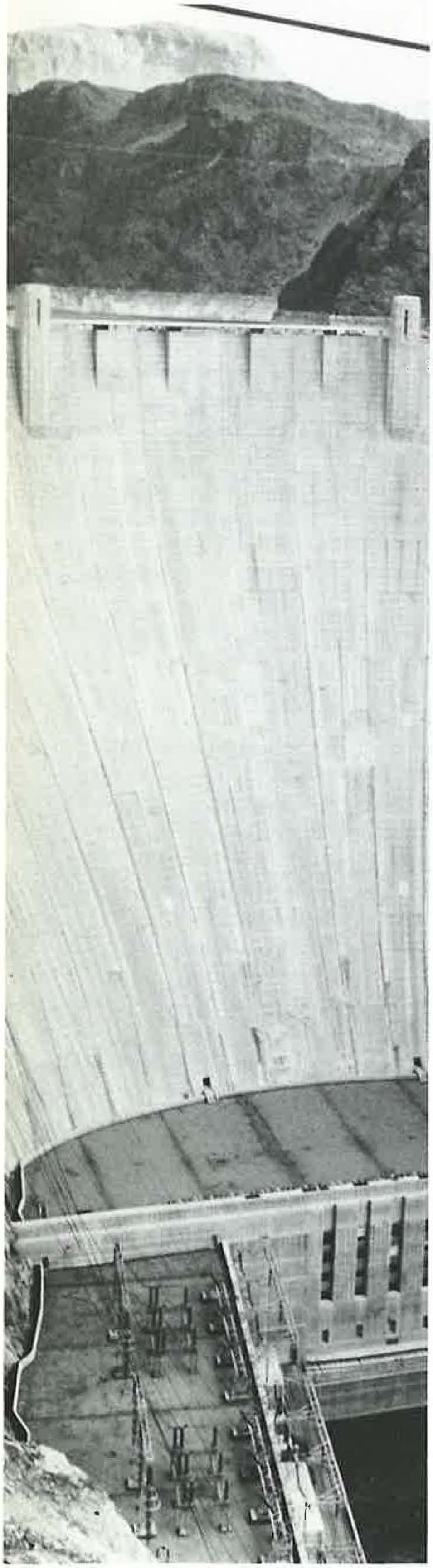

In Defense of Engineers

DAVID P. BILLINGTON

The 16th century was an era of religious crisis and *reformation* in the West, and the late 18th century was a time of political *revolution*. Today, we are in the midst of a technological *reordering* of the world. Technology, from nuclear arms to pocket calculators, has changed radically the way we live. On television, in congressional committees, and around dinner tables, the dangers and dividends of technological change are constantly discussed. Yet Americans' knowledge of technology—its whys and wherefores, its true values—is meager.

Americans seem to have concluded that a broad education, spanning the arts and sciences, is impossible in today's complex world, that knowledge must be increasingly specialized and segmented, sliced fine, and filed away. At American universities, liberal arts students often graduate without even a rudimentary education in technology. Institutions of higher learning seem to have deserted the notion that there is a unity to all knowledge. Science as curiosity, politics as civic virtue, and art as imagination are all waning concepts, often ridiculed as "elitist," or worse—not even discussed.

While relatively few American scholars study technology, many academics readily blame it for what they consider the "sterility" and "narrowness" of modern life. In his best-selling book for Random House, *The Greening of America* (1970), Charles A. Reich portrayed modern men as "prisoners of the technological state, exploited by its economy, tied to its goals, regimented by its factories and offices, deprived of all those sides of life [that] find no functional utility in the industrial machine." Reich's lament still seems to ring true to many Americans, in and out of academe.

When people talk about technology today, they usually mean the *products* of modern engineering: computers, power plants, automobiles, nuclear weapons. Today, technology is essentially synonymous with modern engineering, though technology has been with us since primitive man first sharpened a stone into a knife, while professional engineering is a child of the Industrial Revolution. But what exactly is this elusive activity? How do we define its products?

Most people probably would give one of two answers. Some would say that engineering consists of applying laws of nature to the needs of mankind, that it is simply an "applied science." Others would reply that engineering is the business of building machines and other mechanisms.

D. P. Billington is professor of civil engineering at Princeton University. He was elected to the National Academy of Engineering in 1986. This article is reprinted from the New Year's 1986 issue of *The Wilson Quarterly* and is adapted from the author's 1985 Harrelson Lecture at North Carolina State University and a subsequent paper presented at the Southern University Conference. The article also appeared in *The Bridge*, National Academy of Engineering, Summer 1986.

Both answers miss the mark. The central activity of engineering is design, and the primary motive for design is the creation of an object that works. Engineers do not sit down at the drawing board aiming to apply some abstract scientific law. Of course, they take all of the help they can get from scientists—as well as from politicians, business executives, and others. They do study the laws of nature, but chiefly to ensure that their works do not violate them; they are not engaged in some kind of scavenger hunt for inspiration. Engineers are about as dependent on modern scientific theories and discoveries as poets are on the hypotheses of modern linguists.

Then there is the common misconception that modern machines, tools, and other devices are engineering's only artifacts. What kind of machine is a highway or a dam or a bridge? No kind at all. Contemplating this question is about the same as asking what kind of painting is *The Thinker* or the *Pietà?* They are sculptures, but each still belongs, along with paintings, in the general category known as the visual arts. In the same way, the Brooklyn Bridge is not a machine but a structure, yet it also falls within the realm of modern engineering.

Structures and machines are the two sides of technology, and they cannot be understood only as isolated objects. They are parts of larger *systems*. Without the streets that feed it, the Brooklyn Bridge would be useless. It is part of the transportation network of New York City. The car crossing it is the the product of a system of manufacture.

Engineering's systems can be divided into two complementary types: *networks*, such as streets or electric power grids, and *processes*, such as the assembly line or the refining of oil.

A network, like a structure, is a static system through which something travels, whereas a process, like a machine, is a dynamic system through which something is changed.

These are not exclusionary terms. Traveling over city streets, cars and trucks do change (sometimes disastrously), but the engineer's goal in laying out roads is to preserve the vehicles as intact as possible. A mechanical process, by contrast, changes individual parts into a coherent whole: in a chemical plant, the idea is to convert raw materials into a finished product. The network transmits, the process transmutes. The structure fixes, the machine frees.

These patterns are fundamental to society itself. No civilized life is possible without transmission and transmutation, without fixed principles and basic freedoms. In our politics, the U.S. Constitution is fixed and contemporary laws are in flux. There are static arts, such as painting and sculpture, and relatively dynamic ones, such as dance and drama.

This language suggests a deep affinity between engineering and the liberal arts. In the public mind, engineering remains essentially a branch of the natural sciences. Just as the natural sciences in the West were misunderstood prior to the 20th century due to their classification as a branch of philosophy, so engineering has suffered in the house of science. Early in the 20th century, for example, a number of American engineers embraced the mathematical "deflection theory" as a guide to bridge design, which led to the construction of thinner and thinner suspension bridge decks. Then, in November 1940, the 4-month old, 2,800-foot-long Tacoma Narrows Bridge collapsed during a storm, its deck twisted like a bobsled track.

A century before, the great engineers Thomas Telford (1757–1834) and John A. Roebling (1806–1869) had warned of the danger of thin decks. But engineers who see their profession as an applied science tend not to look back. Engineers as designers of large-scale works for society must.

Science is discovery, engineering is design. Scientists study the natural, engineers create the artificial. Scientists create general theories out of observed data; engineers make things, often using only very approximate theories.

Modern engineering must be approached on its own terms if it is to be understood. It is practically oriented, but it is not a technique like repairing a car engine or using a word processor. In teaching my own course on engineering for liberal arts students, I find that they are drawn to the discipline by the same force that brings others to the natural sciences: curiosity. They want to find out how structures and machines work.

Science and engineering may share the same techniques of discovery—physical experiments, mathematical formulation—but students quickly learn that the techniques have vastly different applications in the two disciplines. En-

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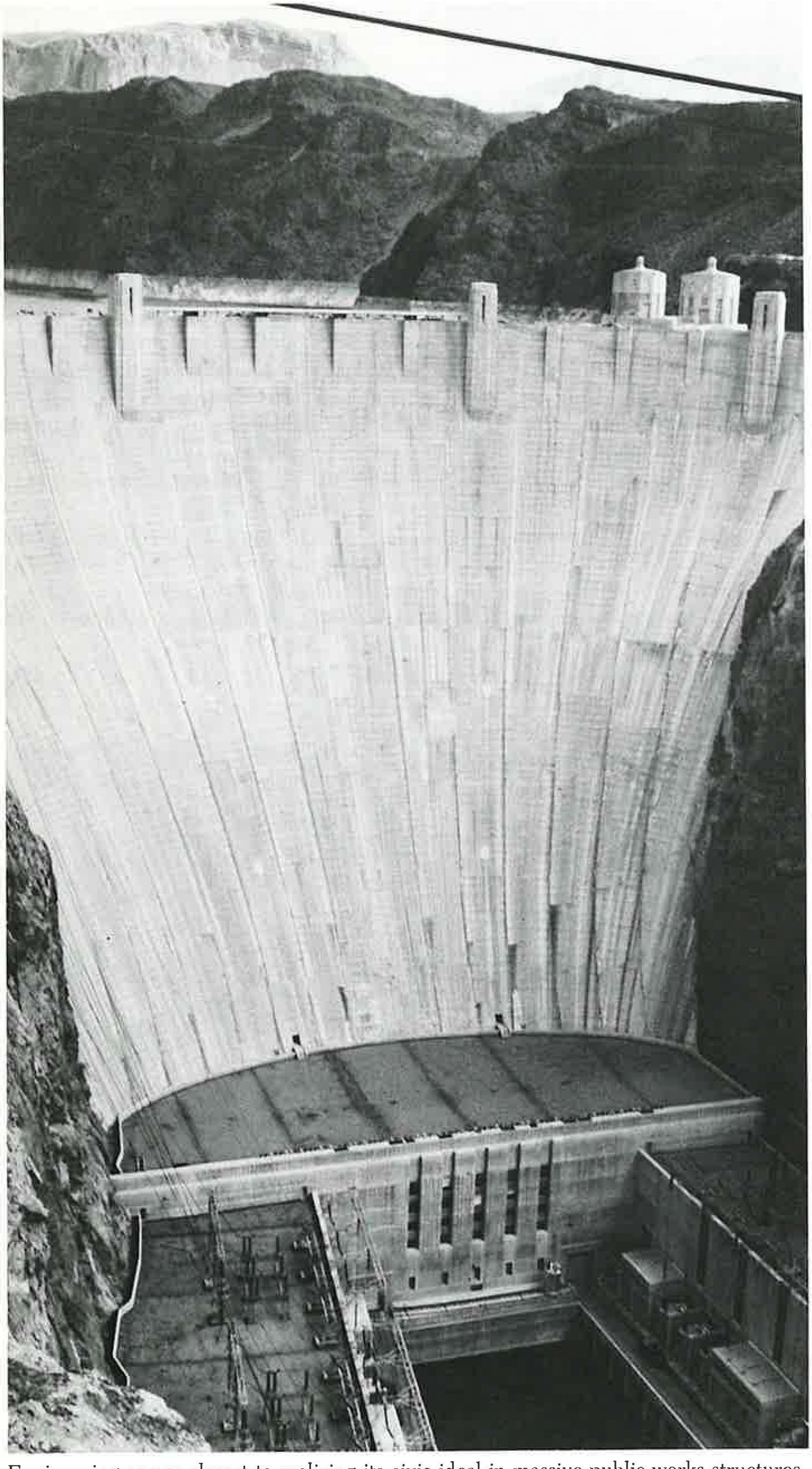

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gineering analysis is a matter of observing and testing the actual working of bridges, automobiles, and other objects made by people, while scientific analysis relies on closely controlled laboratory experiments or observations of natural phenomena and on general mathematical theories that explain them. The engineer studies objects in order to change them; the scientists, to explain them.

The emphasis on *practice* links engineering to the social sciences. In America, successful engineering requires not only technical competence but an understanding of the public will—whether expressed by voters, who decide if engineers' public works projects will be built, or by buyers of privately produced machines and structures, who "vote" in the marketplace. To the scientists alone in their laboratories, public opinion is largely irrelevant. The scientific ideal is to follow curiosity where it leads.

Engineering is linked to natural science through its techniques of analysis, but it parallels the study of economics, business management, and politics in its attention to labor costs and practices, production schedules, and local legislation (zoning laws, safety regulations). Bridge designers, for example, must know that union work rules in some locales make it more economical to use steel than concrete. They have to weigh the environmental impact of placing the bridge at different points, the effect on the fortunes of nearby communities, and the cost of each option.

In that sense, engineering shares with the social sciences an underlying ideal about the common life. The worth of engineering artifacts—bridges, automobiles, computers—is measured in terms of their benefit to society. This is the ancient ideal of civic virtue. "As a great work of art, and as a successful specimen of bridge engineering," Roebling said of his Brooklyn Bridge, "this structure will forever testify to the energy, enterprise, and wealth of that community which shall secure its erection."

One of the best-known offspring of engineering's concern with the public weal is cost-benefit analysis. But the discipline's civic ideal is far deeper, far richer. Cost-benefit analysis can help quantify the pluses and minuses of building a bridge or a highway, but it is no substitute for human judgment and creativity.

Engineering comes closest to realizing its civic ideal in massive public works such as the Hoover Dam, which straddles the Colorado River with one side anchored in Arizona, the other in Nevada. Hailed as visionary when it was completed in 1935 (only 7 years after Congress authorized construction), the dam was actually the logical culmination of earlier engineering achievements. Yet this massive concrete structure—660 feet thick at its base and 726 feet high, and linked to a complex system of conduits, generators, and roads—attained a new level of engineering elegance. It tames a wild river, transforming its roaring currents into static water pressure that powers 17 giant turbines. Simply, economically, the dam delivers hydroelectric power, irrigation, and flood control to six Western states. In ways large and small, it has altered their destinies.

It says something about the engineer's art that the dam was named not to honor Herbert C. Hoover the President but Hoover the engineer, who, as Secretary of Commerce during the Coolidge administration, negotiated the complex six-state agreement needed to begin work on the dam.

Engineers, said the French modernist architect Le Corbusier, are "healthy and virile, active and useful, balanced and happy in their work, but only the architect, by his arrangement of forms, realizes an order which is a pure creation of his spirit. . . . It is then we experience the sense of beauty." Le Corbusier's image of engineers as happy, unimaginative technocrats is now probably the popular view. In the universities, Le Corbusier's silly dictum has been taken at face value, and architecture has been accepted as central to the liberal arts (which it is) while engineering has been deemed irrelevant (which it is not).

Underlying this misconception is the notion that engineering is a purely rational activity, that for each technological problem there exists, as Jacques Ellul put it in *The Technological Society* (trans. 1964), a single solution that is the "one best way." All that engineers have to do is find it. Technology seems to dictate that artistic expression or personal taste are frills that engineers must do without. This is the logical outcome of the applied science view of technology. Blind to engineering's aesthetic achievements, many writers see only the march of logic and efficiency, trampling art, sensitivity, and humanity itself. Some years ago, Aldous Huxley, scion of a family of distinguished scientists and author of *Brave New World* (1932), asserted that modern "technological systems of production and organization are virtually fool-proof." He added, "if anything is fool-proof, it is also spontaneity-proof, inspiration-proof."

"One cannot walk through a mass production factory and not feel that one is in Hell," W. H. Auden once declared. Today, it is a fashionable view that modern Western society is a kind of technological wasteland, devoid of humanity, permeated by television and toxic wastes. In 1984, pundits by the dozen claimed that George Orwell's 1949 prophecy had come true, that in many ways *1984* was as much fact as fiction. Such critics of technology stress its power, never its imaginative depth.

Is there at the core of technology as an activity any room for the individual imagination? Ellul claimed that the answer is no. During the 19th century, he noted, manufacturers tried to ornament their products: sewing machines bore cast-iron flowers; tractor casings were engraved with bulls' heads. "That it was wasteful to supply such embellishments soon became evident," Ellul wrote. "The machine can become precise only to the degree that its design is elaborated with

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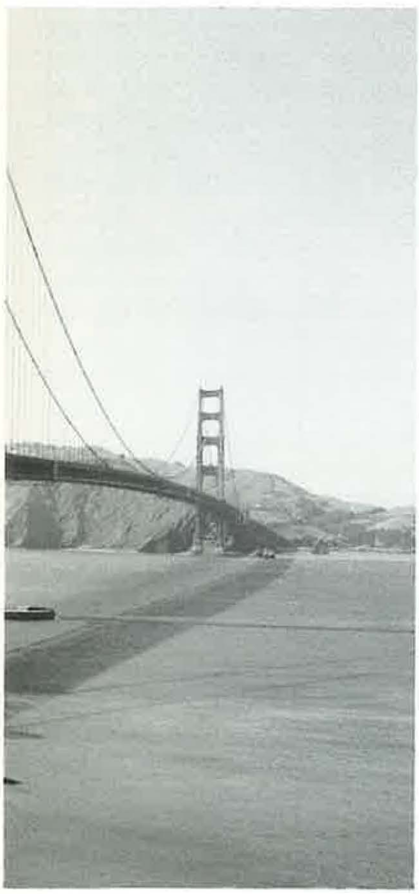
mathematical rigor in accordance with use. . . . There [is] no room in practical activity for gratuitous aesthetic preoccupations." Engineers, Ellul claimed, quickly adopted the utilitarian view that "the line best adapted to use is the most beautiful."

A century earlier, just after the birth of engineering as a formal discipline, Robert Fulton described the artistry of engineering in other terms. The engineer, he wrote, "should sit down among levers, screws, wedges, wheels, etc., like a poet among the letters of the alphabet, considering them as the exhibition of his thoughts, in which a new arrangement transmits a new idea to the world."

Artists' and writers' reactions give the lie to Ellul's bleak view. The majesty of the Brooklyn Bridge, designed by the German-born Roebling and completed in 1883 under the supervision of his son, Washington A. Roebling, inspired the painter Joseph Stella and the lyric poet Hart Crane to create their own works of art.[1] The beauty of San Francisco's Golden Gate Bridge stirs many who visit the City by the Bay. "Other art forms seem pretty piddling next to dams that challenge mountains, roads that leap chasms," architecture critic Ada Louise Huxtable wrote in the *New York Times* in 1964. "These structures stand in positive, creative contrast to the willful negativism and transient novelty that have made so much painting and literature, for example, a kind of diminishing, naughty game. The evidence is incontrovertible: building is the great art of our time."

Salginatobel Bridge (near Schiers, Canton of Graubuenden, Switzerland) by Robert Maillart (1872–1940). The Swiss structural engineer and bridge builder, whose work is the prototypical example of imagination in engineering, was the first to experiment with steel reinforced concrete to develop new forms for steel and concrete bridges and buildings.



Engineering first received its full aesthetic due in 1947, when New York's Museum of Modern Art mounted an exhibition of the works of Robert Maillart (1872–1940), the Swiss structural engineer and bridge builder. As many artists, architects, and art critics had already discovered, Maillart's work is the prototypical example of imagination in engineering. Maillart was the first structural engineer to realize that steel reinforced concrete, developed during the 1890s, could be used to experiment with new forms never seen in steel and concrete structures. And that is what he did, often to stunning effect, in dozens of bridges and buildings in Switzerland. It is wrong to say that Maillart made his structures beautiful by adding to their cost or even by adding superfluous materials. He did, in fact, just the reverse.

But, somebody will say, is that not the point? Is not the beauty of Maillart's works due precisely to the efficiency and economy of his designs?

It is all too easy to show that the world is filled with efficient and economical structures that are ugly and oppressive. Just look at the average railroad truss bridge. An engineer can no more create a beautiful structure based on these principles than can a poet write fine verse solely by limiting his arsenal of words. Something else is needed, and that something is imagination—a talent for putting things together in unique ways

[1] Roebling himself declared, "Public works should educate public taste. . . . In the erection of public edifices, therefore, some expense may and ought to be incurred to satisfy the artistic aspiration of a young and growing community." More often than not, however, Roebling's own designs did not require extra outlays. Even if they are inclined to add expensive ornamentation, structural designers cannot afford to do so. Because designers must always meet tight budgets, their incentive is to achieve the greatest beauty with the minimum materials possible.

that work, that are beautiful, personal, and permanent.

To assert that Maillart had imagination is not to prove it. How do we know that Hart Crane had a rich imagination? We read his finely wrought verse, his uniquely configured words, and their beauty moves us. But the general public needs some help in interpreting fine poetry. The same is true of the appreciation of structures. There is ample evidence that artistically sensitive people are moved by Maillart's works. Yet we still need to find a deeper basis for claiming that Maillart's works are triumphs of the imagination, not just products of technical expertise. We need to explore his *intentions*.

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From private letters and public reports, it is clear that Maillart thought aesthetically right from the beginning of his engineering career. He conceived of his first independent design, his 1900 plan for the modest Zuoz Bridge in Switzerland, as an aesthetic and technical innovation. In 1908, he invented a "slab" warehouse (so called because the concrete slab floors were supported by smoothly shaped "mushroom" columns, without cross beams), calling it both "more beautiful and more rational" than similar structures—not more beautiful *because* it was more rational. During his last decade, when he became known in artistic circles, Maillart wrote frequently about aesthetics. He clearly intended his structures to be both beautiful and economical.

Could he merely have fooled himself? The answer is that if Maillart's talents were purely technical, if he had hit upon the "one best way," his work would have set a new standard for design that others would have to follow. It did not. Engineers learned from Maillart, but the best ones do not copy him any more than serious artists paint pictures exactly like those of Leonardo da Vinci or Pablo Picasso.

Advocates of the "one best way" must assume that an optimum can always be found if we have computers that are powerful enough and analysts who are clever enough. But that is an illusion. There are two basic quantitative measures of designs: efficiency (minimum materials) and economy (minimum cost), and they are not reducible to any single measure. Efficiency is a measure of the type found in natural science; independent of time and place, it depends upon constraints such as gravity, wind, and the properties of steel and concrete. Economy, on the other hand, is constrained by labor practices, political controls, and other social factors. These can vary radically from place to place and from one time to another. Gothic cathedrals might be built efficiently today, but certainly not economically.

Thus, engineers are always confronted with two ideals, efficiency and economy, and the world's best computer could not tell them how to reconcile the two. There is never "one best way." Like doctors or politicians or poets, engineers face a vast array of choices every time they begin work, and every design is subject to criticism and compromise.

How can we judge the works of engineers? It would be madness to study poetry by reading a random sample of all the poems every published. But if we start with a master such as Shakespeare, we see poetry's potential. We recognize its beauty and permanence and learn that it provides themes that allow us to perceive the unity of all knowledge. And so it is with the works of Roebling and Maillart and the many other great structural artists of the past 200 years. Their works are the products of their imaginations, they are beautiful and permanent, and they provide us with themes that can satisfy the human urge for curiosity, virtue, and imagination.

What is true of structural engineering holds, in varying measures, for other forms of engineering as well. The integrated circuit and the space shuttle *Columbia* are each in their own ways works of beauty and imagination, and each can contribute to the common good. At the beginning of the 20th century, Americans embraced technology with an innocent faith in its beneficence. Today, many reject it with an equally naive conviction that it is evil. To live happily with technology, Americans must learn that engineering is a human activity with products that can be understood, enjoyed, and judged by ordinary human beings.