CHAPTER 3

Pharaohs and Engineers

Neolithic societies never reached the complexity of kingdoms. They never built large cities, or large enclosed structures like palaces or temples; they had no need for writing to keep records; and they never established a tradition of higher learning or institutionalized science. These features arose only when Neolithic societies coalesced into civilizations—a second great transformation in human social evolution.

This revolution is often referred to as the Urban Revolution. Whatever its name, changes that began around 6,000 years ago in the Near East ushered in the first civilizations, replete with all the social and historical consequences accompanying cities, high population densities, centralized political and economic authority, the origin and organization of regional states, the development of complex and stratified societies, monumental architecture, and the beginnings of writing and higher learning. The transition was another techno-economic revolution, this time arising out of the need for intensified agricultural production to sustain increasingly large populations that pressed against the carrying capacities of their habitats. As an episode in human history and the history of technology, the Urban Revolution proved to be unrivaled in its consequences until the Industrial Revolution that took root in eighteenth-century Europe.

A new mode of intensified agriculture, distinct from Neolithic horticulture or pasturage, provided the underpinnings of the first civilizations. In that mode simple gardening was superseded by field agriculture based on large-scale water-management networks constructed and maintained as public works by conscripted labor gangs (the corvée) under the supervision of state-employed engineers. In the Old World the ox-drawn scratch plow replaced the hoe and digging stick. And subsistence-level farming gave way to the production of large surpluses of cereals (estimated at a minimum of 50 percent above Neolithic levels) that could be taxed, stored, and redistributed. Centralized political authorities dominated by a pharaoh or king came into being to manage these complex systems of agricultural production. Along with hydraulically intensified agriculture (generally artificial irrigation) and a centralized state authority, the Urban Revolution sustained much larger populations, urban centers, coercive institutions in the form of armies, tax collectors, and police, expanded trade, palaces and temples, a priestly class, religious institutions, and higher learning. In such bureaucratically organized societies, cadres of learned scribes developed mathematics, medicine, and astronomy.

Taming the Rivers

The Urban Revolution unfolded independently in multiple centers across the Old and New Worlds. The same remarkable pattern of Neolithic settlements coalescing into centralized kingdoms based on intensified agriculture occurs at least six times in six different sites around the globe: in Mesopotamia after 3500 BCE, in Egypt after 3400 BCE, in the Indus River Valley after 2500 BCE, in China after 1800 BCE, in Mesoamerica at about 500 BCE, and in South America after 300 BCE. The origin and development of these civilizations were essentially independent and not the result of diffusion from a single center, and hence they are known as the pristine civilizations.

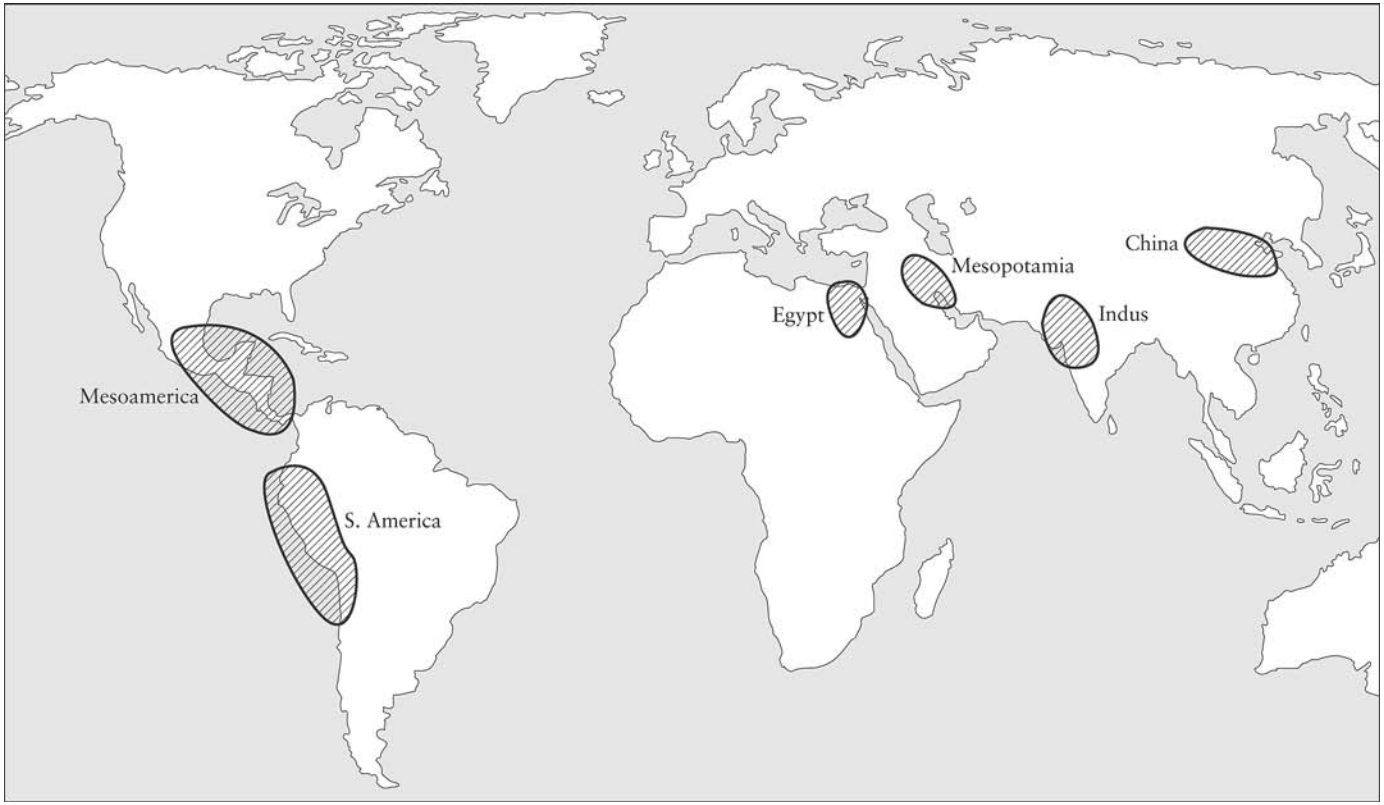
Why did civilization arise independently and repeatedly on a worldwide scale after the fourth millennium BCE in those particular sites? Several explanations have been proposed. The precise processes involved in the leap to civilization are research questions actively debated by archaeologists and anthropologists, but many scholars emphasize the importance of hydrology and ecology, and they recognize that intensified agriculture, abetted by large-scale hydraulic engineering projects, was a key element in the formation of large, highly centralized bureaucratic states. The fact alone that pristine civilizations arose in hydrologically distressed regions—that is, where too little or too much water required hydraulic engineering for the successful practice of intensified agriculture—gives credence to what is called the hydraulic hypothesis, linking the rise of civilization with the technology of large-scale hydraulic systems. Under a hot, semitropical sun, irrigation agriculture is extraordinarily productive and yields that can literally fuel large populations become possible. Silt-laden rivers provide water for irrigation and, especially when controlled artificially, they enrich the soils around them. Irrigation agriculture and flood control required hydraulic engineering works and some level of communal action to build and maintain them and to distribute water when and where needed: marshes had to be drained; dams, dikes, canals, sluices, conduits, terraces, catchments, and embankments had to be built; and ditches had to be kept free of debris. Water disputes had to be settled by some authority, and grain surpluses had to be stored, guarded, and redistributed. The interacting effects of the geographical setting and the techniques of hydraulic agriculture reinforced trends toward an authoritarian state.

Along these lines, the notion of "environmental circumscription" provides the key explanatory concept: civilizations arose in prehistoric river valleys and flood plains that were environmentally restricted agricultural zones beyond which intensive farming was impossible or impractical. In these constricted habitats, like the Nile River Valley, expanding Neolithic populations soon pressed against the limits imposed by desert, cataracts, and sea, leading to pressures to intensify food production. Warfare became chronic and developed beyond raiding to involve conquest and subjugation since, in a habitat already filled, the losers could no longer bud off and form a new agricultural community. Whereas previously in both the Paleolithic and Neolithic, defeated groups could generally move on to a new locale, in environmentally restricted areas such as the Nile River Valley agriculturalists had nowhere to go. Victors not only took over land and smaller irrigation works but subjugated and dominated defeated groups, sparing their lives in return for their labor as slaves and peasants in maintaining systems of intensified farming. Once this process started, the historical momentum favoring confederating and centralizing forces was irreversible. Neolithic communities thus became increasingly stratified, culminating in a dominant elite in command of an agricultural underclass as regional powers subsumed local ones. Time and again civilization and the state emerged wherever these ecological and demographic conditions occurred.

Further research will doubtless amplify this picture, but for now a common pattern with common characteristics seems apparent. History is too easily thought of as a sequence of unique events—what has been lampooned as "one damned thing after another." But the recurrent rise of civilizations in the Near East, in the Far East, and in the New World testifies to significant regularities in the historical record.

The model described above admirably fits the first human civilization arising on the flood plain between the Tigris and the Euphrates Rivers in present-day Iraq. This was ancient Mesopotamia, the land "between the rivers." By 4000 BCE Neolithic villages filled the Mesopotamian plain. Local authorities drained marshes in the lower delta and, later, installed extensive irrigation works on the flood plain upriver. Great walled cities such as Uruk, Ur, and Sumer, with populations between 50,000 and 200,000, arose after 3500 BCE, and the dynastic civilization of the Sumerians developed fully by 2500 BCE. Possibly because of the shifting and unpredictable courses and flood patterns of the Tigris and Euphrates, no single kingdom or polity dominated Mesopotamia as in Egypt, but rather a series of city-states along with empires based on them rose and fell over the succeeding millennia.

Mesopotamian civilization shows a great deal of continuity over


China
Mesopotamia
Egypt
Indus
Mesoamerica
S. America

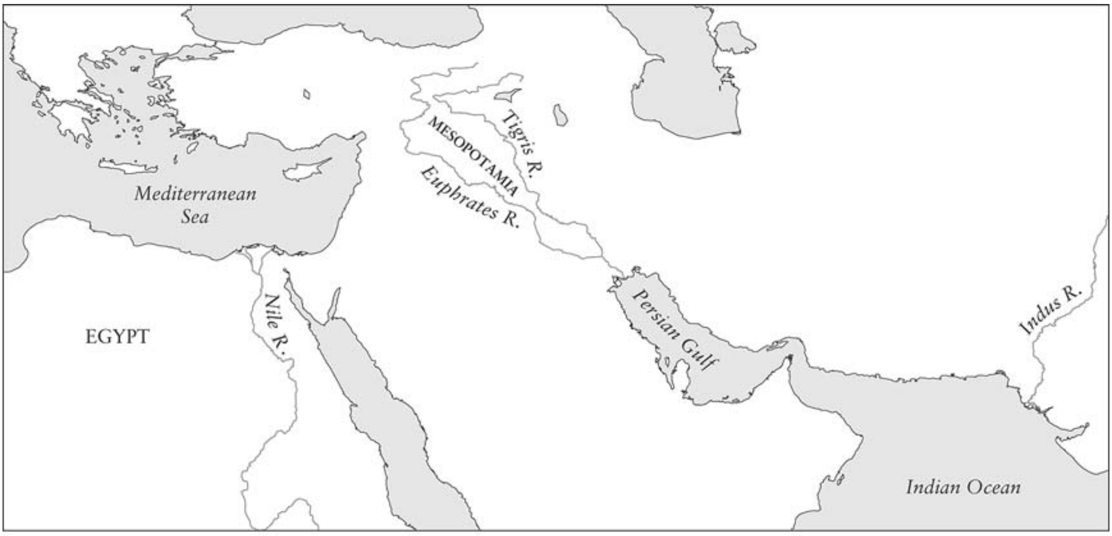
thousands of years, even though different groups, from different portions of Mesopotamia, took their turns at cultural, political, and military ascendance. When the Babylonians of central Mesopotamia became the dominant power, they absorbed a good deal of Sumerian culture and adapted Sumerian script for writing their own language. When Assyria (a kingdom in northern Mesopotamia) began to control the region, it similarly absorbed much of Babylonian culture.

All of these civilizations were based on irrigation agriculture. Main canals were upward of 75 feet wide and ran for several miles, with hundreds of connecting channels. All Mesopotamian civilizations developed centralized political authority and complex bureaucracies to collect, store, and redistribute agricultural surpluses. All are characterized by monumental building, including most notably great brick temple complexes and pyramids known as ziggurats. For example, Ur-Nammu's ziggurat of Third Dynasty Ur (dating to approximately 2000 BCE) formed part of a larger complex measuring 400 by 200 yards. Nebuchadnezzar's tower (600 BCE) rose over 90 meters (270 feet) and was, according to tradition, the basis of the biblical story of the Tower of Babel. Mesopotamian civilization also developed writing, mathematics, and a very sophisticated and mature astronomy.

Ancient Egypt illustrates a similar route to civilization. The Nile River Valley is a circumscribed strip of green hemmed in by a sea of desert to the east and west, mountains to the south, and the Mediterranean to the north; it forms a narrow ribbon 12–25 miles wide and hundreds of miles long. Neolithic settlements proliferated along the Nile, and already in the sixth millennium BCE kingdoms emerged; seven predynastic kingdoms have been identified down to roughly 3400–3200 BCE. (Egyptologists agree about the order of events, but they differ by centuries on dating, especially in the early dynasties and Old Kingdom Egypt.) Sometime in that period King Menes united the two kingdoms of Upper and Lower Egypt, thus becoming the first Egyptian pharaoh of what we know as the first dynasty. And, according to tradition, Menes also organized hydraulic works, having embanked the Nile at Thebes. The explosive growth of Egyptian civilization followed. Based on managing the annual flooding of the Nile, Egypt manifested all the earmarks of high civilization, including large-scale building in the great pyramids at Giza, which were early creations of Egyptian civilization. Centralized authority grew correspondingly at an early date; 20,000 soldiers came to compose the Egyptian army; the pharaohs became legal heirs to all property in Egypt and controlled absolutely their 2.5 million subject-tenants; bureaucracy, writing, mathematics, elementary astronomy, expanded crafts, and all the other complexities of civilization displayed themselves in turn.

Less is known of civilization in the Indus River Valley, but the outlines of its historical development are plain. Neolithic settlements appeared along the Indus by 7000 BCE. Civilization may have arisen

Map 3.1. The earliest civilizations. The transition from Neolithic horticulture to intensified agriculture occurred independently in several regions of the Old and New Worlds. Increasing population in ecologically confined habitats apparently led to new technologies to increase food production. *(opposite)*



Map 3.2. Hydraulic civilizations. The first civilizations formed in ancient Mesopotamia (modern Iraq) on the flood plain of the Euphrates and Tigris Rivers, astride the Nile River in Egypt, and along the Indus River. The agricultural benefits of annual flooding were intensified by hydraulic management.

indigenously or some of its incipient features may possibly have arrived with settlers or traders from Mesopotamia. One way or another, the alluvial flood plain of the Indus River Valley provided the indispensable setting for Indus civilization, and irrigation agriculture the requisite means. The cities of Mohenjo-daro and Harappa in modern-day Pakistan date to 2300 BCE. Harappan civilization, as it is known, thereafter spread inland and along the coast of the Arabian Sea. Peoples of the Indus River Valley farmed the arid plains, and they built embankments to protect cities against erratic, silt-laden floods. Indicative of strong central government, Harappan towns were rigidly planned walled communities with laid-out streets and blocks, towers, granaries, and sewers, and all the trappings of civilization. At the center of Mohenjo-daro, for example, stood an enclosed citadel (200 × 400 yards) with its 40-foot-high brick mound. Within, the Great Bath held a manmade pool 12 meters long, seven meters wide, and almost three meters deep, and archaeologists have identified what may be priestly residences and an assembly hall. The population of Mohenjo-daro has been estimated at 40,000. Harappan metallurgists used copper, bronze, gold, silver, tin, and other metals; potters produced glazed pots; and writing and higher learning developed. Limited evidence suggests that even at an early period authoritarian regimes with a strong priestly-bureaucratic-military class already held command. But after 1750 BCE the original urban culture of the Indus declined, probably because of climate and ecological factors, including the changing course of the Indus River.

In China a similar pattern repeated itself along the Yellow River (the Hwang-Ho). By 2500 BCE thousands of late Neolithic villages spread out along the river, and as irrigation agriculture began to be practiced, kingdoms arose. Yü the Great, the putative founder of the semimythical first dynasty (Hsia), is legendary in China as the ruler who "controlled the waters." The Shang (Yin) dynasty (1520–1030 BCE), which marks the documented beginning of Chinese civilization, made itself master of the Yellow River plain by dint of extensive irrigation works. Later, engineers brought irrigation techniques to the more southern Yangtze River. Rice cultivation spread northward from south China and also involved hydraulic control. One of the roles of government throughout Chinese history was to build and maintain waterworks; as a result, dikes, dams, canals, and artificial lakes (such as the 165-acre Lake Quebei) proliferated across China. Deliberate government policies of water conservancy and agricultural improvement also involved drainage. To effect these installations, massive corvée labor was extracted from the peasantry.

The early Chinese built cities with protective walls, palaces, and ceremonial centers. Their society became highly stratified; Chinese emperors functioned as high priests, and great emphasis was placed on royal burials that included the emperor's entourage, sacrificed by the hundreds to accompany him. China was first unified in 221 BCE, and unprecedented authority became centralized in the emperor, backed administratively by an elaborate and formidable bureaucracy associated with royal courts. The population of China under the control of the emperor has been estimated at 60 million at the beginning of the Christian Era. The early Chinese state built granaries and maintained standing armies. Sophisticated bronze metallurgy was also practiced, with the bronze tripod the symbol of administrative power invested in officials. As for monumental building, in addition to hydraulic works, the Great Wall of China has been hailed as the largest building project in history. Construction of the first 1,250 miles of the Great Wall (on the divide between steppe and arable land) began in the fourth and third centuries BCE and was finished in 221–207 BCE, coincident with the first unification of China. (In later historical times the total length of Chinese defensive walls extended to over 3,000 miles.) The Grand Canal (originally built in 581–618 CE), the interior waterway stretching 1,100 miles from Hangchow to Beijing, deserves mention as another example of monumental building associated with Chinese civilization. On the order of 5.5 million people labored on the project in which 2 million workers may have perished. No less characteristically, writing, mathematics, and astronomy came to be part of Chinese civilization.

Swamps and Deserts

The separate and independent rise of civilizations in the Old and New Worlds represents a great experiment in human social and cultural development. Despite departures in the New World, notably the absence of cattle, the wheel, and the plow, the independent appearance of civilization in the Western Hemisphere and the deep parallels among pristine civilizations in regions where water management was necessary lend support to the hydraulic hypothesis and the view that regularities in history derive from the material and technical bases of human existence.

Recent findings have confirmed that humans entered the Americas and hunted and gathered their way to southern Chile by at least 12,500 years ago. In Central (or Meso-) America, Paleolithic hunter-gatherers gave way to fully settled Neolithic villages by 1500 BCE. Increasingly complex Neolithic settlements filled the humid lowlands and coastal regions of Central America by 1000 BCE. Olmec culture flourished from 1150 to 600 BCE inland along rivers flowing into the Gulf of Mexico and is sometimes said to be the first American "civilization." But in fact the Olmecs seem to have been at a high Neolithic stage comparable to the megalithic culture at Stonehenge. Olmec "towns" held populations of fewer than 1,000. Nonetheless, they built ceremonial centers with burial mounds, and they are known for colossal Olmec stone heads, some over 20 tons in weight and transported 100 miles, according to one report. They developed a calendar and, suggestive of the origins of true civilization, hieroglyphic writing. The Olmecs declined after 600 BCE, but they provided cultural models that later, more fully formed American civilizations built upon.

Founded around 500 BCE, the first true city in the New World was at Monte Albán looking down on the semiarid Oaxaca Valley in Central Mexico. Small-scale irrigation agriculture was practiced in the valley, and Monte Albán was a planned city that possibly represented the confederation or consolidation of three regional powers into what became Zapotec civilization. Engineers leveled the top of the mountain for a large astronomically oriented acropolis, stone temples, pyramids, and a ball court. Two miles of stone walls encircled the city; 15,000 people lived there by 200 BCE, 25,000 by the eighth century CE. Before its subsequent decline, Zapotec scribes wrote with hieroglyphs and possessed a complex calendar.

Coexisting with Monte Albán but an order of magnitude larger, the huge city of Teotihuacán arose in the dry Teotihuacán Valley near modern Mexico City after 200 BCE. Estimates for the population of the city at its peak in the period 300–700 CE range from 125,000 to 200,000, making it the largest and most powerful urban center in Mesoamerica; it was the fifth largest city in the world in 500 CE, and it remained one of the world's largest urban centers for several hundred years. Oriented astronomically, the planned town of Teotihuacán covered eight square miles, and the main avenue ran for over three miles. The largest structure was the gigantic Temple of the Sun, a huge stepped pyramid nearly 200 feet high, 35 million cubic feet in volume, with a temple on top. There were 600 other pyramids and temples in Teotihuacán and several thousand apartment complexes. As in other early civilizations, hydraulic works and irrigation agriculture made Teotihuacán possible. In addition to farming land in the seasonally flooded upper valley, Teotihuacános built canals and installed extensive, permanent irrigation works along the San Juan River in the lower valley. Teotihuacán itself was well supplied with water by the river, canals, and reservoirs. Control over a highly developed obsidian trade also increased the prosperity of the city. What archaeologists have identified as a gigantic royal palace and a major bureaucratic/administrative center testify both to extreme social and economic stratification and to centralization of power into royal/priestly authority. At its height the civilization of Teotihuacán dominated the great central valley of Mexico.

Contemporaneous with civilization in the dry valleys of central Mexico, Mayan civilization rose in the wet lowlands of the Yucatán and flourished for a thousand years between 100 BCE and the ninth century CE. Until the 1970s the archaeology of Mayan civilization seemed to discredit any link between civilization and the taming of waters. But an interpretative revolution in Mayan studies followed from the discoveries of extensive Mayan engineering installations covering 741 acres at Pulltrouser Swamp in modern Belize. The problem for lowland Mayan agriculture was not too little water, but too much, a problem the Maya overcame by farming raised fields (three feet high, 15–30 feet wide, and 325 feet long at Pulltrouser) with canals and drainage channels in between. The works drained water from fields, the muck in canals served as fertilizer, and the system overall proved capable of producing surpluses sufficient to support large populations. And it required collective effort to build and maintain. The distinctive Mayan form of intensified wetland agriculture now reveals the hydraulic underpinnings of Mayan civilization.

The largest Mayan city was Tikal, which had a population of 77,000 before its collapse about 800 CE. Population densities during the Maya Classic Period are estimated to have been 10 to 15 times greater than that supported in the remaining jungles of Central America today. Monumental building dominated Mayan cities, especially temple platforms and large stepped pyramids, similar to ziggurats, with a stairway leading to a temple on top. Political authority was centralized in noble classes and Mayan kings. And the Maya developed the most sophisticated mathematical, calendrical, and astronomical systems of any civilization in the Americas.

In the rise of civilization in South America, the pattern repeats itself yet again. Collectively covering millions of acres, Peruvian irrigation systems represent the largest archaeological artifact in the Western Hemisphere. The many short rivers flowing from the Andes Mountains to the Pacific across an arid coastal plain are now seen to form the ecological equivalent of the Nile River. Early village settlement arose in more than sixty of these extremely dry coastal valleys, and increasingly elaborate and well-engineered irrigation systems became essential to support the civilizations that developed there. One of the irrigation canals of the Chimu people, for example, ran 44 miles; their capital at

Fig. 3.1. Teotihuacán. Cities and monumental building are defining features of all civilizations. Here, the huge Temple of the Sun dominates the ancient Mesoamerican city of Teotihuacán.

Chan-Chan covered nearly seven square miles. In joining existing irrigation systems, Moche civilization expanded out of the Moche River Valley after 100 BCE, ultimately occupying 250 miles of desert coastline and up to 50 miles inland. The Moche urban center at Pampa Grande had a population of 10,000, and the Huaca del Sol pyramid, made of 147 million adobe bricks, stood 135 feet high. Moche civilization endured for nine centuries.

In southern Peru another center of civilization arose in the highlands around Lake Titicaca. There, based on the cultivation of potatoes, a fecund agricultural system of raised and ridged fields similar to Mayan wet farming fueled a line of civilizations. One report puts the population of the mountain city of Tiwanaku at 40,000–120,000 at the city's zenith between 375 and 675 CE. The succeeding Incas installed irrigation works and practiced water management on a larger scale than their predecessors, and militarily the Incas were the first to unite the productive resources of the coastal plains and the mountain highlands. At its peak in the fifteenth century CE, the Inca empire extended 2,700 miles and included 6 to 8 million people (some say 10 million). Monumental building is well represented in the Inca capital of Cuzco with its exquisite mortarless masonry and water supply and drainage systems, in remote Machu Picchu with its steeply terraced fields, and no less in the incredible system of roads that united the Inca empire. Two road systems—one coastal, one in the mountains—ran for 2,200 miles each, and all together the Incas built 19,000 miles of path and road, a huge engineering achievement accomplished without metal tools. The state maintained an elaborate system of grain-storage facilities and redistribution mechanisms. The Inca emperor was the sacred focus of an absolutist state rivaling ancient Egypt in despotism, and like the Egyptian pharaohs, dead Inca emperors in Peru were mummified and worshiped.

Thus, time and again the Urban Revolution produced civilizations that depended on large-scale hydraulic engineering, and it repeatedly transformed human existence from Neolithic roots. The similarities of ancient American civilizations and those of the Old World have often been noticed and sometimes attributed to diffusion from the Old World to the New. But rather than invoking exotic contact across space and time to explain these parallels, would it not be less remarkable simply to say that similar material, historical, and cultural conditions produced similar civilizations?

Men of Metal

Based on the new technologies of irrigation and field agriculture, the worldwide rise of urban civilization marks a fundamental and irreversible turning point in the history of technology and in human affairs generally. A cascade of ancillary technologies accompanied the rise of civilization, including, at least in the Old World, bronze metallurgy. The mastery of bronze (copper alloyed with tin) still lends its name to the new civilization as the Bronze Age. Metals offer several advantages over stone as tools and weapons, and in the long run metals replaced stone. Metalworking embodies a complicated set of technologies, including mining ore, smelting, and hammering or casting the product into useful tools and objects; and bronze metallurgy requires furnaces with bellows to raise temperatures to 1100°C. In the New World, bronze did not replace the digging stick, stone hammers, chisels, or the obsidian blade for tools, but highly expert gold and silver metallurgy developed nonetheless for decorative and ornamental purposes. The sophisticated gold craftsmanship of pre-Columbian Indians in Peru is justly renowned, and Chimu metallurgists apparently used techniques amounting to chemical electroplating of gold.

Control over mineral resources thus became significant in the early civilizations. Sinai copper mines proved of great importance to Egyptian pharaohs; tin for making bronze had to be transported over long distances throughout the Near East; and, as mentioned, an extensive obsidian trade developed in Mesoamerica. Increased trade and expanded economic activity stand out among the earmarks of early civilizations. Occupational specialization and a sharpened division of labor likewise characterized civilized life from the outset. Craft production was no longer exclusively part-time or carried on as a household system of production, but rather became the business of specialized crafts whose practitioners earned their daily bread primarily in exchange for the practice of their craft skills. Certain "industrial" quarters of early cities were apparently given over to certain crafts and craft specialists. Among the new technologies of the Bronze Age, one might also mention brewing beer from bread, which became a noteworthy activity in Mesopotamia, where the famous Hammurabi Code regulated beer parlors in detail. Likewise in Inca Peru, ceremonial consumption of intoxicating beverages amounted to a redistribution of state-owned vegetable protein.

As a feature of the rise of state-level civilizations, humans began to exploit new sources of energy and power to do work. The muscle power of the ox (a castrated bull) was applied to pull the plow, and the horse was domesticated and entered humanity's service. The Hittites of second millennium BCE Anatolia first harnessed the horse and the ass to a wheeled cart, thus creating the chariot and transforming warfare throughout the Near East. In the first millennium BCE the camel began to provide essential transport. So, too, did the llama in South America and the elephant in India and South Asia. Wind power became a new energy source tapped for the first time with the rise of civilization. The Nile River especially, with the current flowing north and the prevailing winds blowing south, became a highway for sailboats and a factor contributing to the unity of ancient Egypt. Boats also came to ply the waters between Mesopotamia and the Indus River Valley. Slavery arose coincident with civilization, and the corvée, while less coercive than slavery, fits into this same category of the human use of human beings.

Pyramids

Monumental architecture in the form of pyramids, temples, and palaces is diagnostic of high civilization and is remarkable in the history of technology, not only as a set of extraordinary technical accomplishments, but also as indicative of the institution and practice of architecture and the developed crafts and trades associated with engineering. The Egyptian pyramids provide the classic example of monumental building by an early civilization. The case is well documented, and it encapsulates the themes raised thus far regarding agriculture, civilization, and the Urban Revolution.

Consider first the sheer immensity of the Great Pyramid at Giza. Built on the west bank of the Nile during the zenith of the pyramid-building era between 2789 and 2767 BCE (or possibly 2589–2566 BCE) by Khufu (Cheops), the first pharaoh of the Fourth Dynasty, the Great Pyramid is the largest solid-stone structure ever built: it consists of an unbelievable 94 million cubic feet of masonry, made up of 2.3 million blocks averaging 2.5 tons apiece, with a total weight of 6 million tons; it covers 13.5 acres, in 210 courses of stone, and stands 485 feet high and

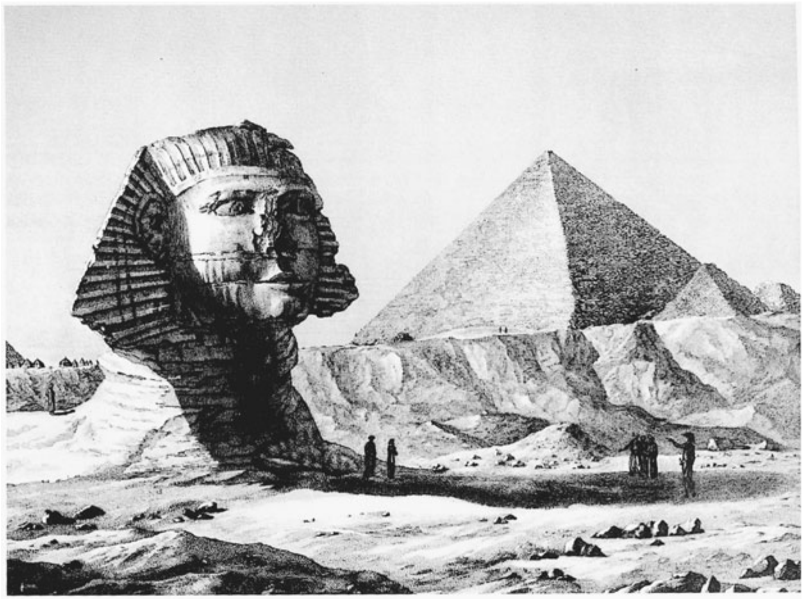


Fig. 3.2. The Great Pyramid at Giza. An engineering marvel of the third millennium BCE, the Great Pyramid of Cheops (Khufu) at Giza culminated the tradition of pyramid building in Egyptian civilization. Some modern interpreters see it as a monumental exercise in political "state building." The Cheops pyramid is on the right.

763 feet on a side; chambers, buttresses, and passageways lie within. Sheathed with polished stone, the scale of the construction—not to mention the beauty of the finished structure—has not been surpassed in the nearly five millennia of human history since the Great Pyramid was built.

The architects and engineers who built the Great Pyramid and the others like it commanded some elementary and some not-so-elementary practical mathematics. Design and material requirements demanded such expertise, as did the very exact north-south and east-west alignment. Ancient Egyptian engineers and architects understood the mathematics and appreciated the elegance of perfect pyramids, but the Egyptian pyramids (and monumental building generally) need to be seen primarily as stupendous engineering achievements.

According to a report by the fifth-century BCE Greek historian Herodotus, 100,000 people toiled for twenty years to build the Great Pyramid; perhaps 4,000–5,000 craftsmen worked at the site year round. The techniques of pyramid construction are now well understood, and excepting the possible use of a cantilevered machine to lift stones, no categorically new building methods developed compared to what one finds in Neolithic building techniques. Simple tools and practical procedures carried the day but, characteristic of the new powers of civilization, more people, by orders of magnitude, were deployed and construction completed that much faster than at Neolithic sites.

Such an extraordinary monument did not suddenly appear in the Egyptian desert. Rather, the Great Pyramid culminates a clear progression of pyramid building coincident with the growth and expansion of the Egyptian agrarian state.

Several fanciful theories have been put forward to explain why the

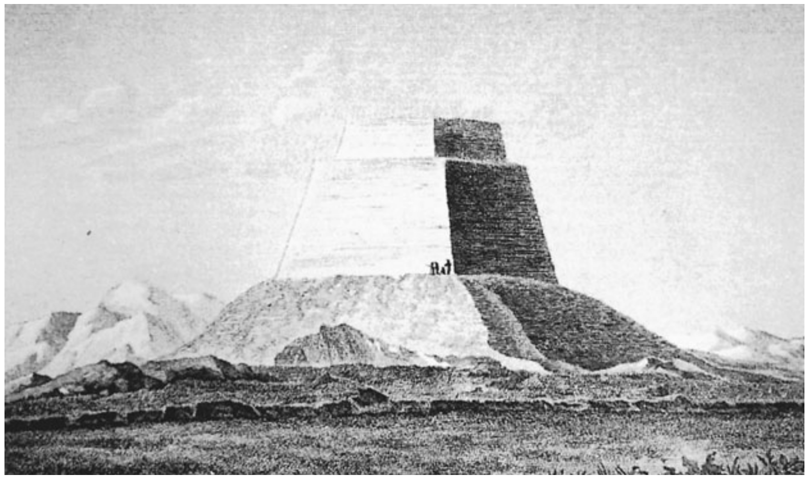


Fig. 3.3. The pyramid at Meidum. Built at a steep angle, the outer casing of the pyramid at Meidum collapsed around its central core during construction.

Great Pyramid and preceding and succeeding pyramids were built, but the function of these structures as tombs for pharaohs seems irrefutable, even if it may not have been their only purpose. A problem exists, however: at some periods at least, the number of new pyramids exceeded the number of pharaohs; and several pyramids were built simultaneously by a single pharaoh. Moreover, most of the truly monumental pyramids came into being in just over a century in the late Third and early Fourth Dynasties. According to one account, in four generations over 112 years between 2834 and 2722 BCE, six pharaohs built thirteen pyramids. Clearly, something more than burying the dead is needed to explain the extraordinary sociocultural phenomenon of the Egyptian pyramids.

One explanation of pyramid building from an engineering point of view attempts to explain the more or less continuous construction that took place on the west bank of the Nile during the heyday of pyramid building. In this interpretation, pyramid building was an activity pursued in its own right as an exercise in statecraft. The sequence of the early pyramids comprised giant public-works projects designed to mobilize the population during the agricultural off-season and to reinforce the idea and reality of the state in ancient Egypt. More than one pyramid arose simultaneously because a labor pool—and surely an increasingly large labor pool—was available and because the geometry of pyramids dictates that fewer laborers are required near the top of a pyramid than at the bottom, thus permitting the transfer of labor to newly started projects. Monumental building was therefore a kind of institutional muscle-flexing by the early Egyptian state, somewhat akin to the arms industry today.

The engineering key to this argument comes from two particular pyramids. The first, the pyramid at Meidum, begun by the pharaoh Huni (Uni), who reigned for 24 years between 2837 and 2814 BCE, and continued by his son Sneferu, stood 80 feet high and ran 130 feet on its side. It was to have been the first true pyramid with sheer, sloping sides and no visible steps. However, the pyramid at Meidum turned out to be an engineering disaster and a monumental structural failure, as the outer stone casing collapsed in rubble around the inner core of the pyramid. Designed with the evidently excessive slope of 54 degrees, the collapsed ruin may still be seen by the traveler.

The second pyramid at issue is the succeeding "Bent" pyramid at Dashur, also built by King Sneferu. It is a huge pyramid 335 feet high, 620 feet on a side, with a volume of 50 million cubic feet. Extraordinarily, the Bent pyramid is truly bent, angled, like Meidum, at 54 degrees on the lower half and 43 degrees on the top. One supposes that when the pyramid at Meidum failed, engineers reduced the slope of the Bent pyramid, still under construction, as a precaution. The next pyramid built by Sneferu, the Red pyramid, retained the safer slope of 43 degrees. (The Great Pyramid and later pyramids returned to increased elevations over 50 degrees, but used improved internal buttressing techniques.)

One does not have to follow every detail in order to accept the general point. The Egyptian pyramids were large state-run construction projects. A surplus of idle agricultural workers available seasonally for three months a year during the Nile floods provided the labor pool. (Agricultural productivity was thus not affected by the demand for labor for pyramid building.) Contrary to a once-common belief, forced slave labor did not build the pyramids, but labor was conscripted (like military conscription today) and organized in work gangs. Workers received food supplied by state granaries, and the completed pyramids served as tombs for departed pharaohs. Inevitably, elaborate theologies, priestly ceremonies, and ancillary technologies (such as mummifying) grew up around burying pharaohs. But in their construction the pyramids functioned primarily as gigantic public-works projects, the effect of which helped maintain the economy of irrigation agriculture

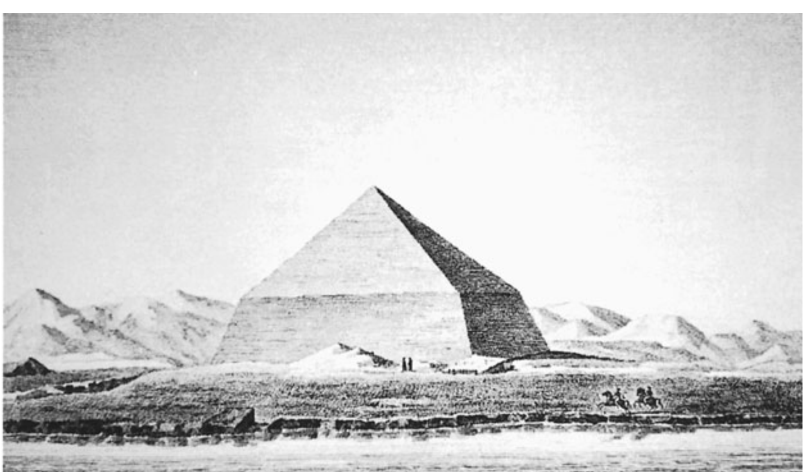


Fig. 3.4. The Bent pyramid. The lower portion of this pyramid rises at the same angle as the pyramid at Meidum, but ancient Egyptian engineers reduced the slope for the upper portion to ensure its stability. The Bent and Meidum pyramids were apparently constructed concurrently with engineers decreasing the angle of the Bent pyramid once they learned of the failure at Meidum.

in the Nile River Valley and bolstered centralizing political and social forces, notably the state. Indeed, the heyday of pyramid building was the heyday of political centralization in Old Kingdom Egypt. The pyramids were symbolic as well as literal exercises in state building.

Writing

One earmark of the earliest civilizations, already alluded to, was the elaboration and institutionalization of higher learning—writing, record-keeping, literature, and science. The fact that aspects of arithmetic, geometry, and astronomy originated in all of the earliest civilizations merits close attention, and it specifically suggests that such societies imposed a distinctive mark on the scientific traditions they fostered.

Knowledge in the first civilizations was subordinated to utilitarian ends and provided useful services in record-keeping, political administration, economic transactions, calendrical exactitude, architectural and engineering projects, agricultural management, medicine and healing, religion, and astrological prediction. Since higher learning was heavily skewed toward useful knowledge and its applications, in this sociological sense practically oriented science, in fact, preceded pure science or abstract theoretical research later fostered by the Greeks.

State and temple authorities patronized the acquisition and application of knowledge by cadres of learned scribes. The early states all created and maintained bureaucracies and a bureaucratic civil service which, in some measure, dealt with knowledge of mathematics and the natural world. A number of bureaucratic institutions prevailed in Mesopotamian city-states which employed learned civil servants, court astrologers, and specialized calendar keepers. Similarly in ancient Egypt, expert knowledge was institutionalized in the "House of Life," a scriptorium and center of learning that primarily maintained ritual knowledge and customs, but that harbored magical, medical, astronomical, mathematical, and possibly other lore and expertise. Archival halls and temple libraries also existed, and the record speaks of Egyptian savants, hierarchies of court doctors, magicians, and learned priests.

Again and again, higher learning with practical applications was supported by state and temple authorities and deployed to maintain the state and its agricultural economy. Knowledge became the concern of cadres of professional experts employed in state institutions whose efforts were bent to the service of sustaining society rather than to any individualistic craving for discovery. An additional characteristic of this bureaucratic pattern of science is the fact that scribal experts were anonymous; not a single biography of the individuals who over hundreds of years contributed to science in the first civilizations has come down to us.

Another odd characteristic of the first scientific traditions seems to be a penchant to record knowledge in the form of lists rather than in any analytical system of theorems or generalizations. Science in the first civilizations was characteristically pursued with a notable lack of abstraction or generality and without any of the naturalistic theory or the goal of knowledge as an end in its own right that the Greeks later emphasized.

Writing and reckoning were first and foremost practical technologies with practical origins meeting the practical needs of early civilizations. Centralized authority and bureaucracies responsible for redistributing large surpluses required the recording of verbal and quantitative information. All early civilizations developed arithmetical systems and systems of permanent record-keeping. The archaeological discovery of what amount to ancient Mesopotamian invoices—insignia sealed in clay—underscores the economic and utilitarian roots of writing and reckoning. Eighty-five percent of cuneiform tablets uncovered at Uruk (3000 BCE), for example, represent economic records, and Egyptian temple and palace records are similar. Ultimately writing came to supplant oral traditions and the skills and techniques of human memory. While the vast majority of early written records concern economic, legal, commercial, votive/religious, and administrative affairs, a significant literary component also came into being.

The scribal art was highly valued everywhere, and its practitioners enjoyed high social status. Educated scribes made up a privileged caste patronized by palace or temple, and literacy offered a pathway to power. It led to employment in huge and varied bureaucracies and often to high status in government. The large bureaucracies of the hydraulic civilizations, many of which left continuous records over thousands of years, provided civil service careers for junior and senior administrators, as well as specialized posts in specialized institutions as accountants, astrologer/astronomers, mathematicians, doctors, engineers, and teachers. No wonder that novice scribes were the sons (and occasionally the daughters) of the elite.

Civilization brought with it the first schools, institutions where writing was formally taught. In Mesopotamia scribal schools known as the é-dubba or "tablet house" taught writing, mathematics, and later a literature of myths and sayings. Many Mesopotamian tablets record the countless writing and calculating exercises performed by generations of students in schools that operated in the same location teaching the same curriculum for a thousand years and longer. In Egypt, writing was institutionalized in scribal schools and other institutions that contained scriptoria and libraries, and student exercises form a large part of the written records that have survived.

Although writing and record-keeping are characteristic features of all civilizations, writing systems have varied considerably. The earliest, the cuneiform system of writing on clay tablets, arose with Sumerian civilization in ancient Mesopotamia. Over the millennia of Mesopotamian civilization innumerable cuneiform clay tablets were dried or

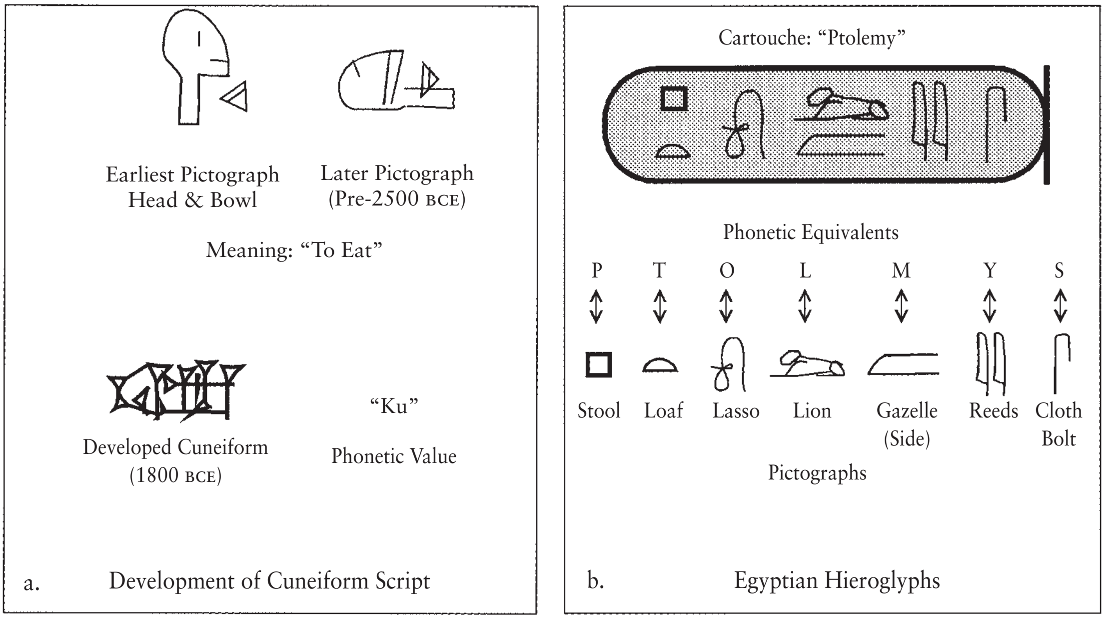


Fig. 3.5a–b. Babylonian and Egyptian writing systems. Different civilizations developed different techniques for recording information in writing. Most began with representations called pictographs. Many later used signs to represent the sounds of a spoken language.

baked, stored, and catalogued in great libraries and archives, with tens of thousands ultimately preserved. Cuneiform—or wedge writing—is so called because Sumerian scribes used a wedge-shaped reed stylus to inscribe clay tablets. Sumerian scribes in the third millennium BCE self-consciously developed a sophisticated system of 600–1,000 signs (called ideograms) represent the idea of a word or an action, as in "I ♥ my dog." Later, the number of Sumerian characters was reduced, but the scribal art remained very difficult to master and literacy remained restricted to a scribal profession. Cuneiform signs assumed sound (or phonographic) values at an early period and were written as syllables voicing the Sumerian language. Indeed, Old Babylonian (Akkadian), a different language from the original Sumerian, came to be written using Sumerian phonetic values. In other words, pictographs originally pictured things, whereas the signs later came to represent sounds of spoken languages. Sumerian continued to be taught in the é-dubba as a dead language after the eighteenth century BCE, similar to the way Latin was taught in European universities until the nineteenth and twentieth centuries. Sumerian and Babylonian languages had written grammars, and many tablets record word lists, bilingual lexicons, and bilingual texts.

Pictographic writing is known in Egypt from predynastic times, and the hieroglyphs ("sacred carvings") of ancient Egypt were used by the first dynasty, around 3000 BCE. The idea of writing may have passed from Mesopotamia, but specific Egyptian writing developed independently. Hieroglyphs are ideographic, but from an early period Egyptian writing incorporated phonographic elements voicing the Egyptian language. Six thousand formal Egyptian hieroglyphs have been identified, but pharaonic engravers and scribes commonly used only 700–800 across the millennia. Formal hieroglyphs were obviously not easy to write, so scribes developed simpler scripts (called hieratic and demotic) for the day-to-day maintenance of Egyptian civilization. (Among the technologies that made this possible was papyrus paper.) The last hieroglyphic inscription dates from 394 CE, after which knowledge of ancient Egyptian writing was lost. Only the acclaimed Rosetta stone—an inscription dated to 196 BCE with its text written in hieroglyphics, demotic, and Greek—discovered by Napoleon's soldiers in 1799 and deciphered by J.-F. Champollion in 1824—allows us to read again the records of the ancient Egyptian scribes. It should also be noted that purely phonetic alphabets where the sign stands only for a vowel or consonant sound—such as the Greek or Roman alphabets—are a late historical development of secondary civilizations, first appearing after 1100 BCE with the Phoenicians.

Reckoning

Mathematical methods developed along with writing and out of the same practical needs. The ancient Greek historian Herodotus made the point when he placed the origins of geometry (or "earth measure") in Egypt and the need to resurvey fields after the Nile floods. Along these lines, with the agricultural surpluses generated by irrigation agriculture came the first money (in ancient Babylonia and in Shang dynasty China) and the first standardized weights and measures (in ancient Egypt, the Indus River Valley, and in early China). Although pure mathematics later became an abstract game played by mathematicians, the practical, economic, and craft roots of early mathematics remain visible in these applications.

Each of the early civilizations developed its own system of mathematics. The ancient Sumerians and Babylonians evolved a sexigesimal or base-60 system (in contrast with our own decimal or base-10 system). Although not entirely consistent and initially lacking a zero, it was the first place-value system, where the "digits" represented powers of 60. Sexigesimal remnants can be found today in the 60-minute hour, the 60-second minute, and the 360 degrees of the circle. In contrast, Egyptian numbers resembled later Roman numerals with separate signs for the decimal numbers and no place value. Such a number system was more cumbersome and less efficient in handling the calculating requirements of Egyptian civilization.

As for mathematical operations, Babylonian mathematicians, using tables of numbers—multiples, reciprocals, squares, cubes, Pythagorean triplets, and the like—could perform many complex calculations, including recipe-like procedures that calculated compound interest and solved quadratic and cubic equations. In ancient Egypt, the "method of duplication," that is, the process of multiplication by doubling and

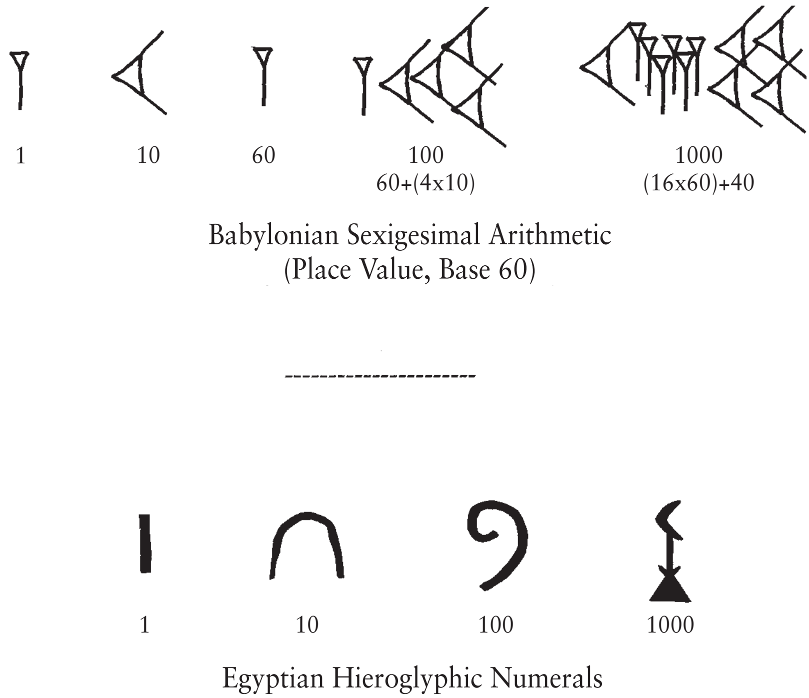


Fig. 3.6. Babylonian and Egyptian number systems. Different civilizations developed different numeral systems and reckoning methods. The Babylonian system was a base-60, place-value system with number signs for the values 1 and 10. Egyptian hieroglyphic numerals represented values of 10 in a manner reminiscent of later Roman numerals. No civilization was without a system to record numerical information.

redoubling numbers, was especially handy with a Roman-style number system. Egyptian mathematicians arrived at a superior estimate of the value of π (256/81 or 3.16 compared to the rough value of 3 of Babylonian mathematics and the Bible), and they developed tables that facilitated working with fractions.

In every early civilization the problems tackled by mathematicians reflect the practical and utilitarian direction of their interests. Engineering and supply problems predominated, generally solved by mathematical recipes involving little or no abstract understanding of numbers. The solution was usually arrived at recipe-style ("add 2 cups of sugar, 1 cup of milk," etc.), much like a computer program would handle the underlying equation ("square a, multiply $a \times b$, add a^2 and ab"). Although we do not know how the recipes were concocted, they were computationally sound and gave correct answers.

The Greeks had yet to invent abstract mathematics, but in a few restricted instances some very esoteric nonutilitarian "playfulness" becomes apparent in the achievements of the early scribes. In Babylonia, for example, mathematicians calculated the square root of 2 to the equivalent of six decimal places, beyond any conceivable need in engineering or reckoning. Similarly in China expert mathematicians computed π to the very high and, practically speaking, useless accuracy of seven decimal places. However, as interesting as they are, even these steps toward abstract mathematics developed in the context of broad programs of study directed at practical ends. In ancient Mesopotamia tables of exponential functions that would appear to be as abstract as an excessively accurate approximation of the square root of 2 were, in fact, used to calculate compound interest, and "quadratic equations" were solved in connection with other problems. Linear equations were solved to determine shares of inheritance and the division of fields. Lists of coefficients for building materials may have been used for the quick calculation of carrying loads. Coefficients for precious metals and for economic goods presumably had equally practical applications. And calculation of volumes reflected no idle interest in geometry but was applied in the construction of canals and other components of the infrastructure.

Time, the Gods, and the Heavens

All agricultural civilizations developed calendrical systems based on astronomical observations, and in several of the first civilizations we can identify what can only be called sophisticated astronomical research. The utility and necessity of accurate calendars in agrarian societies seems self-evident, not only for agricultural purposes, but also for regulating ritual activities. The commercial and economic role of the calendar in, for example, dating contracts and future transactions likewise seems clear.

In Mesopotamia a highly accurate calendar was in place by 1000 BCE, and by 300 BCE Mesopotamian calendrical experts had created a mathematically abstract calendar valid for centuries ahead. Since they had adopted lunar calendars of 12 lunar months or 354 days, which is obviously out of sync with the solar year of 365¼ days, an extra lunar month occasionally had to be inserted (or intercalated) to keep lunar months and (seasonal) solar years in harmony; Babylonian astronomers inserted seven intercalary months over periods of 19 years. Ancient Egyptian priest/astronomers maintained two different lunar calendars, but a third solar/civil calendar governed official Egyptian life. That calendar consisted of 12 months of 30 days and five festival days. Each year the 365-day civil calendar thus deviated from the solar year by one-quarter day; and so over the long course of Egyptian history the civil year drifted backward and every 1,460 years (4 times 365) completely circled the solar/agricultural year. The civil and solar calendars thus coincided in 2770 BCE and again in 1310 BCE. This unwieldy calendrical confusion is resolved when one remembers that the central event in Egypt—the annual, highly regular Nile flood could be predicted independently from the seasonal first appearance of the star Sirius above the horizon.

Calendars, astronomy, astrology, meteorology, and magic formed part of a general pattern, repeated in Mesopotamia, Egypt, India, China, and the Americas. Despite our modern biases it is not possible or justifiable to separate astronomy from astrology or astronomers from astrologers and magicians in these early civilizations, for the enterprises formed an inseparable unity. In predicting the fate of crops, the outcome of military action, or the future affairs of the king, astrology and occult learning were universally seen as useful knowledge. Indeed, along with calendrical astronomy (which, after all, predicted the seasons), they exemplify the pattern of knowledge of nature turned to practical ends.

Of all the ancient scientific traditions, Babylonian astronomy was the best developed, and it merits detailed attention. In ancient Babylonia a shift in divination from reading the entrails of animals to an astral religion may have encouraged the study of the heavens. Astronomical observations were recorded as early as 2000 BCE, and continuous observations date from 747 BCE. By the fifth century BCE Babylonian astronomers could track the principal heavenly bodies indefinitely into the future. Mesopotamian astronomers fully mastered solstices, equinoxes, and the cycles of the sun and moon. In particular, later Babylonian astronomy understood and could predict solar and lunar eclipses and eclipse magnitudes. Astronomers computed and extrapolated the risings, settings, and visibility of planets, especially Venus as a morning and evening star. The legacy of Babylonian astronomy and the sexigesimal system was great, not only for our measure of the circle in degrees, but also for the seven-day week and the identification of the planets. Indeed, many technical procedures of Babylonian astronomy were handed down and adopted by later Greek and Hellenistic astronomers. What needs emphasis here is the *research* conducted by Babylonian astronomers. Obviously, they observed the heavens, no doubt with sighting instruments, and kept accurate records. We now know that they did much more than observe and keep records; they also conducted systematic research to solve very specific scientific problems in astronomy.

It is instructive to examine the "new moon problem" as a case in point. For calendrical and religious reasons Babylonian astronomers needed to know the length of the lunar month in days. The interval between full moons or new moons varies between 29 and 30 days (the average is 29.53 days). Which was it going to be in any given month? Several independent variables affect the outcome: the relative distance between the sun and moon in the heavens as seen from the earth (AB on the figure), the season of the year (α), and longer-term lunar cycles (CD). With these independent variables at play the reappearance of the new moon obviously becomes difficult to predict. Babylonian astronomers conducted research and mastered the "new moon problem" to the point of being able to create exact astronomical tables that reliably predicted when a new moon would be visible. The "new moon problem" indicates active scientific research by ancient Babylonian astronomers on a very specific problem (29 or 30 days?). This research was based on observation, mathematical analysis, and modeling of the phe-

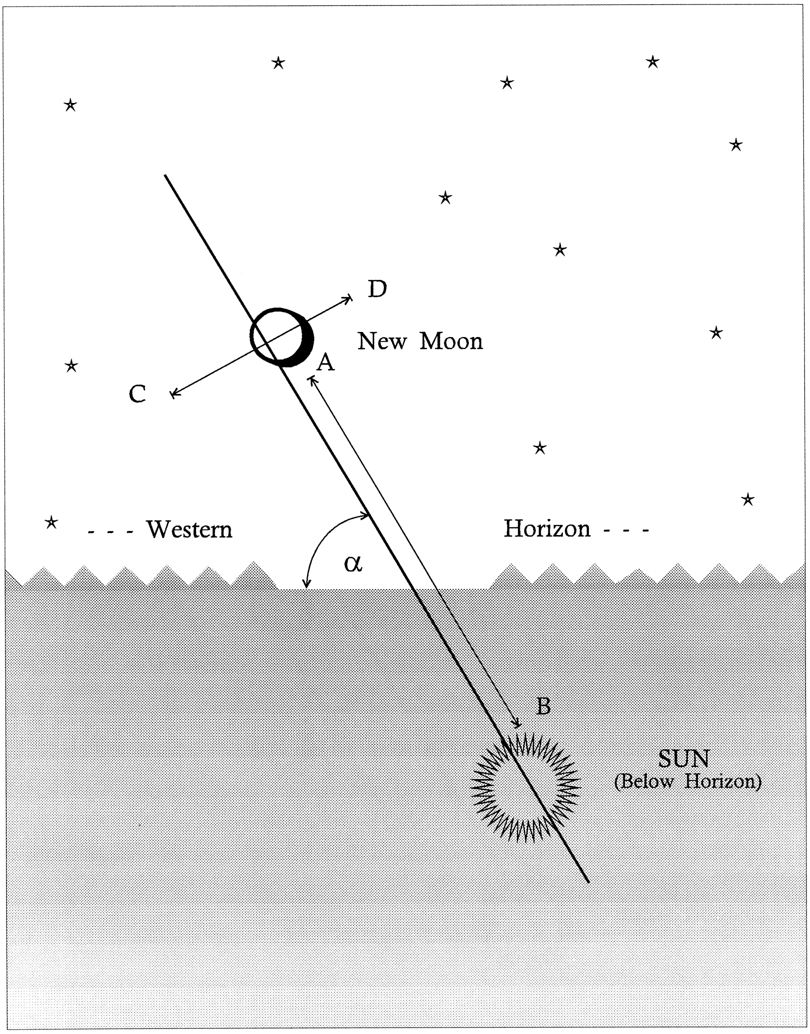


Fig. 3.7. The earliest scientific research. Ancient Babylonian astronomers systematically investigated variables determining the first appearance of the new moon each lunar month. More than simply observing the phenomena, Babylonian astronomers investigated patterns in the variations of these factors, reflecting a maturing science of astronomy.

nomena, and was theoretical insofar as more attention was paid to the abstract models of mathematical cycles than to what was visibly going on in the heavens.

Medicine and the social organization of medicine also formed a distinct feature of the bureaucratic model of state support for useful knowledge. Cadres of official medical practitioners appeared in every early state, and their practical and empirical knowledge of anatomy, surgery, and herbal medicines grew as a result of state support for medical learning. The Edwin Smith medical papyrus from the Egyptian New Kingdom (ca. 1200 BCE) is often cited for its "rational," nontheistic approaches to medical cases.

Similarly, alchemy and alchemical expertise began to be patronized at an early date in the first civilizations; the roots of alchemy doubtless lay in the practice of ancient metallurgy, a case, if ever there was one, of technology giving rise to science. Alchemy, like astrology, offered the promise of utility, and the theme of state support for alchemy winds its way through all cultures until the modern era. The distinction that we draw between the rational and the pseudoscientific was not recognized. All of these investigations seemed to be fields of useful knowledge.

A cautious word needs to be added about the cosmologies and worldviews of the earliest civilizations. It seems safe to assume that these were all societies in which religion played a prominent role. For the most part their heavens were divine, magical, and inhabited by gods; heavenly bodies were often associated with sacred deities, and the heavens embodied myths and stories of gods. Thus in Egypt, the goddess Nut held up the sky, and deceased pharaohs became stars. In Babylonia the movement of the planets represented the movement of celestial gods. In ancient Mesoamerica, according to the Maya, the earth was a giant reptile floating in a pond. The Chinese held more organic and less pantheistic views of the cosmos. But none of the first civilizations developed any theoretical models of the cosmos as a whole, certainly no abstract, mechanical, or naturalistic ones. Little is recognizable in these cultures as independent naturalistic inquiries into the natural world or as a conception of "nature" to be studied abstractly.

The first civilizations tended to treat knowledge extensively, by drawing up encyclopedic tables and lists of words, numbers, gods, plants, animals, stones, cities, rulers, occupations, or scribes, sometimes indiscriminately. This manner of coping with and recording knowledge—what has been called the "science of lists"—may have been favored generally in societies that had not yet invented formal logic and analytical thought. The laborious drudgery that went into them, intellectually unrewarding to the individuals who compiled the data, may have been possible only where the state patronized battalions of scribes as civil servants.

In sum, deriving from practical necessity, science repeatedly emerged part and parcel with civilization. Writing and arithmetic were new technologies applicable to the solution of many practical problems. Institutions and the institutionalized status of specialized experts underwritten by the state served the same utilitarian purposes. The evidence of advanced calendars, sophisticated astronomical puzzle-solving, and occasional mathematical "playfulness" make plain the high level of scientific accomplishment in the first civilizations. Lacking was the abstract dimension of theory that we recognize as a further hallmark of science. What has to be explained, therefore, is the origin of scientific theory and the pursuit of natural knowledge for its own sake, what came to be called natural philosophy—the philosophy of nature. If science in the form of mathematics and astronomy arose independently and many times over with the first civilizations, natural philosophy originated uniquely with the Greeks.