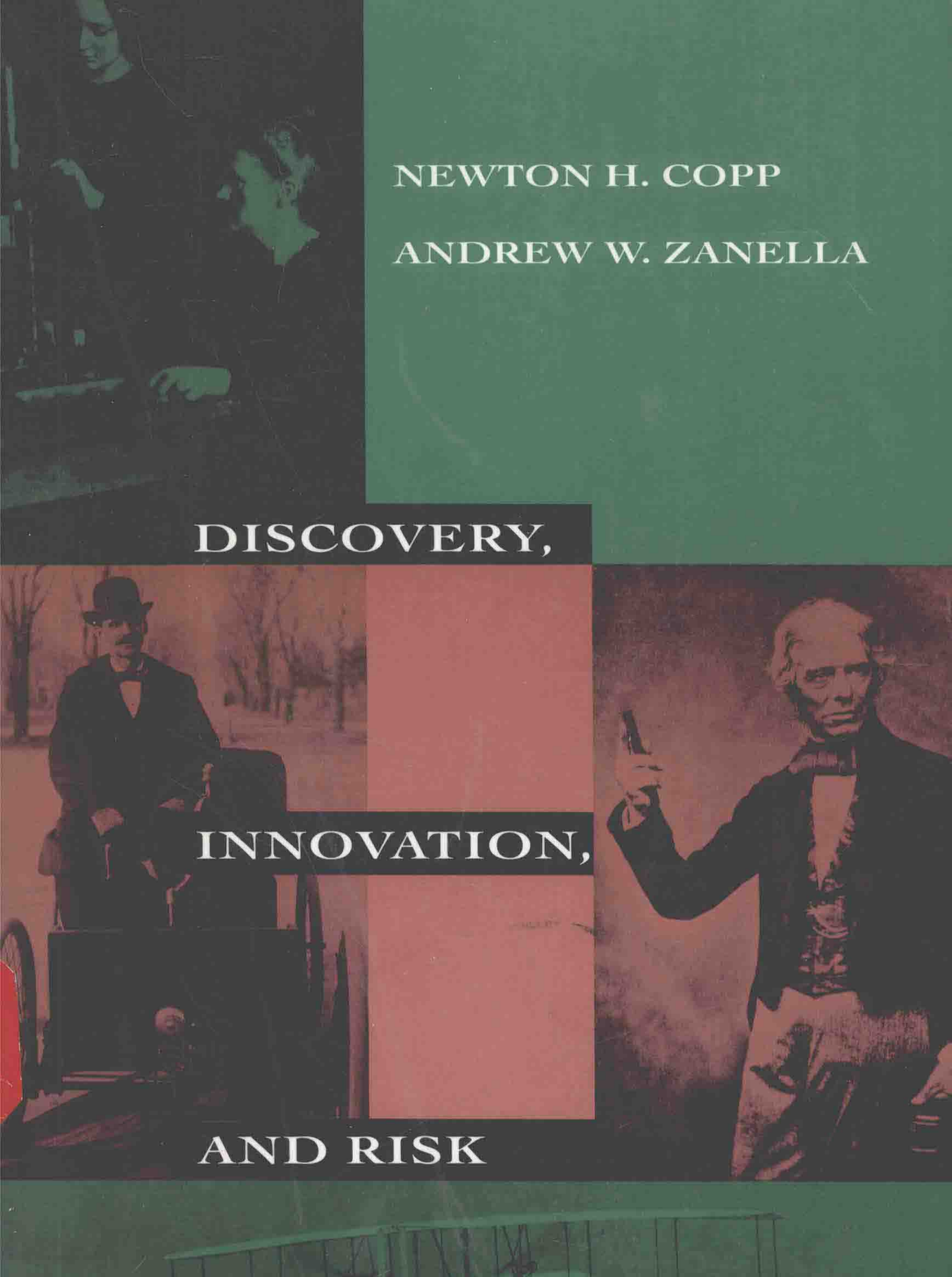

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ANDREW W. ZANELLA

DISCOVERY, INNOVATION, AND RISK

CASE STUDIES IN SCIENCE AND TECHNOLOGY

Discovery, Innovation, and Risk

Case Studies in Science and Technology

Newton Copp and Andrew Zanella

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Preface

The New Liberal Arts Program

In 1982, the Alfred P. Sloan Foundation began the New Liberal Arts program to foster an understanding of technology and quantitative reasoning in students attending liberal arts colleges. The Sloan Foundation appealed to thirty-six colleges and fourteen universities around the United States to develop materials for the undergraduate curriculum that would further the goals of the program. The New Liberal Arts series, which includes this book, represents part of that effort.

Focus of this Book

Some things are more easily defined by stating what they are not than by trying to determine exactly what they are. This book is not an introduction to the natural sciences; neither is it an introduction to engineering—many very good books have already been written in each of these areas. This book represents our attempt to look simultaneously, cross-eyed if you will, at both science and engineering in the historical context of particular technological developments. Our major purpose in creating this unusual amalgam is to provide a meaningful technological framework within which major scientific principles in biology, chemistry, and physics may be discussed. Detailed treatment of the relevant scientific principles, however, is left to the instructor.

The impulse to write this book came from a realization that most people do not relate directly with the practice and findings of science but instead interact indirectly through technology. We live not so much in an age of science as in an age of scientific technology. The blossoming of the natural sciences that has been going on for roughly three hundred years appears to most people through the technological achievements of the last century, a period overlapping much of what historians have named the Second Industrial Revolution. In this brief period, an increasingly complex interplay between science and engineering within our culture has produced the airplane, modern pharmaceuticals, gasoline and the automobile, telecommunications, commercial electricity, modern highway systems, and other technological marvels that have shaped our culture. Modern technology thus provides the most meaningful context for understanding the principles and impact of modern science, and yet many general science courses lack material on modern technology and the interplay between science and engineering that has produced it. We hope this book will fill that gap.

Each chapter focuses on a specific technology, and the most conspicuously relevant scientific principles are introduced as they apply to each case. A full appreciation of the technological advances discussed in this book includes a quantitative view of the subject matter. In keeping with this notion, simple calculations are included where appropriate to complete the story and provide a level of detail that we hope increases the reader's appreciation for the elegance of the achievements. Various chapters will read differently depending upon whether the mathematics are more central to the arguments, as in chapters 4 and 7, or less central, as in chapter 10. Likewise, the study of new material implies that a new vocabulary is encountered; to facilitate understanding, a glossary of technical terms is provided at the end of the book for handy reference. When a technological advance has a particular bearing on urban life, we have chosen Los Angeles to illustrate its impact. There are several reasons for this choice apart from the fact that we live near Los Angeles. A massive westward redistribution of the population in the United States occurred during the Second Industrial Revolution and redefined the southwestern states as a desirable region in which to live rather than as a forbidding desert. The desert environment has placed a premium on innovative technological solutions to the problems associated with supporting a large population. Los Angeles represents a particularly good illustration for these solutions, as well as for the attending problems, because its growth has been unusually rapid. Finally, the lessons that can be learned from studying Los Angeles apply to many other large cities around the country.

Our intent is not to provide a thorough treatment of the scientific principles but to develop a technological context in which various scientific principles are applicable. We hope that this approach offers material relevant to students and faculty interested in science without excluding those whose interests lie in the history of science and technology and without duplicating unnecessarily much of the material commonly offered in general science courses. The examples were chosen to illustrate events in each of the major divisions of engineering including civil, electrical, mechanical, chemical, and medical as well as to touch on principles in physics, chemistry, and biology. Not all of the examples represent spectacular achievements, but they do represent undeniably significant contributions to our modern culture that arose during the Second Industrial Revolution.

Each of the chapters, except the first and the last, falls into one of three sections: discovery, innovation, and risk. The section on discovery emphasizes technological developments that sprang directly from the discovery of new scientific principles (chapters 2 and 3) or from the fresh application of scientific reasoning to an engineering problem (chapter 4). Scientific discovery and reasoning does not always foster technological development as directly as described in these early chapters. The cases in the section on innovation show that a great deal of technical innovation can proceed without a full understanding of the underlying science (chapter 5), or that it may grow in a climate of scientific inquiry without direct support provided by recent scientific discoveries (chapters 6 and 7). Regardless of the relationship between science and technology that spawned a major development, new developments often bring risks. Three case studies are presented in chapters 8, 9, and 10 to indicate the scientific and technical aspects of the danger as well as to suggest the power and limits of science and engineering in reducing risks in our technological society. By placing each topic in its historical context, we hope to communicate a sense of how human understanding and control of nature have increased in fits and starts as engineers and scientists struggled to solve specific problems. As small as the glimpse may be, we also hope that these studies help the reader share our growing appreciation for nature and what human beings manage to do with it.

Acknowledgments

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Much of the material in this book was developed in a series of workshops sponsored by the Sloan Foundation and conducted at Princeton University. Four of our colleagues in these workshops generously agreed to share the results of their work and cooperate with us in converting their materials into chapters. Alfonso Albano (Bryn Mawr College) wrote the original draft of the chapter on telegraphy. The chapter on gasoline was developed from a manuscript written by J. Nicholas Burnett (Davidson College). William Case (Grinnell College) contributed the analyses and discussion of the Walnut Lane and the Felsenau bridges to the chapter on prestressed concrete. The chapter on flight grew out of a manuscript written by Robert Prigo (Middlebury College). We are indebted to these four people for unselfishly contributing their time and expertise to this project.

We also want to thank Peter Myers, Ken Stunkel, David Billington, John Truxal, John Moeur, our colleagues in the Joint Science Department of Claremont McKenna, Pitzer, and Scripps Colleges of The Claremont Colleges, and several anonymous reviewers for carefully evaluating portions of this book and helping us correct and clarify the manuscript. Finally, we thank Helen Wirtz for her help in designing and drawing many of the illustrations. Portions of this book have appeared in several monographs.

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Introduction

Science Joins Engineering

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The Pace of Change

Anyone born in the United States at the start of the Civil War and fortunate enough to live eighty-four years until the end of World War II would have experienced a pace of change remarkable, perhaps unparalleled, in human history. In 1861, we were a nation of thirty-four states with only a few wagon trails connecting the eastern seaboard with the vast, sparsely populated and largely unincorporated reaches of the west. Within a single lifetime, America was transformed socially, culturally, politically, militarily, and technologically into a world-power nation of forty-eight states linked increasingly tightly by telecommunications networks, nearly two million miles of improved roads, airline routes, and electrical power networks. The fastest way to get mail from New York to Sacramento, California early in 1861 involved putting it on a train for a two-day trip to St. Joseph, Missouri, then transferring it to the saddle bags of Pony Express riders who took at least eight more days to carry it the remaining 2,000 miles. The speed of mail delivery by this route astonished people at the time, but it quickly paled in comparison to the virtually instantaneous communication made possible by the first transcontinental telegraph line erected in the same year. This event established the first truly high-speed, long-distance communication channel between the two coasts of the North American continent and was a harbinger of the important technological changes soon to come.

During the first thirty years of someone's life spanning this eight-four-year period, the steam engine served as the major source of machine power with energy drawn from burning wood and coal. But by the person's fortieth birthday, the technological seeds had been sown that would develop rapidly into extensive networks of electrical power lines. Dramatic improvements in the ability to transmit electricity long distances allowed its consumers to locate their homes and businesses far from the oil deposits, coal fields, or rivers that supplied the energy. This valued aspect of electricity played a central role in opening the American Southwest for settlement and industry after the turn of the century.

In the person's forty-second year, the ancient dream of human flight became a reality as the first powered, piloted airplane took to the air near Kitty Hawk, North Carolina. Supported by advances in the refining of oil to produce gasoline, the aircraft industry developed so rapidly that the person's seventy-fifth birthday could have been celebrated by flying coast to coast in a little more than eighteen hours, a trip that took at least five days before the advent of airplanes. At about the same time as the first powered airplane flight, Americans stood a 33 percent chance of dying from an infectious disease. Pneumonia, tuberculosis, diphtheria, and gastrointestinal infections such as cholera ranked among the ten major causes of death in the United States. A battery of vaccines and antibiotics developed mostly after 1920, along with improvements in sanitation and the average standard of living, produced a 75 percent cut in the mortality from these causes by 1935 and eliminated all infectious diseases except pneumonia from the top ten list within the next thirty years.

A life that began in the same year as transcontinental telegraphy and lasted eighty-four years ended in the year that atomic fission first promised abundant power even as it destroyed two Japanese cities. This event, perhaps more than any other, symbolizes the uncertainty rooted in the technological changes that unfolded between 1861 and 1945. The technological developments of this period have become so integrated into the fabric of our lives that we are hard pressed to find a single facet of the nation's well-being that does not depend on them. Telecommunications, transportation, medicines, and energy do not exhaust the list of technological fields crucial to us, but they comprise a significant part of it. Advances along these fronts have come so rapidly that we appear to be stunned by the pace of change even as we take it for granted. Coping with the consequences of change, the benefits as well as the problems, now commands a considerable amount of attention from writers, social critics, politicians, and others.

Science, Engineering, and Technology

The obvious question is how did all of this happen in such a short amount of time? A complete answer to this question, if one could be obtained at all, would necessarily refer to the almost unimaginably complex interactions among the myriad components of a society in a growing nation. One portion of this web of interactions, however, deserves special attention: the relationship between science and technology. By this we mean the relationship between engineering and the natural sciences that grew notably closer over the past 100 to 150 years.

Modern science gradually separated from its ancestral field of natural philosophy but retained the understanding of nature as its overriding goal. Scientists seek general patterns in nature that can be summarized in models and theories. Theories are then used to formulate predictions that are tested experimentally, leading to further support or refutation of the theory. Many people, including some scientists, would take exception to this highly simplified view of the scientific enterprise, but it serves to point out that science, or basic research, is not explicitly concerned with practical applications. Nuclear physicists in the 1920s wanted to understand the atomic nucleus. They had no intention of building a bomb.

The profession of engineering, on the other hand traces its major roots to craftsmanship and works toward increasing our control over nature for human benefit. The engineer may be helped by an understanding of general patterns in nature, but that is not the ultimate goal of the profession. Engineers have come to use much of the methodology of science, but the nature of the questions differ from science as engineers seek better machines, structures, systems, chemicals, or processes. Problems of scale become important to the engineer as do problems of cost and other aspects that influence utility. While general scientific theories set the broad constraints, final designs must be informed by more detailed considerations than general descriptions of nature can provide.

Modern technology results from engineering, but this has not always been the case. Fabrics, dyes, medicines, pottery, metal tools and weapons, the plow, the stirrup, other useful items, and even dozens of crops were developed over the course of human history without benefit of professional engineers or scientists. The developers of the early water wheels, for example, were not physicists or mechanical engineers, but they knew about tapping the power in falling water and had the skill, the tools, and the materials to do it. Likewise, the first steam power enthusiasts were simply trying to remove water from mines. They probably had no idea that they were launching a technological revolution.

The trial-and-error approach to technology should not be demeaned—it fostered the First Industrial Revolution in the eighteenth century. This transition in western society sprang from the intelligent efforts of British inventors, craftsmen, machinists, toolmakers, and businesspeople. The antecedents of the revolution go back to the Middle Ages when wind and water power were harnessed to run hammers, saws, and grain mills, thus beginning the emancipation of people and animals from being the main sources of such power. The eighteenth century witnessed a great leap forward when the steam engine was developed to run water pumps, initially, then looms and other machinery. Mills and factories, no longer constrained to locations near running water, were built on sites closer to raw materials and became centers for the growth of large cities.

The technology of the First Industrial Revolution developed more from the practical experiences of the craftsmen than from sound theoretical foundations. New structures, machines, and materials reflected common sense and creative insights, rather than scientific data and principles, because scientific information was largely unavailable at the time. This is not to say that scientific principles were ignored when they were understood. When James Watt designed steam engines in the late 1700s, he certainly knew that the pressure of a gas depends on its temperature, but he had no theoretical knowledge of the laws of thermodynamics. These laws were not formulated until the nineteenth century and eventually proved crucial in designing safer, more efficient engines. Iron, the signature material of the First Industrial Revolution, also was developed without