The Innovators

The Engineering Pioneers Who Made America Modern

DAVID P. BILLINGTON

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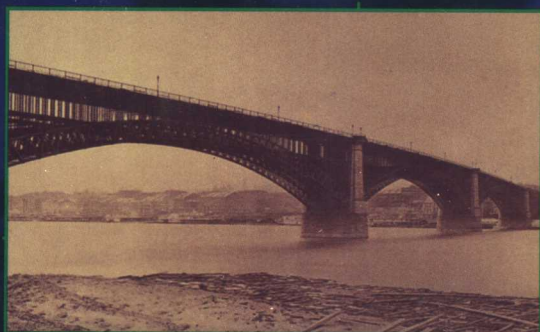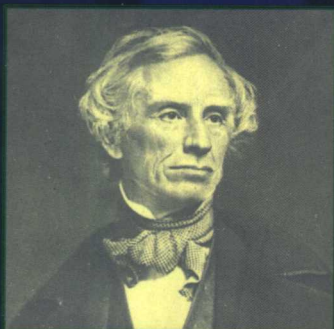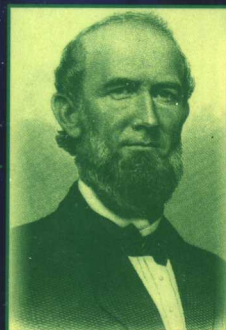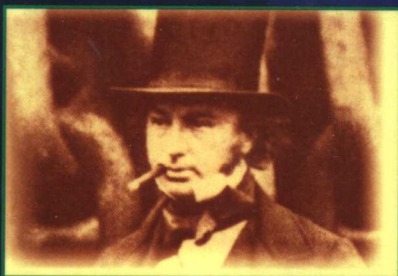
David P. Billington

To Phyllis and to David

Preface

This book is an engineering history of the United States that differs in two ways from most histories of American technology.

First, the book is written from an engineering perspective rather than from the standpoint of social history, and it is also selective in its emphasis on those engineering innovations that were basic to the industrialization of the United States: large-scale structures, prime movers, wide-area networks, and large-scale processes.

Second, the book also focuses on the roles of key figures. The engineering pioneers of U.S. history could have done little without a society that supplied them with capital, trained personnel, and abundant materials and that strongly encouraged new enterprise. Although it is not intended to be a general history of technology in the United States, this book will explain how engineering ideas drew on the unique conditions that existed in nineteenth-century America. At the center of the story, though, are a handful of talented individuals. Where many textbook accounts would lead students to believe that the great industries of the United States were the work of financiers and thieves, this book rescues from historical oblivion the engineers who actually built major industries and in many cases ran them ethically, such as the railroad builder J. Edgar Thomson.

The book treats U.S. engineering history as an interplay of three perspectives: what great engineers actually did, the political and economic conditions within which they worked, and the influence that these designers and their works had on the nation. This three-sided view implies technical discussion, historical context, and cultural impact. We shall discover that the essence of engineering lies not just in natural science, as is usually thought, but also in social science and the humanities. We will explore the scientific basis of engineering through elementary formulas, its social context through issues of politics and economics, and its cultural significance in terms of its impact on the imagination and experience of artists and critics.

The narrative text briefly describes the history of major engineering events, arranged by topic in roughly chronological order. Included are formulas that clarify these events, but the more detailed discussions of these expressions of

scientific ideas are placed in pagelong "sidebars" meant for those readers interested in seeing how the engineers' calculations served as one basis for their designs. The formulas in the text express far more than scientific ideas; they are engineering formulations that also include the social issues of regulated loads, visually striking forms, economy of motion, acceptable risks, the bureaucracy of centralized power supply, environmental issues, the production of wealth, and the private support of culture.

The origins of this book go far back to my undergraduate years in the late 1940s, when I was required to take a course given by our dean, Kenneth Condit, who called it "Industrial Development." He had also invented a program, called "Basic Engineering," in which we took courses in all main branches of engineering. Condit's ideas stuck in my mind so that four decades later, when asked by our associate dean, Ahmet Cakmak, to develop a new freshman course, I began the work that has led to this book. That course now has four main parts: Connecting the Continent, 1776–1883; The Rise of the Great American Industries, 1876–1939; Regional Restructuring, 1921–1964; and Information and Infrastructure, 1946–1996. This book represents the first part of the course, and I plan to prepare a volume for each of the remaining three parts.

Acknowledgments

My teaching from 1958 on has been inspired and sustained by Norman Sollenberger, my primary academic mentor, as well as by the late Joseph Elgin, our dean from 1954 to 1972. I am also indebted to my close Princeton colleague Robert Mark and to John Abel, now at Cornell University. Then, in 1983, support from the Alfred P. Sloan Foundation in its program "The New Liberal Arts" allowed me to begin work on the new course with the firm backing of the foundation's president, the late Albert Rees, and his program officer, Samuel Goldberg. Thanks to their continuing support, I could work with stimulating Princeton colleagues, Mark, Michael Mahoney, and John Mulvey as well as with John Truxal and Marian Visich, Jr. from the State University of Stony Brook. They taught me a great deal as did a group of professors of natural science from liberal arts colleagues: William Case at Grinnell College, Alfonso Albano at Bryn Mawr College, J. Nicholas Burnett at Davidson College, and Newton Copp and Andrew Zanella at the Claremont colleges. That group also included Edwin T. Layton, Jr. from the University of Minnesota who brilliantly guided and instructed us in the history of technology. Robert Prigo of Middlebury College added to our group and crucial help has come from historians Carl Condit, Arthur Donovan, Eugene Ferguson, Brooke Hindle, Thomas Hughes, Ronald Kline, the late John Kouwenhoven, the late Melvin Kranzberg, Ronald Paxton, Robert Post, Walter Vincenti, and Robert Vogel. I also thank Merritt Roe Smith, a longtime friend and advisor as well as Atle Gjelsvik who deepened my understanding of boat design.

Crucial to the development of the course, and hence this book, have been my teaching colleagues at Princeton: Bradley Dickinson, John Gillham,

Richard Golden, Michael Littman, as well as Peter Bogucki, Hal McCulloch, Roy Jackson, Paul Prucnal, and Fred Dryer. Our present dean, James Wei, has continuously and enthusiastically supported this effort. Of great importance has been my six-year scholarly collaboration with politics professor Jameson Doig. Together we taught an American Studies seminar linked to the course and together we have been studying the relationship between engineering and politics in the United States. The National Science Foundation also provided crucial support.

I have had gifted graduate students working both as teaching assistants and research assistants during the evolution of this book, beginning with Scott Hunter and including Christopher Peck, Ron Wakefield, Rosemary Secoda, John Matteo, Roger Haight, and Karen Mielich. Susan Lyons and Nicholas Edwards have not only served in the course but also have worked directly on this present book acting as effective collaborators on its final form.

For all their help, I also want to thank my editors at Wiley, Charity Robey and Emily Loose, as well as Jennifer Ballentine and the staff of Professional Book Center, who put the book together.

My longtime friend and collaborator, J. Wayman Williams, has done research, made slides, desktop-published monographs, organized exhibitions, and for this book developed the sidebars as well as provided me with a challenging critique of the text. My secretary, Kathy Posnett, has committed many versions of the text to hard copy while keeping things running well in the office.

Finally, my family deserves the highest praise for their help and sustenance. My brother, Jim, a distinguished historian, has given me both an understanding of historical scholarship and a model of personal and professional integrity. My son, Philip, who is a writer, drafted several chapters in early versions of the book and my daughter, Sarah, who is an engineer, read critically some chapters. The greatest help of all came from my son David, an historian, who carefully read the entire text, suggested many changes including reorganization of major parts, gave me a critical assessment of the leading ideas, and did the index. His keen editorial eye and his deep sense of history shaped the final manuscript.

My wife, Phyllis, has given me the constant help that makes everything possible. While I read, calculate, or write, her romantic piano music fills the house and reminds us both that such music itself arose in parallel with the industrial revolution about some of whose themes this book attempts to tell.

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David P. Billington
Princeton University

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Contents

I

Iron, Steam, and Early Industry, 1776–1855

1 Modern Engineering and the Transformation of America

Formulas in History

This book tells the story of some major events during the first century of the United States seen through the lens of modern engineering. My central thesis is that engineering has transformed not only the material life of our nation but also its politics and its culture. Although such a thesis is hardly new, I have chosen to include, as a natural part of the story, the engineering description of the transforming events, the central facts of which must be expressed in quantitative terms through some fundamental formulas of the engineer.

My goal is to use these formulas to clarify and deepen readers' understanding of history, not to give readers an engineer's facility with calculations. Because history, even the history of technology, is normally written without such formulas, I need to explain why they are central here.

Formulas are, literally, symbolic images of physical relationships. The formulas presented in this book are rigorously correct but radically simplified versions of what engineers today regularly use to design modern works. These relationships do not involve any mathematics beyond high school algebra, geometry, and trigonometry and usually employ very little of those subjects, either. These formulas are intended to be accessible.

These relationships provide a means of understanding the origins of main events in our history. When Leonard Gale showed Samuel Morse how to get enough magnetism to his receiver, the telegraph became a reality. Gale knew what to do because he knew the relationships among

magnetic flux, current, and turns of wire around the soft iron core of the magnet. He knew the formula, and this knowledge, combined with Morse's skill as a designer and organizer, eventually led to a major event in the history of the United States: the innovation of telegraphic communication.[1]

The formula for magnet flux or for stresses in the walls of boilers gives us a new means of understanding and evaluating events in the modern world, not only of the nineteenth century but of the late twentieth century as well, where electric power generation and containment vessel safety are political issues critical to modern society.

These formulas carry more meaning than scientific relationships: They also convey social meaning by their implications of danger and of economy. It is easy to see in them the way in which reductions in materials or increases in pressures lead to competitive economies and to greater risks of failure. The dialogues between the experts and the public, between the engineer and the politician, between the designer and the journalist, all require a common language free from jargon but enlivened by the clarity of formula.

Finally, it is crucial for the public, politicians, and journalists to know that formulas do not solve problems. Formulas suggest designs, stimulate insights, and define limits, but they never provide ways to the best solutions, as so many technologically illiterate writers on engineering suppose. Formulas do not define a "one best way" or an optimum. Formulas represent a discipline, not a design; they can be used to avoid disasters but they can never ensure full safety or essential elegance.

Transformations

In the mid-1820s a young immigrant from England, Thomas Cole, painted an American landscape as wilderness, a painting without sign of people, where the terror of the untracked scene expressed raw nature. Two decades later, Cole, by then a leading American painter, created a landscape entitled *The Pic-Nic*. It is the same nature as before except there are people quietly enjoying a summer outing in the woods. There is no wilderness, no terror; nature had been domesticated.[2] What caused the change in vision? What transformed Cole's landscape and by the late 1840s the landscape of the northeastern United States?

The steamboat and the railroad brought people into the forest and transported Cole himself up the Hudson Valley, where he had moved from New York City. With those new vehicles went also an expanding iron industry and the new electrical telegraphy. Engineering was transforming

the United States and with it the physical landscape, the political process, and the artistic sensibility. This book tells the story of that transformation through the central symbols of engineering: formulas.

Formulas are not merely the means for mathematical manipulations. They are the relationships essential to a modern industrial society. They carry scientific meaning, of course, but they also express major social ideas that cannot be exhibited more clearly otherwise. These ideas and these meanings have gradually reconstructed U.S. life over the past two centuries. This book carries the story of that change up to the 1880s, by which time the United States had emerged as the world's leading industrial nation.

This emergence depended first upon a series of major engineering events: the steamboat, the textile factory town, the continental railroad, electric telegraph, the iron and steel industry, the steel bridge, and the incandescent light. But each new event caused immediate political problems unforeseen in the late eighteenth century; engineering innovations made essential new political structures. They also gave rise to a new aesthetic. These interactions between engineering and society form the context within which the relationships of transformation operate. I commence this study of engineering in the modern world with a more detailed exploration of these relationships.

Transformations and Engineering Works

The three modes of transformation—nature, politics, and art—represent the three basic studies in the liberal arts—natural science, social science, and the humanities. Modern engineering, to be properly understood, must be studied in the context of these liberal arts. If the context is the liberal arts, which can be a definition of culture, then what is engineering?

Rather than postulate some abstract and general definition, I propose to follow a more traditional line. People expend great energy, for example, trying to define art. Agreement rarely results. Rather, people successfully teach art history without precise definitions by teaching the works upon whose enduring value the profession agrees. Although there will always be disagreement at the edges, any course in painting will be defective that leaves out the works of Michelangelo, Leonardo da Vinci, and Rembrandt up to Picasso, Klee, and Mondrian.

Similarly, art history can be taught by period: classical, medieval, Renaissance, and so on. In any case it depends not upon scientific-type definitions of theory and applications but rather upon examples and

ideas. In addition to individual artists and schools of art, there are also categories of art: painting, sculpture, and architecture as the classical visual arts, for example. In the same way we can identify engineering works through four primary categories: structures, machines, networks, and processes. Furthermore, we can observe that modern engineering in the United States divides itself into periods, the earliest of which corresponds to the development of the prototypical modern material, industrialized iron and steel.

As steel became the building material of the modern world and its offspring, the railroads, became the greatest business of its time, there arose the U.S. industries of oil, electricity, and automobiles. This second period, characterized by central power and private mobility at high speed, dominated the first half of the twentieth century and led naturally into a third period during which the nation turned to major regional restructuring of the landscape through new political instruments such as the Port of New York Authority and the Tennessee Valley Authority. Finally, following World War II, the nation entered the period of high technology that culminated in the microchip and the computer. At the same time, the United States became aware of the deterioration of its built infrastructure of power, water, rails, and roads.

Along with categories and periods comes a set of major events personified by individual pioneers whose innovations have set them apart. Therefore, in tracing the first century of early modern engineering in this book, I focus on the four categories and the people whose works best typify the innovations that transformed the nation.

Raw nature cannot support civilization without four types of transformation: structures for public works; machines for private enterprise; networks for the supply of water, light, power, and signals; and processes for the conversion of natural resources into useful materials. Each type of engineering work has its own character, yet none can exist alone; they are interdependent. But for an introduction each is described separately, and in later chapters each is illustrated by major specific events that changed our society.

Transformation by Structures

Modern structures begin with the use of iron for large-scale works, the first of which was the 1779 Iron Bridge, a cast-iron arch in England. The key formula for understanding this arch bridge is:

$$H = \frac{qL^2}{8d}$$

where H is the horizontal force (in pounds) needed at each of the two side supports to keep the arch from spreading, q is the load on the bridge (in pounds per foot of bridge deck length), L is the horizontal span of the arch (in feet), and d is the vertical rise of the arch (in feet).[*] The figure explains these symbols, which are the same (but with the curve inverted) for the cable suspension bridge.

In the suspension bridge the traffic loads are taken by the horizontal deck to the vertical connecting lines or suspenders that, in turn, pull down on the cables, which carry all the loads by tension (pulling apart) to the tower tops. There the cables push the towers down vertically and pull the towers inward horizontally by the same force, H, given in the formula. To prevent the towers from leaning, the cables go over the towers and are anchored near the deck, usually on the shore. These anchor cables often support the side spans through vertical suspenders as well.

In a cable, the horizontal force H also represents the total cable force at midspan, where the cable itself is horizontal. The larger the force, the more steel the cable requires, so that the equation expresses not only the size of a force but also the amount of material needed for safe design. Moreover, the size of the force H depends directly on the ratio of main span to cable sag, or L/d. Finally, the bridge weight including traffic loads, expressed by qL, directly influences the size of H and hence cable material. The maximum cable tension actually occurs at the tower, but the difference is not great and does not change the following argument.

The scientific fact of the bridge, expressed by the formula, is that vertical loads (qL) are converted into a horizontal force (H) by means of the ratio of span to sag (L/d). That represents a primary discipline of engineering design; that fact is indisputable, and no modern bridge can be built without it. However, the formula gives no hint as to how to proportion the structure, which means the formula cannot serve as a basis for design. We must find another factor, and that comes from the social perspective, which includes cost, benefit, and politics.

The first social issue—qL, the load on the bridge—contains two parts: the traffic load and the weight of the bridge span itself. In the modern world, a public agency sets the traffic load, and that act is political. Will the bridge carry the heaviest trucks or even armored tanks, and how many lanes will it have? Such decisions represent choices bounded by unrestricted use and limited budgets. Large bridges require large public funds for construction, which in a free, democratic society must be justified publicly.

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[*] In this text I employ the units regularly used in British and U.S. engineering throughout the period covered.
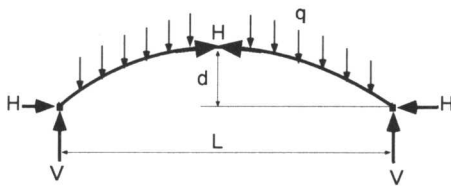
How Structures Work

Arch Bridge
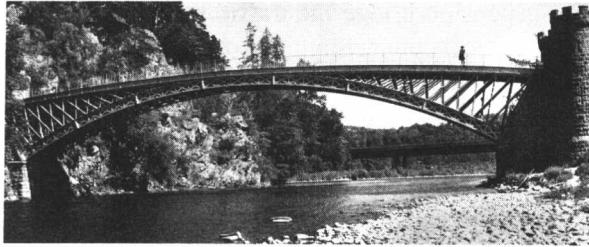
H = horizontal thrust in the arch or cable at midspan (pounds)
q = load (pounds per foot)
L = span (feet)
d = rise of the arch or sag of the cable at midspan (feet)
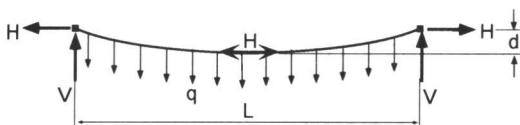V = vertical force (pounds)

$$H = \frac{qL^2}{8d}$$

$$V = \frac{qL}{2}$$

Cable Suspension Bridge

$$H = \frac{qL^2}{8d}$$

$$V = \frac{qL}{2}$$

A second social fact, arising from the ratio L/d, is the cost of towers and cable. Where that ratio is small, then the towers must be high (large d means tall towers) but the cables may be small (large d means small H). The first simple formula tells us these facts, and the size of H controls the amount of steel in the cable through a second formula

$$A = \frac{H}{f}$$

where A is the cross-sectional area (in square inches) of the steel in the cables and f is the allowable stress in the steel (in pounds per square inch of cross-sectional area). The formula is scientific because it expresses a fact of physics; it is independent of any social factors. Having H from the first formula, then for any value of f there will be only one possible solution A.

But the formula also expresses a social fact because someone must choose f. The term *allowable stress* is not a scientific but rather a social statement. Scientifically, a steel wire of a given size, say, $\frac{1}{4}$ inch in diameter (about $A = 0.05$ square inches), will break when pulled by a certain force H, say, 10,000 pounds. That is a scientific fact. The breaking stress f_B would be about 200,000 pounds per square inch, but no one wants a bridge designed such that the real traffic load plus bridge dead weight stresses the cables to the breaking point. Therefore, someone must decide how high the stress can go and thus increase A in order to reduce f. The social consequence of increasing A is greater cost (more steel in the cables), but there is the social benefit of a greater safety factor (the ratio f_B/f). Such factors are set by codes that have legal force and result in the end from choices made by the general public. In the simplest possible terms, the public can get for the same cost three bridges instead of two bridges if it is willing to reduce the safety factor for each of the three by 33 percent (see figure). In a poor country struggling to industrialize, such a decision might be wise, and indeed many U.S. railroad bridges of the nineteenth century were built with low safety factors in order to quickly construct long lines to widely separated settlements.

Finally, the bridge design results not only from scientific facts and social factors, but also from symbolic ideas. These ideas come from individual designers whose image of the bridge transcends all formulas. The best designers see their creations as works of art so that they have aesthetic, ethical, and spiritual meaning. Yet at the same time designers must work within the laws of nature and the patterns of society. Even these symbolic ideas are visible in our simple formulas, although they cannot be fully caught by any formula or indeed by any verbal formulation. The ratio L/d expresses the primary bridge proportion. Contrast the Golden Gate