artifacts – that new kinds of made things are never pure creations of theory, ingenuity, or fancy.

If technology is to evolve, then novelty must appear in the midst of the continuous. Chapters III and IV survey the varied sources of novelty – the human imagination, socioeconomic and cultural forces, the diffusion of technology, the advancement of science – in primitive cultures as well as in modern industrialized nations. The conclusion drawn from this survey is that any society, at any time, commands more potential for technological innovation than it can ever hope to exploit.

Because only a small fraction of novel technological possibilities are sufficiently developed to become part of the material life of a people, selection must be made from among competing novel artifacts. Ultimately, the selection is made in accordance with the values and perceived needs of society and in harmony with its current understanding of "the good life." The selection process, and the forces that drive it, are covered in chapters V and VI.

In concluding, chapter VII addresses the issue of technological progress and human betterment. The traditional conception of progress is found to be internally flawed and incompatible with technological evolution. However, progress can be redefined so that it no longer conflicts with an evolutionary perspective.

Because a book of this breadth could not be written without the rich scholarly resources produced by historians of technology in the past several decades, I wish to acknowledge my debt to the authors listed in the bibliography. Specifically, I have made extensive use of the ideas and insights of George Kubler and Nathan Rosenberg.

I owe a special obligation to two close friends: William Coleman, my fellow editor for the Cambridge History of Science Series, who guided me in handling the evolutionary analogy; and Eugene S. Ferguson, my colleague at the University of Delaware, who counseled me on every aspect of the book. It is no exaggeration to say that this volume could not have taken its final form without their help.

Finally, I want to thank Catherine E. Hutchins of the *Winterthur Portfolio* for editing the text, Marie B. Perrone for typing the manuscript, Kenneth Marchionno for preparing the illustrations, and my wife and family for their long and consistent support.

From Basalla, George. 1988.
The Evolution of Technology

CHAPTER I

Diversity, Necessity, and Evolution

Diversity

The rich and bewildering diversity of life forms inhabiting the earth has intrigued humankind for centuries. Why should living things appear as paramecia and hummingbirds, as sequoia trees and giraffes? For many centuries the answer to this question was provided by the creationists. They claimed that the diversity of life was a result and expression of God's bountiful nature: In the fullness of his power and love he chose to create the wonderful variety of living things we encounter on our planet.

By the middle of the nineteenth century, and especially after the publication of Charles Darwin's *Origin of Species* in 1859, the religious explanation of diversity was challenged by a scientific one. According to this new interpretation, both the diversification of life at any given moment and the emergence of novel living forms throughout time were the result of an evolutionary process. In support of Darwin's theories, biologists have proceeded to identify and name more than 1.5 million species of flora and fauna and have accounted for this diversity by means of reproductive variability and natural selection.

Another example of diversity of forms on this earth, however, has been often overlooked or too readily taken for granted – the diversity of things made by human hands. To this category belongs "the vast universe of objects used by humankind to cope with the physical world, to facilitate social intercourse, to delight our fancy, and to create symbols of meaning."[1]

Because distinct species cannot be identified with any precision among items of human manufacture, obtaining an accurate count of the different kinds of made things is difficult. A very rough approximation of that figure can be reached by using the number of patents granted as an indicator of the diversity of the made world. In the United States alone more than 4.7 million patents have been issued since 1790. If each of these patents is counted as the equivalent of an organic species, then the technological can be said to have a diversity three times greater than the organic. Although faulty at several points, this attempt at measuring comparative diversification suggests that the diversity of the technological realm approaches that of the organic realm.

The variety of made things is every bit as astonishing as that of living things. Consider the range that extends from stone tools to microchips, from waterwheels to spacecraft, from thumbtacks to skyscrapers. In 1867 Karl Marx was surprised to learn, as well he might have been, that five hundred different kinds of hammers were produced in Birmingham, England, each one adapted to a specific function in industry or the crafts (Figure I.1). What forces led to the proliferation of so many variations of this ancient and common tool? Or more generally, why are there so many different kinds of things?

Our attempts to understand diversification in the made world, or even to appreciate its richness, have been hampered by the assumption that the things we make are merely so many instruments enabling us to cope with the natural environment and maintain the necessities of life. Traditional wisdom about the nature of technology has customarily stressed the importance of necessity and utility. Again and again we have been told that technologists through the ages provide humans with the utilitarian objects and structures necessary for survival.

Because necessity and utility alone cannot account for the variety and novelty of the artifacts fashioned by humankind, we must seek other explanations, especially ones that can incorporate the most general assumptions about the meaning and goals of life. This search can be facilitated by applying the theory of organic evolution to the technological world.

The history of technology, a discipline that focuses on the invention, production, and uses of material artifacts, benefits from the application of an evolutionary analogy as an explanatory device. A theory that explains the diversity of the organic realm can help us account for the variety of made things. This venture does have its pitfalls, however, as poet e. e. cummings warned, "A world of made is not a world of born."[2]

The evolutionary metaphor must be approached with caution because there *are* vast differences between the world of the made and the world of the born. One is the result of purposeful human activity, the other the outcome of a random natural process. One produces a sterile physical object, the other a living being capable of reproducing itself. Emphatically, I do not propose the establishment of a one-to-one correspondence between these markedly different domains. In the narrative and analysis that follow, I employ the evolutionary metaphor or analogy selectively, with the expectation that this metaphor will give us insights otherwise unavailable to the history of technology.

The nature of metaphor and its role in this book need additional clarification. Metaphors are not ornaments arbitrarily superimposed on discourse for poetic purposes. Metaphors or analogies are at the heart of all extended analytical and critical thought. Without metaphors literature would be barren, science and philosophy would scarcely exist, and history would be reduced to a chronicle of events.

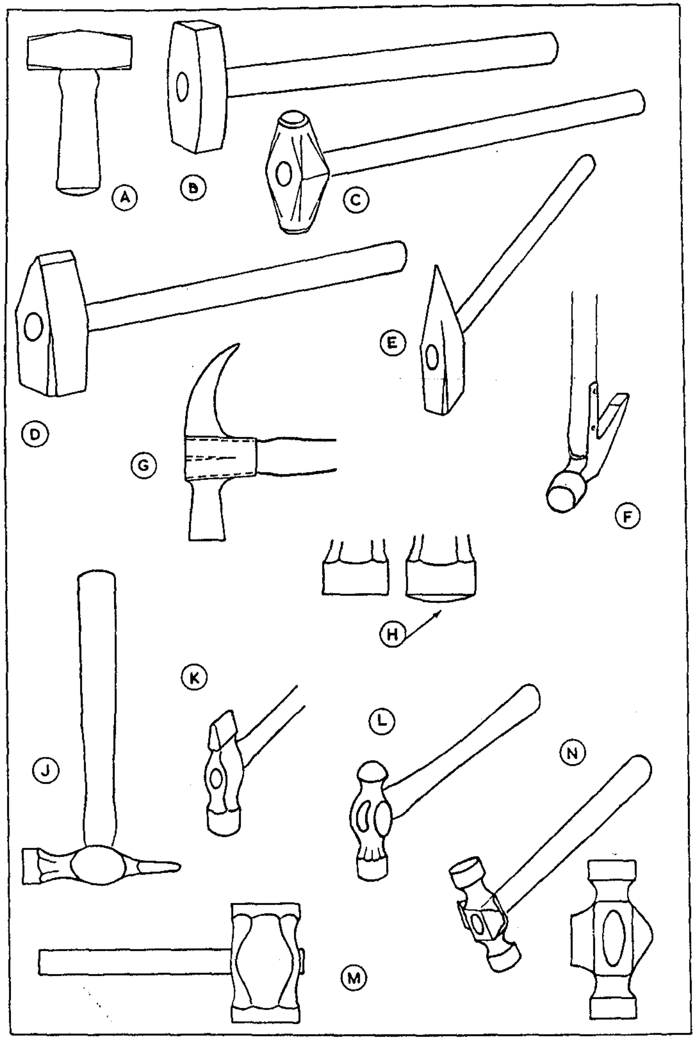
Historians have long relied on metaphors in interpreting the past, especially organic metaphors invoking birth, growth, development, maturity, health, disease, senescence, and death. For the past century or so, those who specialize in the history of science and technology have routinely drawn upon a powerful political metaphor, that of revolution, to explain happenings in those areas. Thus, in suggesting that evolutionary theory be employed in understanding technological change, I am not introducing metaphor into a field that had never known the concept before; however, I am introducing a new metaphor and urging that its wider implications be considered seriously.

I ask that readers grant me the same indulgence they have extended to those who write about scientific and industrial revolutions. Just as historians of science and technology are not held responsible for all points of similarity between political revolt and radical scientific, technological, and industrial change, so I should not be taken to task if I do not draw parallels between every feature of the made and living worlds.

In one respect my use of metaphor differs from that of most historians: They utilize metaphors implicitly and often unconsciously; in this book I make explicit and conscious use of mine. Although our choice of, and approach to, metaphors may differ, we share the same aim – to make sense of the past.

Necessity

A well-known Aesop's fable is particularly relevant to the discussion of technology, diversity, and necessity. Once upon a time, wrote



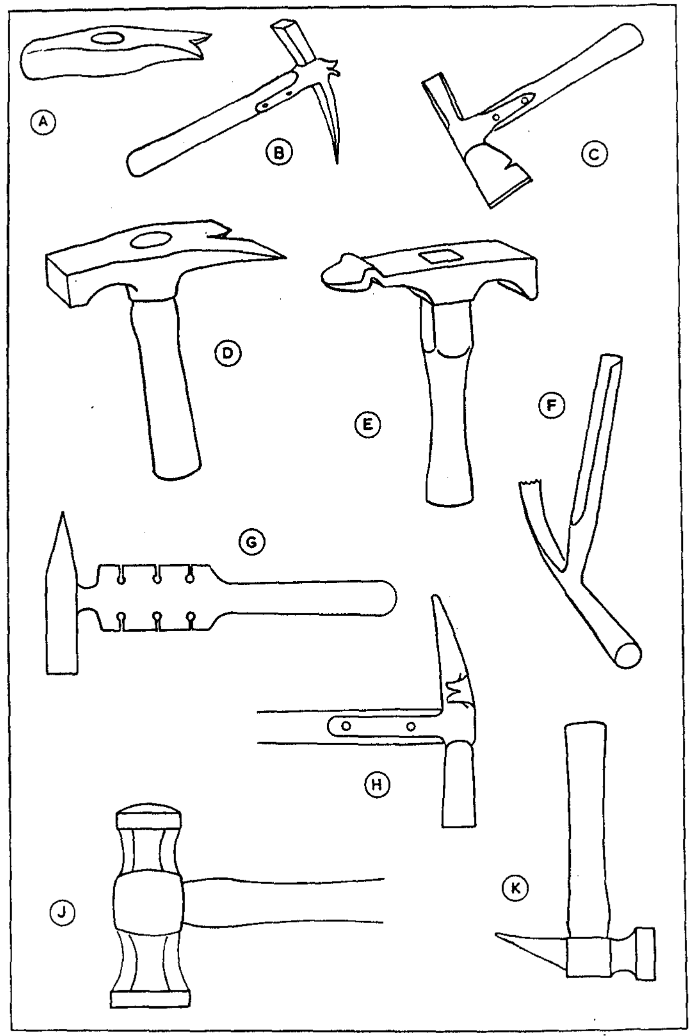


Figure I. 1. Artifactual diversity as reflected in the forms of hammers used by English country craftsmen. I: A,B,C,D,E, – Stone mason's hammers used to break, cut, square, and dress stone; F,G – Carpenter's hammer with strengthened head; H – Curved hammer head, used to protect wood's surface when driving a nail; J – General woodworking hammer; K – Straight-peen blacksmith's hammer; L – Ball-peen, a general metalworking hammer; M – Chair-maker's hammer; N – Horse-shoeing hammer (two views). II: A – Head of claw hammer used to withdraw nails; B – Slater's pick hammer; C – Lath hatchet; D – Cooper's nailing adze, used on barrel hoops; E – Butter firkin, used to open and close butter casks; F – Combination cheese-taster and hammer; G – Saw-sharpening and saw-setting hammer; H – Upholsterer's or saddler's hammer; J,K – Shoemaker's hammers. Source: Percy W. Blandford, *Country craft tools* (Newton Abbot, 1974), pp. 49, 55.

Aesop, a crow about to die of thirst came upon a tall pitcher partially filled with water. He tried again and again to drink from it, stooping and straining his neck, but his short beak could not reach the surface of the water. When he failed in an attempt to overturn the heavy vessel, the bird despaired of ever quenching his thirst. Then he had a bright idea. Seeing loose pebbles nearby, the crow began dropping them into the pitcher. As the stones displaced the water, its level rose. Soon the crow was able to drink his fill. The moral: necessity is the mother of invention. Modern commentators have elaborated on this message by praising those individuals who, when placed in seemingly impossible situations, do not despair but instead use wit and ingenuity to invent new devices and machines that solve the dilemma, meet basic biological needs, and contribute to material progress.

The belief that necessity spurs on inventive effort is one that has been constantly invoked to account for the greatest part of technological activity. Humans have a need for water, so they dig wells, dam rivers and streams, and develop hydraulic technology. They need shelter and defense, so they build houses, forts, cities, and military machines. They need food, so they domesticate plants and animals. They need to move through the environment with ease, so they invent ships, chariots, carts, carriages, bicycles, automobiles, airplanes, and spacecraft. In each of these instances humans, like the crow in Aesop's story, use technology to satisfy a pressing and immediate need.

If technology exists primarily to supply humanity with its most basic needs, then we must determine precisely what those needs are and how complex a technology is required to meet them. Any complexity that goes beyond the strict fulfillment of needs could be judged superfluous and must be explained on grounds other than necessity.

In surveying the needs and techniques essential to human beings a modern commentator might ask: Do we need automobiles? We are often told that automobiles are absolutely essential, yet the automobile is barely a century old. Men and women managed to live full and happy lives before Nikolaus A. Otto devised his four-stroke internal combustion engine in 1876.

A search for the origins of the gasoline-engine-powered motorcar reveals that it was not necessity that inspired its inventors to complete their task. The automobile was not developed in response to some grave international horse crisis or horse shortage. National leaders, influential thinkers, and editorial writers were not calling for the replacement of the horse, nor were ordinary citizens anxiously hoping that some inventors would soon fill a serious societal and personal need for motor transportation. In fact, during the first decade of existence, 1895–1905, the automobile was a toy, a plaything for those who could afford to buy one.

The motor truck was accepted even more slowly than the automobile. The success of military truck transportation during World War I combined with an intensive lobbying effort by truck manufacturers and the Army after the war finally resulted in the displacement of the horse-drawn wagon and, at a later date, the railroad. But the motor truck was not created to overcome obvious deficiencies of horse- and steam-powered hauling. As was the case with automobiles, the need for trucks arose after, not before, they were invented. In other words, the *invention* of vehicles powered by internal combustion engines gave birth to the *necessity* of motor transportation.

Because motor cars and trucks appeared at the end of a century filled with intense technological activity, they might be considered poor examples on which to base an argument. Perhaps if an earlier invention was identified, one that did not coincide with widespread, deliberate technological innovation and its accompanying belief in material progress, the necessity that brought it forth could be isolated more easily. The wheel holds promise of being just such an invention.

The Wheel

Popularly perceived as one of the oldest and most important inventions in the history of the human race, the wheel is invariably listed with fire as the greatest technical achievement of the Stone Age. In comic strips and cartoons, stone wheels and fire are portrayed as joint creations of prehistoric cave dwellers. This familiar portrayal, which first appeared in the late nineteenth century, is currently exemplified by the *B.C.* comic strip.

Those who have a better knowledge of the early history of human culture know that the origins of fire and the wheel do not date to the same time period. Fire has been in use for at least 1.5 million years, whereas the wheel is more than 5,000 years old. Even at this level of historical understanding, however, there is a tendency to pair the two items, placing them in a special category above and beyond all other human accomplishments. For example, when distinguished economic historian David S. Landes assessed the significance of the mechanical clock recently he conceded that it was "not in a class with fire and the wheel"[3] and hence deserved a lower ranking.

Whatever the degree of historical sophistication, most people believe that the use of wheeled transportation is a signal of civilization. The two are thought to be so closely linked that the progress made by cultures has been judged by measuring the extent to which they have exploited rotary motion for transportation. By that standard, to be without the wheel altogether is sufficient to set a culture apart from the civilized world.

In searching for the origins of this wonderful invention, there is no need to explore nature's realm. With the exception of a few microorganisms, no animal propels itself by means of a set of organic wheels spinning freely on axles. The source of the wheel must be sought among made things.

Before the coming of the wheel, large heavy objects were moved on sledges – wooden platforms with or without runners. Cylindrical rollers (smoothed logs) placed beneath the vehicle were used to facilitate the movement of the sledges, and it is thought that these rollers inspired the invention of the wheel.

Whatever the inspiration, wheels made their initial appearance in the fourth millennium B.C. across a broad area extending from the Tigris to the Rhine rivers. Current archaeological findings indicate that wheeled vehicles were invented in Mesopotamia and from there diffused to northwest Europe within a very short time. The first wheels were either solid wooden disks cut from a single plank or tripartite models consisting of three wooden slabs trimmed to shape and fastened together with cleats.

A strict reading of the archaeological record suggests that the first wheeled vehicles were used for ritualistic and ceremonial purposes. The earliest illustrations show them being used to carry effigies of deities or important persons. The oldest remains of wheeled conveyances are found in tombs; such vehicles, interred with the deceased as part of a religious burial ceremony, have been uncovered at various sites in the Near East and Europe.

Vehicles buried with the dead were often of the type used on the battlefield. Thus the ritualistic and ceremonial uses of the wheel were closely related to its employment in war. Military requirements exerted a powerful influence upon the subsequent development of wheeled vehicles. For example, pictorial and physical evidence supports the idea that the four-wheeled "battle wagon" and the two-wheeled "straddle car" (a chariotlike vehicle) of Mesopotamia were used early as moving platforms from which javelins could be hurled. The innovative spoked wheel, which demanded a high level of craftsmanship, was first utilized on war chariots in the second millennium

B.C. to create light and fast-moving vehicles that could be maneuvered easily during battle.

In addition to ritualistic and military uses, the wheel was also used in transporting goods. Although this third function is not directly recorded in the earliest archaeological evidence, we assume that wheeled vehicles could be, and were, used for more mundane purposes at an early date. Documentary evidence of wagons transporting farm goods such as hay, onions, reeds dates from 2375 to 2000 B.C., about a thousand years after the wheel's initial appearance. However, this time lag may simply reflect the ritualistic, ceremonial, and military nature of much of our arachaeological evidence. Despite the lack of strong proof for the transport function of wheeled vehicles in earliest times, it can be argued that the utilitarian aspect of the wheel was primary and that the necessity of transporting farm goods was the source of the invention of the wagon and cart.

Our discussion of the wheel and its uses has been confined to a relatively small geographical area. The story of the wheel in the rest of the world remains to be told. Wheeled vehicles appeared in India in the third and in Egypt and China in the second millennium B.C. As for Southeast Asia, Africa south of the Sahara, Australasia, Polynesia, and North and South America, people in those vast regions managed to survive, and in many cases prosper, without the help of the wheel. Not until modern times was rotary motion for transportation purposes introduced into these lands.

Especially interesting is the case of Mesoamerica (roughly Mexico and Central America). Although wheeled transport was unknown there prior to the arrival of the Spanish, Mesoamericans did make miniature wheeled objects. From the fourth to the fifteenth centuries A.D., clay figurines of various animals were fitted with axles and wheels to make them mobile (Figure I.2). Whether these figurines were toys or cult or votive objects is unknown; however, irrespective of their purpose, they show that the mechanical principle of the wheel was thoroughly understood and applied by people who never put it into use for transporting goods.

How are we to explain this failure to exploit an invention commonly held to be one of the two greatest technical achievements of all time? If we assume we are dealing with a people whose intellectual development was so stunted that they were unable to make practical use of the wheel, how can we account for the fact that they were capable of independently inventing the wheel in the first place? And how do we explain the flowering of the Aztec and Maya cultures with their many accomplishments in the arts and sciences?

The answer to these questions is simple. Mesoamericans did not

Figure I.2. Wheeled clay figurine made by the Aztecs (Mexico). Animal figurines employing the principle of the wheel and axle are found throughout Mesoamerica. They date from ca. A.D. 300 to the coming of the Spanish in the sixteenth century, a period when there was no wheeled transportation in the region. Source: Stuart Piggott, *The earliest wheeled transport* (Ithaca, N.Y., 1983), p. 15. Neg. no. 326744; courtesy Department of Library Services, American Museum of Natural History.

use wheeled vehicles because it was not feasible to do so given the topographical features of their land and the animal power available to them. Wheeled transport depends on adequate roads, a difficult requirement in a region noted for its dense jungles and rugged landscape. Large draft animals capable of pulling heavy wooden vehicles, were also needed, but Mesoamericans had no domesticated animals that could be put to that use. Men and women of Mexico and Central America traveled along trails and over rough terrain carrying loads on their backs. It was unnecessary to build roads for these human carriers of goods.

An even more persuasive case can be made against the universal superiority and applicability of the wheel by returning to its place of origin in the Near East. Between the third and seventh centuries A.D., the civilizations of the Near East and North Africa gave up wheeled vehicular transportation and adopted a more efficient and speedier way of moving goods and people: They replaced the wagon and cart with the camel. This deliberate rejection of the wheel in

the very region of its invention lasted for more than one thousand years. It came to an end only when major European powers, advancing their imperialistic schemes for the Near East, reintroduced the wheel.

The camel as a pack animal was favored over wheeled transportation for reasons that become evident when the camel is compared with the typical ox-drawn vehicle. The camel can carry more, move faster, and travel farther, on less food and water, than an ox. Pack camels need neither roads nor bridges, they can traverse rough ground and ford rivers and streams, and their full strength is devoted to carrying a load and not wasted on dragging a wagon's deadweight. Once the camel and ox are compared, one wonders why the wheel was ever adopted in that region in the first place. A large share of the burden of goods in the Near East was always carried by pack animals. A bias for the wheel led Western scholars to underrate the utility of pack animals and overemphasize the contribution made by wheeled vehicles in the years before the camel replaced the wheel.

The more we learn about the wheel, the clearer it becomes that its history and influence have been distorted by the extraordinary attention paid to it in Europe and the United States. The Western judgment that the wheel is a universal need (as crucial to life as fire) is of recent origin. Fire, not the wheel, was the precious gift Prometheus stole from the gods and bestowed upon humanity. Similarly, fire, and not the wheel, was traditionally portrayed as the great civilizing agent in the literary and visual arts of Western culture. Not until the late nineteenth and early twentieth centuries did popular writers on technology elevate the wheel to the premier place it holds today.

This history of the wheel began as a search for a significant technological advancement that was produced in response to a universal human need. It has ended with the wheel seen as a culture-bound invention whose meaning and impact have been exaggerated in the West. Although this review is not meant to detract from the real importance of the wheel in modern technology, it does raise serious doubts about using it as a criterion to evaluate other cultures.

By putting wheeled transport into a broader cultural, historical, and geographical perspective, three important points emerge: First, wheeled vehicles were not necessarily invented to facilitate the movement of goods; second, Western civilization is a wheel-centered civilization that has carried rotary motion in transportation to a high state of development; and, third, the wheel is not a unique mechanical contrivance necessary, or useful, to all people at all times.

Fundamental Needs

The pursuit of need and invention has revealed that necessity is a relative term. A necessity for one people, generation, or social class may have no utilitarian value or may be a superficial luxury for another people, generation, or social class. At the same time that Europeans were energetically advancing wheeled transportation, Near Easterners were abandoning their experiment with the wheel, and Mesoamericans were adapting rotary motion to clay figurines. The story of the comparative reception and use of the wheel could be repeated for the other so-called necessities of modern life. Far from fulfilling universal needs, they derive their importance within a specific cultural context or value system.

This arouses the suspicion that it might be possible to strip away the false necessities, the trivial ones to which we have merely become accustomed, to reveal a core of fundamental needs applicable to humans living in any age and place. These universal needs would provide a firm ground on which to base an understanding of culture, including technology.

According to functionalist anthropologists and sociobiologists, every aspect of culture, material and nonmaterial, can be traced directly to the satisfaction of a basic need. In their view culture is nothing more than humanity's response to the fulfillment of its nutritive, reproductive, defensive, and hygienic needs. Critics of the biological theory, however, have proposed a number of strong counterarguments. Some have noted that phenomena central to culture, such as art, religion, and science, have very tenuous connections to human survival. Likewise, agriculture and architecture, which supposedly can be linked to the need for nutrition and shelter, manifest themselves in ways only remotely explicable by biological necessity. Modern agribusiness, for example, is motivated by much more than the concern for providing nourishment to humanity; a skyscraper is not simply a structure to protect people from the vagaries of the weather.

Some scholars argue that language is the most important feature of culture and that language, not biology, determines our definition of what we consider to be necessary or utilitarian. In their estimation, necessity is not something imposed by nature upon humanity but is a conceptual category created by cultural choice. Both sets of critics acknowledge external material constraints on culture; however, those constraints are seen as remote and of minor importance when compared with the immense range of cultural possibilities open to humankind. Biological necessity operates negatively and at extreme limits. It decrees what is impossible, not what is possible.

Another critical approach to theories of culture based on preexisting fundamental needs evaluates the role of technology in the animal kingdom. Its proponents conclude that no technology whatsoever is required to meet animal needs. Proof of this assertion is found by observing the animal realm where the necessities of life are procured without the intervention of technology. Unlike the crow in Aesop's fable, birds in real life do not obtain water by resorting to elaborate technological stratagems. Birds and other animals do not dig wells or construct canals, aqueducts, and pipelines. Nature provides water, food, and shelter to them directly without any intervening made structures. Of course, some animals use sticks, stones, and leaves as crude tools for gathering food and as weapons for defending themselves, but animal tool behavior is so rudimentary and limited that it can scarcely be compared with the technology of the simplest of human cultures. There are no fire-using animals nor are there animals that routinely fashion new tools, improve upon old tool designs, use tools to make other tools, or pass on accumulated technical knowledge to offspring.

Given these facts, it is misleading to connect animal tool use to human technology by means of a smooth curve of transition. Even the earliest and crudest tools produced by humans imply considerable foresight and a level of mentality that sets them apart from the most sophisticated tools made by animals. As Karl Marx pointed out, the worst human architect is superior to the best insect nest or hive builder because only humans are able to envision structures in their imagination before erecting them.

Animals exist and thrive without fire or the simplest shaped stone utensils. Insofar as we are animals, on the zoological plane of existence, we too could live without them. Of course, without technology we could neither occupy nor visit many regions of the earth we now inhabit. Nor could we do most of the things we do in our everyday lives. But we could survive, and survival is what we have in mind when we ask how elementary a level of technology is required to meet our basic needs.

Because technology is not necessary in meeting the animal needs of humans, philosopher José Ortega y Gasset defines technology as the production of the superfluous. He remarks that technology was just as superfluous in the remote Stone Age as it is today. Like the rest of the animal kingdom we, too, could have lived without fire and tools. For reasons that are obscure, we began to cultivate technology and in the process created what has come to be known as human life, the good life, or well-being. The struggle for well-being certainly entails the idea of needs but those needs are constantly changing. At one time need prompted the building of pyramids and temples, at another time it inspired movement about the earth's surface in self-propelled vehicles, journeys to the moon, and the incineration and irradiation of entire cities.

We cultivate technology to meet our perceived needs, not a set of universal ones legislated by nature. According to French philosopher Gaston Bachelard the conquest of the superfluous gives us a greater spiritual stimulus than the conquest of the necessary because humans are creations of desire, not need.

A perceived need often coincides with an animal need, like the requirement for nourishment. Nevertheless, we must not lose sight of the fact that humans have now chosen an excessively complex, technological means of satisfying basic necessities. Instead of relying on nature directly for sustenance, we have devised the wholly unnecessary techniques of agriculture and cooking. They are unnecessary because plants and animals are able to grow and even thrive without human intervention, and because food need not be processed by fire before it is fit for human consumption. Agriculture and cooking are not prerequisites for human survival; they only become necessary when we choose to define our well-being as including them.

Humans have a different relationship with the natural world than do animals. Nature simply and directly sustains animal life. For humans, nature serves as a source of materials and forces that can be utilized in pursuit of what they choose to call for the moment their well-being.

Because the resources of nature are varied, and because human values and tastes differ from culture to culture, from time to time, and from person to person, we should not be surprised to find a tremendous diversity in the products of technology. The artifacts that constitute the made world are not a series of narrow solutions to problems generated in satisfying basic needs but are material manifestations of the various ways men and women throughout time have chosen to define and pursue existence. Seen in this light, the history of technology is a part of the much broader history of human aspirations, and the plethora of made things are a product of human minds replete with fantasies, longings, wants, and desires. The artifactual world would exhibit far less diversity if it operated primarily under the constraints imposed by fundamental needs.

Organic–Mechanical Analogies

Explaining artifactual diversity by means of a theory of technological evolution requires that we compare living organisms and mechanical

devices. Such analogical thinking is a modern phenomenon with few precedents in antiquity. Aristotle, who wrote extensively on biological matters, made little use of mechanical analogies in his explication of the organic world. Not until the Renaissance did European thinkers begin to draw parallels between the organic and the mechanical. This association of what had hitherto been thought to be disparate elements was the result of the appearance of a host of new technological contrivances and the emergence of modern science.

Initially the flow of organic–mechanical analogies moved from technology to biology. Structures and processes in living organisms were described and explained in mechanical terms. In the middle of the nineteenth century there occurred a movement of metaphors in the opposite direction. The counterflow of metaphor was of critical importance; for the first time the development of technology was interpreted through organic analogies.

Widespread industrial growth, the geologist's ability to establish the antiquity of the earth, and the appearance of the Darwinian theory of evolution facilitated the application of organic analogies to the technological realm. This new mode of metaphorization had its most notable and lasting affects upon literature and anthropology. The literary uses of the organic–mechanical metaphor can be conveniently studied in the writings of Samuel Butler, the anthropological in the work of General Augustus Henry Pitt-Rivers (original surname Lane-Fox). Both of these men lived in mid-Victorian England and both were deeply influenced by Charles Darwin's *Origin of Species*.

In his utopian novel *Erewhon* (1872) and essays such as "Darwin Among the Machines" (1863) Samuel Butler whimsically explored the idea that machines developed in a fashion remarkably similar to the evolution of living beings. His ideas inspired the popular evolutionary fantasy novels of nineteenth- and twentieth-century science fiction in which rapidly evolving machines surpass and supplant humans whose own evolutionary development has stagnated. Butler's influence is also evident in modern speculative essays that predict either the coming of a new symbiotic relationship between humans and machines or the supersession of humankind by new forms of technology that are capable of self-replication, such as robots and computers.

Victorians proud of their industrial accomplishments were warned by Butler that it was to their advantage to pause and contemplate the wider implications of technological change. Machines, he said, have undergone a series of very rapid transformations from the simple stick wielded by our early ancestors to the steam engine of today. This development in the direction of greater complexity raises the possibility of the addition of a mechanical kingdom, comprised of all forms of mechanical life, to the existing plant and animal kingdoms.

Identifying machines as a new class of living beings would allow Victorians to arrange them into genera, species, and varieties, suggested Butler, and proceed from this classificatory exercise to the construction of an evolutionary tree illustrating the connections between the various forms of mechanical life. Darwin's theory, therefore, is perfectly compatible with the mechanical kingdom. The history of technology is filled with examples of machines slowly changing over time and replacing older models, of vestigial structures remaining as parts of mechanisms long after they had lost their original functions, and of machines engaged in a struggle for survival, albeit with the help of humans. The animal or plant breeder who practices artificial selection by choosing certain specimens for propagation is doing precisely what the machine builder and the industrialist do with mechanical life when they plan a new technological venture.

To skeptics who objected that machines cannot be said to live and evolve because they are incapable of reproducing themselves, Butler responded that in the mechanical kingdom reproduction is accomplished in a different fashion. The propagation of mechanical life depends on a group of fertile contrivances, called machine tools, that are able to produce a wide variety of sterile machines.

A more pressing issue than reproduction, cautioned Butler, is the nature of the future relationships of humanity and the machine. Because machines are more powerful, accurate, dependable, and versatile than humans, and because machines are changing rapidly before our eyes, humans cannot help but fall back to second place in a world dominated by technology. Of course, we could try to put a stop to mechanical evolution but that would mean the destruction of every machine and tool, every lever and screw, every piece of shaped material. Because we cannot halt mechanical progress, we must resign ourselves, advised Butler, to assuming the status of servants to our superiors.

Butler's evolutionary speculations, presented in a literary tour de force, enabled him to display his wit and ingenuity, his ambiguous response to advances in technology and science, and his criticisms of popular theological and philosophical propositions. Pitt-Rivers, a career military officer who later devoted his life to ethnology and archaeology, approached technological evolution in an entirely different manner. His acceptance of the evolutionism of Darwin and Herbert Spencer grew out of his military experience and a desire to catalog, classify, and display his personal collection of primitive weapons and tools.

ethnology

Assigned to test new rifles for the British army and prepare an instruction manual for their use in 1852, Pitt-Rivers became interested in the history of firearms. Through his research, he became aware of the gradual and progressive modification in firearm design that had resulted in the creation of ever more powerful and accurate rifles. At about the same time he began assembling a prehistoric artifact collection and investigating relics being unearthed in the British Isles and northern Europe. His contact with these diverse artifacts prompted him to consider the best way to organize them for study and eventual display. Should they be arranged geographically according to their place of origin or was there some more fruitful scheme of classification?

Natural history offered one mode for a classificatory system – the Linnaean ordering of the vegetable and animal kingdoms into genera, species, and varieties. In this system, form was more significant than geography. Because Darwin had shown that taxonomic studies could be made to yield great and fundamental truths about the nature of living things, Pitt-Rivers resolved to ignore the geographical, temporal, and cultural dimensions of artifacts, follow the lead of natural history, and arrange his collection in a series of sequences composed of closely related forms.

Spencer's assertion that the entire history of life was marked by a development from the simple to the complex, the homogeneous to the heterogeneous, inspired Pitt-Rivers to make these the guiding principles in his arrangement of artifacts. He placed them in sequences that began with the very simplest tool, weapon, or utensil and progressed step by small step to the most complex one. This method was more than a convenient way to impose order on the varied products of material culture. Because every artifact was thought to have originated as an idea in the mind of its original maker the sequences bound together the material and intellectual aspects of life. The progressive, continuous series of related artifacts served as proof of the evolution of human culture from its primitive condition to the highest states of civilization.

Pitt-Rivers confined his collecting and classifying labors to preindustrial artifacts, and deliberately avoided the difficulty of dealing with the more complex and sophisticated products of Victorian technology. His focus on the primitive stemmed from a belief that the study of the simplest artifacts would reveal the thought processes of prehistoric men and women and clearly demonstrate the progressive nature of material culture. But, modern critics will interject, the primitive cannot be equated with the prehistoric: We have no right to suppose that the culture of modern Australian aborigines bears any resemblance to Paleolithic culture. Pitt-Rivers and other nineteenth-century evolutionary anthropologists would reply that at any time in history the many societies scattered across the earth reflect the different evolutionary stages through which all human culture has passed. They believed that each culture followed a single, broad course of evolutionary change with only minor deviations. If Australian aborigines used stone tools, then they were at precisely the same stage of cultural development that Paleolithic man had reached hundreds of thousands of years earlier.

Given these assumptions about cultural evolution and artifacts, Pitt-Rivers was not particularly interested in garnering rare or exotic specimens for his collection. Nor was he concerned with accurately dating his artifacts and placing them within a specific cultural context. Instead he searched for forms that filled in the gaps of existing sequences or that could be used to initiate new sequences (Figure I.3 and I.4). The overriding criterion in every case was how well a specimen fit in between two others in a sequence – that is, how much it contributed to the establishment of a continuous transition. In the organic as well as in the technological realms, gaps in a sequence represented missing links that could be filled eventually. If it appeared that there were more artifactual than organic missing links, it was because the collection and classification of plants and animals had been going on for centuries whereas the organization and analysis of made things had barely begun.

Pitt-Rivers was careful not to overstate the case for technological evolution or to draw far-fetched analogies between living organisms and material objects. For example, he felt it was permissible to justify his interest in weaponry and the origins of warfare by linking them to the Darwinian struggle for existence. But humans use weapons in their struggle; the weapons themselves do not fight for survival. Nor are weapons or other artifacts capable of reproduction. Anticipating these objections, Pitt-Rivers introduced the idea of unconscious selection. Through the ages, without premeditation or design, humans had selected the artifacts best suited for certain tasks, rejected those less suited, and gradually modified the surviving artifacts so that they performed their assigned functions better. As a result, artifactual change was directed along a progressive path even though artisans were totally unaware of the long-range implications of the slight improvements they had introduced. In meeting

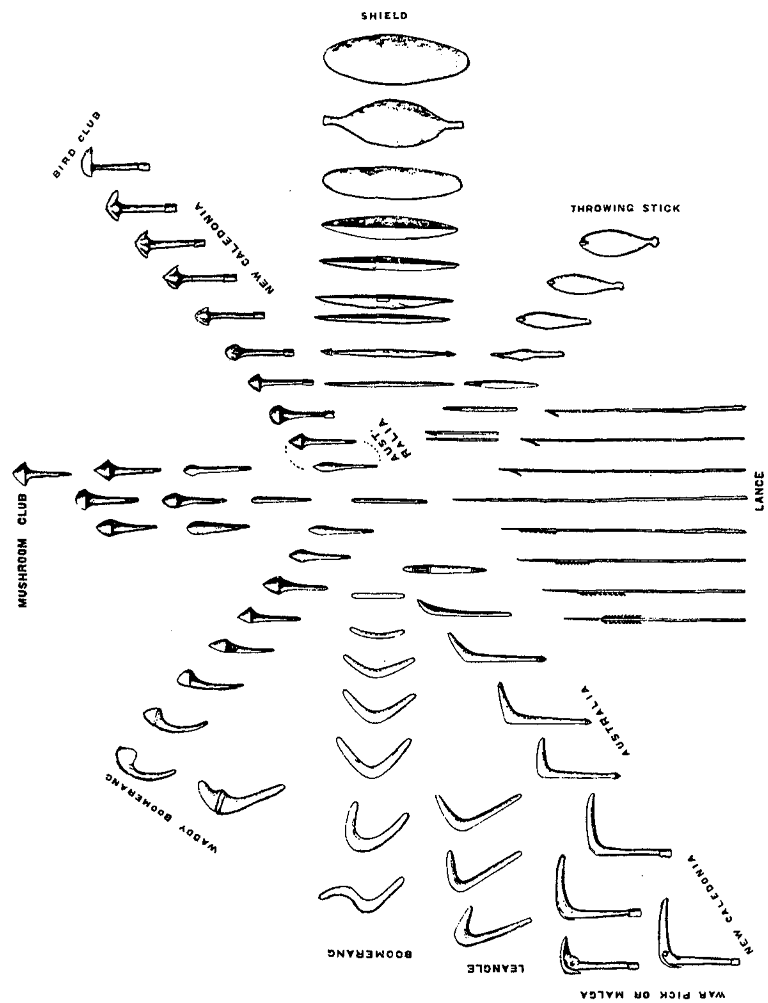


Figure I.3. The evolution of Australian aboriginal weapons. War clubs, boomerangs, lances, throwing sticks, and shields were arranged by Pitt-Rivers so that they would appear as evolutionary sequences radiating out from the simple stick at the center. These are not historical sequences; all of the weapons displayed were in use in modern times. Pitt-Rivers assumed that the simpler artifacts, those located closer to the center, were "survivals" of earlier forms. Source: A. Lane-Fox Pitt-Rivers, *The evolution of culture* (Oxford, 1906), pl. III; reprinted by AMS Press, Inc., New York.

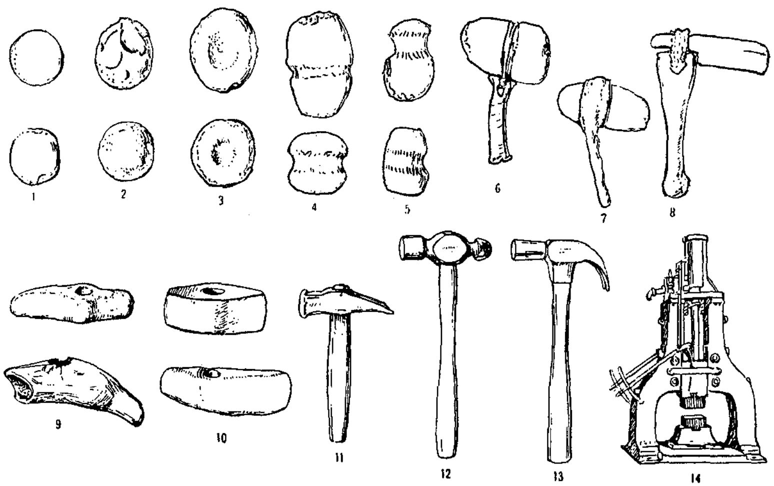


Figure I.4. The evolutionary history of the hammer, from the first crudely shaped pounding stone (1) to James Nasmyth's gigantic steam hammer of 1842 (14). This evolutionary sequence of a familiar hand tool was prepared by the staff of the U.S. National Museum to "indicate how the mind of man has arrived at certain datum points which mark epochs in progress." Following the example set by Pitt-Rivers (Fig. I.3), the "specimens are arranged in the order of their grade of development irrespective of race, place, or time." Source: Walter Hough, "Synoptic Series of Objects in the United States National Museum Illustrating the History of Inventions," *Proceedings of the United States National Museum* 60 (Washington, D.C., 1922), art. 9, p. 2, pl. 16.

an immediate need, they had inadvertently helped to promote technical progress.

For a modern observer to dismiss Pitt-Rivers's ideas as an overenthusiastic and uncritical application of Darwinism to material culture is all too easy. We must remember that he witnessed at first hand the immense success of Darwin's theory in biology and that he was personally acquainted with some of the master's friends. That he might want to make his contribution to the spread of evolutionary doctrine is understandable. On the other hand, twentieth-century anthropologists and historians have rejected the belief that unilinear technological progress is a hallmark of human culture, and they have demonstrated the fallacy of supposing that the cultures of prehistoric and living primitive peoples are virtually identical. These modern criticisms, which seriously challenge key elements of Pitt-

Rivers's theories, have been widely publicized. Less well known are the original and enduring aspects of Pitt-Rivers's approach.

At a time when material culture studies were largely descriptive, if not outright antiquarian, Pitt-Rivers offered a theoretical basis for the integration of intellectual and technological achievements. An artifact was more than an inert object hastily fashioned to meet a need. It was a surviving remnant of the human mind that conceived it. Contrary to many of his contemporaries, Pitt-Rivers believed that technological change was not accomplished by a series of great, unrelated leaps forward by a few heroic inventors. Instead, the form of a modified artifact was based on that of a preexisting predecessor. From this followed the insight that every made thing could be placed within a sequence, which itself was interconnected to other sequences, and that, if we followed these backward in time, they would converge, leading us to the traces of the earliest human artifacts.

Cumulative Change

Butler and Pitt-Rivers were by no means representative of the prevailing view of the nature of technological change. The evolutionary, or continuous, explanation that they adopted was much less widely accepted than the revolutionary, or discontinuous, interpretation. According to the latter, inventions emerge in a fully developed state from the minds of gifted inventors. In this heroic theory of invention, small improvements in technology are ignored or discounted and all emphasis is placed upon the identification of major breakthroughs by specific individuals – for example, the steam engine by James Watt, or the cotton gin by Eli Whitney.

Not long after Darwin published *Origin of Species*, Karl Marx, a great admirer of the English naturalist, called for a critical history of technology written along evolutionary lines. He believed such a history would reveal how little the Industrial Revolution owed to the work of individual inventors. Invention is a social process, argued Marx, that rests on the accumulation of many minor improvements, not the heroic efforts of a few geniuses.

In the first half of the twentieth century, the heroic view of invention was challenged by three American scholars – William F. Ogburn, S. C. Gilfillan, and Abbott Payson Usher – who advanced theories of technological change that drew upon Darwinism. Ogburn, a sociologist and the most influential of the three, began by defining invention as combining existing and known elements of culture in order to form a new element. The outcome of this process is a series of small changes, most of them patentable, but none of them constituting a sharp break with past material culture.

Ogburn claimed that a fixed percentage of individuals with superior inventive ability can be found among all peoples. As the population grows in any country, the number of potential inventors increases proportionally. If these inventors happen to be born into a culture that provides technical training and places a premium on novelty, then inventions are bound to appear in quantity. Initially, the pace of innovation is slow as a stockpile of inventions is established. The subsequent accumulation of novelties stimulates innovation because the number of elements available for combination has grown. Soon the accumulated novelties reach a critical point and a chain reaction takes place greatly accelerating the rate of inventive activity.

Ogburn made no attempt to test his highly abstract theory by determining if it was in agreement with a sizable body of empirical evidence. In contrast, his fellow sociologist S. C. Gilfillan, in the 1930s, wrote companion volumes on invention – the first offering a sociology of invention, the second a detailed study that focused on the evolution of the ship from its origin as a floating log to the modern diesel-engine motorship.

Gilfillan was adamantly opposed to any theory of technological change that assigned inventions to what he called "titular inventors," those whose names were enshrined in the popular mythology of invention. Adhering to the Darwinian model, he wrote of the "undivided continuum of inventional reality"[4] and blamed language, custom, and social conventions for breaking down the continuum into a series of discrete, identifiable inventions.

The test of Gilfillan's theory is found in his second volume. According to him, the ship began as a hollowed-out log that was paddled by hand. When the earliest sailors stood up in their dugout canoes and found that the wind blowing against their garments increased the speed of their vessels, the sail was invented. Reconstructing the entire history of sailing ships from that point, using an evolutionary perspective, is relatively easy. Only the steam-powered craft seemingly disrupts the continuous flow. Gilfillan overcame this obstacle by placing the origin of the steamship in the Byzantine Empire. A war vessel moved by paddle wheels powered by three pair of oxen appears in an illustration from the early sixth century A.D. Paddle-wheel boats using ox or horse power thereafter evolved in a regular fashion. In the eighteenth century Europeans and Americans substituted steam for animal power to turn the paddle wheels. The issue was not the steam engine versus the sail, but the use of a steam engine versus oxen and horses to power a paddle-wheel boat.

Gilfillan concedes that there may be a dozen or so maritime inventions that could be termed abrupt in that they had no known or obvious predecessor. The ancient oxen-driven paddle-wheel boat is one such anomaly. Given that the development of the ship necessitated the accumulation of hundreds of thousands of minor inventions, Gilfillan is not troubled by the few innovations that appear to contradict his evolutionary stand. He maintains that the anomalies can be explained if we recognize that the cumulative process did not always take place in public, with the building of full-scale vessels. Gradual improvements may have been made in a series of rough sketches, formal drawings, or models before the results were tried in a full-size working ship. In this fashion abrupt inventions in the evolution of the ship can be dispensed with and Gilfillan's continuous curve of change reinstated.

Economic historian Abbott P. Usher, however, found the theories of invention put forth by Ogburn and Gilfillan excessively mechanistic. Inventors were depicted as mere instruments in a rigidly predetermined historical process. By emphasizing the social character of invention, and calling attention to the cumulative effects of small improvements, the two had ignored the importance of the individual inventor's efforts and insights. They would have us believe, Usher argued, that when the critical number of novel elements is reached the invention will appear automatically, with only a little help from an inventor.

Therefore, Usher proposed the *cumulative synthesis approach* to invention, an approach that modified the continuous explanation and enriched it with the findings of Gestalt psychology. Usher's theory contained four premises.

1. *Perception of the problem* – an incomplete or unsatisfactory pattern in need of resolution is recognized.
2. *Setting the stage* – data related to the problem is assembled.
3. *Act of insight* – a solution to the problem is found by a mental act that is not predetermined. This act goes beyond the *act of skill* normally expected of a trained professional.
4. *Critical revision* – the solution is fully explored and revised (with possible refinements made because of new acts of insight).

Central to Usher's thesis are the acts of insight that essentially solve the problem. These acts are as important to major, or strategic, inventions as they are to minor ones. The cumulative synthesis of lesser individual inventions eventually produces the strategic inventions better known to history. Yet the process is neither automatic nor predetermined. Sheer numbers of inventions do not guarantee that a major technological change will occur. The key is always the inventor's act of insight by which certain elements are chosen, combined in innovative ways, and made to yield a solution.

The acts of insight might be probed by psychologists, but they are, for the most part, inexplicable. They introduce the role of the mental faculties to the process of invention and by their presence indicate precisely at what point economic forces can be brought to bear. When the stage is being set (step 2) and the solution critically revised (step 4), economic intervention is likely to be effective. The acts of insight (step 3), on the other hand, are unresponsive to economic influence. They belong to the psychological, not the economic, realm.

Even though Usher came to study the inventive process as an economic historian, his theory transcended a strict economic or social explanation. By stressing the psychological aspects of invention, he served notice that the emergence of novelty must be dealt with in a broader context. Economists and economic historians who currently study invention do not follow Usher's lead on the importance of the acts of insight. Many of them do, however, accept his Darwinian-inspired idea that technical progress is the result of cumulative change.

A Modern Theory of Technological Evolution

My survey of past attempts to explain technological change by use of an evolutionary model has laid the groundwork for a consideration of the theory I will develop in this book. The study of Butler and Pitt-Rivers revealed that artifacts, like plant- and animal-life forms, can be arranged in continuous, chronological sequences. However, a modern theory of technological evolution cannot be built on an evocation of Darwinism for the purposes of literary and social satire (Butler), or on hypothetical chains of related primitive weapons (Pitt-Rivers). It is likewise unsatisfactory to limit the choice of illustrative examples to a single field of technology (Gilfillan), or to pursue a highly theoretical approach and ignore the technical details of artifactual change (Ogburn). Therefore, my theory will be supported throughout by detailed case studies of artifacts chosen from diverse technologies, cultures, and historical eras.

Butler, Pitt-Rivers, Gilfillan, Ogburn, and Usher all stressed the accumulation over time of small variations that finally yielded novel artifacts. Usher, by introducing "acts of insight" into the inventive process, drew attention to the role of individual creativity but he remained convinced that major inventions resulted from the cumulative synthesis of a series of minor ones. In the cumulative theory of invention change is slow and inevitable, and there is little room for the bold innovations of gifted individuals. My theory of technological evolution recognizes the larger changes, often associated with name inventors, as well as smaller changes made over a long duration. Hence, I accept periods of rapid technological change and times of relative stability.

Anyone advocating the continuous nature of technological change must acknowledge, and account for, the popularity of the opposing discontinuous view. There are many people who believe that technology advances by leaps from one great invention to another as the genius inventor creates a host of wonderful inventions through sheer mental effort. I reveal the sources of this belief by examining the relevant ideas and institutions of Western civilization that fostered its origin and growth.

Finally, my theory of technological evolution, unlike any of its predecessors, is rooted in four broad concepts: diversity, continuity, novelty, and selection. As I have already shown, the made world contains a far greater variety of things than are required to meet fundamental human needs. This *diversity* can be explained as the result of technological evolution because artifactual *continuity* exists; *novelty* is an integral part of the made world; and a *selection* process operates to choose novel artifacts for replication and addition to the stock of made things. The remainder of this book will be devoted to a thorough analysis of the theoretical and artifactual ramifications of these four concepts.