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ARTICLE  from the Encyclopædia Britannica

history of technology, the development over time of systematic techniques for making and doing things. The term technology, a combination of the Greek technē, "art, craft," with logos, "word, speech," meant in Greece a discourse on the arts, both fine and applied. When it first appeared in English in the 17th century, it was used to mean a discussion of the applied arts only, and gradually these "arts" themselves came to be the object of the designation. By the early 20th century, the term embraced a growing range of means, processes, and ideas in addition to tools and machines. By mid-century, technology was defined by such phrases as "the means or activity by which man seeks to change or manipulate his environment." Even such broad definitions have been criticized by observers who point out the increasing difficulty of distinguishing between scientific inquiry and technological activity.

A highly compressed account of the history of technology such as this one must adopt a rigorous methodological pattern if it is to do justice to the subject without grossly distorting it one way or another. The plan followed in the present article is primarily chronological, tracing the development of technology through phases that succeed each other in time. Obviously, the division between phases is to a large extent arbitrary. One factor in the weighting has been the enormous acceleration of Western technological development in recent centuries; Eastern technology is considered in this article in the main only as it relates to the development of modern technology.

Within each chronological phase a standard method has been adopted for surveying the technological experience and innovations. This begins with a brief review of the general social conditions of the period under discussion, and then goes on to consider the dominant materials and sources of power of the period, and their application to food production, manufacturing industry, building construction, transport and communications, military technology, and medical technology. In a final section the sociocultural consequences of technological change in the period are examined. This framework is modified according to the particular requirements of every period—discussions of new materials, for instance, occupy a substantial place in the accounts of earlier phases when new metals were being introduced but are comparatively unimportant in descriptions of some of the later phases—but the general pattern is retained throughout. One key factor that does not fit easily into this pattern is that of the development of tools. It has seemed most convenient to relate these to the study of materials, rather than to any particular application, but it has not been possible to be completely consistent in this treatment. Further discussion of specific areas of technological development is provided in a variety of other articles: for example, see electronics; exploration; information processing.
General considerations

Essentially, techniques are methods of creating new tools and products of tools, and the capacity for constructing such artifacts is a determining characteristic of manlike species. Other species make artifacts: bees build elaborate hives to deposit their honey, birds make nests, and beavers build dams. But these attributes are the result of patterns of instinctive behaviour and cannot be varied to suit rapidly changing circumstances. Humanity, in contrast with other species, does not possess highly developed instinctive reactions but does have the capacity to think systematically and creatively about techniques. Humans can thus innovate and consciously modify the environment in a way no other species has achieved. An ape may on occasion use a stick to beat bananas from a tree, but a man can fashion the stick into a cutting tool and remove a whole bunch of bananas. Somewhere in the transition between the two, the hominid, the first manlike species, emerges. By virtue of his nature as a toolmaker, man is therefore a technologist from the beginning, and the history of technology encompasses the whole evolution of humankind.

In using rational faculties to devise techniques and modify the environment, humankind has attacked problems other than those of survival and the production of wealth with which the term technology is usually associated today. The technique of language, for example, involves the manipulation of sounds and symbols in a meaningful way, and similarly the techniques of artistic and ritual creativity represent other aspects of the technological incentive. This article does not deal with these cultural and religious techniques, but it is valuable to establish their relationship at the outset because the history of technology reveals a profound interaction between the incentives and opportunities of technological innovation on the one hand and the sociocultural conditions of the human group within which they occur on the other.

Social involvement in technological advances

An awareness of this interaction is important in surveying the development of technology through successive civilizations. To simplify the relationship as much as possible, there are three points at which there must be some social involvement in technological innovation: social need, social resources, and a sympathetic social ethos. In default of any of these factors it is unlikely that a technological innovation will be widely adopted or be successful.

The sense of social need must be strongly felt, or people will not be prepared to devote resources to a technological innovation. The thing needed may be a more efficient cutting tool, a more powerful lifting device, a laboursaving machine, or a means of utilizing new fuels or a new source of energy. Or, because military needs have always provided a stimulus to technological innovation, it may take the form of a requirement for better weapons. In modern societies, needs have been generated by advertising. Whatever the source of social need, it is essential that enough people be conscious of it to provide a market for an artifact or commodity that can meet the need.

Social resources are similarly an indispensable prerequisite to a successful innovation. Many inventions have foundered because the social resources vital for their realization—the capital, materials, and skilled personnel—were not available. The notebooks of Leonardo da Vinci are full of ideas for helicopters, submarines, and airplanes, but few of these reached even the model stage because resources of one sort or another were lacking. The resource of capital involves the existence of surplus productivity and an organization capable of directing the available wealth into channels in which the inventor can use it. The resource of materials involves the availability of appropriate metallurgical, ceramic, plastic, or textile substances that can perform whatever functions a new invention requires of them. The resource of skilled personnel implies the presence of technicians capable of constructing new artifacts and devising novel processes. A society, in short, has to be well primed with suitable resources in order to sustain technological innovation.

A sympathetic social ethos implies an environment receptive to new ideas, one in which the dominant social groups are prepared to consider innovation seriously. Such receptivity may be limited to specific fields of innovation—for example, improvements in weapons or in navigational techniques—or it may take the form of a more generalized attitude of inquiry, as was the case among the industrial middle classes in Britain during the 18th century, who were willing to cultivate new ideas and inventors, the breeders of such ideas. Whatever the psychological basis of inventive genius, there can be no doubt that the existence of socially important groups willing to encourage inventors and to use their ideas has been a crucial factor in the history of technology.
Social conditions are thus of the utmost importance in the development of new techniques, some of which will be considered below in more detail. It is worthwhile, however, to register another explanatory note. This concerns the rationality of technology. It has already been observed that technology involves the application of reason to techniques, and in the 20th century it came to be regarded as almost axiomatic that technology is a rational activity stemming from the traditions of modern science. Nevertheless, it should be observed that technology, in the sense in which the term is being used here, is much older than science, and also that techniques have tended to ossify over centuries of practice or to become diverted into such para-rational exercises as alchemy. Some techniques became so complex, often depending upon processes of chemical change that were not understood even when they were widely practiced, that technology sometimes became itself a "mystery" or cult into which an apprentice had to be initiated like a priest into holy orders, and in which it was more important to copy an ancient formula than to innovate. The modern philosophy of progress cannot be read back into the history of technology; for most of its long existence technology has been virtually stagnant, mysterious, and even irrational. It is not fanciful to see some lingering fragments of this powerful technological tradition in the modern world, and there is more than an element of irrationality in the contemporary dilemma of a highly technological society contemplating the likelihood that it will use its sophisticated techniques in order to accomplish its own destruction. It is thus necessary to beware of overfacile identification of technology with the "progressive" forces in contemporary civilization.

On the other hand it is impossible to deny that there is a progressive element in technology, as it is clear from the most elementary survey that the acquisition of techniques is a cumulative matter, in which each generation inherits a stock of techniques on which it can build if it chooses and if social conditions permit. Over a long period of time the history of technology inevitably highlights the moments of innovation that show this cumulative quality as some societies advance, stage by stage, from comparatively primitive to more sophisticated techniques. But although this development has occurred and is still going on, it is not intrinsic to the nature of technology that such a process of accumulation should occur, and it has certainly not been an inevitable development. The fact that many societies have remained stagnant for long periods of time, even at quite developed stages of technological evolution, and that some have actually regressed and lost the accumulated techniques passed on to them, demonstrates the ambiguous nature of technology and the critical importance of its relationship with other social factors.

**Modes of technological transmission**

Another aspect of the cumulative character of technology that will require further investigation is the manner of transmission of technological innovations. This is an elusive problem, and it is necessary to accept the phenomenon of simultaneous or parallel invention in cases in which there is insufficient evidence to show the transmission of ideas in one direction or another. The mechanics of their transmission have been enormously improved in recent centuries by the printing press and other means of communication and also by the increased facility with which travelers visit the sources of innovation and carry ideas back to their own homes. Traditionally, however, the major mode of transmission has been the movement of artifacts and craftsmen. Trade in artifacts has ensured their widespread distribution and encouraged imitation. Even more important, the migration of craftsmen—whether the itinerant metalworkers of early civilizations or the German rocket engineers whose expert knowledge was acquired by both the Soviet Union and the United States after World War II—has promoted the spread of new technologies.

The evidence for such processes of technological transmission is a reminder that the material for the study of the history of technology comes from a variety of sources. Much of it relies, like any historical examination, on documentary matter, although this is sparse for the early civilizations because of the general lack of interest in technology on the part of scribes and chroniclers. For these societies, therefore, and for the many millennia of earlier unrecorded history in which slow but substantial technological advances were made, it is necessary to rely heavily upon archaeological evidence. Even in connection with the recent past, the historical understanding of the processes of rapid industrialization can be made deeper and more vivid by the study of "industrial archaeology." Much valuable material of this nature has been accumulated in museums, and even more remains in the place of its use for the observation of the field worker. The historian of technology must be prepared to use all these sources, and to call upon the skills of the archaeologist, the engineer, the architect, and other specialists as appropriate.

**Technology in the ancient world**
The beginnings—Stone Age technology (to c. 3000 bce)

The identification of the history of technology with the history of humanlike species does not help in fixing a precise point for its origin, because the estimates of prehistorians and anthropologists concerning the emergence of human species vary so widely. Animals occasionally use natural tools such as sticks or stones, and the creatures that became human doubtless did the same for hundreds of millennia before the first giant step of fashioning their own tools. Even then it was an interminable time before they put such toolmaking on a regular basis, and still more aeons passed as they arrived at the successive stages of standardizing their simple stone choppers and pounders and of manufacturing them—that is, providing sites and assigning specialists to the work. A degree of specialization in toolmaking was achieved by the time of the Neanderthals (70,000 bce); more-advanced tools, requiring assemblage of head and haft, were produced by Cro-Magnons (perhaps as early as 35,000 bce); while the application of mechanical principles was achieved by pottery-making Neolithic (New Stone Age; 6000 bce) and Metal Age peoples (about 3000 bce).

Earliest communities

For all except approximately the past 10,000 years, humans lived almost entirely in small nomadic communities dependent for survival on their skills in gathering food, hunting and fishing, and avoiding predators. It is reasonable to suppose that most of these communities developed in tropical latitudes, especially in Africa, where climatic conditions are most favourable to a creature with such poor bodily protection as humans have. It is also reasonable to suppose that tribes moved out thence into the subtropical regions and eventually into the landmass of Eurasia, although their colonization of this region must have been severely limited by the successive periods of glaciation, which rendered large parts of it inhospitable and even uninhabitable, even though humankind has shown remarkable versatility in adapting to such unfavourable conditions.

The Neolithic Revolution

Toward the end of the last ice age, some 15,000 to 20,000 years ago, a few of the communities that were most favoured by geography and climate began to make the transition from the long period of Paleolithic, or Old Stone Age, savagery to a more settled way of life depending on animal husbandry and agriculture. This period of transition, the Neolithic Period, or New Stone Age, led eventually to a marked rise in population, to a growth in the size of communities, and to the beginnings of town life. It is sometimes referred to as the Neolithic Revolution because the speed of technological innovation increased so greatly and human social and political organization underwent a corresponding increase in complexity. To understand the beginnings of technology, it is thus necessary to survey developments from the Old Stone Age through the New Stone Age down to the emergence of the first urban civilizations about 3000 bce.

Stone

The material that gives its name and a technological unity to these periods of prehistory is stone. Though it may be assumed that primitive humans used other materials such as wood, bone, fur, leaves, and grasses before they mastered the use of stone, apart from bone antlers, presumably used as picks in flint mines and elsewhere, and other fragments of bone implements, none of these has survived. The stone tools of early humans, on the other hand, have survived in surprising abundance, and over the many millennia of prehistory important advances in technique were made in the use of stone. Stones became tools only when they were shaped deliberately for specific purposes, and, for this to be done efficiently, suitable hard and fine-grained stones had to be found and means devised for shaping them and particularly for putting a cutting edge on them. Flint became a very popular stone for this purpose, although fine sandstones and certain volcanic rocks were also widely used. There is much Paleolithic evidence of skill in flaking and polishing stones to make scraping and cutting tools. These early tools were held in the hand, but gradually ways of protecting the hand from sharp edges on the stone, at first by wrapping one end in fur or grass or setting it in a wooden handle, were devised. Much later the technique of fixing the stone head to a haft converted these hand tools into more versatile tools and weapons.

With the widening mastery of the material world in the Neolithic Period, other substances were brought into service, such as clay for pottery and brick, and increasing competence in handling textile raw materials led to the creation of the first woven
fabrics to take the place of animal skins. About the same time, curiosity about the behaviour of metallic oxides in the presence of fire promoted one of the most significant technological innovations of all time and marked the succession from the Stone Age to the Metal Age.

Power

The use of fire was another basic technique mastered at some unknown time in the Old Stone Age. The discovery that fire could be tamed and controlled and the further discovery that a fire could be generated by persistent friction between two dry wooden surfaces were momentous. Fire was the most important contribution of prehistory to power technology, although little power was obtained directly from fire except as defense against wild animals. For the most part, prehistoric communities remained completely dependent upon manpower, but, in making the transition to a more settled pattern of life in the New Stone Age, they began to derive some power from animals that had been domesticated. It also seems likely that by the end of prehistoric times the sail had emerged as a means of harnessing the wind for small boats, beginning a long sequence of developments in marine transport.

Tools and weapons

The basic tools of prehistoric peoples were determined by the materials at their disposal. But once they had acquired the techniques of working stone, they were resourceful in devising tools and weapons with points and barbs. Thus, the stone-headed spear, the harpoon, and the arrow all came into widespread use. The spear was given increased impetus by the spear thrower, a notched pole that gave a sling effect. The bow and arrow were an even more effective combination, the use of which is clearly demonstrated in the earliest "documentary" evidence in the history of technology, the cave paintings of southern France and northern Spain, which depict the bow being used in hunting. The ingenuity of these primitive hunts was also shown in their slings, throwing-sticks (the boomerang of the Australian Aborigines is a remarkable surviving example), blowguns, bird snares, fish and animal traps, and nets. These tools did not evolve uniformly, as each primitive community developed only those instruments that were most suitable for its own specialized purposes, but all were in use by the end of the Stone Age. In addition, the Neolithic Revolution had contributed some important new tools that were not primarily concerned with hunting. These were the first mechanical applications of rotary action in the shape of the potter's wheel, the bow drill, the pole lathe, and the wheel itself. It is not possible to be sure when these significant devices were invented, but their presence in the early urban civilizations suggests some continuity with the late Neolithic Period. The potter's wheel, driven by kicks from the operator, and the wheels of early vehicles both gave continuous rotary movement in one direction. The drill and the lathe, on the other hand, were derived from the bow and had the effect of spinning the drill piece or the workpiece first in one direction and then in the other.

Developments in food production brought further refinements in tools. The processes of food production in Paleolithic times were simple, consisting of gathering, hunting, and fishing. If these methods proved inadequate to sustain a community, it moved to better hunting grounds or perished. With the onset of the Neolithic Revolution, new food-producing skills were devised to serve the needs of agriculture and animal husbandry. Digging sticks and the first crude plows, stone sickles, querns that grind grain by friction between two stones and, most complicated of all, irrigation techniques for keeping the ground watered and fertile—all these became well established in the great subtropical river valleys of Egypt and Mesopotamia in the millennia before 3000 bce.

Building techniques

Prehistoric building techniques also underwent significant developments in the Neolithic Revolution. Nothing is known of the building ability of Paleolithic peoples beyond what can be inferred from a few fragments of stone shelters, but in the New Stone Age some impressive structures were erected, primarily tombs and burial mounds and other religious edifices, but also, toward the end of the period, domestic housing in which sun-dried brick was first used. In northern Europe, where the Neolithic transformation began later than around the eastern Mediterranean and lasted longer, huge stone monuments, of which Stonehenge in England is the outstanding example, still bear eloquent testimony to the technical skill, not to mention the imagination and mathematical competence, of the later Stone Age societies.
Manufacturing

Manufacturing industry had its origin in the New Stone Age, with the application of techniques for grinding corn, baking clay, spinning and weaving textiles, and also, it seems likely, for dyeing, fermenting, and distilling. Some evidence for all these processes can be derived from archaeological findings, and some of them at least were developing into specialized crafts by the time the first urban civilizations appeared. In the same way, the early metalworkers were beginning to acquire the techniques of extracting and working the softer metals, gold, silver, copper, and tin, that were to make their successors a select class of craftsmen. All these incipient fields of specialization, moreover, implied developing trade between different communities and regions, and again the archaeological evidence of the transfer of manufactured products in the later Stone Age is impressive. Flint arrowheads of particular types, for example, can be found widely dispersed over Europe, and the implication of a common locus of manufacture for each is strong.

Such transmission suggests improving facilities for transport and communication. Paleoolithic people presumably depended entirely on their own feet, and this remained the normal mode of transport throughout the Stone Age. Domestication of the ox, the donkey, and the camel undoubtedly brought some help, although difficulties in harnessing the horse long delayed its effective use. The dugout canoe and the birch-bark canoe demonstrated the potential of water transport, and, again, there is some evidence that the sail had already appeared by the end of the New Stone Age.

It is notable that the developments so far described in human prehistory took place over a long period of time, compared with the 5,000 years of recorded history, and that they took place first in very small areas of the Earth’s surface and involved populations minute by modern criteria. The Neolithic Revolution occurred first in those parts of the world with an unusual combination of qualities: a warm climate, encouraging rapid crop growth, and an annual cycle of flooding that naturally regenerated the fertility of the land. On the Eurasian-African landmass such conditions occur only in Egypt, Mesopotamia, northern India, and some of the great river valleys of China. It was there, then, that men and women of the New Stone Age were stimulated to develop and apply new techniques of agriculture, animal husbandry, irrigation, and manufacture, and it was there that their enterprise was rewarded by increasing productivity, which encouraged the growth of population and triggered a succession of sociopolitical changes that converted the settled Neolithic communities into the first civilizations. Elsewhere the stimulus to technological innovation was lacking or was unrewarded, so that those areas had to await the transmission of technical expertise from the more highly favoured areas. Herein is rooted the separation of the great world civilizations, for while the Egyptian and Mesopotamian civilizations spread their influence westward through the Mediterranean and Europe, those of India and China were limited by geographical barriers to their own hinterlands, which, although vast, were largely isolated from the mainstream of Western technological progress.

The Urban Revolution (c. 3000–500 bce)

The technological change so far described took place very slowly over a long period of time, in response to only the most basic social needs, the search for food and shelter, and with few social resources available for any activity other than the fulfillment of these needs. About 5,000 years ago, however, a momentous cultural transition began to take place in a few well-favoured geographical situations. It generated new needs and resources and was accompanied by a significant increase in technological innovation. It was the beginning of the invention of the city.

Craftsmen and scientists

The accumulated agricultural skill of the New Stone Age had made possible a growth in population, and the larger population in turn created a need for the products of specialized craftsmen in a wide range of commodities. These craftsmen included a number of metalworkers, first those treating metals that could be easily obtained in metallic form and particularly the soft metals, such as gold and copper, which could be fashioned by beating. Then came the discovery of the possibility of extracting certain metals from the ores in which they generally occur. Probably the first such material to be used was the carbonate of copper known as malachite, then already in use as a cosmetic and easily reduced to copper in a strong fire. It is impossible to be precise about the time and place of this discovery, but its consequences were tremendous. It led to the search for other metallic ores, to the development of metallurgy, to the encouragement of trade in order to secure specific metals, and to the further development of specialist skills. It contributed substantially to the emergence of
urban societies, as it relied heavily upon trade and manufacturing industries, and thus to the rise of the first civilizations. The Stone Age gave way to the early Metal Age, and a new epoch in the story of humankind had begun.

By fairly general consent, civilization consists of a large society with a common culture, settled communities, and sophisticated institutions, all of which presuppose a mastery of elementary literacy and numeration. Mastery of the civilized arts was a minority pursuit in the early civilizations, in all probability the carefully guarded possession of a priestly caste. The very existence of these skills, however, even in the hands of a small minority of the population, is significant because they made available a facility for recording and transmitting information that greatly enlarged the scope for innovation and speculative thought.

Hitherto, technology had existed without the benefit of science, but, by the time of the first Sumerian astronomers, who plotted the motion of the heavenly bodies with remarkable accuracy and based calculations about the calendar and irrigation systems upon their observations, the possibility of a creative relationship between science and technology had appeared. The first fruits of this relationship appeared in greatly improved abilities to measure land, weigh, and keep time, all practical techniques, essential to any complex society, and inconceivable without literacy and the beginnings of scientific observation. With the emergence of these skills in the 3rd millennium BCE, the first civilizations arose in the valleys of the Nile and of the Tigris-Euphrates.

**Copper and bronze**

The fact that the era of the early civilizations coincides with the technological classification of the Copper and Bronze ages is a clue to the technological basis of these societies. The softness of copper, gold, and silver made it inevitable that they should be the first to be worked, but archaeologists now seem to agree that there was no true “Copper Age,” except perhaps for a short period at the beginning of Egyptian civilization, because the very softness of that metal limited its utility for everything except decoration or coinage. Attention was thus given early to means of hardening copper to make satisfactory tools and weapons. The reduction of mixed metallic ores probably led to the discovery of alloying, whereby copper was fused with other metals to make bronze. Several bronzes were made, including some containing lead, antimony, and arsenic, but by far the most popular and widespread was that of copper and tin in proportions of about 10 to 1. This was a hard yellowish metal that could be melted and cast into the shape required. The bronze smiths took over from the coppersmiths and goldsmiths the technique of heating the metal in a crucible over a strong fire and casting it into simple clay or stone molds to make axheads or spearheads or other solid shapes. For the crafting of hollow vessels or sculpture, they devised the so-called cire perdue technique, in which the shape to be molded is formed in wax and set in clay, the wax then being melted and drained out to leave a cavity into which the molten metal is poured.

Bronze became the most important material of the early civilizations, and elaborate arrangements were made to ensure a continuous supply of it. Metals were scarce in the alluvial river valleys where civilization developed and therefore had to be imported. This need led to complicated trading relationships and mining operations at great distances from the homeland. Tin presented a particularly severe problem, as it was in short supply throughout the Middle East. The Bronze Age civilizations were compelled to search far beyond their own frontiers for sources of the metal, and in the process knowledge of the civilized arts was gradually transmitted westward along the developing Mediterranean trade routes.

In most aspects other than the use of metals, the transition from the technology of the New Stone Age to that of early civilizations was fairly gradual, although there was a general increase in competence as specialized skills became more clearly defined, and in techniques of building there were enormous increases in the scale of enterprises. There were no great innovations in power technology, but important improvements were made in the construction of furnaces and kilns in response to the requirements of the metalworkers and potters and of new artisans such as glassworkers. Also, the sailing ship assumed a definitive shape, progressing from a vessel with a small sail rigged in its bows and suitable only for sailing before the prevailing wind up the Nile River, into the substantial oceangoing ship of the later Egyptian dynasties, with a large rectangular sail rigged amidships. Egyptian and Phoenician ships of this type could sail before the wind and across the wind, but for making headway into the wind they had to resort to manpower. Nevertheless, they accomplished remarkable feats of navigation, sailing the length of the Mediterranean and even passing through the Pillars of Hercules into the Atlantic.
Irrigation

Techniques of food production also showed many improvements over Neolithic methods, including one outstanding innovation in the shape of systematic irrigation. The civilizations of Egypt and Mesopotamia depended heavily upon the two great river systems, the Nile and the Tigris-Euphrates, which both watered the ground with their annual floods and rejuvenated it with the rich alluvium they deposited. The Nile flooded with regularity each summer, and the civilizations building in its valley early learned the technique of basin irrigation, ponding back the floodwater for as long as possible after the river had receded, so that enriched soil could bring forth a harvest before the floods of the following season. In the Tigris-Euphrates valley the irrigation problem was more complex, because the floods were less predictable, more fierce, and came earlier than those of the northward-flowing Nile. They also carried more alluvium, which tended to choke irrigation channels. The task of the Sumerian irrigation engineers was that of channeling water from the rivers during the summer months, impounding it, and distributing it to the fields in small installments. The Sumerian system eventually broke down because it led to an accumulation of salt in the soil, with a consequent loss of fertility. Both systems, however, depended on a high degree of social control, requiring skill in measuring and marking out the land and an intricate legal code to ensure justice in the distribution of precious water. Both systems, moreover, depended on intricate engineering in building dikes and embankments, canals and aqueducts (with lengthy stretches underground to prevent loss by evaporation), and the use of water-raising devices such as the shadoof, a balanced beam with a counterweight on one end and a bucket to lift the water on the other.

Urban manufacturing

Manufacturing industry in the early civilizations concentrated on such products as pottery, wines, oils, and cosmetics, which had begun to circulate along the incipient trade routes before the introduction of metals; these became the commodities traded for the metals. In pottery, the potter’s wheel became widely used for spinning the clay into the desired shape, but the older technique of building pots by hand from rolls of clay remained in use for some purposes. In the production of wines and oils various forms of press were developed, while the development of cooking, brewing, and preservatives justified the assertion that the science of chemistry began in the kitchen. Cosmetics too were an offshoot of culinary art.

Pack animals were still the primary means of land transport, the wheeled vehicle developing slowly to meet the divergent needs of agriculture, trade, and war. In the latter category, the chariot appeared as a weapon, even though its use was limited by the continuing difficulty of harnessing a horse. Military technology brought the development of metal plates for armour.

Building

In building technology the major developments concerned the scale of operations rather than any particular innovation. The late Stone Age communities of Mesopotamia had already built extensively in sun-dried brick. Their successors continued the technique but extended its scale to construct the massive square temples called ziggurats. These had a core and facing of bricks, the facing walls sloping slightly inward and broken by regular pilasters built into the brickwork, the whole structure ascending in two or three stages to a temple on the summit. Sumerians were also the first to build columns with brick made from local clay, which also provided the writing material for the scribes.

In Egypt, clay was scarce but good building stone was plentiful, and builders used it in constructing the pyramids and temples that remain today as outstanding monuments of Egyptian civilization. Stones were pulled on rollers and raised up the successive stages of the structure by ramps and by balanced levers adapted from the water-raising shadoof. The stones were shaped by skilled masons, and they were placed in position under the careful supervision of priest-architects who were clearly competent mathematicians and astronomers, as is evident from the precise astronomical alignments. It seems certain that the heavy labour of construction fell upon armies of slaves, which helps to explain both the achievements and limitations of early civilizations. Slaves were usually one of the fruits of military conquest, which presupposes a period of successful territorial expansion, although their status as a subject race could be perpetuated indefinitely. Slave populations provided a competent and cheap labour force for the major constructional works that have been described. On the other hand, the availability of slave labour discouraged technological innovation, a social fact that goes far toward explaining the
comparative stagnation of mechanical invention in the ancient world.

**Transmitting knowledge**

In the ancient world, technological knowledge was transmitted by traders, who went out in search of tin and other commodities, and by craftsmen in metal, stone, leather, and the other mediums, who passed their skills to others by direct instruction or by providing models that challenged other craftsmen to copy them. This transmission through intermediary contact was occurring between the ancient civilizations and their neighbours to the north and west during the 2nd millennium BCE. The pace quickened in the subsequent millennium, distinct new civilizations arising in Crete and Mycenae, in Troy and Carthage. Finally, the introduction of the technique of working iron profoundly changed the capabilities and resources of human societies and ushered in the Classical civilizations of Greece and Rome.

**Technological achievements of Greece and Rome (500 BCE–500 CE)**

The contributions of Greece and Rome in philosophy and religion, political and legal institutions, poetry and drama, and in the realm of scientific speculation stand in spectacular contrast with their relatively limited contributions in technology. Their mechanical innovation was not distinguished, and, even in the realms of military and construction engineering, in which they showed great ingenuity and aesthetic sensibility, their work represented more a consummation of earlier lines of development than a dramatic innovation. This apparent paradox of the Classical period of the ancient world requires explanation, and the history of technology can provide some clues to the solution of the problem.

**The mastery of iron**

The outstanding technological factor of the Greco-Roman world was the smelting of iron, a technique—derived from unknown metallurgists, probably in Asia Minor, about 1000 BCE—that spread far beyond the provincial frontiers of the Roman Empire. The use of the metal had become general in Greece and the Aegean Islands by the dawn of the Classical period about 500 BCE, and it appears to have spread quickly westward thereafter. Iron ore, long a familiar material, had defied reduction into metallic form because of the great heat required in the furnace to perform the chemical transformation (about 1,535 °C [2,795 °F] compared with the 1,083 °C [1,981 °F] necessary for the reduction of copper ores). To reach this temperature, furnace construction had to be improved and ways devised to maintain the heat for several hours. Throughout the Classical period these conditions were achieved only on a small scale, in furnaces burning charcoal and using foot bellows to intensify the heat, and even in these furnaces the heat was not sufficient to reduce the ore completely to molten metal. Instead, a small spongy ball of iron—called a bloom—was produced in the bottom of the furnace. This was extracted by breaking open the furnace, and then it was hammered into bars of wrought iron, which could be shaped as required by further heating and hammering. Apart from its greater abundance, iron for most purposes provided a harder and stronger material than the earlier metals, although the impossibility of casting it into molds like bronze was an inconvenience. At an early date some smiths devised the cementation process for reheating bars of iron between layers of charcoal to carburize the surface of the iron and thus to produce a coat of steel. Such case-hardened iron could be further heated, hammered, and tempered to make knife and sword blades of high quality. The very best steel in Roman times was Seric steel, brought into the Western world from India, where it was produced in blocks a few inches in diameter by a crucible process, melting the ingredients in an enclosed vessel to achieve purity and consistency in the chemical combination.

**Mechanical contrivances**

Though slight, the mechanical achievements of the Greco-Roman centuries were not without significance. The world had one of its great mechanical geniuses in Archimedes, who devised remarkable weapons to protect his native Syracuse from Roman invasion and applied his powerful mind to such basic mechanical contrivances as the screw, the pulley, and the lever. Alexandrian engineers, such as Ctesibius and Hero, invented a wealth of ingenious mechanical contrivances including pumps, wind and hydraulic organs, compressed-air engines, and screw-cutting machines. They also devised toys and automata such as the aeolipile, which may be regarded as the first successful steam turbine. Little practical use was found for these inventions, but the Alexandrian school marks an important transition from very simple mechanisms to the more complex devices that properly deserve to be considered "machines." In a sense it provided a starting point for modern
mechanical practice.

The Romans were responsible, through the application and development of available machines, for an important technological transformation: the widespread introduction of rotary motion. This was exemplified in the use of the treadmill for powering cranes and other heavy lifting operations, the introduction of rotary water-raising devices for irrigation works (a scoop wheel powered by a treadmill), and the development of the waterwheel as a prime mover. The 1st-century-bce Roman engineer Vitruvius gave an account of watermills, and by the end of the Roman era many were in operation.

Agriculture

Iron Age technology was applied to agriculture in the form of the iron (or iron-tipped) plowshare, which opened up the possibility of deeper plowing and of cultivating heavier soils than those normally worked in the Greco-Roman period. The construction of plows improved slowly during these centuries, but the moldboard for turning over the earth did not appear until the 11th century ce, so that the capacity of turning the sod depended more on the wrists of the plowman than on the strength of his draft team; this discouraged tackling heavy ground. The potentialities of the heavy plow were thus not fully exploited in the temperate areas of Europe until after the Roman period. Elsewhere, in the drier climates of North Africa and Spain, the Romans were responsible for extensive irrigation systems, using the Archimedean screw and the noria (an animal- or water-powered scoop wheel) to raise water.

Building

Though many buildings of the Greeks survive as splendid monuments to the civilized communities that built them, as technological monuments they are of little significance. The Greeks adopted a form of column and lintel construction that had been used in Egypt for centuries and was derived from experience of timber construction. In no major sense did Greek building constitute a technological innovation. The Romans copied the Greek style for most ceremonial purposes, but in other respects they were important innovators in building technology. They made extensive use of fired brick and tile as well as stone; they developed a strong cement that would set under water; and they explored the architectural possibilities of the arch, the vault, and the dome. They then applied these techniques in amphitheatres, aqueducts, tunnels, bridges, walls, lighthouses, and roads. Taken together, these constructional works may fairly be regarded as the primary technological achievement of the Romans.

Other fields of technology

In manufacturing, transport, and military technology, the achievements of the Greco-Roman period are not remarkable. The major manufacturing crafts—the making of pottery and glass, weaving, leatherworking, fine-metalworking, and so on—followed the lines of previous societies, albeit with important developments in style. Superbly decorated Athenian pottery, for example, was widely dispersed along the trade routes of the Mediterranean, and the Romans made good quality pottery available throughout their empire through the manufacture and trade of the standardized red ware called terra sigillata, which was produced in large quantities at several sites in Italy and Gaul.

Transport

Transport, again, followed earlier precedents, the sailing ship emerging as a seagoing vessel with a carvel-built hull (that is, with planks meeting edge-to-edge rather than overlapping as in clinker-built designs), and a fully developed keel with sternpost and sternpost. The Greek sailing ship was equipped with a square or rectangular sail to receive a following wind and one or more banks of oarsmen to propel the ship when the wind was contrary. The Greeks began to develop a specialized fighting ship, provided with a ram in the prow, and the cargo ship, dispensing with oarsmen and relying entirely upon the wind, was also well established by the early years of Classical Greece. The Romans took over both forms, but without significant innovation. They gave much more attention to inland transport than to the sea, and they constructed a remarkable network of carefully aligned and well-laid roads, often paved over long stretches, throughout the provinces of the empire. Along these strategic highways the legions marched rapidly to the site of any crisis at which their presence was
required. The roads also served for the development of trade, but their primary function was always military, as a vital means of keeping a vast empire in subjection.

**Military technology**

Roman military technology was inventive on occasion, as in the great siege catapults, depending on both torsion and tension power. But the standard equipment of the legionnaire was simple and conservative, consisting of an iron helmet and breastplate, with a short sword and an iron-tipped spear. As most of their opponents were also equipped with iron weapons and sometimes with superior devices, such as the Celtic chariots, the Roman military achievements depended more on organization and discipline than on technological superiority.

The Greco-Roman era was distinguished for the scientific activity of some of its greatest philosophers. In keeping with Greek speculative thought, however, this tended to be strongly conceptual so that it was in mathematics and other abstract studies that the main scientific achievements are to be found. Some of these had some practical significance, as in the study of perspective effects in building construction. Aristotle in many ways expressed the inquiring empiricism that has caused scientists to seek an explanation for their physical environment. In at least one field, that of medicine and its related subjects, Greek inquiry assumed a highly practical form, Hippocrates and Galen laying the foundations of modern medical science. But this was exceptional, and the normal Hellenic attitude was to pursue scientific enquiry in the realm of ideas without much thought of the possible technological consequences.

**From the Middle Ages to 1750**

**Medieval advance (500–1500 ce)**

The millennium between the collapse of the Western Roman Empire in the 5th century ce and the beginning of the colonial expansion of western Europe in the late 15th century has been known traditionally as the Middle Ages, and the first half of this period consists of the five centuries of the Dark Ages. We now know that the period was not as socially stagnant as this title suggests. In the first place, many of the institutions of the later empire survived the collapse and profoundly influenced the formation of the new civilization that developed in western Europe. The Christian church was the outstanding institution of this type, but Roman conceptions of law and administration also continued to exert an influence long after the departure of the legions from the western provinces. Second, and more important, the Teutonic tribes who moved into a large part of western Europe did not come empty-handed, and in some respects their technology was superior to that of the Romans. It has already been observed that they were people of the Iron Age, and although much about the origins of the heavy plow remains obscure these tribes appear to have been the first people with sufficiently strong iron plowshares to undertake the systematic settlement of the forested lowlands of northern and western Europe, the heavy soils of which had frustrated the agricultural techniques of their predecessors.

The invaders came thus as colonizers. They may have been regarded as “barbarians” by the Romanized inhabitants of western Europe who naturally resented their intrusion, and the effect of their invasion was certainly to disrupt trade, industry, and town life. But the newcomers also provided an element of innovation and vitality. About 1000 ce the conditions of comparative political stability necessary for the reestablishment of a vigorous commercial and urban life had been secured by the success of the kingdoms of the region in either absorbing or keeping out the last of the invaders from the East, and thereafter for 500 years the new civilization grew in strength and began to experiment in all aspects of human endeavour. Much of this process involved recovering the knowledge and achievements of the ancient world. The history of medieval technology is thus largely the story of the preservation, recovery, and modification of earlier achievements. But by the end of the period Western civilization had begun to produce some remarkable technological innovations that were to be of the utmost significance.

**Innovation**

The word innovation raises a problem of great importance in the history of technology. Strictly, an innovation is something entirely new, but there is no such thing as an unprecedented technological innovation because it is impossible for an inventor to work in a vacuum and, however ingenious his invention, it must arise out of his own previous experience. The
task of distinguishing an element of novelty in an invention remains a problem of patent law down to the present day, but the problem is made relatively easy by the possession of full documentary records covering previous inventions in many countries. For the millennium of the Middle Ages, however, few such records exist, and it is frequently difficult to explain how particular innovations were introduced to western Europe. The problem is especially perplexing because it is known that many inventions of the period had been developed independently and previously in other civilizations, and it is sometimes difficult if not impossible to know whether something is spontaneous innovation or an invention that had been transmitted by some as yet undiscovered route from those who had originated it in other societies.

The problem is important because it generates a conflict of interpretations about the transmission of technology. On the one hand there is the theory of the diffusionists, according to which all innovation has moved westward from the long-established civilizations of the ancient world, with Egypt and Mesopotamia as the two favourite candidates for the ultimate source of the process. On the other hand is the theory of spontaneous innovation, according to which the primary determinant of technological innovation is social need. Scholarship is as yet unable to solve the problem so far as technological advances of the Middle Ages are concerned because much information is missing. But it does seem likely that at least some of the key inventions of the period—the windmill and gunpowder are good examples—were developed spontaneously. It is quite certain, however, that others, such as silk working, were transmitted to the West, and, however original the contribution of Western civilization to technological innovation, there can be no doubt at all that in its early centuries at least it looked to the East for ideas and inspiration.

Byzantium

The immediate eastern neighbour of the new civilization of medieval Europe was Byzantium, the surviving bastion of the Roman Empire based in Constantinople (Istanbul), which endured for 1,000 years after the collapse of the western half of the empire. There the literature and traditions of Hellenic civilization were perpetuated, becoming increasingly available to the curiosity and greed of the West through the traders who arrived from Venice and elsewhere. Apart from the influence on Western architectural style of such Byzantine masterpieces as the great domed structure of Hagia Sophia, the technological contribution of Byzantium itself was probably slight, but it served to mediate between the West and other civilizations one or more stages removed, such as the Islamic world, India, and China.

Islam

The Islamic world had become a civilization of colossal expansive energy in the 7th century and had imposed a unity of religion and culture on much of southwest Asia and North Africa. From the point of view of technological dissemination, the importance of Islam lay in the Arab assimilation of the scientific and technological achievements of Hellenic civilization, to which it made significant additions, and the whole became available to the West through the Moors in Spain, the Arabs in Sicily and the Holy Land, and through commercial contacts with the Levant and North Africa.

India

Islam also provided a transmission belt for some of the technology of East and South Asia, especially that of India and China. The ancient Hindu and Buddhist cultures of the Indian subcontinent had long-established trading connections with the Arab world to the west and came under strong Muslim influence themselves after the Mughal conquest in the 16th century. Indian artisans early acquired an expertise in ironworking and enjoyed a wide reputation for their metal artifacts and textile techniques, but there is little evidence that technical innovation figured prominently in Indian history before the foundation of European trading stations in the 16th century.

China

Civilization flourished continuously in China from about 2000 bce, when the first of the historical dynasties emerged. From the beginning it was a civilization that valued technological skill in the form of hydraulic engineering, for its survival
depended on controlling the enriching but destructive floods of the Huang He (Yellow River). Other technologies appeared at a remarkably early date, including the casting of iron, the production of porcelain, and the manufacture of brass and paper. As one dynasty followed another, Chinese civilization came under the domination of a bureaucratic elite, the mandarins, who gave continuity and stability to Chinese life but who also became a conservative influence on innovation, resisting the introduction of new techniques unless they provided a clear benefit to the bureaucracy. Such an innovation was the development of the water-powered mechanical clock, which achieved an ingenious and elaborate form in the machine built under the supervision of Su Song in 1088. This was driven by a waterwheel that moved regularly, making one part-revolution as each bucket on its rim was filled in turn.

The links between China and the West remained tenuous until modern times, but the occasional encounter such as that resulting from the journey of Marco Polo in 1271–95 alerted the West to the superiority of Chinese technology and stimulated a vigorous westward transfer of techniques. Western knowledge of silk working, the magnetic compass, papermaking, and porcelain were all derived from China. In the latter case, Europeans admired the fine porcelain imported from China for several centuries before they were able to produce anything of a similar quality. Having achieved a condition of comparative social stability, however, the Chinese mandarinate did little to encourage innovation or trading contacts with the outside world. Under their influence, no social group emerged in China equivalent to the mercantile class that flourished in the West and did much to promote trade and industry. The result was that China dropped behind the West in technological skills until the political revolutions and social upheavals of the 20th century awakened the Chinese to the importance of these skills to economic prosperity and inspired a determination to acquire them.

Despite the acquisition of many techniques from the East, the Western world of 500–1500 was forced to solve most of its problems on its own initiative. In doing so it transformed an agrarian society based upon a subsistence economy into a dynamic society with increased productivity sustaining trade, industry, and town life on a steadily growing scale. This was primarily a technological achievement, and one of considerable magnitude.

**Power sources**

The outstanding feature of this achievement was a revolution in the sources of power. With no large slave labour force to draw on, Europe experienced a labour shortage that stimulated a search for alternative sources of power and the introduction of laboursaving machinery. The first instrument of this power revolution was the horse. By the invention of the horseshoe, the padded, rigid horse collar, and the stirrup, all of which first appeared in the West in the centuries of the Dark Ages, the horse was transformed from an ancillary beast of burden useful only for light duties into a highly versatile source of energy in peace and war. Once the horse could be harnessed to the heavy plow by means of the horse collar, it became a more efficient draft animal than the ox, and the introduction of the stirrup made the mounted warrior supreme in medieval warfare and initiated complex social changes to sustain the great expense of the knight, his armour, and his steed, in a society close to the subsistence line.

Even more significant was the success of medieval technology in harnessing water and wind power. The Romans had pioneered the use of waterpower in the later empire, and some of their techniques probably survived. The type of water mill that flourished first in northern Europe, however, appears to have been the Norse mill, using a horizontally mounted waterwheel driving a pair of grindstones directly, without the intervention of gearing. Examples of this simple type of mill survive in Scandinavia and in the Shetlands; it also occurred in southern Europe, where it was known as the Greek mill. It is possible that a proportion of the 5,624 mills recorded in the Domesday Book of England in 1086 were of this type, although it is probable that by that date the vertically mounted undershot wheel had established itself as more appropriate to the gentle landscape of England; the Norse mill requires a good head of water to turn the wheel at an adequate grinding speed without gearing for the upper millstone (the practice of rotating the upper stone above a stationary bed stone became universal at an early date). Most of the Domesday water mills were used for grinding grain, but in the following centuries other important uses were devised in fulling cloth (shrinking and felting woolen fabrics), sawing wood, and crushing vegetable seeds for oil. Overshot wheels also were introduced where there was sufficient head of water, and the competence of the medieval millwrights in building mills and earthworks and in constructing increasingly elaborate trains of gearing grew correspondingly.
The sail had been used to harness wind power from the dawn of civilization, but the windmill was unknown in the West until the end of the 12th century. Present evidence suggests that the windmill developed spontaneously in the West; though there are precedents in Persia and China, the question remains open. What is certain is that the windmill became widely used in Europe in the Middle Ages. Wind power is generally less reliable than waterpower, but where the latter is deficient wind power is an attractive substitute. Such conditions are found in areas that suffer from drought or from a shortage of surface water and also in low-lying areas where rivers offer little energy. Windmills have thus flourished in places such as Spain or the downlands of England on the one hand, and in the fenlands and polders of the Netherlands on the other hand. The first type of windmill to be widely adopted was the post-mill, in which the whole body of the mill pivots on a post and can be turned to face the sails into the wind. By the 15th century, however, many were adopting the tower-mill type of construction, in which the body of the mill remains stationary with only the cap moving to turn the sails into the wind. As with the water mill, the development of the windmill brought not only greater mechanical power but also greater knowledge of mechanical contrivances, which was applied in making clocks and other devices.

Agriculture and crafts

With new sources of power at its disposal, medieval Europe was able greatly to increase productivity. This is abundantly apparent in agriculture, where the replacement of the ox by the faster gaited horse and the introduction of new crops brought about a distinct improvement in the quantity and variety of food, with a consequent improvement in the diet and energy of the population. It was also apparent in the developing industries of the period, especially the woolen cloth industry in which the spinning wheel was introduced, partially mechanizing this important process, and the practice of using waterpower to drive fulling stocks (wooden hammers raised by cams on a driving shaft) had a profound effect on the location of the industry in England in the later centuries of the Middle Ages. The same principle was adapted to the paper industry late in the Middle Ages, the rags from which paper was derived being pulverized by hammers similar to fulling stocks.

Meanwhile, the traditional crafts flourished within the expanding towns, where there was a growing market for the products of the rope makers, barrel makers (coopers), leatherworkers (curriers), and metalworkers (goldsmiths and silversmiths), to mention only a few of the more important crafts. New crafts such as that of the soapmakers developed in the towns. The technique of making soap appears to have been a Teutonic innovation of the Dark Ages, being unknown in the ancient civilizations. The process consists of decomposing animal or vegetable fats by boiling them with a strong alkali. Long before it became popular for personal cleansing, soap was a valuable industrial commodity for scouring textile fabrics. Its manufacture was one of the first industrial processes to make extensive use of coal as a fuel, and the development of the coal industry in northern Europe constitutes another important medieval innovation, no previous civilization having made any systematic attempt to exploit coal. The mining techniques remained unsophisticated as long as coal was obtainable near the surface, but as the search for the mineral led to greater and greater depths the industry copied methods that had already evolved in the metal-mining industries of north and central Europe. The extent of this evolution was brilliantly summarized by Georgius Agricola in his De re metallica, published in 1556. This large, abundantly illustrated book shows techniques of shafting, pumping (by treadmill, animal power, and waterpower), and of conveying the ore from the mines in trucks, which anticipated the development of the railways. It is impossible to date precisely the emergence of these important techniques, but the fact that they were well established when Agricola observed them suggests that they had a long ancestry.

Architecture

Relatively few structures survive from the Dark Ages, but the later centuries of the medieval period were a great age of building. The Romanesque and Gothic architecture that produced the outstanding aesthetic contribution of the Middle Ages embodied significant technological innovations. The architect-engineers, who had clearly studied Classical building techniques, showed a readiness to depart from their models and thus to devise a style that was distinctively their own. Their solutions to the problems of constructing very tall masonry buildings while preserving as much natural light as possible were the cross-rib vault, the flying buttress, and the great window panels providing scope for the new craft of the glazier using
coloured glass with startling effect.

**Military technology**

The same period saw the evolution of the fortified stronghold from the Anglo-Saxon motte-and-bailey, a timber tower encircled by a timber and earth wall, to the formidable, fully developed masonry castle that had become anachronism by the end of the Middle Ages because of the development of artillery. Intrinsic to this innovation were the invention of gunpowder and the development of techniques for casting metals, especially iron. Gunpowder appeared in western Europe in the mid-13th century, although its formula had been known in East Asia long before that date. It consists of a mixture of carbon, sulfur, and saltpetre, of which the first two were available from charcoal and deposits of volcanic sulfur in Europe, whereas saltpetre had to be crystallized by a noxious process of boiling stable sweepings and other decaying refuse. The consolidation of these ingredients into an explosive powder had become an established yet hazardous industry by the close of the Middle Ages.

The first effective cannon appear to have been made of wrought-iron bars strapped together, but although barrels continued to be made in this way for some purposes, the practice of casting cannon in bronze became widespread. The technique of casting in bronze had been known for several millennia, but the casting of cannon presented problems of size and reliability. It is likely that the bronzesmiths were able to draw on the experience of techniques devised by the bell founders as an important adjunct to medieval church building, as the casting of a large bell posed similar problems of heating a substantial amount of metal and of pouring it into a suitable mold. Bronze, however, was an expensive metal to manufacture in bulk, so that the widespread use of cannon in war had to depend upon improvements in iron-casting techniques.

The manufacture of cast iron is the great metallurgical innovation of the Middle Ages. It must be remembered that from the beginning of the Iron Age until late in the Middle Ages the iron ore smelted in the available furnaces had not been completely converted to its liquid form. In the 15th century, however, the development of the blast furnace made possible this fusion, with the result that the molten metal could be poured directly into molds ready to receive it. The emergence of the blast furnace was the result of attempts to increase the size of the traditional blooms. Greater size made necessary the provision of a continuous blast of air, usually from bellows driven by a waterwheel, and the combination increased the internal temperature of the furnace so that the iron became molten. At first, the disk of solid iron left in the bottom of the furnace was regarded as undesirable waste by the iron manufacturer; it possessed properties completely unlike those of the more familiar wrought iron, being crystalline and brittle and thus of no use in the traditional iron forge. But it was soon discovered that the new iron could be cast and turned profit, particularly in the manufacture of cannon.

**Transport**

Medieval technology made few contributions to inland transport, though there was some experimentation in bridge building and in the construction of canals; lock gates were developed as early as 1180, when they were employed on the canal between Brugge (now in Belgium) and the sea. Roads remained indifferent where they existed at all, and vehicles were clumsy throughout the period. Wayfarers like Chaucer's pilgrims traveled on horseback, and this was to remain the best mode of inland transport for centuries to come.

Sea transport was a different story. Here the Middle Ages produced a decisive technological achievement: the creation of a reliable oceangoing ship depending entirely on wind power instead of a combination of wind and muscle. The vital steps in this evolution were, first, the combination of the traditional square sail, used with little modification from Egyptian times through the Roman Empire to the Viking long boats, with the triangular lateen sail developed in the Arab dhow and adopted in the Mediterranean, which gave it the "lateen" (Latin) association attributed to it by the northern seafarers. This combination allowed ships so equipped to sail close to the wind. Second, the adoption of the sternpost rudder gave greatly increased maneuverability, allowing ships to take full advantage of their improved sail power in tacking into a contrary wind. Third, the introduction of the magnetic compass provided a means of checking navigation on the open seas in any weather. The convergence of these improvements in the ships of the later Middle Ages, together with other improvements in construction and equipment—such as better barrels for carrying water, more reliable ropes, sails, and anchors, the availability of navigational charts (first recorded in use on board ship in 1270), and the astrolabe (for measuring the angle of the Sun or a star above the horizon)—lent confidence to adventurous mariners and thus led directly to the voyages of
discovery that marked the end of the Middle Ages and the beginning of the expansion of Europe that has characterized modern times.

Communications

While transport technology was evolving toward these revolutionary developments, techniques of recording and communication were making no less momentous advances. The medieval interest in mechanical contrivances is well illustrated by the development of the mechanical clock, the oldest of which, driven by weights and controlled by a verge, an oscillating arm engaging with a gear wheel, and dated 1386, survives in Salisbury Cathedral, England. Clocks driven by springs had appeared by the mid-15th century, making it possible to construct more compact mechanisms and preparing the way for the portable clock. The problem of overcoming the diminishing power of the spring as it unwound was solved by the simple compensating mechanism of the fusee—a conical drum on the shaft that permitted the spring to exert an increasing moment, or tendency to increase motion, as its power declined. It has been argued that the medieval fascination with clocks reflects an increased sense of the importance of timekeeping in business and elsewhere, but it can be seen with equal justice as representing a new sense of inquiry into the possibilities and practical uses of mechanical devices.

Even more significant than the invention of the mechanical clock was the 15th-century invention of printing with movable metal type. The details of this epochal invention are disappointingly obscure, but there is general agreement that the first large-scale printing workshop was that established at Mainz by Johannes Gutenberg, which was producing a sufficient quantity of accurate type to print a Vulgate Bible about 1455. It is clear, however, that this invention drew heavily upon long previous experience with block printing—using a single block to print a design or picture—and on developments in typesetting and ink making. It also made heavy demands on the paper industry, which had been established in Europe since the 12th century but had developed slowly until the invention of printing and the subsequent vogue for the printed word. The printing press itself, vital for securing a firm and even print over the whole page, was an adaptation of the screw press already familiar in the winepress and other applications. The printers found an enormous demand for their product, so that the technique spread rapidly and the printed word became an essential medium of political, social, religious, and scientific communication as well as a convenient means for the dissemination of news and information. By 1500 almost 40,000 recorded editions of books had been printed in 14 European countries, with Germany and Italy accounting for two-thirds. Few single inventions have had such far-reaching consequences.

For all its isolation and intellectual deprivation, the new civilization that took shape in western Europe in the millennium 500 to 1500 achieved some astonishing feats of technological innovation. The intellectual curiosity that led to the foundation of the first universities in the 12th century and applied itself to the recovery of the ancient learning from whatever source it could be obtained was the mainspring also of the technological resourcefulness that encouraged the introduction of the windmill, the improvement and wider application of waterpower, the development of new industrial techniques, the invention of the mechanical clock and gunpowder, the evolution of the sailing ship, and the invention of large-scale printing. Such achievements could not have taken place within a static society. Technological innovation was both the cause and the effect of dynamic development. It is no coincidence that these achievements occurred within the context of a European society that was increasing in population and productivity, stimulating industrial and commercial activity, and expressing itself in the life of new towns and striking cultural activity. Medieval technology mirrored the aspiration of a new and dynamic civilization.

The emergence of Western technology (1500–1750)

The technological history of the Middle Ages was one of slow but substantial development. In the succeeding period the tempo of change increased markedly and was associated with profound social, political, religious, and intellectual upheavals in western Europe.

The emergence of the nation-state, the cleavage of the Christian church by the Protestant Reformation, the Renaissance and its accompanying scientific revolution, and the overseas expansion of European states all had interactions with developing technology. This expansion became possible after the advance in naval technology opened up the ocean routes to Western navigators. The conversion of voyages of discovery into imperialism and colonization was made possible by the new firepower. The combination of light, maneuverable ships with the firepower of iron cannon gave European adventurers a decisive advantage, enhanced by other technological assets.
The Reformation, not itself a factor of major significance to the history of technology, nevertheless had interactions with it; the capacity of the new printing presses to disseminate all points of view contributed to the religious upheavals, while the intellectual ferment provoked by the Reformation resulted in a rigorous assertion of the vocational character of work and thus stimulated industrial and commercial activity and technological innovation. It is an indication of the nature of this encouragement that so many of the inventors and scientists of the period were Calvinists, Puritans, and, in England, Dissenters.

The Renaissance

The Renaissance had more obviously technological content than the Reformation. The concept of "renaissance" is elusive. Since the scholars of the Middle Ages had already achieved a very full recovery of the literary legacy of the ancient world, as a "rebirth" of knowledge the Renaissance marked rather a point of transition after which the posture of deference to the ancients began to be replaced by a consciously dynamic, progressive attitude. Even while they looked back to Classical models, Renaissance men looked for ways of improving upon them. This attitude is outstandingly represented in the genius of Leonardo da Vinci. As an artist of original perception he was recognized by his contemporaries, but some of his most novel work is recorded in his notebooks and was virtually unknown in his own time. This included ingenious designs for submarines, airplanes, and helicopters and drawings of elaborate trains of gears and of the patterns of flow in liquids. The early 16th century was not yet ready for these novelties: they met no specific social need, and the resources necessary for their development were not available.

An often overlooked aspect of the Renaissance is the scientific revolution that accompanied it. As with the term Renaissance itself, the concept is complex, having to do with intellectual liberation from the ancient world. For centuries the authority of Aristotle in dynamics, of Ptolemy in astronomy, and of Galen in medicine had been taken for granted. Beginning in the 16th century their authority was challenged and overthrown, and scientists set out by observation and experiment to establish new explanatory models of the natural world. One distinctive characteristic of these models was that they were tentative, never receiving the authoritarian prestige long accorded to the ancient masters. Since this fundamental shift of emphasis, science has been committed to a progressive, forward-looking attitude and has come increasingly to seek practical applications for scientific research.

Technology performed a service for science in this revolution by providing it with instruments that greatly enhanced its powers. The use of the telescope by Galileo to observe the moons of Jupiter was a dramatic example of this service, but the telescope was only one of many tools and instruments that proved valuable in navigation, mapmaking, and laboratory experiments. More significant were the services of the new sciences to technology, and the most important of these was the theoretical preparation for the invention of the steam engine.

The steam engine

![Image of a scientist]

The researches of a number of scientists, especially those of Robert Boyle of England with atmospheric pressure, of Otto von Guericke of Germany with a vacuum, and of the French Huguenot Denis Papin with pressure vessels, helped to equip practical technologists with the theoretical basis of steam power. Distressingly little is known about the manner in which this knowledge was assimilated by pioneers such as Thomas Savery and Thomas Newcomen, but it is inconceivable that they could have been ignorant of it. Savery took out a patent for a "new Invention for Raising of Water and occasioning Motion to all Sorts of Mill Work by the Impellent Force of Fire" in 1698 (No. 356). His apparatus depended on the condensation of steam in a vessel, creating a partial vacuum into which water was forced by atmospheric pressure.

Credit for the first commercially successful steam engine, however, must go to Newcomen, who erected his first machine near Dudley Castle in Staffordshire in 1712. It operated by atmospheric pressure on the top face of a piston in a cylinder, in the lower part of which steam was condensed to create a partial vacuum. The piston was connected to one end of a rocking beam, the other end of which carried the pumping rod in the mine shaft. Newcomen was a tradesman in Dartmouth, Devon, and his engines were robust but unsophisticated. Their heavy fuel consumption made them uneconomical when used where coal was expensive, but in the British coalfields they performed an essential service by keeping deep mines clear of water.
and were extensively adopted for this purpose. In this way the early steam engines fulfilled one of the most pressing needs of British industry in the 18th century. Although waterpower and wind power remained the basic sources of power for industry, a new prime mover had thus appeared in the shape of the steam engine, with tremendous potential for further development as and when new applications could be found for it.

Metallurgy and mining

One cause of the rising demand for coal in Britain was the depletion of the woodland and supplies of charcoal, making manufacturers anxious to find a new source of fuel. Of particular importance were experiments of the iron industry in using coal instead of charcoal to smelt iron ore and to process cast iron into wrought iron and steel. The first success in these attempts came in 1709, when Abraham Darby, a Quaker ironfounder in Shropshire, used coke to reduce iron ore in his enlarged and improved blast furnace. Other processes, such as glassmaking, brickmaking, and the manufacture of pottery, had already adopted coal as their staple fuel. Great technical improvements had taken place in all these processes. In ceramics, for instance, the long efforts of European manufacturers to imitate the hard, translucent quality of Chinese porcelain culminated in Meissen at the beginning of the 18th century; the process was subsequently discovered independently in Britain in the middle of the century. Stoneware, requiring a lower firing temperature than porcelain, had achieved great decorative distinction in the 17th century as a result of the Dutch success with opaque white tin glazes at their Delft potteries, and the process had been widely imitated.

The period from 1500 to 1750 witnessed a steady expansion in mining for minerals other than coal and iron. The gold and silver mines of Saxony and Bohemia provided the inspiration for the treatise by Agricola, De re metallica, mentioned above, which distilled the cumulative experience of several centuries in mining and metalworking and became, with the help of some brilliant woodcuts and the printing press, a worldwide manual on mining practice. Queen Elizabeth I introduced German miners to England in order to develop the mineral resources of the country, and one result of this was the establishment of brass manufacture. This metal, an alloy of copper and zinc, had been known in the ancient world and in Eastern civilizations but was not developed commercially in western Europe until the 17th century. Metallic zinc had still not been isolated, but brass was made by heating copper with charcoal and calamine, an oxide of zinc mined in England in the Mendip Hills and elsewhere, and was worked up by hammering, annealing (a heating process to soften the material), and wire-drawing into a wide range of household and industrial commodities. Other nonferrous metals such as tin and lead were sought out and exploited with increasing enterprise in this period, but as their ores commonly occurred at some distance from sources of coal, as in the case of the Cornish tin mines, the employment of Newcomen engines to assist in drainage was rarely economical, and this circumstance restricted the extent of the mining operations.

New commodities

Following the dramatic expansion of the European nations into the Indian Ocean region and the New World, the commodities of these parts of the world found their way back into Europe in increasing volume. These commodities created new social habits and fashions and called for new techniques of manufacture. Tea became an important trade commodity but was soon surpassed in volume and importance by the products of specially designed plantations, such as sugar, tobacco, cotton, and cocoa. Sugar refining, depending on the crystallization of sugar from the syrupy molasses derived from the cane, became an important industry. So did the processing of tobacco, for smoking in clay pipes (produced in bulk at Delft and elsewhere) or for taking as snuff. Cotton had been known before as an Eastern plant, but its successful transplantation to the New World made much greater quantities available and stimulated the emergence of an important new textile industry.

The woollen cloth industry in Britain provided a model and precedent upon which the new cotton industry could build. Already in the Middle Ages, the processes of cloth manufacture had been partially mechanized upon the introduction of fulling mills and the use of spinning wheels. But in the 18th century the industry remained almost entirely a domestic or cottage one, with most of the processing being performed in the homes of the workers, using comparatively simple tools.
that could be operated by hand or foot. The most complicated apparatus was the loom, but this could usually be worked by a single weaver, although wider cloths required an assistant. It was a general practice to install the loom in an upstairs room with a long window giving maximum natural light. Weaving was regarded as a man's work, spinning being assigned to the women of the family (hence, "spinsters"). The weaver could use the yarn provided by up to a dozen spinsters, and the balanced division of labour was preserved by the weaver's assuming responsibility for supervising the cloth through the other processes, such as fulling. Pressures to increase the productivity of various operations had already produced some technical innovations by the first half of the 18th century. The first attempts at devising a spinning machine, however, were not successful; and without this, John Kay's technically successful flying shuttle (a device for hitting the shuttle from one side of the loom to the other, dispensing with the need to pass it through by hand) did not fulfill an obvious need. It was not until the rapid rise of the cotton cloth industry that the old, balanced industrial system was seriously upset and that a new, mechanized system, organized on the basis of factory production, began to emerge.

Agriculture

Another major area that began to show signs of profound change in the 18th century was agriculture. Stimulated by greater commercial activity, the rising market for food caused by an increasing population aspiring to a higher standard of living, and by the British aristocratic taste for improving estates to provide affluent and decorative country houses, the traditional agricultural system of Britain was transformed. It is important to note that this was a British development, as it is one of the indications of the increasing pressures of industrialization there even before the Industrial Revolution, while other European countries, with the exception of the Netherlands, from which several of the agricultural innovations in Britain were acquired, did little to encourage agricultural productivity. The nature of the transformation was complex, and it was not completed until well into the 19th century. It consisted partly of a legal reallocation of land ownership, the "enclosure" movement, to make farms more compact and economical to operate. In part also it was brought about by the increased investment in farming improvements, because the landowners felt encouraged to invest money in their estates instead of merely drawing rents from them. Again, it consisted of using this money for technical improvements, taking the form of machinery—such as Jethro Tull's mechanical sower—of better drainage, of scientific methods of breeding to raise the quality of livestock, and of experimenting with new crops and systems of crop rotation. The process has often been described as an agricultural revolution, but it is preferable to regard it as an essential prelude to and part of the Industrial Revolution.

Construction

Construction techniques did not undergo any great change in the period 1500–1750. The practice of building in stone and brick became general, although timber remained an important building material for roofs and floors, and, in areas in which stone was in short supply, the half-timber type of construction retained its popularity into the 17th century. Thereafter, however, the spread of brick and tile manufacturing provided a cheap and readily available substitute, although it suffered an eclipse on aesthetic grounds in the 18th century, when Classical styles enjoyed a vogue and brick came to be regarded as inappropriate for facing such buildings. Brickmaking, however, had become an important industry for ordinary domestic building by then and, indeed, entered into the export trade as Dutch and Swedish ships regularly carried brick as ballast to the New World, providing a valuable building material for the early American settlements. Cast iron was coming into use in buildings, but only for decorative purposes. Glass was also beginning to become an important feature of buildings of all sorts, encouraging the development of an industry that still relied largely on ancient skills of fusing sand to make glass and blowing, molding, and cutting it into the shapes required.

Land reclamation

More substantial constructional techniques were required in land drainage and military fortification, although again their importance is shown rather in their scale and complexity than in any novel features. The Dutch, wrestling with the sea for centuries, had devised extensive dikes; their techniques were borrowed by English landowners in the 17th century in an attempt to reclaim tracts of fenlands.

Military fortifications
In military fortification, the French strongholds designed by Sébastien de Vauban in the late 17th century demonstrated how warfare had adapted to the new weapons and, in particular, to heavy artillery. With earthen embankments to protect their salients, these star-shaped fortresses were virtually impregnable to the assault weapons of the day. Firearms remained cumbersome, with awkward firing devices and slow reloading. The quality of weapons improved somewhat as gunsmiths became more skilled.

Transport and communications

Like constructional techniques, transport and communications made substantial progress without any great technical innovations. Road building was greatly improved in France, and, with the completion of the Canal du Midi between the Mediterranean and the Bay of Biscay in 1662, large-scale civil engineering achieved an outstanding success. The canal is 150 miles (241 km) long, with a hundred locks, a tunnel, three major aqueducts, many culverts, and a large summit reservoir.

The sea remained the greatest highway of commerce, stimulating innovation in the sailing ship. The Elizabethan galleon with its great maneuverability and firepower, the Dutch herring busses and fluitschips with their commodious hulls and shallow draft, the versatile East Indiamen of both the Dutch and the British East India companies, and the mighty ships of the line produced for the French and British navies in the 18th century indicate some of the main directions of evolution.

The needs of reliable navigation created a demand for better instruments. The quadrant was improved by conversion to the octant, using mirrors to align the image of a star with the horizon and to measure its angle more accurately: with further refinements the modern sextant evolved. Even more significant was the ingenuity shown by scientists and instrument makers in the construction of a clock that would keep accurate time at sea: such a clock, by showing the time in Greenwich when it was noon aboard ship would show how far east or west of Greenwich the ship lay (longitude). A prize of £20,000 was offered by the British Board of Longitude for this purpose in 1714, but it was not awarded until 1763 when John Harrison’s so-called No. 4 chronometer fulfilled all the requirements.

Chemistry

Robert Boyle’s contribution to the theory of steam power has been mentioned, but Boyle is more commonly recognized as the “father of chemistry,” in which field he was responsible for the recognition of an element as a material that cannot be resolved into other substances. It was not until the end of the 18th and the beginning of the 19th century, however, that the work of Antoine Lavoisier and John Dalton put modern chemical science on a firm theoretical basis. Chemistry was still struggling to free itself from the traditions of alchemy. Even alchemy was not without practical applications, for it promoted experiments with materials and led to the development of specialized laboratory equipment that was used in the manufacture of dyes, cosmetics, and certain pharmaceutical products. For the most part, pharmacy still relied upon recipes based on herbs and other natural products, but the systematic preparation of these eventually led to the discovery of useful new drugs.

The period from 1500 to 1750 witnessed the emergence of Western technology in the sense that the superior techniques of Western civilization enabled the nations that composed it to expand their influence over the whole known world. Yet, with the exception of the steam engine, this period was not marked by outstanding technological innovation. What was, perhaps, more important than any particular innovation was the evolution, however faltering and partial and limited to Britain in the first place, of a technique of innovation, or what has been called “the invention of invention.” The creation of a political and social environment conducive to invention, the building up of vast commercial resources to support inventions likely to produce profitable results, the exploitation of mineral, agricultural, and other raw material resources for industrial purposes, and, above all, the recognition of specific needs for invention and an unwillingness to be defeated by difficulties, together produced a society ripe for an industrial revolution based on technological innovation. The technological achievements of the period 1500–1750, therefore, must be judged in part by their substantial contribution to the spectacular innovations of the following period.

The Industrial Revolution (1750–1900)
The term Industrial Revolution, like similar historical concepts, is more convenient than precise. It is convenient because history requires division into periods for purposes of understanding and instruction and because there were sufficient innovations at the turn of the 18th and 19th centuries to justify the choice of this as one of the periods. The term is imprecise, however, because the Industrial Revolution has no clearly defined beginning or end. Moreover, it is misleading if it carries the implication of a once-for-all change from a “preindustrial” to a “postindustrial” society, because, as has been seen, the events of the traditional Industrial Revolution had been well prepared in a mounting tempo of industrial, commercial, and technological activity from about 1000 ce and led into a continuing acceleration of the processes of industrialization that is still proceeding in our own time. The term Industrial Revolution must thus be employed with some care. It is used below to describe an extraordinary quickening in the rate of growth and change and, more particularly, to describe the first 150 years of this period of time, as it will be convenient to pursue the developments of the 20th century separately.

The Industrial Revolution, in this sense, has been a worldwide phenomenon, at least in so far as it has occurred in all those parts of the world, of which there are very few exceptions, where the influence of Western civilization has been felt. Beyond any doubt it occurred first in Britain, and its effects spread only gradually to continental Europe and North America. Equally clearly, the Industrial Revolution that eventually transformed these parts of the Western world surpassed in magnitude the achievements of Britain, and the process was carried further to change radically the socioeconomic life of Asia, Africa, Latin America, and Australasia. The reasons for this succession of events are complex, but they were implicit in the earlier account of the buildup toward rapid industrialization. Partly through good fortune and partly through conscious effort, Britain by the early 18th century came to possess the combination of social needs and social resources that provided the necessary preconditions of commercially successful innovation and a social system capable of sustaining and institutionalizing the processes of rapid technological change once they had started. This section will therefore be concerned, in the first place, with events in Britain, although in discussing later phases of the period it will be necessary to trace the way in which British technical achievements were diffused and superseded in other parts of the Western world.

**Power technology**

An outstanding feature of the Industrial Revolution has been the advance in power technology. At the beginning of this period, the major sources of power available to industry and any other potential consumer were animate energy and the power of wind and water, the only exception of any significance being the atmospheric steam engines that had been installed for pumping purposes, mainly in coal mines. It is to be emphasized that this use of steam power was exceptional and remained so for most industrial purposes until well into the 19th century. Steam did not simply replace other sources of power: it transformed them. The same sort of scientific inquiry that led to the development of the steam engine was also applied to the traditional sources of inanimate energy, with the result that both waterwheels and windmills were improved in design and efficiency. Numerous engineers contributed to the refinement of waterwheel construction, and by the middle of the 19th century new designs made possible increases in the speed of revolution of the waterwheel and thus prepared the way for the emergence of the water turbine, which is still an extremely efficient device for converting energy.

**Windmills**

Meanwhile, British windmill construction was improved considerably by the refinements of sails and by the self-correcting device of the fantail, which kept the sails pointed into the wind. Spring sails replaced the traditional canvas rig of the windmill with the equivalent of a modern venetian blind, the shutters of which could be opened or closed, to let the wind pass through or to provide a surface upon which its pressure could be exerted. Sail design was further improved with the “patent” sail in 1807. In mills equipped with these sails, the shutters were controlled on all the sails simultaneously by a lever inside the mill connected by rod linkages through the windshaft with the bar operating the movement of the shutters on each sweep. The control could be made more fully automatic by hanging weights on the lever in the mill to determine the maximum wind pressure beyond which the shutters would open and spill the wind. Conversely, counterweights could be attached to keep the shutters in the open position. With these and other modifications, British windmills adapted to the increasing demands on power technology. But the use of wind power declined sharply in the 19th century with the spread of steam and the increasing scale of power utilization. Windmills that had satisfactorily provided power for small-scale industrial processes were unable to compete with the production of large-scale steam-powered mills.
Steam engines

Although the qualification regarding older sources of power is important, steam became the characteristic and ubiquitous power source of the British Industrial Revolution. Little development took place in the Newcomen atmospheric engine until James Watt patented a separate condenser in 1769, but from that point onward the steam engine underwent almost continuous improvements for more than a century. Watt’s separate condenser was the outcome of his work on a model of a Newcomen engine that was being used in a University of Glasgow laboratory. Watt’s inspiration was to separate the two actions of heating the cylinder with hot steam and cooling it to condense the steam for every stroke of the engine. By keeping the cylinder permanently hot and the condenser permanently cold, a great economy on energy used could be effected. This brilliantly simple idea could not be immediately incorporated in a full-scale engine because the engineering of such machines had hitherto been crude and defective. The backing of a Birmingham industrialist, Matthew Boulton, with his resources of capital and technical competence, was needed to convert the idea into a commercial success. Between 1775 and 1800, the period over which Watt’s patents were extended, the Boulton and Watt partnership produced some 500 engines, which despite their high cost in relation to a Newcomen engine were eagerly acquired by the tin-mining industrialists of Cornwall and other power users who badly needed a more economic and reliable source of energy.

During the quarter of a century in which Boulton and Watt exercised their virtual monopoly over the manufacture of improved steam engines, they introduced many important refinements. Basically they converted the engine from a single-acting (i.e., applying power only on the downward stroke of the piston) atmospheric pumping machine into a versatile prime mover that was double-acting and could be applied to rotary motion, thus driving the wheels of industry. The rotary action engine was quickly adopted by British textile manufacturer Sir Richard Arkwright for use in a cotton mill, and although the ill-fated Albion Mill, at the southern end of Blackfriars Bridge in London, was burned down in 1791, when it had been in use for only five years and was still incomplete, it demonstrated the feasibility of applying steam power to large-scale grain milling. Many other industries followed in exploring the possibilities of steam power, and it soon became widely used.

Watt’s patents had the temporary effect of restricting the development of high-pressure steam, necessary in such major power applications as the locomotive. This development came quickly once these patents lapsed in 1800. The Cornish engineer Richard Trevithick introduced higher steam pressures, achieving an unprecedented pressure of 145 pounds per square inch (10 kilograms per square centimetre) in 1802 with an experimental engine at Coalbrookdale, which worked safely and efficiently. Almost simultaneously, the versatile American engineer Oliver Evans built the first high-pressure steam engine in the United States, using, like Trevithick, a cylindrical boiler with an internal fire plate and flue. High-pressure steam engines rapidly became popular in America, partly as a result of Evans’ initiative and partly because very few Watt-type low-pressure engines crossed the Atlantic. Trevithick quickly applied his engine to a vehicle, making the first successful steam locomotive for the Penydarren tramroad in South Wales in 1804. The success, however, was technological rather than commercial because the locomotive fractured the cast iron track of the tramway: the age of the railroad had to await further development both of the permanent way and of the locomotive.

Meanwhile, the stationary steam engine advanced steadily to meet an ever-widening market of industrial requirements. High-pressure steam led to the development of the large beam pumping engines with a complex sequence of valve actions, which became universally known as Cornish engines; their distinctive characteristic was the cutoff of steam injection before the stroke was complete in order to allow the steam to do work by expanding. These engines were used all over the world for heavy pumping duties, often being shipped out and installed by Cornish engineers. Trevithick himself spent many years improving pumping engines in Latin America. Cornish engines, however, were probably most common in Cornwall itself, where they were used in large numbers in the tin and copper mining industries.

Another consequence of high-pressure steam was the practice of compounding, of using the steam twice or more at descending pressures before it was finally condensed or exhausted. The technique was first applied by Arthur Woolf, a Cornish mining engineer, who by 1811 had produced a very satisfactory and efficient compound beam engine with a high-pressure cylinder placed alongside the low-pressure cylinder, with both piston rods attached to the same pin of the parallel motion, which was a parallelogram of rods connecting the piston to the beam, patented by Watt in 1784. In 1845 John McNaught introduced an alternative form of compound beam engine, with the high-pressure cylinder on the opposite end of the beam from the low-pressure cylinder, and working with a shorter stroke. This became a very popular design. Various other methods of compounding steam engines were adopted, and the practice became increasingly widespread; in
the second half of the 19th century triple- or quadruple-expansion engines were being used in industry and marine propulsion. By this time also the conventional beam-type vertical engine adopted by Newcomen and retained by Watt began to be replaced by horizontal-cylinder designs. Beam engines remained in use for some purposes until the eclipse of the reciprocating steam engine in the 20th century, and other types of vertical engine remained popular, but for both large and small duties the engine designs with horizontal cylinders became by far the most common.

A demand for power to generate electricity stimulated new thinking about the steam engine in the 1880s. The problem was that of achieving a sufficiently high rotational speed to make the dynamos function efficiently. Such speeds were beyond the range of the normal reciprocating engine (i.e., with a piston moving backward and forward in a cylinder). Designers began to investigate the possibilities of radical modifications to the reciprocating engine to achieve the speeds desired, or of devising a steam engine working on a completely different principle. In the first category, one solution was to enclose the working parts of the engine and force a lubricant around them under pressure. The Willans engine design, for instance, was of this type and was widely adopted in early British power stations. Another important modification in the reciprocating design was the uniflow engine, which increased efficiency by exhausting steam from ports in the centre of the cylinder instead of requiring it to change its direction of flow in the cylinder with every movement of the piston. Full success in achieving a high-speed steam engine, however, depended on the steam turbine, a design of such novelty that it constituted a major technological innovation. This was invented by Sir Charles Parsons in 1884. By passing steam through the blades of a series of rotors of gradually increasing size (to allow for the expansion of the steam) the energy of the steam was converted to very rapid circular motion, which was ideal for generating electricity. Many refinements have since been made in turbine construction and the size of turbines has been vastly increased, but the basic principles remain the same, and this method still provides the main source of electric power except in those areas in which the mountainous terrain permits the economic generation of hydroelectric power by water turbines. Even the most modern nuclear power plants use steam turbines because technology has not yet solved the problem of transforming nuclear energy directly into electricity. In marine propulsion, too, the steam turbine remains an important source of power despite competition from the internal-combustion engine.

Electricity

The development of electricity as a source of power preceded this conjunction with steam power late in the 19th century. The pioneering work had been done by an international collection of scientists including Benjamin Franklin of Pennsylvania, Alessandro Volta of the University of Pavia, Italy, and Michael Faraday of Britain. It was the latter who had demonstrated the nature of the elusive relationship between electricity and magnetism in 1831, and his experiments provided the point of departure for both the mechanical generation of electric current, previously available only from chemical reactions within voltaic piles or batteries, and the utilization of such current in electric motors. Both the mechanical generator and the motor depend on the rotation of a continuous coil of conducting wire between the poles of a strong magnet; turning the coil produces a current in it, while passing a current through the coil causes it to turn. Both generators and motors underwent substantial development in the middle decades of the 19th century. In particular, French, German, Belgian, and Swiss engineers evolved the most satisfactory forms of armature (the coil of wire) and produced the dynamo, which made the large-scale generation of electricity commercially feasible.

The next problem was that of finding a market. In Britain, with its now well-established tradition of steam power, coal, and coal gas, such a market was not immediately obvious. But in continental Europe and North America there was more scope for experiment. In the United States Thomas Edison applied his inventive genius to finding fresh uses for electricity, and his development of the carbon-filament lamp showed how this form of energy could rival gas as a domestic illuminant. The problem had been that electricity had been used successfully for large installations such as lighthouses in which arc lamps had been powered by generators on the premises, but no way of subdividing the electric light into many small units had been devised. The principle of the filament lamp was that a thin conductor could be made incandescent by an electric current provided that it was sealed in a vacuum to keep it from burning out. Edison and the English chemist Sir Joseph Swan experimented with various materials for the filament and both chose carbon. The result was a highly successful small lamp, which could be varied in size for any sort of requirement. It is relevant that the success of the carbon-filament lamp did not immediately mean the supersession of gas lighting. Coal gas had first been used for lighting by William Murdock at his home in Redruth, Cornwall, where he was the agent for the Boulton and Watt company, in 1792. When he moved to the
headquarters of the firm at Soho in Birmingham in 1798, Matthew Boulton authorized him to experiment in lighting the buildings there by gas, and gas lighting was subsequently adopted by firms and towns all over Britain in the first half of the 19th century. Lighting was normally provided by a fishtail jet of burning gas, but under the stimulus of competition from electric lighting the quality of gas lighting was greatly enhanced by the invention of the gas mantle. Thus improved, gas lighting remained popular for some forms of street lighting until the middle of the 20th century.

Lighting alone could not provide an economical market for electricity because its use was confined to the hours of darkness. Successful commercial generation depended upon the development of other uses for electricity, and particularly on electric traction. The popularity of urban electric trams and the adoption of electric traction on subway systems such as the London Underground thus coincided with the widespread construction of generating equipment in the late 1880s and 1890s. The subsequent spread of this form of energy is one of the most remarkable technological success stories of the 20th century, but most of the basic techniques of generation, distribution, and utilization had been mastered by the end of the 19th century.

**Internal-combustion engine**

Electricity does not constitute a prime mover, for however important it may be as a form of energy it has to be derived from a mechanical generator powered by water, steam, or internal combustion. The internal-combustion engine is a prime mover, and it emerged in the 19th century as a result both of greater scientific understanding of the principles of thermodynamics and of a search by engineers for a substitute for steam power in certain circumstances. In an internal-combustion engine the fuel is burned in the engine: the cannon provided an early model of a single-stroke engine; and several persons had experimented with gunpowder as a means of driving a piston in a cylinder. The major problem was that of finding a suitable fuel, and the secondary problem was that of igniting the fuel in an enclosed space to produce an action that could be easily and quickly repeated. The first problem was solved in the mid-19th century by the introduction of town gas supplies, but the second problem proved more intractable as it was difficult to maintain ignition evenly. The first successful gas engine was made by Etienne Lenoir in Paris in 1859. It was modeled closely on a horizontal steam engine, with an explosive mixture of gas and air ignited by an electric spark on alternate sides of the piston when it was in midstroke position. Although technically satisfactory, the engine was expensive to operate, and it was not until the refinement introduced by the German inventor Nikolaus Otto in 1878 that the gas engine became a commercial success. Otto adopted the four-stroke cycle of induction-compression-firing-exhaust that has been known by his name ever since. Gas engines became extensively used for small industrial establishments, which could thus dispense with the upkeep of a boiler necessary in any steam plant, however small.

**Petroleum**

The economic potential for the internal-combustion engine lay in the need for a light locomotive engine. This could not be provided by the gas engine, depending on a piped supply of town gas, any more than by the steam engine, with its need for a cumbersome boiler; but, by using alternative fuels derived from oil, the internal-combustion engine took to wheels, with momentous consequences. Bituminous deposits had been known in Southwest Asia from antiquity and had been worked for building material, illuminants, and medicinal products. The westward expansion of settlement in America, with many homesteads beyond the range of city gas supplies, promoted the exploitation of the easily available sources of crude oil for the manufacture of kerosene (paraffin). In 1859 the oil industry took on new significance when Edwin L. Drake bored successfully through 69 feet (21 metres) of rock to strike oil in Pennsylvania, thus inaugurating the search for and exploitation of the deep oil resources of the world. While world supplies of oil expanded dramatically, the main demand was at first for the kerosene, the middle fraction distilled from the raw material, which was used as the fuel in oil lamps. The most volatile fraction of the oil, gasoline, remained an embarrassing waste product until it was discovered that this could be burned in a light internal-combustion engine; the result was an ideal prime mover for vehicles. The way was prepared for this development by the success of oil engines burning crude fractions of oil. Kerosene-burning oil engines, modeled closely on existing gas engines, had emerged in the 1870s, and by the late 1880s engines using the vapour of heavy oil in a jet of compressed air and working on the Otto cycle had become an attractive proposition for light duties in places too isolated to use town gas.
The greatest refinements in the heavy-oil engine are associated with the work of Rudolf Diesel of Germany, who took out his first patents in 1892. Working from thermodynamic principles of minimizing heat losses, Diesel devised an engine in which the very high compression of the air in the cylinder secured the spontaneous ignition of the oil when it was injected in a carefully determined quantity. This ensured high thermal efficiency, but it also made necessary a heavy structure because of the high compression maintained, and also a rather rough performance at low speeds compared with other oil engines. It was therefore not immediately suitable for locomotive purposes, but Diesel went on improving his engine and in the 20th century it became an important form of vehicular propulsion.

Meantime the light high-speed gasoline (petrol) engine predominated. The first applications of the new engine to locomotion were made in Germany, where Gottlieb Daimler and Carl Benz equipped the first motorcycle and the first motorcar respectively with engines of their own design in 1885. Benz's "horseless carriage" became the prototype of the modern automobile, the development and consequences of which can be more conveniently considered in relation to the revolution in transport.

By the end of the 19th century, the internal-combustion engine was challenging the steam engine in many industrial and transport applications. It is notable that, whereas the pioneers of the steam engine had been almost all Britons, most of the innovators in internal combustion were continental Europeans and Americans. The transition, indeed, reflects the general change in international leadership in the Industrial Revolution, with Britain being gradually displaced from its position of unchallenged superiority in industrialization and technological innovation. A similar transition occurred in the theoretical understanding of heat engines: it was the work of the Frenchman Sadi Carnot and other scientific investigators that led to the new science of thermodynamics, rather than that of the British engineers who had most practical experience of the engines on which the science was based.

It should not be concluded, however, that British innovation in prime movers was confined to the steam engine, or even that steam and internal combustion represent the only significant developments in this field during the Industrial Revolution. Rather, the success of these machines stimulated speculation about alternative sources of power, and in at least one case achieved a success the full consequences of which were not completely developed. This was the hot-air engine, for which a Scotsman, Robert Stirling, took out a patent in 1816. The hot-air engine depends for its power on the expansion and displacement of air inside a cylinder, heated by the external and continuous combustion of the fuel. Even before the exposition of the laws of thermodynamics, Stirling had devised a cycle of heat transfer that was ingenious and economical. Various constructional problems limited the size of hot-air engines to very small units, so that although they were widely used for driving fans and similar light duties before the availability of the electric motor, they did not assume great technological significance. But the economy and comparative cleanliness of the hot-air engine were making it once more the subject of intensive research in the early 1970s.

The transformation of power technology in the Industrial Revolution had repercussions throughout industry and society. In the first place, the demand for fuel stimulated the coal industry, which had already grown rapidly by the beginning of the 18th century, into continuing expansion and innovation. The steam engine, which enormously increased the need for coal, contributed significantly toward obtaining it by providing more efficient mine pumps and, eventually, improved ventilating equipment. Other inventions such as that of the miners' safety lamp helped to improve working conditions, although the immediate consequence of its introduction in 1816 was to persuade mineowners to work dangerous seams, which had thitherto been regarded as inaccessible. The principle of the lamp was that the flame from the wick of an oil lamp was enclosed within a cylinder of wire gauze, through which insufficient heat passed to ignite the explosive gas (firedamp) outside. It was subsequently improved, but remained a vital source of light in coal mines until the advent of electric battery lamps. With these improvements, together with the simultaneous revolution in the transport system, British coal production increased steadily throughout the 19th century. The other important fuel for the new prime movers was petroleum, and the rapid expansion of its production has already been mentioned. In the hands of John D. Rockefeller and his Standard Oil organization it grew into a vast undertaking in the United States after the end of the Civil War, but the oil-extraction industry was not so well organized elsewhere until the 20th century.

Development of industries

Metallurgy
Another industry that interacted closely with the power revolution was that concerned with metallurgy and the metal trades. The development of techniques for working with iron and steel was one of the outstanding British achievements of the Industrial Revolution. The essential characteristic of this achievement was that changing the fuel of the iron and steel industry from charcoal to coal enormously increased the production of these metals. It also provided another incentive to coal production and made available the materials that were indispensable for the construction of steam engines and every other sophisticated form of machine. The transformation that began with a coke-smelting process in 1709 was carried further by the development of crucible steel in about 1740 and by the puddling and rolling process to produce wrought iron in 1784. The first development led to high-quality cast steel by fusion of the ingredients (wrought iron and charcoal, in carefully measured proportions) in sealed ceramic crucibles that could be heated in a coal-fired furnace. The second applied the principle of the reverberatory furnace, whereby the hot gases passed over the surface of the metal being heated rather than through it, thus greatly reducing the risk of contamination by impurities in the coal fuels, and the discovery that by puddling, or stirring, the molten metal and by passing it hot from the furnace to be hammered and rolled, the metal could be consolidated and the conversion of cast iron to wrought iron made completely effective.

Iron and steel

The result of this series of innovations was that the British iron and steel industry was freed from its reliance upon the forests as a source of charcoal and was encouraged to move toward the major coalfields. Abundant cheap iron thus became an outstanding feature of the early stages of the Industrial Revolution in Britain. Cast iron was available for bridge construction, for the framework of fireproof factories, and for other civil-engineering purposes such as Thomas Telford’s novel cast-iron aqueducts. Wrought iron was available for all manner of mechanical devices requiring strength and precision. Steel remained a comparatively rare metal until the second half of the 19th century, when the situation was transformed by the Bessemer and Siemens processes for manufacturing steel in bulk. Henry Bessemer took out the patent for his converter in 1856. It consisted of a large vessel charged with molten iron, through which cold air was blown. There was a spectacular reaction resulting from the combination of impurities in the iron with oxygen in the air, and when this subsided it left mild steel in the converter. Bessemer was virtually a professional inventor with little previous knowledge of the iron and steel industry; his process was closely paralleled by that of the American iron manufacturer William Kelly, who was prevented by bankruptcy from taking advantage of his invention. Meanwhile, the Siemens-Martin open-hearth process was introduced in 1864, utilizing the hot waste gases of cheap fuel to heat a regenerative furnace, with the initial heat transferred to the gases circulating round the large hearth in which the reactions within the molten metal could be carefully controlled to produce steel of the quality required. The open-hearth process was gradually refined and by the end of the 19th century had overtaken the Bessemer process in the amount of steel produced. The effect of these two processes was to make steel available in bulk instead of small-scale ingots of cast crucible steel, and thenceforward steel steadily replaced wrought iron as the major commodity of the iron and steel industry.

Low-grade ores

The transition to cheap steel did not take place without technical problems, one of the most difficult of which was the fact that most of the easily available low-grade iron ores in the world contain a proportion of phosphorus, which proved difficult to eliminate but which ruined any steel produced from them. The problem was solved by the British scientists S.G. Thomas and Percy Gilchrist, who invented the basic slag process, in which the furnace or converter was lined with an alkaline material with which the phosphorus could combine to produce a phosphatic slag; this, in turn, became an important raw material in the nascent artificial-fertilizer industry. The most important effect of this innovation was to make the extensive phosphoric ores of Lorraine and elsewhere available for exploitation. Among other things, therefore, it contributed significantly to the rise of the German heavy iron and steel industry in the Ruhr. Other improvements in British steel production were made in the late 19th century, particularly in the development of alloys for specialized purposes, but these contributed more to the quality than the quantity of steel and did not affect the shift away from Britain to continental Europe and North America of dominance in this industry. British production continued to increase, but by 1900 it had been overtaken by that of the United States and Germany.

Mechanical engineering
Closely linked with the iron and steel industry was the rise of mechanical engineering, brought about by the demand for steam engines and other large machines, and taking shape for the first time in the Soho workshop of Boulton and Watt in Birmingham, where the skills of the precision engineer, developed in manufacturing scientific instruments and small arms, were first applied to the construction of large industrial machinery. The engineering workshops that matured in the 19th century played a vital part in the increasing mechanization of industry and transport. Not only did they deliver the locomotives, and other hardware in steadily growing quantities, but they also transformed the machine tools on which these machines were made. The lathe became an all-metal, power-driven machine with a completely rigid base and a slide rest to hold the cutting tool, capable of more sustained and vastly more accurate work than the hand- or foot-operated wooden-framed lathes that preceded it. Drilling and slotting machines, milling and planing machines, and a steam hammer invented by James Nasmyth (an inverted vertical steam engine with the hammer on the lower end of the piston rod), were among the machines devised or improved from earlier woodworking models by the new mechanical engineering industry. After the middle of the 19th century, specialization within the machinery industry became more pronounced, as some manufacturers concentrated on vehicle production while others devoted themselves to the particular needs of industries such as coal mining, papermaking, and sugar refining. This movement toward greater specialization was accelerated by the establishment of mechanical engineering in the other industrial nations, especially in Germany, where electrical engineering and other new skills made rapid progress, and in the United States, where labour shortages encouraged the development of standardization and mass-production techniques in fields as widely separated as agricultural machinery, small arms, typewriters, and sewing machines. Even before the coming of the bicycle, the automobile, and the airplane, therefore, the pattern of the modern engineering industry had been clearly established. The dramatic increases in engineering precision, represented by the machine designed by British mechanical engineer Sir Joseph Whitworth in 1856 for measuring to an accuracy of 0.000001 inch (even though such refinement was not necessary in everyday workshop practice), and the corresponding increase in the productive capacity of the engineering industry, acted as a continuing encouragement to further mechanical innovation.

Textiles

The industry that, probably more than any other, gave its character to the British Industrial Revolution was the cotton-textile industry. The traditional dates of the Industrial Revolution bracket the period in which the processes of cotton manufacture in Britain were transformed from those of a small-scale domestic industry scattered over the towns and villages of the South Pennines into those of a large-scale, concentrated, power-driven, mechanized, factory-organized, urban industry. The transformation was undoubtedly dramatic both to contemporaries and to posterity, and there is no doubting its immense significance in the overall pattern of British industrialization. But its importance in the history of technology should not be exaggerated. Certainly there were many interesting mechanical improvements, at least at the beginning of the transformation. The development of the spinning wheel into the spinning jenny, and the use of rollers and moving trolleys to mechanize spinning in the shape of the frame and the mule, respectively, initiated a drastic rise in the productivity of the industry. But these were secondary innovations in the sense that there were precedents for them in the experiments of the previous generation; that in any case the first British textile factory was the Derby silk mill built in 1719; and that the most far-reaching innovation in cotton manufacture was the introduction of steam power to drive carding machines, spinning machines, power looms, and printing machines. This, however, is probably to overstate the case, and the cotton innovators should not be deprived of credit for their enterprise and ingenuity in transforming the British cotton industry and making it the model for subsequent exercises in industrialization. Not only was it copied, belatedly and slowly, by the woolen-cloth industry in Britain, but wherever other nations sought to industrialize they tried to acquire British cotton machinery and the expertise of British cotton industrialists and artisans.

One of the important consequences of the rapid rise of the British cotton industry was the dynamic stimulus it gave to other processes and industries. The rising demand for raw cotton, for example, encouraged the plantation economy of the southern United States and the introduction of the cotton gin, an important contrivance for separating mechanically the cotton fibres from the seeds, husks, and stems of the plant.

Chemicals

In Britain the growth of the textile industry brought a sudden increase of interest in the chemical industry, because one
formidable bottleneck in the production of textiles was the long time that was taken by natural bleaching techniques, relying on sunlight, rain, sour milk, and urine. The modern chemical industry was virtually called into being in order to develop more rapid bleaching techniques for the British cotton industry. Its first success came in the middle of the 18th century, when John Roebuck invented the method of mass producing sulfuric acid in lead chambers. The acid was used directly in bleaching, but it was also used in the production of more effective chlorine bleaches, and in the manufacture of bleaching powder, a process perfected by Charles Tennant at his St. Rollox factory in Glasgow in 1799. This product effectively met the requirements of the cotton-textile industry, and thereafter the chemical industry turned its attention to the needs of other industries, and particularly to the increasing demand for alkali in soap, glass, and a range of other manufacturing processes. The result was the successful establishment of the Leblanc soda process, patented by Nicolas Leblanc in France in 1791, for manufacturing sodium carbonate (soda) on a large scale; this remained the main alkali process used in Britain until the end of the 19th century, even though the Belgian Solvay process, which was considerably more economical, was replacing it elsewhere.

Innovation in the chemical industry shifted, in the middle of the 19th century, from the heavy chemical processes to organic chemistry. The stimulus here was less a specific industrial demand than the pioneering work of a group of German scientists on the nature of coal and its derivatives. Following their work, W.H. Perkin, at the Royal College of Chemistry in London, produced the first artificial dye from aniline in 1856. In the same period, the middle third of the 19th century, work on the qualities of cellulosic materials was leading to the development of high explosives such as nitrocellulose, nitroglycerine, and dynamite, while experiments with the solidification and extrusion of cellulosic liquids were producing the first plastics, such as celluloid, and the first artificial fibres, so-called artificial silk, or rayon. By the end of the century all these processes had become the bases for large chemical industries.

An important by-product of the expanding chemical industry was the manufacture of a widening range of medicinal and pharmaceutical materials as medical knowledge increased and drugs began to play a constructive part in therapy. The period of the Industrial Revolution witnessed the first real progress in medical services since the ancient civilizations. Great advances in the sciences of anatomy and physiology had had remarkably little effect on medical practice. In 18th-century Britain, however, hospital provision increased in quantity although not invariably in quality, while a significant start was made in immunizing people against smallpox culminating in Edward Jenner’s vaccination process of 1796, by which protection from the disease was provided by administering a dose of the much less virulent but related disease of cowpox. But it took many decades of use and further smallpox epidemics to secure its widespread adoption and thus to make it effective in controlling the disease. By this time Louis Pasteur and others had established the bacteriological origin of many common diseases and thereby helped to promote movements for better public health and immunization against many virulent diseases such as typhoid fever and diphtheria. Parallel improvements in anesthetics (beginning with Sir Humphry Davy’s discovery of nitrous oxide, or “laughing gas,” in 1799) and antiseptics were making possible elaborate surgery, and by the end of the century X-rays and radiology were placing powerful new tools at the disposal of medical technology, while the use of synthetic drugs such as the barbiturates and aspirin (acetylsalicylic acid) had become established.

Agriculture

The agricultural improvements of the 18th century had been promoted by people whose industrial and commercial interests made them willing to experiment with new machines and processes to improve the productivity of their estates. Under the same sort of stimuli, agricultural improvement continued into the 19th century and was extended to food processing in Britain and elsewhere. The steam engine was not readily adapted for agricultural purposes, yet ways were found of harnessing it to threshing machines and even to plows by means of a cable between powerful traction engines pulling a plow across a field. In the United States mechanization of agriculture began later than in Britain, but because of the comparative labour shortage it proceeded more quickly and more thoroughly. The McCormick reaper and the combine harvester were both developed in the United States, as were barbed wire and the food-packing and canning industries, Chicago becoming the centre for these processes. The introduction of refrigeration techniques in the second half of the 19th century made it possible to convey meat from Australia and Argentina to European markets, and the same markets encouraged the growth of dairy farming and market gardening, with distant producers such as New Zealand able to send their butter in refrigerated ships to wherever in the world it could be sold.
Civil engineering

For large civil-engineering works, the heavy work of moving earth continued to depend throughout this period on human labour organized by building contractors. But the use of gunpowder, dynamite, and steam diggers helped to reduce this dependence toward the end of the 19th century, and the introduction of compressed air and hydraulic tools also contributed to the lightening of drudgery. The latter two inventions were important in other respects, such as in mining engineering and in the operation of lifts, lock gates, and cranes. The use of a tunneling shield, to allow a tunnel to be driven through soft or uncertain rock strata, was pioneered by the French émigré engineer Marc Brunel in the construction of the first tunnel underneath the Thames River in London (1825–42), and the technique was adopted elsewhere. The iron bell or caisson was introduced for working below water level in order to lay foundations for bridges or other structures, and bridge building made great advances with the perfecting of the suspension bridge—by the British engineers Thomas Telford and Isambard Kingdom Brunel and the German American engineer John Roebling—and the development of the truss bridge, first in timber, then in iron. Wrought iron gradually replaced cast iron as a bridge-building material, although several distinguished cast-iron bridges survive, such as that erected at Ironbridge in Shropshire between 1777 and 1779, which has been fittingly described as the “Stonehenge of the Industrial Revolution.” The sections were cast at the Coalbrookdale furnace nearby and assembled by mortising and wedging on the model of a timber construction, without the use of bolts or rivets. The design was quickly superseded in other cast-iron bridges, but the bridge still stands as the first important structural use of cast iron. Cast iron became very important in the framing of large buildings, the elegant Crystal Palace of 1851 being an outstanding example. This was designed by the ingenious gardener-turned-architect Sir Joseph Paxton on the model of a greenhouse that he had built on the Chatsworth estate of the duke of Devonshire. Its cast-iron beams were manufactured by three different firms and tested for size and strength on the site. By the end of the 19th century, however, steel was beginning to replace cast iron as well as wrought iron, and reinforced concrete was being introduced. In water-supply and sewage-disposal works, civil engineering achieved some monumental successes, especially in the design of dams, which improved considerably in the period, and in long-distance piping and pumping.

Transport and communications

Transport and communications provide an example of a revolution within the Industrial Revolution, so completely were the modes transformed in the period 1750–1900. The first improvements in Britain came in roads and canals in the second half of the 18th century. Although of great economic importance, these were not of much significance in the history of technology, as good roads and canals had existed in continental Europe for at least a century before their adoption in Britain. A network of hard-surfaced roads was built in France in the 17th and early 18th centuries and copied in Germany. Pierre Trésaguet of France improved road construction in the late 18th century by separating the hard-stone wearing surface from the rubble substrata and providing ample drainage. Nevertheless, by the beginning of the 19th century, British engineers were beginning to innovate in both road- and canal-building techniques, with J.L. McAdam’s inexpensive and long-wearing road surface of compacted stones and Thomas Telford’s well-engineered canals. The outstanding innovation in transport, however, was the application of steam power, which occurred in three forms.

Steam locomotive

First was the evolution of the railroad: the combination of the steam locomotive and a permanent travel way of metal rails. Experiments in this conjunction in the first quarter of the 19th century culminated in the Stockton & Darlington Railway, opened in 1825, and a further five years of experience with steam locomotives led to the Liverpool and Manchester Railway, which, when it opened in 1830, constituted the first fully timetabled railway service with scheduled freight and passenger traffic relying entirely on the steam locomotive for traction. This railway was designed by George Stephenson, and the locomotives were the work of Stephenson and his son Robert, the first locomotive being the famous Rocket, which won a competition held by the proprietors of the railway at Rainhill, outside Liverpool, in 1829. The opening of the Liverpool and Manchester line may fairly be regarded as the inauguration of the railway era, which continued until World War I. During this time railways were built across all the countries and continents of the world, opening up vast areas to the markets of industrial society. Locomotives increased rapidly in size and power, but the essential principles remained the same as those established by the Stephensons in the early 1830s: horizontal cylinders mounted beneath a multitubular boiler with a firebox at the rear and a tender carrying supplies of water and fuel. This was the form developed from the Rocket, which had
diagonal cylinders, being itself a stage in the transition from the vertical cylinders, often encased by the boiler, which had been typical of the earliest locomotives (except Trevithick’s Penydarren engine, which had a horizontal cylinder). Meanwhile, the construction of the permanent way underwent a corresponding improvement on that which had been common on the preceding tramroads: wrought-iron, and eventually steel, rails replaced the cast-iron rails, which cracked easily under a steam locomotive, and well-aligned track with easy gradients and substantial supporting civil-engineering works became a commonplace of the railroads of the world.

Road locomotive

The second form in which steam power was applied to transport was that of the road locomotive. There is no technical reason why this should not have enjoyed a success equal to that of the railway engine, but its development was so constricted by the unsuitability of most roads and by the jealousy of other road users that it achieved general utility only for heavy traction work and such duties as road rolling. The steam traction engine, which could be readily adapted from road haulage to power farm machines, was nevertheless a distinguished product of 19th-century steam technology.

Steamboats and ships

The third application was considerably more important, because it transformed marine transport. The initial attempts to use a steam engine to power a boat were made on the Seine River in France in 1775, and several experimental steamships were built by William Symington in Britain at the turn of the 19th century. The first commercial success in steam propulsion for a ship, however, was that of the American Robert Fulton, whose paddle steamer the “North River Steamboat,” commonly known as the Clement after its first overnight port, plied between New York and Albany in 1807, equipped with a Boulton and Watt engine of the modified beam or side-lever type, with two beams placed alongside the base of the engine in order to lower the centre of gravity. A similar engine was installed in the Glasgow-built Comet, which was put in service on the Clyde in 1812 and was the first successful steamship in Europe. All the early steamships were paddle-driven, and all were small vessels suitable only for ferry and packet duties because it was long thought that the fuel requirements of a steamship would be so large as to preclude long-distance cargo carrying. The further development of the steamship was thus delayed until the 1830s, when I.K. Brunel began to apply his ingenious and innovating mind to the problems of steamship construction. His three great steamships each marked a leap forward in technique. The Great Western (launched 1837), the first built specifically for oceanic service in the North Atlantic, demonstrated that the proportion of space required for fuel decreased as the total volume of the ship increased. The Great Britain (launched 1843) was the first large iron ship in the world and the first to be screw-propelled; its return to the port of Bristol in 1970, after a long working life and abandonment to the elements, is a remarkable testimony to the strength of its construction. The Great Eastern (launched 1858), with its total displacement of 18,918 tons, was by far the largest ship built in the 19th century. With a double iron hull and two sets of engines driving both a screw and paddles, this leviathan was never an economic success, but it admirably demonstrated the technical possibilities of the large iron steamship. By the end of the century, steamships were well on the way to displacing the sailing ship on all the main trade routes of the world.

Printing and photography

Communications were equally transformed in the 19th century. The steam engine helped to mechanize and thus to speed up the processes of papermaking and printing. In the latter case the acceleration was achieved by the introduction of the high-speed rotary press and the Linotype machine for casting type and setting it in justified lines (i.e., with even right-hand margins). Printing, indeed, had to undergo a technological revolution comparable to the 15th-century invention of movable type to be able to supply the greatly increasing market for the printed word. Another important process that was to make a vital contribution to modern printing was discovered and developed in the 19th century: photography. The first photograph was taken in 1826 or 1827 by the French physicist J.N. Niepce, using a pewter plate coated with a form of bitumen that hardened on exposure. His partner L.-J.-M. Daguerre and the Englishman W.H. Fox Talbot adopted silver compounds to give light sensitivity, and the technique developed rapidly in the middle decades of the century. By the 1890s George Eastman in the United States was manufacturing cameras and celluloid photographic film for a popular market, and the first experiments with the cinema were beginning to attract attention.
Telegraphs and telephones

The great innovations in communications technology, however, derived from electricity. The first was the electric telegraph, invented or at least made into a practical proposition for use on the developing British railway system by two British inventors, Sir William Cooke and Sir Charles Wheatstone, who collaborated on the work and took out a joint patent in 1837. Almost simultaneously, the American inventor Samuel F.B. Morse devised the signaling code that was subsequently adopted all over the world. In the next quarter of a century the continents of the world were linked telegraphically by transoceanic cables, and the main political and commercial centres were brought into instantaneous communication. The telegraph system also played an important part in the opening up of the American West by providing rapid aid in the maintenance of law and order. The electric telegraph was followed by the telephone, invented by Alexander Graham Bell in 1876 and adopted quickly for short-range oral communication in the cities of America and at a somewhat more leisurely pace in those of Europe. About the same time, theoretical work on the electromagnetic properties of light and other radiation was beginning to produce astonishing experimental results, and the possibilities of wireless telegraphy began to be explored. By the end of the century, Guglielmo Marconi had transmitted messages over many miles in Britain and was preparing the apparatus with which he made the first transatlantic radio communication on Dec. 12, 1901. The world was thus being drawn inexorably into a closer community by the spread of instantaneous communication.

Military technology

One area of technology was not dramatically influenced by the application of steam or electricity by the end of the 19th century: military technology. Although the size of armies increased between 1750 and 1900, there were few major innovations in techniques, except at sea where naval architecture rather reluctantly accepted the advent of the iron steamship and devoted itself to matching ever-increasing firepower with the strength of the armour plating on the hulls. The quality of artillery and of firearms improved with the new high explosives that became available in the middle of the 19th century, but experiments such as the three-wheeled iron gun carriage, invented by the French army engineer Nicolas Cugnot in 1769, which counts as the first steam-powered road vehicle, did not give rise to any confidence that steam could be profitably used in battle. Railroads and the electric telegraph were put to effective military use, but in general it is fair to say that the 19th century put remarkably little of its tremendous and innovative technological effort into devices for war.

In the course of its dynamic development between 1750 and 1900, important things happened to technology itself. In the first place, it became self-conscious. This change is sometimes characterized as one from a craft-based technology to one based on science, but this is an oversimplification. What occurred was rather an increase in the awareness of technology as a socially important function. It is apparent in the growing volume of treatises on technological subjects from the 16th century onward and in the rapid development of patent legislation to protect the interests of technological innovators. It is apparent also in the development of technical education, uneven at first, being confined to the French polytechnics and spreading thence to Germany and North America but reaching even Britain, which had been most opposed to its formal recognition as part of the structure of education, by the end of the 19th century. Again, it is apparent in the growth of professional associations for engineers and for other specialized groups of technologists.

Second, by becoming self-conscious, technology attracted attention in a way it had never done before, and vociferous factions grew up to praise it as the mainspring of social progress and the development of democracy or to criticize it as the bane of modern man, responsible for the harsh discipline of the "dark Satanic mills" and the tyranny of the machine and the squalor of urban life. It was clear by the end of the 19th century that technology was an important feature in industrial society and that it was likely to become more so. Whatever was to happen in the future, technology had come of age and had to be taken seriously as a formative factor of the utmost significance in the continuing development of civilization.

The 20th century

Technology from 1900 to 1945

Recent history is notoriously difficult to write, because of the mass of material and the problem of distinguishing the significant from the insignificant among events that have virtually the power of contemporary experience. In respect to the recent history of technology, however, one fact stands out clearly: despite the immense achievements of technology by
1900, the following decades witnessed more advance over a wide range of activities than the whole of previously recorded history. The airplane, the rocket and interplanetary probes, electronics, atomic power, antibiotics, insecticides, and a host of new materials have all been invented and developed to create an unparalleled social situation, full of possibilities and dangers, which would have been virtually unimaginable before the present century.

In venturing to interpret the events of the 20th century, it will be convenient to separate the years before 1945 from those that followed. The years 1900 to 1945 were dominated by the two World Wars, while those since 1945 were preoccupied by the need to avoid another major war. The dividing point is one of outstanding social and technological significance: the detonation of the first atomic bomb at Alamogordo, N.M., in July 1945.

There were profound political changes in the 20th century related to technological capacity and leadership. It may be an exaggeration to regard the 20th century as "the American century," but the rise of the United States as a superstate was sufficiently rapid and dramatic to excuse the hyperbole. It was a rise based upon tremendous natural resources exploited to secure increased productivity through widespread industrialization, and the success of the United States in achieving this objective was tested and demonstrated in the two World Wars. Technological leadership passed from Britain and the European nations to the United States in the course of these wars. This is not to say that the springs of innovation went dry in Europe. Many important inventions of the 20th century originated there. But it was the United States that had the capacity to assimilate innovations and take full advantage from them at times when other countries were deficient in one or other of the vital social resources without which a brilliant invention cannot be converted into a commercial success. As with Britain in the Industrial Revolution, the technological vitality of the United States in the 20th century was demonstrated less by any particular innovations than by its ability to adopt new ideas from whatever source they come.

The two World Wars were themselves the most important instruments of technological as well as political change in the 20th century. The rapid evolution of the airplane is a striking illustration of this process, while the appearance of the tank in the first conflict and of the atomic bomb in the second show the same signs of response to an urgent military stimulus. It has been said that World War I was a chemists' war, on the basis of the immense importance of high explosives and poison gas. In other respects the two wars hastened the development of technology by extending the institutional apparatus for the encouragement of innovation by both the state and private industry. This process went further in some countries than in others, but no major belligerent nation could resist entirely the need to support and coordinate its scientific-technological effort. The wars were thus responsible for speeding the transformation from "little science," with research still largely restricted to small-scale efforts by a few isolated scientists, to "big science," with the emphasis on large research teams sponsored by governments and corporations, working collectively on the development and application of new techniques. While the extent of this transformation must not be overstated, and recent research has tended to stress the continuing need for the independent inventor at least in the stimulation of innovation, there can be little doubt that the change in the scale of technological enterprises had far-reaching consequences. It was one of the most momentous transformations of the 20th century, for it altered the quality of industrial and social organization. In the process it assured technology, for the first time in its long history, a position of importance and even honour in social esteem.

Fuel and power

There were no fundamental innovations in fuel and power before the breakthrough of 1945, but there were several significant developments in techniques that had originated in the previous century. An outstanding development of this type was the internal-combustion engine, which was continuously improved to meet the needs of road vehicles and airplanes. The high-compression engine burning heavy-oil fuels, invented by Rudolf Diesel in the 1890s, was developed to serve as a submarine power unit in World War I and was subsequently adapted to heavy road haulage duties and to agricultural tractors. Moreover, the sort of development that had transformed the reciprocating steam engine into the steam turbine occurred with the internal-combustion engine, the gas turbine replacing the reciprocating engine for specialized purposes such as aero-engines, in which a high power-to-weight ratio is important. Admittedly, this adaptation had not proceeded very far by 1945, although the first jet-powered aircraft were in service by the end of the war. The theory of the gas turbine, however, had been understood since the 1920s at least, and in 1929 Sir Frank Whittle, then taking a flying instructor's course with the Royal Air Force, combined it with the principle of jet propulsion in the engine for which he took out a patent in the following year. But the construction of a satisfactory gas-turbine engine was delayed for a decade by the lack of
resources, and particularly by the need to develop new metal alloys that could withstand the high temperatures generated in the engine. This problem was solved by the development of a nickel-chromium alloy, and, with the gradual solution of the other problems, work went on in both Germany and Britain to seize a military advantage by applying the jet engine to combat aircraft.

Gas-turbine engine

The principle of the gas turbine is that of compressing and burning air and fuel in a combustion chamber and using the exhaust jet from this process to provide the reaction that propels the engine forward. In its turbopropeller form, which developed only after World War II, the exhaust drives a shaft carrying a normal airscrew (propeller). Compression is achieved in a gas-turbine engine by admitting air through a turbine rotor. In the so-called ramjet engine, intended to operate at high speeds, the momentum of the engine through the air achieves adequate compression. The gas turbine has been the subject of experiments in road, rail, and marine transport, but for all purposes except that of air transport its advantages have not so far been such as to make it a viable rival to traditional reciprocating engines.

Petroleum

As far as fuel is concerned, the gas turbine burns mainly the middle fractions (kerosene, or paraffin) of refined oil, but the general tendency of its widespread application was to increase still further the dependence of the industrialized nations on the producers of crude oil, which became a raw material of immense economic value and international political significance. The refining of this material itself underwent important technological development. Until the 20th century it consisted of a fairly simple batch process whereby oil was heated until it vaporized, when the various fractions were distilled separately. Apart from improvements in the design of the stills and the introduction of continuous-flow production, the first big advance came in 1913 with the introduction of thermal cracking. This process took the less volatile fractions after distillation and subjected them to heat under pressure, thus cracking the heavy molecules into lighter molecules and so increasing the yield of the most valuable fuel, petrol or gasoline. The discovery of this ability to tailor the products of crude oil to suit the market marks the true beginning of the petrochemical industry. It received a further boost in 1936, with the introduction of catalytic cracking. By the use of various catalysts in the process, means were devised for still further manipulating the molecules of the hydrocarbon raw material. The development of modern plastics followed directly on this (see below Plastics). So efficient had the processes of utilization become that by the end of World War II the petrochemical industry had virtually eliminated all waste materials.

Electricity

All the principles of generating electricity had been worked out in the 19th century, but by its end these had only just begun to produce electricity on a large scale. The 20th century witnessed a colossal expansion of electrical power generation and distribution. The general pattern has been toward ever-larger units of production, using steam from coal- or oil-fired boilers. Economies of scale and the greater physical efficiency achieved as higher steam temperatures and pressures were attained both reinforced this tendency. Experience in the United States indicates the trend: in the first decade of the 20th century, a generating unit with a capacity of 25,000 kilowatts with pressures up to 200–300 pounds per square inch at 400–500 °F (about 200–265 °C) was considered large, but by 1930 the largest unit was 208,000 kilowatts with pressures of 1,200 pounds per square inch at a temperature of 725 °F, while the amount of fuel necessary to produce a kilowatt-hour of electricity and the price to the consumer had fallen dramatically. As the market for electricity increased, so did the distance over which it was transmitted, and the efficiency of transmission required higher and higher voltages. The small direct-current generators of early urban power systems were abandoned in favour of alternating-current systems, which could be adapted more readily to high voltages. Transmission over a line of 155 miles (250 km) was established in California in 1908 at 110,000 volts, and Hoover Dam in the 1930s used a line of 300 miles (480 km) at 287,000 volts. The latter case may serve as a reminder that hydroelectric power, using a fall of water to drive water turbines, was developed to generate electricity where the climate and topography make it possible to combine production with convenient transmission to a market. Remarkable levels of efficiency were achieved in modern plants. One important consequence of the ever-expanding consumption of electricity in the industrialized countries has been the linking of local systems to provide vast power grids, or
pools, within which power can be shifted easily to meet changing local needs for current.

**Atomic power**

Until 1945, electricity and the internal-combustion engine were the dominant sources of power for industry and transport in the 20th century, although in some parts of the industrialized world steam power and even older prime movers remained important. Early research in nuclear physics was more scientific than technological, stirring little general interest. In fact, from the work of Ernest Rutherford, Albert Einstein, and others to the first successful experiments in splitting heavy atoms in Germany in 1938, no particular thought was given to engineering potential. The war led the Manhattan Project to produce the fission bomb that was first exploded at Alamogordo, N.M. Only in its final stages did even this program become a matter of technology, when the problems of building large reactors and handling radioactive materials had to be solved. At this point it also became an economic and political matter, because very heavy capital expenditure was involved. Thus, in this crucial event of the mid-20th century, the convergence of science, technology, economics, and politics finally took place.

**Industry and innovation**

There were technological innovations of great significance in many aspects of industrial production during the 20th century. It is worth observing, in the first place, that the basic matter of industrial organization became one of self-conscious innovation, with organizations setting out to increase their productivity by improved techniques. Methods of work study, first systematically examined in the United States at the end of the 19th century, were widely applied in U.S. and European industrial organizations in the first half of the 20th century, evolving rapidly into scientific management and the modern studies of industrial administration, organization and method, and particular managerial techniques. The object of these exercises was to make industry more efficient and thus to increase productivity and profits, and there can be no doubt that they were remarkably successful, if not quite as successful as some of their advocates maintained. Without this superior industrial organization, it would not have been possible to convert the comparatively small workshops of the 19th century into the giant engineering establishments of the 20th, with their mass-production and assembly-line techniques. The rationalization of production, so characteristic of industry in the 20th century, may thus be legitimately regarded as the result of the application of new techniques that form part of the history of technology since 1900.

**Improvements in iron and steel**

Another field of industrial innovation in the 20th century was the production of new materials. As far as volume of consumption goes, humankind still lives in the Iron Age, with the utilization of iron exceeding that of any other material. But this dominance of iron has been modified in three ways: by the skill of metallurgists in alloying iron with other metals; by the spread of materials such as glass and concrete in building; and by the appearance and widespread use of entirely new materials, particularly plastics. Alloys had already begun to become important in the iron and steel industry in the 19th century (apart from steel itself, which is an alloy of iron and carbon). Self-hardening tungsten steel was first produced in 1868 and manganese steel, possessing toughness rather than hardness, in 1887. Manganese steel is also nonmagnetic; this fact suggests great possibilities for this steel in the electric power industry. In the 20th century steel alloys multiplied. Silicon steel was found to be useful because, in contrast to manganese steel, it is highly magnetic. In 1913 the first stainless steels were made in England by alloying steel with chromium, and the Krupp works in Germany produced stainless steel in 1914 with 18 percent chromium and 8 percent nickel. The importance of a nickel-chromium alloy in the development of the gas-turbine engine in the 1930s has already been noted. Many other alloys also came into widespread use for specialized purposes.

**Building materials**

Methods of producing traditional materials like glass and concrete on a larger scale also supplied alternatives to iron, especially in building; in the form of reinforced concrete, they supplemented structural iron. Most of the entirely new materials were nonmetallic, although at least one new metal, aluminum, reached proportions of large-scale industrial significance in the 20th century. The ores of this metal are among the most abundant in the crust of the Earth, but, before the provision of plentiful cheap electricity made it feasible to use an electrolytic process on an industrial scale, the metal was
extracted only at great expense. The strength of aluminum, compared weight for weight with steel, made it a valuable material in aircraft construction, and many other industrial and domestic uses were found for it. In 1900 world production of aluminum was 3,000 tons, about half of which was made using cheap electric power from Niagara Falls. Production rose rapidly since.

Electrolytic processes had already been used in the preparation of other metals. At the beginning of the 19th century, Davy pioneered the process by isolating potassium, sodium, barium, calcium, and strontium, although there was little commercial exploitation of these substances. By the beginning of the 20th century, significant amounts of magnesium were being prepared electrolytically at high temperatures, and the electric furnace made possible the production of calcium carbide by the reaction of calcium oxide (lime) and carbon (coke). In another electric furnace process, calcium carbide reacted with nitrogen to form calcium cyanamide, from which a useful synthetic resin could be made.

Plastics

The quality of plasticity is one that had been used to great effect in the crafts of metallurgy and ceramics. The use of the word plastics as a collective noun, however, refers not so much to the traditional materials employed in these crafts as to new substances produced by chemical reactions and molded or pressed to take a permanent rigid shape. The first such material to be manufactured was Parkesine, developed by the British inventor Alexander Parkes. Parkesine, made from a mixture of chloroform and castor oil, was “a substance hard as horn, but as flexible as leather, capable of being cast or stamped, painted, dyed or carved.” The words are from a guide to the International Exhibition of 1862 in London, at which Parkesine won a bronze medal for its inventor. It was soon followed by other plastics, but—apart from celluloid, a cellulose nitrate composition using camphor as a solvent and produced in solid form (as imitation horn for billiard balls) and in sheets (for men’s collars and photographic film)—these had little commercial success until the 20th century.

The early plastics relied upon the large molecules in cellulose, usually derived from wood pulp. Leo H. Baekeland, a Belgian American inventor, introduced a new class of large molecules when he took out his patent for Bakelite in 1909. Bakelite is made by the reaction between formaldehyde and phenolic materials at high temperatures; the substance is hard, infusible, and chemically resistant (the type known as thermosetting plastic). As a nonconductor of electricity, it proved to be exceptionally useful for all sorts of electrical appliances. The success of Bakelite gave a great impetus to the plastics industry, to the study of coal tar derivatives and other hydrocarbon compounds, and to the theoretical understanding of the structure of complex molecules. This activity led to new dyestuffs and detergents, but it also led to the successful manipulation of molecules to produce materials with particular qualities such as hardness or flexibility. Techniques were devised, often requiring catalysts and elaborate equipment, to secure these polymers—that is, complex molecules produced by the aggregation of simpler structures. Linear polymers give strong fibres, film-forming polymers have been useful in paints, and mass polymers have formed solid plastics.

Synthetic Fibres

The possibility of creating artificial fibres was another 19th-century discovery that did not become commercially significant until the 20th century, when such fibres were developed alongside the solid plastics to which they are closely related. The first artificial textiles had been made from rayon, a silklke material produced by extruding a solution of nitrocellulose in acetic acid into a coagulating bath of alcohol, and various other cellulose materials were used in this way. But later research, exploiting the polymerization techniques being used in solid plastics, culminated in the production of nylon just before the outbreak of World War II. Nylon consists of long chains of carbon-based molecules, giving fibres of unprecedented strength and flexibility. It is formed by melting the component materials and extruding them; the strength of the fibre is greatly increased by stretching it when cold. Nylon was developed with the women’s stocking market in mind, but the conditions of war gave it an opportunity to demonstrate its versatility and reliability as parachute fabric and towlines. This and other synthetic fibres became generally available only after the war.

Synthetic Rubber

The chemical industry in the 20th century put a wide range of new materials at the disposal of society. It also succeeded in
replacing natural sources of some materials. An important example of this is the manufacture of artificial rubber to meet a world demand far in excess of that which could be met by the existing rubber plantations. This technique was pioneered in Germany during World War I. In this effort, as in the development of other materials such as high explosives and dyestuffs, the consistent German investment in scientific and technical education paid dividends, for advances in all these fields of chemical manufacturing were prepared by careful research in the laboratory.

**Pharmaceuticals and medical technology**

An even more dramatic result of the growth in chemical knowledge was the expansion of the pharmaceutical industry. The science of pharmacy emerged slowly from the traditional empiricism of the herbalist, but by the end of the 19th century there had been some solid achievements in the analysis of existing drugs and in the preparation of new ones. The discovery in 1856 of the first aniline dye had been occasioned by a vain attempt to synthesize quinine from coal tar derivatives. Greater success came in the following decades with the production of the first synthetic antifever drugs and painkilling compounds, culminating in 1899 in the conversion of salicylic acid into acetylsalicylic acid (aspirin), which is still the most widely used drug. Progress was being made simultaneously with the sulfonal hypnotics and the barbiturate group of drugs, and early in the 20th century Paul Ehrlich of Germany successfully developed an organic compound containing arsenic—606, denoting how many tests he had made, but better known as Salvarsan—which was effective against syphilis. The significance of this discovery, made in 1910, was that 606 was the first drug devised to overwhelm an invading microorganism without offending the host. In 1935 the discovery that Prontosil, a red dye developed by the German synthetic dyestuff industry, was an effective drug against streptococcal infections (leading to blood poisoning) introduced the important sulfa drugs. Alexander Fleming's discovery of penicillin in 1928 was not immediately followed up, because it proved very difficult to isolate the drug in a stable form from the mold in which it was formed. But the stimulus of World War II gave a fresh urgency to research in this field, and commercial production of penicillin, the first of the antibiotics, began in 1941. These drugs work by preventing the growth of pathogenic organisms. All these pharmaceutical advances demonstrate an intimate relationship with chemical technology.

Other branches of medical technology made significant progress. Anesthetics and antiseptics had been developed in the 19th century, opening up new possibilities for complex surgery. Techniques of blood transfusion, examination by X-rays (discovered in 1895), radiation therapy (following demonstration of the therapeutic effects of ultraviolet light in 1893 and the discovery of radium in 1898), and orthopedic surgery for bone disorders all developed rapidly. The techniques of immunology similarly advanced, with the development of vaccines effective against typhoid and other diseases.

**Food and agriculture**

The increasing chemical understanding of drugs and microorganisms was applied with outstanding success to the study of food. The analysis of the relationship between certain types of food and human physical performance led to the identification of vitamins in 1911 and to their classification into three types in 1919, with subsequent additions and subdivisions. It was realized that the presence of these materials is necessary for a healthy diet, and eating habits and public health programs were adjusted accordingly. The importance of trace elements, very minor constituents, was also discovered and investigated, beginning in 1895 with the realization that goitre is caused by a deficiency of iodine.

As well as improving in quality, the quantity of food produced in the 20th century increased rapidly as a result of the intensive application of modern technology. The greater scale and complexity of urban life created a pressure for increased production and a greater variety of foodstuffs, and the resources of the internal-combustion engine, electricity, and chemical technology were called upon to achieve these objectives. The internal-combustion engine was utilized in the tractor, which became the almost universal agent of mobile power on the farm in the industrialized countries. The same engines powered other machines such as combine harvesters, which became common in the United States in the early 20th century, although their use was less widespread in the more labour-intensive farms of Europe, especially before World War II. Synthetic fertilizers, an important product of the chemical industry, became popular in most types of farming, and other chemicals—pesticides and herbicides—appeared toward the end of the period, effecting something of an agrarian revolution. Once again, World War II gave a powerful boost to development. Despite problems of pollution that developed later, the introduction of DDT as a highly effective insecticide in 1944 was a particularly significant achievement of chemical
technology. Food processing and packaging also advanced—dehydration techniques such as vacuum-contact drying were introduced in the 1930s—but the 19th-century innovations of canning and refrigeration remained the dominant techniques of preservation.

Civil engineering

Important development occurred in civil engineering in the first half of the 20th century, although there were few striking innovations. Advancing techniques for large-scale construction produced many spectacular skyscrapers, bridges, and dams all over the world but especially in the United States. The city of New York acquired its characteristic skyline, built upon the exploitation of steel frames and reinforced concrete. Conventional methods of building in brick and masonry had reached the limits of feasibility in the 1800s in office blocks up to 16-stories high, and the future lay with the skeleton frame or cage construction pioneered in the 1880s in Chicago. The vital ingredients for the new tall buildings or skyscrapers that followed were abundant cheap steel—for columns, beams, and trusses—and efficient passenger elevators. The availability of these developments and the demand for more and more office space in the thriving cities of Chicago and New York caused the boom in skyscraper building that continued until 1931, when the Empire State Building, with its total height of 1,250 feet (381 metres) and 102 stories, achieved a limit not exceeded for 40 years and demonstrated the strength of its structure by sustaining the crash impact of a B-25 bomber in July 1945 with only minor damage to the building. The Great Depression brought a halt to skyscraper building from 1932 until after World War II.

Concrete, and more especially reinforced concrete (that is, concrete set around a framework or mesh of steel), played an important part in the construction of the later skyscrapers, and this material also led to the introduction of more imaginative structural forms in buildings and to the development of prefabrication techniques. The use of large concrete members in bridges and other structures has been made possible by the technique of prestressing: by casting the concrete around stretched steel wires, allowing it to set, then relaxing the tension in the wires, it is possible to induce compressive stresses in the concrete that offset the tensile stresses imposed by the external loading, and in this way the members can be made stronger and lighter. The technique was particularly applicable in bridge building. The construction of large-span bridges received a setback, however, with the dramatic collapse of the Tacoma Narrows (Washington) Suspension Bridge in the United States in 1940, four months after it was completed. This led to a reassessment of wind effects on the loading of large suspension bridges and to significant improvements in subsequent designs. Use of massed concrete has produced spectacular high arch dams, in which the weight of water is transmitted in part to the abutments by the curve of the concrete wall; such dams need not depend upon the sheer bulk of impervious material as in a conventional gravity or embankment dam.

Transportation

Some of the outstanding achievements of the 20th century are provided by transportation history. In most fields there was a switch from steam power, supreme in the previous century, to internal combustion and electricity. Steam, however, retained its superiority in marine transport: the steam turbine provided power for a new generation of large ocean liners beginning with the Mauretania, developing 70,000 horsepower and a speed of 27 knots (27 nautical miles, or 50 km, per hour) in 1906 and continuing throughout the period, culminating in the Queen Elizabeth, launched in 1938 with about 200,000 horsepower and a speed of 28.5 knots. Even here, however, there was increasing competition from large diesel-powered motor vessels. Most smaller ships adopted this form of propulsion, and even the steamships accepted the convenience of oil-burning boilers in place of the cumbersome coal burners with their large bunkers.

On land, steam fought a long rearguard action, but the enormous popularity of the automobile deprived the railways of much of their passenger traffic and forced them to seek economies in conversion to diesel engines or electric traction, although these developments had not spread widely in Europe by the outbreak of World War II. Meanwhile, the automobile stimulated prodigious feats of production. Henry Ford led the way in the adoption of assembly-line mass production; his spectacularly successful Model T, the ‘Tin Lizzie,’ was manufactured in this way first in 1913, and by 1923 production had risen to nearly two million per year. Despite this and similar successes in other countries, the first half of the 20th century was not a period of great technological innovation in the motorcar, which retained the main design features given to it in the last decade of the 19th century. For all the refinements (for example, the self-starter) and multitudinous varieties, the major fact of the
automobile in this period was its quantity.

The airplane is entirely a product of the 20th century, unlike the automobile, to which its development was intimately related. This is not to say that experiments with flying machines had not taken place earlier. Throughout the 19th century, to go back no further, investigations into aerodynamic effects were carried out by inventors such as Sir George Cayley in England, leading to the successful glider flights of Otto Lilienthal and others. Several designers perceived that the internal-combustion engine promised to provide the light, compact power unit that was a prerequisite of powered flight, and on Dec. 17, 1903, Wilbur and Orville Wright in their Flyer I at the Kill Devil Hills in North Carolina achieved sustained, controlled, powered flight, one of the great “firsts” in the history of technology. The Flyer I was a propeller-driven adaptation of the biplane gliders that the Wright brothers had built and learned to fly in the previous years. They had devised a system of control through elevator, rudder, and a wing-warping technique that served until the introduction of ailerons. Within a few years the brothers were flying with complete confidence, astonishing the European pioneers of flight when they took their airplane across the Atlantic to give demonstrations in 1908. Within a few months of this revelation, however, the European designers had assimilated the lesson and were pushing ahead the principles of aircraft construction. World War I gave a great impetus to this technological development, transforming small-scale scattered aircraft manufacture into a major industry in all the main belligerent countries, and transforming the airplane itself from a fragile construction in wood and glue into a robust machine capable of startling aerobatic feats.

The end of the war brought a setback to this new industry, but the airplane had evolved sufficiently to reveal its potential as a medium of civil transport, and during the interwar years the establishment of transcontinental air routes provided a market for large, comfortable, and safe aircraft. By the outbreak of World War II, metal-framed-and-skinned aircraft had become general, and the cantilevered monoplane structure had replaced the biplane for most purposes. War again provided a powerful stimulus to aircraft designers; engine performance was especially improved, and the gas turbine received its first practical application. Other novel features of these years included the helicopter, deriving lift from its rotating wings, or rotors, and the German V-1 flying bomb, a pilotless aircraft.

The war also stimulated the use of gliders for the transport of troops, the use of parachutes for escape from aircraft and for attack by paratroops, and the use of gas-filled balloons for antiaircraft barrages. The balloon had been used for pioneer aeronautical experiments in the 19th century, but its practical uses had been hampered by the lack of control over its movements. The application of the internal-combustion engine to a rigid-frame balloon airship by Ferdinand von Zeppelin had temporarily made a weapon of war in 1915, although experience soon proved that it could not survive in competition with the airplane. The apparently promising prospects of the dirigible (that is, maneuverable) airship in civil transport between the wars were ended by a series of disasters, the worst of which was the destruction of the Hindenburg in New Jersey in 1937. Since then the airplane has been unchallenged in the field of air transport.

Communications

The spectacular transport revolution of the 20th century was accompanied by a communications revolution quite as dramatic, although technologically springing from different roots. In part, well-established media of communication like printing participated in this revolution, although most of the significant changes—such as the typewriter, the Linotype, and the high-speed power-driven rotary press—were achievements of the 19th century. Photography was also a proved and familiar technique by the end of the 19th century, but cinematography was new and did not become generally available until after World War I, when it became enormously popular.

The real novelties in communications in the 20th century came in electronics. The scientific examination of the relationship between light waves and electromagnetic waves had already revealed the possibility of transmitting electromagnetic signals between widely separated points, and on Dec. 12, 1901, Guglielmo Marconi succeeded in transmitting the first wireless message across the Atlantic. Early equipment was crude, but within a few years striking progress was made in improving the means of transmitting and receiving coded messages. Particularly important was the development of the thermionic valve, a device for rectifying (that is, converting a high-frequency oscillating signal into a unidirectional current capable of registering as a sound) an electromagnetic wave. This was essentially a development from the carbon-filament electric lightbulb. In 1883 Edison had found that in these lamps a current flowed between the filament and a nearby test electrode, called the plate, if the electric potential of the plate was positive with respect to the filament. This current, called the Edison
effect, was later identified as a stream of electrons radiated by the hot filament. In 1904 Sir John Ambrose Fleming of Britain discovered that by placing a metal cylinder around the filament in the bulb and by connecting the cylinder (the plate) to a third terminal, a current could be rectified so that it could be detected by a telephone receiver. Fleming’s device was known as the diode, and two years later, in 1906, Lee De Forest of the United States made the significant improvement that became known as the triode by introducing a third electrode (the grid) between the filament and the plate. The outstanding feature of this refinement was its ability to amplify a signal. Its application made possible by the 1920s the widespread introduction of live-voice broadcasting in Europe and America, with a consequent boom in the production of radio receivers and other equipment.

This, however, was only one of the results derived from the application of the thermionic valve. The idea of harnessing the flow of electrons was applied in the electron microscope, radar (a detection device depending on the capacity of some radio waves to be reflected by solid objects), the electronic computer, and in the cathode-ray tube of the television set. The first experiments in the transmission of pictures had been greeted with ridicule. Working on his own in Britain, John Logie Baird in the 1920s demonstrated a mechanical scanner able to convert an image into a series of electronic impulses that could then be reassembled on a viewing screen as a pattern of light and shade. Baird’s system, however, was rejected in favour of electronic scanning, developed in the United States by Philo Farnsworth and Vladimir Zworykin with the powerful backing of the Radio Corporation of America. Their equipment operated much more rapidly and gave a more satisfactory image. By the outbreak of World War II, television services were being introduced in several countries, although the war suspended their extension for a decade. The emergence of television as a universal medium of mass communication is therefore a phenomenon of the postwar years. But already by 1945 the cinema and the radio had demonstrated their power in communicating news, propaganda, commercial advertisements, and entertainment.

Military technology

It has been necessary to refer repeatedly to the effects of the two World Wars in promoting all kinds of innovation. It should be observed also that technological innovations transformed the character of war itself. One weapon developed during World War II deserves a special mention. The principle of rocket propulsion was well known earlier, and its possibilities as a means of achieving speeds sufficient to escape Earth’s gravitational pull had been pointed out by such pioneers as the Russian Konstantin Tsioiokovsky and the American Robert H. Goddard. The latter built experimental liquid-fueled rockets in 1926. Simultaneously, a group of German and Romanian pioneers was working along the same lines, and it was this team that was taken over by the German war effort in the 1930s and given the resources to develop a rocket capable of delivering a warhead hundreds of miles away. At the Peenemünde base on the island of Usedom in the Baltic, Wernher von Braun and his team created the V-2. Fully fueled, it weighed 14 tons; it was 40 feet (12 metres) long and was propelled by burning a mixture of alcohol and liquid oxygen. Reaching a height of more than 100 miles (160 km), the V-2 marked the beginning of the space age, and members of its design team were instrumental in both the Soviet and U.S. space programs after the war.

Technology had a tremendous social impact in the period 1900–45. The automobile and electric power, for instance, radically changed both the scale and the quality of 20th-century life, promoting a process of rapid urbanization and a virtual revolution in living through mass production of household goods and appliances. The rapid development of the airplane, the cinema, and radio made the world seem suddenly smaller and more accessible. In the years following 1945 the constructive and creative opportunities of modern technology could be exploited, although the process has not been without its problems.

Space-age technology

The years since World War II ended have been spent in the shadow of nuclear weapons, even though they have not been used in war since that time. These weapons underwent momentous development: the fission bombs of 1945 were superseded by the more powerful fusion bombs in 1950, and before 1960 rockets were shown capable of delivering these weapons at ranges of thousands of miles. This new military technology had an incalculable effect on international relations, for it contributed to the polarization of world power blocs while enforcing a caution, if not discipline, in the conduct of
international affairs that was absent earlier in the 20th century.

The fact of nuclear power was by no means the only technological novelty of the post-1945 years. So striking indeed were the advances in engineering, chemical and medical technology, transport, and communications that some commentators wrote, somewhat misleadingly, of the "second Industrial Revolution" in describing the changes in these years. The rapid development of electronic engineering created a new world of computer technology, remote control, miniaturization, and instant communication. Even more expressive of the character of the period was the leap over the threshold of extraterrestrial exploration. The techniques of rocketry, first applied in weapons, were developed to provide launch vehicles for satellites and lunar and planetary probes and eventually, in 1969, to set the first men on the Moon and bring them home safely again. This astonishing achievement was stimulated in part by the international ideological rivalry already mentioned, as only the Soviet Union and the United States had both the resources and the will to support the huge expenditures required. It justifies the description of this period, however, as that of "space-age technology."

Power

The great power innovation of this period was the harnessing of nuclear energy. The first atomic bombs represented only a comparatively crude form of nuclear fission, releasing the energy of the radioactive material immediately and explosively. But it was quickly appreciated that the energy released within a critical atomic pile, a mass of graphite absorbing the neutrons emitted by radioactive material inserted into it, could generate heat, which in turn could create steam to drive turbines and thus convert the nuclear energy into usable electricity. Atomic power stations were built on this principle in the advanced industrial world, and the system is still undergoing refinement, although so far atomic energy has not vindicated the high hopes placed in it as an economic source of electricity and presents formidable problems of waste disposal and maintenance. Nevertheless, it seems probable that the effort devoted to experiments on more direct ways of controlling nuclear fission will eventually produce results in power engineering.

Meanwhile, nuclear physics was probing the even more promising possibilities of harnessing the power of nuclear fusion, of creating the conditions in which simple atoms of hydrogen combine, with a vast release of energy, to form heavier atoms. This is the process that occurs in the stars, but so far it has only been created artificially by triggering off a fusion reaction with the intense heat generated momentarily by an atomic fission explosion. This is the mechanism of the hydrogen bomb. So far scientists have devised no way of harnessing this process so that continuous controlled energy can be obtained from it, although researches into plasma physics, generating a point of intense heat within a stream of electrons imprisoned in a strong magnetic field, hold out some hopes that such means will be discovered in the not-too-distant future.

Alternatives to fossil fuels

It may well become a matter of urgency that some means of extracting usable power from nuclear fusion be acquired. At the present rate of consumption, the world’s resources of mineral fuels, and of the available radioactive materials used in the present nuclear power stations, will be exhausted within a period of perhaps a few decades. The most attractive alternative is thus a form of energy derived from a controlled fusion reaction that would use hydrogen from seawater, a virtually limitless source, and that would not create a significant problem of waste disposal. Other sources of energy that may provide alternatives to mineral fuels include various forms of solar cell, deriving power from the Sun by a chemical or physical reaction such as that of photosynthesis. Solar cells of this kind are already in regular use on satellites and space probes, where the flow of energy out from the Sun (the solar wind) can be harnessed without interference from the atmosphere or the rotation of the Earth.

Gas turbine

The gas turbine underwent substantial development since its first successful operational use at the end of World War II. The high power-to-weight ratio of this type of engine made it ideal for aircraft propulsion, so that in either the pure jet or turboprop form it was generally adopted for all large aircraft, both military and civil, by the 1960s. The immediate effect of the adoption of jet propulsion was a spectacular increase in aircraft speeds, the first piloted airplane exceeding the speed of sound in level flight being the American Bell X-1 in 1947, and by the late 1960s supersonic flight was becoming a
practicable, though controversial, proposition for civil-airline users. Ever larger and more powerful gas turbines were designed to meet the requirements of airlines and military strategy, and increasing attention was given to refinements to reduce the noise and increase the efficiency of this type of engine. Meanwhile, the gas turbine was installed as a power unit in ships, railroad engines, and automobiles, but in none of these uses did it proceed far beyond the experimental stage.

Materials

The space age spawned important new materials and uncovered new uses for old materials. For example, a vast range of applications have been found for plastics that have been manufactured in many different forms with widely varied characteristics. Glass fibre has been molded in rigid shapes to provide motorcar bodies and hulls for small ships. Carbon fibre has demonstrated remarkable properties that make it an alternative to metals for high-temperature turbine blades. Research on ceramics has produced materials resistant to high temperatures suitable for heat shields on spacecraft. The demand for iron and its alloys and for the nonferrous metals has remained high. The modern world has found extensive new uses for the latter: copper for electrical conductors, tin for protective plating of less-resistant metals, lead as a shield in nuclear power installations, and silver in photography. In most of these cases the development began before the 20th century, but the continuing increase in demand for these metals is affecting their prices in the world commodity markets.

Automation and the computer

Both old and new materials were used increasingly in the engineering industry, which was transformed since the end of World War II by the introduction of control engineering, automation, and computerized techniques. The vital piece of equipment has been the computer, especially the electronic digital computer, a 20th-century invention the theory of which was expounded by the English mathematician and inventor Charles Babbage in the 1830s. The essence of this machine is the use of electronic devices to record electric impulses coded in the very simple binary system, using only two symbols, but other devices such as punched cards and magnetic tape for storing and feeding information have been important supplementary features. By virtue of the very high speeds at which such equipment can operate, even the most complicated calculations can be performed in a very short space of time.

The Mark I digital computer was at work at Harvard University in 1944, and after the war the possibility of using it for a wide range of industrial, administrative, and scientific applications was quickly realized. The early computers, however, were large and expensive machines, and their general application was delayed until the invention of the transistor revolutionized computer technology. The transistor is another of the key inventions of the space age. The product of research on the physics of solids, and particularly of those materials such as germanium and silicon known as semiconductors, the transistor was invented by John Bardeen, Walter H. Brattain, and William B. Shockley at Bell Telephone Laboratories in the United States in 1947. It was discovered that crystals of semiconductors, which have the capacity to conduct electricity in some conditions and not in others, could be made to perform the functions of a thermionic valve but in the form of a device that was much smaller, more reliable, and more versatile. The result has been the replacement of the cumbersome, fragile, and heat-producing vacuum tubes by the small and strong transistor in a wide range of electronic equipment. Most especially, this conversion has made possible the construction of much more powerful computers while making them more compact and less expensive. Indeed, so small can effective transistors be that they have made possible the new skills of miniaturization and microminiaturization, whereby complicated electronic circuits can be created on minute pieces of silicon or other semiconducting materials and incorporated in large numbers in computers. From the late 1950s to the mid-1970s the computer grew from an exotic accessory to an integral element of most commercial enterprises, and computers made for home use became widespread in the '80s.

The potential for adaptation and utilization of the computer seems so great that many commentators have likened it to the human brain, and there is no doubt that human analogies have been important in its development. In Japan, where computer and other electronics technology made giant strides since the 1950s, fully computerized and automated factories were in operation by the mid-1970s, some of them employing complete workforces of robots in the manufacture of other robots. In the United States the chemical industry provides some of the most striking examples of fully automated, computer-controlled manufacture. The characteristics of continuous production, in contrast to the batch production of most engineering establishments, lend themselves ideally to automatic control from a central computer monitoring the information
fed back to it and making adjustments accordingly. Many large petrochemical plants producing fuel and raw materials for manufacturing industries are now run in this way, with the residual human function that of maintaining the machines and of providing the initial instructions. The same sort of influences can be seen even in the old established chemical processes, although not to the same extent: in the ceramics industry, in which continuous firing replaced the traditional batch-production kilns; in the paper industry, in which mounting demand for paper and board encouraged the installation of larger and faster machines; and in the glass industry, in which the float-glass process for making large sheets of glass on a surface of molten tin requires close mechanical control.

In medicine and the life sciences the computer has provided a powerful tool of research and supervision. It is now possible to monitor complicated operations and treatment. Surgery made great advances in the space age; the introduction of transplant techniques attracted worldwide publicity and interest. But perhaps of greater long-term significance is research in biology, with the aid of modern techniques and instruments, that began to unlock the mysteries of cell formation and reproduction through the self-replicating properties of the DNA molecules present in all living substances and thus to explore the nature of life itself.

Food production

Food production has been subject to technological innovation such as accelerated freeze-drying and irradiation as methods of preservation, as well as the increasing mechanization of farming throughout the world. The widespread use of new pesticides and herbicides in some cases reached the point of abuse, causing worldwide concern. Despite such problems, farming was transformed in response to the demand for more food; scientific farming, with its careful breeding, controlled feeding, and mechanized handling, became commonplace. New food-producing techniques such as aquaculture and hydroponics, for farming the sea and seabed and for creating self-contained cycles of food production without soil, respectively, are being explored either to increase the world supply of food or to devise ways of sustaining closed communities such as may one day venture forth from the Earth on the adventure of interplanetary exploration.

Civil engineering

One industry that has not been deeply influenced by new control-engineering techniques is construction, in which the nature of the tasks involved makes dependence on a large labour force still essential, whether it be in constructing a skyscraper, a new highway, or a tunnel. Nevertheless, some important new techniques appeared since 1945, notably the use of heavy earth-moving and excavating machines such as the bulldozer and the tower crane. The use of prefabricated parts according to a predetermined system of construction became widespread. In the construction of housing units, often in large blocks of apartments or flats, such systems are particularly relevant because they make for standardization and economy in plumbing, heating, and kitchen equipment. The revolution in home equipment that began before World War II has continued apace since, with a proliferation of electrical equipment.

Transport and communications

Many of these changes were facilitated by improvements in transport and communications. Transport developments have for the most part continued those well established in the early 20th century. The automobile proceeded in its phenomenal growth in popularity, causing radical changes in many of the patterns of life, although the basic design of the motorcar has remained unchanged. The airplane, benefiting from jet propulsion and a number of lesser technical advances, made spectacular gains at the expense of both the ocean liner and the railroad. However, the growing popularity of air transport brought problems of crowded airspace, noise, and airfield siting.

World War II helped bring about a shift to air transport: direct passenger flights across the Atlantic were initiated immediately after the war. The first generation of transatlantic airliners were the aircraft developed by war experience from the Douglas DC-3 and the pioneering types of the 1930s incorporating all-metal construction with stressed skin, wing flaps and slots, retractable landing gear, and other advances. The coming of the big jet-powered civil airliner in the 1950s kept pace with the rising demand for air services but accentuated the social problems of air transport. The solution to these problems may lie partly in the development of vertical takeoff and landing techniques, a concept successfully pioneered by a British military
aircraft, the Hawker Siddeley Harrier. Longer-term solutions may be provided by the development of air-cushion vehicles derived from the Hovercraft, in use in the English Channel and elsewhere, and one of the outstanding technological innovations of the period since 1945. The central feature of this machine is a down-blast of air, which creates an air cushion on which the craft rides without direct contact with the sea or ground below it. The remarkable versatility of the air-cushion machine is beyond doubt, but it has proved difficult to find very many transportation needs that it can fulfill better than any craft already available. Despite these difficulties, it seems likely that this type of vehicle will have an important future. It should be remembered, however, that all the machines mentioned so far, automobiles, airplanes, and Hovercraft, use oil fuels, and it is possible that the exhaustion of these will turn attention increasingly to alternative sources of power and particularly to electric traction (electric railroads and autos), in which field there have been promising developments such as the linear-induction motor. Supersonic flight, for nearly 30 years an exclusive capability of military and research aircraft, became a commercial reality in 1975 with the Soviet Tu-144 cargo plane; the Concorde supersonic transport (SST), built jointly by the British and French governments, entered regular passenger service early in 1976.

In communications also, the dominant lines of development continue to be those that were established before or during World War II. In particular, the rapid growth of television services, with their immense influence as media of mass communication, was built on foundations laid in the 1920s and 1930s, while the universal adoption of radar on ships and airplanes followed the invention of a device to give early warning of aerial attack. But in certain features the development of communications in the space age has produced important innovations. First, the transistor, so significant for computers and control engineering, made a large contribution to communications technology. Second, the establishment of space satellites, considered to be a remote theoretical possibility in the 1940s, became part of the accepted technological scene in the 1960s, and these have played a dramatic part in telephone and television communication as well as in relaying meteorological pictures and data. Third, the development of magnetic tape as a means of recording sound and, more recently, vision provided a highly flexible and useful mode of communication. Fourth, new printing techniques were developed. In phototypesetting, a photographic image is substituted for the conventional metal type. In xerography, a dry copying process, an ink powder is attracted to the image to be copied by static electricity and then fused by heating. Fifth, new optical devices such as zoom lenses increased the power of cameras and prompted corresponding improvements in the quality of film available to the cinema and television. Sixth, new physical techniques such as those that produced the laser (light amplification by stimulated emission of radiation) made available an immensely powerful means of communication over long distances, although these are still in their experimental stages. The laser also acquired significance as an important addition to surgical techniques and as an instrument of space weaponry. The seventh and final communications innovation is the use of electromagnetic waves other than light to explore the structure of the universe by means of the radio telescope and its derivative, the X-ray telescope. This technique was pioneered after World War II and has since become a vital instrument of satellite control and space research. Radio telescopes have also been directed toward the Sun's closest neighbors in space in the hope of detecting electromagnetic signals from other intelligent species in the universe.

Military technology

Military technology in the space age has been concerned with the radical restructuring of strategy caused by the invention of nuclear weapons and the means of delivering them by intercontinental ballistic missiles. Apart from these major features and the elaborate electronic systems intended to give an early warning of missile attack, military reorganization has emphasized high maneuverability through helicopter transport and a variety of armed vehicles. Such forces were deployed in wars in Korea and Vietnam, the latter of which also saw the widespread use of napalm bombs and chemical defoliants to remove the cover provided by dense forests. World War II marked the end of the primacy of the heavily armoured battleship. Although the United States recommissioned several battleships in the 1980s, the aircraft carrier became the principal capital ship in the navies of the world. Emphasis now is placed on electronic detection and the support of nuclear-powered submarines equipped with missiles carrying nuclear warheads. The only major use of nuclear power since 1945, other than generating large-scale electric energy, has been the propulsion of ships, particularly missile-carrying submarines capable of cruising underwater for extended periods.

Space exploration
The rocket, which has played a crucial part in the revolution of military technology since the end of World War II, acquired a more constructive significance in the U.S. and Soviet space programs. The first spectacular step was Sputnik 1, a sphere with an instrument package weighing 184 pounds (83 kilograms), launched into space by the Soviets on Oct. 4, 1957, to become the first artificial satellite. The feat precipitated the so-called space race, in which achievements followed each other in rapid succession. They may be conveniently grouped in four chronological although overlapping stages.

The first stage emphasized increasing the thrust of rockets capable of putting satellites into orbit and on exploring the uses of satellites in communications, in weather observation, in monitoring military information, and in topographical and geological surveying.

The second stage was that of the manned space program. This began with the successful orbit of the Earth by the Soviet cosmonaut Yury Gagarin on April 12, 1961, in the Vostok 1. This flight demonstrated mastery of the problems of weightlessness and of safe reentry into the Earth's atmosphere. A series of Soviet and U.S. spaceflights followed in which the techniques of space rendezvous and docking were acquired, flights up to a fortnight were achieved, and men "walked" in space outside their craft.

The third stage of space exploration was the lunar program, beginning with approaches to the Moon and going on through automatic surveys of its surface to manned landings. Again, the first achievement was Soviet: Luna 1, launched on Jan. 2, 1959, became the first artificial body to escape the gravitational field of the Earth, fly past the Moon, and enter an orbit around the Sun as an artificial planet. Luna 2 crashed on the Moon on Sept. 13, 1959; it was followed by Luna 3, launched on Oct. 4, 1959, which went around the Moon and sent back the first photographs of the side turned permanently away from the Earth. The first soft landing on the Moon was made by Luna 9 on Feb. 3, 1966; this craft carried cameras that transmitted the first photographs taken on the surface of the Moon. By this time excellent close-range photographs had been secured by the United States Rangers 7, 8, and 9, which crashed into the Moon in the second half of 1964 and the first part of 1965; and between 1966 and 1967 the series of five Lunar Orbiters photographed almost the entire surface of the Moon from a low orbit in a search for suitable landing places. The U.S. spacecraft Surveyor 1 soft-landed on the Moon on June 2, 1966; this and following Surveyors acquired much useful information about the lunar surface. Meanwhile, the size and power of launching rockets climbed steadily, and by the late 1960s the enormous Saturn V rocket, standing 353 feet (108 metres) high and weighing 2,725 tons (2,472,000 kilograms) at lift-off, made possible the U.S. Apollo program, which climaxd on July 20, 1969, when Neil Armstrong and Edwin Aldrin clambered out of the Lunar Module of their Apollo 11 spacecraft onto the surface of the Moon. The manned lunar exploration thus begun continued with a widening range of experiments and achievements for a further five landings before the program was curtailed in 1972.

The fourth stage of space exploration looked out beyond the Earth and the Moon to the possibilities of planetary exploration. The U.S. space probe Mariner 2 was launched on Aug. 27, 1962, and passed by Venus the following December, relaying back information about that planet indicating that it was hotter and less hospitable than had been expected. These findings were confirmed by the Soviet Venera 3, which crash-landed on the planet on March 1, 1968, and by Venera 4, which made the first soft landing on Oct. 18, 1967. Later probes of the Venera series gathered further atmospheric and surficial data. The U.S. probe Pioneer Venus 1 orbited the planet for eight months in 1978, and in December of that year four landing probes conducted quantitative and qualitative analyses of the Venusian atmosphere. Surface temperature of approximately 900 °F reduced the functional life of such probes to little more than one hour.

Research on Mars was conducted primarily through the U.S. Mariner and Viking probe series. During the late 1960s, photographs from Mariner orbiters demonstrated a close visual resemblance between the surface of Mars and that of the Moon. In July and August 1976, Vikings 1 and 2, respectively, made successful landings on the planet; experiments designed to detect the presence or remains of organic material on the Martian surface met with mechanical difficulty, but results were generally interpreted as negative. Photographs taken during the early 1960s by the U.S. probes Voyagers 1 and 2 permitted unprecedented study of the atmospheres and satellites of Jupiter and Saturn and revealed a previously unknown configuration of rings around Jupiter, analogous to those of Saturn.

In the mid-1980s the attention of the U.S. space program was focused primarily upon the potentials of the reusable space
shuttle vehicle for extensive orbital research. The U.S. space shuttle *Columbia* completed its first mission in April 1981 and made several successive flights. It was followed by the *Challenger*, which made its first mission in April 1983. Both vehicles were used to conduct myriad scientific experiments and to deploy satellites into orbit. The space program suffered a tremendous setback in 1986 when, at the outset of a *Challenger* mission, the shuttle exploded 73 seconds after lift off, killing the crew of seven. The early 1990s saw mixed results for NASA. The $1.5 billion Hubble Space Telescope occasioned some disappointment when scientists discovered problems with its primary mirror after launch. Interplanetary probes, to the delight of both professional and amateur stargazers, relayed beautiful, informative images of other planets.

At the dawn of the space age it is possible to perceive only dimly its scope and possibilities. But it is relevant to observe that the history of technology has brought the world to a point in time at which humankind, equipped with unprecedented powers of self-destruction, stands on the threshold of extraterrestrial exploration.

**Perceptions of technology**

**Science and technology**

Among the insights that arise from this review of the history of technology is the light it throws on the distinction between science and technology. The history of technology is longer than and distinct from the history of science. Technology is the systematic study of techniques for making and doing things; science is the systematic attempt to understand and interpret the world. While technology is concerned with the fabrication and use of artifacts, science is devoted to the more conceptual enterprise of understanding the environment, and it depends upon the comparatively sophisticated skills of literacy and numeracy. Such skills became available only with the emergence of the great world civilizations, so it is possible to say that science began with those civilizations, some 3,000 years BCE, whereas technology is as old as humanlike life. Science and technology developed as different and separate activities, the former being for several millennia a field of fairly abstruse speculation practiced by a class of aristocratic philosophers, while the latter remained a matter of essentially practical concern to craftsmen of many types. There were points of intersection, such as the use of mathematical concepts in building and irrigation work, but for the most part the functions of scientist and technologist (to use these modern terms retrospectively) remained distinct in the ancient cultures.

The situation began to change during the medieval period of development in the West (500–1500 CE), when both technical innovation and scientific understanding interacted with the stimuli of commercial expansion and a flourishing urban culture. The robust growth of technology in these centuries could not fail to attract the interest of educated men. Early in the 17th century the natural philosopher Francis Bacon recognized three great technological innovations—the magnetic compass, the printing press, and gunpowder—as the distinguishing achievements of modern man, and he advocated experimental science as a means of enlarging man’s dominion over nature. By emphasizing a practical role for science in this way, Bacon implied a harmonization of science and technology, and he made his intention explicit by urging scientists to study the methods of craftsmen and urging craftsmen to learn more science. Bacon, with Descartes and other contemporaries, for the first time saw man becoming the master of nature, and a convergence between the traditional pursuits of science and technology was to be the way by which such mastery could be achieved.

Yet the wedding of science and technology proposed by Bacon was not soon consummated. Over the next 200 years, carpenters and mechanics—practical men of long standing—built iron bridges, steam engines, and textile machinery without much reference to scientific principles, while scientists—still amateurs—pursued their investigations in a haphazard manner. But the body of men, inspired by Baconian principles, who formed the Royal Society in London in 1660 represented a determined effort to direct scientific research toward useful ends, first by improving navigation and cartography, and ultimately by stimulating industrial innovation and the search for mineral resources. Similar bodies of scholars developed in other European countries, and by the 19th century scientists were moving toward a professionalism in which many of the goals were clearly the same as those of the technologists. Thus, Justus von Liebig of Germany, one of the fathers of organic chemistry and the first proponent of mineral fertilizer, provided the scientific impulse that led to the development of synthetic dyes, high explosives, artificial fibres, and plastics, and Michael Faraday, the brilliant British experimental scientist in the field of electromagnetism, prepared the ground that was exploited by Thomas A. Edison and many others.

The role of Edison is particularly significant in the deepening relationship between science and technology, because the
prodigious trial-and-error process by which he selected the carbon filament for his electric lightbulb in 1879 resulted in the creation at Menlo Park, N.J., of what may be regarded as the world's first genuine industrial research laboratory. From this achievement the application of scientific principles to technology grew rapidly. It led easily to the engineering rationalism applied by Frederick W. Taylor to the organization of workers in mass production, and to the time-and-motion studies of Frank and Lilian Gilbreth at the beginning of the 20th century. It provided a model that was applied rigorously by Henry Ford in his automobile assembly plant and that was followed by every modern mass-production process. It pointed the way to the development of systems engineering, operations research, simulation studies, mathematical modeling, and technological assessment in industrial processes. This was not just a one-way influence of science on technology, because technology created new tools and machines with which the scientists were able to achieve an ever-increasing insight into the natural world. Taken together, these developments brought technology to its modern highly efficient level of performance.

**Criticisms of technology**

Judged entirely on its own traditional grounds of evaluation—that is, in terms of efficiency—the achievement of modern technology has been admirable. Voices from other fields, however, began to raise disturbing questions, grounded in other modes of evaluation, as technology became a dominant influence in society. In the mid-19th century the non-technologists were almost unanimously enchanted by the wonders of the new man-made environment growing up around them. London's Great Exhibition of 1851, with its arrays of machinery housed in the truly innovative Crystal Palace, seemed to be the culmination of Francis Bacon's prophetic forecast of man's increasing dominion over nature. The new technology seemed to fit the prevailing laissez-faire economics precisely and to guarantee the rapid realization of the Utilitarian philosophers' ideal of "the greatest good for the greatest number." Even Marx and Engels, espousing a radically different political orientation, welcomed technological progress because in their eyes it produced an imperative need for socialist ownership and control of industry. Similarly, early exponents of science fiction such as Jules Verne and H.G. Wells explored with zest the future possibilities opened up to the optimistic imagination by modern technology, and the American utopian Edward Bellamy, in his novel *Looking Backward* (1888), envisioned a planned society in the year 2000 in which technology would play a conspicuously beneficial role. Even such late Victorian literary figures as Lord Tennyson and Rudyard Kipling acknowledged the fascination of technology in some of their images and rhythms.

Yet even in the midst of this Victorian optimism, a few voices of dissent were heard, such as Ralph Waldo Emerson's ominous warning that "Things are in the saddle and ride mankind." For the first time it began to seem as if "things"—the artifacts made by man in his campaign of conquest over nature—might get out of control and come to dominate him. Samuel Butler, in his satirical novel *Erewhon* (1872), drew the radical conclusion that all machines should be consigned to the scrap heap. And others such as William Morris, with his vision of a reversion to a craft society without modern technology, and Henry James, with his disturbing sensations of being overwhelmed in the presence of modern machinery, began to develop a profound moral critique of the apparent achievements of technologically dominated progress. Even H.G. Wells, despite all the ingenious and prophetic technological gadgetry of his earlier novels, lived to become disillusioned about the progressive character of Western civilization: his last book was titled *Mind at the End of Its Tether* (1945). Another novelist, Aldous Huxley, expressed disenchantment with technology in a forceful manner in *Brave New World* (1932). Huxley pictured a society of the near future in which technology was firmly enthroned, keeping human beings in bodily comfort without knowledge of want or pain, but also without freedom, beauty, or creativity, and robbed at every turn of a unique personal existence. An echo of the same view found poignant artistic expression in the film *Modern Times* (1936), in which Charlie Chaplin depicted the depersonalizing effect of the mass-production assembly line. Such images were given special potency by the international political and economic conditions of the 1930s, when the Western world was plunged in the Great Depression and seemed to have forfeited the chance to remodel the world order shattered by World War I. In these conditions, technology suffered by association with the tarnished idea of inevitable progress.

Paradoxically, the escape from a decade of economic depression and the successful defense of Western democracy in World War II did not bring a return of confident notions about progress and faith in technology. The horrific potentialities of nuclear war were revealed in 1945, and the division of the world into hostile power blocs prevented any such euphoria and served to stimulate criticisms of technological aspirations even more searching than those that have already been mentioned. J. Robert Oppenheimer, who directed the design and assembly of the atomic bombs at Los Alamos, N.M., later opposed the decision to build the thermonuclear (fusion) bomb and described the accelerating pace of technological change
with foreboding:

One thing that is new is the prevalence of newness, the changing scale and scope of change itself, so that the world alters as we walk in it, so that the years of man’s life measure not some small growth or rearrangement or moderation of what he learned in childhood, but a great upheaval.

The theme of technological tyranny over individuality and traditional patterns of life was expressed by Jacques Ellul, of the University of Bordeaux, in his book The Technological Society (1964, first published as La Technique in 1954). Ellul asserted that technology had become so pervasive that man now lived in a milieu of technology rather than of nature. He characterized this new milieu as artificial, autonomous, self-determining, nihilistic (that is, not directed to ends, though proceeding by cause and effect), and, in fact, with means enjoying primacy over ends. Technology, Ellul held, had become so powerful and ubiquitous that other social phenomena such as politics and economics had become situated in it rather than influenced by it. The individual, in short, had come to be adapted to the technical milieu rather than the other way round.

While views such as those of Ellul have enjoyed a considerable vogue since World War II—and spawned a remarkable subculture of hippies and others who sought, in a variety of ways, to reject participation in technological society—it is appropriate to make two observations on them. The first is that these views are, in a sense, a luxury enjoyed only by advanced societies, which have benefited from modern technology. Few voices critical of technology can be heard in developing countries that are hungry for the advantages of greater productivity and the rising standards of living that have been seen to accrue to technological progress in the more fortunate developed countries. Indeed, the antitechnological movement is greeted with complete incomprehension in these parts of the world, so that it is difficult to avoid the conclusion that only when the whole world enjoys the benefits of technology can we expect the subtler dangers of technology to be appreciated, and by then, of course, it may be too late to do anything about them.

The second observation about the state of technological pessimism in the advanced countries is that it has not managed to slow the pace of technological advance, which seems, if anything, to have accelerated. The gap between the first powered flight and the first human steps on the Moon was only 66 years, and that between the disclosure of the fission of uranium and the detonation of the first atomic bomb was a mere six and a half years. The advance of the information revolution based on the electronic computer has been exceedingly swift, so that, despite the denials of the possibility by elderly and distinguished experts, the sombre spectre of sophisticated computers replicating higher human mental functions and even human individuality should not be relegated too hurriedly to the classification of science fantasy. The biotechnic stage of technological innovation is still in its infancy, and, if the recent rate of development is extrapolated forward, many seemingly impossible targets could be achieved in the next century. Not that this will be any consolation to the pessimists, as it only indicates the ineffectiveness to date of attempts to slow down technological progress.

The technological dilemma

Whatever the responses to modern technology, there can be no doubt that it presents contemporary society with a number of immediate problems that take the form of a traditional choice of evils, so that it is appropriate to regard them as constituting a “technological dilemma.” This is the dilemma between, on the one hand, the overdependence of life in the advanced industrial countries on technology, and, on the other hand, the threat that technology will destroy the quality of life in modern society and even endanger society itself. Technology thus confronts Western civilization with the need to make a decision, or rather, a series of decisions, about how to use the enormous power available to society constructively rather than destructively. The need to control the development of technology, and so to resolve the dilemma, by regulating its application to creative social objectives, makes it ever more necessary to define these objectives while the problems presented by rapid technological growth can still be solved.

These problems, and the social objectives related to them, may be considered under three broad headings. First is the problem of controlling the application of nuclear technology. Second is the population problem, which is twofold: it seems necessary to find ways of controlling the dramatic rise in the number of human beings and, at the same time, to provide food and care for the people already living on the Earth. Third, there is the ecological problem, whereby the products and wastes of technical processes have polluted the environment and disturbed the balance of natural forces of regeneration. When
these basic problems have been reviewed, it will be possible, finally, to consider the effect of technology on life in town and countryside, and to determine the sort of judgments about technology and society to which a study of the history of technology leads.

**Nuclear technology**

The solution to the first problem, that of controlling nuclear technology, is primarily political. At its root is the anarchy of national self-government, for as long as the world remains divided into a multiplicity of nation-states, or even into power blocs, each committed to the defense of its own sovereign power to do what it chooses, nuclear weapons merely replace the older weapons by which such nation-states maintained their independence in the past. The availability of a nuclear armory has emphasized the weaknesses of a world political system based upon sovereign nation-states. Here, as elsewhere, technology is a tool that can be used creatively or destructively. But the manner of its use depends entirely on human decisions, and in this matter of nuclear self-control the decisions are those of governments. There are other aspects of the problem of nuclear technology, such as the disposal of radioactive waste and the quest to harness the energy released by fusion, but, although these are important issues in their own right, they are subordinate to the problem of the use of nuclear weapons in warfare.

**Population explosion**

Assuming that the use of nuclear weapons can be averted, world civilization will have to come to grips with the population problem in the next few decades if life is to be tolerable on planet Earth in the 21st century. The problem can be tackled in two ways, both drawing on the resources of modern technology.

In the first place, efforts may be made to limit the rate of population increase. Medical technology, which through new drugs and other techniques has provided a powerful impulse to the increase of population, also offers means of controlling this increase through contraceptive devices and through painless sterilization procedures. Again, technology is a tool that is neutral in respect to moral issues about its own use, but it would be futile to deny that artificial population control is inhibited by powerful moral constraints and taboos. Some realignment of these conflicts is essential, however, if stability in world population is to be satisfactorily achieved. Perhaps the experience of China, already responsible for one-quarter of the world’s population, is instructive here: in an attempt to prevent the population growth from exceeding the ability of the country to sustain the existing standards of living, the government imposed a “one-child family” campaign in the 1970s, which is maintained by draconian social controls.

In the second place, even the most optimistic program of population control can hope to achieve only a slight reduction in the rate of increase, so an alternative approach must be made simultaneously in the shape of an effort to increase the world’s production of food. Technology has much to contribute at this point, both in raising the productivity of existing sources of food supply, by improved techniques of agriculture and better types of grain and animal stock, and in creating new sources of food, by making the deserts fertile and by systematically farming the riches of the oceans. There is enough work here to keep engineers and food technologists busy for many generations.

**Ecological balance**

The third major problem area of modern technological society is that of preserving a healthy environmental balance. Though humans have been damaging the environment for centuries by overcutting trees and farming too intensively and though some protective measures, such as the establishment of national forests and wildlife sanctuaries, were taken decades ago, great increases in population and in the intensity of industrialization are promoting a worldwide ecological crisis. This includes the dangers involved in destruction of the equatorial rainforests, the careless exploitation of minerals by open-mining techniques, and the pollution of the oceans by radioactive waste and of the atmosphere by combustion products. These include oxides of sulfur and nitrogen, which produce acid rain, and carbon dioxide, which may affect the world’s climate through the greenhouse effect. It was the danger of indiscriminate use of pesticides such as DDT after World War II that first alerted opinion in advanced Western countries to the delicate nature of the world’s ecological system, presented in a trenchant polemic by American science writer Rachel Carson in her book *Silent Spring* (1962); this was
followed by a spate of warnings about other possibilities of ecological disaster. The great public concern about pollution in the advanced nations is both overdue and welcome. Once more, however, it needs to be said that the fault for this waste-making abuse of technology lies with man himself rather than with the tools he uses. For all his intelligence, man in communities behaves with a lack of respect for the environment that is both shortsighted and potentially suicidal.

Technological society

Much of the 19th-century optimism about the progress of technology has dispersed, and an increasing awareness of the technological dilemma confronting the world makes it possible to offer a realistic assessment of the role of technology in shaping society today.

Interactions between society and technology

In the first place, it can be clearly recognized that the relationship between technology and society is complex. Any technological stimulus can trigger a variety of social responses, depending on such unpredictable variables as differences between human personalities; similarly, no specific social situation can be relied upon to produce a determinable technological response. Any "theory of invention," therefore, must remain extremely tentative, and any notion of a "philosophy" of the history of technology must allow for a wide range of possible interpretations. A major lesson of the history of technology, indeed, is that it has no precise predictive value. It is frequently possible to see in retrospect when one particular artifact or process had reached obsolescence while another promised to be a highly successful innovation, but at the time such historical hindsight is not available and the course of events is indeterminable. In short, the complexity of human society is never capable of resolution into a simple identification of causes and effects driving historical development in one direction rather than another, and any attempt to identify technology as an agent of such a process is unacceptable.

The putative autonomy of technology

Secondly, the definition of technology as the systematic study of techniques for making and doing things establishes technology as a social phenomenon and thus as one that cannot possess complete autonomy, unaffected by the society in which it exists. It is necessary to make what may seem to be such an obvious statement because so much autonomy has been ascribed to technology, and the element of despair in interpretations like that of Jacques Ellul is derived from an exaggerated view of the power of technology to determine its own course apart from any form of social control. Of course it must be admitted that once a technological development, such as the transition from sail to steam power in ships or the introduction of electricity for domestic lighting, is firmly established, it is difficult to stop it before the process is complete. The assembly of resources and the arousal of expectations both create a certain technological momentum that tends to prevent the process from being arrested or deflected. Nevertheless, the decisions about whether to go ahead with a project or to abandon it are undeniably human, and it is a mistake to represent technology as a monster or a juggernaut threatening human existence. In itself, technology is neutral and passive: in the phrase of Lynn White, Jr., "Technology opens doors; it does not compel man to enter." Or, in the words of the traditional adage, it is a poor craftsman who blames his tools, and so, just as it was naive for 19th-century optimists to imagine that technology could bring paradise on Earth, it seems equally simplistic for pessimists today to make technology itself a scapegoat for human shortcomings.

Technology and education

A third theme to emerge from this review of the history of technology is the growing importance of education. In the early millennia of human existence, a craft was acquired in a lengthy and laborious manner by serving with a master who gradually trained the initiate in the arcane mysteries of the skill. Such instruction, set in a matrix of oral tradition and practical experience, was frequently more closely related to religious ritual than to the application of rational scientific principles. Thus, the artisan in ceramics or sword making protected the skill while ensuring that it would be perpetuated. Craft training was institutionalized in Western civilization in the form of apprenticeship, which has survived as a framework for instruction in technical skills. Increasingly, however, instruction in new techniques requires access both to general theoretical knowledge and to realms of practical experience that, on account of their novelty, were not available through traditional apprenticeship. Thus, the requirement for a significant proportion of academic instruction has become an important feature
of most aspects of modern technology. This accelerated the convergence between science and technology in the 19th and 20th centuries and created a complex system of educational awards representing the level of accomplishment from simple instruction in schools to advanced research in universities. French and German academies led in the provision of such theoretical instruction, while Britain lagged somewhat in the 19th century, owing to its long and highly successful tradition of apprenticeship in engineering and related skills. But by the 20th century all the advanced industrial countries, including newcomers like Japan, had recognized the crucial role of a theoretical technological education in achieving commercial and industrial competence.

The recognition of the importance of technological education, however, has never been complete in Western civilization, and the continued coexistence of other traditions has caused problems of assimilation and adjustment. The British author C.P. Snow drew attention to one of the most persistent problems in his perceptive essay The Two Cultures (1959), in which he identified the dichotomy between scientists and technologists on the one hand and humanists and artists on the other as one between those who did understand the second law of thermodynamics and those who did not, causing a sharp disjunction of comprehension and sympathy. Arthur Koestler put the same point in another way by observing that the traditionally humanities-educated Westerner is reluctant to admit that a work of art is beyond comprehension but will cheerfully confess to not understanding how a radio or heating system works. Koestler characterized such a modern individual as an "urban barbarian," isolated from a technological environment that he or she possesses without understanding. Yet the growing prevalence of "black-box" technology, in which only the rarefied expert is able to understand the enormously complex operations that go on inside the electronic equipment, makes it more and more difficult to avoid becoming such a barbarian. The most helpful development would seem to be not so much seeking to master the expertise of others in our increasingly specialized society as encouraging those disciplines that provide bridges between the two cultures, and here there is a valuable role for the history of technology.

The quality of life

A fourth theme, concerned with the quality of life, can be identified in the relationship between technology and society. There can be little doubt that technology has brought a higher standard of living to people in advanced countries, just as it has enabled a rapidly rising population to subsist in the developing countries. It is the prospect of rising living standards that makes the acquisition of technical competence so attractive to these countries. But however desirable the possession of a comfortable sufficiency of material goods, and the possibility of leisure for recreative purposes, the quality of a full life in any human society has other even more important prerequisites, such as the possession of freedom in a law-abiding community and of equality before the law. These are the traditional qualities of democratic societies, and it has to be asked whether technology is an asset or a liability in acquiring them. Certainly, highly illiberal regimes have used technological devices to suppress individual freedom and to secure obedience to the state: the nightmare vision of George Orwell's Nineteen Eighty-four (1949), with its telescreens and sophisticated torture, has provided literary demonstration of this reality, should one be needed. But the fact that high technological competence requires, as has been shown, a high level of educational achievement by a significant proportion of the community holds out the hope that a society that is well educated will not long endure constraints on individual freedom and initiative that are not self-justifying. In other words, the high degree of correlation between technological success and educational accomplishment suggests a fundamental democratic bias about modern technology. It may take time to become effective, but, given sufficient time without a major political or social disruption and a consequent resurgence of national assertiveness and human selfishness, there are sound reasons for hoping that technology will bring the people of the world into a closer and more creative community.

Such, at least, must be the hope of anybody who takes a long view of the history of technology as one of the most formative and persistently creative themes in the development of humankind from the Paleolithic cave dwellers of antiquity to the dawn of the space age. Above all other perceptions of technology, the threshold of space exploration on which humankind stands provides the most dynamic and hopeful portent of human potentialities. Even while the threat of technological self-destruction remains ominous and the problems of population control and ecological imbalance cry out for satisfactory solutions, man has found a clue of his own future in terms of a quest to explore and colonize the depths of an infinitely fascinating universe. As yet, only a few visionaries have appreciated the richness of this possibility, and their projections are too easily dismissed as nothing more than imaginative science fiction. But in the long run, if there is to be a long run for our uniquely technological but willful species, the future depends upon the ability to acquire such a cosmic perspective, so it is
important to recognize this now and to begin the arduous mental and physical preparations accordingly. The words of Arthur C. Clarke, one of the most perceptive of contemporary seers, in his Profiles of the Future (1962), are worth recalling in this context. Thinking ahead to the countless aeons that could stem from the remarkable human achievement summarized in the history of technology, he surmised that the all-knowing beings who may evolve from these humble beginnings may still regard our own era with wistfulness: “But for all that, they may envy us, basking in the bright afterglow of Creation; for we knew the Universe when it was young.”

ARTICLE  Additional Reading


R.J. Forbes, Man, the Maker: A History of Technology and Engineering (1950, reissued 1958), is a good outline of the history of technology; as is D.S.L. Cardwell, Technology, Science and History: A Short Study of the Major Developments in the History of Western Mechanical Technology and Their Relationships with Science and Other Forms of Knowledge (1972). R.A. Buchanan, Technology and Social Progress (1965), may be found useful as an introductory text.


The principal sources of periodical literature are Technology and Culture (quarterly), the journal of the Society for the History of Technology, containing excellent annual bibliographical reviews; and Newcomen Society for the Study of the History of Engineering and Technology, Transactions (annual).

Robert Angus Buchanan