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"Engineering in the Modern World"

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Technology is a key driver of the modern world. It is also one of the least understood aspects of this world. My father and a colleague, Michael Littman, teach a one-semester course in the engineering school at Princeton University, "Engineering in the Modern World," in which I and others have worked as a preceptor, researcher, or teaching assistant.[1] The course enrolls about 200 liberal arts and engineering students each fall and provides an overview of technical breakthroughs from the eighteenth century to the present. The ideas and content of the course provide engineering literacy in an accessible form that secondary students as well as undergraduates could find useful and engaging. Some of this material could be included in a world history survey.

Modern Engineering

To give students a framework for understanding modern technology, "Engineering in the Modern World" distinguishes between (1) science and engineering, (2) normal and radical innovation, (3) structure, machine, network, and process as the major kinds of engineering works, and (4) physical principles, social context, and individual vision as perspectives on innovation.

The core of modern technology is engineering. There is no general theory, method, or approach that is true of all engineering but there is a basic difference between engineering and natural science that is a starting point for understanding each. Science is the *discovery* of things that occur in nature. Engineering is the *design* of things that do not exist in nature by themselves.[2] An engineer cannot design without knowing the laws of nature and the natural properties of things, but science does not tell how to design a railroad, a car, an airplane, or a computer.

A second distinction is between two kinds of engineering, normal and radical. *Normal* engineering and its associated invention and innovation occur in technologies that have been established for some time. Its aim is to make incremental improvements to existing things, or to make new things that use an already established idea. A more powerful auto engine and a faster microprocessor are incremental innovations. The first MP3 players were a new use of an existing innovation, the microchip. Normal innovation is rapid, on-going, and often confused with all of innovation.

A very different activity is *radical* innovation. Occurring rarely, it usually begins with the reflection and insight of one or two individuals. It often deeply challenges conventional expert peer-group thinking, and the innovations that result bring into existence, or make practical, fundamentally new technologies and new industries that transform civilization. Our course focuses on a small number of radical innovations and on the original thinking that went into conceiving them.

We consider radical the innovations of malleable iron, steel, the metal arch and suspension cable bridge, the steam engine, the steamboat, the railroad, and the telegraph and telephone. We add to these electric power, the refining of gasoline, the automobile, and the airplane. Finally, we include nuclear energy, the jet engine, the U.S. space program, modern highways and skyscrapers, and the principal innovations in electronics: the vacuum tube (for radio and television), the transistor, the microchip, the computer, and the Internet. We do not cover agriculture and public health but a handful of breakthroughs in each field were also transformative.[3]

The distinction between normal and radical innovation is not absolute. Both demand original thinking. Radical prototypes also need improvement by normal engineering before they are ready for large-scale use, and the cumulative impact of normal improvements can be as dramatic as the original breakthroughs. But transformations begin with radical insights that need to be recognized as such.

"Engineering in the Modern World" groups innovation under four types: structure, machine, network, and process. A *structure* is an object that works by standing still, while a *machine* is an object that works by moving or having parts that move. A *network* transmits something from one point to another with a minimum of loss. A *process* transmutes something at its beginning into something else at its end. Arch and cable bridges are structures, while cars and planes are machines. The telephone and the electric power grid are networks, and steel and oil refining are processes.

We limit our scope to large-scale structures, machines that are prime movers, networks that cross long distances, and processes that are large in scale. A few innovations, such as the transistor and the microchip, are very small in actual size, but we include them because their impact was comparable to the much larger things. The four types of engineering works correspond to the four original branches of modern engineering: civil, mechanical, electrical, and chemical. Engineering today consists of many more specialties than these, but engineering works still consist primarily of one of these four types, or of some combination of them.

Finally, we examine each radical innovation from three perspectives. To explain how each works, we give a simple equation and/or diagram to represent the physical relationships involved. On a single-arch bridge, for example, the weight or load carried by the arch at its midpoint becomes a nearly horizontal force that must be resisted at the abutments. This force is given by an equation that relates the load, the length of the roadway deck, and the vertical rise of the arch.[4]

The design of a bridge also depends, however, on how much society wants to balance safety against cost. A heavier arch may carry a given load more safely but will cost more. This balance is a social determination. By seeing how engineering problems embed social questions as well as physical ones, students learn that engineering is not just a matter of conforming to physical necessity but also of making choices.

Lastly, engineering works can have larger consequences, including social, aesthetic, and environmental impacts. The third perspective examines these larger consequences. Judgments with regard to them reflect the individual vision of the designer as well as the needs and wants of society. Radical innovations can also have effects that are not foreseen at the time and these also need to be examined.

The above framework gives students a vocabulary and an approach for understanding the modern technical world. The ideas are derived from actual engineering and permit an accessible and coherent description of technical events. The equations we use are at the level of first-year algebra, but historians could use our framework without the equations and formulas.

Engineering and Modern History

Students at both the secondary and tertiary levels learn the history of modern technology in terms of certain events and consequences. In most surveys, the industrial revolution that began in Britain and Europe in the eighteenth century was an economic and social transformation in which a key development was a textile factory system based on a handful of devices made mostly out of wood. The steam engine, iron and coal, crop rotation, and canal building also occurred, along with a new spirit of mechanical thinking and improvement. A few decades later, the railroad and the telegraph appeared and connected societies and the world together.

A second industrial revolution came in the late nineteenth century, with what is sometimes called "science-based" industry. The paradigm of this change was the chemical industry, and electric power distribution, electrical products, steel and oil, automobiles, and airplanes are thought to have resulted from a greater reliance on science. The new technologies organized human activity on a much larger scale and moved increasing numbers of people into cities. Further into the twentieth century, government became a source of technical change, through nuclear energy and space travel, and finally the world changed again with the information revolution.

History teaching goes into more depth in describing these events, but the ones above tend to be the main points. Much of the picture they convey is true. But much of it contains misconceptions that reflect a lack of engineering knowledge. Historians may not be able to teach the needed engineering. But before proposing work-arounds at the secondary and tertiary levels, teachers of history need to see under the two sub-headings below (and in the related end notes) the engineering that is missing and why it matters.

The industrial revolution. Textiles and their manufacturing were important in the early industrial era, as were improvements in agriculture. But four breakthroughs in structure, machine, network, and process were more relevant to modern industrial development and should receive more emphasis.

The first breakthrough was a new process, the smelting of inexpensive malleable iron. The principle of iron smelting is best explained by a simplified chemical reaction that shows the change of iron ore into pure iron and waste gas by adding carbon and air.[5] The Bessemer and open-hearth processes for steel-making in the 1850s added a stage to metallurgy that can be described briefly without equations. Students should know that the Bessemer process produced rails mainly to complete and make more durable the nineteenth century railway network. The open-hearth process provided the better steel needed for the bridges and buildings of the twentieth century.

The new iron enabled Thomas Telford to pioneer modern structural engineering in his 1812 arch bridge at Craigellachie in Scotland and in his 1826 suspension bridge across the Menai Straits in Wales. Both bridges can be described by the horizontal force mentioned above.[6] The Severn Iron Bridge of 1779, often used to illustrate the use of iron, was not a modern design, since the shape imitated a Roman stone bridge. Telford's more graceful arch and cable bridges in Scotland and Wales took advantage of what iron could do and are better examples of iron as a modern structural material. The principles exemplified by his bridges are still basic to bridge design today.

The 1765 steam engine of James Watt, although an improvement of an earlier engine, was in fact a radically new kind of machine. The Soho Foundry, where Watt and his partner Matthew Boulton made engines, should be part of any discussion of the factory system. But the steam engine's meaning is missed without the simple formula for horsepower that Watt devised to measure its efficiency.[7] The same formula also measured the efficiency of steamboat and railway engines in the nineteenth century and continues to be the standard for measuring internal combustion engines in automobiles today. A single idea thus explains the key machines of the last three centuries.

After taking steam power as far as the steamboat and the railroad, the early industrial revolution can be completed with the electric telegraph and the network to which it gave rise. The telegraph requires understanding the relation of electricity and magnetism and how Ohm's Law relates voltage, current, and resistance.[8] Students should then learn briefly how the telegraph originated and how it connected the world by land and sea. The telegraph was the first practical use of an electric circuit. The later innovations of the telephone, electric power, and electronics were more complex technologies, but the idea basic to all of them was some form of an electric circuit.

Technology since the 1870s. The breakthroughs that have shaped modern life since the late nineteenth century have also belonged to the four categories of structure, machine, network, and process: reinforced concrete and skyscraper towers; automobiles, airplanes, jet engines, and space travel; electric power, telephony, electronics for broadcasting (the vacuum tube) and electronics for computing (the transistor and the microchip); and refined gasoline and nuclear power. In addition to the four equations introduced with the industrial revolution, students could learn two new equations from this later phase, one for electric power and one consisting of a chemical reaction that can occur in gasoline refining.[9]

The main reason for students to learn these innovations is historical literacy. Just as students should understand key political, economic, social, and religious ideas, and the key ideas of modern science, so also should they learn the key ideas of modern engineering. What students have not had are explanations of the key engineering ideas that are technically meaningful, brief, and accessible. Our course and supporting scholarship are an effort to meet this need.

A second reason for learning these ideas is to understand how technical change actually occurred. Historians have tried to explain this change by attributing it to two very broad notions. One is a society that believes rational ordering and progressive change are possible in the world. The other is a society in which such things as the rule of law, market freedom, and resource endowments are available. Ideas and conditions such as these in most cases were necessary, but they were not sufficient.

What prompted most radical innovations were engineering barriers that directly stimulated new ways of thinking about what was possible. James Watt saw that existing stationary steam engines could not be improved without a basic departure, the separate condenser. Although Watt's formula for horsepower endured, railway innovators had to abandon Watt's engine to create mobile engines using high-pressure steam.

Alexander Graham Bell invented his 1876 telephone out of an effort to improve telegraphy, which in the early 1870s faced a crisis as the number of messages began to overwhelm the capacity of new lines to carry them. Thomas Edison's innovation of an electric power network in 1878-82 overturned the view of many experts that basic scientific laws made such a thing impossible. The Wright brothers recognized in 1899 that the key to heavier-than-air flight was not to design an aircraft for passive equilibrium against variable winds, a complex problem that misled other researchers at the time, but to design an airplane to maneuver in response to such winds. A fuel supply crisis would have throttled the growth of automobiles using internal combustion engines if William Burton had not found in 1912 a radical way to increase the gasoline yield from crude oil that conserved the supply of petroleum.[10]

The modern computer is also a result of overcoming a barrier. The core of the computer today is the integrated circuit or microchip, co-invented by Jack Kilby and Robert Noyce in 1958-59. The device was a response to an approaching limit in the density of electronic circuits. Instead of making circuit elements and connecting wires smaller, Kilby and Noyce did away with discrete parts and connections by printing circuits on a single material, the silicon chip. Normal engineering then gradually reduced these circuits to microscopic sizes.[11] These will face a limit someday too.

Although students do not need to know in detail how science and engineering relate to each other, teachers should be careful not to perpetuate the misconception that modern technology owes its creativity to modern science. Advances in technology have often required a closer study of the natural phenomena involved and the chemical industry has owed much to scientific research. The work of research in other industries was to improve technologies that engineers had already brought into existence. In its discovery of radio waves and nuclear fission, basic science stimulated radical innovation. But basic science played no such role in the inception of modern iron and steel, the steam engine, the railway, the automobile, or the airplane. Scientists discovered electromagnetism but outsiders invented the telegraph and the telephone; and in electric power distribution, scientific arguments against it had to be set aside. Modern gasoline refining was a black-box problem solved by chemical engineering. Refined silicon made possible the microchip but the integrated circuit was an engineering insight.

Radical innovators often had training in science and made use of scientific discoveries. But these innovators did not simply apply what scientists believed to be possible. The innovators thought independently and often had to prove their ideas against accepted engineering wisdom too. (The history of science is a similar story of people with new ideas having to win acceptance from peer groups.) Science played a very important role in the normal engineering that followed radical breakthroughs, and the line between what scientists and engineers do today has become less sharply drawn as members of one group now often find themselves employed in the activity characteristic of the other. But the activity of one group is not derivative of the other.[12]

How Much Engineering Can Historians Teach?

The physical principles and mathematics that we use to describe radical innovations are at the level of what students in the United States learn in grades eight, nine, and ten. However, history teachers at both the secondary and tertiary levels would have difficulty presenting these ideas, especially those that involve equations. There are four ways to work around this difficulty.

First, at the secondary level, world history teachers could focus what they teach about the industrial revolution on iron making, bridge structures, the steam engine and the railway, and the telegraph. Although what is taught of these might need review for historical accuracy, teachers could present them without equations or detailed physical description. However, students should learn that each of these innovations was a work of modern engineering and was either a structure, machine, network, or process. Students should be able to describe in one word the behavior that identifies each innovation as one of these four types. Teachers may cover later breakthroughs more selectively but should identify later innovations with the four types so that students see the continuity as well as the change that each breakthrough embodied.

Second, science teachers at the secondary level could describe in more technical depth the thinking behind the innovations and how they worked. The author plans to address science teachers to explain how they might do this. The major innovations and their equations exemplify ideas of force, motion, circuit, and chemical reaction that in most countries can be found in mandated science and mathematics standards. Science teachers could reinforce these ideas by teaching how historic engineering innovations embodied them and how their innovators came to the insights that led to breakthroughs.

Joint teaching in history and science may also be possible in a limited way. Teachers could give joint assignments on one or more innovations after classes in history and science have covered the necessary material. The history teacher could grade for the larger context while the science teacher could grade for technical content. Some students could also do longer papers and projects that integrate history, math, and science through engineering examples. Integrating these disciplines can give students the chance to make connections between subjects that are normally taught in isolation. Students may also see more clearly the relevance of learning material that may be difficult for them.

Many engineering breakthroughs were American, and in the United States the history side of this teaching might be shared with teachers of American history. Student papers and projects could focus on significant works in the students' own countries if the original innovations occurred somewhere else.

Third, at the university and college level, it may be better if historians not try to teach the material collaboratively with scientists or engineers. However, the undergraduate world history survey should describe the key technical events of the modern world in terms of structure, machine, network, and process, and should add the distinction between normal and radical innovation. Students should learn why and how innovators shifted from normal engineering to radical rethinking and insight.

Finally, to explore the technical material more deeply, undergraduate institutions could offer a separate dedicated course on major innovations, similar to ours, as a way for students to fulfill a science and technology requirement in the core curriculum. In most institutions, the core represents only the humanities, the social sciences, and the natural sciences. Our material integrates aspects of all three and could represent engineering in the core curriculum in an accessible way.[13] In the summers of 2004 and 2005, engineering and science faculty from twenty institutions attended short workshops at Princeton to learn how to give our course.[14] We hope to continue this outreach and show interested engineering and science faculty how a course in historic engineering examples can fulfill a core requirement. The author would like to help history teachers at both the secondary and tertiary levels who would like to include some of our material in their teaching.

The world history survey has traditionally covered modern technology as a series of inventions significant mainly for their consequences. Just as importantly, though, technology is a body of foundational ideas in engineering that are as important to know as the foundational ideas of modern science. With them, students can see the continuity as well as the changes that major innovations represent, and at the tertiary level students can learn the circumstances that gave rise to these breakthroughs. This knowledge can also help educators and policy makers better understand the sources of innovation and the qualities of mind needed to encourage and sustain innovative capacities.

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Notes

1. A number of faculty and staff have served as preceptors (section teachers), and graduate civil engineering students have contributed research and served as teaching assistants. For published texts, see David P. Billington, *The Innovators: The Engineering Pioneers Who Made America Modern* (New York: John Wiley and Sons, 1996); and 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). Errata sheets for each book are not included; please write the junior author. A third volume carrying the story from 1939 to the present is being researched and written.

2. Modern engineering as a profession includes engineers whose work involves management, operations, and inspection and maintenance. But the principal function of engineering schools is to educate people in engineering design, and design is the core skill of engineers.

3. Our choices subsume those in George Constable and Bob Somerville, *A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives* (Washington DC: National Academies Press, 2003). For the distinction between normal and radical design, we are indebted to Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore: Johns Hopkins University Press, 1990), pp. 3-15.

4. See David P. Billington, *The Innovators*, pp. 6-12. The equation for horizontal force, $H = qL^2/8d$, in an arch bridge states that the weight (q) per foot of roadway deck length, multiplied by the roadway deck length or span (L) in feet squared, divided by eight times the vertical rise of the arch (d) in feet, gives the horizontal force (H) in pounds at the midpoint of the arch. A vertical force (V) in pounds

also operates at the midpoint and is described by the equation $V = qL/2$. For a cable suspension bridge, the same formulas for H and V apply but represent the forces at the midpoint of the cable. On a cable bridge, the variable d is the cable sag or vertical distance from the midpoint to the elevation of the tower tops.

5. For iron smelting in a blast furnace, see David P. Billington, *The Innovators*, pp. 17-19. The chemical equation is $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$, which states that one molecule of iron ore (Fe_2O_3) and three molecules of carbon monoxide (CO), the latter produced by blasting hot air onto coke (prebaked coal), react to produce two molecules of iron (Fe) and three molecules of carbon dioxide (CO_2). Limestone is also used in the process but can be neglected here.

6. See again note 4 above. For Telford, see ibid., pp. 29-39.

7. For Watt and his horsepower formula, $\mathrm{Hp} = PLAN/33{,}000$, see ibid., pp. 23-29. In a cylinder in which pressure pushes a piston, the letters *PLAN* represent the pressure (P) in pounds per square inch, stroke length (L) in feet, piston head area (A) in square inches, and number of power strokes per minute (N). Watt estimated that a horse could lift 330 pounds of water 100 feet high in one minute, and the product of 100 feet and 330 pounds gives the denominator of his formula. For modern automobiles, the formula measures what is called the *indicated horsepower* of the engine. The formula can be used for multiple-cylinder engines with adjustments to N.

8. For the telegraph, see ibid., pp. 120-133. Ohm's Law, $V = IR$, holds that voltage (V) equals current (I) times resistance (R). The telegraph overcame resistance in the lines and apparatus by having sufficient voltage to carry the current where needed. The opening and closing of the circuit magnetically activated a sounder.

9. The two equations are Joule's Law for electric power and a chemical reaction that illustrates gasoline refining. Joule's Law, $P = VI$, states that power (P) equals voltage (V) times current (I). Rewritten (from Ohm's Law) as $P = I^2R$, the law makes clear that raising R reduces I and helps explain Edison's search for a high-resistance light bulb. The chemical reaction, $2C_{14}H_{30} \rightarrow C_8H_{18} + C_{20}H_{42}$, states that two molecules of a kerosene ($C_{14}H_{30}$) crack into one molecule of a gasoline (C_8H_{18}) and one molecule of a fuel oil ($C_{20}H_{42}$). The reaction illustrates how the 1912 breakthrough in oil refining, the Burton process, turned some of the denser fractions of crude oil into gasoline, saving oil, ninety percent of which would otherwise have been wasted. Joule's Law applies to electricity as direct current. [The process equations for iron and gasoline are particular cases of a general principle, the conservation of mass, while the other four equations state general principles themselves.] For technologies since the 1870s, see Billington and Billington, *Power Speed and Form*. Those since 1939 will be included in the third volume of our trilogy, forthcoming.

10. For the barriers after 1870, see Billington and Billington, *Power Speed and Form*, pp. 17-25, 40-45, 65-72, 108-110, 128. For the scientific argument that Edison's system was impossible, and why this argument was wrong, see pp. 220-223. Edison himself failed to perceive the advantage of using alternating current for long-distance transmission in place of his system using direct current. As a result, George Westinghouse had the opportunity to build an alternating current system that is now the dominant form of electricity used today.

11. For 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).

12. The Society for the History of Technology originally formed in part to address and correct mistaken notions of how science related to engineering. See the symposium papers in *Technology and Culture*, 17:4 (October 1976).

13. "Engineering in the Modern World" gives technical background for about thirty innovations but students only need to learn about eighteen formulas. The number of innovations and formulas can vary slightly each year. Students take a mid-term and a final exam, each consisting of short identifications, calculation problems, and historical essay questions. About half of the students take the course for laboratory science credit, perform supervised model experiments, and solve problems with the models on which they write reports. The other half take the course for history credit and write term papers on a structure, machine, network, or process of their choice, examining it as a physical idea (with numbers) and as a historical event. The course can satisfy a science/technology requirement without the models lab.

14. See *The 2004 Symposium and Workshop at Princeton University, August 8-13, 2004* (Princeton, 2004); and *Second Annual Summer Symposium and Workshop, August 7-10, 2005* (Princeton, 2005). Copies on request.