use of the radio telephone, which gives better telephonic communication over great distances than do the land-line and cable. A public transatlantic radio telephone service was opened in 1926. Radio communication over long distances is considerably cheaper to operate than the cable method. As Norton Leonard puts it: 'It requires thousands of miles of extremely expensive cable to cross an ocean. Large ships must be kept in readiness to repair the lines, which are often damaged by anchors, sea animals, and earthquakes. They are by no means free from disturbances akin to static, and their capacity is comparatively small. Transoceanic wireless requires only two stations, which are vastly cheaper to build and operate than the cables. The use of different wave-lengths at different times has removed the last vestiges of undependability. But nevertheless the wireless charges the same rates as the cable. This is because the cable companies, by means of alliances with land-wire networks, have prevented wireless from undercutting their monopoly. If it should try, it would have no effective means of delivering or collecting messages.'[1]

Television also approached practicability shortly before the second World War. Its history actually goes back a surprisingly long way. Telegraphy of single pictures was achieved experimentally before 1850 and a workable system of radio picture telegraphy was devised by Korn of Germany in 1907. A transoceanic commercial radio photogram service was in operation in 1926, though the process did not become important till about 1935. As regards television—the instantaneous transmission of moving pictures—the basic principles were enunciated by Casselle in 1855 and an apparatus was built by Senlecq in 1877—only four years after the discovery of the principle of the selenium photocell. Nipkow invented the scanning disc in 1882. In 1901

[1] *Tools of Tomorrow* (London, 1935), p. 266.

Fessenden designed a radio television system. By 1911 television had been achieved, crude and imperfect, certainly not fit to have any æsthetic or entertainment value, but nevertheless, a portent of what was to come with the improvement of radio technique and the arrival of modern photo-cells and other electronic devices.[1] Credit for the first really useful television system is usually given to Baird whose apparatus was first demonstrated in 1926, though, in fact, many inventors and scientists contributed largely to the development. From 1929 onwards the B.B.C. transmitted experimental programmes on the Baird system, but by 1937 it was decided to replace this by another system depending on the use of a very remarkable form of photo-cell called the 'Emitron' tube. While even up to 1939 television transmission was by no means satisfactory, it appeared to have advanced sufficiently far to promise possibilities of great developments in the next few years.

Another important invention arising from electronic technique is the 'talking-picture'. A 'talkie' system was designed by Ruhmer in 1900, while in 1906 Eugene Lauste produced a system which was essentially modern in form and apparently satisfactory in most respects. It failed, however, from lack of amplification. Nevertheless, it was in the same year that the triode valve, the essential constituent of the amplifier, appeared and amplifiers for radio were rapidly developed thereafter. It might have been expected, therefore, that a combination of Lauste's system with the amplifier, plus some improvement and refinement, would have produced satisfactory 'talkies' within a few

[1] 'Electronics' is the science of devices and machines which depend for their operation on the manipulation of electrons—the radio valve, the photo-cell, and so on. In surveying this chapter the reader will note that while the primary principles of electronics were discovered before 1918, their multifarious development and application was the greatest contribution of the inter-war years to the history of machines. It is also a contribution in which the fundamental scientist, as contrasted with the applied scientist and engineer, played a bigger part than in any previous case.

years. But development was, in fact, remarkably slow. It was not till after de Forest's patent in 1923 that any significant development took place, and the first public sound picture was 'The Jazz Singer' of 1928. Coloured films came a little later. Between 1934 and 1940 the Soviet inventor, Ivanov, developed a stereoscopic cinema, not requiring coloured spectacles or such aids, which gave satisfactory results. Several cinemas were equipped with it in 1940 and from 1941 onwards the apparatus was being manufactured in quantity. It has not so far been used outside the U.S.S.R.

While on this subject, a word on the gramophone and other sound-recording and reproducing devices will be in place. The gramophone was greatly improved by electrical recording in 1924. The system of recording sound on a magnetized steel strip was patented by Poulsen in 1900 and greatly developed by Stille and others from 1924, to yield the Blattnerphone and the later Marconi-Stille recorder of 1933. The system has very great advantages over the gramophone especially in such matters as length of life of the record, but unfortunately it has not yet been allowed to come on the market for general use. It is alleged[1] that the use of this and other recording methods has been intentionally restricted by the powerful gramophone monopolies, though the libel law prevents the publication of evidence which might give proof. Another new system of recording and reproduction using rolls of paper was invented by B. P. Skvortsov just before the beginning of the war, and production was begun in the U.S.S.R. in 1940. The records are said to cost about one-fifth as much as gramophone records besides giving a much longer life.

A large number of the machines and appliances that we have discussed in the last few pages are related to life in a fundamentally different way from the machines of earlier times. They are used for the direct satisfaction of some need

[1] See, for example, O. W. Roskill in *Engineering 156* (1943), p. 385.

of the consumer, instead of for the production of some article which the consumer desires. Till the nineteenth century almost every machine or tool worthy of discussion was an instrument of production. It made the cloth the consumer would use, or carried it from the factory to the shop. There were exceptions, of course, like clocks or passenger transport. But towards 1900 there began to appear machines intended for the consumer to use directly for his personal benefit—the telephone, the cinema, the gramophone, the bicycle, the motor-car. This tendency grew strong after 1918. Motor-cars became fairly common. The 'talkies' became an essential part of life. In the home machines became familiar—the vacuum cleaner, the washing machine, the refrigerator, the radio, etc., where earlier perhaps the only important machine found in the home was the mangle. The use of advanced machinery in production remained, of course, the basis of a high standard of living, but machines used for pleasure or personal convenience came to play an important part. The number of telephones per thousand people in the U.S.A. was less than 5 in 1895; by 1910 it had reached 82; by 1930, 164. Thereafter it declined to only 130 in 1939. This last draws our attention to the fact that, widespread as they were, telephones (apart from those used in business, which formed about one-third of the total) were confined to a small section of the population, the comparatively well-to-do. A saturation point was reached at which all those who could afford telephones possessed them, and as a result of the depression in the thirties the number actually declined. It was the same in other cases. Of the homes in the U.S.A. wired for electricity in 1936, only 48 per cent had vacuum cleaners, only 34 per cent refrigerators. We quote American figures because these problems have been seriously studied by a number of committees set up by the U.S. Government; similar figures for Great Britain are difficult to estimate, but they would almost certainly be lower. Referring to these and other electrical appliances, the official U.S. Government publication, *Technological Trends*, remarks (p. 325): 'The wonder is not that so many homes are now employing these electrical servants—but rather that so many are failing (usually for economic reasons) to utilize these conveniences'. Considerations similar to those we mentioned in discussing failures to make full use of up-to-date techniques at the beginning of this chapter apply again in this case. If there had been a shortage of man-power, then these electrical and mechanical appliances could have been manufactured no more quickly and it would have been natural and necessary that only a proportion of the people should have them. But, as there were many millions of unemployed, it would have been possible to manufacture at a higher rate and provide at least a higher proportion, if not all, with modern conveniences and labour-saving devices.

CHAPTER X

THE SECOND WORLD WAR (1939–45)

RECENT events always appear in foreshortened perspective. That fact has made it very difficult to achieve a proper balance in the previous chapter; the reader of the future will doubtless find that important achievements have been under-rated in it and that too much stress has been laid on others—only time will show truly the relative importance of the various inventions and techniques. The difficulty is far greater in the present chapter. At the time when it is being written (January 1946), it is perhaps possible to evaluate with reasonable accuracy the relative importance of various inventions in helping to win the war. But it is more important for a book of this type to assess their value for the peaceful progress of the future; and in that it is only possible to give an assessment that seems reasonable at the moment, and add the qualification that it must be revised in the light of future experience.

But even now it is clear that these years will stand among the most brilliant periods of advance in mechanical matters and that the troubles which before 1939 sometimes prevented the full utilization of our mechanical equipment were during the war years largely swept away. Private interests were subjected to the national need. Wasteful competition on the one hand, and the restriction of production by monopoly on the other, were over-ridden by national control. The *Handbook of U.S.A.*, issued by the U.S. Office of War Information, tells us: 'In pre-war days, the intricate maze of cartels (international commercial agreements), while protecting private interests and profits, tended to limit production. After the United States entered the war, alien-held patents came under the control of the Alien Property Custodian, and thus helped to speed U.S. production'—and similar steps were taken in Great Britain. The State took control of production and insisted on the use of the most efficient methods possible (with some unfortunate exceptions). Joint Production Committees, by giving the workers a share in policy formulation, played a big part in the drive for efficiency. Research and the development of new inventions were also subjected to Government control, and indeed largely carried out in Government establishments. The result was a very great raising of the technical level in many industries, as the best possible machines were widely introduced. At the same time there came a number of important new inventions.

The most difficult to evaluate, yet probably far and away the most important for the future of mankind, was the release of nuclear energy. The chain of events which had its first culmination in the atomic bomb began in 1896, when Becquerel discovered radio-activity. There is no space here to describe the research carried on by scientists in all parts of the world, and most notably by Lord Rutherford and his associates, which led up to the discovery by Hahn and Strassman in 1938 of the particular property of the uranium nucleus, which was to lead to the release of nuclear energy. They did not fully understand their results, but the correct explanation was given in 1939 by Frisch and Meitner. It was found that when a particular kind of sub-atomic particle, the neutron, enters the nucleus of an uranium atom, this nucleus splits into two roughly equal parts, a vast amount of energy is set free, and more neutrons are produced which, given the right circumstances, could be made to split more uranium nuclei, thus giving a process that would build up into an enormous release of energy.

Then came the war. Scientists in Great Britain and U.S.A. convinced their respective Governments that this process of *nuclear fission* (as it is called) was likely to yield a bomb thousands of times more powerful than any previously known. Vast research projects were set in motion by the two Governments, at first separately, later jointly. £500 million was spent on research, development, construction of the plant, and the eventual manufacture of atomic bombs. A point that emerges is the magnitude of the results that are obtainable, the rate at which technical advance can be pushed forward, when full financial facilities are given to scientists and engineers. As Sir John Anderson said, 'In four years our scientists have solved a problem that in peace might have taken twenty-five to fifty years'.

The atomic bomb, we all hope, is but a passing phase in the history of the world. But what of the possible uses of atomic energy for peaceful and constructive purposes? It is too early yet to prophesy with any certainty, but this much we can say: the consequences, for good or evil, of the release of nuclear energy will be tremendous. This is the most fundamental step forward in man's control of nature since he learnt to control fire, perhaps 200,000 years ago. That is not just a dramatic statement made for effect. It is based on the scientific nature of the discovery. There are, to the best of our present knowledge, three fundamentally different kinds of natural forces—gravitational forces, chemical or electro-magnetic forces, and nuclear forces. Animals have some limited mastery of gravitational forces—some birds carry snails aloft and drop them to break the shells. But no animal has any significant control of chemical forces. It took man to achieve that—when he learnt to control and use the most important of chemical processes, fire. In one sense technical history since then has been the story of how man learnt to make better and better use of his control over gravitational forces and chemical forces (and this book, apart from the first page of Chapter I, is a mere snapshot of the last thirtieth of that story). Man learnt, for example, to use gravitational forces to drive water-wheels. He learnt to use chemical forces to drive steam-engines. Although it is not at first sight obvious, all the forces involved in electrical machinery are of the same fundamental nature as chemical forces. During all this time men were merely finding new ways of using old forces. Now, in the last few years, they have learned to control a third, fundamentally different, type of force—the force that binds the particles of the nuclei of atoms. These nuclear forces are far more powerful than the others, because they are, as it were, nearer to the centre of the basic plan of the universe.

When men first discovered how to use fire, they can have had no conception of the many uses it would eventually be put to—they would not have foreseen steam-engines or alloy steels, or plastics. All they would see at first would be possibilities of applying fire as a substitute for something else to do something that was already familiar—to warm them when the sun failed, to give light on moonless nights. Only gradually they learned the other possibilities of fire—cookery, pottery, metals, steam-engine, and so on. In the same way, we today cannot foresee what will be the consequences of this equally fundamental conquest of nuclear forces. We can only say that it will probably transform the life of humanity just as fundamentally as did that ancient discovery of fire. But there will be one big difference. It took 200,000 years to work out the consequences of the control of fire. Nowadays progress is incomparably faster, and it will probably only take a very few generations for nuclear energy to make corresponding changes in human life.

We can, however, make limited forecasts about applications of nuclear energy to processes which are already familiar—for example, about the production of power for peaceful industrial purposes. At least we know that atomic energy need not necessarily be released in the violent form that was used for the bomb. It can be released, in the form of heat, as slowly and quietly as may be desired—and in fact energy is released very slowly in one of the processes for making the bomb. Already it would be possible to run a steam-engine on atomic energy—but at present it would not be efficient enough for practical purposes. However, the broad principles of an atomic engine are now understood, and further, it is possible to formulate at least some of the main practical difficulties to be overcome. On this basis it seems reasonable to forecast that atomic energy may be available for driving central electric power stations within a period of between ten and fifty years. Whether it is nearer ten or nearer fifty depends on many factors, but probably most of all on whether an effort is devoted to this task comparable to that which was put into the production of the atomic bomb.

Now the amount of energy (or power) available is one of the most important factors in determining how much each man and woman in the community can produce, and therefore in determining the standard of living. Mankind's progress has been quite largely conditioned by the amount of energy he was able to command—first only his own muscles, then step by step animal-power, wind- and water-power, coal and oil. This new control over nuclear energy is likely further to increase our power resources, at least considerably, perhaps enormously. There is, of course, a limit to the amount of uranium available. But the release of nuclear energy from uranium is only a first step. Just as man's use of fire was not confined to burning wood, with which he probably started, but was extended gradually to many other fuels, so also it is likely that we shall eventually learn to obtain nuclear energy from many other materials besides uranium—and we shall do so incomparably faster. There is every reason to think that before reserves of uranium are exhausted, nuclear power will be obtained in many other ways.

Even at first, when nuclear processes may not perhaps greatly increase the total power available, they will at least extend greatly the range of circumstances in which power can be used. Since the weight of uranium involved is negligible compared with the weight of fuel in other power processes, power will become readily available in places where transport problems have hitherto prevented its use; and that may open up new fields of natural resources which have hitherto been unavailable for exploitation. In addition, the process of fission promises many other benefits, for example in medical research, which are outside the scope of this book.

Thus, provided—and the proviso is a very serious one—provided men find a way of overcoming the threat of destruction involved in the atomic bomb, the work that led to it will probably prove to be the first step in a technical revolution that could raise living standards far above anything that has yet been thought possible and could finally abolish all poverty and want.

The development of atomic energy provides an excellent illustration of a trend that has been growing strongly in recent years. It was the product of fifty years of scientific research, much of which was done without any reference to possible particular applications, followed by five years of

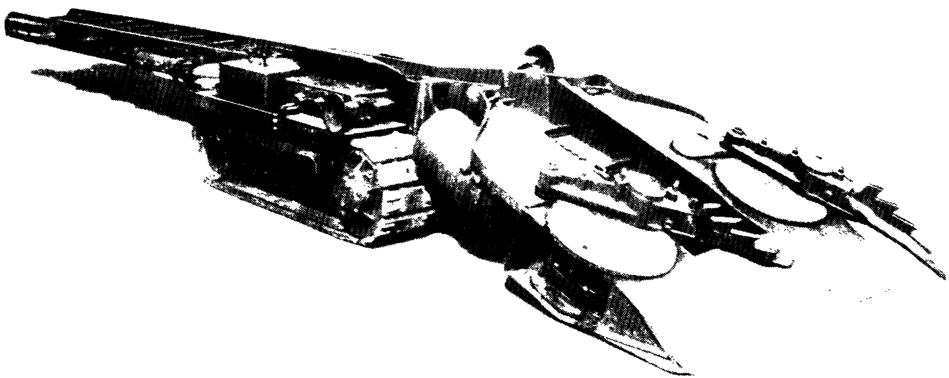


Fig. 44. A power loader for loading coal from the floor on to a face conveyor.

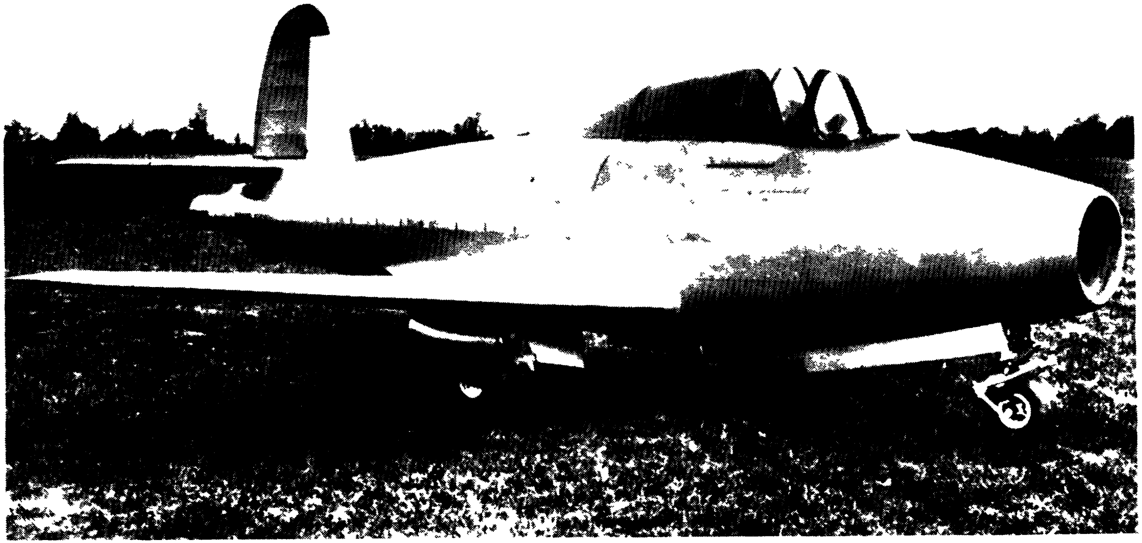


Fig. 45 The first Whittle jet-propelled plane

applied science and engineering directed to the solution of a particular practical problem. It is more and more becoming true that the best way to produce technical advances of great benefit to humanity is not to devote the largest possible amount of scientific research to the immediate practical problems, but rather to ensure that a large amount of fundamental scientific research is undertaken and that full use is made of its results by applied scientists and industrialists. Quite apart from other reasons (such as cultural ones) for doing fundamental scientific research, it is now the case that the community as a whole is likely to benefit more from it than from most other human activities (with certain obvious provisos, which the alternatives presented by the atomic bomb well illustrate).

Some other wartime inventions, though probably less significant from a long term point of view than the release of atomic energy, are likely to yield beneficial results much sooner. The most important of these were in the air—the jet-propelled plane, practical helicopters, and, in its own way, the flying bomb—to say nothing of the amazing increases in speed, efficiency, altitude and so on, that took place in the conventional aeroplane. Proposals for the jet-propulsion of aircraft go back to 1920 and earlier. During the thirties several workers in various countries tackled the problem. In Britain, Whittle began his work about 1929. By 1937 engines of his design were run successfully on the test-bed. He received little support, however, and it was not till 1939 that orders were placed for trial planes for development work. Thereafter progress was rapid. In 1941 full-scale trials were successful (Figure 45) and by early 1942 the first planes for use were coming off the production line. There is little information on other systems. A plane on the Italian Campini system was tried in 1940, flying for ten minutes, and again in 1941, but was apparently not outstandingly successful. By 1944 the Germans as well as the Allies were using jet-propelled planes.

Helicopters, as we noted in the last chapter, had reached limited success by about 1937. They were still far from suitable for general use, and once more it was during the war that the practical machine arrived—in the form of the Sikorsky helicopter (Figure 46), which is now in regular commercial production. A typical early model of this machine is capable of absolutely vertical take-off and landing, requiring only a platform 40 feet square; it can hover perfectly stationary in the air or fly forward, backward or sideways, at speeds something like a really fast sports car. Its fuel consumption is very moderate. It played an important part in defeating the submarine menace and promises to be equally important in post-war transport—America's leading bus company has applied for permission to start a service of helicopter buses, and it has also been proposed to use it for mail services.

Much more problematical is the value of the elements involved in the German terror weapon, the flying bomb, which was evolved in principle just before the war, but, in view of technical difficulties, not brought to a practical state till 1943. The flying bomb itself has, of course, no permanent value for mankind, but the principles involved in it require consideration. The controlling devices are not particularly new, being paralleled by the automatic pilots of pre-war times. But the engine, an intermittent jet-propulsion unit, is extremely original. It is amazingly simple, being little more than a few feet of piping. It has no moving parts, except simple valves for admitting the air and fuel, and these are automatically closed by the pressure of each explosion and opened as the pressure decreases, so that they are not connected to any other part. In fact it is a petrol engine of construction about as simple as a water-wheel! The result is an engine, far cheaper to produce than any other, weighing about a quarter as much as a reciprocating internal combustion engine of the same power. On the other hand its fuel consumption is about eight times as great as that of the conventional engine. It is difficult to say if this can be reduced enough to make the engine serviceable for peaceful purposes.

Not strictly 'in the air', but closely connected with it, is radio-location or radar, the use of radio to detect and accurately fix the position of invisible aircraft and other objects. Like the other developments mentioned above, work on radio-location began well before the war (about 1935, though the transition from earlier techniques for measuring the height of the Heaviside layer and the altitude of aircraft is not clearly marked) and it had probably advanced much more than the others before the outbreak of war. In Great Britain its earlier forms were by then ready for immediate practical application. By contrast, Dr. Lyman Chalkley, chief economic analyst to the U.S. Government's Board of Economic Warfare, has alleged that radio-location was not adequately developed before the war in the U.S.A. because it did not appear to have any profitable peacetime uses. On the outbreak of war, he said, America 'had to start practically from scratch, meanwhile losing ships and planes and men, because the profit motive had not guided up to the development of radar from a state of laboratory curiosity to the manufacture of practical instruments'.

During the war the technique of radar was carried to new heights. The refinement that goes by the name of 'centimetric radar' was the result of brilliant research and (like all radar advances) of fine team-work. It increased the accuracy of the primary application of radar to the detection of aircraft, and widened greatly the range of circumstances in which it was applicable. But it did far more than that in making practicable the application of the radar technique to a wide variety of purposes. Radar moved on from the status of a particular method of solving a particular problem, to the far higher status of a technique of very wide applicability and very great potential importance. For example, the safety of aircraft will be very materially improved by the application of radar to blind landing systems and to such devices as 'H2S' (or its improved version, 'H2X'), which provides the pilot, even when flying through fog or cloud, with a picture of the country over which he is passing. Similarly the safety of ships will be greatly improved by the corresponding device which, though it operates from the ship itself, gives the navigator in all weathers a map of his surroundings, just as if he were looking down on them from an aeroplane (Figure 47). Clearly radar in its many forms has before it a great future of usefulness—Sir Robert Watson-Watt, who did more, perhaps, than anyone else to bring it into being, has even suggested that it might solve the problem of running trains to time in fog!

As well as these major inventions, the war saw many other examples of mechanical ingenuity—as in PLUTO ('pipe line under the ocean') or the Mulberry harbour. Many of these will have no direct peacetime applications, but doubtless the engineering experience that was gained in executing them will be of great value in the reconstruction period.

If the war years had produced no more than the initial steps towards the constructive use of atomic energy and the bringing into practical use of the four inventions of jet-propulsion, helicopters, radio-location and the more doubtful flying-bomb engine, they would still rank as one of the periods—perhaps *the* period—of most rapid mechanical progress in world history. There may be further important advances, still secret at the time of writing. And in addition there must be numerous problems on which important advances have been made during the war and which, given the right conditions, can be fully solved in the first few years of peace.

Of course, each one of the outstanding wartime inventions that we know about depended to a considerable extent on work carried out before the war. Nevertheless, while granting credit for pre-war work, we must note that the war years have been remarkable for bringing to perfection and putting into practical use a considerably greater number of outstanding inventions than any comparable period in the previous fifty years. This would seem to be more than a coincidence. It appears that in pre-war years, though inventive ability was there, various factors prevented the inventor from receiving sufficient encouragement. The two-year gap between successful Whittle engines and the orders for trial planes indicates this, as do Dr. Chalkley's remarks quoted above. The same idea is expressed by G. G. Smith; in discussing, before the announcement of Whittle's success, the prospects for successful jet-propulsion, he wrote: 'Under the stress of war conditions, funds are available for research and experiments, the best equipped brains can be applied to problems and vested interests are not allowed to impede developments'.[1] The statement by Sir John Anderson which was quoted earlier points towards the same sort of conclusion. We postpone till the next chapter consideration of just how invention can be restrained by social factors. Here we are merely concerned to note how the needs of war removed the restraints and in two or three years brought to a successful culmination inventions that at peacetime rates might not have seen practical development for several years.

Less spectacular, but probably equally significant, were the advances that were made in production methods. Between 1939 and 1943 total production in Britain increased by over 40 per cent, compared with only 13 per cent in the twenty-five years 1913–38. A short calculation from these figures shows that the average annual rate of increase in production in the war was some seventeen times as much as the average over the previous twenty-five years. All this was in spite of the difficulties of importing essential machinery and materials in wartime, in spite of the effects of bombing,

[1] *Flight*, 9 October 1941; reprinted in his *Gas Turbines and Jet Propulsion for Aircraft* (3rd edition, London, 1944), p. 40.

the strain on transport and the four-and-a-half million men in the Forces.

Only one-twelfth of the increase came from longer working hours. The rest arose from the better organization of industry under Government control, from full employment, the recruiting of new workers to industry, and from increased efficiency arising from the more widespread adoption of modern machines and up-to-date methods. The rise in the technical level of industry was shown by the increase in labour productivity (output per man-hour), estimated at some 15 per cent (more than twice as fast as in peacetime) over all industries and some 30–35 per cent in the munitions industries.

Most of the improved efficiency in engineering arose from the spreading throughout the industry of the modern machines and techniques that had been developed during the past decade or so, but had not previously been widely applied. Tungsten carbide tools, whose use before the war had been restricted (as we have seen) by the policy of international cartels, came into very general use. The machine-tool industry played a valiant part in providing, on an enormously increased scale, the various types of highly productive machines for which demands arose, and especially the more robust and rigid machines required for using carbide tools. Machine tools, formerly mostly 'built' as individual units, now came to be largely mass-produced. Some U.S.A. figures are available. In pre-war times American sales of machine tools reached a peak of about $200 million in four separate years—1918, 1929, 1937, 1939. In 1942 the sales were $1,300 million and the average for the years 1940–43 was over $900 million, or four-and-a-half times the pre-war peak. At the end of 1939 the U.S.A. had 1,500 million dollars' worth of machines less than fourteen years old; by the end of 1943 she had 4,500 million dollars' worth. Apart from their role in winning the war, the effect of this modernization on post-war standards of living should be revolutionary.

Much of the increased productivity arose from the wider application of mass-production methods and from a multitude of refinements and improvements in these methods. Among the latter is the outstanding innovation of 'quality control'. The essence of interchangeable production is that the measurements of each piece must be identical within certain permitted limits of error, called 'tolerances'. Due to wear of tools and other factors, a machine which is set to produce the pieces accurately will gradually lose its accuracy until eventually the errors will exceed the tolerances. Any such pieces will then have to be rejected as 'scrap'. The old method was simply to inspect occasional samples and when these were found to be outside the required limits, the machine would be adjusted. But meanwhile many pieces would have been produced with too great errors and these would all be wasted. Quality control uses the science of statistics to avoid this. From the permitted tolerances a new set of inner limits are calculated; when the errors on more than a certain number of samples exceed these, the pieces are still sufficiently good for use, but it is a warning to the inspector that the machine is liable soon to become so inaccurate as to produce scrap. It is therefore stopped and adjusted immediately and wastage of time and material is avoided. The statistical principles on which quality control is based have been known for many years and in limited fields the method has been used for a couple of decades, but it was only during the war that quality control has been widely applied and the full possibilities of the method have been developed. The effects of this and other improvements in production methods are shown by the case of the Sten gun, which was made so cheap as to be classed as a 'consumable store' to be thrown away when no longer serviceable. Its cost was reduced to about thirty shillings, as against about as many pounds for a similar article before the war.

Mass-production methods were also applied to work of an entirely new order of size—for example, in the U.S.A. to the prefabrication in factories of complete parts of a ship, ready for rapid assembly on the slips. A single American factory in 1943 was producing parts enabling a shipyard to launch two 10,000-ton ships a week. By these and similar methods the U.S.A. was able to reach the amazing production of 3,876 merchant vessels in three years—an average of 25 a week.

Equally far-reaching changes took place in agriculture. Agriculture in Britain became one of the pivots of the war effort. By means of guaranteed prices and other aids, the Government encouraged farmers to aim for maximum output—which required, among other things, greater mechanization. The number of tractors in use more than trebled from 55,000 in 1939 to 175,000 in 1944; the number of tractor implements rose from 200,000 in 1939 to 1,175,000 in 1943; and the number of combine harvesters from 150 to 1,500. On the basis of the number of machines to a given area, Britain's agriculture became the most highly mechanized in Europe. The previous tendency to use machinery to less than its full capacity was partly overcome by pooling schemes.

In war conditions sugar-beet and (because of their high energy content) potatoes became especially important. Much attention was given to the improvement of machines for dealing with them. About 1943 the latest beet-harvesters, which lifted the beet, topped it and deposited it in piles at intervals, were said to be completely effective in most circumstances. Potato-planters and lifters (Figure 48) were also improved. Advanced types of planters in 1943 saved 80 per cent of the labour involved. Lifters which dug the potatoes, picked them up, sorted and loaded them were brought to success, though not used on a wide scale. Another example of wartime inventions was a machine for picking up sheaves of corn, carrying them to and loading them on to the stack. The result of this mechanization,

Fig 46 Helicopter

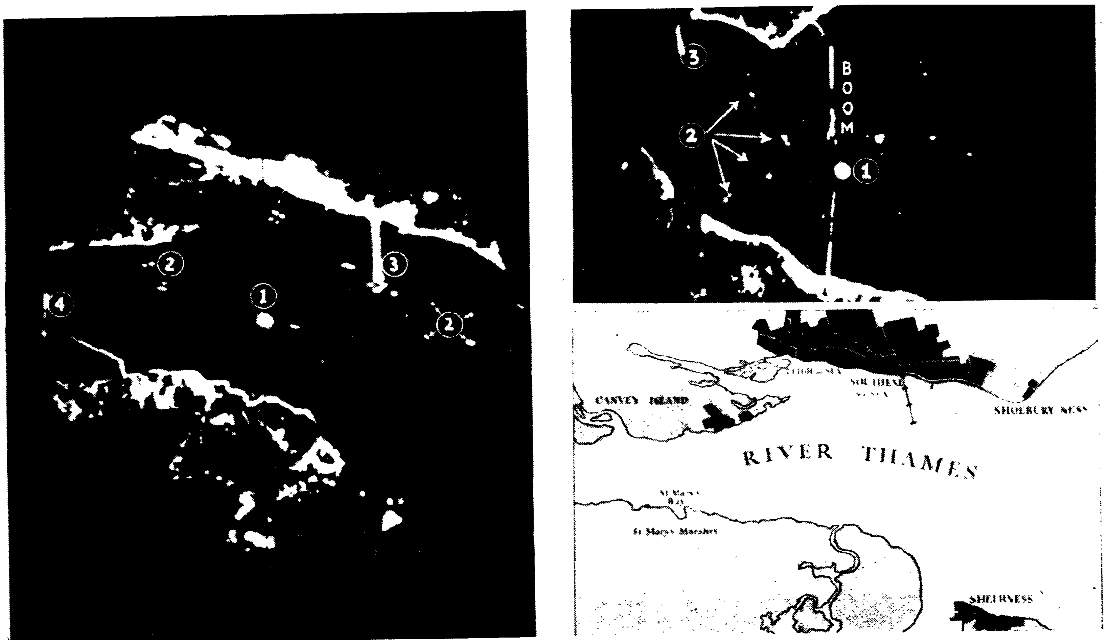


Fig. 47. (Left) The Thames Estuary as revealed by radar equipment aboard a ship. The points marked are (1) the ship that 'took the picture'; (2) other ships and buoys; (3) Southend Pier, with ships lying off the end; (4) oiling jetty on south bank of the river. The bright patches round the coasts indicate built up areas. Compare the map. (Top Right) The ship is passing through the boom off Southend.

Fig. 48. A recent potato harvester.

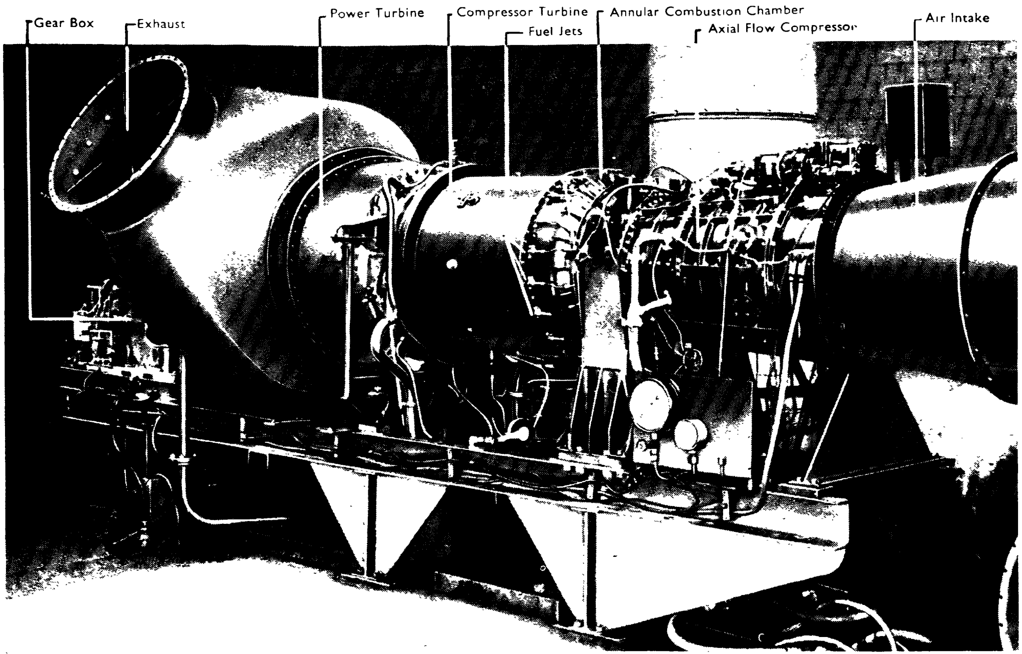


Fig. 49. A post-war gas-turbine for use in a Royal Navy gunboat.

with other improvements, was a 70 per cent increase in Britain's agricultural production between 1939 and 1943. Britain's agriculture supplied two-thirds of her food requirements in 1943 against one-third before the war.

There were unfortunately some industries in which these amazing increases in efficiency did not take place in Britain. The most notable was coal-mining. Coal, always the life-blood of industry, became even more important in war. Every aspect of production depended on it. Yet, instead of increasing to satisfy the increased calls for fuel, the production of coal actually *decreased*—from 231 million tons in 1939 to 193 million in 1944. The factors operating to reduce output included some that were unavoidable, such as loss of man-power in the call-up and the increasing age of those that were left. But these factors were common to many industries and their effect would have been corrected, as elsewhere, by increased use of machinery. Yet the mine-owners held to the policy of pre-war years. There were only 40 more coal-cutters in use in 1943 than in 1939, though the number increased by another 424 in 1944, and the quantity of coal cut by machine actually decreased from 142 million tons in 1939 to 132 million tons in 1944. Similarly, although the number of face and gate conveyors rose from 8,271 in 1939 to 9,492 in 1944, the use of them was such that the amount of coal conveyed fell from 134 million tons in 1939 to 127 million tons in 1944 (after reaching a peak of 137 million tons in 1940). Power loaders might have helped greatly to solve the man-power problem; yet only 192 of them were in use in 1944. American experts, visiting the mines, found over a million pounds' worth of machinery lying idle and estimated that its use would have increased the output by twelve or fifteen million tons a year. As a result of this policy, the supply of coal fell well below Britain's needs. In their homes the people suffered from the shortage. Factory supplies had to be rationed and no doubt production was held back and the war prolonged.

We have much less information on the progress of machinery in the Soviet Union during the war than for Britain and the U.S.A. We have no information at all on important new inventions, if any, made there during those years. Even production statistics are vague (probably intentionally to mislead the enemy) and those given below will probably need revision. Nevertheless, they give an impression of vast expansion. Pig-iron production increased 20 per cent between mid-1942 and mid-1943 and another 34 per cent between then and mid-1944. On the other hand, of course, the destruction of plant by the Germans greatly reduced Russia's productive capacity. (If these increases had taken place over the whole of the pre-war plant then taking into account also the 52 per cent increase between 1937 and 1942, the U.S.S.R. would already have overtaken Britain and France in *per capita* production of iron and be well on the way to overhauling Germany and the U.S.A. The calculation is a hypothetical one, but it does indicate the speed of expansion in that part of the industry which escaped destruction by the enemy.) Similar increases are shown in other aspects of basic production—coal production increased 32 per cent between July 1943 and July 1944, and so on.

Industry was apparently expanding even more rapidly than before the war in those parts of the Soviet Union which were not overrun by the Nazis. Electrification gives some idea of the expansion. The output of steam-driven power stations in 1943 was 20 per cent more than the total for 1940 and 1941. New plant was being rapidly built. The total capacity of new plant installed in 1944 was reckoned at nearly 3 million kW., which is almost as much as the new installations in Britain in the first ten years of the Grid. But, of course, much of the Soviet generating plant was destroyed by the Fascists and it will be no small task to replace it. Yet in spite of this, *Soviet War News* was able to announce at the end of 1944, 'There is every reason to expect that in

1945 the Soviet power stations will exceed their pre-war capacity'.

These figures give us little idea of how the *efficiency* of Soviet industry increased during the war. We learn a little more from figures on labour productivity, which for industry as a whole increased by about 40 per cent between 1942 and 1944 and, for example, in coal-mining by 32 per cent between 1943 and 1944. Such increases as these could not be obtained merely by working harder, though that must play a part. They must indicate at least a multitude of small inventions and improvements contributing to efficient working, and possibly some major steps forward. We hear something of the former (though without details) in the form of reports of the vast numbers of inventions and suggestions coming from the workers themselves, reports like this: 'A two months' "rationalization suggestions" campaign, which has just ended [in November 1944] in the factories of the Commissariat of Light Industry, has resulted in the submission by the workers of over 3,000 inventions and proposals for improvements . . . the 810 suggestions already put into effect in the factories will economize materials, power and labour to the value of 60,000,000 roubles a year.'

And yet, though figures like those given are some help, a far more vivid indication of the expansion and increasing efficiency of Soviet industry is provided by the successes of the Red Army. No army could have withstood the long retreats of 1941 and 1942 and then advanced so rapidly in 1943 and 1944, no army could have produced such concentrations of fire power—in some cases one artillery piece per yard over hundreds of miles of front—unless it were backed, not only by a civil population determined to win no matter what the sacrifice, but also by an industry of tremendous efficiency.

CHAPTER XI

RETROSPECT AND SUMMARY

It is a long road that we have travelled since the discovery of agriculture initiated the great changes this book has discussed. It is well to contrast the mechanical equipment of men today with what their ancestors possessed just before the dawn of civilization—to contrast the crude flint sickle of Figure 1 with the powerful and accurate combine harvester of Figure 35; or the early sailing ship and wheeled cart with the railway train, car, steamer, aeroplane—and even helicopter—that give us transport today.

Consider the contrast in the power available to do man's work. Apart from sailing ships and a very imperfect harnessing of animals, till two thousand years ago man's own muscles provided the only source of power. Athens became a very rich city because on an average each freeman had the muscles of half a slave to work for him. But in 1935 the 1,231 million h.p. of engines of all types in the U.S.A. were equivalent to some *seventy* slaves available to work for every man, woman and child in the country. Britain was a little less well off with the power equivalent of about fifty slaves per head. Since then the number of these power 'slaves' has been steadily increasing. Britain's production of aeroplane engines alone from 1939 to 1944 provided some thirty further 'slaves' per head—not in the most useful form for peacetime work, it is true, but the equivalent could be achieved in five years of peace. And the release of nuclear energy foreshadows yet further increases in our power resources.

Even these figures of the brute force available to work for us understate the case. Our machines work far more quickly and accurately than the old-world slaves with their crude equipment. One girl with a modern spinning machine produces as much cotton as 300 spinsters using the seventeenth-century spinning wheel, and probably as much as many thousands of spinsters using the simple spindle that remained in use till the late Middle Ages. One man with a threshing machine replaces 135 men with hinged flails (and the latter is a comparatively advanced threshing tool). In 1830 it took 57·7 man-hours to produce a bushel of wheat, using a sickle and flail; in 1896 with a binder and stationary thresher it took 8·8 man-hours; and in 1930 with a combine harvester only 3·3. One man with a tractor ploughs as much ground as fifty men and a hundred oxen using the improved ploughs of the eighteenth century. A modern paper-making machine turns out 10,000 square feet for the same labour as one square foot with the handicraft methods of the late eighteenth century. Of course, in each case we must add a proportion of the man-hours required to make the machine but even when this is done the gain in productivity remains immense.

If the neolithic barbarian with his limited equipment could exist, even with what would now be thought a terribly high death-rate, if the people of the seventeenth century could live and a fairish number of them could enjoy a moderate, though by no means excessive, comfort, then surely we today with our technical equipment advanced far beyond theirs can ensure at the very least a decent standard of living for all. The progress of the last eight thousand years has given us the means to provide plenty for all. It has been reckoned that if the equipment of the U.S.A. were everywhere brought up to the highest technical standards available in the inter-war years, then the pre-war production of the States could be doubled and simultaneously working hours reduced to one-third of their present level, or alternatively with the present working day production could be multiplied six-fold, providing six times the present supply of commodities to raise the standard of living—just what plan should be followed depends simply on the decision of the people as to whether more goods or more leisure is primarily desirable. Every other country could reach the same standard. It would take some time to do so, of course. But, as we have already emphasized, the only limiting factor, other than those which are self-imposed, is the supply of man-power available to modernize equipment. All that is required is social organization to ensure that, instead of mass unemployment, every available worker is used to raise the technical level and therefore indirectly, the standard of living. The time taken would vary from country to country. In countries like Britain and U.S.A. where technical levels are already high and where, unfortunately, there were large numbers of unemployed left unused in the inter-war years, the process could be very rapid. In backward countries like India a longer period would be needed. All this leaves out of account the tremendous advances in productive efficiency during the war years, advances which, if properly used after the war, would have already taken us well on the way to a world of plenty. And it also neglects the tremendous impetus that would be given to new invention, leading to yet higher productivity, if the raising of the standard of living were made the first object of our social effort. On the adverse side, there is the terrible destruction of mechanical equipment and other plant during the war, which has to be made up.

Let us look back along the road from early neolithic times to the present day and try to see in broad perspective how the advances have been achieved. One way of doing this is to compile a sort of score sheet of the fundamental technical methods, the fundamental tools and machines available to mankind at each stage. The details of such a score sheet are set out in the Appendix. Here we need only say that it is arranged in such a way that the total score up to any particular date represents approximately the number of different fundamental tools and machines at mankind's disposal and their importance. The progressive increase in this score is shown in Figure 50, where the dates are marked along the bottom and the height of the curve at each date represents the total score for fundamental inventions made up to that date; in other words, it represents the mechanical equipment available to men at that date. It cannot give an exact picture of progress, since the methods used are subject to several kinds of error (3),[1] but it will give a reasonable idea of the general pattern of progress. The slope of this curve at any point will then represent the rate at which invention is going on at that time. One of the first things we note about the diagram is that *in general* the higher the curve is at a given point, the faster it rises there. There are exceptions of course—between 3000 and 1000 B.C. the rate of growth is much less than before 3000 B.C.—but we have seen that such periods of slowing down of progress were due to the action of artificial forces like the structure of a particular society. So it is reasonable to assume that the *natural* way of growth, when such factors are eliminated, is that the rate of invention increases with the resources of the time, that is, with the score of inventions previously made. We might expect this to be so because every invention when established makes easier the achievement of another—Darby's invention of coke smelting, leading to plentiful cast iron, provided the essential material for many nineteenth-century inventions; every improvement in transport made possible the use of more highly centralized plant and so of more productive machines—and because, in more general terms, every invention, by increasing the rate of production, increased the amount of socially available time which need not be spent on the actual production of necessities and which could (if social organization permitted it) be devoted by some specialists to the task of further invention.

[1] References in this form are to the correspondingly numbered sections of the Appendix.

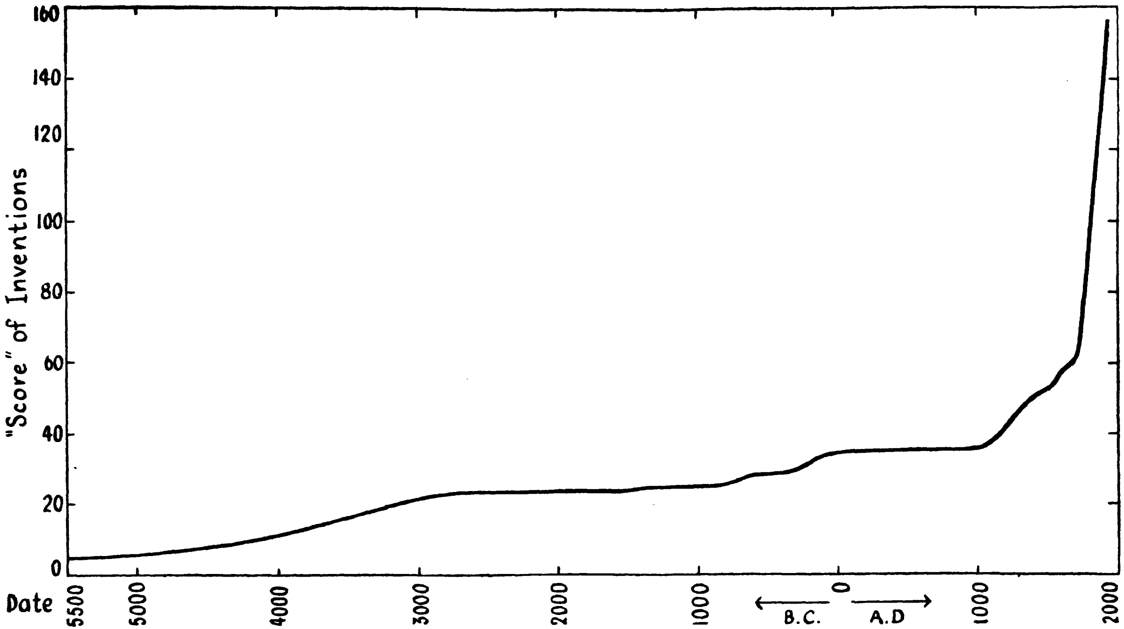


Fig. 50. Man's mechanical equipment throughout the ages. The height of the curve for any date represents approximately the number of fundamental types of machines and tools at man's disposal.

Now growth of this type is familiar in many branches of science—a colony of microbes grows like this when lack of food or external causes are not restricting it—and methods of analysing it have been worked out. When they are applied to the present case they give the results shown in Figure 51. In this graph (4) the height of the curve at any point represents the rate of increase of the score of inventions relative to the score at the time, that is the rate of technical progress relative to the technical level already reached. More precisely, the height of the curve represents the *percentage increase* in the technical level that on the average occurred in one year at the time concerned. We can call this the '*relative invention rate*'. If the rate of invention always followed the law of growth mentioned in the last paragraph—the higher the technical level, the faster its advance—then the relative invention rate would be constant and the graph of Figure 51 would be a horizontal straight line (5). The variations in the height of the actual curve can therefore be taken as an indication of the variations in technical progressiveness from time to time. The higher the curve, the more progressive the period.

The variations in this curve reflect in a very interesting way the trends that we have discussed in earlier chapters. We note first the long period of rapid progress of the two or three millennia before 3000 B.C., which we discussed in Chapters I and II and which, it will be recalled, so affected man's way of life as to bring about the change from barbarism to civilization and with it the social revolution from a (more or less) equalitarian society to one with very sharp and very great class-divisions. The sharp dip in the curve at B shows how these class-divisions, when they eventually hardened into something like a caste system, reacted on invention, bringing about an almost complete cessation of progress. The next three or four thousand years, as the curve shows, saw no progress comparable to that before 3000 B.C.—only occasional short periods of rather less rapid advance. Indeed invention of fundamental importance was completely absent for nearly a thousand years, and the curve does not begin to rise again significantly till at C, where the beginning of the Iron Age overlaps with the slight revival of inventiveness of the later Bronze Age which we noted at the end of Chapter II. Iron made metals much more generally available and provided the conditions for the use of such machinery as a pulley and the rotary quern. And so to a peak at D in the great days of the Athenian culture. But here the contradictions arising from the division of the Greek world into tiny and usually warring city states and especially the troubles arising from the enormous growth of industrial slavery asserted themselves and the curve shows a sharp decline at E(6). Then the Alexandrian conquest and the subsequent immense Hellenistic expansion partially eliminated these contradictions and provided the conditions for nearly three centuries of the most rapid progress (shown at F) the world had seen since 3000 B.C. Once more the contradictions involved in the Iron Age slave states asserted themselves, and under the Roman Empire at G progress of importance again ceased entirely. Then came the decay of the Roman Empire and the barbarian invasions, bringing on the one hand an acute shortage of labour (since the mechanism of slave-supply failed) and therefore an incentive to use machines, and on the other a social structure which gave the craftsman a more favourable position than at most times since 3000 B.C. There followed first a period in which machines like the water-wheel were spread over Europe and used on a greatly increased scale. Naturally this is not reflected in a curve concerned with inventions, but shortly before the millennium this spreading of old techniques changed into the invention of new techniques, and at H the relative invention rate begins to rise rapidly. And now at I the curve rises higher than at A. At last, after 4,000 years the rate of progress has exceeded that of the societies just before civilization. But all is not yet plain sailing. The curve

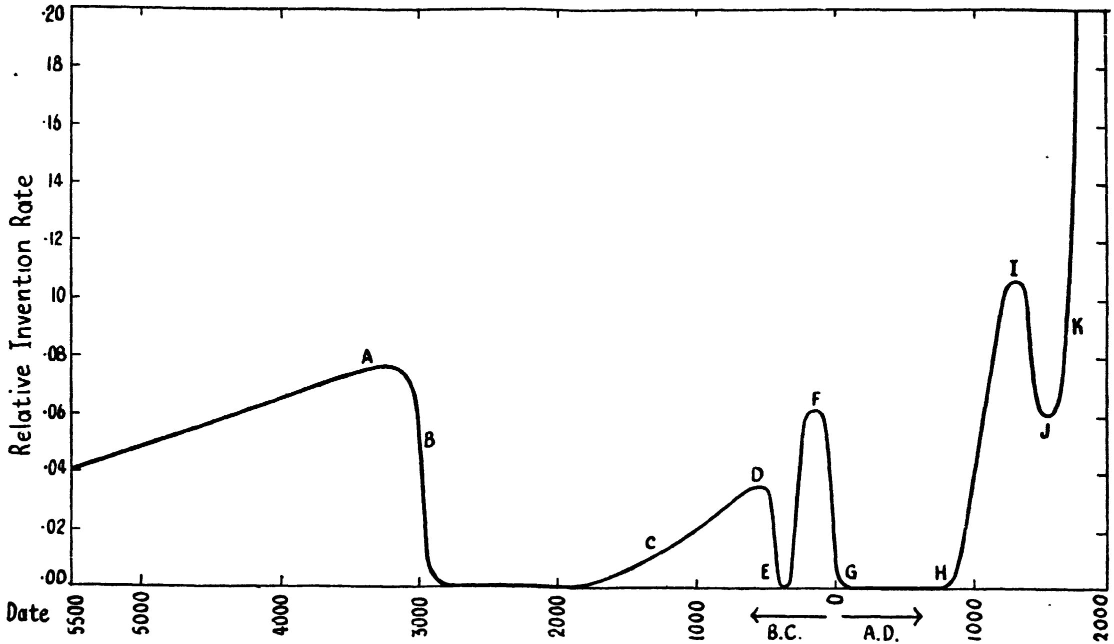


Fig. 51. The relative invention rate. The height of the curve at any date represents the percentage increase in man's mechanical equipment occurring on the average in one year. When the curve is high, progress is rapid; when it is low, progress is slow.

hesitates at I and drops back to J(7). And then about 1700, at K, the curve turns sharply upwards, so steeply as to be nearly indistinguishable from the vertical. The modern era of rapid progress has begun. The curve shoots off the page and by the end of the nineteenth century reaches a height corresponding to three-and-a-half times the height of Figure 51.

The temporary downward turn of the curve between I and K is interesting. We are prompted to ask what forces prevented the rate of progress from increasing continually from say A.D. 900, why the increase should have been interrupted between 1300 and 1700. The elements of the answer have already been given at the end of Chapter V and the beginning of Chapter VI. The new machinery brought into use by the inventions of the Middle Ages could only be fully used by a new structure of industry: capitalist industry. The political and social system of feudalism prevented the full development of capitalism. In doing so it prevented the fullest use of the new machinery. But more than that, since the then new methods could not be used to the full, there was less opportunity for the use of further inventions and less incentive for the inventor. Thus the feudal structure of society, by preventing industrial organization from keeping pace with technical development, was responsible for holding back the rate of invention. Nevertheless, invention went on. The adverse factors did not kill it. The curve does not continue to rise at I, but at least even in decline it remains well above zero. Invention still went on, only partly inhibited by adverse social circumstances, and at the same time the new technical methods were being more and more widely used and with them the capitalist industrial structure continually expanded—till at last, in England first, later elsewhere, the 'bourgeois revolution' (see Chapter VI) burst the restricting bonds of feudalism. And when the restrictions were removed, the invention rate shot up to completely new levels (after K in the Figure 51).

This example shows clearly two of the relations between technical invention and social structure.[1] First it shows how social structure affects the rate of invention. After the stagnation of the Roman Empire, feudalism gave a new impetus to technical progress and the invention rate rose rapidly until about A.D. 1300. Then the feudal structure, no longer suitable for using the new techniques it had produced, slowed down the rate of invention until a new social structure—capitalism—appeared, giving full encouragement to technical progress, and therewith the invention rate rose sky high. We have seen other examples of this. The reader can follow out similar effects; for example, between 1000 B.C. and the beginning of our own era he can see how the rise of industrial slavery affected the rate of technical progress. These examples lead us to the general conclusion that *the form of society has a very great effect on the rate of inventions* and that *a form of society which in its young days encourages technical progress can, as a result of the very inventions it engenders, eventually come to retard further progress* until a new social structure replaces it.

The converse is also true. Technical progress affects the structure of society. It is not the only factor, but it is a very important and fundamental one. The leap from feudalism to capitalism resulted, as we have already seen, largely from medieval technical advances; it came when feudalism proved itself an inadequate vehicle for further progress. Similarly—an example which we considered in detail in Chapter II—the inventions of the millennia before 3000 B.C. created new conditions which necessitated the change-over from a classless society to one in which the main feature of social structure was class-division. Thus we reach the conclusion

[1] Strictly we should take into account not merely the tools and machines with which we are concerned here, but also all techniques—agricultural, chemical, etc.—but as these have on the whole advanced roughly parallel to mechanics and as mechanical techniques have usually outweighed the others in importance till recently, we shall not go far wrong in considering only the relations of tools and machines with society.

complementary to our first one, that *technical progress—invention and the spread of the use of invention—is a fundamental factor in determining social structure and in bringing about the necessity for a change from one social structure to another.*

We have been considering some of the details of Figure 51. But, when we look at the curve in the large, one fact stands out as far more striking than any of these: that there have been two great periods of technical progress, the two or three thousand years before 3000 B.C. and the centuries since about A.D. 1100 (but particularly since 1700), and in between there was very little technical advance. Between these two there were only a few short periods of very moderate progress. Because they are so outstanding, these two periods of rapid progress are worthy of special names and they have been called the First and Second Industrial Revolutions respectively. Nothing in the technical sphere (and this is just as true of other techniques as of tools and machines) that happened to mankind in between is in any way to be compared to what happened in these two industrial revolutions. Now we have already stressed several times the world-shaking effects of the first industrial revolution—the creation of civilization, the creation of transport facilities which bound the former villages into larger and larger states and concurrently enlarged the outlook of men, the transformation of classless into class society, the provision of an adequate amount of leisure for at least a small number of men, the leisure that was an important factor in the creation of the many forms of art and literature, of science and philosophy. The second industrial revolution has not yet lasted half as long as the first, but progress in it is far and away more rapid. Should we not expect it to produce changes just as great as those which the first produced? Until two or three centuries ago, those who said: 'Thus it has been and thus it will remain. There is nothing new under the sun' were justified in their error; for indeed since 3000 B.C. very little new had happened and archæology had not yet rediscovered the progress before that date. But today, living in the midst of this second colossal industrial revolution and knowing that its technical changes must produce effects just as great as those of the first, there is but little excuse for those who deny that the life of mankind can be fundamentally changed in all respects. That final upward sweep of Figure 50, showing the progress of the last 250 years in which the number of mechanical methods at man's disposal has more than doubled, must surely bring vast changes in its train. Every aspect of our present life must be regarded as transitory. Just as the first industrial revolution gave plenty and the leisure to enjoy it to a few men, so now the second can give plenty and the leisure to enjoy it to all men. Just as the first transformed the isolated villages into great states, so the second has already made the world economically a single unit and calls upon mankind to transform the conflicting states into a single world unity. Just as the possibility of wealth for a few provided by the first industrial revolution brought about the creation of class-divisions, so also the possibility of plenty for all provided by the second gives the opportunity for their abolition and the creation in their place of true 'liberty, equality and fraternity' at last. And what the ultimate effects of the second industrial revolution will be on the arts, on philosophy, on science, is beyond our present comprehension.

Beyond noting that it rises so fast that it cannot be included in Figure 51, we have said little of the behaviour of the curve representing the relative invention rate in the later stages of the second revolution. We can, however, learn something from it. Figure 52 shows how the curve behaves over the last hundred and fifty years (8). It has been drawn on a different scale, but the height of the curve reached in the first industrial revolution has been marked in for comparison. The most striking thing about this diagram, if for the moment we agree to neglect the last few years, is that the rate of invention rose to a peak in the nineties and after that declined quite rapidly (with a temporary slight recovery corresponding to the 1914–18 War). In recent years the amount of detailed improvement has continually increased, but when we consider only inventions of fundamental importance (as our curve does), we find that the invention rate increased until the nineties, then declined, and in the 1930s reached a level well below the peak and about equal to the level reached a century and a half ago (9). We are not progressing as fast as we did fifty years ago. Others have also noted this fact (10). Because they have been concerned with invention in all spheres instead of merely tools and machines and because the lists they used were shorter than ours and because they counted all inventions as equal instead of assigning them points in rough correspondence to their importance, they have placed the peak at different times; but they do agree that there has been a decline in recent times.

So pronounced a decline requires an explanation. It can hardly be due to omissions made in compiling our list, since to raise the curve in the 1930s to the level of 1895 (to say nothing of continuing the upward trend of the nineteenth century) would require us to find between 1930 and 1940 rather more than four further inventions of importance comparable to the steam-engine. We can hardly have omitted inventions to this extent. Is it because the actual possibilities of technical progress are coming to an end—as Furnas implies when he says, 'Almost everything has been discovered; not quite everything, for we are still dribbling along, but almost'? The Pharaohs of Egypt must have thought that the cessation of invention in their time was because everything had been discovered—but they were wrong. It is a big responsibility to prophesy that further progress is impossible. There can be no evidence to back the prophecy; even if we could not think of any further inventions that are needed, we should do no more

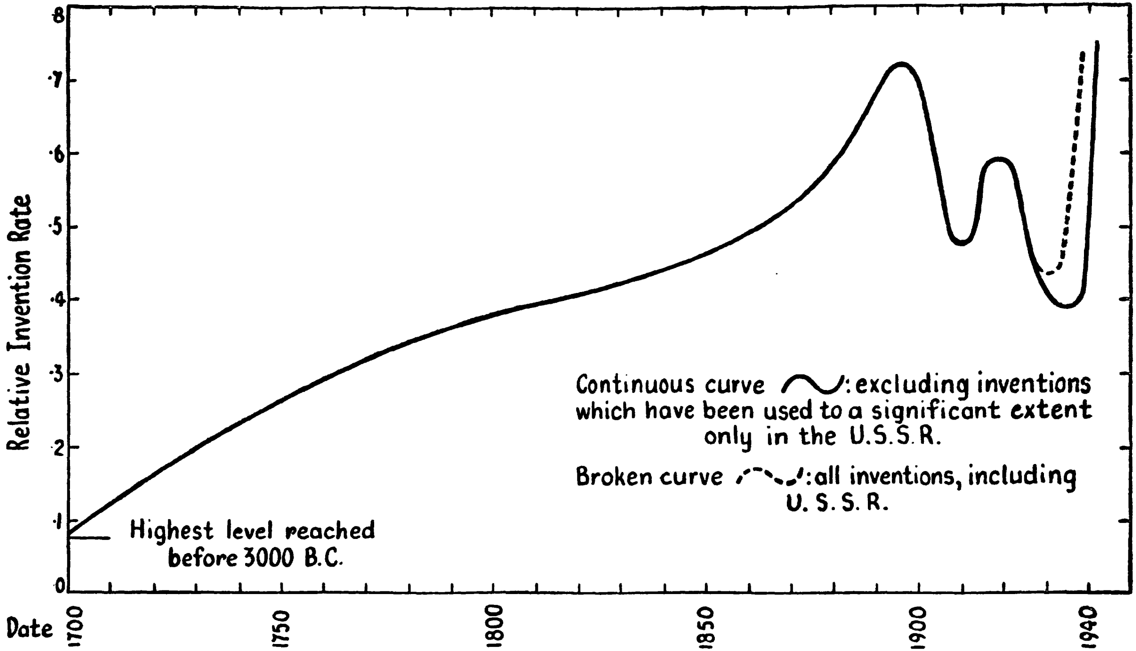


Fig. 52. The relative invention rate in modern times. Continuation of the curve of Fig. 51, but on a different scale. The line marking the highest level reached before 3000 B.C. enables the two to be compared.

than demonstrate our own limitations. And in point of fact it is not difficult to think of many inventions that will probably some day be made—a reliable continuously variable gear, a static-electrical high-tension generator suitable for general use, high-tension direct-current transmission, efficient methods of storing power, self-sharpening tools on machines, and so on. All these are being tried at present (our limited vision hardly allows us to go beyond that) and some day most of them will be successful. In addition, we have the important fact (which we discuss later) that during the second World War the invention rate again began to rise rapidly. It seems, therefore, that there are still many inventions waiting to be made, but that some causes which we must find are slowing down the rate at which inventions are actually being made.

Is it because the further inventions that remain to be made are far more difficult than before? It is hard to believe that some time in the nineties all the comparatively simple problems were exhausted and quite suddenly the difficulties of further advance increased, so that within fifty years the rate of invention fell by nearly fifty per cent. Instead, if this were the cause, we should expect the curve slowly to come to the horizontal and then just as slowly to decline. Of course, invention does become more difficult as progress continues (and we shall have more to say on this later). From the beginning of history the new inventions to be made became progressively more difficult—the water-wheel was more difficult than the sail, the steam-engine than the water-wheel, the turbine than the reciprocating engine. But at the same time mankind's resources have increased, techniques previously invented helped with each new step, the general advance of technique allowed a greater proportion of the time of the community to be devoted to solving the next problem. Thus, in spite of the ever-increasing difficulties of the tasks, the invention rate increased except when social factors prevented it. It is unreasonable to suggest that suddenly in the nineties difficulties outstripped resources.

Now we have already met some previous cases in which the invention rate declined after a period of comparatively rapid advance—after 3000 B.C., about 400 B.C., in the Roman Empire, between A.D. 1300 and 1700. And in each one of these cases we found social causes: various trends arising from the social structure of the times, the way in which production and consumption were controlled, acted in such a way as to discourage further invention. This suggests that there may be social causes behind the decline of recent years. We can begin by noting what new social and economic phenomena have arisen in the last half century. We have already mentioned some of these in Chapters VII and IX—the permanent difficulty that manufacturers found in selling their products, chronic unemployment, and the formation of cartels and monopolies. We have already seen in Chapter IX occasional examples of the ways in which these things can retard progress. Chiefly they act by restricting production; but that means less incentive to install the latest types of machinery, and that in turn means less encouragement to invent new machinery. Sometimes they go further and actively discourage new invention.

An outstanding (but by no means untypical) example of how the chronic difficulty of selling products discourages invention is provided by the case of the Rust brothers' cotton-picker (see Chapter IX). This invention was not brought into general use (except in the U.S.S.R.) because of a fear of what *Technological Trends* calls 'overproduction', meaning, of course, the curious situation in which people who obviously need cotton goods are prevented by mal-distribution of purchasing power from buying them. It is not often that inventors foresee this difficulty and deliberately restrict the use of their machines as the Rust brothers did. More usually it happens that the *producers fearing 'over-production' simply do not use the* machine.

The difficulty of selling products leads to huge and wasteful competitive advertising campaigns, to the employment of enormous sales staffs to search for customers. In a pre-war motor car costing £600 there was about £90 worth of direct factory labour, whereas about £240 went to the cost of selling the car. Now it quite clearly does not cost anything like that sum merely to convey the car to the consumer and provide a man who will hand it over in exchange for his money. The reasons for the disparity are clearly put by Norton Leonard[1] when he says that the trouble 'starts with the development of a machine or method which cuts to a fraction the cost of making some useful article. All the established manufacturers who can afford it buy the machine, increasing their potential output many times. To pay for their investment they all calculate that they will have to capture larger proportions of the available market. Therefore they advertise widely and expansively. They increase their sales forces, allow larger commission, resort to all the tricks known to commercialism. The price of the product may fall to some extent, but most of the advantages of the new method have been cancelled by the cost of selling and the enforced idleness of the over-numerous machines. In many cases today the retail price of an article produced chiefly by automatic machines is three or four times the cost of production.'. The community thus loses most of the potential value of the improved machinery. But more than that, he continues, 'One effect of this is to slow down the introduction of the newest and most efficient equipment. The manufacturers look ahead, see trouble approaching, and so they do not invest their money in machines which would certainly cut their legitimate production costs, but might not yield tangible profits.' And if the best existing machinery is not being used, what

[1] *Tools of Tomorrow* (London 1935) pp. 155–6.

encouragement is there to invent yet better? All this is, of course, purely artificial. There is no lack of real market for the products, in the sense of people who need them. The difficulties arise from the distribution of purchasing power in such a way that those who need the goods cannot buy them. There may be disagreement as to *how* these faults of distribution should be corrected, but it is clear that *when* they are corrected, not only will the people reap a fuller benefit from our advanced methods of production, but also the rate of invention will be enormously boosted.

Unemployment is merely this same faulty distribution looked at from the other side. The goods are not sold, production is cut down and therefore men are thrown out of work. And unemployment was the other reason given for restricting the use of the Rust cotton-picker. It is again true that few inventors will act with such complete consciousness of the potential effects of their work, but in a less conscious way they will be deterred by the fact that their invention may increase unemployment. In attempts to employ some of the workless a retrogression to more primitive methods has sometimes occurred. W. I. Sirovich, speaking in the U.S. Congress, said: 'One of the western states last year entered into a number of contracts for paving roads containing the specific stipulation that labor-saving machinery should not be used, with the intention of increasing the number of jobs provided. I am not informed whether the men were required to dig up and remove the dirt with their hands, or whether they were allowed to do two or three times as much work with a shovel.'[1]

Unemployment retards technical progress in another way. The mass of men eager to find jobs depresses wage-rates, so that it is often cheaper to use primitive methods involving much hand-labour than to introduce automatic machinery. Men are retained, because they are cheap, on soul-destroying

[1] Quoted by Bernhard J. Stern in 'Frustration of Technology', *Science and Society* 2 (1937), p. 1f.

monotonous repetition work which could be done as well or better by automatic machinery. That is why, for example, the use of the photo-cell in production has not yet approached its possibilities.

The tendency to form cartels and monopolies also restricts production—indeed, one of the reasons for forming them is to maintain high prices by agreed restriction of output—and therefore holds back technical progress in the way we have been discussing. But monopoly often acts in a more direct way. This problem has much concerned the Government of the United States. Under the New Deal policy a number of Government committees have considered it and issued reports from which we quote below. One of them[1] says: '. . . opposition has always come from vested interests which could see their property and income menaced by new inventions. Railroads were opposed by the owners of turnpikes and stagecoach lines. The use of gas for lighting was opposed because it would destroy the whale-oil business. Later electric lighting was fought by the gas companies. The telephone came into existence over the bitter opposition of the telegraph companies. The radio telegraph was fought by the telegraph companies. The radio telephone was fought by the telephone, telegraph and radio telegraph interests. Although corporate organizations do develop and utilize many inventions, sometimes corporations will fight successfully against the passage of laws requiring them to adopt modern improvements . . . As Charles F. Kettering, vice-president of General Motors, said in an address in 1927: "Bankers regard research as most dangerous and a thing that makes banking hazardous due to the rapid changes it brings about in industry". A banker who finances a new development that will destroy his present investments is asleep at the switch. Progress depends, therefore, to some extent on free resources of capital that cannot be controlled

[1] U.S. National Resources Committee: *Technology and Planning* (Washington, 1937), pp. 5-6.

from any central point. With the tendency to centralization of control in business and banking the openings for free initiative are more and more restricted.'

Opposition of vested interests when a new invention threatened their income is, of course, not entirely a new phenomenon of the last fifty years. The opposition to the railways, discussed in Chapter VII and mentioned in this quotation, is an early example; similarly, the later opposition to mechanical road transport by the railways themselves. Even these early cases occur mostly in industries like transport and communications which tend strongly to monopoly. But the growth of monopolies as a general feature of economic structure introduces new factors. In the early days of free competition it was comparatively easy to overcome the opposition. Backing could easily be obtained from some rival; one of the many competing producers would be willing to use the new technique. And so the opposition of vested interests seldom retarded progress seriously. But a monopoly has power of a quite different order—a power well described by Henry A. Wallace, recently Vice-President of U.S.A., when he said in September 1943: 'The peoples and the Governments of the world had unwittingly let the cartels and the monopolies form a super-government by means of which they could monopolise and divide whole fields of science and carve up the markets of the world. The people must get back their power to deal with this super-government. This super-government has misused the peoples of the United States, not only with regard to rubber [here he is referring to secret agreements between American monopolies and the German chemical combine I.G. Farbenindustrie, which greatly restricted America's pre-war development of synthetic rubber], but in a host of other critical industries as well. . . . These cliques have their own international government, by which they arrive at private quotas. Their emissaries are found in the Foreign Offices of many of the important nations of the world. They create their own system of tariffs and determine who shall be given permission to produce, to buy and to sell. . . . This secret agreement [on synthetic rubber] between an American monopoly and a German cartel was subject to no public authority. It was far more important than most treaties, but it was never acted upon by the U.S. Senate.'

Such is the power of monopoly. It controls a whole industry. If it refuses to use an invention, there is no rival to whom the inventor can turn. The huge capital investment required for efficiency in modern industry prevents any new rival from entering the field in order to exploit a new method. Of course, a monopoly is seldom absolutely complete, but even so it has plenty of power and plenty of methods by which it can prevent technical innovation. The introduction of an invention will usually depend on the utilization at some stage of a technique already in use. The monopoly may have patent control of the latter and so prevent the introduction of the former. Another common method is by buying up the patents of the inventions, so that others cannot use them and then not using them themselves. The patent law of most countries in theory forbids this; in theory if a patent is not used anybody can bring a legal action and obtain permission to use it. In practice the costs of such action are so great that the monopoly can in fact suppress the use of a patent. For example, in 1934 the American Bell Telephone Company controlled 9,234 patents, of which they were using only 4,225. In spite of arguments put up by the Company, the Federal Communications Commission investigating the situation concluded that 3,433 of the remainder, which might have been socially useful, were suppressed by the Company to protect their own interests against competitors.

Sometimes the monopoly merely restricts the use of a new method, as with tungsten carbide (see Chapter IX). Sometimes it prevents its use at all. *Technological Trends* (one of the New Deal publications) says (page 53): 'Changes within the electric industry have been retarded by the buying and suppressing of patents by the large corporations which dominate the field. . . . A superior electric lamp, which it is estimated will save electric light users $10,000,000 a year, has been invented but has not been put on the market.' Later in the same document (page 353), C. C. Furnas says: 'The author knows of one metallurgist who made his own safety-razor blade, sharpened it, and nitrided it. It has been used daily, without re-sharpening, for 2 years. Naturally the razor-blade manufacturers are not interested.' In Great Britain concrete examples are difficult to come by, partly because there have been no Government inquiries, partly because the libel law endangers anybody who publishes a specific instance. British companies have several times been mentioned in connection with charges of entering into restrictive international agreements brought against various American corporations by the U.S. Government. The accusations have naturally been denied in Britain, but there has been no opportunity to decide the matter, judicially or otherwise. While proven cases are lacking, general statements have been made by many authorities who are in a position to know the truth; for example, by Sir Alexander Gibb in his presidential address to the Engineering Section of the British Association in 1937: 'Of course, here, as always in research, it is the case that the greater the success of research, the more immediate and drastic the effect on existing plant and equipment. That is where the rub sometimes lies . . . and many valuable inventions have been bought up by vested interests and suppressed. . . . It is therefore not surprising that there is not always an enthusiasm for unrestricted research.'[1] A specific example is provided by the railways, whose monopoly position is so strong that they do not even need to buy patents, but merely to refuse to use a new method.

[1] *Report of the British Association*, September, 1937, pp. 158-9.

The British Government appointed a committee to consider railway electrification. Its findings were summarized by Mr. S. B. Donkin, President of the Institution of Civil Engineers: 'The finding of the Weir Committee, published in 1931, was unanimous in favour of complete main line electrification. The Committee emphasized that comparison between such electrification and either suburban electrification already in operation in this country or main line electrification undertaken in many countries abroad, would be misleading. Nevertheless the Committee found that under the conditions of railway working in Great Britain, electrification would reduce the cost of operating the railway system, and, therefore increase the efficiency of utilization of the coal resources of the country; it would reduce the average schedule running time of main line trains; by increasing the bulk use of electricity it would have a most favourable effect on the cost of electricity for other purposes; and finally, the cleanliness of an electrified system would have an effect on the health and well-being of the urban population which could not be assessed in terms of money alone. . . . It is unfortunate that up to the present the recommendation of the Committee in favour of complete main line electrification has not been accepted.'[1]

In this connection the inevitable increase in difficulty of further progress has some importance. We have seen that resources also grow, giving us the means of overcoming the increasing difficulties. But for success these resources have to be concentrated. Modern industrial research requires large staffs working co-operatively, great laboratories and expensive equipment. We have the means to provide these, but at present the only organizations that can afford such staffs and equipment are the great industrial monopolies (unless, of course, the state takes over the responsibility). So we are at present in the position where the

[1] *Transactions of the International Engineering Congress, Glasgow*, 1938, pp. 52–3.

monopolies control a large part of the resources required for research leading to further technical advance, but at the same time the monopolies have interests which tend to reduce their enthusiasm for invention, especially for fundamental inventions which revolutionize the methods of industry. As the American Government document, *Economic and Political Aspects of International Cartels*, referred to above, puts it (p. 32): 'Desiring to limit expansion of output and avoid the development of uncontrolled substitute processes, cartels are necessarily suspicious of new technological developments. They readily undertake research to discover new uses for their old products but often discourage the development of new processes or new products.' This explains the fact, noted above, that the number of detailed improvements has increased rapidly in modern times, while the number of fundamental inventions has been on the decline. In a word, the greatest opportunities for invention lie with the enormous resources of large concerns, but these have often very little incentive to use their resources to produce major technological changes. The effect is shown in W. M. Grosvenor's calculation[1] that only 12 out of 75 of the most important inventions between 1889 and 1929 were produced by the research of the monopolies. The rest, we may suppose, depended on some more or less fortunate set of circumstances putting the necessary resources in other hands.

There is, of course, a real problem behind this question of obsolescence. It may not benefit the community in some cases to change the methods of production too quickly; that might mean too great a loss on the older plant to be fully compensated by the increased production of the new. But the question that arises is: who shall decide at what rate changes should be made—the community as a whole or the few people who control an industrial monopoly?

[1] 'The Seeds of Progress' in *Chemical Markets 24* (1929), p. 24. Quoted in Stern, op. cit.

So there are at least three social factors that tend to restrict the use of the most advanced methods and ultimately to slow down the progress of invention. First, the faulty distribution system, which creates the chronic difficulty of selling products and therefore reduces the incentive to introduce advanced techniques. Second, mass unemployment, which discourages invention through the fear of displacing labour and, by depressing wage-rates, often makes it cheaper to use monotonous labour instead of introducing highly automatic machines. Third, monopoly with its tendency to protect its own interests even at the cost of progress. These are not necessarily the only retarding factors, but at least they are three important ones.

There is some further evidence that these are the main causes. In Figure 52 we have drawn two curves for the later years. The broken curve includes all the important inventions made in the period. The continuous curve uses only those inventions which have come into use to a significant extent outside the Soviet Union; it excludes techniques like the underground gasification of coal, hydro-mechanical coal-mining, mechanical cotton-picking, combined heat and power production, the stereoscopic cinema, etc., which have found little or no use in other countries (11). The curves only begin to differ about 1930, since it was only about then that the U.S.S.R. recovered sufficiently from the effects of the 1914–18 War and the wars of intervention to play a significant part in the furtherance of technical methods. (As Tsarist Russia did not contribute one single fundamental invention, we do not have to alter the curve before 1917.) We note immediately that the curve which includes the U.S.S.R. rises between 1930 and 1940 to about the level of the former peak in the eighties and looks as if it will continue to rise steeply thereafter. But the curve which excludes the inventions used only in the U.S.S.R. remains at a low level. The significance of this is that the Soviet Union is the first state to change its social structure in such a way as to eliminate faulty distribution and unemployment and to abolish the control of industry by private monopolies. This would seem to indicate a connection between these phenomena and the lowered invention rate.

The events of the second World War point in the same direction. Here, through government control, sectional interests were largely subjected to the national needs of the Allies, unemployment disappeared, and the need for armaments abolished marketing difficulties. The result, as we have seen, was that the technical level of industry was rapidly advanced towards the best possible and in addition several notable inventions appeared. It is not possible to estimate accurately the changes in the invention rate during the war. We have no knowledge at all of important inventions (if any) from the U.S.S.R., so that we cannot continue the broken curve. And for the continuous curve our information is probably still incomplete. Yet in spite of this the relative invention rate rises very rapidly to about, or even above, the level of the former peak (12). War removed, at least temporarily, the social restrictions, and immediately the rate of invention shot up to its former level. Certainly the second industrial revolution is not at an end.

It is not the purpose of this book to suggest the steps necessary to solve the problem of the effect of social conditions on technical advance. We only state the facts (or some of them) to enable the reader to play his part in solving it. Briefly those facts are: that the second industrial revolution, unfinished though it is, has already shown us the way to provide plenty for all mankind; and that certain social factors, which have arisen in the last half century, have so far retarded the realization of this possibility and (except during the war, when they have been largely eliminated) have tended to hold back the progress of the second industrial revolution. If the great advances in the happiness of mankind which this industrial revolution makes possible are to be realized, some means must be found of overcoming the social problems. There can be little doubt that, just as the social factors which retarded progress in past eras were overcome, so also those of today can be overcome and the world of plenty can be realized.

APPENDIX

THE RELATIVE INVENTION RATE

(1) *Basis of Compilation.* The list of inventions began from a list of some 2,000 dates in technical history, which was compiled from many sources as an aid to writing this book. Many of these dates referred to such matters as statistics on the use made of machines, or the circumstances in which inventions were made, or to inventions of minor importance, improvements, etc. The list used in compiling the 'score sheet', which is given below in (2), modified by (8), contains only fundamental inventions extracted from the longer list. It includes, incidentally, a number of inventions which have not been mentioned in the text. The emphasis is strongly on inventions of fundamental importance, improvements and modifications being almost always omitted.

As regards score, *one point* is given for a fundamental invention affecting a large sector of industry—for example, inventions in transport (e.g. railways), basic materials (e.g. cast iron), fundamental engineering tools (planing machine), power (Watt's engine), etc. *Half a point* is given for a fundamental invention affecting only one industry—for example, the spinning jenny or the seed-drill. Inventions of somewhat lesser importance are given correspondingly lower scores; and in particular, many lesser inventions of the first class are given only the half point of the second class. In the lists (2) and (8), all scores have been multiplied by ten, in order to avoid the use of fractions.

As regards dating, the decision is made in terms of the *use* of the invention. Drawings, plans, or even models, that did not have practical consequences (e.g. many of Leonardo's) are ignored; and the invention included in the list is that which led more or less directly to use on a significant scale. But even with this definition, it is often impossible to decide just which of many steps is to be regarded as the critical invention. There are also cases (like the water-wheel) where the technique came into use in two stages. Thus in many cases the score appertaining to a single invention has been shared between a number of dates. These cases are indicated in (2) by writing after the description of the invention, one or more dates in brackets, which denote the dates of the other steps with which the score is shared. For example, the score for the power loom is shared between 1787 and 1821. In a few cases, for example, the electric generator, the invention thus shared has seemed to merit, and is given, rather more than the usual maximum of 1 or ½.

The idea of a fundamental invention is naturally open to widely varying interpretations, and we therefore note here a few cases in which there is likely to be most difference of opinion. In the Middle Ages several applications of water-power to different purposes have been included, whereas in the eighteenth and nineteenth centuries similar applications of steam-power have not. We make this difference because the former were important steps in the development of the general idea that power can be applied to all manner of things, whereas the latter were merely applications of a new prime mover in a time when that idea was familiar. From the end of the eighteenth century on, we have strictly omitted all inventions of the type that would come under the head, 'the mechanization of this or that particular industry'. This has been done on the grounds that there was seldom a fundamental inventive step involved—merely, as it were, the working out of the decision to apply machinery in a new field. It would in any case be beyond our powers to follow through the mechanization of all industries, while to select particular cases would almost certainly introduce biases arising from the fact that various industries underwent mechanization at different times. Thus the inventions included in the list for the last century and a half are mainly (*a*) inventions in fundamental spheres like machine tools, transport, power, etc., and (*b*) inventions that created their own industries, like radio. There are two exceptions, coal-mining and agriculture, which have been included because they nearly fall in (*a*); unlike many other particular industries, their inclusion does not distort the general picture, because their mechanization has been going on for at least two centuries and is still in progress. In industries like textiles, in which the main mechanical inventions come in the eighteenth century, we have also included the nineteenth-century dates which complete their story.

The list has been confined to the main stream of civilization from Egypt and Mesopotamia in and before the Bronze Age, through Greece and later Europe in the Iron Age, and so to the world civilization of today. Inventions taking place, for example, in China before the time of direct links with the west, are noted in square brackets, thus [ ], in order to give them a perspective, but are not given a score.

The detailed list of inventions begins with those that accompanied the invention of agriculture. For the purposes of the calculations that follow it is necessary to know the initial score at this point, and this has been assumed as five (fifty in the list below, where everything is multiplied by ten). This is largely an arbitrary figure, but has been taken on the *ad hoc* assumption that the inventions which accompanied or immediately followed the invention of agriculture (namely the hoe, sickle, saddle quern, flail, bow-drill, pottery, spindle, loom, ground and polished tools) but preceded the invention of smelting, roughly doubled the mechanical equipment of humanity. An alteration of this initial score will change the form of Figure 51 in the following way. If the initial score is increased above five, the effect would be to decrease proportionately the height of the curve at the extreme left of Figure 51, the decrease becoming less and less as one proceeds towards the right—in other words, the importance of the early period would be diminished. If the initial score is decreased, the effect would be the reverse.

The dates before 2750 B.C. are extremely rough and have been chosen to correspond approximately to the known archæological evidence, but at the same time to give a reasonably smooth curve. In the later parts of the list, 'c.' means 'about', 'f.' means 'and the following years', and '(say)' indicates that a development was extremely gradual or its dates extremely vague and that the particular date given has been chosen as a reasonable compromise.

(2) *The Table of Inventions and Scores.* (To avoid fractions, each score is multiplied by ten.)

Invention	Date B.C.	Score
Score up to invention of agriculture	—	50
Hoe		5
Sickle		5
Saddle quern		5
Flail (unhinged)		5
Bow-drill	5500–4250	5
Pottery		5
Spindle		5
Loom		5
Ground and polished tools		5
Copper mining processes		5
Copper smelting		10
Copper smith's auxiliary tools and processes	4250–3750	5
Casting		10
Silver working		3
Lead working		3

Invention	Date B.C.	Score
Wheeled vehicles		10
Plough		10
Harness	3750–3250	10
Sail		10
Potter's wheel		5
Shaduf		3
Balance		10
Bronze		10
Bellows		5
Cire perdu casting		5
Developed tools of many crafts	3250–2750	15
Wheel of pots		5
Building techniques as in pyramids		5
Spoked wheels	c. 1800	2
Iron smelting (1100)	(say) 1400	3
Windlass	(say) 1300	5

Invention		Date B.C.	Score
Effective use of iron begins (1400)		c. 1100	7
Improved and more varied craftsmen's and farmer's tools — 10, distributed as follows: 700, 1; 650, 2; 600, 3; 550, 2; 500, 2			
Pulley		c. 700	10
Rotary quern		c. 600	5
[Draw loom, China]		c. 550	–
Sheep shears		c. 500	5
Beam press	(say)	500	2
Building tackle, crude cranes, etc. (200)		c. 450	2
Animal-driven quern		c. 450	5
Limited generalization of animal power (A.D. 1225)	(say)	400	3
Screw of Archimedes	(say)	250	5
Advanced cranes (450)	(say)	200	3
Heavy plough	(say)	200	5
Nail - making anvil	(say)	200	5
Wire - drawing blocks	(say)	150	5
Animal - driven wheel of pots		c. 150	5
Force pump		c. 150	5

Invention		Date B.C.	Score
Carpenter's plane	(say)	100	5
Watermill	(say)	80	10
Screw press	(say)	50	5
Sheers with block and tackle	(say)	25	2
[Chinese harness]	(say)	0	–
		A.D.	
Overshot water wheel — limited use (1350)		c. 475	2
[Block printing, China]	(say)	550	–
[Stirrups, China]	(say)	650	–
Modern saddle harness in Europe	(say)	850	5
Horseshoe		c. 900	10
[Persian windmill]	(say)	950	–
Modern draft harness in Europe (1200)	(say)	950	5
[Movable type, China]		1041	–
Hinged flail	(say)	1050	5
European windmill		c. 1105	10
Woodcuts for capital letters, Europe (1289)		1147	2
Water - power fulling	(say)	1150	3
Water - power crushing	(say)	1150	3
Magnetic compass		1195	5
Water - power sawing	(say)	1200	3

Invention		Date	Score
Water - power tilt-hammer	(say)	1200	3
Completion of evolution of harness (950)	(say)	1200	5
As consequence of last item, fuller generalization of animal-power (400 B.C.)	(say)	1225	7
Mechanical clock		1232	5
Modern type plough	(say)	1250	5
Wheelbarrow	(say)	1250	4
Modern rudder	(say)	1250	10
Mechanical reeling and twisting of silk		1272	5
Block printing in Europe (1147)		1289	3
Water - driven blast		1295	3
Spinning wheel		1298	5
Lock gates	(say)	1300	5
Water - driven grindstone	(say)	1310	3
Water - driven trip forge-hammer	(say)	1320	3
Perfected escapement		1348	5
Lathe	(say)	1350	10
Overshot water-wheel, fuller use (475)	(say)	1350	3
Wire - drawing machine	c.	1350	5

Invention		Date	Score
Movable type, imperfect, Europe(1450)		1381	1
[Metal type, Korea]		1390	–
Cast iron	(say)	1400	10
Crank motion	(say)	1400	5
Rolling - mills (1700, 1784)	(say)	1425	2
Perfected movable type, Europe(1381)		1450	4
Spring clock	c.	1490	5
Powered town water supplies	(say)	1500	5
Perfected spinning machine with flyer and treadle		1530	5
Railways at mines		1546	5
Power gig-mill	(say)	1550	3
Machines of *De Re Metallica*	(say)	1550	5
Screw - cutting lathe	(say)	1550	5
Mandrel lathe	(say)	1550	5
Ribbon loom (1621)		1579	1
Turret windmill	(say)	1580	5
Knitting machine		1589	5
Cementation steel		1614	5
Ribbon loom (1579)		1621	4
Pendulum clock (1661)		1641	2
Worcester's engine	(say)	1650	1

Invention	Date A.D.	Score
Balance spring	1658	5
Huygens' marine clock (1641)	1661	3
Plunger pump	1675	3
Centrifugal pump (1818)	1680	1
Anchor escapement (1715)	1680	2
Savery's steam-engine	1698	3
Polhem's improved rolling mill (1425, 1784)	(say) 1700	2
Polhem's primitive mass production	(say) 1700	2
Screw guides in lathe mandrel	c. 1700	5
Wet sand casting	1708	5
Newcomen engine	1712	5
Dead beat escapement (1680)	1715	3
Smelting with coke	(say) 1717	10
Seed drill (restricted use and not modern type) (1782)	(say) 1730	1
Newcomen engine used for rotary motion via water-wheel	1732	1
Flying-shuttle	1733	5

Invention	Date A.D.	Score
Spinning by rollers	1738	5
Cast steel	1740	5
Elements of slide rest	1741	5
Automatic ribbon loom	1745	5
Carding machine	1748	5
Fantail for windmill	1750	3
Successful chronometer	(say) 1766	5
Spinning jenny	1768	5
Arkwright's water frame	1769	5
Watt's first patent (1776)	1769	5
Wilkinson's improved cylinder borer	1775	5
Reverberatory puddling furnace (1784)	1776	2
Watt's first engine (1769)	1776	5
Crompton's mule	1779	5
Compound steam-engine (1804)	1781	2
Watt's rotative engine	1781	10
Seed drill (1730)	1782	4
Watt's double-acting expansive engine	1782	5
Balloon	1783	5
Cotton-printing machine	1783	5

Invention	Date A.D.	Score
Cort's perfected rolling - mill (1425, 1700)	1784	2
Perfected puddling in reverberatory furnace(1776)	1784	3
Attempted interchangeable manufacture (1800)	1785	1
First really useful thresher (Meikle)	1786	5
Cartwright's power loom (1821)	1787	2
Miller and Symington's steamship (1802, 1807)	1788	2
Cotton gin	1793	5
Maudslay improves lathe	1794f	10
Hydraulic press	1796	5
Trevithick's road locomotive(1825)	1797	2
Breast waterwheel (say)	1799	5
Whitney's interchangeable manufacture (1785)	1800	9
Charlotte Dundas (1788, 1807)	1802	3
High - presure-steam-engine	1802	5
Trevithick's rail engine (1811, 1814, 1829)	1803	1
Compound engine reintroduced (1781)	1804	3
Jacquard loom	1804	5
Fulton's *Clermont* (1788, 1802)	1807	5
Considerable development of railway locomotives (1803, 1814, 1829)	1811	3
Stephenson's first locomotive (1803, 1811, 1829)	1814	2
Centrifugal pump in practice (1680)	1818	4
Milling machine	1818	10
Lathe for irregular turning	1818	5
Planing machine (say)	1820	10
First practical calculating machine, Thomas de Colmar (1892)	1820	1
Horrocks perfects power loom (1787)	1821	3
Brown's internal combustion engine—first to be used in practice (1838, 1860, 1867, 1876)	1823	1

Invention	Date A.D.	Score
Successful steam carriages (1797)	c. 1825	3
Automatic spinning mule	1825	5
Bell's reaper; first (moderately) successful (1831, 1834)	1826	1
Water turbine	1827	10
Hot blast in smelting	1828	5
'Rocket' (1803, 1811, 1814)	1829	4
Ring spinning	1830	5
Manning's reaper (1826, 1834)	1831	1
Electric bell	1831	1
Pixii's electric generator (1835, 1845, 1865, 1870, 1882, 1883)	1832	1
McCormick's reaper (1826, 1831)	1834	3
Primary accomplishments in drop-forging, die-stamping, etc.	c. 1835	5
Commutator (1832, 1845, 1865, 1870, 1882, 1883)	1835	2
Colt's revolver	1835	2
Screw propeller	(say) 1836	5
Telegraph	1837	10

Invention	Date A.D.	Score
Barnett gas engine (1823, 1860, 1867, 1876)	1838	1
Steam-hammer	1839	5
Practical arc lamp	1844	5
Electro-magnets in generator (1832, 1835, 1865, 1870, 1882, 1883)	1845	2
Rotary printing press	1845	5
Turret lathe	c. 1845	10
Howe's sewing machine	1846	5
Compressed air in mining	1849	5
Cable ploughing	1850	5
Combing machine	1850	5
Cylindrical grinder (1864)	c. 1850	2
Haymaking, changeover to machine and horse-rake	c. 1850	5
First true disc-type coal-cutter (1868, 1875)	1852	1
Practical maize planter	1853	5
Aluminium factory (1886)	1855	2
Bessemer steel	1856	10

Invention	Date A.D.	Score
First bar-type coal-cutter (1885, 1895)	1856	1
Two-horse straddle-row cultivator	1856	5
First commercially successful gas-engine, Lenoir (1823, 1838, 1867, 1876)	1860	2
Combine harvester (1875)	1860f.	1
Universal milling machine	1861	5
Machine gun	1861	2
First commercial grinder (1850)	1864	3
Improved winding in generator (1832, 1835, 1845, 1870, 1882, 1883)	1865	2
Open-hearth steel	1867	5
Early Otto gas-engine (1823, 1838, 1860, 1876)	1867	2
Combine seed drill	1867	5
Practical typewriter	1868	5
Fairly successful disc coal-cutter (1852, 1875)	1868	1

Invention	Date A.D.	Score
Early gyro-tiller (1930)	1868	1
First practical chain-type coal-cutter (1901)	1869	1
Refrigerator begins to come into practice (1873)	c. 1870	2
Automatic lathe	(say) 1870	10
Gramme's ring armature (1832, 1835, 1845, 1865, 1882, 1883)	1870	2
Electric furnace for steel	1870	5
Mushet's tool-steel	1871	10
Linde's ammonia compression refrigerator (1870)	1873	3
First petroleum engine (1885)	1873	3
Essentially modern disc-type coal-cutter (1852, 1868)	1875	3
Combine harvesters spread (1860)	c. 1875	4
Otto's Silent Gas-engine (1823, 1838, 1860, 1867)	1876	4
Telephone	1876	10
Basic Bessemer process	1877	5

Invention	Date A.D.	Score
Phonograph (1887)	1877	1
Benz's motor-car (1889)	1878	1
Basic open-hearth process	1878	5
Sheaf - binding harvester	1878	5
Incandescent electric lamp	1880	5
Public electric lighting	1881	5
Almost perfected electric generator (1832, 1835, 1845, 1865, 1870, 1883)	1882	4
Alloy steels, for armaments only (1910)	1882f.	2
Carbon brush for generators (1832, 1835, 1845, 1865, 1870, 1882)	1883	1
Steam turbine	1884	10
Daimler's petrol engine (1873)	1885	7
Duprez, pioneeringon long-distance transmission of electricity (1887, 1889)	(say) 1885	3
Improved bar-type coal-cutter (1856, 1895)	1885	1

Invention	Date A.D.	Score
Electricity in mining	1885	3
Developmentof heavy oil engine	c. 1885	5
Electric welding	1886	5
Electrolytic aluminium (1855)	1886	5
Poly-phase electricity (1885, 1889)	1887	3
Automatic telephone (1920)	1887	1
Gramophone and auxiliary processes (1877)	1887	4
Dunlop tyre	1889	5
Motor-car (1878)	1889	4
Ferranti's H.T. generation (1885, 1887)	1889	4
Tractor with internal combustion engine (1914)	1890	1
Multi - spindle lathe	(say) 1890f.	5
Diesel's main patent (1897)	1892	4
Northrop loom	1892	5
Brunsviga calculating machine (1820)	1892	4
Abrasives from electric furnace	1893	5
Linde's liquid air plant	1895	5

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Invention	Date A.D.	Score
Cinematograph (say)	1895	5
Essentially modern bar-type coal-cutter (1856, 1885)	1895	3
Radio telegraphy	1896	10
Swathe-turner (haymaking)	1896	3
Turbinia	1897	5
Diesel's first engine (1892)	1897	6
High-speed tool-steel	1898	10
Submarine (say)	1898	5
Fessenden's radio telephony (1914, 1918, 1920)	1900	1
Zeppelin's airship	1900	5
Oxygen cutting and welding (say)	1900	5
Magnetic recording (1924, 1933)	1900	1
Percussive coal-cutter	1901	5
Modern chain-type coal-cutter (1869)	1901	4
Scraper conveyor in mining	1902	5
Claude's liquid air plant	1902	5
Aeroplane	1903	10
Convertible swathe-turner and side-delivery rake in haymaking	1903	3
Coal loader, early step (1922)	1903	1
Thermionic valve (1906)	1904	5
Band conveyor in mining	1905	5
Triode valve (1904)	1906	5
Lauste's 'talkie' patent (1923, 1928)	1906	1
Radio picture telegraphy (1926)	1907	2
Radio direction finding	1907	3
Thermit welding	1908	5
Duralumin	1909	5
Alloy steel spread into general use (1882)	c. 1910	3
Crude television (1926, 1937)	1911	1
Conveyor belt mass-production	1913f.	10
Jigger-type conveyor in mining	1913	5
Early hydraulic coal-burster (1936)	1913	1
Tractor spreads in practice (1890)	c. 1914	4
Radio telephone on way to practical (1900, 1918, 1920)	1914	2

Invention	Date A.D.	Score
Magnesium from brine	1915	5
Tank	1916	5
Centreless grinding (1928)	1916	2
Various aircraft developments during war	(say) 1916	5
Various radio developments during war	(say) 1916	5
Various machine shop developments during war	(say) 1916	5
Radio telephony established (1900, 1914, 1920)	1918	4
Handley - Page slot (aircraft)	1919	3
Broadcasting (1900, 1914, 1918)	1920f.	3
Centrifugal casting	1920	5
Automatic telephone in use (1887)	1920	4
Commercial application of coal - loader begins (1903)	c. 1922	4
Pumpless absorption refrigerator	1923	5
De Forest's 'talkie' patent (1906, 1928)	1923	3
Beam radio	1924	5
Electric recording for gramophone	1924	3
Stille's work on magnetic recording (1900, 1933)	1924f.	2
First patent for variable pitch airscrew (1934)	1924	2
Autogyro	c. 1925	5
Tungsten carbide tools	c. 1926	10
Transoceanic radio picture telegraphy (1907)	1926	3
Baird's television (1911, 1937)	1926	3
Quality control, limited development (1941)	1926f.	2
Centreless grinder in general practice (1916)	c. 1928	3
First 'talkie' (1906, 1923)	1928	1
Modern gyro-tiller (1868)	c. 1930	4
Improved magnetic recording (1900, 1924)	1933	2
Early developments in stereo cinema (1938)	1934	1U

Invention	Date	Score
Variable pitch airscrew problem solved (1924)	c. 1934	3
Gas - turbine, some progress (1939)	c. 1935	3
Heat-and-power electricity generation	(say) 1935	7U
Beginning of radio-location (1940, 1943)	1935	2
Cotton - picker (partial) success	1936	3U and 2
Hydraulic coal-burster(1913)	1936	4
'Emitron' television (1911, 1926)	1937	1
Combine coal cutter-loaders (value not yet proven)	c. 1937	2
Hydro-mechanical mining	1937	5U
Whittle's successful jet engines (1941)	1937	3
Principle of flying bomb engine (1943)	1938	1
Helicopter, partial successes (1941)	c. 1938	3
Underground gasification of coal	c. 1938	5U
Developed stereo-cinema (1934)	c. 1938	4U
Significant development of gas-turbine (1935)	c. 1939	7
Kapitza's turbine refrigerator	1939	5U
Radio-location, further development(1935, 1943)	1940	3
Helicopter, full success(1938)	c. 1941	7
Jet - propelled aeroplane (1937)	1941	7
Quality control, full development (1926)	c. 1941	8
Flying bomb engine (1938)	1943	4
Radar developments over a wide field (1935, 1940)	c. 1943	5
Release of atomic energy	1943	10

For the twentieth century certain adjustments are made to compensate for errors inherent in this way of presenting the list. These are explained in (8) page 223. The meaning of the 'U' which follows certain scores is explained in (11) page 225.

(3) *Critique of the Significance of Deductions made from the List.* The most obvious weakness of this list is that it is not complete. Apart from the author's own incomplete knowledge, there are many critical steps in technical history which the historian and archæologist have not yet elucidated. It is conceivable that the omissions might be systematic to such an extent that they would upset the general forms of Figures 51 and 52, and therefore invalidate conclusions drawn from them. But at most points of the curve it would require a very heavy concentration of omissions to have a significant effect—a heavier concentration than seems likely. In two places, however, the danger is perhaps big enough to be significant: (i) in the Iron Age down to Roman times, where archæological investigation has not been so thorough as for the Bronze Age (a particular case of doubt is noted in (6) page 222), and (ii) in the last half century, where a foreshortening of perspective might seriously affect the matter of omissions. In the latter case, we take certain special precautions, as described in (8) page 223.

There are very great difficulties in comparing the values of inventions separated by, say, a millennium or more in time. Further, as mentioned in (1), the choice of the initial score at 5500 B.C. also affects the relative heights of the curves at widely different times. Thus, although we have made some deductions from the relative heights of the curve of Figure 50 at widely different times, these should be viewed with caution. On the other hand, the difficulties in comparing inventions chronologically close to one another are much smaller. Thus the fact that the curve is rising or falling at a particular point and the rate of rise or fall are likely to be significant, as are comparisons of the heights of the curve over periods of two or three centuries; so deductions made from these properties of the curves bear a greater weight. The choice of the initial score at 5500 B.C. has little effect on these latter considerations.

(4) Figure 51 is the graph of $100 \frac{d}{dt}(log y) = 100 \frac{dy}{dt}\Big/ y$ against t, where y is the score of inventions up to time t. The curve has been smoothed to eliminate wobbles which do not appear to be significant, but merely to represent inevitable accidents affecting invention, or where dates are not accurately known.

(5) The statement marked (5) in the text is, of course, only true if the law of growth is that the rate of growth, $\frac{dy}{dt}$, is *proportional* to the score y. It might be proportional to y^2, $\sqrt{y}$, etc. But the law $\frac{dy}{dt} \propto y$ is the simplest law of growth and is normally assumed to be the true one unless there is evidence to the contrary. Some further evidence that this is the appropriate law against which to analyse the rate of invention is given by the fact that the main peaks of Figure 51 before 1700, representing the periods of least restricted advance, are very roughly of equal heights.

(6) The decline at E is the most doubtful point on the graph. We know of no important invention between 400 and 300 B.C. But the period has not yet been well investigated archæologically, so that there may be important omissions here. It is rather unlikely that the drop at E would be entirely eliminated by fuller knowledge, but it might be very greatly diminished.

(7) If the figures calculated from our score sheet are literally interpreted, this decline would be very much more violent. The maximum height at I would then be ·120 and

the minimum at J would be ·031, and there would be violent oscillations between I and K. However, detailed examination of the list appears to indicate that accidental factors may have accentuated the decline, and that it is best to interpret it cautiously as in the graph. The calculations do, however, make it quite clear that after the hesitation it is just about 1700 that the relative invention rate shoots up rapidly and without hesitation.

(8) There are special difficulties in ensuring that our list of inventions adequately represents the history of the last fifty years. When the decline remarked on in the text became obvious, we reallocated the score in the modern period on a specially 'generous' basis, in order to ensure that the bias, if any, should be against the conclusions that we draw—i.e. that the conclusions should stand up to the test of having the evidence heavily weighted against them. Thus items like the hydraulic coal-burster, electrical recording for the gramophone, and the various steps in magnetic recording are given points, although it is extremely doubtful if they should rank as inventions of fundamental importance in the sense in which that term has been interpreted for earlier periods.

In addition there are a number of trends in modern times which do not express themselves as inventions in a clear-cut sense, but rather as gradual improvements. As this is partly a sign of changed conditions of progress, and as the results of some of these trends do add up in the long run to effects equivalent to those of fundamental inventions, we felt it necessary to make some allowance for them. This is done, as in the appended table, by allowing a score for each trend, and distributing it over the period 1900–44 in the way that seems best to fit the general impression one receives of each trend. The points thus obtained have been added to those of the main table (2), before calculating the relative invention rate for the modern period.

Trend	Total score	Distribution of score				
		1900–10	1910–20	1920–30	1930–39	1939–44
Use of photo-electric cell and similar devices for the automatic control of machinery .	15		1	3	8	3
Miscellaneous advances and refinements in machine tools, other than those listed in (2), (especially those arising from mass-production of motor-cars)	10		3	2	2	3
Cumulative improvements in agricultural machinery, other than as listed in (2) (especially machinery for planting and harvesting roots and miscellaneous crops)	15	2	3	3	3	4
Further developments of light alloys after 1909 . .	5		1	1	2	1
Plastics developments . .	10	1	1	3	3	2
Aircraft advances, other than those listed in (2), (e.g. application of supercharger) .	5			2	2	1
Totals	60	3	9	14	20	14

The curve of Figure 52 has again been smoothed to eliminate minor peaks and hollows of no significance. But actually in this case there was little smoothing to be done; and after 1870 the curve actually passes through all the points obtained by calculating the relative invention rate over ten-year periods.

(9) It should be noted that it makes very little difference to the shape of the curve over so short a period as 150 years

if we graph the simple invention rate $\frac{dy}{dt}$, instead of the relative invention rate. The whole curve is pushed upwards slightly towards the right. The decline after 1900 becomes a little less pronounced, but just as obviously real. We emphasize this, lest anybody should think that the decline after 1900 arises from the use of the *relative* invention rate.

(10) Among those who have noted declines in invention in recent times are C. C. Furnas in *The Next Hundred Years* (London, 1936), pp. 292–4; the U.S. Government document, *Technology in Our Economy* (Washington, 1941), pp. 184–5; and more vaguely, Corrington Gill in *Unemployment and Technological Change* (Washington, 1940), another U.S. Government document. G. Sarton in *The Study of the History of Science* (Cambridge, Mass., 1936) reached a similar conclusion for science in general, but more tentatively and (we think) on less certain evidence.

(11) The scores which are thus used for the broken curve in Figure 52 but not for the continuous curve are those marked 'U' in Table (2) pages 219–20. We emphasize that we are not here concerned with the place of invention, but only with the question of its use to a significant extent. In this connection the reader who is interested might make a similar comparison between England and the rest of the world between 1640 and 1800 (in this case the place of invention is the easier criterion to use). This gives an even more striking example of the concentration of technical progress in a country which, ahead of the rest, has made appropriate social changes.

(12) Although all the wartime inventions we have recorded are dated 1943 or earlier (the release of atomic energy was achieved in 1943, though the bomb did not fall till 1945), we have nevertheless calculated on the basis that

they occupied the *five* years, 1939–44. If one reduces the period to four years, the relative invention rate is raised to about ·94 for 1941.

The graph also shows a similar, but less pronounced, tendency for the decline in the invention rate to be arrested during the first World War. Though the 1914–18 War produced remarkable developments in certain fields of applied science (e.g. chemicals and surgery), its effects were much less marked than those of 1939–45, and particularly so in mechanical matters. Even those mechanical developments which did tend to arrest the decline were not so much new inventions as very rapid developments in such matters as flying and radio, which amounted in effect to inventions. *One* obvious reason why the first World War had so much less effect on the invention rate than did the second is that in it the subjection of private interests to those of the nation as a whole was much less thorough.

SUGGESTIONS FOR FURTHER READING

A comprehensive bibliography of the subject would necessarily contain many books in foreign languages and references to periodicals which are not generally available. The list below merely indicates some of the more easily available works in English which are not of a highly technical nature. A few more works will be found in footnote references to the text.

A. P. Usher: *A History of Mechanical Inventions* (New York, 1929) covers the history of most of the main types of machinery (but not of manual tools) from classical times till about the end of the nineteenth century. It contains an excellent bibliography of ten pages, which will enable the reader to follow up particular interests. A. P. M. Fleming, and H. J. Brocklehurst: *A History of Engineering* (London, 1925) covers approximately the same period, but deals to some extent with different topics.

Both these books neglect the history of pre-classical times and are rather weak on classical times. For a first approach to these periods one can do no better than begin with two of V. Gordon Childe's books: *What Happened in History* (London, 1942), which deals with general social history till the end of Roman times, putting tools and machines, as well as other aspects of science and technology, in their social setting; and *The Story of Tools* (London, 1944), an excellent brief sketch of the evolution of tools and machines to the end of classical times (with a few words on later periods), particularly valuable for its sixty-odd illustrations. H. Peake: *Early Steps in Human Progress* (London, n.d.) consists of a series of chapters dealing separately with various techniques from the earliest times to the early Iron Age, with comparisons with modern primitive peoples. There is a vast amount of interesting detail on early techniques and a wealth of illustration in A. Neuburger: *The Technical Arts and Sciences of the Ancients* (London, 1930), but this book should be used with caution, as it contains a rather large number of errors and lacks historical perspective.

For other particular periods the following works are useful:

A. Wolf's two books: *A History of Science, Technology and Philosophy in the Sixteenth and Seventeenth Centuries* (London, 1935), and *A History of Science, Technology and Philosophy in the Eighteenth Century* (London, 1938) both contain excellent chapters on mechanical matters and are very well illustrated.

E. Cressy: *A Hundred Years of Mechanical Engineering* (London, 1937) covers, in spite of its title, the period from the later eighteenth century till about 1930.

For recent times works which cover the whole field in a fully satisfactory way are, naturally enough, not available. E. Cressy: *Discoveries and Inventions of the Twentieth Century* (3rd edition, London, 1930) contains a lot of interesting information, but is not fully satisfactory; in any case, it is not now up to date. In the past ten years the Government of the U.S.A. has produced a series of interesting reports on technical and related matters, of which the most outstanding is *Technological Trends* (Washington, 1937). This considers the main technical developments of the last few decades in relation to their social implications; it also contains an historical chapter on resistances to technical progress. Some of the other American documents have already been mentioned in footnotes. In the last few years the British Government has also begun to issue reports on technical matters, of which two are particularly important. First, *Coal-Mining: Report of the Technical Advisory Committee* (Chairman, C. C. Reid) (London, H.M.S.O., 1945), which documents in detail the technical state of the British industry over the last few decades, with comparisons with other countries; and second, the *Report of the Cotton Textile Mission to the United States of America, March–April*, 1944 (Chairman, F. Platt) (London, H.M.S.O., 1944), giving a detailed comparison of British and American practice, with the emphasis largely on machinery.

For the history of machine tools, see J. W. Roe: *English and American Tool Builders* (New Haven, 1916). This covers the period from the later eighteenth century till about 1900 and contains a useful bibliography.

For the development of power machinery an excellent book is H. P. Vowles: *The Quest for Power* (London, 1931). It deals not only with power, but also with other mechanical developments that necessarily preceded and accompanied its development. There are many books on the steam-engine, a very useful example being H. W. Dickinson: *A Short History of the Steam Engine* (Cambridge, 1939), covering events from the sixteenth century almost to the date of publication.

A very readable short book on the coal industry, including much on its machinery, is D. H. Rowlands: *Coal—and All About It* (London, 1945). For recent times this can be supplemented with the Reid report referred to above.

For agriculture and its associated techniques in their earliest development see E. Cecil Curwen's *Plough and Pasture* (London 1947), Volume 4 in the Past and Present series.

M. J. B. Davy has written two excellent books on the history of flying: *Interpretive History of Flight* (London, 1937), and *Air Power and Civilisation* (London, 1941). They cover approximately the same material, the latter being rather the more 'popular' of the two.

The development and production of the atomic bomb as well as the scientific work that led up to it, is dealt with in *Atomic Energy*, by H. D. Smyth, the official U.S. Report on the subject (reprinted by H.M.S.O., 1945). The reader who has not had a scientific training will probably find this difficult to follow unless he prepares by reading first a simple account of atomic physics, such as A. K. Solomon: *Why Smash Atoms?* (London, 1946), which explains the subject largely in a historical way, ending with a discussion of atomic energy.

Information on mechanical developments in the U.S.S.R. is mostly to be found in scattered papers. A certain amount in very general terms is contained in *The U.S.S.R. Speaks for Itself* (London, 1943), while interesting articles on the subject have appeared in the quarterly periodical *The Anglo-Soviet Journal*.

Of books concerned with social aspects of mechanical invention in recent times, several have been mentioned in footnotes to Chapters IX and XI and in the Appendix (the fact that we take a particular quotation or fact from a book does not, of course, imply whole-hearted approval of the book as a whole—the reader must judge for himself the very varying quality of these works). On the subject of cartels, their effects on technical progress and their role in aiding the military expansion of Germany, see, besides the American reports mentioned in footnotes, Guenter Reimann: *Patents for Hitler* (London, 1945), and J. Borkin and C. A. Welsh: *Germany's Master Plan* (London, 1945).

J. B. Jefferys' *The Story of the Engineers* (London, 1946) presents the history of mechanical progress from 1800 onwards from the point of view of the engineering worker. It deals largely with Trade Union history, but puts this in its technical setting.

The Science Museum, South Kensington, has published a series of handbooks which in many cases form the best introductions to the history of particular subjects. A good example is G. F. Westcott: *Pumping Machinery*, Part I.—Historical Notes (London, H.M.S.O., 1932).

Biographies of particular engineers are far too numerous to mention here. They may be found in most library catalogues under the name of the biographee as well as the biographer. We may, however, single out Samuel Smiles: *The Lives of the Engineers*, 5 volumes (London, 1874, and popular edition 1904), a series of biographies of British engineers, both civil and mechanical, up to the early nineteenth century.

Many papers on the history of tools and machines are to be found in the *Transactions of the Newcomen Society*, a periodical devoted to the history of technology. Many of the engineering periodicals also contain from time to time articles on historical subjects, and they are, of course, essential to those who wish to bring their history right up to date. We do not intend to indicate an order of merit when we single out from the many such journals the following examples: *Engineering*, *The Engineer*, *Machinery*, *The Aeroplane*, *Flight*, and the recently begun Government journal, *Agricultural Engineering Record*, dealing with the work of the National Institute of Agricultural Engineering. There are also more 'learned' journals like the *Proceedings of the Institution of Mechanical Engineers*, which sometimes contain historical papers which are not highly technical. Of the many journals dealing with prehistoric and early historic times, the most suitable for the general reader is *Antiquity*. The monthly *Discovery* deals with science in general, both historical and current, and includes a proportion of articles on machinery—for example, Volume 6 (1945), pp. 281–90, contains an excellent account of the development of radar by Sir Robert Watson-Watt himself.

Finally it should be remembered that most public libraries are arranged on a classified system and that books on particular topics can usually be found by that means.

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