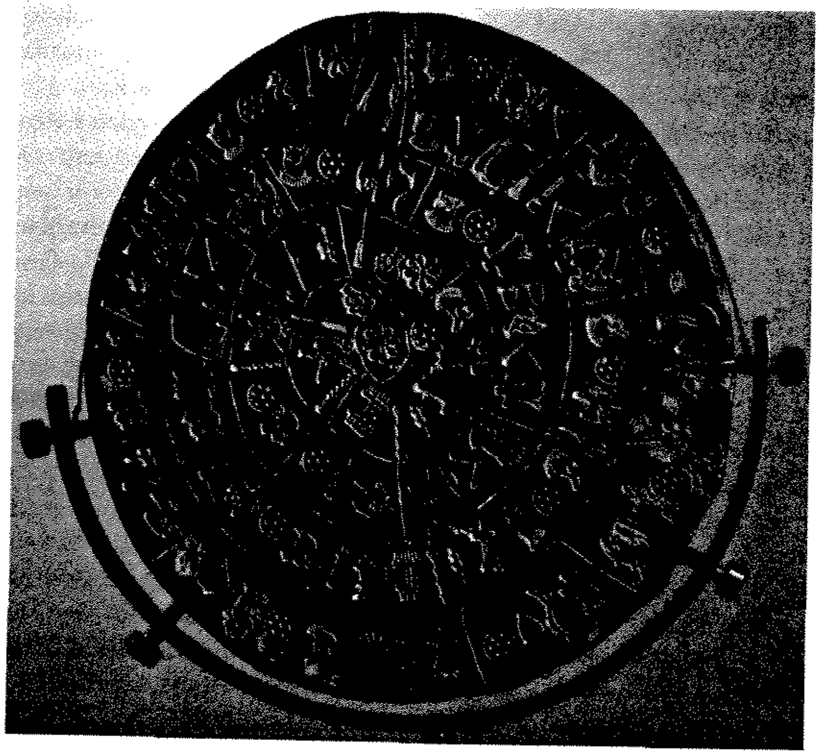
CHAPTER 13

NECESSITY'S MOTHER

ON JULY 3, 1908, ARCHAEOLOGISTS EXCAVATING THE ancient Minoan palace at Phaistos, on the island of Crete, chanced upon one of the most remarkable objects in the history of technology. At first glance it seemed unprepossessing: just a small, flat, unpainted, circular disk of hard-baked clay, 6½ inches in diameter. Closer examination showed each side to be covered with writing, resting on a curved line that spiraled clockwise in five coils from the disk's rim to its center. A total of 241 signs or letters was neatly divided by etched vertical lines into groups of several signs, possibly constituting words. The writer must have planned and executed the disk with care, so as to start writing at the rim and fill up all the available space along the spiraling line, yet not run out of space on reaching the center (page 240).

Ever since it was unearthed, the disk has posed a mystery for historians of writing. The number of distinct signs (45) suggests a syllabary rather than an alphabet, but it is still undeciphered, and the forms of the signs are unlike those of any other known writing system. Not another scrap of the strange script has turned up in the 89 years since its discovery. Thus, it remains unknown whether it represents an indigenous Cretan script or a foreign import to Crete.

For historians of technology, the Phaistos disk is even more baffling; its



One side of the two-sided Phaistos Disk.

estimated date of 1700 B.C. makes it by far the earliest printed document in the world. Instead of being etched by hand, as were all texts of Crete's later Linear A and Linear B scripts, the disk's signs were punched into soft clay (subsequently baked hard) by stamps that bore a sign as raised type. The printer evidently had a set of at least 45 stamps, one for each sign appearing on the disk. Making these stamps must have entailed a great deal of work, and they surely weren't manufactured just to print this single document. Whoever used them was presumably doing a lot of writing. With those stamps, their owner could make copies much more quickly and neatly than if he or she had written out each of the script's complicated signs at each appearance.

The Phaistos disk anticipates humanity's next efforts at printing, which similarly used cut type or blocks but applied them to paper with ink, not

to clay without ink. However, those next efforts did not appear until 2,500 years later in China and 3,100 years later in medieval Europe. Why was the disk's precocious technology not widely adopted in Crete or elsewhere in the ancient Mediterranean? Why was its printing method invented around 1700 B.C. in Crete and not at some other time in Mesopotamia, Mexico, or any other ancient center of writing? Why did it then take thousands of years to add the ideas of ink and a press and arrive at a printing press? The disk thus constitutes a threatening challenge to historians. If inventions are as idiosyncratic and unpredictable as the disk seems to suggest, then efforts to generalize about the history of technology may be doomed from the outset.

Technology, in the form of weapons and transport, provides the direct means by which certain peoples have expanded their realms and conquered other peoples. That makes it the leading cause of history's broadest pattern. But why were Eurasians, rather than Native Americans or sub-Saharan Africans, the ones to invent firearms, oceangoing ships, and steel equipment? The differences extend to most other significant technological advances, from printing presses to glass and steam engines. Why were all those inventions Eurasian? Why were all New Guineans and Native Australians in A.D. 1800 still using stone tools like ones discarded thousands of years ago in Eurasia and most of Africa, even though some of the world's richest copper and iron deposits are in New Guinea and Australia, respectively? All those facts explain why so many laypeople assume that Eurasians are superior to other peoples in inventiveness and intelligence.

If, on the other hand, no such difference in human neurobiology exists to account for continental differences in technological development, what does account for them? An alternative view rests on the heroic theory of invention. Technological advances seem to come disproportionately from a few very rare geniuses, such as Johannes Gutenberg, James Watt, Thomas Edison, and the Wright brothers. They were Europeans, or descendants of European emigrants to America. So were Archimedes and other rare geniuses of ancient times. Could such geniuses have equally well been born in Tasmania or Namibia? Does the history of technology depend on nothing more than accidents of the birthplaces of a few inventors?

Still another alternative view holds that it is a matter not of individual inventiveness but of the receptivity of whole societies to innovation. Some societies seem hopelessly conservative, inward looking, and hostile to change. That's the impression of many Westerners who have attempted to help Third World peoples and ended up discouraged. The people seem perfectly intelligent as individuals; the problem seems instead to lie with their societies. How else can one explain why the Aborigines of northeastern Australia failed to adopt bows and arrows, which they saw being used by Torres Straits islanders with whom they traded? Might all the societies of an entire continent be unreceptive, thereby explaining technology's slow pace of development there? In this chapter we shall finally come to grips with a central problem of this book: the question of why technology did evolve at such different rates on different continents.

THE STARTING POINT for our discussion is the common view expressed in the saying "Necessity is the mother of invention." That is, inventions supposedly arise when a society has an unfulfilled need: some technology is widely recognized to be unsatisfactory or limiting. Would-be inventors, motivated by the prospect of money or fame, perceive the need and try to meet it. Some inventor finally comes up with a solution superior to the existing, unsatisfactory technology. Society adopts the solution if it is compatible with the society's values and other technologies.

Quite a few inventions do conform to this commonsense view of necessity as invention's mother. In 1942, in the middle of World War II, the U.S. government set up the Manhattan Project with the explicit goal of inventing the technology required to build an atomic bomb before Nazi Germany could do so. That project succeeded in three years, at a cost of $2 billion (equivalent to over $20 billion today). Other instances are Eli Whitney's 1794 invention of his cotton gin to replace laborious hand cleaning of cotton grown in the U.S. South, and James Watt's 1769 invention of his steam engine to solve the problem of pumping water out of British coal mines.

These familiar examples deceive us into assuming that other major inventions were also responses to perceived needs. In fact, many or most inventions were developed by people driven by curiosity or by a love of tinkering, in the absence of any initial demand for the product they had in mind. Once a device had been invented, the inventor then had to find an application for it. Only after it had been in use for a considerable time did consumers come to feel that they "needed" it. Still other devices, invented to serve one purpose, eventually found most of their use for other, unanticipated purposes. It may come as a surprise to learn that these inventions in search of a use include most of the major technological breakthroughs of modern times, ranging from the airplane and automobile, through the internal combustion engine and electric light bulb, to the phonograph and transistor. Thus, invention is often the mother of necessity, rather than vice versa.

A good example is the history of Thomas Edison's phonograph, the most original invention of the greatest inventor of modern times. When Edison built his first phonograph in 1877, he published an article proposing ten uses to which his invention might be put. They included preserving the last words of dying people, recording books for blind people to hear, announcing clock time, and teaching spelling. Reproduction of music was not high on Edison's list of priorities. A few years later Edison told his assistant that his invention had no commercial value. Within another few years he changed his mind and did enter business to sell phonographs—but for use as office dictating machines. When other entrepreneurs created jukeboxes by arranging for a phonograph to play popular music at the drop of a coin, Edison objected to this debasement, which apparently detracted from serious office use of his invention. Only after about 20 years did Edison reluctantly concede that the main use of his phonograph was to record and play music.

The motor vehicle is another invention whose uses seem obvious today. However, it was not invented in response to any demand. When Nikolaus Otto built his first gas engine, in 1866, horses had been supplying people's land transportation needs for nearly 6,000 years, supplemented increasingly by steam-powered railroads for several decades. There was no crisis in the availability of horses, no dissatisfaction with railroads.

Because Otto's engine was weak, heavy, and seven feet tall, it did not recommend itself over horses. Not until 1885 did engines improve to the point that Gottfried Daimler got around to installing one on a bicycle to create the first motorcycle; he waited until 1896 to build the first truck.

In 1905, motor vehicles were still expensive, unreliable toys for the rich. Public contentment with horses and railroads remained high until World War I, when the military concluded that it really did need trucks. Intensive postwar lobbying by truck manufacturers and armies finally convinced the public of its own needs and enabled trucks to begin to supplant horse-drawn wagons in industrialized countries. Even in the largest American cities, the changeover took 50 years.

Inventors often have to persist at their tinkering for a long time in the absence of public demand, because early models perform too poorly to be useful. The first cameras, typewriters, and television sets were as awful as Otto's seven-foot-tall gas engine. That makes it difficult for an inventor to foresee whether his or her awful prototype might eventually find a use and thus warrant more time and expense to develop it. Each year, the United States issues about 70,000 patents, only a few of which ultimately reach the stage of commercial production. For each great invention that ultimately found a use, there are countless others that did not. Even inventions that meet the need for which they were initially designed may later prove more valuable at meeting unforeseen needs. While James Watt designed his steam engine to pump water from mines, it soon was supplying power to cotton mills, then (with much greater profit) propelling locomotives and boats.

THUS, THE COMMONSENSE view of invention that served as our starting point reverses the usual roles of invention and need. It also overstates the importance of rare geniuses, such as Watt and Edison. That "heroic theory of invention," as it is termed, is encouraged by patent law, because an applicant for a patent must prove the novelty of the invention submitted. Inventors thereby have a financial incentive to denigrate or ignore previous work. From a patent lawyer's perspective, the ideal invention is one that arises without any precursors, like Athene springing fully formed from the forehead of Zeus.

In reality, even for the most famous and apparently decisive modern inventions, neglected precursors lurked behind the bald claim "X invented Y." For instance, we are regularly told, "James Watt invented the steam engine in 1769," supposedly inspired by watching steam rise from a teakettle's spout. Unfortunately for this splendid fiction, Watt actually got the idea for his particular steam engine while repairing a model of Thomas Newcomen's steam engine, which Newcomen had invented 57 years earlier and of which over a hundred had been manufactured in England by the time of Watt's repair work. Newcomen's engine, in turn, followed the steam engine that the Englishman Thomas Savery patented in 1698, which followed the steam engine that the Frenchman Denis Papin designed (but did not build) around 1680, which in turn had precursors in the ideas of

the Dutch scientist Christiaan Huygens and others. All this is not to deny that Watt greatly improved Newcomen's engine (by incorporating a separate steam condenser and a double-acting cylinder), just as Newcomen had greatly improved Savery's.

Similar histories can be related for all modern inventions that are adequately documented. The hero customarily credited with the invention followed previous inventors who had had similar aims and had already produced designs, working models, or (as in the case of the Newcomen steam engine) commercially successful models. Edison's famous "invention" of the incandescent light bulb on the night of October 21, 1879, improved on many other incandescent light bulbs patented by other inventors between 1841 and 1878. Similarly, the Wright brothers' manned powered airplane was preceded by the manned unpowered gliders of Otto Lilienthal and the unmanned powered airplane of Samuel Langley; Samuel Morse's telegraph was preceded by those of Joseph Henry, William Cooke, and Charles Wheatstone; and Eli Whitney's gin for cleaning short-staple (inland) cotton extended gins that had been cleaning long-staple (Sea Island) cotton for thousands of years.

All this is not to deny that Watt, Edison, the Wright brothers, Morse, and Whitney made big improvements and thereby increased or inaugurated commercial success. The form of the invention eventually adopted might have been somewhat different without the recognized inventor's contribution. But the question for our purposes is whether the broad pattern of world history would have been altered significantly if some genius inventor had not been born at a particular place and time. The answer is clear: there has never been any such person. All recognized famous inventors had capable predecessors and successors and made their improvements at a time when society was capable of using their product. As we shall see, the tragedy of the hero who perfected the stamps used for the Phaistos disk was that he or she devised something that the society of the time could not exploit on a large scale.

MY EXAMPLES SO far have been drawn from modern technologies, because their histories are well known. My two main conclusions are that technology develops cumulatively, rather than in isolated heroic acts, and that it finds most of its uses after it has been invented, rather than being invented to meet a foreseen need. These conclusions surely apply with much greater force to the undocumented history of ancient technology. When Ice Age hunter-gatherers noticed burned sand and limestone residues in their hearths, it was impossible for them to foresee the long, serendipitous accumulation of discoveries that would lead to the first Roman glass windows (around A.D. 1), by way of the first objects with surface glazes (around 4000 B.C.), the first free-standing glass objects of Egypt and Mesopotamia (around 2500 B.C.), and the first glass vessels (around 1500 B.C.).

We know nothing about how those earliest known surface glazes themselves were developed. Nevertheless, we can infer the methods of prehistoric invention by watching technologically "primitive" people today, such as the New Guineans with whom I work. I already mentioned their knowledge of hundreds of local plant and animal species and each species' edibility, medical value, and other uses. New Guineans told me similarly about dozens of rock types in their environment and each type's hardness, color, behavior when struck or flaked, and uses. All of that knowledge is acquired by observation and by trial and error. I see that process of "invention" going on whenever I take New Guineans to work with me in an area away from their homes. They constantly pick up unfamiliar things in the forest, tinker with them, and occasionally find them useful enough to bring home. I see the same process when I am abandoning a campsite, and local people come to scavenge what is left. They play with my discarded objects and try to figure out whether they might be useful in New Guinea society. Discarded tin cans are easy: they end up reused as containers. Other objects are tested for purposes very different from the one for which they were manufactured. How would that yellow number 2 pencil look as an ornament, inserted through a pierced ear-lobe or nasal septum? Is that piece of broken glass sufficiently sharp and strong to be useful as a knife? Eureka!

The raw substances available to ancient peoples were natural materials such as stone, wood, bone, skins, fiber, clay, sand, limestone, and minerals, all existing in great variety. From those materials, people gradually learned to work particular types of stone, wood, and bone into tools; to convert particular clays into pottery and bricks; to convert certain mixtures of sand, limestone, and other "dirt" into glass; and to work available pure soft metals such as copper and gold, then to extract metals from ores, and finally to work hard metals such as bronze and iron.

A good illustration of the histories of trial and error involved is furnished by the development of gunpowder and gasoline from raw materials. Combustible natural products inevitably make themselves noticed, as when a resinous log explodes in a campfire. By 2000 B.C., Mesopotamians were extracting tons of petroleum by heating rock asphalt. Ancient Greeks discovered the uses of various mixtures of petroleum, pitch, resins, sulfur, and quicklime as incendiary weapons, delivered by catapults, arrows, firebombs, and ships. The expertise at distillation that medieval Islamic alchemists developed to produce alcohols and perfumes also let them distill petroleum into fractions, some of which proved to be even more powerful incendiaries. Delivered in grenades, rockets, and torpedoes, those incendiaries played a key role in Islam's eventual defeat of the Crusaders. By then, the Chinese had observed that a particular mixture of sulfur, charcoal, and saltpeter, which became known as gunpowder, was especially explosive. An Islamic chemical treatise of about A.D. 1100 describes seven gunpowder recipes, while a treatise from A.D. 1280 gives more than 70 recipes that had proved suitable for diverse purposes (one for rockets, another for cannons).

As for postmedieval petroleum distillation, 19th-century chemists found the middle distillate fraction useful as fuel for oil lamps. The chemists discarded the most volatile fraction (gasoline) as an unfortunate waste product—until it was found to be an ideal fuel for internal-combustion engines. Who today remembers that gasoline, the fuel of modern civilization, originated as yet another invention in search of a use?

ONCE AN INVENTOR has discovered a use for a new technology, the next step is to persuade society to adopt it. Merely having a bigger, faster, more powerful device for doing something is no guarantee of ready acceptance. Innumerable such technologies were either not adopted at all or adopted only after prolonged resistance. Notorious examples include the U.S. Congress's rejection of funds to develop a supersonic transport in 1971, the world's continued rejection of an efficiently designed typewriter keyboard, and Britain's long reluctance to adopt electric lighting. What is it that promotes an invention's acceptance by a society?

Let's begin by comparing the acceptability of different inventions within the same society. It turns out that at least four factors influence acceptance.

The first and most obvious factor is relative economic advantage compared with existing technology. While wheels are very useful in modern industrial societies, that has not been so in some other societies. Ancient Native Mexicans invented wheeled vehicles with axles for use as toys, but not for transport. That seems incredible to us, until we reflect that ancient Mexicans lacked domestic animals to hitch to their wheeled vehicles, which therefore offered no advantage over human porters.

A second consideration is social value and prestige, which can override economic benefit (or lack thereof). Millions of people today buy designer jeans for double the price of equally durable generic jeans—because the social cachet of the designer label counts for more than the extra cost. Similarly, Japan continues to use its horrendously cumbersome kanji writing system in preference to efficient alphabets or Japan's own efficient kana syllabary—because the prestige attached to kanji is so great.

Still another factor is compatibility with vested interests. This book, like probably every other typed document you have ever read, was typed with a QWERTY keyboard, named for the left-most six letters in its upper row. Unbelievable as it may now sound, that keyboard layout was designed in 1873 as a feat of anti-engineering. It employs a whole series of perverse tricks designed to force typists to type as slowly as possible, such as scattering the commonest letters over all keyboard rows and concentrating them on the left side (where right-handed people have to use their weaker hand). The reason behind all of those seemingly counterproductive features is that the typewriters of 1873 jammed if adjacent keys were struck in quick succession, so that manufacturers had to slow down typists. When improvements in typewriters eliminated the problem of jamming, trials in 1932 with an efficiently laid-out keyboard showed that it would let us double our typing speed and reduce our typing effort by 95 percent. But QWERTY keyboards were solidly entrenched by then. The vested interests of hundreds of millions of QWERTY typists, typing teachers, typewriter and computer salespeople, and manufacturers have crushed all moves toward keyboard efficiency for over 60-years.

While the story of the QWERTY keyboard may sound funny, many similar cases have involved much heavier economic consequences. Why does Japan now dominate the world market for transistorized electronic consumer products, to a degree that damages the United States's balance of payments with Japan, even though transistors were invented and patented in the United States? Because Sony bought transistor licensing rights from Western Electric at a time when the American electronics consumer industry was churning out vacuum tube models and reluctant to compete with its own products. Why were British cities still using gas street lighting into the 1920s, long after U.S. and German cities had converted to electric street lighting? Because British municipal governments had invested heavily in gas lighting and placed regulatory obstacles in the way of the competing electric light companies.

The remaining consideration affecting acceptance of new technologies is the ease with which their advantages can be observed. In A.D. 1340, when firearms had not yet reached most of Europe, England's earl of Derby and earl of Salisbury happened to be present in Spain at the battle of Tarifa, where Arabs used cannons against the Spaniards. Impressed by what they saw, the earls introduced cannons to the English army, which adopted them enthusiastically and already used them against French soldiers at the battle of Crécy six years later.

THUS, WHEELS, DESIGNER jeans, and QWERTY keyboards illustrate the varied reasons why the same society is not equally receptive to all inventions. Conversely, the same invention's reception also varies greatly among contemporary societies. We are all familiar with the supposed generalization that rural Third World societies are less receptive to innovation than are Westernized industrial societies. Even within the industrialized world, some areas are much more receptive than others. Such differences, if they existed on a continental scale, might explain why technology developed faster on some continents than on others. For instance, if all Aboriginal Australian societies were for some reason uniformly resistant to change, that might account for their continued use of stone tools after metal tools had appeared on every other continent. How do differences in receptivity among societies arise?

A laundry list of at least 14 explanatory factors has been proposed by historians of technology. One is long life expectancy, which in principle should give prospective inventors the years necessary to accumulate technical knowledge, as well as the patience and security to embark on long development programs yielding delayed rewards. Hence the greatly increased life expectancy brought by modern medicine may have contributed to the recently accelerating pace of invention.

The next five factors involve economics or the organization of society: (1) The availability of cheap slave labor in classical times supposedly discouraged innovation then, whereas high wages or labor scarcity now stimulate the search for technological solutions. For example, the prospect of changed immigration policies that would cut off the supply of cheap Mexican seasonal labor to Californian farms was the immediate incentive for the development of a machine-harvestable variety of tomatoes in California. (2) Patents and other property laws, protecting ownership rights of inventors, reward innovation in the modern West, while the lack of such protection discourages it in modern China. (3) Modern industrial societies provide extensive opportunities for technical training, as medieval Islam did and modern Zaire does not. (4) Modern capitalism is, and the ancient Roman economy was not, organized in a way that made it potentially rewarding to invest capital in technological development. (5) The strong individualism of U.S. society allows successful inventors to keep earnings for themselves, whereas strong family ties in New Guinea ensure that someone who begins to earn money will be joined by a dozen relatives expecting to move in and be fed and supported.

Another four suggested explanations are ideological, rather than economic or organizational: (1) Risk-taking behavior, essential for efforts at innovation, is more widespread in some societies than in others. (2) The scientific outlook is a unique feature of post-Renaissance European society that has contributed heavily to its modern technological preeminence. (3) Tolerance of diverse views and of heretics fosters innovation, whereas a strongly traditional outlook (as in China's emphasis on ancient Chinese classics) stifles it. (4) Religions vary greatly in their relation to technological innovation: some branches of Judaism and Christianity are claimed to be especially compatible with it, while some branches of Islam, Hinduism, and Brahmanism may be especially incompatible with it.

All ten of these hypotheses are plausible. But none of them has any necessary association with geography. If patent rights, capitalism, and certain religions do promote technology, what selected for those factors in postmedieval Europe but not in contemporary China or India?

At least the direction in which those ten factors influence technology seems clear. The remaining four proposed factors—war, centralized government, climate, and resource abundance—appear to act inconsistently: sometimes they stimulate technology, sometimes they inhibit it. (1) Throughout history, war has often been a leading stimulant of technological innovation. For instance, the enormous investments made in nuclear weapons during World War II and in airplanes and trucks during World War I launched whole new fields of technology. But wars can also deal devastating setbacks to technological development. (2) Strong centralized government boosted technology in late-19th-century Germany and Japan, and crushed it in China after A.D. 1500. (3) Many northern Europeans assume that technology thrives in a rigorous climate where survival is impossible without technology, and withers in a benign climate where clothing is unnecessary and bananas supposedly fall off the trees. An opposite view is that benign environments leave people free from the constant struggle for existence, free to devote themselves to innovation. (4) There has also been debate over whether technology is stimulated by abundance or by scarcity of environmental resources. Abundant resources might stimulate the development of inventions utilizing those resources, such as water mill technology in rainy northern Europe, with its many rivers—but why didn't water mill technology progress more rapidly in even rainier New Guinea? The destruction of Britain's forests has been suggested as the reason behind its early lead in developing coal technology, but why didn't deforestation have the same effect in China?

This discussion does not exhaust the list of reasons proposed to explain why societies differ in their receptivity to new technology. Worse yet, all of these proximate explanations bypass the question of the ultimate factors behind them. This may seem like a discouraging setback in our attempt to understand the course of history, since technology has undoubtedly been one of history's strongest forces. However, I shall now argue that the diversity of independent factors behind technological innovation actually makes it easier, not harder, to understand history's broad pattern.

FOR THE PURPOSES of this book, the key question about the laundry list is whether such factors differed systematically from continent to continent and thereby led to continental differences in technological development. Most laypeople and many historians assume, expressly or tacitly, that the answer is yes. For example, it is widely believed that Australian Aborigines as a group shared ideological characteristics contributing to their technological backwardness: they were (or are) supposedly conservative, living in an imagined past Dreamtime of the world's creation, and not focused on practical ways to improve the present. A leading historian of Africa characterized Africans as inward looking and lacking Europeans' drive for expansion.

But all such claims are based on pure speculation. There has never been a study of many societies under similar socioeconomic conditions on each of two continents, demonstrating systematic ideological differences between the two continents' peoples. The usual reasoning is instead circular: because technological differences exist, the existence of corresponding ideological differences is inferred.

In reality, I regularly observe in New Guinea that native societies there differ greatly from each other in their prevalent outlooks. Just like industrialized Europe and America, traditional New Guinea has conservative societies that resist new ways, living side by side with innovative societies that selectively adopt new ways. The result, with the arrival of Western technology, is that the more entrepreneurial societies are now exploiting Western technology to overwhelm their conservative neighbors.

For example, when Europeans first reached the highlands of eastern New Guinea, in the 1930s, they "discovered" dozens of previously uncontacted Stone Age tribes, of which the Chimbu tribe proved especially aggressive in adopting Western technology. When Chimbus saw white settlers planting coffee, they began growing coffee themselves as a cash crop. In 1964 I met a 50-year-old Chimbu man, unable to read, wearing a traditional grass skirt, and born into a society still using stone tools, who had become rich by growing coffee, used his profits to buy a sawmill for $100,000 cash, and bought a fleet of trucks to transport his coffee and timber to market. In contrast, a neighboring highland people with whom I worked for eight years, the Daribi, are especially conservative and uninterested in new technology. When the first helicopter landed in the Daribi area, they briefly looked at it and just went back to what they had been doing; the Chimbus would have been bargaining to charter it. As a result, Chimbus are now moving into the Daribi area, taking it over for plantations, and reducing the Daribi to working for them.

On every other continent as well, certain native societies have proved very receptive, adopted foreign ways and technology selectively, and integrated them successfully into their own society. In Nigeria the Ibo people became the local entrepreneurial equivalent of New Guinea's Chimbus. Today the most numerous Native American tribe in the United States is the Navajo, who on European arrival were just one of several hundred tribes. But the Navajo proved especially resilient and able to deal selectively with innovation. They incorporated Western dyes into their weaving, became silversmiths and ranchers, and now drive trucks while continuing to live in traditional dwellings.

Among the supposedly conservative Aboriginal Australians as well, there are receptive societies along with conservative ones. At the one extreme, the Tasmanians continued to use stone tools superseded tens of thousands of years earlier in Europe and replaced in most of mainland Australia too. At the opposite extreme, some aboriginal fishing groups of southeastern Australia devised elaborate technologies for managing fish populations, including the construction of canals, weirs, and standing traps.

Thus, the development and reception of inventions vary enormously from society to society on the same continent. They also vary over time within the same society. Nowadays, Islamic societies in the Middle East are relatively conservative and not at the forefront of technology. But medieval Islam in the same region was technologically advanced and open to innovation. It achieved far higher literacy rates than contemporary Europe; it assimilated the legacy of classical Greek civilization to such a degree that many classical Greek books are now known to us only through Arabic copies; it invented or elaborated windmills, tidal mills, trigonometry, and lateen sails; it made major advances in metallurgy, mechanical and chemical engineering, and irrigation methods; and it adopted paper and gunpowder from China and transmitted them to Europe. In the Middle Ages the flow of technology was overwhelmingly from Islam to Europe, rather than from Europe to Islam as it is today. Only after around A.D. 1500 did the net direction of flow begin to reverse.

Innovation in China too fluctuated markedly with time. Until around A.D. 1450, China was technologically much more innovative and advanced than Europe, even more so than medieval Islam. The long list of Chinese inventions includes canal lock gates, cast iron, deep drilling, efficient animal harnesses, gunpowder, kites, magnetic compasses, movable type, paper, porcelain, printing (except for the Phaistos disk), sternpost rudders, and wheelbarrows. China then ceased to be innovative for reasons about which we shall speculate in the Epilogue. Conversely, we think of western Europe and its derived North American societies as leading the modern world in technological innovation, but technology was less advanced in western Europe than in any other "civilized" area of the Old World until the late Middle Ages.

Thus, it is untrue that there are continents whose societies have tended to be innovative and continents whose societies have tended to be conservative. On any continent, at any given time, there are innovative societies and also conservative ones. In addition, receptivity to innovation fluctuates in time within the same region.

On reflection, these conclusions are precisely what one would expect if a society's innovativeness is determined by many independent factors. Without a detailed knowledge of all of those factors, innovativeness becomes unpredictable. Hence social scientists continue to debate the specific reasons why receptivity changed in Islam, China, and Europe, and why the Chimbus, Ibos, and Navajo were more receptive to new technology than were their neighbors. To the student of broad historical patterns, though, it makes no difference what the specific reasons were in each of those cases. The myriad factors affecting innovativeness make the historian's task paradoxically easier, by converting societal variation in innovativeness into essentially a random variable. That means that, over a large enough area (such as a whole continent) at any particular time, some proportion of societies is likely to be innovative.

WHERE DO INNOVATIONS actually come from? For all societies except the few past ones that were completely isolated, much or most new technology is not invented locally but is instead borrowed from other societies. The relative importance of local invention and of borrowing depends mainly on two factors: the ease of invention of the particular technology, and the proximity of the particular society to other societies.

Some inventions arose straightforwardly from a handling of natural raw materials. Such inventions developed on many independent occasions in world history, at different places and times. One example, which we have already considered at length, is plant domestication, with at least nine independent origins. Another is pottery, which may have arisen from observations of the behavior of clay, a very widespread natural material, when dried or heated. Pottery appeared in Japan around 14,000 years ago, in the Fertile Crescent and China by around 10,000 years ago, and in Amazonia, Africa's Sahel zone, the U.S. Southeast, and Mexico thereafter.

An example of a much more difficult invention is writing, which does not suggest itself by observation of any natural material. As we saw in Chapter 12, it had only a few independent origins, and the alphabet arose apparently only once in world history. Other difficult inventions include the water wheel, rotary quern, tooth gearing, magnetic compass, windmill, and camera obscura, all of which were invented only once or twice in the Old World and never in the New World.

Such complex inventions were usually acquired by borrowing, because they spread more rapidly than they could be independently invented locally. A clear example is the wheel, which is first attested around 3400 B.C. near the Black Sea, and then turns up within the next few centuries over much of Europe and Asia. All those early Old World wheels are of a peculiar design: a solid wooden circle constructed of three planks fastened together, rather than a rim with spokes. In contrast, the sole wheels of Native American societies (depicted on Mexican ceramic vessels) consisted of a single piece, suggesting a second independent invention of the wheel—as one would expect from other evidence for the isolation of New World from Old World civilizations.

No one thinks that that same peculiar Old World wheel design appeared repeatedly by chance at many separate sites of the Old World within a few centuries of each other, after 7 million years of wheelless human history. Instead, the utility of the wheel surely caused it to diffuse rapidly east and west over the Old World from its sole site of invention. Other examples of complex technologies that diffused east and west in the ancient Old World, from a single West Asian source, include door locks, pulleys, rotary querns, windmills—and the alphabet. A New World example of technological diffusion is metallurgy, which spread from the Andes via Panama to Mesoamerica.

When a widely useful invention does crop up in one society, it then tends to spread in either of two ways. One way is that other societies see or learn of the invention, are receptive to it, and adopt it. The second is that societies lacking the invention find themselves at a disadvantage vis-à-vis the inventing society, and they become overwhelmed and replaced if the disadvantage is sufficiently great. A simple example is the spread of muskets among New Zealand's Maori tribes. One tribe, the Ngapuhi, adopted muskets from European traders around 1818. Over the course of the next 15 years, New Zealand was convulsed by the so-called Musket Wars, as musketless tribes either acquired muskets or were subjugated by tribes already armed with them. The outcome was that musket technology had spread throughout the whole of New Zealand by 1833: all surviving Maori tribes now had muskets.

When societies do adopt a new technology from the society that invented it, the diffusion may occur in many different contexts. They include peaceful trade (as in the spread of transistors from the United States to Japan in 1954), espionage (the smuggling of silkworms from Southeast Asia to the Mideast in A.D. 552), emigration (the spread of French glass and clothing manufacturing techniques over Europe by the 200,000 Huguenots expelled from France in 1685), and war. A crucial case of the last was the transfer of Chinese papermaking techniques to Islam, made possible when an Arab army defeated a Chinese army at the battle of Talas River in Central Asia in A.D. 751, found some papermakers among the prisoners of war, and brought them to Samarkand to set up paper manufacture.

In Chapter 12 we saw that cultural diffusion can involve either detailed "blueprints" or just vague ideas stimulating a reinvention of details. While Chapter 12 illustrated those alternatives for the spread of writing, they also apply to the diffusion of technology. The preceding paragraph gave examples of blueprint copying, whereas the transfer of Chinese porcelain technology to Europe provides an instance of long-drawn-out idea diffusion. Porcelain, a fine-grained translucent pottery, was invented in China around the 7th century A.D. When it began to reach Europe by the Silk Road in the 14th century (with no information about how it was manufactured), it was much admired, and many unsuccessful attempts were made to imitate it. Not until 1707 did the German alchemist Johann Böttger, after lengthy experiments with processes and with mixing various minerals and clays together, hit upon the solution and establish the now famous Meissen porcelain works. More or less independent later experiments in France and England led to Sèvres, Wedgwood, and Spode porcelains. Thus, European potters had to reinvent Chinese manufacturing methods for themselves, but they were stimulated to do so by having models of the desired product before them.

DEPENDING ON THEIR geographic location, societies differ in how readily they can receive technology by diffusion from other societies. The most isolated people on Earth in recent history were the Aboriginal Tasmanians, living without oceangoing watercraft on an island 100 miles from Australia, itself the most isolated continent. The Tasmanians had no contact with other societies for 10,000 years and acquired no new technology other than what they invented themselves. Australians and New Guineans, separated from the Asian mainland by the Indonesian island chain, received only a trickle of inventions from Asia. The societies most accessible to receiving inventions by diffusion were those embedded in the major continents. In these societies technology developed most rapidly, because they accumulated not only their own inventions but also those of other societies. For example, medieval Islam, centrally located in Eurasia, acquired inventions from India and China and inherited ancient Greek learning.

The importance of diffusion, and of geographic location in making it possible, is strikingly illustrated by some otherwise incomprehensible cases of societies that abandoned powerful technologies. We tend to assume that useful technologies, once acquired, inevitably persist until superseded by better ones. In reality, technologies must be not only acquired but also maintained, and that too depends on many unpredictable factors. Any society goes through social movements or fads, in which economically useless things become valued or useful things devalued temporarily. Nowadays, when almost all societies on Earth are connected to each other, we cannot imagine a fad's going so far that an important technology would actually be discarded. A society that temporarily turned against a powerful technology would continue to see it being used by neighboring societies and would have the opportunity to reacquire it by diffusion (or would be conquered by neighbors if it failed to do so). But such fads can persist in isolated societies.

A famous example involves Japan's abandonment of guns. Firearms reached Japan in A.D. 1543, when two Portuguese adventurers armed with harquebuses (primitive guns) arrived on a Chinese cargo ship. The Japanese were so impressed by the new weapon that they commenced indigenous gun production, greatly improved gun technology, and by A.D. 1600 owned more and better guns than any other country in the world.

But there were also factors working against the acceptance of firearms in Japan. The country had a numerous warrior class, the samurai, for whom swords rated as class symbols and works of art (and as means for subjugating the lower classes). Japanese warfare had previously involved single combats between samurai swordsmen, who stood in the open, made ritual speeches, and then took pride in fighting gracefully. Such behavior became lethal in the presence of peasant soldiers ungracefully blasting away with guns. In addition, guns were a foreign invention and grew to be despised, as did other things foreign in Japan after 1600. The samurai-controlled government began by restricting gun production to a few cities, then introduced a requirement of a government license for producing a gun, then issued licenses only for guns produced for the government, and finally reduced government orders for guns, until Japan was almost without functional guns again.

Contemporary European rulers also included some who despised guns and tried to restrict their availability. But such measures never got far in Europe, where any country that temporarily swore off firearms would be promptly overrun by gun-toting neighboring countries. Only because Japan was a populous, isolated island could it get away with its rejection of the powerful new military technology. Its safety in isolation came to an end in 1853, when the visit of Commodore Perry's U.S. fleet bristling with cannons convinced Japan of its need to resume gun manufacture.

That rejection and China's abandonment of oceangoing ships (as well as of mechanical clocks and water-driven spinning machines) are well-known historical instances of technological reversals in isolated or semi-isolated societies. Other such reversals occurred in prehistoric times. The extreme case is that of Aboriginal Tasmanians, who abandoned even bone tools and fishing to become the society with the simplest technology in the modern world (Chapter 15). Aboriginal Australians may have adopted and then abandoned bows and arrows. Torres Islanders abandoned canoes, while Gaua Islanders abandoned and then readopted them. Pottery was abandoned throughout Polynesia. Most Polynesians and many Melanesians abandoned the use of bows and arrows in war. Polar Eskimos lost the bow and arrow and the kayak, while Dorset Eskimos lost the bow and arrow, bow drill, and dogs.

These examples, at first so bizarre to us, illustrate well the roles of geography and of diffusion in the history of technology. Without diffusion, fewer technologies are acquired, and more existing technologies are lost.

BECAUSE TECHNOLOGY BEGETS more technology, the importance of an invention's diffusion potentially exceeds the importance of the original invention. Technology's history exemplifies what is termed an autocatalytic process: that is, one that speeds up at a rate that increases with time, because the process catalyzes itself. The explosion of technology since the Industrial Revolution impresses us today, but the medieval explosion was equally impressive compared with that of the Bronze Age, which in turn dwarfed that of the Upper Paleolithic.

One reason why technology tends to catalyze itself is that advances depend upon previous mastery of simpler problems. For example, Stone Age farmers did not proceed directly to extracting and working iron, which requires high-temperature furnaces. Instead, iron ore metallurgy grew out of thousands of years of human experience with natural outcrops of pure metals soft enough to be hammered into shape without heat (copper and gold). It also grew out of thousands of years of development of simple furnaces to make pottery, and then to extract copper ores and work copper alloys (bronzes) that do not require as high temperatures as does iron. In both the Fertile Crescent and China, iron objects became common only after about 2,000 years of experience of bronze metallurgy. New World societies had just begun making bronze artifacts and had not yet started making iron ones at the time when the arrival of Europeans truncated the New World's independent trajectory.

The other main reason for autocatalysis is that new technologies and materials make it possible to generate still other new technologies by recombination. For instance, why did printing spread explosively in medieval Europe after Gutenberg printed his Bible in A.D. 1455, but not after that unknown printer printed the Phaistos disk in 1700 B.C.? The explanation is partly that medieval European printers were able to combine six technological advances, most of which were unavailable to the maker of the Phaistos disk. Of those advances—in paper, movable type, metallurgy, presses, inks, and scripts—paper and the idea of movable type reached Europe from China. Gutenberg's development of typecasting from metal dies, to overcome the potentially fatal problem of nonuniform type size, depended on many metallurgical developments: steel for letter punches, brass or bronze alloys (later replaced by steel) for dies, lead for molds, and a tin-zinc-lead alloy for type. Gutenberg's press was derived from screw presses in use for making wine and olive oil, while his ink was an oil-based improvement on existing inks. The alphabetic scripts that medieval Europe inherited from three millennia of alphabet development lent themselves to printing with movable type, because only a few dozen letter forms had to be cast, as opposed to the thousands of signs required for Chinese writing.

In all six respects, the maker of the Phaistos disk had access to much less powerful technologies to combine into a printing system than did Gutenberg. The disk's writing medium was clay, which is much bulkier and heavier than paper. The metallurgical skills, inks, and presses of 1700 B.C. Crete were more primitive than those of A.D. 1455 Germany, so the disk had to be punched by hand rather than by cast movable type locked into a metal frame, inked, and pressed. The disk's script was a syllabary with more signs, of more complex form, than the Roman alphabet used by Gutenberg. As a result, the Phaistos disk's printing technology was much clumsier, and offered fewer advantages over writing by hand, than Gutenberg's printing press. In addition to all those technological drawbacks, the Phaistos disk was printed at a time when knowledge of writing was confined to a few palace or temple scribes. Hence there was little demand for the disk maker's beautiful product, and little incentive to invest in making the dozens of hand punches required. In contrast, the potential mass market for printing in medieval Europe induced numerous investors to lend money to Gutenberg.

HUMAN TECHNOLOGY DEVELOPED from the first stone tools, in use by two and a half million years ago, to the 1996 laser printer that replaced my already outdated 1992 laser printer and that was used to print this book's manuscript. The rate of development was undetectably slow at the beginning, when hundreds of thousands of years passed with no discernible change in our stone tools and with no surviving evidence for artifacts made of other materials. Today, technology advances so rapidly that it is reported in the daily newspaper.

In this long history of accelerating development, one can single out two especially significant jumps. The first, occurring between 100,000 and 50,000 years ago, probably was made possible by genetic changes in our bodies: namely, by evolution of the modern anatomy permitting modern speech or modern brain function, or both. That jump led to bone tools, single-purpose stone tools, and compound tools. The second jump resulted from our adoption of a sedentary lifestyle, which happened at different times in different parts of the world, as early as 13,000 years ago in some areas and not even today in others. For the most part, that adoption was linked to our adoption of food production, which required us to remain close to our crops, orchards, and stored food surpluses.

Sedentary living was decisive for the history of technology, because it enabled people to accumulate nonportable possessions. Nomadic hunter-

gatherers are limited to technology that can be carried. If you move often and lack vehicles or draft animals, you confine your possessions to babies, weapons, and a bare minimum of other absolute necessities small enough to carry. You can't be burdened with pottery and printing presses as you shift camp. That practical difficulty probably explains the tantalizingly early appearance of some technologies, followed by a long delay in their further development. For example, the earliest attested precursors of ceramics are fired clay figurines made in the area of modern Czechoslovakia 27,000 years ago, long before the oldest known fired clay vessels (from Japan 14,000 years ago). The same area of Czechoslovakia at the same time has yielded the earliest evidence for weaving, otherwise not attested until the oldest known basket appears around 13,000 years ago and the oldest known woven cloth around 9,000 years ago. Despite these very early first steps, neither pottery nor weaving took off until people became sedentary and thereby escaped the problem of transporting pots and looms.

Besides permitting sedentary living and hence the accumulation of possessions, food production was decisive in the history of technology for another reason. It became possible, for the first time in human evolution, to develop economically specialized societies consisting of non-food-producing specialists fed by food-producing peasants. But we already saw, in Part 2 of this book, that food production arose at different times in different continents. In addition, as we've seen in this chapter, local technology depends, for both its origin and its maintenance, not only on local invention but also on the diffusion of technology from elsewhere. That consideration tended to cause technology to develop most rapidly on continents with few geographic and ecological barriers to diffusion, either within that continent or on other continents. Finally, each society on a continent represents one more opportunity to invent and adopt a technology, because societies vary greatly in their innovativeness for many separate reasons. Hence, all other things being equal, technology develops fastest in large productive regions with large human populations, many potential inventors, and many competing societies.

Let us now summarize how variations in these three factors—time of onset of food production, barriers to diffusion, and human population size—led straightforwardly to the observed intercontinental differences in the development of technology. Eurasia (effectively including North

Africa) is the world's largest landmass, encompassing the largest number of competing societies. It was also the landmass with the two centers where food production began the earliest: the Fertile Crescent and China. Its east–west major axis permitted many inventions adopted in one part of Eurasia to spread relatively rapidly to societies at similar latitudes and climates elsewhere in Eurasia. Its breadth along its minor axis (north–south) contrasts with the Americas' narrowness at the Isthmus of Panama. It lacks the severe ecological barriers transecting the major axes of the Americas and Africa. Thus, geographic and ecological barriers to diffusion of technology were less severe in Eurasia than in other continents. Thanks to all these factors, Eurasia was the continent on which technology started its post-Pleistocene acceleration earliest and resulted in the greatest local accumulation of technologies.

North and South America are conventionally regarded as separate continents, but they have been connected for several million years, pose similar historical problems, and may be considered together for comparison with Eurasia. The Americas form the world's second-largest landmass, significantly smaller than Eurasia. However, they are fragmented by geography and by ecology: the Isthmus of Panama, only 40 miles wide, virtually transects the Americas geographically, as do the isthmus's Darien rain forests and the northern Mexican desert ecologically. The latter desert separated advanced human societies of Mesoamerica from those of North America, while the isthmus separated advanced societies of Mesoamerica from those of the Andes and Amazonia. In addition, the main axis of the Americas is north–south, forcing most diffusion to go against a gradient of latitude (and climate) rather than to operate within the same latitude. For example, wheels were invented in Mesoamerica, and llamas were domesticated in the central Andes by 3000 B.C., but 5,000 years later the Americas' sole beast of burden and sole wheels had still not encountered each other, even though the distance separating Mesoamerica's Maya societies from the northern border of the Inca Empire (1,200 miles) was far less than the 6,000 miles separating wheel- and horse-sharing France and China. Those factors seem to me to account for the Americas' technological lag behind Eurasia.

Sub-Saharan Africa is the world's third largest landmass, considerably smaller than the Americas. Throughout most of human history it was far more accessible to Eurasia than were the Americas, but the Saharan desert is still a major ecological barrier separating sub-Saharan Africa from

Eurasia plus North Africa. Africa's north–south axis posed a further obstacle to the diffusion of technology, both between Eurasia and sub-Saharan Africa and within the sub-Saharan region itself. As an illustration of the latter obstacle, pottery and iron metallurgy arose in or reached sub-Saharan Africa's Sahel zone (north of the equator) at least as early as they reached western Europe. However, pottery did not reach the southern tip of Africa until around A.D. 1, and metallurgy had not yet diffused overland to the southern tip by the time that it arrived there from Europe on ships.

Finally, Australia is the smallest continent. The very low rainfall and productivity of most of Australia makes it effectively even smaller as regards its capacity to support human populations. It is also the most isolated continent. In addition, food production never arose indigenously in Australia. Those factors combined to leave Australia the sole continent still without metal artifacts in modern times.

Table 13.1 translates these factors into numbers, by comparing the continents with respect to their areas and their modern human populations. The continents' populations 10,000 years ago, just before the rise of food production, are not known but surely stood in the same sequence, since many of the areas producing the most food today would also have been productive areas for hunter-gatherers 10,000 years ago. The differences in population are glaring: Eurasia's (including North Africa's) is nearly 6 times that of the Americas, nearly 8 times that of Africa's, and 230 times that of Australia's. Larger populations mean more inventors and more competing societies. Table 13.1 by itself goes a long way toward explaining the origins of guns and steel in Eurasia.

All these effects that continental differences in area, population, ease of

TABLE 13.1 **Human Populations of the Continents**

Continent	*1990 Population*	*Area (square miles)*
Eurasia and North Africa	4,120,000,000	24,200,000
(Eurasia)	(4,000,000,000)	(21,500,000)
(North Africa)	(120,000,000)	(2,700,000)
North America and South America	736,000,000	16,400,000
Sub-Saharan Africa	535,000,000	9,100,000
Australia	18,000,000	3,000,000

diffusion, and onset of food production exerted on the rise of technology became exaggerated, because technology catalyzes itself. Eurasia's considerable initial advantage thereby was translated into a huge lead as of A.D. 1492—for reasons of Eurasia's distinctive geography rather than of distinctive human intellect. The New Guineans whom I know include potential Edisons. But they directed their ingenuity toward technological problems appropriate to their situations: the problems of surviving without any imported items in the New Guinea jungle, rather than the problem of inventing phonographs.

a summary of human history that can be accounted, for the time being, as Darwinian in its authority." —Thomas M. Disch, *New Leader*

"A wonderfully engrossing book. . . . Jared Diamond takes us on an exhilarating world tour of history that makes us rethink all our ideas about ourselves and other peoples and our places in the overall scheme of things." —Christopher Ehret, Professor of African History, UCLA

"Jared Diamond masterfully draws together recent discoveries in fields of inquiry as diverse as archaeology and epidemiology, as he illuminates how and why the human societies of different continents followed widely divergent pathways of development over the past 13,000 years."

—Bruce D. Smith, Director, Archaeobiology Program, Smithsonian Institution

"The question, 'Why did human societies have such diverse fates?' has usually received racist answers. Mastering information from many different fields, Jared Diamond convincingly demonstrates that head starts and local conditions can explain much of the course of human history. His impressive account will appeal to a vast readership."

—Luca Cavalli-Sforza, Professor of Genetics, Stanford University

GUNS, GERMS, AND STEEL

THE FATES OF HUMAN SOCIETIES

Jared Diamond

W. W. Norton & Company
New York London

1999