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To my wife and collaborator,

Catherine Crook de Camp
PREFACE

The system of indicating dates in this book is based upon those used by the late George Sarton in his History of Science and by Joseph Needham in his Science and Civilisation in China. Centuries are indicated by Roman numerals preceded by + or − according to whether they are centuries of the Christian era or B.C.; hence −VIII means eighth century B.C. Years are treated likewise, with Arabic instead of Roman numerals; for instance, +412 = A.D. 412. The plus sign is, however, omitted from years after +1000, because the meaning of the numeral is obvious in such cases.

In the text, most Greek names are spelled in the Greek manner, instead of the Latin (hence Keraunos instead of Ceraunus) because I like it better and think it will in time prevail. But in the notes and bibliography, most names of Greek writers are given in Latinized or Anglicized form to make it easier to find standard editions and translations.

For help in one way or another with this work—procuring books for me, answering questions, checking my translations, and criticizing parts of the text—I am grateful to Allen T. Bonnell, Lionel Casson, Jack Coggins, Bern Dibner, Caroline Gordon Dosker, A. G. Drachmann, I. E. S. Edwards, R. J. Forbes, Umberto Forti, Samuel Freiha, Samuel N. Kramer, Willy Ley, William McDermott, Robert P. Multhauf, Derek J. de Solla Price, Pellegrino Claudio Sestieri, Guido Ucetti, Donald N. Wilbur, Howard H. Williams, and Conway Zirkle; and to the Burndy Library (Norwalk, Conn.), the Swarthmore College Library, the Union Library Catalogue, and the University of Pennsylvania Library. Finally, my wife's work of editing the manuscript has gone far beyond the call of duty.

L. Sprague de Camp
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ONE

Civilization, as we know it today, owes its existence to the engineers. These are the men who, down the long centuries, have learned to exploit the properties of matter and the sources of power for the benefit of mankind. By an organized, rational effort to use the material world around them, engineers devised the myriad comforts and conveniences that mark the difference between our lives and those of our forefathers thousands of years ago.

The story of civilization is, in a sense, the story of engineering—that long and arduous struggle to make the forces of nature work for man's good. The story of engineering, pieced together from dusty manuscripts and crumbling relics, explains as well the state of the world today as all the accounts of kings and philosophers, generals and politicians.

To appreciate the accomplishments of the engineers, we must understand the changes that have taken place in human life during the last million years. A million years ago, at the beginning of the Pleistocene Period, our ancestors were small, apelike primates, much like the man-apes whose fossil remains have been found in Africa.

Two things distinguished our ancestors from modern apes, such as the gorilla and chimpanzee. First, they lived mostly on the ground and regularly walked upright, so that their limbs were proportioned much like ours. They did not have the long hooklike arms, the short bowed legs,
and handlike feet of modern apes. Their brains were essentially the same as those of modern apes.

Probably as early as 100,000 years ago, before the last advance of the Pleistocene glaciers, and certainly by 10,000 years ago, the forces of evolution had caused these man-apes to evolve into men, every bit as human in form and as intelligent as we are. Differences in climate in different parts of the world had split the human stock into three major and several minor races.

These men, like all the men who had gone before them, lived by food-gathering. They sought a precarious livelihood by hunting, fishing, picking berries, and digging up edible roots and tubers. They greedily gobbled lizards, insects, and carrion. Today only small bands of African Bushmen and Pygmies, a few Australian aborigines, and a handful of Eskimos—a tiny fraction of 1 per cent of humanity—subsist in this manner.

Because of the difficulty of getting food, in Pleistocene times only a few hundred thousand people existed on the entire face of the globe. But there is no reason to think that we today are one bit cleverer than the men of -8000, at the time of the great Neolithic agricultural revolution that turned hunters into peasants. For one thing, 10,000 years is too short a time for evolution to have had a measurable effect. For another, many geneticists believe that civilization causes the human stock slowly to degenerate, by enabling persons with unfavorable mutations to live and breed, when in a wild state they would quickly perish.

However that may be, man has spent about 99 per cent of his history, since he first learned to make tools, as a hunting and food-gathering tribesman. Civilization has arisen only during the remaining 1 per cent of this time, since 9,000 to 10,000 years ago, when men discovered how to raise crops and tame animals. These discoveries enabled a square mile of fertile land to support 20 to 200 times as many people as before and freed some of these people for other, specialized occupations.

This revolution seems to have first taken place in the hills that curve around to the north of Iraq and Syria. From Iraq and Syria the Agricultural Revolution quickly spread to the valleys of the Nile and the Indus, which in their turn became centers of cultural radiation.

The Agricultural Revolution brought about changes fully as drastic in people’s lives as those caused by the Industrial Revolution of the last two centuries. Permanent villages took the place of temporary campsites. One theory holds that men were first persuaded to give up their wandering life by the discovery that mashed grass-seeds could be used to make beer, since they had to stay put long enough for the mash to ferment.

In another three or four thousand years, some of the farming villages of the Near and Middle East grew into cities. Then with a rush came metals, writing, large-scale government, science, and all the other features of civilization.

As farmers learned to raise more food than they themselves needed, other men were able to spend all their time in making useful things, which they exchanged for surplus foods. Thus specialization arose.

Human society had long known a couple of specialists: the tribal priest or wizard and the tribal chief or war leader. As specialization increased, merchants, physicians, poets, smiths, and craftsmen of many kinds came into being. Instead of making their own houses, carts, wells, and boats, men began to buy them from workmen skilled in these arts. Soon the arts advanced to the point where even a wise and experienced workman could not know all that had to be known about his craft.

As the chiefs evolved into kings and the wizards into high priests, they waxed rich and powerful. They acquired helpers, messengers, bodyguards, and other servants, who outranked the simple peasants. Slavery—at first a humane invention, which made it no longer necessary to slaughter one’s prisoners of war—introduced still another class. Thus society became seamed and fissured into a multitude of specialized occupations.

Wealth and experience piled up. Men undertook projects too large for a single craftsman, even with the help of his sons and apprentices. These projects called for the work of hundreds or even thousands of men, organized and directed towards a common goal. Hence arose a new class of men: the technicians or engineers, who could negotiate with a king or a priesthood for building a public work, plan the details, and direct the workmen. These men combined practical experience with knowledge of general, theoretical principles. Sometimes they were inventors as well as contractors, designers, and foremen, but all were men who could imagine something new and transform a mental picture into physical reality.

Invention has been going on ever since our apish ancestors learned to feed a fire and flake a flint. But the conditions under which invention takes place, and the pace of invention, have changed greatly since the beginning of historic times.

Some primitive inventions, like the manioc squeezer of the South American Indians, the Australian boomerang, and the Eskimo toggle-joint harpoon, are extremely ingenious. They point to inventive talents as keen as anything the civilized world can show.
Nevertheless, during nearly all of the last million years, invention progressed with glacial slowness. Men chopped with ax heads held in the fist for hundreds of thousands of years before they learned to fasten handles to their axes. During the earlier part of the Pleistocene Period, it is possible that men were too stupid to be very inventive. By 100,000 years ago, however, men had probably become quite as intelligent as we are—but still technology advanced at a crawl.

The reasons for the sloth of invention in primitive societies are not hard to understand. For one thing, primitive peoples live a hand-to-mouth existence. Most of their foods cannot be stored, so that they have no economic surplus. Therefore they can less well afford to risk experiment than more advanced peoples. If an experiment fails, they die.

As a result, primitive societies are very conservative. Tribes customs prescribe exactly how everything shall be done, on pain of the gods' displeasure. An inventor is likely to be liquidated as a dangerous deviationist.

Peasant farmers are almost equally conservative. Man's inventive faculties are stimulated by the breakdown of established custom that takes place in the urban environment; hence most inventions have been made by city dwellers.

Another cause of the slowness of primitive invention is the scarcity of inventors. A hunting and food-gathering technology can support only a very small population for a given area. Thus, the few hundred thousand members of the human species living at any time before the Agricultural Revolution were divided into many isolated little hunting bands.

Such a band seldom exceeds fifty or a hundred people, counting the many but short-lived children. Because the radius of action of the hunters is limited to the distance they can walk to kill their game and carry it back to camp, an increase in numbers does not enlarge the area that can be hunted at one time. It merely causes the same area to be hunted more intensively. So, if the band grows too large, game in the neighborhood becomes scarce; and the band must migrate or starve. Eventually it will have to split up. Perhaps human factiousness—our tendency to divide up into factions on almost any pretext (racial, religious, cultural, political, economic, or sporting) and fight it out—is a survival mechanism evolved during man's hunting phase, to insure that hunting bands split up before they grew too large to feed themselves.

Now, in any society, only a few human beings ever have original ideas or make inventions. Of these inventors, only a fraction have the courage, stubbornness, and energy to keep on bettering their inventions until they really work and to keep on promoting them until they persuade others to take them up.

A rough idea of the percentage of inventors among modern Americans can be obtained from the statistics of the United States Patent Office. The Patent Office issues about 40,000 patents every year. So we can estimate that the mid-twentieth-century American population of 180,000,000 people produces about one patentable invention each year for every 4,500 citizens.

Suppose, now, that all Americans were wiped out except one band of forty-five people. If this group continued to produce inventions at the same rate, it would turn out only one invention every century! This is of course a gross oversimplification. But it does indicate why a small tribal society, no matter how clever the tribesmen, cannot be expected to produce inventions rapidly.

In actual fact, the rate of inventions among Stone Age hunters was enormously slower than among our imaginary band of forty-five Americans. For modern Americans are encouraged to invent in ways that primitive folk are not. We are used to the thought that men can improve their lot by inventing things, and that invention is a worthy act. On the contrary, primitive people, who have all they can do to keep alive and who cannot afford to support a fellow tribesman in idleness while he dreams up new ideas, regard inventors with glowing suspicion.

Suppose now that there are two bands of forty-five Americans. If they are isolated from each other, each band will produce one invention a century, so that each progresses at the same rate as before. Their cultures will diverge somewhat, as they will hit upon the same inventions only rarely, by chance. But each group will plod along at the same old rate of one invention a century.

However, if they meet and join forces, then all ninety persons will take advantage of the inventions produced by any one of them. The combined group will produce inventions twice a century instead of once. In other words, they will progress technologically twice as fast.

To sum up: Progress in civilization depends upon invention, and a rapid rate of invention in turn depends upon the sizable populations that are only possible under civilization. The crucial inventions that made such progress possible—knowledge of raising domesticated, edible animals and plants—took place in Syria and Iraq about -8000.

Once the Agricultural Revolution had taken place, much denser and more numerous populations than had ever before existed could and did live in the valleys of the Nile, the Euphrates, and the Indus. As the
Reverend Thomas Malthus pointed out a hundred and sixty years ago, people quickly breed up to the greatest density the land will support at the current technological level. At that point the population levels off, because excess people are destroyed by starvation, pestilence, or war.

The mere fact of having large interconnected populations, then, meant that inventions took place at a faster rate than before, and these inventions in turn made denser and more widely interconnected populations possible. Hence civilized men tended to draw farther and farther ahead of their primitive fellows.

Moreover, the inventions on which civilization was founded tended to spread. These inventions did not spread out evenly in all directions. They spread along trade routes, and they spread to lands where these ideas could be profitably applied. They were stopped by strong natural barriers, such as deserts and oceans; and they died out where conditions made them useless.

Thus the idea of raising cotton or dates could not spread to Europe, because the cotton tree and the date palm will not grow there. The wheel failed to spread from Iraq to neighboring Arabia, because there was no place in the wastes of the Arabian desert where wheeled vehicles would have been very useful.

As a result of this speed-up and spread of technology, a high level of civilization had been achieved a thousand years before Christ in a broad belt stretching from the lands around the Mediterranean through the Middle East, India, and Southeast Asia to China. Any new invention, originating at one end of this Main Civilized Belt, traveled in a few centuries to the other. China, partly isolated at one end of the Belt by the Mongolian deserts, the Tibetan mountains, and the jungles of Southeast Asia, was a thousand years late in getting started but soon became as civilized as the rest.

Some of these advances in technics spread to Central Asia and Central Europe as well. Civilization had little effect on northern Europe and northern Asia, however, because the population of these lands was very thinly scattered and conditions of life were so different from those of the Belt that most inventions made in warmer lands were of little use there.

Civilization also failed to penetrate Negro Africa, being stopped by the barrier of the Sahara Desert, the swamps of the White Nile, and the mountains of Abyssinia. This barrier isolated sub-Saharan Africa as effectively as if it had been an island. Furthermore, Old World civilization failed to leap the watery barriers to reach the Pacific Islands, Australia, or the Americas. In another millennium, however, the peoples of Central and South America began independently to develop their own civilizations.

It would seem, then, that the main factor in determining whether any particular people took part in the technological adventure that followed the Agricultural Revolution was neither race, nor climate, nor local resources. The main factor was simply a matter of geography—where the people lived with respect to the river valleys in which this revolution took place. Those lucky enough to dwell along the cultural highways from China to Spain received the benefits of the speed-up; those who lived elsewhere did not, or did so only tardily.

I have spoken of the spread of inventions through the Main Civilized Belt and into lands outside this area. A few decades ago, a tremendous dispute on the spread of inventions arose among anthropologists. This dispute is called the Diffusionist Controversy.

The basis of the argument is this: If you find the same culture trait—such as a blowgun or a flood legend—in two widely separated groups of people, and the intermediate peoples lack this trait altogether, did the two groups invent it independently, or did they somehow get it from the same source?

Certain Britons—the psychologist Rivers, the anatomist Elliot Smith, and the anthropologist W. J. Perry—developed the extreme diffusionist or dispersionist theory. According to this hypothesis, all civilization came from one (or at most a few) Old World centers. The diffusionists deemed invention so rare that the same invention could never have been made independently by different peoples. Wherever close similarity was found, even on opposite sides of the globe, they averred that the trait had been spread by trade or migration.

Hence the diffusionists inferred, for instance, that the Mayas and Aztecs must have learned to build pyramids from the ancient Egyptians—despite the fact that, when the Mayas and Aztecs began to erect these structures, Egypt was already thousands of years old and had long since stopped building pyramids. They argued that all human civilization must have originated in one spot on the earth. Elliot Smith named Egypt, but others found their source of illumination in Brazil, the Ohio Valley, India, the Arctic, or Plato's fictional Atlantis.

Diffusionism became a cult. This cult attracted people of the sort who seek arcane wisdom in the measurements of King Khufu's pyramid or hunt for the Lost Ten Tribes of Israel among the Irish, the Iroquois, the Japanese, or the Zulus. By insisting that the same invention could never have been made twice over, the cult appealed to people who,
never having had an original idea themselves, find it impossible to imagine anybody else having one.

In later years this nonsense declined as sane anthropologists pointed out, over and over, that every invention contains some borrowing and every borrowing some invention. Where you draw the line between diffusion and original invention, then, is a matter of convenience.

Furthermore, there are many well-known cases of independent invention. As we shall see, the crossbow was independently invented in the Far East and in the Mediterranean. In civilized countries, simultaneous invention occurs all the time. That is why the United States Patent Office has a special procedure called an “interference” to find out who in such a case is legally entitled to the patent.

On the other hand, there are many cases of worldwide diffusion of an invention. Thus the bow reached the Americas from Asia, and later the tobacco pipe traveled around the world during the Age of Exploration. It is often hard to decide whether an invention traveled from one land to another or was independently created. Each case must be judged on its merits.

A specimen or a working diagram of an invention need not make the journey. A man may hear a rumor of an invention practiced in some foreign land, and the mere idea is enough to set him to thinking and tinkering in order to develop a similar invention on his own. Several systems of writing, devised by West African natives in +XIX, furnish examples of this “stimulus diffusion” as the anthropologists call it.

The first engineers were irrigators, architects, and military engineers. The same man was usually expected to be an expert at all three kinds of work. This was still the case thousands of years later, in the Renaissance, when Leonardo, Michelangelo, and Dürer were not only all-round engineers but outstanding artists as well. Specialization within the engineering profession has developed only in the last two or three centuries.

Irrigators laid out the canal systems on which the early river-valley civilizations depended. The Babylonian _gigallu_ or irrigation inspector was such an expert. Irrigation enabled farmers to raise so much more food that an increasing number of specialists, relieved of peasant's chores, were able to gather in cities to practice their specialities. Today's city is still essentially a place where specialists live and work, even though the farming class, once almost the whole population, has dwindled in industrial lands to a small minority.

Soon the kings who ruled these early cities desired houses larger and more comfortable than the huts of stone, clay, and reeds wherein they had been living. So they called upon architects to build them palaces.

Next, priests insisted that the gods would be offended if they were not housed at least as splendidly as the kings. So the architects put up temples, containing statues of the gods and other works of art.

To protect the wealth of the gods and the kings, military engineers built walls and dug moats around cities. In the lower Euphrates Valley, where there is practically no stone, walls were made of brick. Elsewhere they were made of stone—preferably the largest stones that could be moved.

Even before mortar was invented, men could build a good solid wall of small stones, which would stand up to the weather for years. However, all an enemy had to do to such a wall was to pry out a few stones with his spear, and the wall collapsed.

Therefore, many early fortifiers made their walls of very large stones, trimmed to fit roughly together. The sheer weight of these stones prevented the foe from pulling them out, especially if defenders atop the wall were raining missiles upon him. Such walls are called “cyclopean” because the ancient Greeks, seeing the ruins of walls of that kind built several centuries earlier, thought they must have been made by the mythical one-eyed giants called Cyclopes.

The hoards of metals, jewels, fine raiment, and foodstuffs in the temples and palaces also required men and means to keep track of them. Thus came about the invention of arithmetic and writing. Writing was done on the surfaces of some local material: in Egypt, on paper made of strips of papyrus reed; in Mesopotamia, on slabs of clay; in India, on paper made from palm fronds; in China, on strips of bamboo. Stone, wood and leather were also used as writing materials. In Mesopotamia, writing originated in the little clay tokens—spheres, disks, cones, and pyramids—used to keep accounts of property. Then it was found easier to draw pictures of the spheres and so forth on wet clay than to model them.

Many ancient writings on stone and clay have survived; but those on perishable materials have disappeared, save where people were interested enough to copy and recopy them.

As a result, the high school student of ancient history gets the curious impression that during the Golden Age of Greece, the Greeks were the only people in the world who were really alive. It seems as though the folk of all the other lands were standing around like waxen dummies in a state of suspended animation.

Of course that is not true. During the Golden Age of Greece, all
along the Main Civilized Belt from Spain to China, teeming multitudes toiled. Everywhere princes preened; politicians plotted; priests prayed; merchants haggled; warriors clashed; thinkers pondered; lovers sighed; drunkards reeled; poets declaimed; prophets ranted; sorcerers conjured; charlatans beguiled; slaves shirked; thieves filched; and people joked, quarreled, sang, wept, lusted, blundered, yearned, schemed, and carried on the business of living in quite as lively a fashion as the Greeks were doing.

But, because the Greeks put their experiences down in writing, and because good luck has saved a small part of these writings for us, we know a lot about them. We know much, for instance, of the little up-country brawls of tiny Greek city-states. On the other hand, we know almost nothing about the score of thunderous battles by which Darius the Great and his generals defeated the many rival claimants to the Persian throne, although these battlefields may have seen quite as brilliant feats of generalship and as gallant deeds of dought as the fields of Koronea and Leuktra.

For the same reason, we know quite a lot about Greek and Roman engineering, but very little about ancient Iranian, Indian, and Chinese engineering. In Iran, India, and China either the subject was not written about, or the writings have perished; or, where records have come down, many have never been published in European languages.

Even today, numbers of ancient manuscripts lie in the great libraries of Asia and North Africa, unread, uncatalogued, and untranslated. Many might shed additional light on medieval oriental science and engineering. Some may even be translations of supposedly lost Greek works on these subjects. One of the most urgent tasks of scholarship is the publication and translation of these works before the originals are vaporized in another war. A few scholars work at this task as time and chance permit, but the number of workers is small for the size of the job.

As nearly as we can reconstruct the evidence, the earliest civilizations were patchworks of little independent city-states, ever fighting one another. Government varied as power shuffled back and forth among the dominant groups: the king and his cronies, the priesthood, the senate (a gathering of the heads of the richest families), and the assembly (a meeting of the fighting men of the group). Women, poor men, and slaves, having neither wealth, arms, nor magical powers, did not count.

The government—whether a theocracy, a monarchy, or a republic—controlled not only the dwellers in the city but also as many of the peas-
or the son of a god, or at least the special agent of a god. His word was law. Government was a centralized, authoritarian despotism of—it would seem to us—the most tyrannical and oppressive sort.

Moreover, nobody seems to have seriously considered a large-scale government of any other kind. In ancient republics the voters, who were only a fraction of the total population, had to gather together to vote in person. Although such a scheme shares power to some extent and works fairly well in a small city-state, it is impractical in a large nation.

There were plenty of revolts, revolutions, and civil wars in the ancient empires. It was a rare king whose death did not result in a war among his would-be successors, and provinces that had once been separate nations repeatedly sought to regain their independence. But, while many kings were overthrown or murdered, the sole result was to replace one despot by another who, his supporters hoped, would prove a better king.

Sometimes a watershed empire broke up into parts as a result of domestic disorder or foreign conquest. But, after a few decades of the joys and sorrows of anarchy and incessant strife, the people of the watershed were once more prepared to submit to the rule of an all-powerful emperor.

From the rise of the first watershed empires down to the achievement of temporary world mastery by Europe after 1600, man’s history largely consists of the story of the mighty empires that rose in the Main Civilized Belt, spread far beyond the confines of a single watershed, flourished for a time, and withered away. Sometimes they lasted for centuries, sometimes for a few years only.

Thus the Assyrian Empire gave way to the Median, and that to the Persian, and that to the Macedonian, and that to the Roman, and that to the Arab, and that to the Turkish. A long succession of other empires, in Iran, India, China, and Central Asia, flourished beside these westerly realms. And many of the rulers of these domains—however good or bad in other respects—were among the world’s greatest builders of public works and, therefore, the greatest patrons of the engineering profession.

For, whatever their sins and oppressions, some early despots did much for those they ruled. A king with any brains tries to make his people prosper, if only so that he can tax them. Rulers of ancient empires built roads, which fostered commerce and communication. But the principal purpose of these roads, as of the governmental postal systems that operated over them, was to keep a swift stream of commands and inquiries flowing out from the capital to all parts of the realm, and an equally lively stream of information and tribute flowing back, for the benefit of the ruler. However they might disagree on other matters, a king and his subjects had a common interest in keeping up roads and canals, suppressing brigandage and piracy, and maintaining order.

Nowadays we draw fine distinctions among the meanings of such words as craftsman, engineer, technician, and inventor. The United States Patent Office has elaborate rules for deciding whether an invention is original, or whether it is merely “an improvement obvious to one skilled in the art,” such as a change in size, strength, speed, proportions, or materials.

In speaking of ancient technical men, however, there is no point in observing such delicate differences. Every time an ancient craftsman made something that was not a close copy of a previous article, he invented, even though his invention might not be patentable according to modern laws.

We think of an engineer as a man who designs some structure or machine, or who directs the building of it, or who operates and maintains it. In practice most ancient engineers were inventors; while most ancient inventors, at least after the rise of civilization, could also be classed as engineers. So let us lump all these ancient innovators and designers together as “engineers.”

Despite the enormous importance of engineers and inventors in making our daily life what it is, history does not tell much about them. The earliest historical records were made by priests praising their gods and poets flattering their kings. Neither cared much about such mundane matters as technology.

As a result, ancient legend and history are one-sided. We hear much about mighty kings and heroic warriors, somewhat less about priests, philosophers, and artists, and very little about the engineers who built the stages on which these players performed their parts. The warriors Achilles and Hector were celebrated in song and story—but the forgotten genius who, about the time of the siege of Troy, invented the safety pin, lies wholly forgotten. Everybody has heard of Julius Caesar—but who knows about his contemporary Sergius Orata, the Roman building contractor who invented central indirect house heating? Yet Orata has affected our daily lives far more than Caesar ever did.

Nevertheless, of all the phases of civilized life, the advance of technology gives the best ground for belief in progress. If there is any consistent pattern of evolution in politics and government, it is not easy to discern. Great soldiers and statesmen have built up empires—but a few generations later these empires faded away as though they had never
been. In the field of government, many people thought half a century ago that there was a natural evolutionary trend towards the democratic republic—but then many parts of the world turned in the other direction, towards authoritarian despotism. It is mere soothsaying to predict what form of government, if any, will finally prevail.

Likewise, great world religions like Buddhism, Judaism, Christianity, Islam, and Hinduism, with their tightly organized priesthoods and their closely reasoned theologies, have in the last two thousand years won most of the world away from the unorganized pagan and tribal cults. But the world religions differ basically among themselves and are no nearer to scientific proof of their discordant claims about the nature of man and the gods than when they were founded. Today, in many lands, they are losing ground to the pseudo-scientific philosophy of Marxism.

Pure science has advanced enormously in the last three centuries. But, looked at over the whole stretch of recorded history, the advance of science has been erratic. It has leaped ahead in sudden spurts, shot off on pseudo-scientific tangents like astrology and alchemy, become embroiled in religious and political conflicts, and sometimes been repudiated by whole nations.

In the arts, people’s tastes have changed from age to age, but in a capricious and faddish manner. People have often abandoned some canon of beauty in painting, sculpture, architecture, music, or poetry and embraced another simply because they were bored with the old and eager to try something new.

But through all the ages of history, one human institution—technology—has plodded ahead. While empires rose and fell, forms of government went through their erratic cycles, science flared up and guttered out, men burned each other over differences of creed, and the masses pursued bizarre fads and fashions, the engineers went ahead with raising their city walls, erecting their temples and palaces, paving their roads, digging their canals, tinkering with their machines, and soberly and rationally building upon the discoveries of those who had gone before.

So, if there is any one progressive, consistent movement in human history, it is neither political, nor religious, nor aesthetic. Until recent centuries it was not even scientific. It is the growth of technology, under the guidance of the engineers.

Technology has progressed continuously from the time of the Agricultural Revolution 10,000 years ago, slowly and hesitantly at first, then with increasing sureness and speed. The sixteenth century marked the beginning of modern engineering because, from that time on, profes-
42 attacked China to compel the Chinese government to let British merchants sell opium in China, the British easily scattered the spear-armed rabble the Chinese sent against them.

While China, Islam, and the Byzantine Empire stagnated and India remained sunken in mystical dreams of cycles and karma, medieval western Europe sprang into the lead in the useful arts of peace and war. By the time the older civilizations became aware of the threat from this vigorous new culture, it was too late to catch up, except at the cost of drastic and painful revolutions in their own civilizations.

THE EUROPEAN ENGINEERS

NINE

At first the decline of civilization in western Europe, after the fall of Rome, was gradual. We have the letters of two scholarly men, Sidonius and Cassiodorus, who lived while the barbarians were actually carving up the West Roman Empire into German kingdoms. These letters show little awareness that the writers were living at a time of great change, or that they deemed the upheavals around them unusual.

In fact, at the end of +VIII, civilization revived a little. King Karl of the Franks—Charlemagne to us—conquered most of Europe from the Oder to the Pyrenees. On Christmas, +800, the Pope crowned Charlemagne Roman Emperor, although this big, hearty, semi-literate German had even less in common with Augustus and Hadrian than did the other “Roman” Emperor in Constantinople. Nevertheless this shadowy title, assumed by a long line of German and Austrian kings, continued like an un laid ghost to trouble the politics of Europe down to Napoleonic times.

Charlemagne, however, tried to live up to his imperial title. To revive the Roman road system, he appointed a road commission and commanded his feudal lords to co-operate with the commissioners. The commission repaired some old Roman roads and built others, but the work petered out after Charlemagne’s death.

Charlemagne also built a huge wooden bridge across the Rhine at Mainz. It took ten years to build. Then it caught fire—whether by accident or arson—and burned up in three hours.
In addition, the new Emperor of Europe embarked on a grandiose plan to link the headwaters of the Rhine and Danube rivers by a canal. But his engineers were not up to their task. They were defeated by quicksands, heavy rains, and (according to the chronicles) by the hideous laughter of fiends at night, which terrified the workmen. The clergy, who wrote the chronicles, thought that God thus showed his disapproval of changing the face of nature. A Rhine-Danube canal was finally completed in +XIX, fiends or no fiends.

Charlemagne's empire broke up at his death, and the Vikings began raiding the lands of the former West Roman Empire. By +900 they had reduced western Europe to its lowest estate in a thousand years. At the same time, another wave of Mongolian nomads, the Magyars, ravaged Europe far and wide from their bases in Hungary before they settled down to adopt the rudiments of civilization.

During this age of chaos, Roman buildings were demolished to make crude fortifications of the stone. Communities tore up nearby Roman roads and broke down Roman bridges to make it harder for marauding armies to reach them. Most Europeans lived again in isolated villages, much as they had lived in the early days of the Agricultural Revolution, by farming and home manufacture.

Then, little by little, civilization began to recover. Mining revived in Muslim Spain and in Central Europe. Coinage, which had almost vanished, came back into use. Venice began her career as the leading shipping center of the Inner Sea. And brisk manufacturing activity sprang up in the cities of northern Italy.

Here too republicanism, which had seemed to perish from the earth with the triumph of Augustus, revived. And in +XIII some Italian city-states gained eternal honor by being the first governments in the world to abolish slavery.

Several importations and inventions helped to raise the dismal European standard of living. Cotton and sugar cane were for the first time planted on the shores of the Mediterranean. The horseshoe, already invented, came into general use. So did the new horse collar, which made it possible to plow with horses. Where oxen continued to be used as draft animals, improvements in their harness and the practice of shoeing them made their efforts more effective.

A new kind of plow appeared in northern Europe. This was a heavy wheeled plow with a coulter or knife to slice open the turf in front of the share. The coulter made it easier to plow the thickly grassed fields of the damp northern lands.

Another source of power, the water mill, became common everywhere.

But water power was not now limited to swift streams, because the tidal water mill appeared in +XI. Millwrights built basins in bays and estuaries. They let water run into these basins at high tide and out again at low, turning water wheels both ways.

During the Dark Ages, as the period from +VI to +X is called (though some modern historians dislike the term), engineering and architecture ceased to be recognized professions. The work of engineers and architects was carried on by craftsmen such as master masons. During the decline, construction in stone became rare. Wood and plaster were used instead, whence the familiar half-timbered medieval house.

Kings and popes, using clerics as architects, continued to put up churches in the Romanesque style: plain, massive stone buildings with small windows and many round arches. The curious "central" type of church flourished for several centuries. This was built in the shape of a circle or a polygon, with the altar and pulpit in the middle and the aisles radiating out from them like spokes. The emperor Constantine began the first of these churches, the octagonal Domus Aurea, at Antioch in +327.

The literature of the time consists mainly of dryly terse monkish annals, religious tracts, and highly fictional lives of saints. However, technology was not entirely mute. Some time in +X, a certain Eratosthenes wrote a book called *On the Arts of the Romans*.

About a century later, the German monk Theophilus wrote a longer book, which drew upon Eratosthenes and other sources and which was called *A Treatise on Various Arts* (Schedula diversarum artium). Theophilus' work deals with the arts that a cleric needed to know for decorating churches, making religious vessels and other accessories, and illuminating manuscripts. He tells how to make paint, glue, gold leaf, tin leaf, glass (clear and stained), metalworking tools, and wire. He explains how to temper a file, build an organ, cast a church bell, carve ivory, and cut glass. His first chapter is called: "On the Mixture of Colors for the Nude," which is a little startling for a medieval monk until we realize that Theophilus is merely giving directions for mixing the pigments for flesh tints in paintings.

Among Theophilus' formulas is an alchemical one that must have reached him from the Islamic world. It reads:

There is also a gold called Spanish gold, which is composed from red copper, powder of basilisk, and human blood and acid. The Gentiles, whose skillfulness in this art is proverbial, make basilisks in this manner. They have, underground, a house walled with stones everywhere, above and below, with
two very small windows, so narrow that scarcely any light can appear through them; in this house they place two old cocks of twelve or fifteen years, and they give them plenty of food. When these have become fat, through the heat of their condition, they unite and lay eggs. Which being laid, the cocks are taken out and toads are placed in, which may hatch the eggs, and to which bread is given for food. The eggs being hatched, chickens issue out, like hens' chickens, to which after seven days grow the tails of serpents, and immediately, if there were not a stone pavement in the house, they would enter the earth. Guarding against which, their masters have round vessels of large size, perforated all over, the mouths of which are narrow, in which they place these chickens, and close the mouths with copper coverings and inter them in the ground, and they are nourished with the fine earth entering the holes for six months. After this they uncover them and apply a copious fire, until the animals inside are completely burnt. Which done, when they have become cold, they are taken out and carefully ground, adding to them a third part of the blood of a red man, which blood has been dried and ground. These two compositions are tempered with sharp acid in a clean vessel; they then take very thin sheets of the purest red copper, and annoint this composition over them on both sides, and place them in the fire. And when they have become glowing, they take them out and quench and wash them in the same consecution; and they do this for a long time, until this composition issues through the copper, and it takes the color of gold. This gold is proper for all work.  

The mythical basilisk was a kind of pygmy dragon, which could turn people to stone by looking at them and therefore was hunted with mirrors in which it stared itself to death. Aside from this excursion into magic, however, Theophilus' work is sober and sensible.

Another factor in the revival of European civilization was the importation of literature from lands where letters had never fallen so low. Moreover, some Roman writings had been saved in the lands of the former Western Empire by Benedictine monks, who copied and recopied the manuscripts as a work of merit.

From +X on, other manuscripts trickled in from the Byzantine Empire and the Caliphate. Some were Greek, some Arabic translations from Greek, and some original Arabic works. As Greek and Arabic were almost unknown in western Europe, these works had to be translated into Latin, the international language of the time. The main center of the work of translation was Spain, and many of the translators were Jews.

At the beginning of +VIII, the Muslims conquered all of Iberia except a strip along the northern coast. Arab rule was in many ways more endurable than the Roman-Visigothic government whose place it took; but the Arabs, with their usual political fecklessness, quickly broke up into a lot of quarreling petty states. In the North a similar group of Christian states took form and began to win the Spanish peninsula back from the Muslims.

For most of two centuries, Iberia was a constellation of Muslim and Christian states, which fought incessantly. Not taking religion too seriously, a Christian and a Muslim lord often cheerfully formed an alliance to fight other Christian or Muslim lords.

Despite all this jovial murder and mayhem, Muslim Spain was at this time the most civilized part of western Europe. In this lively and liberal Christian-Muslim Spanish world, most of the translation of Greek and Arabic works into Latin took place.

At the end of +XII, however, a wave of Berbers from Morocco, newly converted to Islam and filled with the fanaticism of ignorance, overran the peninsula. Combining the political anarchism of the Arabs with a brutish hatred of thought and knowledge that was all their own, the Berbers soon ended the Golden Age of Muslim Spain, without being able to stop the advance of the Christian states.

Their fanaticism aroused a counter-fanaticism among the Christians. The Church became ever more powerful in Christian Iberia. It imposed such effective thought control that, even while Spain was rising to be the leading power of Europe (+XVI), it was also becoming the intellectual cipher that it has been ever since.

The terms "Middle Age" and "medieval" are not hard and fast in meaning. The age called by these names can be extended from the fall of the West Roman Empire around +500 to the beginning of the Age of Exploration around 1500. Some historians, however, prefer to consider the age a shorter period. Moderns invented these terms to denote the interval between classical times and their own.

Of course, medieval folk did not think of themselves as medieval, or as mere intermediaries between the ancients and the future. They thought of themselves as modern, advanced, and enlightened people. The name "Age of Faith" better describes the medieval period, because during this millennium the conflicts between the major monotheistic religions, Christianity and Islam, and between the sects and schisms within these faiths, were a major fact of life.

The twelfth and thirteenth centuries are sometimes called the High Middle Ages, especially by people who idealize this stage of man's history. During these centuries, the things that we think of as particularly medieval reached their peak. This was the great age of knighthood, of
castles and cathedrals, of the Crusades, of feudalism, of troubadourism, and of scholastic philosophy.

The High Middle Ages were a time of grim asceticism and riotous self-indulgence. Costume was wildly colorful, thanks for advancements in the loom and in dyeing. The buttonhole, invented in +XIV, revolutionized dress as buttons replaced pins and laces. Gems glittered with new brilliance as a result of the recent discovery of faceting. There were frenzied outbreaks of religious hysteria, fanaticism, and cruelty, resulting in such monstrous mischiefs as the Children's Crusade and the massacres of heretics and Jews. Superstitious supernaturalism, typified by the twelve Holy Foreskins venerated as relics in various churches, ran wild. Literacy was still so scarce that in 1215, King John of England did not sign the Magna Carta, because he could not write. He affixed his seal instead.

For us, the High Middle Ages were the time when engineering regained most of the ground lost after the fall of Rome. In some ways, technology advanced well beyond its classical prototypes.

During this time, also, scholars thought and speculated about the behavior of matter. They pondered the nature of motion, force, and gravity in the early modern period, science and engineering came to depend on each other.

The work of the scholars did not, however, much affect the engineering practice of their own time. At that early date, engineers were anonymous craftsmen who worked by rule of thumb, using the skills handed down to them during their apprenticeship. They had little to do with scholars and scientific principles.

Medieval scholars included some very intelligent men and acute reasoners. They made some progress in straightening out physical concepts, although they worked under handicaps. For one thing, like the ancient Greeks, they made little use of experiment.

Furthermore, most medieval thinkers took Aristotle's doctrines in physics as basic truths. As these doctrines were nearly all wrong, the medieval scholars' advances in physics consisted for a long time of finding the errors in Aristotle and laboriously convincing their colleagues that "the master of those that know," as they called him, could make mistakes.

Finally, the scholars had difficulty in handling such concepts as force, mass, weight, distance, velocity, and acceleration because no hard-and-fast, clear-cut, agreed-upon use of words had yet been worked out. Hence, when a medieval scholar wrote of "quantity of motion," it is hard to tell whether he meant the distance an object moves, or its speed, or some combination of these.

A leading scientific scholar of the High Middle Ages was the English monk Roger Bacon (1214–92). Having studied at Oxford, Bacon spent most of his adult life as a lecturer at the University of Paris.

Although his voluminous writings summarized much of the scientific beliefs of his period and added something to human knowledge, Bacon has been overrated in modern times. For most of the last fifteen years of his life he was imprisoned by his fellow Franciscans for uttering "novelties," the nature of which is not known. Therefore, many have supposed that Bacon was a scientific martyr persecuted by the Church.

From the scanty records, however, it appears that Bacon was religiously more orthodox than those who condemned him. He may have gotten into trouble for any of several possible reasons: because he violated a Franciscan rule against writing books; because he was a quarrelsome man who berated his colleagues as ignorant asses; because his friend Pope Clement IV, on whose protection he counted, died; and lastly because he got involved in a power struggle within the Franciscan order.

Nevertheless, Bacon's works contain many interesting features. He wrote much of value on optics, although most of his ideas on this subject were taken from the Muslim scientist ibn-al-Haytham. He wrote the first known European account of gunpowder (at least, the first of whose date we can be fairly sure) and foresaw its use in warfare. He preached the importance of experiment when most clerical scholars avoided it as dangerously close to black magic.

On the other hand, much of his work we should call superstitious. He attributes the victories of the Mongols, then sweeping Asia from Honan to Hungary, to the Mongols' having better astrologers than their foes. And, because his writings did not begin to be published until +XVIII, half a millennium after Bacon's time, they had little influence on the development of science and technology.

In a famous passage, Bacon predicts the results of applying experimental science to the useful arts:

Vessels can be made which row without men, so that they can sail onward like the greatest river or sea-going craft, steered by a single man; and their Likewise carriages can speed is greater than if they were filled with oarsmen. Likewise carriages can be built which are drawn by no animal but travel with incredible power, as be built which are drawn by no animal but travel with incredible power, as be built which are drawn by no animal but travel with incredible power. Flying machines we hear of the chariots armed with scythes of the ancients. Flying machines we hear of the chariots armed with scythes of the ancients. Flying machines we hear of the chariots armed with scythes of the ancients. Flying machines we hear of the chariots armed with scythes of the ancients.
it by a skillful mechanism and traverses the air like a bird in flight. Moreover, instruments can be made which, though themselves small, suffice to raise or to press down the heaviest weight. . . . Similar instruments can be constructed, such as Alexander the Great ordered, for walking on the water or for diving.  

Furthermore, Bacon’s studies in optics convinced him that:

If a man looks at letters or other small objects through the medium of a crystal or of glass or of some other transparent body placed above the letters, and it is the smaller part of a sphere whose convexity is toward the eye, . . . he will see the letters much better and they will appear larger to him . . . Therefore this instrument is useful to the aged and those with weak eyes. For they can see a letter, no matter how small, sufficiently enlarged . . . The wonders of refracted vision are still greater; for it is easily shown by the rules stated that very large objects can be made to appear very small, and the reverse, and very distant objects will seem very close at hand, and conversely . . . Thus from an incredible distance we might read the smallest letters and number of grains of dust and sand . . . So also we might cause the sun, moon, and stars in appearance to descend here below . . .

Now, Bacon never built a telescope or an airplane. Neither did he leave instructions that would enable others to build them. Therefore these statements by Bacon are imaginative speculations, not actual advances in science and engineering.

Nevertheless, Bacon’s speculations have their place in the story of the growth of knowledge. An invention must be imagined before it can be built, even though he who imagines it may not be he who reduces it to practice. From Bacon’s time on, more and more of such conceits found their way into writing. When these inventions had been imagined often enough, people became sufficiently used to the ideas so that some actually began tinkering. Thus, little by little, Bacon’s imaginary devices became realities.

Bacon was but one of many medieval scholars who busied themselves with physical problems. His contemporary Jordanus de Nemore advanced the science of statics, the analysis of the forces in a solid structure bearing a load. He then attacked the problem of resolving a force into its components.

In the next century (+XIV) a group of English scholars at Merton College, Oxford University, straightened out some of the confusion in the French scholar Jean Buridan explained the behavior of moving bodies by a theory of “impetus” not far from the modern theory of inertia.

Others, too, speculated and invented. An English monk, Ellmer of Malmesbury (+XI) built a flying machine—a sort of glider attached to his arms and legs—and leaped from a height. He crashed and broke both legs but, though lame ever after, lived to old age. Perhaps he had heard of a previous attempt at flight by a physician, glass maker, musician, poet, and inventor of Muslim Córdoba, ibn-Flmâs (+IX), who also crashed, injuring his back.

Not much record remains of the thinking of the practical engineers of the Middle Ages—the cathedral builders, the catapult makers, and the millwrights. One of the few such records is the notebook of the craftsman Villard de Honnecourt, about 1230. It consists of thirty-three sheets of parchment covered with sketches and descriptions. Some of the sketches are too rough to give a clear idea of what Villard is driving at; in other cases his designs would not have worked. Still, we can see his ideas taking shape amid the general ferment of the time. Besides methods of cutting voussoirs for arches and driving piles for bridges, Villard shows a catapult, a water-powered sawmill, some automata of the Alexandrian type, and a perpetual-motion machine.

Fig. 21. Sketch for a water-powered sawmill, from the notebook of Villard de Honnecourt.

In connection with Chinese engineering, I have told you about the development of paper and the printing press. European printing, which matured in +XV, was preceded by another invention of equal moment. This was the eyeglass. Besides the other revolutionary changes that took
place at the end of the Middle Ages, paper, printing, and eyeglasses together caused a revolution in reading.

All we know about the origin of eyeglasses is that in 1306, Friar Giordano of Pisa said in a sermon:

It is not twenty years since there was found the art of making eyeglasses which make for good vision, one of the best arts and most necessary that the world has. So short a time it is since there was invented a new art that never existed. I have seen the man who first invented and created it, and I have talked to him.1

Evidently, eyeglasses were invented shortly after 1286. Perhaps the inventor—Friar Giordano unfortunately did not name him—was inspired by the optical writings of Roger Bacon, who died at about that time.

All the first spectacles had convex lenses to correct farsightedness. Most people, if not farsighted to begin with, became so with age as the lenses of their eyes lose their power of adjustment for short-range vision. Eyeglasses to correct for nearsightedness and astigmatism were not made until several centuries later.

Even so, the crude spectacles of +XIV and +XV extended the reading ability of many people who would otherwise have been cut off from this source of knowledge and pleasure in their forties. In earlier times most literate men, no matter how scintillating their intellects, were debarred from reading in their later years. They had either to be read to or give up literature. Now men could go right on reading.

When the printing press was perfected in +XV, books became much cheaper and commoner than before, as had happened earlier when paper replaced papyrus and parchment. Between printing and eyeglasses, the amount of time spent in reading by a whole population was probably increased several fold. This fact by itself would almost account for the speed-up of intellectual and scientific progress during the last few centuries.

Of course, even after literacy had again become common in Europe, there were doubtless millions who, in spite of having learned their letters as children, read practically nothing as adults. Such behavior is not unknown among high school and college graduates of today.

Moreover, the reading revolution was not yet complete. Reading at night by candlelight was still an eyestraining task, which few cared to pursue. It took the invention in 1784 by Argand, a Swiss, of a really bright oil lamp to make nocturnal reading pleasant. Finally, it took nineteenth-century universal education and public libraries to bring about the modern state of affairs, when anybody can read about virtually anything that interests him.

Because most of the engineering of the High Middle Ages was done by unknown masons and other nameless craftmen, we cannot say much about the medieval engineers themselves. But we can talk about their engineering. Let us see how the technology of the time developed, art by art.

Germany, with abundant supplies of coal and iron and its silver, copper, lead, and tin, led the revival of mining and metallurgy. The mining of coal developed in the Middle Ages, although coal had long been dug up and burned where it could be grubbed from the earth's surface. Even Theophrastos, Aristotle's successor, knew of coal as a fuel.

In ancient and medieval times, coal was used only for industrial purposes such as burning lime. It was not used for house heating because houses did not yet have chimneys. If anyone tried to heat a chimneyless house with coal, the suffocating smoke soon drove the dwellers forth.

After the fall of the West Roman Empire, there is no record for several centuries of the use of coal in Europe. Then medieval miners began digging up coal, not only from surface beds but also from shafts run into the ground as they did for other minerals. The use of coal greatly increased men's power over materials because coal furnished much more heat energy than other available fuels in proportion to its bulk and weight. This use waxed so swiftly that in 1307 the lime burners of London were forbidden to fire their kilns with coal, because the smoke bade fair to smother the city.

Rapid deepening of the shafts of coal mines aggravated the problem of drainage. In damp northern Europe, the shafts soon went below the water table, so that they filled up with ground water. By the end of the Middle Ages they had gone so deep that in some mines hundreds of men were kept at work passing buckets up ladders to keep the mine bailed out. This state of affairs led to the invention of horse- and water-powered mechanical pumps.

The smelting and refining of iron also advanced by great strides. Furnaces became larger, more permanent, and more carefully engineered. Early medieval smelters used the Corsican furnace, a semicircular Early medieval smelters used the Corsican furnace, a semicircular Early medieval smelters used the Corsican furnace, a semicircular Early medieval smelters used the Corsican furnace, a semicircular Early medieval smelters used the Corsican furnace, a semicircular
At the same time other improvements appeared. One was the use of coal, at least in the early stages of smelting. The Chinese may have anticipated Europe in this use of coal. Coal could not be employed in the final stages of refining iron because the sulfur and phosphorus in the coal would damage the iron. Men had not yet learned how to turn coal into coke by roasting it, thus driving off the impurities and leaving almost pure carbon behind.

Another advance was the increasing use of water power. Water wheels worked stamping mills, in which ore was broken into small pieces in mortars. It worked bellows, providing a stronger air blast and higher temperatures than could be obtained with muscle-powered bellows. Finally, it lifted trip hammers to pound the finished iron into shape.

The higher temperatures attained in late medieval furnaces made it possible to melt iron, dissolve carbon in it, and cast it. The hotter molten iron is, the faster carbon dissolves into it. The higher carbon content, which makes iron hard and brittle, also lowers its melting point and makes it flow freely.

Ancient smiths had produced cast iron, which they considered spoiled and worthless, only occasionally, by accident. But in late medieval times it was found that, as the Chinese had already learned, cast iron was very useful for some purposes, such as stoves and cannon. Late medieval founders could turn out either wrought or cast iron at will, in masses of hundreds of pounds per charge. The wrought-iron bloom of the classical smith seldom weighed over 50 pounds.

Although the medieval ironmongers could now readily convert wrought iron to cast iron, the latter comprised only a small fraction of all the iron produced. As late as 1750, cast iron still amounted to but 5 per cent of all the iron made.

However, the larger quantities of iron produced in medieval furnaces and the new flexibility of methods of smelting and refining meant that by little, iron began to be used in common tools and machines that had up to then been made entirely of wood.

In addition to the water-powered hammer, the Middle Ages saw the birth of other devices for molding metal: the rolling mill and the draw plate. The draw plate is an iron plate with holes in it for drawing wire. The wire is thinned by pulling it through a hole smaller than itself. The wire drawer of +XIV sat on a swing, which was pulled back and forth by a water wheel and crank. On each back swing, the craftsman seized the wire with tongs and drew it back with him, pulling it through the hole. Before the draw plate, all wire had to be beaten out with a hammer.

The early rolling mills were not used for rolling iron, because iron was too tough for them. Instead, they rolled out the H-shaped bars of lead that held in place all the many little pieces of stained glass in church windows. These inventions affected the production, not merely of iron, but also of all the common metals.

Novel chemical products appeared during the Middle Ages, opening up new possibilities for the manipulation of matter. Gunpowder I have already told you about. Alcohol, judging by its name, was probably an Arab discovery; but the first actual description of it comes from the Italian medical school at Salerno about 1100. Its first use was as a base for perfumes and cosmetics. In +XIII appeared the three strong acids: sulfuric, nitric, and hydrochloric; the first of these may have been discovered by the Arab alchemist, Jābir ibn-Hayyān, as early as +VIII. Before this time, chemists had had no acids stronger than vinegar to work with.

In few respects was medieval Europe more backward, compared to the Roman Empire, than in the planning, building, and keeping up of cities. Down almost to modern times, most European cities were as innocent of sewer systems as some large Asiatic cities are today.

Most medieval European cities grew out of villages, which were sometimes built on the sites of ruined Roman cities. These towns displayed the typical village layout: a tangle of crooked alleys.

In the later Middle Ages and the Renaissance, these cities were faced with a difficulty much like that of modern cities confronted by the automobile age, for which they were never planned. The streets of medieval cities were adequate for pedestrians, with an occasional man on horse or muleback. But, when carts, wagons, and carriages increased, the old irregular layout proved inadequate.

So, from 1300 on, kings and councils issued a blizzard of decrees about parking, speeding, and making U-turns. In 1540, François I of France ordained:

And, under the same penalties, We forbid wagoners and drivers, whether of carts, drays, wagons, or other vehicles, to turn in the streets, but they are to turn at the intersections and corners of said streets to avoid the inconvenience that may arise, such as wounding children or other persons and interfering with other passers-by along the road.  

As today, these regulations failed to cure all the ills they were meant to remedy.
In +XIII, a number of new towns were laid out by English, French, and German rulers. Examples are Monpazier, Carcassonne, Winchelsea, and Neubrandenburg. All were built on the gridiron plan. Usually the marketplace occupied one whole central block, with colonnades around it and the church adjacent. Town planning and urban renewal became active in the Renaissance, notably in the rebuilding of shabby old Rome by the popes.

A fine opportunity for city planning was offered after the great fire of London in 1666. The ashes had not cooled when John Evelyn, the diarist and civil servant, and Christopher Wren the architect rushed around to show Charles II their plans for rebuilding the burned area. They arrived almost at the same time and discovered that their plans had many features in common. Either plan would have been of the greatest advantage to London.

The king passed the plans on to Parliament, which debated them. But it would have taken a lot of effort and money to settle all the claims of the property owners in the district. Moreover, the burnt-out shopkeepers screamed that they would starve unless allowed to reopen for business at once at the same old place in any old shack. While Parliament dithered, the burned area was rebuilt on the old plan (except for some street widening and a new law against wooden houses) and the East End of London has remained a medieval tangle of alleys ever since.

Paving was long unknown in medieval cities. The stroller was blinded by clouds of dust in dry weather and sank to his ankles in muck during wet spells. It was said of anything particularly ghastly that "Il tient comme le boue de Paris"—"It sticks like the mud of Paris."  

In 1184, King Louis Philippe, tiring of the dust and mud, ordered Paris paved. The result, if not so finished a job as the paving of ancient Memphis and Babylon, was a step in the right direction. The paving was done with stones about 7 inches thick and of irregular shape, 20 to 52 inches long. If these stones did not help the drainage problem, they at least kept vehicles from sinking up to the hubs.

For several centuries thereafter, rulers and officials tried to clean up, pave, and modernize the streets of European cities. Their efforts were not very successful. Medieval Europe had fallen so far behind Roman standards of municipal service that it did not surpass the Romans in this regard until the last two centuries. Rome of +100 was better off for street maintenance, sewers, police, and fire protection than London or Paris of 1700.

One difficulty was caused by rulers themselves. Instead of collecting taxes—especially from the untaxed Church and nobility—and spending the money on improvements, they passed laws requiring every citizen to pave the street before his house, to keep it clean, to refrain from encroaching on the public right of way, and to refrain from throwing his garbage and sewage into the street. Dumps were provided outside the town for these purposes. Medieval Nantes even had a law forbidding people to throw dead cats into the water supply.

Most citizens, however, preferred to spend their time and money otherwise than in keeping up their cities, and the nobility simply ignored the rules. After a ruler had issued some resounding decree, there might be sporadic improvement. But soon the law would be quietly forgotten, and the city would become as foul as ever. As if the streets were not narrow enough to begin with, citizens narrowed them still further by extending their own structures out into the right of way.

Attempts to make citizens pave the streets before their houses proved ineffectual. When hauled before the courts, the householders wailed that they had no money to pay the pavers, and that anyway that stretch of street had never been paved. When paving was laid, it was highly irregular, since each property owner had it done as he saw fit.

Moreover, guilds of pavers grew up as certain stonemasons specialized in this trade. These men dug up good paving to compel the householders to hire them to replace it. This racket continued even after such destruction of pavement had been made a capital crime.

Most of us are familiar with the general appearance of medieval European private houses. Wood and plaster half-timbered construction was typical, and the second story often extended forward over the street below. The roofs were high-peaked and covered with thatch or shingle or tile. Domestic chimneys, adapted from those already used in bake ovens and smelting furnaces, appeared in +XIII.

The High Middle Ages, however, saw advances in structural forms. One advance was a greater variety of arches. In addition to the semi-circular arch of the Romans, medieval builders learned from Islam the use of the pointed arch. The pointed arch had the advantage of exerting thrust on its piers a thrust that was more nearly straight down; and, since there was less outward thrust of the lower ends of the arch, there was less tendency to push the piers apart. Therefore, with the pointed arch, the supporting piers or walls did not have to be so massive or so heavily buttressed.

Still another advance was the truss. We have seen the first steps toward the truss in Trajan's Danube bridge. In the Middle Ages, trusses
of timber were used to hold up roofs. However, as nobody could analyze the forces in a truss, medieval roof trusses were often cluttered with extra members that added nothing to their strength. Really efficient trusses, in which every member counted, were developed by the Renaissance architect Palladio (+XVI).

Besides these changes in structure, the methods of designing buildings also changed. The profession of architect reappeared. In the Dark Ages, buildings were planned by master masons or by monks with a taste for design. In the High Middle Ages, professional architects once more evolved from these masons.

Not much is known about these men beyond the bare fact that they existed. We know of Villard de Honnecourt solely because we have his notebook. But these nameless architects were competent men who, if innocent of higher mathematics, nevertheless had a good practical knowledge of weights, strengths, and forces.

Their most signal accomplishment was the development of the Gothic cathedral. While in Italy the Romanesque church with its thick walls and round-topped doors and windows continued to be built right down to the Renaissance, a very different style of church appeared in northern France in the latter half of +XII. Although the Italians called it “Gothic,” meaning “barbarous,” it spread over most of Europe.

The most obvious features of the Gothic church were its pointed arches and its large windows, adapted to the dim light of the gray northern skies. The large windows were achieved by a basic change in structure. The weight of the roof was carried, not by a whole wall as in earlier structures, but by piers, which were incorporated in the outer wall. These piers functioned somewhat like the colonnades that had held up the roofs of Greek temples.

The space between the piers was filled at first by thin walls and later by large stained-glass windows. The fully developed Gothic cathedral anticipated the modern skyscraper with its steel skeleton holding up separate panels of wall. The skeleton does the work while the wall merely keeps out the weather.

In addition, parts of the inner structure were often held up by rows of pillars. But these columns differed from those of antiquity. The capital, which had become the impost block of Byzantine times, dwindled away altogether, so that the ribs of the vaulting sprang directly from the top of the column like branches from the trunk of a tree. The column itself became a pier built up of small stones with a ribbed pattern resembling a cluster of small columns, not unlike the ribbed columns of King Joser’s Egypt.

Vaulting was developed to a new pitch. Medieval architects learned to roof their churches with vaults of stone and tile, because wooden roofs were always catching fire from sparks or lightning. As the people had no means of getting water up to such a height, such a fire always destroyed the whole church.

Vaults were made with a pointed peak like that of a Gothic arch. As in the walls, stresses were concentrated along stone ribs that soared up from one pier to the zenith of the ceiling, often over 100 feet from the floor, and down on the other side. At least, that was the effect, although the architects probably had no such clear engineering concepts in mind.

These heavy roofs naturally posed the problem of outward-spreading thrust. Pointed arches took care of some of the horizontal thrust. To cope with the rest, medieval architects developed the flying buttress. This was a structure of stone, like a small section of an arch, leaning against the piers from outside the building, propping the wall and counterbalancing the thrust of the roof vault.

Another characteristic of the Gothic church was its ornamentation. Sections of the stained-glass windows were divided up not only by partitions of iron and lead but also by delicate curlicues of stone, called “tracery.” The European architect, like the Indian temple builder, liked to fill up with statuary every available space on his building. The roof was embellished with scores of spiky spires, often surmounted by statues. Although some stone saints and angels were works of high art, statues. Although some stone saints and angels were works of high art, were works of high art, so were their headdresses and halos.

Lacking scientific principles, medieval architects developed their methods by guess and by trial. Some of their churches fell down on the heads of the faithful, and some surviving churches contain mistaken, illogical features. The roof of Beauvais Cathedral, whose ceiling was the highest of any—154 feet—collapsed twice in +XIII and had to be rebuilt with stronger supports. The spire, not built until +XVI, also toppled with a crash.

During the High Middle Ages, much of the economic surplus of Europe went into the building of cathedrals, as that of Egypt had once gone into pyramids. Cities vied to build the biggest and most sumptuous churches. Contributions of money and voluntary work brought into being an amazing array of towering Gothic fanes. Regional styles developed. For example, the French liked very tall towers, while the Germans preferred smaller towers but lofty side walls.

In fact, many cities undertook projects larger than they could carry out. Sometimes these churches took three or four centuries to complete,
during which time the plans were several times changed. Some have not been completed to this day; thus the original nave planned for Beauvais Cathedral has never been built.

As a result of these vicissitudes, many Gothic churches have bizarre asymmetries. For instance, one of the pair of towers at the west front of Amiens Cathedral is a whole story taller than the other.

The rage for building giant Gothic cathedrals died out in +XV, although work continued fitfully on churches already begun. The Renaissance produced other building styles, with a strong flavor of classical Rome.

Still, from time to time, since the Middle Ages, architects have reverted to the Gothic form for churches. The original churches built in this style were such remarkable tours de force, they were so huge and splendid and numerous, and their heaven-piercing spires made such a deep impression on the minds of men, that ever since then they have become in many European minds the very symbol of the Christian religion.

After the Gothic cathedral, the most characteristic large building of the High Middle Ages was the castle. The castle or fortress-dwelling was an ancient structure known to antiquity, and found from prehistoric Sardinia to the Far East. But the loose feudal government of medieval Europe, under which any local lord might wage private war on any other, encouraged castle building on an unprecedented scale. These castles ranged from the little family dwelling towers of Scotland and Germany—one-family houses built like miniature castles—to huge fortresses like the citadel at Carcassonne, which was practically a fortified city.

The landscape of Europe and the northern Mediterranean lands was dominated by these castles and their surrounding farms, carved out, as it were, from the primeval forests and worked by miserable serfs. Paths, rather than roads, wound past these castles and on toward the occasional walled town, which was prepared to hold its own against the warring sieges.

When the Crusaders conquered the Byzantine Empire in 1204, they carved the Empire up into feudal domains and dotted the mountain tops of Hellas with castles, whose ruins still rise jaggedly hither and yon against the clear blue sky. One of the world’s largest and best preserved castles, Kerak des Chevaliers, was built in Syria for the Knights Hospitallers of St. John of Jerusalem in the late +XII. It is curious that the best example of medieval European castle architecture should stand today in a Muslim land, while the finest medieval Muslim palace, the Alhambra at Granada, is in Christian Spain.

The art of pre-gunpowder fortification reached its peak in medieval Europe. Although most of the elements of the European castle—the round tower, the crenelated parapet, the moat, and the portcullis—were old, medieval castle-builders combined them with greater skill and care than their predecessors.

In fact, medieval castles reached such a pitch of perfection that few, before the coming of cannon, were ever captured save by surprise or treachery. As in the First World War, defense had a strong if temporary advantage over offense. Hence most wars took the form of indecisive sieges. The besieger tried to starve out the besieged. But, if the latter had prudently prepared for the siege, the attacker might well have to give up first when his men’s short enlistments ran out and they trickled away.

Along with the other arts and sciences, fortification had declined in Europe during the Dark Ages. But then it began to revive. At the time of the Norman conquest of England (1066) the typical castle was no more than a large house of stone or wood, surrounded by a wooden stockade, on a mound surrounded by a ditch.

However, some larger and stouter castles had also been built, with turrets and crenelated parapets on the old Roman model. When the Crusaders saw the vast walls of Constantinople, they brought back to western Europe ideas for still more stubborn strongholds.

The medieval castle thenceupon developed two main features: a tall, thick, crenelated stone wall, the enceinte, surrounding the whole; and a large thick-walled round tower, the keep or donjon, for a last stand. The biggest keep of all was that of Château Coucy, near Soissons, 100 feet in diameter, 180 feet high, and made of walls 18 feet thick. In the First World War, General Erich Ludendorff ordered it blown up, not for any military reason but for the pleasure of destroying things.

The living quarters of early medieval castles, for the most part extremely crude and uncomfortable, were tucked away in odd corners of the structure. Provisions for warmth, cleanliness, and privacy were rudimentary.

The enceinte comprised the main defense. But, if it were overrun, the defenders retired into the keep. As the keep had only one small door and was of such massive masonry that it could not be battered down, the defenders could hold out there as long as their provisions lasted.
Fig. 22. The castle of Coucy, near Soissons (restored), showing the keep-and-enceinte plan, fortified gatehouses, machicolation, and conical roofs on the turrets.

On the other hand, the attackers could just as easily prevent the defenders from coming out.

As a result of crusading experience, castle builders changed from the simple enceinte-and-keep plan to one of concentric walls. Such a structure was really two or three castles, one inside the other. As one line of walls was taken, the garrison retired to the next. Because the inner walls were taller than the outer, missile troops on an inner wall could prevent the enemy from using an outer wall to attack an inner one.
In the later Middle Ages, the keep was revived, but its purpose was now different. The soldiers of the castle owner were likely to be mercenaries instead of feudal retainers. The main purpose of the keep was now to enable the lord to defend himself against his own men-at-arms in case they took it into their heads to cut his throat and share his wealth.

Castle architecture varied according to local conditions. Castles built in lowlands near running water were usually protected by moats. The most remarkable of these waterborne castles is the Pfalzgrafenstein, which rises like some strange stone ship from a low island in the Rhine.

In the mountainous parts of Germany and Austria, on the other hand, castles were perched on the most inaccessible cliffs. Such castles were so difficult for attackers to reach that the owners could afford the luxury of windows in the outer walls. In northern lands, turrets were often surmounted by conical wooden roofs, like witches' hats, to ward the warriors on the battlements against bad weather.

Entrance to a castle was planned to daunt the most determined attacker. If a moat surrounded the castle, the moat was crossed in peaceful times by a drawbridge. The drawbridge is ancient; the Egyptian fortress at Buhen, in Nubia, had a drawbridge that moved on rollers about -2000. In medieval times the drawbridge was raised by chains wound around drums, which were turned by a windlass and gearing. When the drawbridge was raised, the assailants could not cross the moat unless they could drain it or fill it with earth or brushwood. To try to tunnel under it would be to drown the sappers.

If the besieger succeeded in crossing the moat—or climbing the crag, if the castle were perched on a mountain top—he next faced the portcullis. This was a heavy iron gate, lowered from a slot over the entranceway to bar further passage. The portcullis goes back to -IV, when Aineias the Tactician wrote:

And if a large number of the enemy come in after these fugitives and you wish to stop them, you should have ready above the center of the gate a portcullis of the stoutest possible timbers overlaid with iron.7

In Aineias' time, iron was still too costly to make a whole portcullis of it, so he advised iron-sheathed wood. Medieval portcullises, however, were of solid iron.

Besides the drawbridge and portcullis, entrance to a castle might also be strengthened by strong outer gate towers that constituted a small fortress in themselves. Mastiffs or bears might be chained at the outer gate to discourage unwanted visitors.

If an attacker overcame the defenses at the outer gate, he often found that he had to follow a spiral path around the castles to the main gate. The spiral went clockwise so that the attackers' shields, on their left arms, were on the side away from the inner wall and so did the assailants no good.

The cannon, invented in China or Germany, put an end to the castle-building art, or at least transformed it beyond recognition. During its first century, the cannon was so feeble that it had little effect on fortifications. The chronicler of the city of Ulm briefly noted in his entry for 1380: "A knight came and besieged the town and shot at it with thunder guns. It did no harm." A little siege now and then was the sort of thing you had to expect in those days.

However, the gun improved along with all the other devices of the time. By 1414, cannon were formidable enough so that the Elector of Brandenburg and Prussia was able in two days to demolish the castle of a rebellious noble. Soon castle walls were seen to be of no more avail against heavy artillery than magical spells. Lords converted their castles to more or less comfortable mansions and palaces. After the Turkish sultan, Muhammad II, took Constantinople in 1453 with his mighty artillery, it looked as though no stronghold could withstand the new weapon.

After the Turks conquered the Balkan peninsula and Hungary, they besieged Vienna in 1529. Vienna was then under the rule of Emperor Charles V, who reigned over a patchwork empire that included nearly all of western Europe save France and the British Isles. The wall of Vienna was a crumbling little thing only six feet thick, and there was no time to build a proper wall. So Count Salm, the Emperor's general, made the Viennese build thick earthen embankments instead.

Although the Turks outnumbered the defenders by ten to one and were deemed the world's bravest and best-disciplined soldiers, the defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defenders nevertheless beat off their fiercest attacks, while the sultan's defende
throwing heavy stones the counterweighted trebuchet took the place of the classical onager and the two-armed stone thrower.

In the late Middle Ages, for sieges and shipboard fighting, Europeans developed a heavy crossbow as powerful as the much larger dart throwers of classical times. This weapon had a steel bow. Much too stiff to be bent by hand, it was cocked by clamping a windlass with a rack and pinion gear over its butt and cranking the windlass to draw back the string.

Use of these powerful crossbows in open warfare, however, did not prove successful because of their slow rate of fire. For example, the English longbowmen routed the Genoese crossbowmen at Crécy (1346). Although the Genoese weapons were probably more powerful and accurate, the English archers shot so fast that they pincushioned the Genoese before the latter could make much impression, and a volley from three small English cannon completed the rout of the mercenaries.

Among the other machines of medieval Europe, we have seen how clocks evolved from the water clocks and geared astronomical computers of antiquity, with the addition of the escapement from China. Other mechanical advances were the combination of the crank and the foot treadle, applied to turning the lathe and the grindstone.

The advance of machinery was hindered by the guilds. The main purpose of the guilds was to make life easy for the master craftsmen who dominated them. The guilds kept out competition, restricted entry into the guild, and opposed innovations that might upset their business. They enjoyed political power through their representation on the councils of self-governing cities and thus were able to legislate against innovations.

An example of guild activity is the case of Hans Spaičch, a coppesmithe of Nuremberg. In 1561, Hans invented an improved lathe slide rest. Hearing of this, the agitated Council showered Hans with commands: he should make no more such lathes until a committee had examined his first one and reported whether it might harm the city; he should not sell lathes to anybody outside his own craft; he should not leave town without permission. The Council offered Hans 100 florins if he would agree to let them destroy his lathe, which had cost him 300 florins to build, and promise to make no more like it.

After the case had dragged on for years, Hans built another lathe and sold it to a goldsmith, but the Council seized and destroyed it. When, some years later, another coppersmith built and sold one of the improved lathes, the Council decreed that “he shall be imprisoned in a barred dungeon for eight days to teach him not to do it again.”

Despite such handicaps, the design of machinery forged ahead. The most notable advances occurred in the millwright’s art. From the medieval millwright, the mechanical engineer of later times evolved.

Medieval Europe inherited three types of water wheel from the classical world: the undershot, the overshot, and the horizontal. These continued in use with small improvements; see for instance the reversible overshot wheel depicted in Agricola’s mining treatise (Pl. XXI). By moving the spout at the top, one could direct the flow of water into either of two sets of buckets around the rim of this wheel. One set of buckets turned the wheel one way and the other set the other way.

A sore point in the conflict between the medieval social classes was the feudal lords’ assertion of a monopoly on grinding grain within their demesnes. All yeomen, tenants, and serfs were supposed to bring their grain to their lords’ mills to have it ground at a price set by the lord. They were not even supposed to grind their own grain with querns in their own houses. The peasants paid no more heed to these rules than they were compelled to; hence much of the flour milled in medieval Europe was bootleg flour ground in illegal private mills.

In 1274, for example, St. Albans Abbey at Cirencester, England, asserted a feudal monopoly of the milling in Cirencester and demanded that the townsmen surrender their querns. Fifty years later, the townspeople attacked the Abbey with arms and extorted from the Abbot the right to own their own querns. A few years later, the Abbot swooped on the town with his bully boys, searched the houses, and broke all the querns he found save a few that he carried off to pave the parlor floor of the abbey. Quarrels over milling rights dragged on for centuries, and some of these medieval monopolies were not finally done away with until +XIX.

The biggest medieval stride in the use of water power was not so much in the wheels themselves as in the uses to which they were put. In ancient times, water power was used only for milling grain and raising water, save for Ausonius’ solitary mention of a water-powered sawing mill.

The next mention of a water-powered sawmill comes eight centuries later. It is a sketch in Villard de Honnecourt’s notebook (+XIII). The saw is hung by one end from a sapling braced at an angle and attached to the ground by a wooden linkage at its lower end. Four spokes on the mill-wheel axle push down the linkage as the wheel turns, and the spring of the sapling pulls the saw up again each time. This looks like a crude preliminary design that would not work in practice.

All we can say for certain about the origin of the water-powered
The Ancient Engineers

sawmill is that it may have existed in some form from the time of Ausonius to that of Villard, but we know nothing of how these mills worked. In the century after Villard, however, allusions to water-powered sawmills become common in France and Germany. Nevertheless, as late as +XVII and +XVIII, when some enterprising Englishmen tried to set up such mills in England, the mills were wrecked by mobs of hand sawyers, who feared that their bulging muscles would become obsolete.

During the Middle Ages, water power was also applied to the bellows of smelting furnaces, to trip hammers for crushing ore in smeltingeries and bark in tanneries, to fulling mills, and to grinding and polishing arms and other metal wares.

Horses and mules also powered these machines by an apparatus called a horse whim. The animals were hitched to the ends of booms 10 to 15 feet long, or to the rim of a wheel of 10- to 15-foot radius. They could now work much more efficiently than in ancient times. For one thing, with the horse collar they could pull four times as hard. For another, they were allowed to walk around a big enough circle so that they could make full use of their strength.

The biggest novelty in European power machinery, however, was the windmill. The origin of the European windmill is another mystery. In +I, Heron of Alexandria proposed to power a hydraulic organ by means of a little windmill or pinwheel. Nine centuries later, the Iranians of Seistan built windmills to mill their grain.

Now, Heron's pinwheel had a horizontal shaft, like windmills of the familiar European type; whereas the Persian windmill, as we have seen, had a vertical shaft like a revolving door. That was all very well in Seistan, where the wind blows for months from one direction. But it would not be practical in Europe, where the wind blows every which way. Therefore European windmills had to be pivoted, so that they could turn to face the wind.

The earliest trustworthy accounts of windmills in Europe dated from +XII. These windmills are of a type called the post mill. On a pedestal is mounted a small room, roughly cubical, so that it can be turned in any direction by means of a long wooden boom. The room contains the millstones, driven through gearing by a shaft that projects through the wall of the room and carries the sails. The sails may be of wood or a combination of wood and cloth.

The number of sails varied. There were usually four sails, but sometimes there were six or eight. They were usually adjustable for different wind velocities.

Along the northern shore of the Mediterranean, a type of mill still in use has ten cloth sails, like the jib sails of a ship. When the wind freshens, the miller takes in sail by stopping the mill, unhitching one of his sails, winding it around its boom to reduce its exposed area, and tying it fast again.

Whence came the European windmill? Is it an enlargement of Heron's pinwheel? Was it invented in response to a rumor about the windmills of Iran? Nobody knows, although the basic difference of principle between horizontal-shaft and vertical-shaft windmills argues for Heron and against Iran.

Post mills persisted through the High Middle Ages with gradual improvements, such as brakes and means of adjusting the clearance of the millstones. In +XV, however, windmills increased in size in response to the demand for more power. At this time, for instance, the Dutch began to use windmills to drain the many lakes and marshes of their country. As post mills were enlarged, they became unwieldy, since the whole mill had to turn. They were also likely to be wrecked in gales. So the millwrights developed a mill of another type, called the turret, tower, smock, or cap mill. In the turret mill, the main body of the mill is a fixed, solid structure of wood, brick, or stone. On top of this tower is a revolving turret bearing the sails. The first mill of this kind may have been one built by Leonardo da Vinci at Cesena in 1502. The great Florentine dreamer designed such a mill, though it is not certain that it was actually built. Half a century later, the Dutch were using turret mills for drainage.

With this improvement, mills could be made much larger and more efficient. Millwrights soon were turning out turret windmills that developed as much power as three water wheels, or twenty-five horses, or three hundred men.

There are various ways of turning the turret of a smock mill. In Greek mills of the jib-sail type, the turret is turned by hand. The miller levers it around with a crowbar, which engages pegs on the top of the tower wall and recesses in the turret.

The final refinement in windmill construction was the British invention (+XVIII) of the fantail or fly. This was a little windmill mounted on the rear of the turret, with its sails at right angles to those of the main mill. By means of gearing, the fantail kept the mill facing the wind. This was one of the first self-regulating machines.

Renaissance engineers also designed a number of windmills with vertical shafts like those of Iran. They devised systems of guiding the wind by vanes and feathering the sails so that the mill should turn regardless...
of the wind direction. But none of these designs came into general use. The fact is that the horizontal-shaft windmill is more efficient than the other kind, because the whole area of its sails is in use all the time, whereas in a vertical-shaft mill the sails transmit power only during half of each revolution.

Medieval improvements in iron- and steel-making led to advances in armor. During the Dark Ages a man was considered armed if he had a shield on one arm and a sword, spear, or ax in his other hand. If he were well off, he might also wear a simple helmet and a vest of hardened leather. If he were really rich, he might have a shirt of chain or scale mail.

The Byzantines continued the late-Roman practice of armorng mounted men from head to foot. As conditions improved in western Europe, so did the armorer's trade. By the time of the Norman conquest of England, the horseman wore a whole chain-mail suit, with mail sleeves to the elbow and mail breeches to the knee. His helmet came to a point on top and had a vertical bar called a nasal in front of his face and perhaps a neck guard, either of plate or of mail, behind.

Thus armored, the first Crusaders set out for the Holy Land. During the next century, the suit of mail was extended over the whole body, including hands and feet. A mail hood covered all the head and neck except the face. Over the hood the knight might wear a barrel-shaped closed helmet with narrow slits in front to see through.

Chain mail had many advantages. It was flexible, allowed free movement, and was easy to tailor to the wearer's size. But it also had shortcomings. For one thing, the knight had to wear thick padded clothing under it, lest a heavy blow break his bones even though it did not pierce his mail. This padding got terribly hot in summer, especially in the Mediterranean lands. For another, to raise either arm meant dragging up the mail on that whole side of the body. This extra effort helped to wear out the warrior.

The mailed knights of the High Middle Ages proved very effective against the Turks and Arabs of the Near East in the earlier Crusades, until the Saracens learned to deploy armored cavalry, too. But these knights proved helpless against the lightly armored Mongol horsemen, who easily slaughtered whole armies of mailed knights in Poland and Hungary (1241). The secret of Mongol success, however, lay not in particular weapons or armor but in their formidable organization, discipline, and tactics, all of which were in short supply in medieval Europe.

Early in +XIV, just when the gun was appearing, armormen began adding plate to chain mail. At first they strapped a few iron plates on here and there over the mail. By 1400, mounted men wore complete suits of plate armor over mail. Thereafter, chain mail dwindled in area until it only covered a few gaps in the plate, as under the armpits.

People often think of the knight in full plate armor as living in the High Middle Ages. In fact, however, knights wore only chain mail through +XII and +XIII. The complete suit of plate, topped off by a crested helm with a movable visor, belongs not to the High Middle Ages but to the Renaissance, when feudalism was crumbling, knighthood had become a mere picturesque affectation, and the gun was beginning to dominate the battlefield. In fact, the ironclad Renaissance horseman, in addition to all his other hardware, often carried one or two enormous horse pistols in saddle holsters.

Armor for infantry evolved along similar lines, except that a footman, because of the weight, did not wear so complete a suit. While a 75-pound suit of armor might be no great burden to a strong mounted man, it was impractical on foot.

Thus at Agincourt (1415) the French, having experienced disasters with mounted charges against English longbowmen, decided to advance on foot. But a heavy rain had made the battlefield into a bog, into which the full-armored French knights sank to their calves and were slaughtered. During the plate-armor period, more than one knight died of heart failure without striking a blow, simply from the strain of bearing his armor.

In its heyday, however, the full suit of plate armor was a marvelous thing. Its weight was so well distributed, and the joints were so craftily contrived, that as long as his heart held out the wearer could get around almost as actively as he could without armor. Its protection was so complete that in the important battle of Zagonara (1423), when the Florentines in a place that had been flooded by heavy Milanese beat the Florentines in one another, that, it seems to me, is the right way to do it.

Such a suit was also very costly. It had to be fitted to the wearer, and tailoring sheet iron is not so easy as cutting and stitching cloth. During +XV and +XVI, when plate armor was at its height, the weapons of
footmen—bills, halberds, guisarmes, and fauchards—resembled nothing so much as enormous can openers on poles.

While plate armor grew up at the same time as the gun, in the long run the latter prevailed. Early handguns were no more effective than longbows and crossbows. Any of these weapons could pierce armor at close range with a square hit. But at a distance, or with a glancing blow, good armor shed all these missiles.

As guns improved in +XVI and +XVII, armorers made armor thicker to keep out musket balls. Then the armor became so heavy that the wearer could hardly move. As a result, soldiers began giving up armor, piece by piece, starting with the lower legs. Three-quarter suits (down to the knees only) with visored helmets were still worn in the English Civil War (1642–46). But thereafter armor was quickly abandoned and had almost disappeared by 1700, although a few units of heavy cavalry continued to wear cuirasses and helmets down through the Franco-Prussian War (1870–71).

A startling revival of fighting in armor almost occurred as lately as +XIX. Medieval Europe inherited from the Germanic tribes the barbarous custom of trial by battle, rationalized on the dubious grounds that God would grant the victory to the right. In 1817, when everybody thought the custom had been safely embalmed in the history books, an Englishman named Ashford accused another man, Thornton, of murdering Ashford’s sister. Thornton challenged Ashford to present himself in the lists, armed de cap à pied, for the wager of battle with lance and sword. When Ashford failed to appear, armored or otherwise, Thornton claimed he had won his case. The lawyers found to their amazement that indeed Thornton had, because Parliament had never gotten around to abolishing trial by battle—an oversight hastily corrected at the next session.

After the burning of Charlemagne’s wooden bridge over the Rhine, few bridges were built in Europe for several centuries. These few were wooden bridges, too. Some Roman bridges also survived the tooth of time. Otherwise, those who wished to cross rivers went back to using fords and ferries.

Stone bridges revived in +XII. The first bridgebuilders seem to have been the monks of certain monasteries. The story of the fratera pontifices, however, has become so overlaid with legend that it is hard to recover any solid facts about the bridgebuilding brothers.

The most celebrated bridge of this era was the bridge at Avignon, about which a well-known folksong was woven. It is supposed to have been built by a nebulous Saint Bénézet, 1178–88. The original design is doubtful, because the bridge was rebuilt in +XIV.

However, the Pont d’Avignon probably consisted of two bridges in tandem, meeting at an island in the river and forming a blunt angle. Each section consisted of eight spans, more or less, with some more spans across the island. The arches were probably of the semicircular type, copied from those of the Roman aqueduct bridge called the Pont du Gard, twenty-odd miles away. A chapel stood on one of the piers.

At the same time that the Pont d’Avignon was built, an English cleric, Peter Colechurch, collected funds from everybody from king to peasant to build a stone bridge at London. Old London Bridge (1176–1209) showed how backward England was at that time compared to France. It was a crude and crazy affair with nineteen arches, all of different sizes, and a draw span. The arches were of the pointed Gothic type, though for bridges such an arch has no advantage over the semicircular arch.

The piers were erected on starlings or artificial islands. These were boat-shaped structures of piles and stone, all of different sizes and spacings and taking up more than two-thirds of the width of the river. As the Thames at London is a tidal estuary, a strong current runs back and forth. The bridge so choked this flow that at times the water on one side of the bridge was several feet higher than on the other. The water raced between the piers at dizzy speed, and only the most foolhardy boatmen “shot the bridge” at these times.

Further to complicate matters, people began erecting houses on the piers, straddling the roadway, until there were about a hundred such structures, many of three or four stories. Between the overlapping of the bridge above and scouring by the river below, one part or another of the bridge was always crumbling. Hence the song: “London Bridge is falling down, falling down...” In the 1820s the picturesque monstrosity was finally demolished to make way for a new bridge.

Medieval bridges differed in some ways from Roman bridges. One difference was that the builders deliberately made their roadways narrow so that they should be easier to defend. The roadway of the Pont d’Avignon varied from 6 1/2 to 16 feet. Many bridges were fortified. The fortification of Southwark Gate on Old London Bridge helped to break at tication of Southwark Gate on Old London Bridge helped to break argumentation at one point of the bridge. The handsome Pont Valentré at Cahors, France, least two rebellions. The handsome Pont Valentré at Cahors, France, has three 130-foot fortified towers bestriding its roadway, one at each end and one in the middle.

Moreover, medieval piers were provided with pointed cutwaters downstream as well as up. The Romans had furnished bridges with such
cutwaters on the upstream side only. As the engineer Alberti (+XV) correctly explained:

... the water is much more dangerous to the stern than to the head of the piers, which appears from this, that at the stern the water is in a more violent motion than at the head, and forms eddies which turn up the ground at the bottom, while the head stands firm and safe, being guarded and defended by the banks of sand thrown up before it by the channel.11

From +XIV on, bridgebuilders experimented with a variety of arches. One was the segmental arch, beginning with Taddeo Gaddi's Ponte Vecchio or "Old Bridge" at Florence (1345). This arch is an arc of a circle less than a full semicircle. Although its outward thrust is greater than that of the semicircular arch, this did not much matter when the bridge was braced at each end against solid river banks. And the piers, being fewer in proportion to the size of the bridge, interfered less with the flow of the river.

In the Renaissance, other curves were tried. Sometimes, as in the Pont Neuf at Toulouse (1540-1603), the arches were semi-ellipses. That is, they were the upper halves of ellipses lying on their sides. Once the standard types of stone arched bridge had been established in the Renaissance, nearly all large bridges were built this way with little change down to the development of steel bridges in +XIX.

Although the magnificent Roman roads continued to carry a dwindling traffic for several centuries after the fall of the Western Empire, by the High Middle Ages they had largely disappeared. People had pried up their stones for local use, and the feudal system could not support any such elaborate road system. At this time the road net of Europe was a mixture of Roman roads, with or without their original paving; roads, sometimes lightly paved, built under orders of kings and nobles; and supplementary tracks across the land, wide enough only for a single man or beast.

In wet weather, unpaved roads became elongated quagmires. This was no great disadvantage so long as the traffic consisted entirely of men afoot or mounted. Women and old men of the ruling class, unsuited to long mounted journeys, traveled in horse litters. A horse litter was a sedan chair slung between two horses, one fore and the other aft.

During the High Middle Ages, wheeled traffic, which had almost vanished, increased. The roads of Europe then bore a brisk traffic not only of pedestrians, mounted men, pack animals, and litters, but also of wagons, carts, and handcarts.

Technical improvements added to the efficiency of four-wheeled wagons, which had never been very popular in ancient times. One advance was the discovery that horses could be hitched in tandem. This system probably came from China, where it appeared in +II. Thus the load could be increased without requiring a wider road to move on.

Another improvement was making the front wheels small and cutting away the body in front, underneath, so that, as the front axle turned on its pivot, either wheel could roll in under the body without striking it. In this way the wagon could make sharper turns than had been possible in ancient times.

Throughout the High Middle Ages, a few persistent souls put tops on four-wheeled wagons and board seats inside for passengers. Lacking brakes, these vehicles were kept from running away downhill by chaining one wheel fast so that it could not turn. Because of the cost, discomfort, and lack of suitable roads, these springless vehicles never became really popular. Most of them were state carriages in which royalty rode from time to time to awe their subjects.

In 1457 a clever but nameless mechanic of Kocs, Hungary, built a four-wheeled passenger wagon, nicely appointed and upholstered. Although it was not much of an improvement on the ancient Persian harmanaza or the Roman rheda, it was ahead of anything seen in Europe for many centuries. It probably had the body hung by leather straps from posts that rose from the corners of the bed frame. This primitive springing system substituted a sloshing motion for the hard jouncing of the earlier, springless carriages.

The new vehicle spread. In early +XVI, scores of them rattled the roads of Italy, when there were only three in Paris and one in England. "Coach" is simply a phonetic spelling of Kocs. Although the development of the new art of coachmaking was hindered by a struggle between the wheelwrights' and saddlers' guilds as to which should have the right to make these vehicles, by 1534 Ferrara had a busy firm that did nothing but make coaches.

With straps for springs and leather curtains for windows, these carriages were hardly up to Detroit's standards of comfort. In late +XVII, however, coach design leaped ahead. Brakes, glass windows, and steel springs appeared. In the following century came such luxurious accessories as built-in lanterns and a sword-and-pistol case for coping with highwaymen.

In +XVIII, omnibuses carrying as many as sixty passengers began
to rattle across Europe on regular schedules. For the first time in history, a traveler on land could go whither he wished by simply paying his fare and taking his seat, without having to organize his own safari.

Another revival of ancient usages was the postal system. Beginning in later +XIII, European universities, led by the University of Paris, organized their own letter-carrying systems. In +XV, French and German rulers set up systems of couriers to carry official mail, like the imperial riders of Darius and Hadrian. The kings, seeing that the university postal systems were not only popular but even profitable, first regulated them and then took them over, merging them with their own governmental systems. They also wanted to be able to censor everybody’s letters. By the end of +XVI, public postal systems not unlike those of our times existed, although the cost of sending a letter was still high.

All this increase in traffic, especially wheeled traffic, brought an increasing demand for better roads. For some centuries, kings sought to improve their roads. But they had little success, because they repeated all the errors of their long-dead predecessors. They commanded landowners to maintain roads that ran past their property; they sent agents to round up peasants for forced road work. But, as fast as the roads were slightly improved, the increase of traffic tore them to pieces again. As the kings were never willing or able to build really heavy paved roads of the Roman type, their roads began to dissolve into lines of mudholes as soon as they were completed. This was not entirely the fault of the kings; for, in feudal Europe, the power of a king to make his subjects do what he wished was much less than that of an ancient watershed emperor or a modern commissar.

The story of municipal waterworks in the Middle Ages is one of slowly regaining the ground lost at the fall of Rome. During the High Middle Ages, sporadic efforts were made either to put the ruined Roman aqueducts back into service or to build new ones on the Roman model. In Paris, for instance, the Roman aqueduct built under the emperor Julian was destroyed by Norse invaders in +IX, and for three centuries Parisians depended wholly on wells and on the Seine.

In +XII, two abbeys on the north side of the Seine, finding the river inconveniently far away, built their own aqueducts to lead water by masonry conduits and lead pipes from springs in the hinterland to basins in the monasteries. People living in the neighborhood were allowed to share the water. After 1200, as Paris grew, Parisians demanded more fountains. Not deeming this their proper business, the abbeys turned their waterworks over to the city.

Then, just as had happened in Rome over a thousand years before, lords and royal officers began asking for permits to tap public lines and run private pipes to their houses. At first there seemed no harm in this, as only a little water was diverted and the petitioners were privileged persons. By 1392, the number of taps was so large that the public fountains, being the last delivery points on the lines, often ran dry.

So Charles IV issued a resounding proclamation to reform this abuse: “. . . and We recall, cancel, annul, and revoke all privileges, grants, licenses, rights, duties, permissions, or suffrages . . . excepting only,” he weakly finished, “so far as it affects Us and Our uncles and brother.”113

The result was what one would expect. All the other nabobs in Paris said: if the King and the dukes can have private running water, why cannot I? And private water supplies they proceeded to get, by fair means or foul.

But, as nobody provided additional sources of water, the scramble became more acute than ever. Paris went through another spasm of reform in 1553. This, like the previous one, proved ineffectual because Henri II, like Charles IV, insisted on excepting his royal relatives.

This dismal contest for the available water continued until Henri IV, the French Perikles, firmly grasped the problem in 1600. After another abortive attempt to cut off all the private connections, he sensibly decreed that the pipes might remain, but that the users must pay fees large enough to support the water system.

Furthermore, he authorized a Flemish engineer, Jean Linthaler, to install a pumping station under one of the arches of the Pont Neuf. Here an undershot water wheel worked four pumps, which raised river water high enough so that gravity could speed it to the royal palaces. Henri turned the surplus water over to the public, and Paris was on the way to acquiring a modern water system.

As for sewers, the people of medieval Europe not only started far behind the Romans, but also have only recently begun to catch up. Again Paris may serve as an example.

Medieval Paris had open ditches, intended for storm drains only. People were not supposed to dump household waste into them, but people did. As Paris seldom receives downpours heavy enough to flush out such ditches, the result was noisome in the extreme.

Around 1400, Hugues Aubriot, Provost of Paris under Charles VI and builder of the Bastille, roofed over a stretch of one of these sewers. After Aubriot’s time, the rest were gradually covered.

Paris still lacked a proper sewer system, even though by +XVI the
connection between filth and disease was dimly realized. Around 1550, Henri II repeatedly tried to get the Parliament of Paris to build new sewers. But, as the king did not propose to pay for this work himself, Parliament evaded the king's recommendations.

Later proposals met a similar fate. Arguments about stench and disease made no impression on those who would have had to pay for this improvement. The man of the medieval and Renaissance city, having grown up with the stink of ordure in his nostrils, saw nothing very terrible about it, while the prospect of parting with money made him scream with anguish.

In +XVII, under Louis XIII, a beginning was made towards building a few real sewers. But the great and celebrated web of modern Parisian sewers is only about a century old, having been built under Napoleon III.

In another branch of hydraulic engineering, however, Europeans soon advanced beyond the Romans. This was the building of canals. Small irrigation canals appeared in the Po Valley in the early Middle Ages, as part of the general upsurge of technology that took place in North Italy.

In 1161 the Holy Roman Emperor, Frederick Barbarossa, captured Milan and razed it to the ground. When they rebuilt their city, the Milanesi decided to surround it not only with an impregnable wall but also with a moat. To furnish water for this moat, they dug a canal for sixteen miles—an unheard-of distance then—to the river Ticino, which carries the waters of Lake Maggiore to the Po. This canal they called the Ticinello, or Little Ticino.

At first used only to fill the moat and to irrigate fields along its path, the canal was soon enlarged to navigable size and renamed the Naviglio Grande, or Great Canal. Its story then became the common one of the struggle between farmers, who wanted to lead off enough water to irrigate all their lands and to clutter the channel with water wheels and fish weirs, and boatmen and merchants, who wanted the channel kept full of water and open for navigation.

Historians argue as to when and where the first canal lock was built. Some believe it to have been at Vreeswijk in the Netherlands in 1373, or at Spaarndam a little earlier. Others find the origin of the lock in Italy around 1400.

In any case, about 1400 the Bishop of Milan was building a cathedral. To make it easier to get stone to the site, he persuaded the government of the city to extend branch canals into the city by way of the moat. These branches were also used by merchants for delivery of goods. A single gate controlled the flow of water into the branch canals, which were several feet lower than the moat. As this system did not work very well, two engineers installed a lock in 1438, and later a second lock.

The first clear written description of a canal lock is by the versatile Alberti, who wrote:

Also, if you wish, you can make two gates cutting the river in two places at such a distance one from the other that a boat can lie for its full length between the two; and if the said boat desires to ascend when it arrives at the place, close the lower barrier and open the upper one, and conversely, when it is descending, close the upper and open the lower one. Thus the said boat shall have enough water to float it easily to the main canal, because the closing of the upper gate restrains the water from flowing too violently, with fear of grounding.

In the 1450s, the engineer Bertola da Novate put these ideas into practice. The dukes and republics of North Italy kept Bertola, the ablest canal engineer of his time, busy all his life digging canals for them. Sometimes they quarreled over who should have priority on his services. His only trouble was that his workmen sometimes could not understand his advanced concepts.

All these early canal locks seem to have been of the porticullis type, sliding up and down like a window sash. Later, the hinged gate, swinging like a door, was found more practical.

Besides Milan, other cities of Lombardy also built canals, some as early as the 1180s. At the same time, Mantua began reclaiming marshland. Land reclamation—la bonifica—became a major Italian interest. Whereas the ancient Mesopotamians preserved marshes in which to grow reeds for house-building, and whereas we sometimes preserve marshes to provide refuges for wild life—today's most persecuted minority—medieval Italians wanted to dry up the marshes for the extra farmland. Besides, they had a suspicion that marshes were connected with malaria, even if they did not know how the disease was transmitted. So they energetically dug, ditched, and drained.

Meanwhile, across Europe on the shores of the North Sea, another vast land-reclamation project was taking shape. The Netherlands is a flatland as innocent of stone as Babylonia. Much of it is below sea level, at least at high tide. The coastal region was originally a tangle of marshes, shallow lakes, dunes, tidal flats, and low islands half submerged at high tide. Through this perpetual wetland, the rivers Rhine, Meuse, and Schelde, with many local changes of name, lazily wound their way.

Men long ago began tinkering with this ameboid mixture of land
and water. In -12 the Roman general Nero Claudius Drusus is said to have joined the largest of the lakes, the Flevo Lacus, with the Rhine by way of the Yssel.  

In Drusus' time, the people of the Low Countries were Germanic tribes, some of whose names—Batavi, Frisii—still appear in one form or another on the map. When the Western Empire was crumbling, the Netherlanders were called Franks. Dreaded for their ferocity and treachery, they overran Gaul. Around +500, their fierce and crafty king, Clovis, smashed the remnants of Roman and Gothic power and founded the kingdom of Frank-land, or France.

Many Franks remained in the Low Countries to become the peaceful and progressive Dutch of today. In the early Middle Ages, the Dutch began building dykes to keep within bounds the bodies of water that cut up their country.

During +XIII, a series of floods occurred. In 1277, these culminated in a great storm, which broke through the dunes that formed a natural dyke between the North Sea and the Flevo Lacus. The sea poured in, drowning thousands and enlarging this lake to the Zuider Zee of later times.

Little by little the Dutch once more began dyking, draining, and pumping to turn water back into land. Over the centuries they worked out very efficient methods of doing this, using local materials: sand, clay, straw, seaweed, reeds, brush, and pilings.

Dutch land-reclamation became especially active after 1400, when the Dutch applied windmill-driven pumps to the task. One patch of sub-sea land after another was surrounded by dykes and pumped out, creating what the Dutch call "polders." The Zuider Zee itself is now being liquidated, piece by piece.

And by the bye, the story of the little Dutch boy who stuck his finger in a hole in a dyke could only have been invented by somebody who had never seen a dyke. The story implies that a dyke is some sort of wall. Actually it is a long, low ridge whose slopes are so gentle that you might not even notice them. A typical dyke is about 10 to 16 feet high and 15 to 20 feet wide at the top—but at least 100 feet wide at the bottom.

The remaining aspect of medieval European technology is shipbuilding. During the Dark and early Middle Ages, the ships that plied the Mediterranean and the North Sea were not very different from those of classical times. Galleys were used for war and tubby sailing ships for commerce.

In addition, there grew up a class of merchant galleys, with the same number and arrangement of oars as regular war galleys but with larger hulls, which could hold cargo as well as rowers. These carried goods of large value and small bulk, such as gold, silk, and spices, and took pilgrims to the Holy Land. The pilgrims preferred galleys to roundships because, whereas the latter sailed directly from some European port to the Levant, the galleys, having little sea-keeping capacity, crept along the coast, stopping at famous cities of antiquity. The pilgrims, like any other tourists, wanted to see all there was to be seen. The merchant galley disappeared in +XVI as a result of the high cost of running it, the improvement of the sailing ship, and the development of competing Atlantic routes to the Orient.

There had been some changes in galley design since ancient times. A Mediterranean galley now carried its ram above the waterline, like a thickened bowsprit. In +XIV and +XV, the typical Mediterranean galley was a trireme, with twenty-five to thirty benches on a side and the rowers arranged as shown in Fig. 24. The Byzantine arrangement of rowers, vertically staggered on two levels, had given way to one in which all three rowers of each group sat on one bench but pulled separate oars.

In the 1520s Vettor Fausto, a professor of Greek in Venice, persuaded the Venetian government to let him build a quinquireme he had designed. It should be, he said, like those of the ancient Greeks and Romans, of which he had read in his classical studies.

What Fausto did was to enlarge the ordinary Mediterranean galley so that five men could sit on each bench instead of three. Each, however, still pulled a separate oar. Although this ship beat a standard trireme in a race, the design was not repeated because she proved hard on the rowers, who were excessively crowded and exposed to the weather. Nevertheless, Fausto led a successful career as a shipwright, converting some Venetian merchant galleys to quinquiremes and devising other improvements.

Later in the century a Venetian pupil of Fausto, Giovanni di Zaneto, developed another type of ship. This design, called a galeazza or galleass, was based partly upon the merchant galley, then disappearing, and partly on Fausto's quinquireme. Giovanni, with some mathematical help from Galileo, went back to the Hellenistic system of mounting large oars in a single bank, with five to ten rowers pulling each oar.

For several centuries, Venice was the leading Mediterranean naval power. It was an oligarchic republic, governed by a merchant aristocracy like that of ancient Carthage and ruling a large overseas dominion.
Most of the Venetian empire consisted of Greek islands taken from the Byzantines when the Crusaders temporarily overthrew the Byzantine Empire in 1204.

Venetian shipwrights led the world not only in the design of ships but also in methods of manufacture. For instance, the Arsenal of Venice made serious efforts to standardize the sternposts and other parts of galleys, thus anticipating Eli Whitney and others who, in the early 1800s, developed the principle of interchangeable parts. The Venetian shipyards even employed a kind of assembly-line manufacture, as an admiring Spanish visitor noted in 1436:

And as one enters the gate there is a great street on either hand with the sea in the middle, and on one side are windows opening out of the house of the arsenal, and the same on the other side, and out came a galley towed by a boat, and from the windows they handed out to them, from one the cordage, from another the bread, from another the arms, and from another the ballistas and mortars, and so from all sides everything which was required, and when the galley had reached the end of the street all the men required were on board, together with the complement of oars, and she was equipped from end to end. In this manner there came out ten galleys, fully armed, between the hours of three and nine.¹⁶

Venetian sea power slowly declined from +XVI on. The reasons for this decline were the conquest of the Venetian overseas possessions by the Turks, the withering of the Mediterranean trade routes as new routes opened up in the Age of Exploration, and the failure of Venetian supplies of timber. In particular oak, used for the frames and hull planking, became scarce, despite intelligent efforts by the Venetian government at conservation and reforestation. The Venetian nation disappeared in the Napoleonic wars, coming first under French and then under Austrian rule.

Another change in maritime methods was that rowers, instead of being free workers as in ancient times, became captives chained to their benches. Use of slaves and prisoners first became common in +XV. No doubt this change was fostered by the fact that multitudes of people were captured in the constant wars and piratical raids of the Christian and Muslim powers of the Mediterranean against each other. The Turks, like the Romans of the late Republic, were given to slave-raiding and slave-owning on a huge scale; while, during the Reformation, the French and Spanish kings found the galleys a useful way to dispose of Protestants.
The Venetian navy stuck to free rowers, who could fight in a pinch, as long as it could. But at last even Venice was forced to use prisoners, because employment of such persons had made free workers unwilling to serve as rowers.

A danger of using slaves and prisoners was that, since the rowers comprised a large majority of all the people on board, they might seize the ship, toss the free men overboard, and sail away to become pirates. To prevent this, captive rowers were permanently chained to one place. As a rower had to eat, sleep, and do everything else in that one spot, galleys became so foul that their officers went about with their tasks with handkerchiefs sprinkled with musk pressed to their noses. The rowers sickened and died like flies, while those who lived must have been in such poor condition that they cannot have been very efficient oarsmen. In this respect, at least, they did things better in ancient times.

As for sailing rig, large galleys now bore lateen sails on one, two, or even three masts. Some merchantmen also flew lateen sails, although many still plodded along under one square sail.

The ships of the North Sea differed in small ways from those of the Mediterranean. They struck to the square sail, and they carried but one steering oar or quarter rudder, on the starboard ("steer-board") side. Norse galleys lacked the ram but possessed extremely sleek, graceful, efficient lines, like those of an Adirondack guide boat.

Hulls also differed in construction. In the "carvel-built" Mediterranean hulls the planks were set edge to edge, while in the northern "clinker-built" hulls the planks overlapped. The latter system, adapted to the heavy Atlantic seas, gave a stronger hull but, because this hull was less smooth, a slower ship.

Soon, however, a series of revolutions overtook ship construction. One change was the central rudder, which probably reached Europe from China. Several pictures from about the middle of +XIII. on municipal seals, church windows, and so forth, show this feature.

In the High Middle Ages, naval powers often reinforced their galley fleets with converted merchantmen or nefs. Although these ships could carry large numbers of troops, they were not very successful because, save in heavy weather, galleys could always dodge the wallowing roundships. In late +XIV and early +XV, however, changes occurred, which drastically altered the roles of these ships.

One was the development of a larger roundship with a large mainmast in the center and two smaller masts, one at each end. The foremost normally carried a square sail and the aftermost or mizzen mast a lateen sail. Although these small sails did not make the ship go much faster, they greatly helped in controlling its direction. The ship could be steered by its sails alone. The lateen mizzen was especially useful in holding the ship on a close-hauled course into the wind.

As ships got larger, their rig was divided into more and more sails until the full-rigged ship of the last two centuries evolved. The Age of Exploration (+XV to +XVIII) took place as soon as European ships and navigators had developed to the point where voyages across oceans were practical. During the Age of Exploration, the Dutch were the most active people in the invention of new rigs and sails, such as the gaff-headed sail and the jib or forestay sail.

The other change was placing guns on shipboard. A few guns were mounted along the sides of nefs and in the forward deckhouses of galleys. Galley guns fired straight forward only, so that one aimed the guns by aiming the ship. For over a century, however, not enough guns were mounted on ships to affect the outcome of any battle.

In 1538, however, a Venetian and Genoese fleet set out to attack the mighty Turkish navy. The Genoese admiral, Doria, had 166 galleys, 64 nefs, and a new experimental ship, the Galleon of Venice. The Galleon was a large, solidly built sailing ship bearing the unheard-of number of 128 guns.

The Italians found a smaller Turkish fleet at Preveza. While the Christians were patrolling in front of the harbor, the Galleon fell behind the rest, becalmed. Out rushed the 122 Turkish galleys like wolves to pounce upon the straggler, while Doria timidly watched from a distance.

The Venetians, unable to move, received the onset with a terrific blast of cannon and arquebus fire. The galleys lost way as the fire slaughtered their rowers; one was sunk by a single shot. Others stove in their own bows in ramming the Galleon. All afternoon, the Turks kept attacking in divisions of twenty ships at a time. At nightfall the Venetians, with fifty-three dead and wounded and their deck littered with wreckage, were still holding out. The equally battered Turks withdrew, and the Italians towed the Galleon away.

Although this battle achieved nothing politically, it showed the shape of things to come. At the great galley battle of Lepanto in 1570, which loosened the Turkish grip on the Mediterranean, guns played an important part. Here the combined Italian and Spanish fleets included six Venetian galleasses with seventy guns apiece, the larger cannon being mounted in the deckhouses at the ends and the smaller ones along the sides between the oars.

The weight of the cannon made these ships so heavy that their rowers could scarcely move them, and they had to be towed into action. Never-
The Ancient Engineers

...standing out in front of the allied line, they fearfully strafed the advancing Turkish galleys with gunfire:

Don John's hunting, and his hounds have bayed—
Booms away past Italy the rumor of his raid.
Gun upon gun, hal! hal!
Gun upon gun, hurrah!
Don John of Austria
Has loosed the cannonade.17

This bombardment weakened the Turks and so contributed to the Christian victory.

Thereafter galleys swiftly declined. Although because of their rowers they could move in any direction regardless of the wind, galleys were so flimsy and feebly armed, compared to the full-rigged galleon, that even overwhelming numbers and a flat calm did not assure the victory.

Although Mediterranean powers built a few galleys as late as +XVIII, except for a few with the Spanish Armada they never fought a major battle after Lepanto. They lingered on to the dawn of steam in early +XIX, because they could still do one thing better than sailing warships.

They could pursue pirates, who also used galleys.

With the battle of the Armada in 1588, naval warfare, which for over 3,000 years had consisted mainly of ramming and boarding contests, turned into a series of artillery duels. So it remained right down to part, even in the two World Wars. Therefore, despite the steam-and-steel revolution in ship construction of +XIX, naval warfare became modern, in an important sense, between Lepanto and the Armada.

The name “Renaissance,” literally “rebirth,” is applied to the period, roughly +XV and +XVI, when many medieval things like feudalism, Gothic architecture, and the religious monopoly of the Catholic Church were passing away and many modern things like vernacular literature, centralized national governments, political parties, and experimental science were coming into being.

In the narrowest sense, “Renaissance” refers to the revival of learning that took place, mainly in Italy, with the rediscovery of most of the remains of classical literature that we possess today. Some classical writings had of course never disappeared from circulation, but many more were now exhumed from monastic libraries or imported from the crumbling Byzantine Empire.

Hence there arose a class of scholars who devoted their lives to the discovery, publication, and explanation of classical texts. The study of Greek was revived. Fashionable people acquired at least a veneer of this scholarship; they proved their gentility by laying their speech with quotations from Plato and Cicero.

The period +XV and +XVI, however, involved other revolutionary movements besides the revival of learning. These included the Reformation, the Age of Exploration, and the downfall of the old astronomy, which put the earth at the center of things. And it included the first patent systems for the encouragement of inventions.

It also involved an expansion of engineering. The new engineering, except in the field of architecture, had but little connection with the revival of classical learning. There was, in fact, a good deal of hostility between the humanists or “ancients,” who cared for nothing but the revival of classical literature, and the “moderns,” who wanted to expand and exploit the new discoveries in the arts and sciences.

In architecture, the recovery of the treatise of Vitruvius led to a passion for imitating classical temple design. This vogue has lasted right down to the present, as a glance at the relief of the Lincoln Memorial on a new cent will show you.

For the most part, however, Renaissance engineering grew out of the experience of the Middle Ages. In some ways it lagged behind the examples of antiquity, while in others it leaped ahead of them.

The main change in engineering in the Renaissance was that it waxed much greater in scale. Engineering again became a respected profession. Engineers became famous and even, sometimes, well paid. They were no longer anonymous craftsmen, humbly serving their temporal and spiritual lords. In line with the Renaissance tendency towards uninhibited self-assertion, they promoted themselves, grasped for personal fame, and told off their rivals and employers when they thought themselves wronged.

Moreover, they took direct action against those they considered their enemies. When about 1575 Henri II of France sent the engineer Adam de Craponne to inspect some fortifications at Nantes, which the king suspected of having been faultily built, the builders at first tried to flatter Craponne into giving them a clean bill of health. When that did not work, they invited him to a banquet and poisoned him.

One of the earliest Renaissance engineers was Filippo Brunelleschi (1379–1446). The son of a notary of Florence—the Athens of the Renaissance—Brunelleschi was, like most youths of artistic leanings at
the time, apprenticed to a goldsmith. Here he learned clockmaking. Later he put this knowledge to use in building machines.

Like many Renaissance engineers, Brunelleschi spent most of his time on art and architecture, though he was also active in other fields. He mastered the new science of perspective and applied it to his architecture.

Failing to win a competition for the design of a pair of gates for a church in Florence, Brunelleschi went to Rome with the sculptor Donatello. There he studied for five years. He particularly studied the dome of the Pantheon, as rebuilt by Hadrian.

In Florence stood a cathedral, Santa Maria del Fiore, which had been under construction for over a century. No roof had been built over the crossing of the nave and the transepts. The covering of this part would have to be something unusual, as the space to be roofed was about 138 feet across.

In 1407, hearing that a conference of architects was meeting in Florence to consider this problem, Brunelleschi hurried home to present his proposals. Nothing came of this action and Brunelleschi returned to Rome. Eleven years later he was back in Florence, urging his plan for a huge octagonal dome. His plan seemed so daring that once the committee had him thrown bodily out of its meeting. But he returned with a model and a host of arguments, until he finally won over the committee.

In 1419, Brunelleschi at last received his order to build. The committee, however, had given him an unwanted collaborator, the sculptor Ghiberti, who had won the contest for the church gates. Since Ghiberti knew nothing much about architecture, Brunelleschi determined to get rid of him. By shamming sickness he tricked Ghiberti into undertaking the design for the chain to hold the dome against bursting stress.

There is, you see, an outward, tensile component of stress in the sides of a dome, a short distance up from the base. If too much load is piled on top of the dome, the dome will fail at this point by bursting outward. Although these forces were not mathematically known in Brunelleschi's time, the Florentine still felt that such a stress existed. To counteract it, he proposed to wrap a girdle or chain around the dome.

Ghiberti accordingly produced a design for a chain, which Brunelleschi easily proved to be utterly inadequate. So poor Ghiberti was forced to resign. Then Brunelleschi installed his own chain, made of lengths of oaken timbers bolted together. Modern study shows that Brunelleschi's chain, likewise, was too weak to reinforce the dome appreciably; but the dome was stiff enough to do without it. It is still there despite earthquakes and aerial bombs.

As work progressed, Brunelleschi discovered that his workmen were losing too many hours climbing up and down the lofty ladders of the scaffolding at mealtime. So the resourceful architect installed a canteen on the scaffold.

Brunelleschi finished his task in 1436, although the 600-ton lantern—the name given the stone ornament atop a church dome—was not completed until after his death, and the cathedral itself did not receive its finishing touches until 1888. The dome so dominated the city that the cathedral has come to be called simply il Duomo—"the Dome."

This dome is made of two shells, one inside the other. It measures 143 feet across and 105 feet high. The total height of the cathedral, from pavement to lantern, is 351 feet, the height of a thirty-five-story building. Although Brunelleschi was a leader in the revival of classical architecture, his dome was neither Roman nor Gothic; it was something brand new. Its octagonal form, emphasized by thick ribs, was intermediate between the true dome and the square dome or cloister vault.

Brunelleschi would not have been a true man of the Renaissance if he had not been working on a multitude of other jobs at the same time as the dome. He acted as architect for several buildings, including the huge Pitti Palace for the Medici family, and two churches. He also invented construction machinery. In 1421 the Republic of Florence gave him the first known patent. This was for a canal boat equipped with cranes for handling heavy cargo.

After Brunelleschi's time, in 1474, the Republic of Venice adopted the first formal patent law and in 1594 issued to Galileo a patent on a system for raising water. A patent is a temporary legal monopoly on an invention: a license to stop all others from making, selling, or using specimens of the invention without the patent owner's permission. The purpose of patents is to encourage invention by giving the inventor a profitable monopoly, for a limited time, in return for his making and disclosing the invention, so that it becomes public property after the patent expires. If any one change could have caused our modern technological revolution to begin in classical times instead of 1,500 to 2,000 years later, it would have been a good patent law.

It is not likely, however, that any of the early Renaissance patentees made money from his patent. The territory covered by the Italian city-states was too small, and the requirements of a sound patent law were not worked out until XIX. Yet the beginning of patents and patent laws in Renaissance Italy was one of those portentous developments that, like the revolution in reading, aroused little comment at the time.
but were bound in the long run to bring about a vast overturn in human affairs.

Of course, Brunelleschi had to serve as a military as well as a civil engineer. In 1430 he accompanied the Florentine army to the siege of Lucca, with Ghiberti, Donatello, and two other artists as assistants. Brunelleschi advised diverting the river Serchio by a canal, so that its water should surround Lucca and cut off the town from aid. It worked, though not quite as Brunelleschi had planned. By providing Lucca with a ready-made moat, the scheme kept the Florentines from attacking. So it was they who had to withdraw, to the joy of the Luccans.

A younger friend of Brunelleschi was Leon Battista Alberti (1404–72), born in Florence but reared in Venice because his family was banished during a political struggle.

If the man of the Renaissance was versatile, Alberti was the ideal man of the Renaissance. Painter, poet, philosopher, musician, architect, and engineer, as a youth he faked a Latin comedy in verse so well as to convince some scholars that it was a genuine ancient Roman work. He played the organ and experimented with the camera obscura.

The camera obscura, from which we get our word “camera,” was a closed room, facing the street, with a small aperture for light. It could be made by covering the window with a sheet of thick paper, having a small hole. A screen of sheeting was hung opposite the aperture, and those in the room amused themselves by watching the upside-down images of passers-by on the screen. It was the Renaissance equivalent of television.

Most of his life, Alberti worked for successive popes. Nicholas V employed him to restore the papal palace and to build the Acqua Vergine, one of the new aqueducts which the Renaissance popes constructed to replace the ruined Roman waterworks.

At the behest of Cardinal Colonna, Alberti investigated the Roman ships lying at the bottom of Lake Nemi. He tried to raise one of these ships by windlasses mounted on a raft buoyed by barrels, but all he succeeded in doing was to tear off a piece of the bow.

In addition to all the palaces and churches he designed, Alberti found time to write on many subjects: political philosophy, horse breeding, family life, surveying, sculpture, Greek mythology, and architecture. His main work was De re aedificatoria (or I dieci libri dell’ Architettura), a treatise on building. Although Alberti could not yet apply mathematical measures to the strength of materials, he described the properties of many different kinds of stone and wood for construction. He gave rules of thumb for the proportions of structures, such as this one for bridges:

And there should not be a single stone in the arch but what is in thickness at least one tenth part of the chord of that arch; nor should the chord itself be longer than six times the thickness of the pier, nor shorter than four times.  

Alberti wrote this work in Latin about 1452. During the following years, copies circulated among his friends in manuscript. Some hitch in his arrangements delayed publication until 1485, after the author’s death. When it did appear in printed form, it became very popular. The work was translated into Italian, French, Spanish, and English and led a long and honorable career.

The leading architect after Alberti was Bramante (1444–1514)—born Donato d’Agnolo in Urbino and at some point in his life nicknamed Bramante, “he who wants.” After the wandering life of a Renaissance technician, he arrived in Rome in his fifties to work for the Pope. The list of all his minor architectural works would be tedious. However, he devised a screw press for stamping coins and rediscovered the old Roman art of pouring liquid concrete into wooden forms.

Pope Julius II chose Bramante to rebuild St. Peter’s cathedral, on the site of a ruined early-Christian basilica. Bramante designed a huge building in the form of a cross with four stubby arms and a huge dome over the middle. The four main piers had been erected when the aged Bramante died. A succession of popes and architects wrestled with the task, making little changes here and there, which reduced the whole project to confusion. Moreover, it transpired that much of Bramante’s work had been hasty and unsound.

In 1546, Paul III gave the job to the one man with the force to push the project through despite any obstacles. This was the Florentine Michelagniolo Buonarroti (1475–1564), known to us as Michelangelo. Most of his work was in the pure arts, but he was also an able engineer. At Florence and again at Rome, he was called upon to build fortifications for an expected siege. He built them and then, correctly divining that the city was bound to fall through the defenders’ incompetence, fled through the enemy’s lines.

Michelangelo was one of the most peculiar, difficult, and cantankerous geniuses of the Renaissance world, wherein ruthless individualism was deemed right and normal. A compulsive worker, a compulsive spendy pincher, and rigidly honest in a corrupt age, Michelangelo also had an extraordinary talent for making enemies. While he was still a
youth, a taunt flung at a fellow sculptor bought him a broken nose, which disfigured him for life.

Bramante could not stand him either. Michelangelo believed that Bramante had persuaded Julius II to commission him to decorate the Sistine chapel with frescoes in the hope that he would fail and fall into disgrace. But that may have been Michelangelo’s persecution complex.

During the last few years of his life, Michelangelo was employed on St. Peter’s. He simplified the fussiness of Bramante’s design and raised the dome higher. He died at eighty-nine leaving a tidy fortune in golden ducats, although he had loudly complained all his life that he was poor to the point of starvation. The dome was finally built a quarter-century after Michelangelo’s death, and the whole cathedral was completed in 1626.

Another of Michelangelo’s enemies was a man who ordinarily had no time for enemies and no desire to make them. This was the most famous of all Renaissance geniuses, Leonardo da Vinci (1452–1519).

All educated people have heard of Leonardo as a painter; many have also heard that he was a scientist and an engineer, although they might have trouble naming any particular discovery or invention of his. He is one of history’s most celebrated but most paradoxical characters. He has often been justly acclaimed as one of the greatest of all creative geniuses. Historians of Renaissance science and engineering often give him a whole chapter.

But, when we look into his story, we find that he had hardly any influence at all on the science and engineering of his time. In this regard he has been as much overrated as Roger Bacon.

Was he persecuted? Not at all. Although a religious skeptic, he kept his doubts in his notebooks and so was never bothered by the Church. His lack of impact in the technical and scientific fields was due to his own peculiar nature.

Leonardo was the illegitimate son of a notary of Vinci, a village near Florence. His parents were married almost at once, but not to each other, and Leonardo’s father brought him up. He was apprenticed to the artist and goldsmith Verrocchio in Florence, where he knew Toscanelli, the leading physicist of the age. In his late twenties he painted pictures, some for Lorenzo de’ Medici, political boss of the Republic of Florence.

In 1483 Leonardo removed to Milan, then a bigger city than Paris. Here he met the Duke, Lodovico Sforza, and submitted the following employment résumé:

Having, My Most Illustrious Lord, seen and now sufficiently considered the proofs of those who consider themselves masters and designers of instruments of war and that the design and operation of said instruments is not different from those in common use, I will endeavor without injury to anyone to make myself understood by your Excellency, making known my own secrets and offering thereat to your pleasure, and at the proper time, to put into effect all those things which for brevity are in part noted below—and many more, according to the exigencies of the different cases.

I can construct bridges very light and strong, and capable of easy transportation, and with them pursue or on occasion flee from the enemy, and still others safe and capable of resisting fire and attack, and easy and convenient to place and remove; and have methods of burning and destroying those of the enemy.

I know how, in a place under siege, to remove the water from the moats and make infinite bridges, trellis work, ladders, and other instruments suitable to the said purposes.

Also, if on account of the height of the ditches, or of the strength of the position and the situation, it is impossible in the siege to make use of bombardment, I have means of destroying every fortress or other fortification if it be not built of stone.

I have also means of making cannon easy and convenient to carry, and with them throw out stones similar to a tempest; and with the smoke from them cause great fear to the enemy, to his grave damage and confusion.

And if it should happen at sea, I have the means of constructing many instruments capable of offense and defense and vessels which will offer resistance to the attack of the largest cannon, powder, and fumes.

Also, I have means by tunnels and secret and tortuous passages, made without any noise, to reach a certain and designated point; even if it be necessary to pass under ditches or some river.

Also, I will make covered wagons, secure and indestructible, which, entering with their artillery among the enemy, will break up the largest body of armed men. And behind these can follow infantry unharmed and without any opposition.

Also, if the necessity occurs, I will make cannon, mortars, and field pieces of beautiful and useful shapes, different from those in common use.

Where cannon cannot be used, I will contrive mangonels, dart throwers, and machines for throwing fire, and other instruments of admirable efficiency not in common use; and in short, according to the case may be, I will contrive various and infinite apparatus for offense and defense.

In times of peace I believe that I can give satisfaction equal to any other in architecture, in designing public and private edifices, and in conducting water from one place to another.

Also, I can undertake sculpture in marble, in bronze, or in terra cotta; similarly in painting, that which it is possible to do I can do as well as any other, whoever he may be.
though not definitely proved. When he was living in Florence in his twenties, an anonymous informer accused a youth of the city of homosexual relationships with several men, including Leonardo. The morals police investigated but soon dropped the charge. Whatever his tendencies, Leonardo was one of those who, like his contemporary Michelangelo and like the physicists Henry Cavendish and Willard Gibbs, is so driven by his urge to discover and create that he has little time left for human relationships.

Leonardo was a frugal and abstemious vegetarian. Although he could turn on the charm when he chose, his usual façade was aloof and reserved to the point of secretiveness. He combined boundless curiosity to know and discover and meticulous perfectionism with limitless ambition for fame and accomplishment.

These features united to form one of the most unfortunate, self-defeating characteristics that a fame-seeker can have, namely: inability to complete the tasks he has started. Either Leonardo's plans were too grandiose and hence could never be realized, or Leonardo himself lost interest before the end.

He was a man of the type who sometimes appears among modern scientists, driving laboratory directors mad. The scientist does brilliant work but, when a task is nine-tenths done, he is seized by a passion for some new idea and goes haring off on another line of investigation. Because report-writing bores him, he never reports on his previous work, which remains in the form of scattered notes and, as far as the laboratory is concerned, might as well have never been done at all.

Leonardo's many abortive projects included two colossal equestrian statues, the construction of a canal to Pisa, urban renewal at Florence, completion of the Milan Cathedral, and drainage of the Pomptine Marshes. It was not always his fault that the project failed, but he seldom pushed a task to completion even when he could. He was an incorrigible dabbler and dilettante.

He also tried to master all the sciences. His studies included astronomy, anatomy, aeronautics, botany, geology, geography, phonetics, and physics. The physics included optics, ballistics, component forces, friction, lubrication, stress, levers, pulleys, loaded beams, and strength of materials. He often dropped his work and forgot his obligations for months at a time while he buried himself in another science.

In many scientific fields, Leonardo went as far as any man of his time. Sometimes he anticipated the discoveries of later scientists like Galileo or Stevin. But, as he never published, nothing came of all his studies.

Likewise, he worked on mechanical problems covering an extraordinary range. He designed armored battle cars, a steam gun, a wheel-lock gun, many-barreled cannon, a city built on two levels, a mechanical turnspit, an oil press, a clockwork automobile with a differential gear, mechanical musical instruments, an improved sawdust system with a private entrance for clients of quality, a polygonal fortress like that of his friend Martini, textile machinery, a rolling mill, a grinding machine, a rope-making machine, a diving suit, a submarine, a water mill, a brake with curved shoes, flying machines, a parachute, a printing press, a screw propeller, a screw-cutting machine, a ribbon-drawing machine, valves, pumps, surveying instruments, poison gas, catapults, a file-cutting machine, sprocket chains, spiral gears, a needle-making machine, a coin cutting machine, a crane, a dredge, excavating machines, and a mitered canal lock with a wicket gate.

A mitered lock is one with tongues and grooves along the edges of the valves, which interlock when the gates close. Each pair of valves forms a blunt angle pointing upstream, so that water pressure forces them all the more tightly together. A wicket gate is a small portal in the main gate, set low down, to equalize water levels before the main gate is opened. Otherwise the surge of water tosses boats about like chips.

But, of all these gadgets, only a few—the canal lock, and perhaps the screw-cutting machine and the water mill—were actually reduced to practice. Sometimes the idea was not workable.

One of Leonardo's battle cars, for example, was a turtle-shaped armored vehicle, loopholed for guns. It was supposed to be moved from within by hand-operated cranks. Leonardo soon realized that it would be far too heavy to be thus propelled. Another of Leonardo's designs was for an unmanned two-horse chariot with whirling scythe blades, like that with which the unknown fourth-century author of De rebus bellicis had wished to mechanize the Roman army.

Several inventors of the time made such proto-tanks, but all these war-wagons failed for want of adequate power. Sometimes they were designed to be pulled or pushed by horses or oxen. If, however, the animals were left outside, they would soon be killed, while there was not enough room for them inside. The Spaniards actually tried 200 battle cars against the French at Ravenna in 1512, but the French won anyway.

It was the same with Leonardo's flying machines. He drafted several designs in which batlike wings were to be flapped by human muscle. He may even have tried one out. Convinced that this was not the right way, he designed a helicopter with a big spiral screw-shaped rotor on a verti-
cal shaft. This screw was to be turned by men working a treadmill below.

Not until 1680 was Leonardo's basic error pointed out. Then the physicist Borelli showed that man has no muscles anywhere nearly so massive and powerful, in proportion to his weight, as the flying muscles of birds. Therefore, flight by human muscles might as well be forgotten.

What did Leonardo actually accomplish? He painted several immortal pictures, such as "The Last Supper" and "Mona Lisa" (La Gioconda). He dug some canals, cast some cannon, staged charades for kings and dukes, and made countless notes and sketches.

As he studied, speculated, and designed, Leonardo entered his notes and drawings in notebooks. He wrote from right to left, backwards, either for secrecy or because, being left-handed, he found it easier. He meant, he said, some day to put this mass of material in order and make one or more publishable treatises out of it. But "some day" never came.

When Leonardo died, thirty-odd volumes of notes passed to his friend and pupil Melzi. The complete edition of Leonardo's notes, without the pictures, makes a 1,200-page book. Melzi's heirs sold the collection to various purchasers, so that it became scattered over Europe. The buyers were more interested in the notebooks as collector's items than as technical works, for by then Leonardo's fame as a painter had quite eclipsed his renown as an engineer. Some volumes were lost, but the rest have been collected into various European libraries.

For several centuries, Leonardo's only published work was a treatise on painting extracted from his notebooks and printed in 1551. Nobody even began to publish the rest of the material until the 1880s. By that time the mechanical arts had advanced so far beyond Leonardo's time that his designs were only historical curiosities.

During his life, Leonardo had some influence by personal contacts with other engineers. Some historians of technology claim to find traces of his influence in later sixteenth-century machines. A few men, during the centuries following Leonardo's death, mined the manuscripts for ideas. One such was the mathematician Girolamo Cardano, whose father had been a friend of Leonardo. We cannot tell for sure how much influence Leonardo exerted in this way. But certain it is that his influence would have been many, many times greater if he had published his ideas.

This brings us to the final paradox of Leonardo. Despite his eagerness for fame and his wide knowledge, he failed to grasp the importance of an invention that would have enabled him to achieve his goal: the printing press. He knew all about the printing press, too. In fact, he sketched mechanical improvements for it.

But Leonardo was content to reach for fame by word of mouth only, as most scientists and engineers had been doing from Imhotep on down. He did not realize that even a small printed book would multiply his voice thousands of times over and expand his influence accordingly; or that this influence, applied in this way, might have advanced the mechanical arts by decades. Or, if he did realize these things, he never acted upon his knowledge. And for these reasons I class him, not as the first of the modern engineers, but as the last of the ancient ones.

After Leonardo, the changes leading to the modern era in engineering came thick and fast.

One change was the growth of printed technical literature. In 1482, Valturio brought out De re militari, surveying the state of military engineering. Three years later Alberti summarized construction with his book on building. In early +XVI, many minor technical books—handbooks and how-to books—appeared, such as Bayfius' De re navalis, on shipbuilding (1536).

In 1540 Biringuccio's great treatise on metallurgy, Pirotechnia, was published posthumously. Biringuccio had been influenced by his German colleague Agricola,29 who in turn borrowed passages from Biringuccio's book for his own masterpiece on mining, De re metallica (1556). In 1912 Herbert Hoover, then a young mining engineer, and his wife translated this book into English. Agricola also wrote a perfectly serious book for mining engineers on gnomes and how to get rid of them. However, in some statesmen and scholars of more recent times have believed in queerer things than gnomes; not many years ago the Prime Minister of Canada was an ardent Spiritualist.

Later in the century, Palladio, who perfected the bridge truss, covered the subject of architecture in I quattro libri dell'architettura (1581). Ramelli and Verantius wrote on machinery. Fontana told just how he moved the second biggest of Rome's obelisks from Nero's Circus to a position in front of St. Peter's, in case anyone wanted to move another obelisk. And many other, less famous technical books appeared in print.

Another change was the advance of those pure sciences destined most to affect engineering, especially statics, mechanics, kinematics, and hydraulics. In the Netherlands, Simon Stevin (1548–1620) discovered the triangle of forces. This discovery enabled men to calculate the actual loads on the members of cranes, trusses, and other simple structures.

Stevin also speeded up the process of calculation by inventing the decimal system. The effect of this discovery may be compared with that of the modern introduction of computers. In addition, Stevin devised the
plan of flooding the Dutch polders as a means of defending the Netherlands. In 1672, this defense stopped the invincible armies of Louis XIV in their tracks.

Stevin’s younger contemporary Galileo Galilei (1564–1642) solved the problems of accelerated movement and began the analysis of stresses in beams. He did this in his old age, after his trouble with the Inquisition. The Inquisition had ordered him not to expound the hypothesis of Copernicus, which put the sun, instead of the earth, at the center of the solar system, as Aristarchos had done long before. Galileo, a peppy man who did not suffer fools gladly, published a book arguing this hypothesis anyway. The Inquisitors forced Galileo by threats of torture to recant and put him under house arrest for the rest of his life. Nevertheless, and despite failing eyesight, he managed to complete his Dialogue on Two New Sciences (1636), giving the science of mechanics its greatest impetus since Heron. Although his analysis of the stresses in a beam contained a basic error, others soon corrected this.

After Galileo, Italian science and engineering did not fare so well. For one thing, during +XVI the great powers—France, Spain, and the “Holy Roman” or German Empire—used Italy as their favorite battleground. The divided and mutually hostile Italian city-states were as helpless to resist these mighty, marauding armies as the Greek city-states had been to resist the Macedonians and the Romans many centuries before.

Furthermore, Italy, where the Renaissance had started, received the brunt of the Counter-Reformation of the Catholic Church. One of the more puritanical popes sent workmen through St. Peter’s to remove the genitalia of Michelangelo’s cherubs with hammer and chisel. The counter-reformers cleaned up not only the morals of the clergy but also any scientists suspected of heresy. One of the latter, Domenico Oliva, escaped the tortures of the Inquisition by jumping out a window to his death.

Still, technical progress continued elsewhere, ever faster. Technical men began to organize; the Society of Lynxes, to which Galileo belonged, was the first of many such organizations. The first research institute was founded in 1560, and the first industrial exposition was held at Nuremberg in 1568.

Engineering schools appeared in France in +XVIII. At the same time, specialization within the engineering profession took place. John Smeaton, who had to go to France in the 1750s to round off his technical education, called himself a “civil engineer,” meaning a non-military one. Simultaneously, the experimental vacuum mine pumps of +XVII were evolving into the steam engine.

So, after Leonardo, engineering became modern. We should not be fooled by the gaudy medievalistic costumes of these engineers—the feathered hats, flowing hair, ruffs, laces, and swords. The thoughts in these plumed and periwigged heads were modern thoughts.

Nor was the transition to modern times a matter of any particular invention, such as the steam engine. It was, rather, the coming of a time when technical development became so rapid that men could see the world about them change in their own lifetimes. It is no accident that about +XVI, men began to write of the “wonderful discoveries of this modern age” and to wonder aloud what would happen next.

For that matter, we are still wondering. The pace of change has speeded up until change itself has become one of the most pressing human problems. Older readers can remember streets lit by gas, wagons and carriages drawn by horses, stoves fired by coal or wood, and outside plumbing. Even the younger ones may recall the days before self-service markets and transoceanic air travel.

This constant and rapid change affects those who live under it. As Russell has pointed out: “Few men’s unconscious feels at home except in conditions very similar to those which prevailed when they were children.” Hence people who live in an era of rapid change tend to suffer from a vague but persistent feeling of unease. Something is wrong, though they do not know just what. Some react to this discomfort by wildly irrational fanaticism, as by asserting that fluoridation of drinking water is part of a Communist plot to poison the nation. Moreover, it can be shown that speeding up the rate of change probably fosters crime.

Some blame engineers for these difficulties, but that is futile. The whole process began back in the days of Imhotep. Once started, technology was bound to develop much as it has, although the timing of this development might have varied if political history had been different.

Nay rather, technology started back in the early Pleistocene, when our apish ancestors, instead of evolving fangs, horns, or claws to enable them to make their way in the world, developed brains for the purpose. Once that portentous step had been taken, everything else followed naturally. And now there is no more stopping or turning back than there is on a ski slide, once the skier has pushed off.

Others blame the technical men because they have not succeeded in making everybody kind, honest, and peaceful. Therefore, they say, technical progress has not “civilized” men at all.

But it is a mistake to confuse these virtues with civilization. Civilization is a matter of power over the world of nature and skill in exploiting
this world. It has nothing to do with kindness, honesty, or peacefulness. These virtues are found scattered—rather thinly, alas—throughout the entire human species, although they occur in some people more than in others and are encouraged in some cultures more than in others. No doubt it would be a good thing if they were universal, but the engineer is not the man to ask this of. He can heat your house, dam your river, or build your space ship, but it is hardly fair to expect him also to make you love your fellow man. Priests and philosophers have tried for thousands of years to accomplish this, but with indifferent success.

An engineer is merely a man who, by taking thought, tries to solve human problems involving matter and energy. Since the Mesopotamians tamed their first animal and planted their first seed, engineers have solved a multitude of such problems. In so doing, they have created the teeming, complex, gadget-filled world of today.

But problems are like the Hydra of the myth of Herakles; cut off one head and two more sprout. Scientists and engineers have, by using their intelligence, solved some human problems. But the solutions themselves have given rise to still greater problems—nationalism, nuclear war, population explosion, and degenerative mutation pressure, to name but a few. If civilization is to last, and the problems are not to grow beyond all coping, the rest of mankind, and not just the scientists and engineers, will have to use intelligence also, and more than they have so far.

Otherwise, in place of vanished man, the remote future may see the specialized descendant of some present-day monkey, rat, or lizard beginning to dig his species’ first irrigation ditch—and so starting the whole process over again.

NOTES

CHAPTER ONE


CHAPTER TWO

1. Also spelled Djoser, Zoser, or Zeser. Because of the ambiguities of ancient Egyptian writing, the pronunciation of early Egyptian words is very uncertain. Hence, Hurry (pp. 191 f.) lists 34 ways to spell the name of Imhotep: Aiemhetep, I-em-hotep, Ihotep, Yemhatpe, &c.

2. Manetho (Loeb Classics), pp. 41–45. Joser’s name is also spelled Sesorthos or Sosorthus in other quotations from Manetho, whose name in Greek was Manethōs or Manethōn.

3. Greek, Imouthēs. The h represents a guttural fricative between our h and the ch sound of German ach. For other Egyptian sounds without close English equivalents, see any Arabic grammar.

4. Mastaba is an Arabic word meaning “bench.” Tombs of this type are so called because they were shaped like the benches of mud brick that Egyptian peasants build in front of their huts.

5. Greek, Troia; modern Tūra.


7. These are estimates, based upon what we can see of the pyramid. There is no way to ascertain these figures exactly short of taking the pyramid apart and counting and weighing the stones—especially as a ledge of rock rises into the interior, no man knows how far.


9. Greek, Chephrēn or Kephrēn.

10. Greek, Mykerinos or Mencherēs; Latin, Mycerinus.

11. Greek, Amenemmēs.

12. Or Aahmes; Greek, Amasis. Edwards, p. 196; Fakhry, pp. 234 f.
