Introduction

The United States of America was an agricultural society when it declared independence in 1776. Modern engineering soon brought change. Robert Fulton used steam engines invented in Britain by James Watt to power the first steamboats, which opened America's inland rivers to settlement and trade in the early nineteenth century. The high-pressure steam engine drove railway locomotives that began to interconnect the country over land from the 1830s onward. The use of water power enabled a textile industry to develop in New England, and steam engines began to power manufacturing later in the century. The electric telegraph invented by Samuel F. B. Morse created a communications network before the Civil War (1861-65) that spread in the years that followed. At war's end, though, America was still mostly a nation of farmers.

America rose to industrial greatness by the 1920s on the strength of two super-innovations, electricity and internal combustion.[1] These relied on fossil fuels for energy. Before the 1870s, Americans relied on firewood for fuel. Coal had more energy per pound than wood, though, and in the late nineteenth century, coal began to replace wood as a fuel to drive railway locomotives, power factory equipment, and heat homes and offices. The coming of motor vehicles after 1890 made petroleum an essential fuel as well, and by the 1920s coal and oil were the nation's primary sources of energy. The environmental drawbacks of fossil fuels would become a concern only later; at the time, they met the nation's need for energy and saved its forests from further destruction.

In the 1880s, Thomas Edison designed a system in New York City to supply electricity to homes and offices from a coal-fueled power plant, and industries to make electric lights, motors, and other devices followed as electric power spread. Alexander Graham Bell used electricity to provide a new form of wireline communication, the telephone; and in the 1920s, Americans began to use electromagnetic waves for wireless radio communication and broadcasting. Television broadcasting over such waves began two decades later.

The modern airplane embodied the principles demonstrated by the Wright brothers in their Flyer of 1903; and motor vehicles became the leading sector of modern industry after 1908, when Henry Ford introduced a mass-produced automobile, the Model T. Airplanes and most automobiles relied on internal combustion engines fueled by gasoline. By the 1930s, new refining processes had increased the amount of gasoline that could be obtained from a barrel of oil, from ten to forty percent, and improved its performance in engines. Metallurgical engineering supplied the structural materials needed to make motor vehicles and airplanes, and structural engineers used steel to extend the length of bridges and the height of buildings.

Americans came later to believe that modern industry was the product of modern science. In fact, scientists made their contributions mostly after rather than before the technical breakthroughs outlined above.[2] General Electric and Westinghouse created laboratories in the twentieth century where scientists and engineers developed tungsten light bulbs and alternating current, which were more practical than Edison's original carbon-filament bulbs and direct-current power distribution system. Laboratory engineers streamlined the shapes of automobiles and airplanes in the 1930s, and the Bell

Telephone Laboratories advanced knowledge in many fields besides telephone service. But the new industrial research served mostly to improve technologies already in existence. Growth of the resulting industries, along with advances in agriculture and water supply, turned America from a rural into a mostly urban civilization and enabled the nation to achieve victory in World War II (1939-1945).

In some ways, major engineering innovation in the twentieth century did not change. The most important continuity was the extent to which new technologies built on those that went before them. The formula for a reciprocating automobile engine went back to James Watt in the eighteenth century, who used it to describe the action of steam engines, and the principle of rocket propulsion went back to Newton's third law of motion. The first electronic amplifier, the 1906 triode, had to be enclosed by a glass tube with a vacuum inside; the first transistor in 1947 was a triode that could work without a vacuum. When Steve Wozniak designed the Apple II personal computer in 1977, his basic insight was to combine in an innovative way a new kind of microchip, the microprocessor, with a color television monitor. New innovations opened further possibilities, but each also grew from a foundation of skills, ideas, and things that had developed up to the time of the innovation.[3]

The twentieth century differed, though, in requiring most engineers to possess more formal training in order to innovate. Although their formal education was limited, Edison and the Wright brothers were just as brilliant engineers as any in the decades that followed them.[4] The personal computer began in the late 1970s with the founders of Apple and Microsoft, who were self-taught in what they needed to know. But Hoover Dam, the national highway network, nuclear energy, jet airplanes and spacecraft, longspan bridges and tall buildings, and advances in computing required their engineers to have more formal training in engineering and science. Whatever their training, though, all innovators had to design imaginatively and win backing for their ideas.

The role of government also changed. The United States industrialized with the help of a federal government that gave patent protection, levied tariffs to protect industry against imports, and regulated some domestic practices. But before 1920, private industry was able to rise on the strength of private demand. Afterward, huge dams to provide water and power, and new highways to interconnect the country, required public engineering. Following World War II, the federal government grew much larger for reasons of national defense, and new industries in aerospace and electronics depended on military support for their rise and for much of their continued prosperity. However, the role of government varied with each technology. Its role did not prove any blanket view of government as a means, or a hindrance, to innovative insight.

The major innovations after 1920 each tell a unique story. The great dams brought huge rivers under control, opening the west to modern life much as steamboats and railroads had opened the middle of the country a century earlier to settlement and trade. The Tennessee Valley Authority was the first attempt to use public engineering to lift a huge region out of poverty. The federal highway program facilitated the change to a largely suburban civilization, while the development of nuclear energy brought a new and controversial source of power. With federal backing, the jet engine and the space rocket overcame boundaries of speed, distance, and altitude, but the technologies did not sustain their rapid advance after 1970. The transistor in 1945-47 was a radical breakthrough in electronics, as was the integrated circuit or microchip in 1958-59. The electronic computer and the Internet evolved from military projects. The transistor and microchip originated in the private sector but needed military support to find a market. The military developed early computers and computer networking but it was the private sector that later gave these innovations a mass market.

After 1920, radical innovators had to succeed in a society dominated by large private and public institutions. Yet the innovations covered in this book showed that unconventional insight was still possible in a more bureaucratic age. What mattered was independent vision, and a society willing and able to respond to it.

The Principles of Modern Engineering

The two volumes that preceded this book provide a framework to understand modern engineering in terms of certain distinctions. These inform the present book and also give an accessible language to describe technical innovation.

Normal and radical innovation. Technical innovations are distinguished by their engineering importance to society and this importance can be considered in three senses. Most of what society considers innovations are improvements to existing goods and services. These advances occur frequently and are often crucial to the success of business firms but their importance tends to be short-lived. Microprocessors do the principal work inside computers, for example, and for many years microprocessors doubled in capacity roughly every two years. As a result, however, they became obsolete quickly. A more important kind of innovation introduces a major new use for an existing product, or introduces a new product or process that significantly affects an existing industry. The microprocessor was this kind of new product when it first appeared. To the extent that new microprocessors embodied the idea of the original one, the original product continued to be influential. Finally, a small group of innovations have (or have had) a radically transformative effect on society over a long period of time, such as the development over a century ago of electric power and the motor vehicle. The advances that led to today's digital computing may be comparably radical.

The differences between kinds of innovation are not exact and all are vital to a modern society. The key point is that innovation is not a continuous flow of changes on only one level. For clarity, this book adopts the aeronautical historian Walter Vincenti's distinction of two levels of innovation. Incremental and intermediate innovations can be classified as *normal*, meaning the kinds of innovation that firms and societies do (and need to do) most of the time. The term *radical* describes ideas that transform engineering and society in more basic ways.[5] Admittedly, any choice of these ideas is arbitrary, but most of the events in this book would likely be in any short list of the more radical innovations that occurred in the period from 1920 to the early twenty-first century.

The traditional image of radical innovation is a breakthrough insight by one or two individuals, who then design and demonstrate prototypes. The microchip conceived by Jack Kilby and Robert Noyce came close to this image, although its innovators needed the help of colleagues. Further work remained before microchips were ready for production and the new chips then had to find a market. However, some radical innovations are better seen as larger group efforts. The U. S. highway program began in the 1920s as the vision of a single leader, Thomas MacDonald, but the Interstate Highway System after 1956 involved a team effort to complete over the next three decades. The rocket owed much of its practicality to the work of Robert Goddard before 1945 but the American space program of the 1960s was too big to be the engineering vision of a single person. Team efforts did not mean, however, that their work was somehow the result of impersonal forces. The work of larger groups was still the work of individuals with the ability to think independently, when necessary, as well as the ability to work together toward a singular end.

Engineering and science. A second distinction is the relation between the two activities of engineering and science. The two tend to be regarded by the public as a single whole ("science"), usually with an image of science as the source of new insight and engineering as its application. This image is misleading. Scientists and engineers, broadly speaking, each have a core competency. For scientists, it is the *discovery* of new facts about nature, about things that naturally exist. For engineers, it is the *design* of things that do not naturally exist. Until about 1920, most of the radical advances in modern engineering did not rely on science, in the foregoing sense, as a stimulus. Scientific knowledge has been a more important requirement since then, but engineering design insight is still the key to technical innovation.

Scientists and engineers are both creative in the sense that each questions the boundaries of knowledge: scientists challenge our understanding of nature, while engineers challenge our understanding of what we can design. Both groups have also done the other's work as part of their own. But clarity in terms should matter: when either group studies an aspect of nature or a natural property, it is really doing the work of science, and when either engages in design, it is really doing the work of engineering. To use the term "science" to refer to both activities is to obscure the independent insight that is required to design new things.

This insight can be illustrated by a conflict in the 1870s that arose over how to distribute electricity to lamps. Scientists could show that the maximum transfer of electric power in a circuit required the resistance in the lamps to equal the resistance in the power source (resistance is what causes these things to heat). Experts in the 1870s argued that a network to distribute electric power would have to be designed in this way. However, Thomas Edison recognized that using maximum transfer as a basis for design meant losing half of the energy as wasted heat in the power generator. Instead, he designed a generator with low internal resistance, and after a search for the right ones, lamp bulb filaments capable of withstanding high heat. The result was a system that produced enough electricity to meet demand and reduced waste heat from 50 to 10 percent.[6]

The notion that engineering is applied science, in which science supplies a fundamental insight and engineers merely find practical ways to use it, is to miss the kind of independent insight that Edison possessed. Some may call what engineers do applied science, and engineers today often make use of scientific knowledge. But engineers are designers who think independently and are guided by engineering needs.

Four prototypical ideas. A third set of concepts helps to organize modern engineering. This book and the two previous volumes divide major breakthroughs into four main types of designed objects or systems: structures, machines, networks, and processes. These categories refer to basic function. A *structure* holds up or holds back weight and works by standing as still as possible. The principal breakthroughs in structure have been large-scale water-control projects, modern highways and bridges, and tall buildings. A *machine* works by moving or by having parts that move; examples have been prime movers such as the stationary steam engine, the railway locomotive, and the internal combustion engines used in automobiles and airplanes. A *network* is a system that transmits something from one place to another with a minimum of loss. The telephone network operates in this way, as do the electric power grid, radio and television broadcasting, and the circuits that make possible modern computing. A *process* is a system that transmutes, or changes one kind of thing into another kind of thing. Processes for turning iron into steel, crude oil into gasoline, and other chemicals into useful products are examples. These four ideas gave rise to the four original branches of modern engineering: civil, mechanical, electrical, and chemical.

Engineering schools today divide themselves into a larger multitude of departments, programs, and specialties, and many engineering ideas involve more than one function: the twentieth century automobile, for example, integrated electricity, chemical combustion, mechanical motion, and a steel framework. But the four ideas of structure, machine, network, and process are helpful to understanding the principles at work in the most important innovations, including those in this book.

Three perspectives. The last distinction consists of three questions that all engineers must answer before making a design. First, can the object be made and will it be efficient and safe? These questions typically involve physical relationships that must be calculated and tested. Second, what is the need for, or potential usefulness of, the object? How much will it cost to design and make, and will the benefit be worth the cost? These questions are typically measured in terms of money, which connects engineering to economics and politics. Finally, if the object is practical and useful to make, will it be visible and if so can it have an appealing design that does not add appreciably to its cost? Will it improve the quality of life and have an acceptable impact on society and on the natural environment? These questions are harder to answer with tests and measurements. Answers rely as much on the aesthetic vision and ethical judgment of the designer, as well as on what the surrounding society wants or will allow.

These concerns imply that the engineer has a freedom to make choices. Any design may be one of several ways to accomplish some purpose, and having this freedom gives engineers room to imagine new possibilities. However, this freedom carries an obligation to make responsible choices: to make efficient use of materials and economical use of public or private funds, to adhere to a high ethical standard, and to enhance the natural environment and human life. Society also has a choice in how it funds and makes use of innovations, but as the designer, the engineer has a responsibility that comes first.

Transformative innovations cannot succeed without financial support from government or private investors, and the contributions of workers and consumers are essential to their realization. Society may or may not be ready for them (ideas can occur to more than one person at nearly the same time) and engineers may or may not anticipate their larger consequences. Such radical innovations have usually begun in the insights of engineers who could see beyond what was generally thought possible. The rest of this book aims to give engineers, interested students, and the general reader a grasp of important technical ideas from the twentieth century and of the engineer-innovators who conceived them.

[1] Electricity came to be used either as a source of power (eg. for lighting) or as a new means of communication (eg. wireline telephony). Internal combustion was the combustion of fuel to drive mechanical action, in one or more combustion chambers inside an engine. Steam engines used external combustion, in which fuel burned in a boiler to produce steam. The steam then went into a separate driving mechanism.

[2] For the role of science at the inception of major innovations, see Harold C. Passer, "Electrical Science and the Early Development of the Electrical Manufacturing Industry in the United States," *Annals of Science* (London), 7, No. 4 (December 28, 1951): 383-429; David A. Hounshell, "Two Paths to the Telephone," *Scientific American*, 244 (January 1981): 156-63; Lynwood Bryant, "The Origin of the Automobile Engine," *Scientific American*, 216 (March 1967): 102-113; John D. Anderson, Jr., *A History of Aerodynamics and Its Impact on Flying Machines* (Cambridge: Cambridge University Press, 1997), 192, 242-243; and Sungook Hong, "Marconi and the Maxwellians: The Origins of Wireless Telegraphy Revisited," *Technology and Culture*, 35, No. 4 (October 1994): 717-749. The exception was the chemical industry, in which laboratory science played a central role. The discoveries earlier in the nineteenth century of electrical principles by Ohm, Faraday, Henry, and others were as much principles of electrical engineering as principles of science. They are considered science because their discoverers had no practical motive in mind.

[3] This is one of many useful points in W. Brian Arthur, *The Nature of Technology: What It Is and How It Evolves* (New York: Simon & Schuster/Free Press, 2009).

[4] Some later writers reacted to Edison's self-promotion by denying that he was a modern engineer, calling him a mere inventor instead. For Edison, see Billington and Billington, *Power Speed and Form*, 17-25. For the brilliance of the Wright brothers, see Howard S. Wolko, ed., *The Wright Flyer: An Engineering Perspective* (Washington DC: Smithsonian Institution Press, 1987).

[5] See Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore MD: Johns Hopkins University Press, 1990), pp. 7-9.

[6] For the expert view of electrical power distribution in the 1870s, see Paget Higgs, *The Electric Light in its Practical Application* (London: E. and F. L. Spon, 1879), 158-175. For Edison's response, see Billington and Billington, *Power Speed and Form*, 220-222. Thomas Edison did not design the incandescent light bulb (Sir Joseph Swan invented a low-resistance bulb in the 1840s). What Edison designed was a high-resistance bulb that would make a local system to distribute electric power to lamps efficient and economical, which low-resistance bulbs could not do.