

"The Sources of Modern Engineering Innovation"

David P. Billington and David P. Billington, Jr.

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In recent years, leaders in the advanced democratic countries have expressed concern over the innovative capabilities of their nations.[1] Modern societies will need to meet environmental and natural resource challenges on the horizon that are common to the world as a whole, and individual nations will need as fully as possible to employ their people and to remain militarily and economically viable in a competitive world. To meet these needs will require innovation and creativity of a high order.

An important question, though, is what constitutes productive innovation. Ideas that make money in a market economy do not all benefit society equally and some may be detrimental. Many productive ideas are also incremental in nature. Modern societies need to innovate in deeper ways and calls to renew national innovative capacities make certain assumptions about how to renew and sustain this deeper ability. It is widely believed that universities and other settings where basic scientific research takes place are now the source of deeper innovative ideas. Public and private investments to modernize industry and infrastructure, along with a population better trained in mathematics, science, and technical skills, are seen as also necessary, but basic science is the key.

In 1945, President Roosevelt's science adviser, Vannevar Bush, argued in an influential report that basic or undirected scientific research, ie. inquiry for its own sake, was the stimulus to major engineering innovation up to that time.[2] His report became

the argument for establishing the National Science Foundation in 1950 and his thesis underpins the idea today that basic scientific research is the key to economic growth. However, given the economic performance of advanced societies in the last half century, despite research budgets that have been greater than at any time in history, the premise that basic research propels economic growth deserves closer examination. Three questions need to be asked: Did the engines of economic growth in the late nineteenth and early twentieth centuries arise from basic science? How did basic science contribute after 1945? And will investments in basic research and in science and mathematics education bring deeper kinds of technical innovation in the future?

1.

The United States of America underwent an industrial revolution in the late nineteenth and early twentieth centuries that allowed most of its population to live in cities and then in suburbs. Dramatic advances in food supply, in the availability of fresh water and sanitation, in the generation and use of inanimate energy, and in manufacturing, transportation, housing, and education all raised the standard of living and made America the world's leading economy. These changes benefited from certain national advantages, such as abundant natural resources and a society that encouraged private innovation. However, the transformation of American life was primarily the work of engineering that embodied radically new technical ideas, in which the contribution of science came after the breakthrough, not before it.

Electric power. The modern electric power grid can be said to have begun in 1878, when Thomas Edison conceived the idea of a network to generate and distribute electricity to power indoor incandescent lamps. Two years earlier he had secured private funds for a laboratory in Menlo Park, New Jersey, on the strength of his work as a telegraph engineer. The funding allowed him the freedom to think in new ways about how to use electricity for light and power. But his work was not undirected in the modern meaning of basic research; his support came from bankers who expected a return on their investment within a few short years.[3]

Earlier in the nineteenth century, scientists in Europe and the United States had explored the phenomena of electricity. To discover the principles of an electric circuit (voltage, current, and resistance in a circuit and the basic laws relating them) actually required electrical engineering to come before the science. But the discoverers of these principles are considered scientists because they were interested in knowledge for its own sake and not for any practical purpose. Edison made use of these findings to design useful engineering.[4] However, the idea that he simply applied earlier discoveries to a practical end deeply mischaracterizes what he did. In fact, Edison had to challenge and overturn the scientific judgment of his time.

Leading scientists and engineers argued in the late 1870s that a network of light and power such as Edison proposed could not work. Their argument was that to achieve a maximum transfer of energy in an electric circuit, resistances inside and outside the power source would have to be equal. From this assumption, it could be shown mathematically that the light in the lamps would diminish (depending on the circuit arrangement) by the square or the cube of the number of lamps added to the circuit.

Edison proved this argument false as a basis for engineering by designing an efficient system that used an electric generator with low internal resistance and incandescent lamps with filaments of high resistance.[5]

Rivals had experimented with incandescent light using bulbs with low resistance, and several inventors in the 1870s developed new bulbs of this kind, notably Sir Joseph Swan in England. But Edison knew that to deliver the electric current necessary to power low-resistance bulbs from a distance would have required uneconomically heavy copper wirelines. Edison's development of a high-resistance lamp greatly reduced the current and thus the amount of copper wireline needed. His rivals approached incandescent electric light as an isolated laboratory exercise, in the manner of a scientific experiment rather than an economical innovation.[6]

Edison employed a mathematical physicist, Francis Upton, to perform more complex calculations. Upton was initially skeptical of Edison's system but later he had the candor to admit that he had been wrong: "I cannot imagine why I could not see the elementary facts in 1878 and 1879 more clearly than I did. I came to Mr. Edison a trained man, a postgraduate of Princeton; with a year's experience in Helmholtz's laboratory; with a working knowledge of calculus and a mathematical turn of mind. Yet my eyes were blind..."[7] Upton and later trained minds in electrical engineering proved more adept at solving the narrower and more sophisticated problems of making electric power more efficient. What made Thomas Edison a deeper innovator was his ability to perceive the "elementary facts" that mattered at the inception of the new industry.

It is unlikely that Edison would have been able to obtain funding had he been required at the time to pass review by established peer groups in science or engineering.

However, the image of Edison as merely an applied scientist persists, as does the opposite image of him as an unsystematic tinkerer. (He did rely on trial and error to find a filament for his light bulb, but this search was to supply a part of a highly systematic vision.)

Many today regard his Menlo Park laboratory as the prototype of a highly creative team-research environment. In fact, Edison's lab was not team-oriented in the modern sense because Edison was the source of its major insights, not the group.

Thomas Edison failed to see the advantages of alternating current over his system, which used direct current, and modern civilization owes its electricity supply as much to George Westinghouse, Charles Steinmetz, Nikola Tesla, and other engineers who made alternating current practical. In this later work, formally trained scientists and engineers employed in more specialized tasks played a vital role. The great private industries of the twentieth century created laboratories to employ such people, bringing further advances such as the tungsten filament that replaced Edison's carbon one.[8] But the work of these laboratories was not as radical as Edison's initial vision. To realize his system, Edison made use of modern science but had to possess an independent insight as an engineer to overcome scientific opposition to his ideas.

Internal combustion. The early automobile owed nothing to basic science. The nineteenth century internal combustion engines of Etienne Lenoir and Nikolaus Otto and the early gasoline cars of Karl Benz, Gottlieb Daimler, and René Panhard and Emile Levassor in Europe were the work of engineers. The seminal figure, Nikolaus Otto, invented the modern four-stroke engine cycle but did so without a knowledge of the thermodynamics involved.[9] The auto industry rose to a dominant position in the American economy as a result of Henry Ford's 1908 vision of a revolutionary car, the

Model T. Ford and his engineers then perfected a manufacturing system, the moving assembly line using standardized parts, that enabled him to mass-produce the Model T and reduce the price. Hundreds of thousands of Americans in town and country took to the road as a result, and by the mid-1920s, when consumers finally began to want more variety in cars, America had come to depend on motor vehicles.[10]

Ford had little education but his assembly line is often cited as an example of "scientific management," a term popularized by Frederick Winslow Taylor in a 1911 book.[11] Taylor advocated time and motion studies to make workers more productive, with the aim of making existing production systems more efficient. If Ford had followed Taylor, he would have tried to achieve marginal efficiencies in the earlier method of auto assembly, in which cars never moved until they were finished by workers who moved from car to car to perform particular tasks. Instead, Ford placed workers at different points on an assembly line and moved the cars to them. He timed his assembly-line workers in order to manufacture motor vehicles in a radically new way.[12]

In 1913, a chemist with Standard Oil of Indiana, William Burton, patented a new process that increased from ten to twenty percent the amount of gasoline that could be refined from a barrel of crude oil, and in the 1930s, Eugene Houdry patented a process that raised this amount to forty percent. This work required a knowledge of chemistry but involved chemical engineering, not any new advances in science.[13] In the 1930s, Chrysler introduced the streamlining of closed-body cars, after conducting research on vehicle aerodynamics that reflected a more scientific approach to engineering design.[14] Improvements since then have turned the automobile into a machine of increasing

performance and comfort, but the automobile today is mostly still a work of (very sophisticated) engineering.

The other great innovation to rely on internal combustion, the airplane, resulted from a race between the United States federal government and two bicycle makers in Ohio, in which a well-funded scientific approach failed and an engineering one on a shoestring proved successful. The federal effort to invent the airplane has been all but forgotten but was led by a distinguished astrophysicist, Samuel P. Langley, who headed the Smithsonian Institution in Washington, D.C., from 1887 to 1906. Langley privately spent several years trying to fly unpiloted model airplanes, using small steam engines for propulsion, before he succeeded finally in 1896. Believing that he had proved the concept of powered flight, Langley saw no need to do further work, but two years later, with the Spanish-American War underway, the U.S. Army gave him \$50,000 (over \$1 million in 2012) to build a piloted airplane. A model plane relied on its passive stability to stay aloft, and Langley designed his piloted airplane to be a scaled-up version of a model, with the addition of a gasoline engine but only limited manual controls. Instead of testing the design first as a glider, Langley concentrated on perfecting its parts and making them pass exacting laboratory tests. In two flight attempts at the end of 1903, the full-sized Langley airplane was unable to fly.[15]

Neither Wilbur nor Orville Wright were high school graduates and they financed their research from their meager income making bicycles. From their experience cycling, the Wrights realized that an airplane would be highly unstable in flight, and in the years 1899-1902, the brothers designed a glider in which the pilot could maneuver in three dimensions by pulling wires to bend the rear wing edges like flaps. During months of

slack demand for bicycles, the Wrights conducted full-scale tests on the sand dunes at Kitty Hawk, North Carolina. After failures that they corrected with the help of homemade testing equipment, they achieved in 1902 an efficient glider. Then they designed and added a gasoline engine and propellers. Returning to Kitty Hawk, on December 17, 1903, the Wrights conducted the first steady level flight of a powered airplane.[16]

Langley and the Wright brothers relied on the research of Sir George Cayley, who had proposed the basic crosswing configuration of the modern airplane in 1799 and who had identified the forces of lift and drag that would affect flight. But advances in theoretical aerodynamics over the century that followed were as useless to Langley as they were to the Wrights.[17] Langley failed, though, not because he lacked science, but because he did not think as a good engineer. He worked out his ideas in theory and perfected the details of a design that was flawed overall. The Wrights tested their overall design from the beginning and worked on more detailed problems later. Their research with a soapbox wind tunnel received sophisticated engineering analysis in the 1980s and was found to be brilliantly efficient.[18]

After the Wrights proved their flyer, later engineers made vitally important improvements to aircraft design, such as replacing wing bending with rigid wing flaps. After 1903, theoretical aerodynamics finally made useful advances as well. The United States government set up new research facilities in the 1920s and 1930s that showed the value of streamlining, and engineers in private industry soon designed successful streamlined airplanes, such as the Douglas DC-3. However, the next great advance in aviation, the jet engine, was pioneered by a British engineer, Frank (later Sir Frank) Whittle. The discovery essential to space travel, that rocket thrust was possible in a

vacuum, was a result of engineering research by a physicist, Robert Goddard in the United States.[19]

2.

During the Second World War, the role of scientists changed. Physicists took a leading role in the development of nuclear weapons, in new uses of radio waves, and in other advances vital to the war effort.[20] The need for stronger defenses in the Cold War afterward brought greater public funding of higher education, especially for science and engineering, in the United States. Research performed by universities also expanded with federal funding.[21] The thesis that science discovered new ideas and engineering applied them came to be widely accepted as an explanation of how federal funding for research would sustain the innovation that America needed.

The dominant industries after the war continued to be motor vehicles and the associated steel and oil industries, the aerospace industry associated now mostly with national defense, and electrical and electronic goods and electric power. These industries suffered in the late twentieth century, though, except for electronics, which underwent explosive growth. Invented in 1958-59, the integrated circuit or microchip incorporated the transistor conceived a decade earlier and achieved phenomenal increases in working capacity by the end of the twentieth century. As a result of the advance in microchip design, the electronic computer went from a scientific instrument to the engine of a new economy. Any general view of the role of science and basic research after 1945 must therefore explain how the transistor and the microchip came about.

Modern electronics began with Edison's discovery of an effect that later engineers identified as the ability of electrons to flow through a vacuum. In the triode, invented in 1906, an electron flow went through a small electrified grid in a vacuum tube, amplifying the flow. Triode amplifiers and other improvements to electronic circuit design made long-distance telephony and the transmission and reception of radio (and later television) signals practical. Triodes could also work as fast switches and early computers after World War II used them for this purpose. High rates of burnout made the tubes unreliable in large assemblies, though, and their heat and bulk also limited their use. The need for more compact and reliable electronic equipment in the postwar era made better ways to amplify and switch electricity urgent.[22]

By the 1930s, advances in quantum theory gave scientists a better understanding of how electric charge carried through solid metals called semiconductors, which could conduct or impede the flow of charge. Executives at the Bell Telephone Laboratories believed that such metals might be made to perform the functions of vacuum tubes, and wartime researchers found ways to purify semiconductors and then add impurities to control their conductivity more precisely. These impurities either created excess electrons in the semiconductor or created "holes" inside the metal by reducing the number of electrons. Either the free electrons or the holes could carry electric charge.[23]

As the Second World War was ending in 1945, William Shockley, a physicist returning to Bell Labs from war work, began experiments to test the possibility of amplification through a semiconductor. Shockley positioned a positively charged metal plate close to a sheet of silicon, a semiconductor, that had an excess of (negatively charged) electrons. Science suggested to Shockley that the plate would attract electrons

from inside the silicon and that these would amplify an electric current going through the silicon surface. The aim of the experiment was not scientific knowledge for its own sake, though, but to demonstrate the principle of how a solid metal might replace the vacuum tube as an amplifier. In his experiments, to his surprise, Shockley found the amplification he sought to be negligible.[24]

To investigate what went wrong, Shockley handed the problem to two other physicists at Bell Labs, John Bardeen, a theorist, and Walter Brattain, an experimentalist. Researchers at the Labs agreed that two semiconductors, germanium or silicon, were the best metals to use if amplification through a solid metal was possible. But Bardeen and Brattain decided that they needed to know more about the natural properties of the metals to understand why Shockley's experiments didn't work. Over the years 1946-47, with Brattain's help, Bardeen finally realized what had happened. There were energy states on the semiconductor surface that trapped the electrons and prevented an amplified current from getting out. But holes also migrated close to the surface, below the electrons. By placing a positive charge in contact with the surface, the electrons attracted to the point-contact increased the number of holes underneath, and these could amplify a current that flowed out. Experiments at the end of 1947 (using germanium instead of silicon) demonstrated the effect and the device received the name *transistor*.[25]

The transistor emerged from a decision to investigate the natural properties of metals, a clear instance of basic scientific research. However, this study only occurred because there was an engineering objective, a better amplifier; the work was not truly undirected research in the sense that Vannevar Bush had urged. The transistor would have been impossible without prior advances in physics and in the engineering of

materials, but Bardeen and Brattain could not simply apply quantum physics, because in 1945 the theory did not explain how to prevent electrons going through solid material from becoming trapped on the surface. Instead of simply applying science as Shockley had tried to do, and as the notion of innovation as applied science would require, Bardeen investigated the science more deeply, acting as a pure scientist rather than an applied one. However, he would not have done so without a prior engineering image in his mind of what he was trying to achieve.[26] Shockley soon created a more efficient version of the transistor and manufacturers in the early 1950s improved it further.[27] Transistors made of germanium and then silicon eventually replaced vacuum tubes for most electronic needs, not only as amplifiers but also as switches.

As transistors proved their value, manufacturers tried to use more of them in confined spaces by making circuitry smaller. Transistors and other circuit elements still had to be wired together by hand, though, and it became clear in the mid-1950s that a practical limit would soon be reached to circuit miniaturization. A solution to this problem, the *integrated circuit* or microchip, was the insight of two engineers, Jack Kilby and Robert Noyce. Kilby had earned bachelor's and master's degrees in electrical engineering after World War II and Noyce had received a doctorate in physics, and both began their careers in the early 1950s with private firms that made electronic devices. In May 1958, Kilby moved to a new firm, Texas Instruments in Dallas, Texas, and Noyce and several engineers organized a new firm of their own, Fairchild Semiconductor, near Stanford University in Palo Alto, California, the year before.[28]

In his 2000 Nobel lecture, Kilby described what happened after he arrived in Texas: "When I started at TI in May 1958, I had no vacation coming. So I worked

through a period when about 90 percent of the workforce took what we called 'mass vacation.' I was left with my thoughts and imagination." [29] A solution to the problem of miniaturization then dawned on him. Kilby knew that either of the materials used to make transistors, germanium or silicon, could also be used to make the other components of a circuit, such as resistors and capacitors. Neither was ideal for every component but using one material would remove the need for separate materials. Kilby successfully tested a prototype in which all of the circuit components were made of germanium, although he used wires to connect them. He also made prototypes out of silicon. [30]

Six months after Kilby's insight, Robert Noyce came to the same insight from a different direction. One of his colleagues, Jean Hoerni, had found an efficient way to lay down metallic leads (the planar process), and Noyce realized that it would be simpler if all of the circuit components interconnected in this way could be made of one material. [31] After several years of litigation, Texas Instruments and Fairchild Semiconductor agreed to cross-license their patents. The new microchip could be printed by machine, removing the barrier to miniaturization. No new science pointed to the integrated circuit: it was an engineering insight prompted by an engineering problem. [32]

The microchip nearly failed to find a market as private electronics manufacturers preferred different materials for different circuit components. The three armed services had research programs of their own to solve the problem of miniaturization and showed no interest until it became clear, a few years later, that their own programs led nowhere. Fortunately, NASA needed a compact on-board computer to guide spacecraft and bought microchips in large numbers. The Air Force also soon realized that microchips could be useful to guide ballistic missiles. [33] In 1968, Noyce and several colleagues founded a

new company, Intel, where in 1971 Ted Hoff and other engineers invented a general-purpose microchip, the microprocessor. The new device made possible the compact personal computer that Steve Jobs and Steve Wozniak of Apple Computer made commercially successful in the late 1970s.[34]

3.

In the twentieth century, formal training in science and engineering became essential for most innovators, and science made important contributions in all areas of engineering. However, basic science was not the driver of major innovation predicted in 1945.[35] Project Hindsight, a retrospective study of U.S. defense research, found almost no role for pure science or undirected research in generating militarily significant innovations from 1945 to 1965; instead, engineering needs overwhelmingly defined the research and focused related scientific problems that needed to be solved. This pattern appears to have continued in defense research since then.[36] In the civilian economy, the transistor has been claimed as an outgrowth of basic science but a straightforward application of science did not happen and an engineering need defined the problem that science eventually did help to solve. The microchip was an engineering insight, even though its innovators needed a grasp of modern physics to achieve it.

There is confusion in the public mind over whether there is even a difference between science and engineering. The core activity in science, and the skill in which professional scientists are trained, is the *discovery* of facts that exist in nature. The core activity in engineering, and the skill in which professional engineers are trained, is the

design of things that do not naturally exist. The insight required by each activity cannot derive from the other. Scientists and engineers benefit from, and often perform, each other's work; but when engineers study natural phenomena, they are doing science, and when scientists engage in design, they are working as engineers. The relationship between science and engineering is more complex and interesting than the linear model that "science discovers and engineering applies." Deeper innovation will be harder to sustain if society has a mistaken view of the relationship.

Modern societies now expect private and government laboratories, universities in their research function, and research parks that bring universities and industries together to be the sources of future innovation. The model is Silicon Valley, the area around Stanford University in California where high-technology firms have clustered since the 1950s and 1960s. The potential of this area to incubate new industry was the vision of an individual, Frederick Terman (1901-1982), dean of engineering and then provost of Stanford, who saw the potential of electronics to be a leading economic sector.[37] However, the growth that Terman attracted to the Stanford area largely depended on funding for national defense, and the failure of Silicon Valley and similar regions to offset the declining sectors of the American economy in the late twentieth century suggests that expectations of the model have been too high.

Where society looks for radical insight may not be as important as whether society in a broader sense values such insight, not just for the money it can earn, but for the challenge to conventional thinking that it requires. This is a matter of education. America and other advanced nations are trying to renew their innovative capacities by providing a workforce with generic technical skills and by training a smaller number of

people in higher-order forms of these generic skills. Engineering education imparts a body of standardized knowledge beginning with science and teaches how to solve problems that are in some underlying sense familiar. General education of undergraduate and secondary school students in mathematics and science does the same in a more basic way. Standardized knowledge implies a world in which work is stable and routine, and its emphasis on conventional understanding discourages deeper questioning.

For deeper innovation to continue, engineers will need to emulate radical innovators, and to do so they will need to study them. The study of individual engineers as part of mathematics, science, and engineering education is itself a radical idea, when these disciplines instead stress generic principles and applications. In fact, the study of individual engineers and their greatest works does not require an overhaul of instruction, and a growing body of scholarship and teaching shows how this kind of education can be included in the curriculum.[38]

When technical education includes not just learning standardized best practices and their application to amenable problems, but also learning about those people whose deeper insights raised standards, then a nation's innovative capacities are ready to be renewed more deeply, and new challenges may be faced with greater confidence. The strength of our civilization is its ability to overturn conventional thinking from time to time in constructive ways. By studying and emulating those engineers whose insights have overcome critical barriers in the past, sometimes with the help of science but not simply by trying to apply it, future innovators can learn what real breakthroughs require and may find the inspiration to achieve them.

Notes

1. The major recent statement of this concern in the United States has been *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (Washington DC: National Academies Press, 2005).
2. Vannevar Bush, *Science, The Endless Frontier* (Washington DC: U.S. Government Printing Office, 1945).
3. For Edison's life and work, see Paul Israel, *Edison: A Life of Invention* (New York: John Wiley and Sons, 1998).
4. The scientific ideas that Edison used may be found in his formula manual, *Electrical Tables and Formulas for the Use of Telegraph Inspectors and Operators*, compiled by Latimer Clark and Robert Sabine (London: F. N. Spon, 1871). A photocopy of the manual, with marginal notes in Edison's hand, is in the Papers of Thomas Edison, Rutgers University, New Brunswick, New Jersey.
5. For the views of scientists and engineers on what Edison proposed, see Harold C. Passer, "Electrical Science and the Early Development of the Electrical Manufacturing Industry in the United States," *Annals of Science* [London], Vol. 7, No. 4 (December 28, 1951), pp. 382-392. For the mathematical argument against

- Edison, and its flaw, see David P. Billington and David P. Billington, Jr., *Power Speed and Form: Engineers and the Making of the Twentieth Century* (Princeton: Princeton University Press, 2006), pp. 220-223.
6. See George Wise, "Swan's Way: A Study in Style," *IEEE Spectrum*, Vol. 19, No. 4 (April 1982), pp. 66-70.
 7. For the Upton quote, see Harold Passer, "Electrical Science and the Early Development of the Electrical Manufacturing Industry," p. 388.
 8. See Leonard S. Reich, *The Making of Industrial Research: Science and Business at GE and Bell, 1876-1926* (Cambridge: Cambridge University Press, 1985), pp. 62-128, 142-150.
 9. On Nikolaus Otto, see Lynwood Bryant, "The Origin of the Automobile Engine," *Scientific American*, Vol. 216, No. 3 (March 1967), pp. 102-112.
 10. On Henry Ford, see Douglas Brinkley, *Wheels for the World: Henry Ford, His Company, and a Century of Progress* (New York: Viking Books, 2003). On the engineering of the Model T, see the *Ford Manual: For Owners and Operators of Ford Cars* (Detroit MI: Ford Motor Company, 1914). On the Ford assembly line, see David Hounshell, *From the American System to Mass Production, 1800-1932:*

- The Development of Manufacturing Technology in the United States* (Baltimore MD: Johns Hopkins University Press, 1984), pp. 217-261.
11. See Frederick Winslow Taylor, *The Principles of Scientific Management* (New York: Harper and Brothers, 1911).
 12. See David Hounshell, *From the American System to Mass Production*, pp. 249-253.
 13. For the work of Burton and Houdry, see John Lawrence Enos, *Petroleum Progress and Profits: A History of Process Innovation* (Cambridge MA: MIT Press, 1962), pp. 1-59, 131-162.
 14. For the streamlining of cars, see Carl Breer, *The Birth of the Chrysler Corporation and its Engineering Legacy*, ed. Anthony J. Yanik (Warrendale PA: Society of Automotive Engineers, 1995).
 15. For Langley's research, see Samuel P. Langley and Charles M. Manly, *Langley Memoir on Mechanical Flight*, Smithsonian Contributions to Knowledge, Vol. 27, No. 3 (Washington DC: Smithsonian Institution, 1911). Langley tried to launch his full-scale airplane from a houseboat on the Potomac river in October and December 1903, and on both occasions the airplane snagged in the launch mechanism and plunged into the river. But his airplane required extensive

- structural modifications before a test flight in 1914 was finally successful. See Tom D. Crouch, "The Feud between the Wright Brothers and the Smithsonian," *Invention and Technology*, Vol. 2, No. 3 (Spring 1987), pp. 34-46.
16. On the Wright brothers, see Peter L. Jakab, *Visions of a Flying Machine: The Wright Brothers and the Process of Invention* (Washington DC: Smithsonian Institution Press, 1990).
 17. For Sir George Cayley, see John D. Anderson, Jr., *A History of Aerodynamics and Its Impact on Flying Machines* (Cambridge: Cambridge University Press, 1997), pp. 62-80. For the uselessness of aerodynamic theory to airplane design before 1903, see *ibid.*, pp. 114-138, 192, 242-243.
 18. See Howard S. Wolko, ed., *The Wright Flyer: An Engineering Perspective* (Washington DC: Smithsonian Institution Press, 1987).
 19. For later developments in aviation, see John D. Anderson, Jr., *A History of Aerodynamics and Its Impact on Flying Machines*, pp. 244-446. See also Sir Frank Whittle, "The Birth of the Jet Engine in Britain," in *The Jet Age*, ed. Walter J. Boyne and Donald S. Lopez (Washington DC: Smithsonian Institution, 1979), pp. 3-24; and Robert H. Goddard, "A Method of Reaching Extreme Altitudes," *Nature*, Vol. 105, No. 2652 (August 26, 1920), pp. 809-811.

20. On this war work, see Irvin Stewart, *Organizing Scientific Research for War: The Administrative History of the Office of Scientific Research and Development* (Boston: Little Brown, 1948). Forward by Vannevar Bush.
21. For the growth in federally funded research, see Roger L. Geiger, "Science, Universities, and National Defense, 1945-1970," in "Science After '40," ed. Arnold Thackray, *Osiris*, 2nd ser., Vol. 7 (1992), pp. 26-48.
22. For an overview of electronics in the vacuum tube era, see Abraham Marcus and William Marcus, *Elements of Radio* (New York: Prentice-Hall, 1943).
23. For the origins of the transistor, see Lillian Hoddeson, "The Discovery of the Point-Contact Transistor," *Historical Studies in the Physical Sciences*, Vol. 12, No. 1 (1981), pp. 41-76; and for semiconductors, G. L. Pearson and W. H. Brattain, "History of Semiconductor Research," *Proceedings of the IRE*, Vol. 43, No. 12 (December 1955), pp. 1794-1806.
24. For his contributions to the transistor, see William Shockley, "The Path to the Conception of the Junction Transistor," *IEEE Transactions on Electron Devices*, Vol. ED-23, No. 7 (July 1976), pp. 597-620. For his experiments in 1945, see *ibid.*, pp. 604-605.

25. For the breakthrough to the transistor, see John Bardeen, "Semiconductor Research Leading to the Point-Contact Transistor," Nobel Prize Lecture, December 11, 1956, in *Nobel Lectures in Physics*, Vol. 3 (Singapore: World Scientific Publishing, 1998), pp. 318-341. The Nobel Lecture by Walter Brattain agrees with Bardeen and provides additional detail in *ibid.*, pp. 377-384. For an overview, see also Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age* (New York NY: W. W. Norton, 1997).
26. For the role of science, see M. Gibbons and C. Johnson, "Science, Technology, and the Development of the Transistor," in Barry Barnes and David Edge, eds., *Science in Context: Readings in the Sociology of Science* (Cambridge MA: MIT Press, 1982), pp. 177-185. The engineering image is clear from the title of J. Bardeen and W. H. Brattain, "The Transistor, A Semiconductor Triode," in *Physical Review*, Vol. 74, No. 2 (July 15, 1948), pp. 230-231; reprinted in *Proceedings of the IEEE*, Vol. 86, No. 1 (January 1998), pp. 29-30.
27. For improvements to the transistor, see Ian Ross, "The Invention of the Transistor," *Proceedings of the IEEE*, Vol. 86, No. 1 (January 1998), pp. 7-28.
28. For the lives and work of Kilby and Noyce, see T. R. Reid, *The Chip: How Two Americans Invented the Microchip and Launched a Revolution* (New York: Simon and Schuster, 1984).

29. See Jack S. Kilby, "Turning Potential Into Realities: The Invention of the Integrated Circuit," Nobel Lecture, December 8, 2000, in *Nobel Lectures: Physics*, ed. Gösta Ekspong (Singapore: World Scientific, 2002), pp. 471-485. Quote is from p. 479.
30. See Jack S. Kilby, "Invention of the Integrated Circuit," *IEEE Transactions on Electron Devices*, Vol. ED23, No. 7 (July 1976), pp. 648-654.
31. For the work at Fairchild, see Christophe Lécuyer and David C. Brock, *Makers of the Microchip: A Documentary History of Fairchild Semiconductor* (Cambridge MA: The MIT Press, 2010). The notebook pages showing Noyce's insight are in *ibid.*, pp. 151-155. For his account of the integrated circuit, see Robert N. Noyce, "Microelectronics," *Scientific American*, Vol. 237, No. 3 (September 1977), pp. 63-69.
32. For the litigation between Texas Instruments and Fairchild, see T. R. Reid, *The Chip*, pp. 96-117. For the manufacturing of the integrated circuit, see Bernard T. Murphy, Douglas E. Haggan, and William Troutman, "From Circuit Miniaturization to the Scalable IC," *Proceedings of the IEEE*, Vol. 88, No. 5 (May 2000), pp. 690-703.

33. For the role of the microchip on the U.S. space program, see Eldon C. Hall, *Journey to the Moon: The History of the Apollo Guidance Computer* (Reston VA: American Institute for Aeronautics and Astronautics, 1996).
34. For the microprocessor, see R. N. Noyce and M. E. Hoff, "A History of Microprocessor Development at Intel," *IEEE Micro*, Vol. 1, No. 1 (January-February 1981), pp. 8-21. On the development of the personal computer, see Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (Cambridge MA: Westview Press, 2004), pp. 207-279.
35. For an inquiry into this question, see Donald E. Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Washington DC: Brookings Institution Press, 1997).
36. For Project Hindsight, see Colonel Raymond S. Isenson, *Project Hindsight: Final Report* (Washington: Office of the Director of Defense Research and Engineering, U.S. Department of Defense, 1969). For the engineering-directedness of defense advanced projects research, see also William B. Bonvillian, "Power Play," in *The American Interest*, Vol. 2, No. 2 (November/December 2006), pp. 39-48.
37. See C. Stewart Gillmor, *Fred Terman at Stanford: Building a Discipline, A University, and Silicon Valley* (Stanford CA: Stanford University Press, 2004).

38. Two courses taught by the senior author at Princeton University since 1974 have developed this kind of undergraduate teaching. The concepts may be found in David P. Billington, *The Tower and the Bridge: The New Art of Structural Engineering* (Princeton NJ: Princeton University Press, 1985); David P. Billington, *The Innovators: The Engineering Pioneers Who Made America Modern* (New York NY: John Wiley and Sons, 1996); and David P. Billington and David P. Billington Jr., *Power Speed and Form*. Additional books are forthcoming. With modification, much of this material could also be taught at the secondary level. See David P. Billington, Jr., "Engineering in the Modern World," *World History Bulletin*, Vol. 24, No. 2 (Fall 2008), pp. 22-24. Online at: http://www.thewha.org/bulletins/fall_2008.pdf (retrieved May 2, 2012).