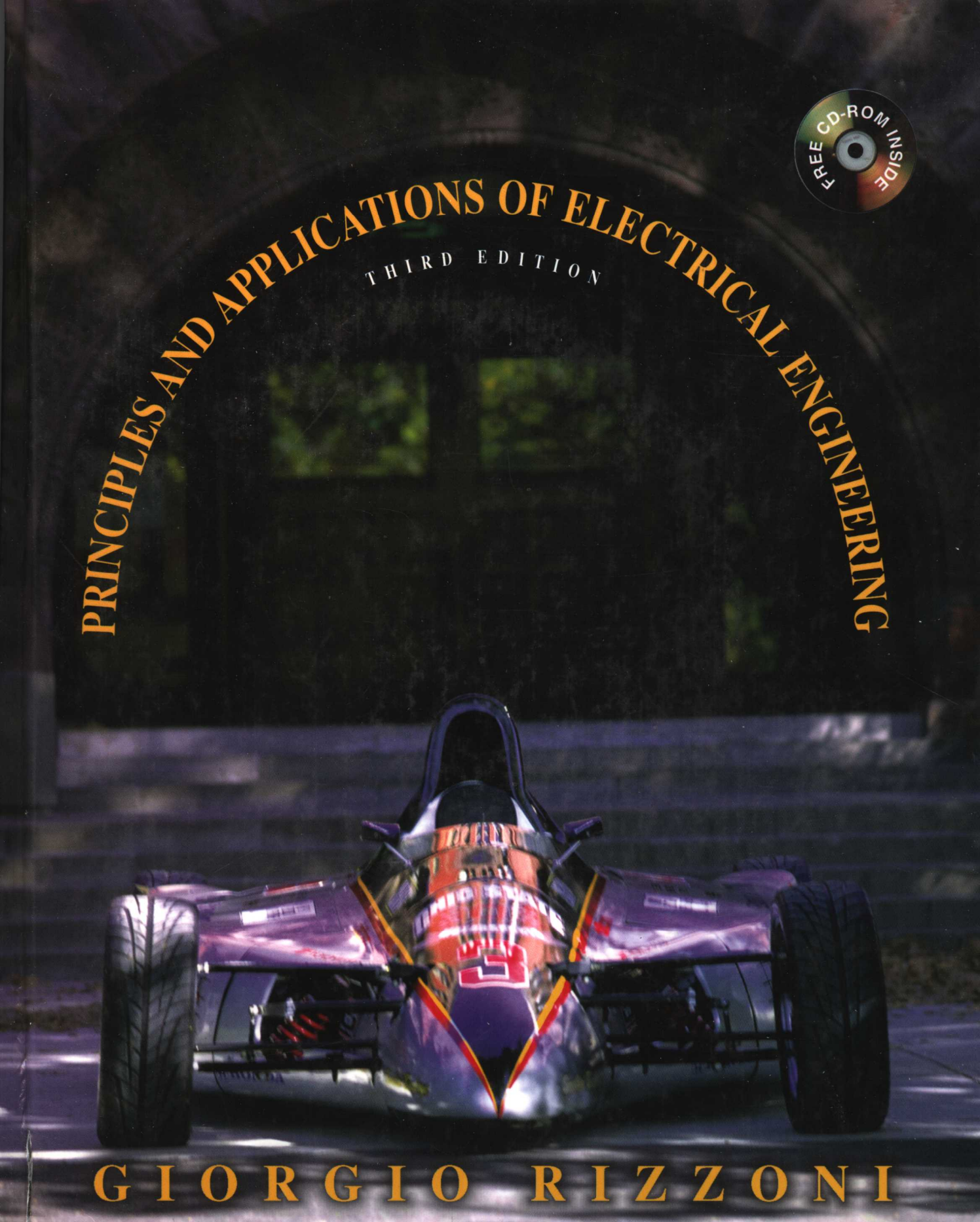
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PRINCIPLES AND APPLICATIONS OF ELECTRICAL ENGINEERING
THIRD EDITION
GIORGIO RIZZONI

PRINCIPLES AND APPLICATIONS OF ELECTRICAL ENGINEERING

Third Edition

Giorgio Rizzoni
The Ohio State University

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ABOUT THE COVER

The cover photo (David H. Koether Photography) depicts The Ohio State University Smokin' Buckeye electric race car, displayed in front of Hayes Hall. Smokin' Buckeye is the winner of the 1996, 1997, and 1998 ABB University Spec Series Championships. The car is powered by a 400-volt battery pack supplying a 150-kW AC induction motor, and has a top speed of 144 miles per hour. Example 1.2 describes the design and performance characteristics of this vehicle in greater detail. For further information, visit the web site http://turbo.eng.ohio-state.edu/~lightning/.

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About the Author

Giorgio Rizzoni received the B.S., M.S., and Ph.D. degrees, all in electrical engineering, from the University of Michigan. He is currently on the faculty of the Department of Mechanical Engineering at The Ohio State University, where he teaches undergraduate courses in system dynamics, measurements, and mechatronics, and graduate courses in automotive powertrain modeling and control, hybrid vehicle modeling and control, system fault diagnosis, and digital signal processing.

Dr. Rizzoni has been involved in the development of innovative curricula and educational programs throughout his career. At the University of Michigan, where he first taught as a Lecturer, he developed a new laboratory and revamped the curriculum for the circuits and electronics engineering service course for non–electrical engineering majors. The first edition of this book was a direct result of that effort. At Ohio State, he has been involved—in collaboration with electrical and mechanical engineering colleagues—in the development of undergraduate and graduate curricula in Mechatronic Systems. Funding for this program was provided, in part, by the National Science Foundation through a curriculum development grant. The second and third editions of this book have been profoundly influenced by this interdisciplinary curriculum development.

Dr. Rizzoni and his colleagues have also developed and implemented a unique year-long graduate course sequence titled *Powertrain Modeling and Control* in collaboration with General Motors. This course sequence is offered to GM employees as a series of distance-learning courses, and is regularly taught on campus to Ohio State electrical and mechanical engineering students.

Most recently, Dr. Rizzoni has been awarded funding from the U.S. Department of Energy to establish a *Graduate Automotive Technology Education Center on Hybrid Vehicle Drivetrains and Control Systems.* This activity has resulted in the development of a graduate curriculum and of research laboratories devoted to the study of future vehicle propulsion technologies.

Dr. Rizzoni's research, in collaboration with The Ohio State University *Center for Automotive Research,* concerns the modeling, simulation, control, and diagnosis of automotive powertrains and hybrid vehicles. His work has been funded by a number of government agencies and corporations, including, among others, DOE, NASA, NSF, DaimlerChrysler, Ford, General Motors, Delphi Automotive Systems, Cummins, IBM, Motorola, and Allied Signal. He has published over 100 papers in peer-reviewed journals and conference proceedings, and has received a number of recognitions, including a 1991 NSF *Presidential Young Investigator Award.*

Dr. Rizzoni is a member of ASME, IEEE, and SAE, and has been an Associate Editor of the *ASME Journal of Dynamic Systems, Measurements, and Control* (1993–99) and of the *IEEE Transactions on Vehicular Technology* (1988–1998). He has served as Guest Editor of Special Issues of the *IEEE Transactions on Control System Technology,* of the *IEEE Control Systems Magazine,* and of *Control Engineering Practice,* and is a past Chair of the Transportation Panel of the ASME *Dynamic Systems and Control Division.*

He is The Ohio State University SAE student branch faculty advisor, and has led teams of electrical and mechanical engineering students through the development of a high-performance electric vehicle, culminating in three consecutive national championships (1996–1998). He is also an advisor of the OSU FutureCar Challenge hybrid-electric vehicle design team. OSU is one of 14 schools to have been awarded this prestigious project, sponsored by the U.S. Department of Energy, and by General Motors, Ford, and DaimlerChrysler through the United States Council for Automotive Research.

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Preface

The pervasive presence of electronic devices and instrumentation in all aspects of engineering design and analysis is one of the manifestations of the electronic revolution that has characterized the second half of the 20th century. Every aspect of engineering practice, and even of everyday life, has been affected in some way or another by electrical and electronic devices and instruments. Computers are perhaps the most obvious manifestations of this presence. However, many other areas of electrical engineering are also important to the practicing engineer, from mechanical and industrial engineering to chemical, nuclear, and materials engineering, the aerospace and astronautical disciplines, and civil engineering. Engineers today must be able to communicate effectively within the interdisciplinary teams in which they work.

OBJECTIVES

The objectives of this book have not changed since work started on the first edition in 1987, even though engineering education and engineering professional practice have seen profound changes in the past decade. The integration of electronics and computer technologies in all engineering academic disciplines and the emergence of digital electronics and microcomputers as a central element of many engineering products and processes have become a common theme across the world.

In this context, the importance of material presented in this book has further increased, and this book is no longer aimed only at electrical engineering service courses in circuits, electronics, and electromechanics, but also at the increasing number of mechatronic systems courses and curricula that are under development in engineering schools around the world.

The basic objective of the book is to present the *principles* of electrical, electronic, and electromechanical engineering to an audience composed of non–electrical engineering majors, and ranging from sophomore students in their required introductory electrical engineering course to seniors and even first-year graduate students enrolled in more specialized courses in electronics, electromechanics, and mechatronics.

A second objective is to present the essential material in an uncomplicated fashion, focusing on the important results and applications, and presenting the students with the most appropriate *analytical and computational tools* to solve a variety of practical problems.

Finally, a third objective of the book is to illustrate, by way of examples, a number of relevant *applications* of electrical engineering principles. These examples are drawn from the author's industrial research experience, and also from ideas contributed by practicing engineers and industrial partners.

The three objectives listed above are met through the use of a number of new features, affecting the pedagogy and content of this book. The next two sections of this preface describe the organization of the book and the major changes that have been implemented in this third edition.

ORGANIZATION AND CONTENT

The organization of the book is nearly unchanged in its basic elements: the book is divided into three sections, devoted to *Circuits, Electronics, and Electromechanics.* Two changes, both resulting from the advice of users of the second edition, have been made to the Circuits section. First, the material on AC circuit analysis and fre-

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quency response, transient response, and system analysis of linear circuits has been reorganized into three chapters (4–6) instead of two, to more clearly separate the concepts of AC circuits and sinusoidal steady-state analysis, transient analysis, and frequency response and transfer function analysis. The second change results in the material on AC power being moved to the end of the section (it is now Chapter 7), to preserve the natural continuity of the material in Chapters 2–6. Instructors who desie to introduce AC power material immediately following the presentation of AC circuit analysis can do so without any difficulty.

The organization of the book continues to be very modular. The same material can be packaged into different sequences to satisfy the needs of different audiences. Figure 1 depicts the possible sequences that have been implemented by past and current users of this book and by this author. Figure 2 depicts some suggestions for advanced courses that would suit curricula in power systems, applied electronics, or mechanatronics. Instructors will find additional suggestions on the organization of course materials at the book's web site: **http://www.mhhe.com/engcs/electrical/rizzoni**. Suggestions from users of the book are welcome!

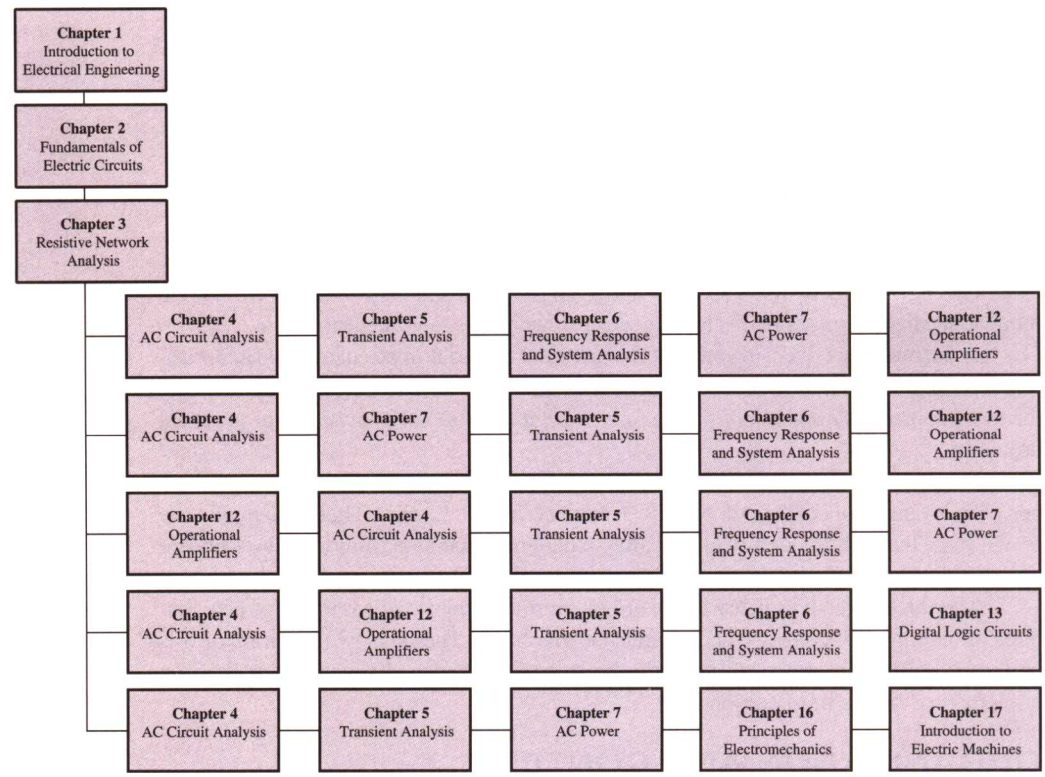

Figure 1 Some suggestions for the organization of an introductory course

CHANGES IN THE THIRD EDITION

While the organization of the book has not changed in a major way, the improvements to the pedagogy and to the supplements are substantial.

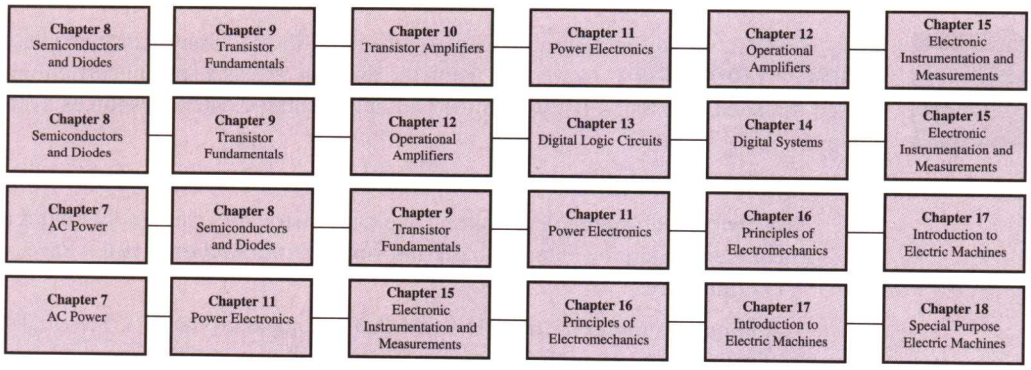

Figure 2 Some suggestions for the organization of an advanced course

Pedagogy

The third edition includes a complete revision of every example in the book. The examples follow a consistent solution methodology, reinforced by the use of "Focus on Methodology" boxes that summarize important solutions methods. The emphasis on electronic instrumentation and measurements—already a feature of the first two editions—is further underscored by the introduction of "Focus on Measurements" sections, consisting of examples based on measurement and instrumentation applications of electrical engineering concepts. Further, the students and instructors can choose to take advantage of **computer-aided solutions** methods and of **Internet resources** found in the enclosed CD-ROM, and identified in the text by the icons for **Virtual Lab** and **Find It on the Web**. These resources significantly extend the material presented in the book, and provide the instructor and the student with material for further study, and for the development of special projects and laboratory and computer exercises.

Supplements

The book includes a wealth of supplements, many available in electronic form. These include:

- A CD-ROM containing computer-aided example solutions, a list of web references for further research, device data sheets, and additional Virtual Lab material, including a demo copy of the *Electronics WorkBench*™ software package.
- A web site that will be dynamically updated to provide students and instructors with instructor notes, additional examples, suggestions for the use of the book, a forum for discussion, and other features. The URL is www.mhhe.com/engcs/electrical/rizzoni.
- A new chapter on electrical communications for schools that teach this subject in their curriculum.
- A completely revised Solutions Manual, available both in paper and electronic form.
- PowerPoint presentation slides of important figures, available on the Online Learning Center.
- Transparency masters of important figures.

Online Learning Center

This book has an Online Learning Center, hosted on the McGraw-Hill web site at **http/www.mhhe.com**. Instructors using the text can access a special curriculum-based threaded discussion list within the Online Learning Center. Resources available are

- PowerPoint presentation slides of important figures from the text.
- A course web site builder called Page Out. Instructors can quickly build a course web site by entering basic information into McGraw-Hill's Page Out interface.
- Additional support for the CD-ROM that accompanies the text. The goal of the Online Learning Center is to provide full-service instructor and course management support for those who request it.
- An Instructor's Solutions Manual with complete solutions to all homework problems.

Acknowledgments

This book has been critically reviewed by the following reviewers. McGraw-Hill and the author would like to thank these reviewers for their invaluable contribution to the third edition of *Principles and Applications of Electrical Engineering.*

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It is impossible for me to adequately express my love for my family, and my gratitude for my wife, Kathryn, and to my wonderful children, Alessandro, Maria, and Michael, who have continuously provided resources, inspiration, support, and good humor throughout this project. I cannot imagine a more loving and happier family.

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CHAPTER 1

Introduction to Electrical Engineering

The aim of this chapter is to introduce electrical engineering. The chapter is organized to provide the newcomer with a view of the different specialties making up electrical engineering and to place the intent and organization of the book into perspective. Perhaps the first question that surfaces in the mind of the student approaching the subject is, Why electrical engineering? Since this book is directed at a readership having a mix of engineering backgrounds (including electrical engineering), the question is well justified and deserves some discussion. The chapter begins by defining the various branches of electrical engineering, showing some of the interactions among them, and illustrating by means of a practical example how electrical engineering is intimately connected to many other engineering disciplines. In the second section, *mechatronic systems engineering* is introduced, with an explanation of how this book can lay the foundation for interdisciplinary mechatronic product design. This design approach is illustrated by an example. The next section introduces the Engineer-in-Training (EIT) national examination. A brief historical perspective is also provided, to outline the growth and development of this relatively young engineering specialty. Next, the fundamental physical quantities and the system of units are defined, to set the stage for the chapters that follow. Finally, the organization of the book is discussed, to give the student, as well as the teacher, a sense of continuity in the development of the different subjects covered in Chapters 2 through 18.

1.1 ELECTRICAL ENGINEERING

The typical curriculum of an undergraduate electrical engineering student includes the subjects listed in Table 1.1. Although the distinction between some of these subjects is not always clear-cut, the table is sufficiently representative to serve our purposes. Figure 1.1 illustrates a possible interconnection between the disciplines of Table 1.1. The aim of this book is to introduce the non-electrical engineering student to those aspects of electrical engineering that are likely to be most relevant to his or her professional career. Virtually all of the topics of Table 1.1 will be touched on in the book, with varying degrees of emphasis. The following example illustrates the pervasive presence of electrical, electronic, and electromechanical devices and systems in a very common application: the automobile. As you read through the example, it will be instructive to refer to Figure 1.1 and Table 1.1.

Table 1.1 Electrical engineering disciplines

Circuit analysis
Electromagnetics
Solid-state electronics
Electric machines
Electric power systems
Digital logic circuits
Computer systems
Communication systems
Electro-optics
Instrumentation systems
Control systems

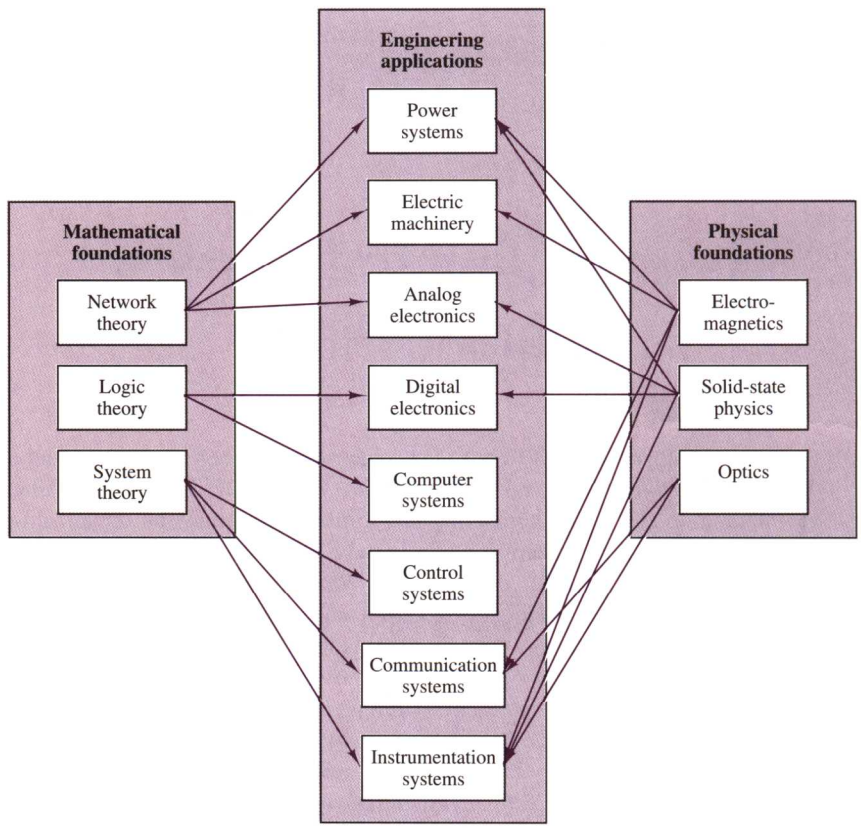

Figure 1.1 Electrical engineering disciplines

EXAMPLE 1.1 Electrical Systems in a Passenger Automobile

A familiar example illustrates how the seemingly disparate specialties of electrical engineering actually interact to permit the operation of a very familiar engineering system: the automobile. Figure 1.2 presents a view of electrical engineering systems in a

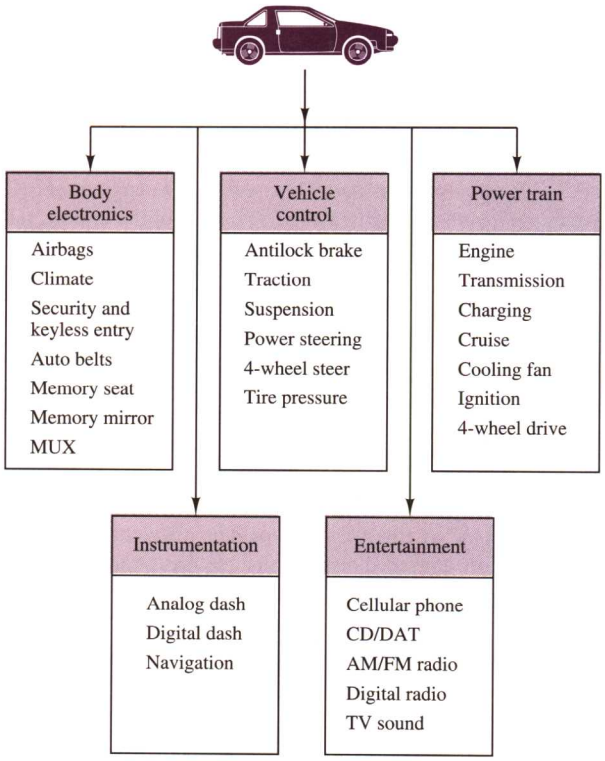

Figure 1.2 Electrical engineering systems in the automobile

modern automobile. Even in older vehicles, the electrical system—in effect, an *electric circuit*—plays a very important part in the overall operation. An inductor coil generates a sufficiently high voltage to allow a spark to form across the spark plug gap, and to ignite the air and fuel mixture; the coil is supplied by a DC voltage provided by a lead-acid battery. In addition to providing the energy for the ignition circuits, the battery also supplies power to many other electrical components, the most obvious of which are the lights, the windshield wipers, and the radio. Electric power is carried from the battery to all of these components by means of a wire harness, which constitutes a rather elaborate electrical circuit. In recent years, the conventional electrical ignition system has been supplanted by *electronic* ignition; that is, solid-state electronic devices called *transistors* have replaced the traditional breaker points. The advantage of transistorized ignition systems over the conventional mechanical ones is their greater reliability, ease of control, and life span (mechanical breaker points are subject to wear).

Other electrical engineering disciplines are fairly obvious in the automobile. The on-board radio receives electromagnetic waves by means of the antenna, and decodes the communication signals to reproduce sounds and speech of remote origin; other common *communication systems* that exploit *electromagnetics* are CB radios and the ever more common cellular phones. But this is not all! The battery is, in effect, a self-contained 12-VDC *electric power system,* providing the energy for all of the aforementioned functions. In order for the battery to have a useful lifetime, a charging system, composed of an alternator and of power electronic devices, is present in every automobile. The alternator is an *electric machine*, as are the motors that drive the power mirrors, power windows, power seats, and other convenience features found in luxury cars. Incidentally, the loudspeakers are also electric machines!

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