THE NATURE OF TECHNOLOGY

As long as there have been people, there has been technology. Indeed, the techniques of shaping tools are taken as the chief evidence of the beginning of human culture. On the whole, technology has been a powerful force in the development of civilization, all the more so as its link with science has been forged. Technology—like language, ritual, values, commerce, and the arts—is an intrinsic part of a cultural system and it both shapes and reflects the system's values. In today's world, technology is a complex social enterprise that includes not only research, design, and crafts but also finance, manufacturing, management, labor, marketing, and maintenance.

In the broadest sense, technology extends our abilities to change the world: to cut, shape, or put together materials; to move things from one place to another; to reach farther with our hands, voices, and senses. We use technology to try to change the world to suit us better. The changes may relate to survival needs such as food, shelter, or defense, or they may relate to human aspirations such as knowledge, art, or control. But the results of changing the world are often complicated and unpredictable. They can include unexpected benefits, unexpected costs, and unexpected risks—any of which may fall on different social groups at different times. Anticipating the effects of technology is therefore as important as advancing its capabilities.

This chapter presents recommendations on what knowledge about the nature of technology is required for scientific literacy and emphasizes ways of thinking about technology that can contribute to using it wisely. The ideas are sorted into three sections: the connection of science and technology, the principles of technology itself, and the connection of technology and society. Chapter 8, The Designed World, presents principles relevant to some of the key technologies of today's world. Chapter 10, Historical Perspectives, includes a discussion of the Industrial Revolution. Chapter 12, Habits of Mind, includes some skills relevant to participating in a technological world.

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TECHNOLOGY AND SCIENCE

Technology Draws on Science and Contributes to It

In earlier times, **technology** grew out of personal experience with the properties of things and with the techniques for manipulating them, out of know-how handed down from experts to apprentices over many generations. The know-how handed down today is not only the craft of single practitioners but also a vast literature of words, numbers, and pictures that describe and give directions. But just as important as accumulated practical knowledge is the contribution to technology that comes from understanding the principles that underlie how things behave—that is, from scientific understanding.

Engineering, the systematic application of scientific knowledge in developing and applying technology, has grown from a craft to become a science in itself. **Scientific knowledge** provides a means of estimating what the behavior of things will be even before we make them or observe them. Moreover, science often suggests new kinds of behavior that had not even been imagined before, and so leads to new technologies. **Engineers use knowledge of science and technology**, together with strategies of design, to solve practical problems.

In return, technology provides the eyes and ears of science—and some of the muscle, too. The electronic computer, for example, has led to substantial progress in the study of weather systems, demographic patterns, gene structure, and other complex systems that would not have been possible otherwise. **Technology is essential to science** for purposes of measurement, data collection, treatment of samples, computation, transportation to research sites (such as Antarctica, the moon, and the ocean floor), sample collection, protection from hazardous materials, and communication. More and more, new instruments and techniques are being developed through technology that make it possible to advance various lines of scientific research.

Technology does not just provide tools for science, however; it also may provide motivation and direction for theory and research. The theory of the conservation of energy, for example, was developed in large part because of the technological problem of increasing the efficiency of commercial steam engines. The mapping of the locations of the entire set of genes in human DNA has been motivated by the technology of genetic engineering, which both makes such mapping possible and provides a reason for doing so.

As technologies become more sophisticated, their links to science become stronger. In some fields, such as solid-state physics (which involves transistors and superconductors), the ability to make something and the ability to study it are so interdependent that science and engineering can scarcely be separated. New technology often requires new understanding; new investigations often require new technology.

Engineering Combines Scientific Inquiry and Practical Values

The component of technology most closely allied to scientific inquiry and to mathematical modeling is engineering. In its broadest sense, engineering consists of construing a problem and designing a solution for it. The basic method is to first devise a general approach and then work out the technical details of the construction of requisite objects (such as an automobile engine, a computer chip, or a mechanical toy) or processes (such as irrigation, opinion polling, or product testing).

Much of what has been said about the nature of science applies to engineering as well, particularly the use of mathematics, the interplay of creativity and logic, the eagerness to be original, the variety of people involved, the professional specialties, public responsibility, and so on. Indeed, there are more people called engineers than people called scientists, and many scientists are doing work that could be described as engineering as well as science. Similarly, many engineers are engaged in science.

Scientists see patterns in phenomena as making the world understandable; engineers also see them as making the world manipulable. Scientists seek to show that theories fit the data; mathematicians seek to show logical proof of abstract connections; engineers seek to demonstrate that designs work. Scientists cannot provide answers to all questions; mathematicians cannot prove all possible connections; engineers cannot design solutions for all problems.

But engineering affects the social system and culture more directly than scientific research, with immediate implications for the success or failure of human enterprises and for personal benefit and harm. Engineering decisions, whether in designing an airplane bolt or an irrigation system, inevitably involve social and personal values as well as scientific judgments.

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DESIGN AND SYSTEMS

The Essence of Engineering Is Design Under Constraint

Every engineering design operates within constraints that must be identified and taken into account. One type of constraint is absolute—for example, physical laws such as the conservation of energy or physical properties such as limits of flexibility, electrical conductivity, and friction. Other types have some flexibility: economic (only so much money is available for this purpose), political (local, state, and national regulations), social (public opposition), ecological (likely disruption of the natural environment), and ethical (disadvantages to some people, risk to subsequent generations). An optimum design takes into account all the constraints and strikes some reasonable compromise among them. Reaching such design compromises—including, sometimes, the decision not to develop a particular technology further—requires taking personal and social values into account. Although design may sometimes require only routine decisions about the combining of familiar components, often it involves great creativity in inventing new approaches to problems, new components, and new combinations—and great innovation in seeing new problems or new possibilities.

But there is no perfect design. Accommodating one constraint well can often lead to conflict with others. For example, the lightest material may not be the strongest, or the most efficient shape may not be the safest or the most aesthetically pleasing. Therefore every design problem lends itself to many alternative solutions, depending on what values people place on the various constraints. For example, is strength more desirable than lightness, and is appearance more important than safety? The task is to arrive at a design that reasonably balances the many trade-offs, with the understanding that no single design is ever simultaneously the safest, the most reliable, the most efficient, the most inexpensive, and so on.

It is seldom practical to design an isolated object or process without considering the broad context in which it will be used. Most products of technology have to be operated, maintained, occasionally repaired, and ultimately replaced. Because all these related activities bear costs, they too have to be considered. A similar issue that is becoming increasingly important with more complex technologies is the need to train personnel to sell, operate, maintain, and repair them. Particularly when technology changes quickly, training can be a major cost. Thus, keeping down demands on personnel may be another design constraint.

Designs almost always require testing, especially when the design is unusual or complicated, when the final product or process is likely to be expensive or dangerous, or when failure has a very high cost. Performance tests of a design may be conducted by using complete products, but doing so may be prohibitively difficult or expensive. So testing is often done by using small-scale physical models, computer simulations, analysis of analogous systems (for example, laboratory animals standing in for humans, earthquake disasters for nuclear disasters), or testing of separate components only.

All Technologies Involve Control

All systems, from the simplest to the most complex, require control to keep them operating properly. The essence of control is comparing information about what is happening with what we want to happen and then making appropriate adjustments. Control typically requires feedback (from sensors or other sources of information) and logical comparisons of that information to instructions (and perhaps to other data input)—and a means for activating changes. For example, a baking oven is a fairly simple system that compares the information from a temperature sensor to a control setting and turns the heating element up or down to keep the temperature within a small range. An automobile is a more complex system, made up of subsystems for controlling engine temperature, combustion rate, direction, speed, and so forth, and for changing them when the immediate circumstances or instructions change. Miniaturized electronics makes possible logical control in a great variety of technical systems. Almost all but the simplest household appliances used today include microprocessors to control their performance.

As controls increase in complexity, they too require coordination, which means additional layers of control. Improvement in rapid communication and rapid processing of information makes possible very elaborate systems of control. Yet all technological systems include human as well as mechanical or electronic components. Even the most automatic system requires human control at some point—to program the built-in control elements, monitor them, take over from them when they malfunction, and change them when the purposes of the system change. The ultimate control lies with people who understand in some depth what the purpose and nature of the control process are and the context within which the process operates.

Technologies Always Have Side Effects

In addition to its intended benefits, every design is likely to have unintended side effects in its production and application. On the one hand, there may be unexpected benefits. For example, working conditions may become safer when materials are molded rather than stamped, and materials designed for space satellites may prove useful in consumer products. On the other hand, substances or processes involved in production may harm production workers or the public in general; for example, sitting in front of a computer may strain the user's eyes and lead to isolation from other workers. And jobs may be affected—by increasing employment for people involved in the new technology, decreasing employment for others involved in the old technology, and changing the nature of the work people must do in their jobs.

It is not only large technologies—nuclear reactors or agriculture—that are prone to side effects, but also the small, everyday ones. The effects of ordinary technologies may be individually small but collectively significant. Refrigerators, for example, have had a predictably favorable impact on diet and on food distribution systems. Because there are so many refrigerators, however, the tiny leakage of a gas used in their cooling systems may have substantial adverse effects on the earth's atmosphere.

Some side effects are unexpected because of a lack of interest or resources to predict them. But many are not predictable even in principle because of the sheer complexity of technological systems and the inventiveness of people in finding new applications. Some unexpected side effects may turn out to be ethically, aesthetically, or economically unacceptable to a substantial fraction of the population, resulting in conflict between groups in the community. To minimize such side effects, planners are turning to systematic risk analysis. For example, many communities require by law that environmental impact studies be made before they will consider giving approval for the introduction of a new hospital, factory, highway, waste-disposal system, shopping mall, or other structure.

Risk analysis, however, can be complicated. Because the risk associated with a particular course of action can never be reduced to zero, acceptability may have to be determined by comparison to the risks of alternative courses of action, or to other, more familiar risks. People's psychological reactions to risk do not necessarily match straightforward mathematical models of benefits and costs. People tend to perceive a risk as higher if they have no control over it (smog versus smoking) or if the bad events tend to come in dreadful peaks (many deaths at once in an airplane crash versus only a few at a time in car crashes). Personal interpretation of risks can be strongly influenced by how the risk is stated—for example, comparing the probability of dying versus the probability of surviving, the dreaded risks versus the readily acceptable risks, the total costs versus the costs per person per day, or the actual number of people affected versus the proportion of affected people.

All Technological Systems Can Fail

Most modern technological systems, from transistor radios to airliners, have been engineered and produced to be remarkably reliable. Failure is rare enough to be surprising. Yet the larger and more complex a system is, the more ways there are in which it can go wrong—and the more widespread the possible effects of failure. A system or device may fail for different reasons: because some part fails, because some part is not well matched to some other, or because the design of the system is not adequate for all the conditions under which it is used. One hedge against failure is overdesign—that is, for example, making something stronger or bigger than is likely to be necessary. Another hedge is redundancy—that is, building in one backup system or more to take over in case the primary one fails.

If failure of a system would have very costly consequences, the system may be designed so that its most likely way of failing would do the least harm. Examples of such "fail-safe" designs are bombs that cannot explode when the fuse malfunctions; automobile windows that shatter into blunt, connected chunks rather than into sharp, flying fragments; and a legal system in which uncertainty leads to acquittal rather than conviction. Other means of reducing the likelihood of failure include improving the design by collecting more data, accommodating more variables, building more realistic working models, running computer simulations of the design longer, imposing tighter quality control, and building in controls to sense and correct problems as they develop.

All of the means of preventing or minimizing failure are likely to increase cost. But no matter what precautions are taken or resources invested, risk of technological failure can never be reduced to zero. Analysis of risk, therefore, involves estimating a probability of occurrence for every undesirable outcome that can be foreseen—and also estimating a measure of the harm that would be done if it did occur. The expected importance of each risk is then estimated by combining its probability and its measure of harm. The relative risk of different designs can then be compared in terms of the combined probable harm resulting from each.

ISSUES IN TECHNOLOGY

The Human Presence

The earth's population has already doubled three times during the past century. Even at that, the human presence, which is evident almost everywhere on the earth, has had a greater impact than sheer numbers alone would indicate. We have developed the capacity to dominate most plant and animal species—far more than any other species can—and the ability to shape the future rather than merely respond to it.

Use of that capacity has both advantages and disadvantages. On the one hand, developments in technology have brought enormous benefits to almost all people. Most people today have access to goods and services that were once luxuries enjoyed only by the wealthy—in transportation, communication, nutrition, sanitation, health care, entertainment, and so on. On the other hand, the very behavior that made it possible for the human species to prosper so rapidly has put us and the earth's other living organisms at new kinds of risk. The growth of agricultural technology has made possible a very large population but has put enormous strain on the soil and water systems that are needed to continue sufficient production. Our antibiotics cure bacterial infection, but may continue to work only if we invent new ones faster than resistant bacterial strains emerge.

Our access to and use of vast stores of fossil fuels have made us dependent on a nonrenewable resource. In our present numbers, we will not be able to sustain our way of living on the energy that current technology provides, and alternative technologies may be inadequate or may present unacceptable hazards. Our vast mining and manufacturing efforts produce our goods, but they also dangerously pollute our rivers and oceans, soil, and atmosphere. Already, by-products of industrialization in the atmosphere may be depleting the ozone layer, which screens the planet's surface from harmful ultraviolet rays, and may be creating a buildup of carbon dioxide, which traps heat and could raise the planet's average temperatures significantly. The environmental consequences of a nuclear war, among its other disasters, could alter crucial aspects of all life on earth.

From the standpoint of other species, the human presence has reduced the amount of the earth's surface available to them by clearing large areas of vegetation; has interfered with their food sources; has changed their habitats by changing the temperature and chemical composition of large parts of the world environment; has destabilized their ecosystems by introducing foreign species, deliberately or accidentally; has reduced the number of living species; and in some instances has actually altered the characteristics of certain plants and animals by selective breeding and more recently by genetic engineering.

What the future holds for life on earth, barring some immense natural catastrophe, will be determined largely by the human species. The same intelligence that got us where we are—improving many aspects of human existence and introducing new risks into the world—is also our main resource for survival.

Technological and Social Systems Interact Strongly

Individual inventiveness is essential to technological innovation. Nonetheless, social and economic forces strongly influence what technologies will be undertaken, paid attention to, invested in, and used. Such decisions occur directly as a matter of government policy and indirectly as a consequence of the circumstances and values of a society at any particular time. In the United States, decisions about which technological options will prevail are influenced by many factors, such as consumer acceptance, patent laws, the availability of risk capital, the federal budget process, local and national regulations, media attention, economic competition, tax incentives, and scientific discoveries. The balance of such incentives and regulations usually bears differently on different technological systems, encouraging some and discouraging others.

Technology has strongly influenced the course of history and the nature of human society, and it continues to do so. The great revolutions in agricultural technology, for example, have probably had more influence on how people live than political revolutions; changes in sanitation and preventive medicine have contributed to the population explosion (and to its control); bows and arrows, gunpowder, and nuclear explosives have in their turn changed how war is waged; and the microprocessor is changing how people write, compute, bank, operate businesses, conduct research, and communicate with one another. Technology is largely responsible for such large-scale changes as the increased urbanization of society and the dramatically growing economic interdependence of communities worldwide.

Historically, some social theorists have believed that technological change (such as industrialization and mass production) causes social change, whereas others have believed that social change (such as political or religious changes) leads to technological change. However, it is clear that because of the web of connections between technological and other social systems, many influences act in both directions.

The Social System Imposes Some Restrictions on Openness in Technology

For the most part, the professional values of engineering are very similar to those of science, including the advantages seen in the open sharing of knowledge. Because of the economic value of technology, however, there are often constraints on the openness of science and engineering that are relevant to technological innovation. A large investment of time and money and considerable commercial risk are often required to develop a new technology and bring it to market. That investment might well be jeopardized if competitors had access to the new technology without making a similar investment, and hence companies are often reluctant to share technological knowledge. But no scientific or technological knowledge is likely to remain secret for very long. Secrecy most often provides only an advantage in terms of time—a head start, not absolute control of knowledge. Patent laws encourage openness by giving individuals and companies control over the use of any new technology they develop; however, to promote technological competition, such control is only for a limited period of time.

Commercial advantage is not the only motivation for secrecy and control. Much technological development occurs in settings, such as government agencies, in which commercial concerns are minimal but national security concerns may lead to secrecy. Any technology that has potential military applications can arguably be subject to restrictions imposed by the federal government, which may limit the sharing of engineering knowledge—or even the exportation of products from which engineering knowledge could be inferred. Because the connections between science and technology are so close in some fields, secrecy inevitably begins to restrict some of the free flow of information in science as well. Some scientists and engineers are very uncomfortable with what they perceive as a compromise of the scientific ideal, and some refuse to work on projects that impose secrecy. Others, however, view the restrictions as appropriate.

Decisions About the Use of Technology Are Complex

Most technological innovations spread or disappear on the basis of free-market forces—that is, on the basis of how people and companies respond to such innovations. Occasionally, however, the use of some technology becomes an issue subject to public debate and possibly formal regulation. One way in which technology becomes such an issue is when a person, group, or business proposes to test or introduce a new technology—as has been the case with contour plowing, vaccination, genetic engineering, and nuclear power plants. Another way is when a technology already in widespread use is called into question—as, for example, when people are told (by individuals, organizations, or agencies) that it is essential to stop or reduce the use of a particular technology or technological product that has been discovered to have, or that may possibly have, adverse effects. In such instances, the proposed solution may be to ban the burial of toxic wastes in community dumps, or to prohibit the use of leaded gasoline and asbestos insulation.

Rarely are technology-related issues simple and one-sided. Relevant technical facts alone, even when known and available (which often they are not), usually do not settle matters entirely in favor of one side or the other. The chances of reaching good personal or collective decisions about technology depend on having information that neither enthusiasts nor skeptics are always ready to volunteer. The long-term interests of society are best served, therefore, by having processes for ensuring that key questions concerning proposals to curtail or introduce technology are raised and that as much relevant knowledge as possible is brought to bear on them. Considering these questions does not ensure that the best decision will always be made, but the failure to raise key questions will almost certainly result in poor decisions. The key questions concerning any proposed new technology should include the following:

- What are alternative ways to accomplish the same ends? What advantages and disadvantages are there to the alternatives? What trade-offs would be necessary between positive and negative side effects of each?
- Who are the main beneficiaries? Who will receive few or no benefits? Who will suffer as a result of the proposed new technology? How long will the benefits last? Will the technology have other applications? Whom will they benefit?
- What will the proposed new technology cost to build and operate? How does that compare to the cost of alternatives? Will people other than the beneficiaries have to bear the costs? Who should underwrite the development costs of a proposed new technology? How will the costs change over time? What will the social costs be?
- What risks are associated with the proposed new technology? What risks are associated with not using it? Who will be in greatest danger? What risk will the technology present to other species of life and to the environment? In the worst possible case, what trouble could it cause? Who would be held responsible? How could the trouble be undone or limited?
- What people, materials, tools, knowledge, and know-how will be needed to build, install, and operate the proposed new technology? Are they available? If not, how will they be obtained, and from where? What energy sources will be needed for construction or manufacture, and also for operation? What resources will be needed to maintain, update, and repair the new technology?
- What will be done to dispose safely of the new technology's waste materials? As it becomes obsolete or worn out, how will it be replaced? And finally, what will become of the material of which it was made and the people whose jobs depended on it?

Individual citizens may seldom be in a position to ask or demand answers for these questions on a public level, but their knowledge of the relevance and importance of answers increases the attention given to the questions by private enterprise, interest groups, and public officials. Furthermore, individuals may ask the same questions with regard to their own use of technology—for instance, their own use of efficient household appliances, of substances that contribute to pollution, of foods and fabrics. The cumulative effect of individual decisions can have as great an impact on the large-scale use of technology as pressure on public decisions can.

Not all such questions can be answered readily. Most technological decisions have to be made on the basis of incomplete information, and political factors are likely to have as much influence as technical ones, and sometimes more. But scientists, mathematicians, and engineers have a special role in looking as far ahead and as far afield as is practical to estimate benefits, side effects, and risks. They can also assist by designing adequate detection devices and monitoring techniques, and by setting up procedures for the collection and statistical analysis of relevant data.