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**Introduction  
to Engineering  
Design and  
Problem Solving**

**M. DAVID BURGHARDT**

# Introduction to Engineering Design and Problem Solving



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## INTRODUCTION TO ENGINEERING DESIGN AND PROBLEM SOLVING

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3 4 5 6 7 8 9 0 DOC/DOC 9 3 2 1 0 9

ISBN 0-07-012188-5

Vice president and editorial director: *Kevin T. Kane*  
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Supplement coordinator: *Carol Loreth*  
Compositor: *Publication Services, Inc.*  
Typeface: *10/12 Century Schoolbook*  
Printer: *R. R. Donnelley & Sons Company*

### Library of Congress Cataloging-in-Publication Data

Burghardt, M. David

Introduction to engineering design and problem solving / M. David

Burghardt

p. cm.

Includes index.

ISBN 0-07-012188-5

1. Engineering design. 2. Engineering mathematics. I. Title.

TA174.B874 1999

620'.0042—dc21

98-18378

<http://www.mhhe.com>



# About the Author

M. David Burghardt is a professor in the engineering department of Hofstra University. He received his Ph.D. in mechanical engineering from the University of Connecticut in 1971 and is a Professional Engineer in New York state and a Chartered Engineer in the United Kingdom. He is the author of several texts on thermodynamics, diesel engines, and freshman engineering. His current research interests are in two primary areas, lightweight diesel engines and improving technological literacy in elementary and secondary schools. He has coordinated the introduction to engineering experience at Hofstra for the past 15 years and his primary teaching responsibilities are in freshman engineering, thermodynamics and technology, and public policy.



# Foreword

Engineering educators have had long-standing debates over the content of introductory freshman engineering courses. Some schools emphasize computer-based instruction, some focus on engineering analysis, some concentrate on graphics and visualization, while others emphasize hands-on design. Two things, however, appear certain: no two schools do exactly the same thing, and at most schools, the introductory engineering courses frequently change from one year to the next. In fact, the introductory engineering courses at many schools have become a smorgasbord of different topics, some classical and others closely tied to computer software applications. Given this diversity in content and purpose, the task of providing appropriate text material becomes problematic, since every instructor requires something different.

McGraw-Hill has responded to this challenge by creating a series of modularized textbooks for the topics covered in most first-year introductory engineering courses. Written by authors who are acknowledged authorities in their respective fields, the individual modules vary in length, in accordance with the time typically devoted to each subject. For example, modules on programming languages are written as introductory-level textbooks, providing material for an entire semester of study, whereas modules that cover shorter topics such as ethics and technical writing provide less material, as appropriate for a few weeks of instruction. Individual instructors can easily combine these modules to conform to their particular courses. Most modules include numerous problems and/or projects, and are suitable for use within an active-learning environment.

The goal of this series is to provide the educational community with text material that is timely, affordable, of high quality, and flexible in how it is used. We ask that you assist us in fulfilling this goal by letting us know how well we are serving your needs. We are particularly interested in knowing what, in your opinion, we have done well, and where we can make improvements or offer new modules.

**Byron S. Gottfried**  
**Consulting Editor**  
**University of Pittsburgh**



# Preface

*Introduction to Engineering Design and Problem Solving* is designed to help beginning engineering students gain a better perspective on engineering, particularly the creative aspects of engineering design coupled with the rigors of analysis. Engineering design and the design process are generally not well understood, and the text focuses on them through discussions of the design process, examples of student work, and words of wisdom from practicing engineers. Engineering analysis is integral to the design process, and fundamentals in electrical engineering, mechanics, and energy are part of the knowledge base necessary for successful designs.

The first chapter examines the human-made world, the world we live in, created by engineers. The processes employed by engineers to create this world embrace science, the study of the natural world, and mathematics, the study of logical constructs, and include elements uniquely their own. There are philosophical values associated with mathematics, science, and engineering, some similar, others divergent. These values will be explored. One of the purposes of Chapter 1 is to set the stage for the later chapters, providing a context for the designs that we create. For instance, in mathematics and science the concept of uniqueness, a correct answer, is vital. The square root of 25 is 5, not about 5, and similarly, the composition of water is  $H_2O$ , not approximately that. However, in the human-made world, optimum or best solutions are important, uniqueness is not. Trade-offs are always made among cost, materials, aesthetics, and other factors. In addition, there may be constraints to be satisfied on the problem in terms of product size, time, and personnel.

Chapter 2 discusses and analyzes the design process. The iterative nature of the design process—problem statement, specifications/clarifications, investigation, brainstorming, creating solutions, evaluation of solutions, and selection of the optimum solution—are examined and illustrated. Creativity is an important aspect to design, and traits and attitudes of creative people

are portrayed to see how we can expand our own inherent creativity. The concepts of invention and innovation are introduced along with multicriteria analysis techniques. The area of ecological design is of growing importance nationally and internationally, and the challenges that it brings are examined.

In Chapter 3 design documentation is explored in its several forms. Engineers document their daily work in a design journal which provides a resource for attorneys filing for patents. The presentation of a created artifact is important, hence the design portfolio and design report are discussed. The design portfolio is a guide which assists students in their first designs; it asks what the problem is, what investigations were carried out in implementing the design process. This is illustrated with an actual student portfolio and its assessment. Once a student has worked with the design portfolio, a design report can be written based on the information in the portfolio.

Chapter 4 puts it all together. Engineering analysis in electrical, mechanical, and energy fundamentals is presented along with critiqued design project reports. The area of electrical engineering includes steady-state dc circuits with applications and logic diagrams and circuits. Engineering mechanics includes two-dimensional forces and moments including the use of free-body diagrams. Strength of materials is introduced; with stress and strain the concept of factor of safety is introduced. Energy analysis includes the conservation of mass and energy for open and closed systems. Examples of extended energy analysis are presented. Several fundamental software applications available to engineers, essential for today's engineering practitioner, are examined.

What is it like in the real world of engineering? Chapter 5 addresses this question through extended interviews with six engineers from various fields. These engineers provide insight into how the business of engineering functions, what to be alert to and proficient in. The excitement of engineering comes alive through their stories, why they chose engineering, career moves, what to look out for, abilities to hone.

Much of engineering analysis rests on the foundation of algebraic word problems—how do you set up and solve equations from information presented in words? This is often a challenge for beginning engineering students, and Appendix A reviews basic algebraic and trigonometric word problems with engineering applications. A review of binary number systems is presented.

Many people have contributed to the development of this text, none more important than my students in freshman engineering. I would like to particularly point out the four students who have assisted me by contributing their design projects for all to see—John Buhse, Joseph DiBiasi, Nancy Forsberg, and Ciro Poccia. In addition I appreciate the critical and very valued review

of the manuscript by Dr. J. Taylor Beard, University of Virginia; Dr. Diane Beaudoin, Arizona State University; Dr. David L. Clark, California State Polytechnic University; Dr. Rajiv Kapadia, Mankato State University; Dr. Terry L. Kohutek, Texas A&M University; Dr. John A. Krogman, University of Wisconsin-Platteville; Dr. Michael E. Mulvihill, Loyola Marymount University; Dr. Melinda Piket-May, University of Colorado; and Dr. Steven Yurgatis, Clarkson University. The text is very much improved by their individual and collective wisdom.

The overall purpose of the book is to interest and excite students about engineering, particularly with the creative challenge and reward of engineering design. It provides a window on the real world of engineering practice, a world of marketplace demands and tremendous opportunities.





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# Understanding the Human-Made World

Engineering and the artifacts of engineering—technology—have been around since the beginnings of human civilization, far longer than mathematics and science; yet most people are terribly ignorant about engineering and technology. In contrast to mathematics and science, engineering and technology are typically not taught in schools in the United States, and the processes creating the enveloping human-made world are largely not understood.

There are many definitions of *engineering*, such as the one from Webster's *College Dictionary*: "the practical application of science and mathematics, as in the design and construction of machines, vehicles, structures, roads and systems." This definition belies the uniqueness of engineering, the body of thought it embodies, and the methodology, uniquely its own, which it employs. Perhaps a more general definition would be a course of study followed by a professional life devoted to the creative solution of problems. Yes, engineers are creative problem solvers, often imagining and designing new technologies as a means to solve problems. Advances that improve the standard of living of people are directly attributable to engineering, from machines that reduce physical labor to systems that provide clean water.

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Table 1.1 indicates some of the differences between mathematics, science, engineering, and the social sciences and humanities. Of course, these are thumbnail sketches, but they will serve to highlight the differences between the disciplines. Science is the study of the natural world, a discipline engaged in discovering the whys and wherefores of natural phenomena. What creates lightning? Why do electrons have a negative charge? There is a process for this investigation—scientific inquiry—in which a hypothesis is posed and logical investigations are undertaken to confirm or deny the hypothesis. Through such investigations, theories are confirmed that explain natural phenomena. Mathematics is used

**Integration of  
Mathematics,  
Science, and  
Engineering**

by engineers and scientists as part of their investigations, and it has its own philosophy and patterns. Mathematics is often used to represent a natural phenomenon or human-made device. For instance, Newton's second law of motion—force is the time rate of change of momentum—is often expressed as  $\mathbf{F} = m \cdot \mathbf{a}$ , a mathematical representation of the law. There are rules of mathematical analysis, called theorems, that allow us to manipulate such equations, such as the commutative law that allows us to represent it as  $\mathbf{F} = \mathbf{a} \cdot m$ .

The social sciences and humanities provide an entirely different view of the world, a world shaped by human perceptions and understandings. For instance, a novel or a political or social event can be analyzed from many different perspectives. A woman may analyze it differently from a man, an urban dweller differently from a rural person, a minority member differently from a majority member, a technical person differently from a nontechnical person. These are the different lenses through which events are viewed, and opinions shaped. We often realize there is no one correct answer, but the superposition of many beliefs creates the societal belief collage.

What discipline brings all these together? Engineering! In creating the human-made world, knowledge from science, mathematics, and social sciences and humanities must be brought to bear. As contrasted with scientific inquiry and mathematical analysis, engineering design does not seek a unique or correct solution, but rather seeks the best or optimum solution after a variety of factors are weighed, such as cost, materials, aesthetics, and marketability. We will discover that the design process is iterative, creative, nonlinear, and exciting. The solutions that our creative minds conceive are tempered by our societal upbringing. The weighing of the trade-offs we make is similarly biased. Hence the optimum solution for one person may not be the optimum solution for another.

Consider the development of the heart pacemaker. This electronic device is implanted in the body to regulate the heartbeat, should it become irregular. Before engineers could proceed very

**Table 1.1** Comparison between different fields of thought

Engineering	Science	Mathematics	Social sciences and humanities
Study of human-made world	Study of natural world	Study of mathematical constructs	Study of human mind and perception
Engineering design	Scientific inquiry	Mathematical analysis	Rhetoric and criticism
Iterative design process, optimum solution	Hypothesis testing and evaluation	Theorems, proofs, rational constructs	Eclectic methods, comparative values
Biotechnology (heart pacemaker)	Biology (physiology)	Sinusoids (modeling heart)	Ethics (who receives assistance)

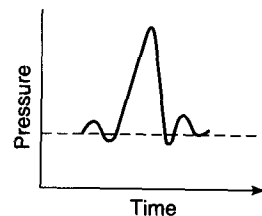
far with the design, they or someone on their design team needed to understand human physiology. What materials could be implanted into the body? What was a normal heartbeat? The heartbeat pattern is important, and mathematical modeling is a technique engineers use to assist them in this determination. For instance, a heartbeat, shown in Figure 1.1, may be modeled as the sum of sinusoidal waves added through superposition.

Technology begets change, often change for the better, as in the case of the pacemaker. But what if the technology is expensive? How will it be determined who should receive the aid? In the United States, two-thirds of the patients receiving kidney dialysis are over 65 years old, while in the Great Britain, no one over the age of 55 receives kidney dialysis treatment as part of the national medical program. Technology can also create vexing problems for which there are no ready solutions. Engineers' voices are needed if wise solutions, balancing different views, are to be found. Thus far, engineers have not been well heard in the halls of Congress. The 103d Congress had one senator (1/100) with an engineering or science background and only eight representatives (8/435).

The concept of best or optimum is one familiar to us all. For instance, when you purchase goods or services, an implicit balancing is going on in your mind. Consider that you want to buy the best potato chip. What are the attributes of potato chips that you think are important? Your list will probably include crispiness, taste, saltiness, greasiness, cost, thickness, size, aroma, packaging, and dippability. Somehow you balance all these factors and reach a conclusion as to which chip is the best for you, recognizing that your brother, sister, parents, and friends may reach different conclusions based on their preferences. An analogous weighing of factors, making trade-offs, is used in the design process to create the optimum solution.

Modern engineering is a fairly new discipline, extending back only as far as the mid-1800s. Of course, companies built machines, important ones, before this time, but the understanding of the laws of science and tools of mathematics was very rudimentary and sometimes totally in error (e.g., the caloric theory of heat). The engineering that you will be experiencing is a blend of mathematical analysis, scientific inquiry, and creative design, built on its centuries-old craft origins. The laws of mechanics were well understood by the mid-1800s, as were the fundamentals of electrical engineering. By the end the 1800s most of the natural laws, such as Maxwell's equations describing electromagnetic waves, were discovered and formulated. Universities began incorporating science and mathematics in engineering studies by the late 1800s, a system that has been refined to the present.

An interesting, albeit troubling, aspect of most history and social studies courses in grades K through 16 is the lack of content on technology and its impact on society. People often admire scientific and technological advances and become quite enamored with



**Figure 1.1**  
Heartbeat.

the gains (e.g., the camcorder, videocassette recorder, personal computer), yet remain ignorant of the processes and knowledge required to effect such gains. When C. P. Snow discussed the separation of the world of science from that of humanities, he discovered that the literary group (those whose schooling and experience fall under the social sciences and humanities heading of Table 1.1) were in many ways much more ignorant of science and technology than scientists and technologists were of literature. You can verify this by reflecting on your own educational background—what portion of your schooling looked at technology, its creation, and its use? This was not always the case; the papers of Benjamin Franklin and Thomas Jefferson reflect an interest in and knowledge of science and technology and its necessity for developing a stable nation. It is unfortunate that the emphasis was lost. Study of the scientific and technological enterprise should not remain the domain of scientists and engineers (if it is addressed at all), but should be included in everyone's education.

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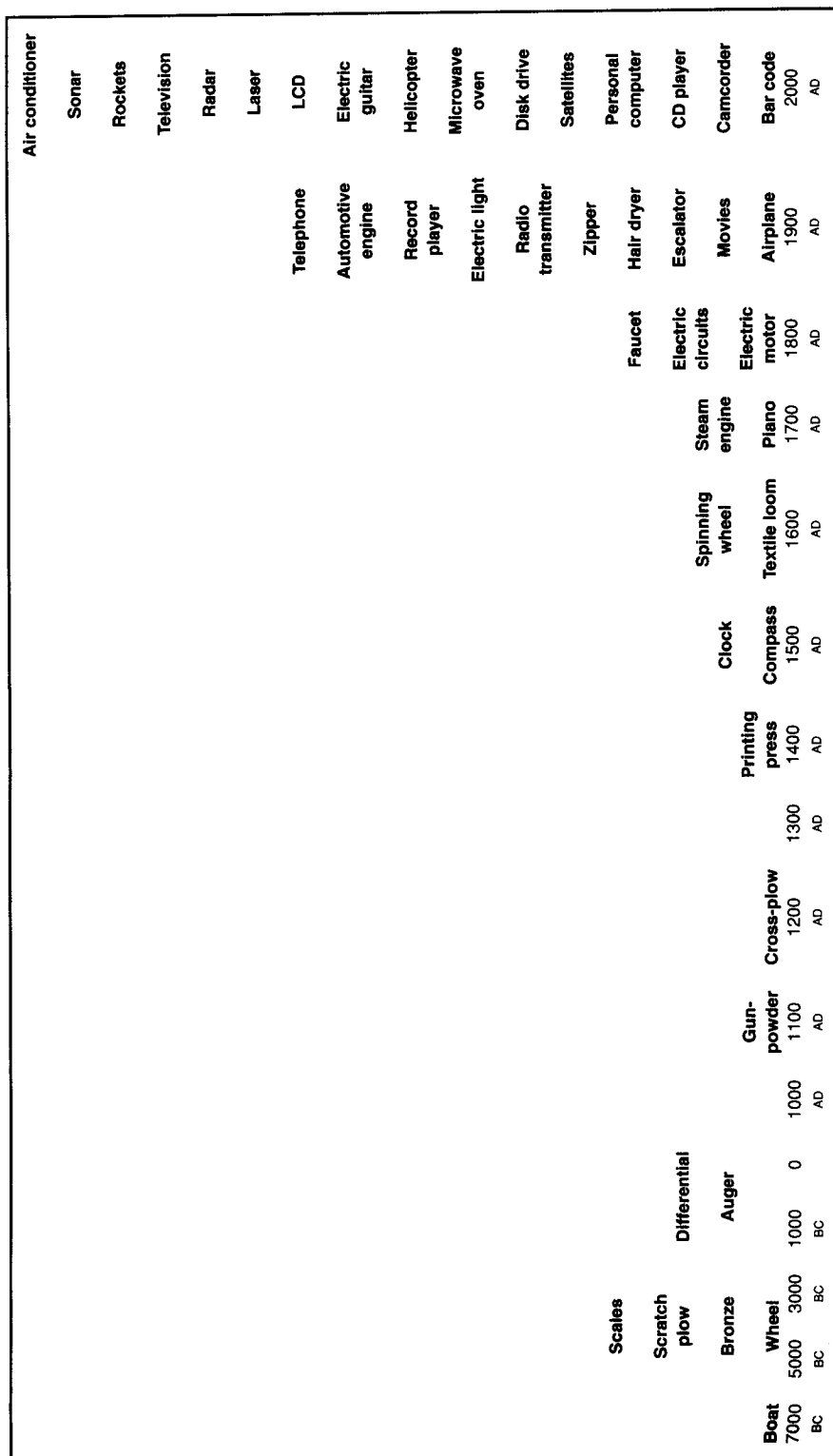
## **A History of Engineering Innovation**

We live in a modern, technologically sophisticated society because of myriad scientific and technological advances that have occurred over thousands of years. Figure 1.2 illustrates a time line for some technological advances that have brought us to where we are today. It is difficult to imagine life without many of them. We will examine some of them to gain insight into the leap of imagination and creativity that engineers have exhibited throughout the course of human history. Notice the tremendous advance in the 19th and 20th centuries as engineering evolved into its modern discipline, fusing craft and creativity with scientific understanding and mathematical analysis.

As we all know, people need food, shelter, and clothing to survive. The first inventions, as people advanced from being hunter-gatherers to living in agriculturally based societies, were ones that facilitated this. The yoke and scratch plow enabled animals to be used in the tilling of land, expanding the acreage on which a person could grow crops and thus increasing the number of people that could be fed. The yoke for oxen, created over 5000 years ago, is still used today (Fig. 1.3). This is a fine example of bioengineering, where the device fits the animal's physiology, permitting the strength of the animal, acting through its chest to the yoke, to be transmitted via a shaft to the plow.

With the increase in societal complexity as civilization advanced, the need for standardized weights and measures became important, a concept that we accept automatically today but one which was a major philosophical advance for that era. How does one establish an equivalency for an amount of cotton versus grain versus metal? We know there is no conservation law for volume, but there is a conservation law for mass. Balance-beam scales





**Figure 1.2**  
Time line of technological advances.