GLOBAL EDITION

Electrical Engineering

Principles and Applications

SEVENTH EDITION

Allan R. Hambley

Pearson

List of Examples

Chapter 1

1.1 Determining Current Given Charge 29
1.2 Power Calculations 34
1.3 Energy Calculation 35
1.4 Kirchhoff's Current Law 38
1.5 Kirchhoff's Voltage Law 42
1.6 Resistance Calculation 49
1.7 Determining Resistance for Given Power and Voltage Ratings 51
1.8 Circuit Analysis Using Arbitrary References 53
1.9 Using KVL, KCL, and Ohm's Law to Solve a Circuit 54

Chapter 2

2.1 Combining Resistances in Series and Parallel 69
2.2 Circuit Analysis Using Series/Parallel Equivalents 72
2.3 Application of the Voltage-Division Principle 76
2.4 Applying the Current- and Voltage-Division Principles 77
2.5 Application of the Current-Division Principle 78
2.6 Node-Voltage Analysis 83
2.7 Node-Voltage Analysis 86
2.8 Node-Voltage Analysis 88
2.9 Node-Voltage Analysis 90
2.10 Node-Voltage Analysis with a Dependent Source 94
2.11 Node-Voltage Analysis with a Dependent Source 95
2.12 Node Voltage Analysis 96
2.13 Mesh-Current Analysis 102
2.14 Mesh-Current Analysis 103
2.15 Writing Mesh Equations Directly in Matrix Form 105
2.16 Mesh-Current Analysis with Controlled Sources 108
2.17 Mesh Current Analysis 109
2.18 Determining the Thévenin Equivalent Circuit 112
2.19 Zeroing Sources to Find Thévenin Resistance 114
2.20 Thévenin Equivalent of a Circuit with a Dependent Source 115
2.21 Norton Equivalent Circuit 117
2.22 Using Source Transformations 119
2.23 Determining Maximum Power Transfer 122
2.24 Circuit Analysis Using Superposition 126
2.25 Using a Wheatstone Bridge to Measure Resistance 128

Chapter 3

3.1 Determining Current for a Capacitance Given Voltage 150
3.2 Determining Voltage for a Capacitance Given Current 152
3.3 Current, Power, and Energy for a Capacitance 154
3.4 Capacitances in Series and Parallel 157
3.5 Calculating Capacitance Given Physical Parameters 159
3.6 What Happened to the Missing Energy? 161
3.7 Voltage, Power, and Energy for an Inductance 165
3.8 Inductor Current with Constant Applied Voltage 166
3.9 Inductances in Series and Parallel 168
3.10 Integration and Differentiation Using the MATLAB Symbolic Toolbox 174

Chapter 4

4.1 Capacitance Discharging Through a Resistance 190
4.2 First-Order *RC* Circuit 192
4.3 Steady-State DC Analysis 194
4.4 *RL* Transient Analysis 196
4.5 *RL* Transient Analysis 198
4.6 Transient Analysis of an *RC* Circuit with a Sinusoidal Source 203
4.7 Analysis of a Second-Order Circuit with a DC Source 210
4.8 Computer-Aided Solution of a First-Order Circuit 219
4.9 Computer-Aided Solution of a Second-Order Circuit 221
4.10 Computer-Aided Solution of a System of Differential Equations 223

Chapter 5

5.1 Power Delivered to a Resistance by a Sinusoidal Source 239
5.2 RMS Value of a Triangular Voltage 240
5.3 Using Phasors to Add Sinusoids 245
5.4 Combining Impedances in Series and Parallel 251
5.5 Steady-State AC Analysis of a Series Circuit 253
5.6 Series and Parallel Combinations of Complex Impedances 255
5.7 Steady-State AC Node-Voltage Analysis 257
5.8 Steady-State AC Mesh-Current Analysis 258
5.9 AC Power Calculations 267
5.10 Using Power Triangles 269
5.11 Power-Factor Correction 271
5.12 Thévenin and Norton Equivalents 273
5.13 Maximum Power Transfer 276
5.14 Analysis of a Wye-Wye System 284
5.15 Analysis of a Balanced Delta–Delta System 287
5.16 Phasor Mesh-Current Analysis with MATLAB 292

Chapter 6

6.1 Using the Transfer Function to Determine the Output 311
6.2 Using the Transfer Function with Several Input Components 313
6.3 Calculation of *RC* Lowpass Output 319
6.4 Decibels and Logarithmic Frequency Scales 325
6.5 Determination of the Break Frequency for a Highpass Filter 332
6.6 Series Resonant Circuit 337
6.7 Parallel Resonant Circuit 340
6.8 Cascaded Ideal Filters 342
6.9 Filter Design 347
6.10 Computer-Generated Bode Plot 348
6.11 Step Response of a First-Order Digital Lowpass Filter 354

Chapter 7

7.1 Converting a Decimal Integer to Binary 380
7.2 Converting a Decimal Fraction to Binary 380
7.3 Converting Decimal Values to Binary 381
7.4 Converting Binary Numbers to Decimal 381
7.5 Adding Binary Numbers 381
7.6 Converting Octal Numbers to Decimal 382
7.7 Converting Hexadecimal Numbers to Decimal 382
7.8 Converting Octal and Hexadecimal Numbers to Binary 382
7.9 Converting Binary Numbers to Octal or Hexadecimal 383
7.10 Subtraction Using Two's-Complement Arithmetic 386
7.11 Using a Truth Table to Prove a Boolean Expression 390
7.12 Applying De Morgan's Laws 393
7.13 Combinatorial Logic Circuit Design 397
7.14 Finding the Minimum SOP Form for a Logic Function 404
7.15 Finding the Minimum POS Form for a Logic Function 405

Chapter 8

8.1 An Assembly-Language Program 451
8.2 Absolute Value Assembly Program 451
8.3 Manual Conversion of Source Code to Machine Code 452
8.4 Subroutine Source Code 453
8.5 Sensor Loading 457
8.6 Specifications for a Computer-Based Measurement System 469

Chapter 9

9.1 Load-Line Analysis 484
9.2 Load-Line Analysis 485
9.3 Load-Line Analysis of a Zener-Diode Voltage Regulator 487
9.4 Analysis of a Zener-Diode Regulator with a Load 488
9.5 Analysis by Assumed Diode States 491
9.6 Piecewise-Linear Model for a Zener Diode 493
9.7 Analysis Using a Piecewise-Linear Model 494

Chapter 10

10.1 Calculating Amplifier Performance 528
10.2 Calculating Performance of Cascaded Amplifiers 530
10.3 Simplified Model for an Amplifier Cascade 531

10.4 Amplifier Efficiency 533
10.5 Determining the Current-Amplifier Model from the Voltage-Amplifier Model 535
10.6 Determining the Transconductance-Amplifier Model 537
10.7 Determining the Transresistance-Amplifier Model 538
10.8 Determining Complex Gain 543
10.9 Amplitude Distortion 547
10.10 Phase Distortion 548
10.11 Determination of the Minimum CMRR Specification 559
10.12 Calculation of Worst-Case DC Output Voltage 563

Chapter 11

11.1 Plotting the Characteristics of an NMOS Transistor 583
11.2 Determination of Q Point for the Fixed- plus Self-Bias Circuit 590
11.3 Determination of g_m and r_d from the Characteristic Curves 595
11.4 Gain and Impedance Calculations for a Common-Source Amplifier 599
11.5 Gain and Impedance Calculations for a Source Follower 603

Chapter 12

12.1 Determining β from the Characteristic Curves 624
12.2 Load-Line Analysis of a BJT Amplifier 627
12.3 Determining the Operating Region of a BJT 635
12.4 Analysis of the Fixed Base Bias Circuit 636
12.5 Analysis of the Fixed Base Bias Circuit 637
12.6 Analysis of a BJT Bias Circuit 638
12.7 Analysis of the Four-Resistor Bias Circuit 641
12.8 Common-Emitter Amplifier 648
12.9 Emitter-Follower Performance 654

Chapter 13

13.1 Analysis of an Inverting Amplifier 671
13.2 Design of a Noninverting Amplifier 679
13.3 Amplifier Design 680
13.4 Summing Amplifier Design 681
13.5 Open-Loop and Closed-Loop Bode Plots 686
13.6 Full-Power Bandwidth 691
13.7 Determining Worst-Case DC Output 693
13.8 Lowpass Active Filter Design 703

Chapter 14

14.1 Magnetic Field around a Long Straight Wire 725
14.2 Flux Density in a Toroidal Core 726
14.3 Flux and Flux Linkages for a Toroidal Core 727
14.4 The Toroidal Coil as a Magnetic Circuit 729
14.5 A Magnetic Circuit with an Air Gap 729
14.6 A Magnetic Circuit with Reluctances in Series and Parallel 731
14.7 Calculation of Inductance 734
14.8 Calculation of Inductance and Mutual Inductance 736
14.9 Determination of Required Turns Ratio 742
14.10 Analysis of a Circuit Containing an Ideal Transformer 744
14.11 Using Impedance Transformations 746
14.12 Reflecting the Source to the Secondary 747
14.13 Regulation and Efficiency Calculations 750

Chapter 15

15.1 Motor Performance Calculations 772
15.2 Idealized Linear Machine 775
15.3 DC Machine Performance Calculations 784
15.4 Shunt-Connected DC Motor 787
15.5 Series-Connected DC Motor 792
15.6 Separately Excited DC Generator 801

Chapter 16

16.1 Induction-Motor Performance 826
16.2 Starting Current and Torque 829
16.3 Induction-Motor Performance 830
16.4 Synchronous-Motor Performance 838
16.5 Power-Factor Control 840

Appendix A

A.1 Complex Arithmetic in Rectangular Form 857
A.2 Polar-to-Rectangular Conversion 858
A.3 Rectangular-to-Polar Conversion 859
A.4 Exponential Form of a Complex Number 861
A.5 Complex Arithmetic in Polar Form 862

Electrical Engineering

Principles and Applications

This page intentionally left blank

Electrical Engineering

Principles and Applications

SEVENTH EDITION

GLOBAL EDITION

Allan R. Hambley

Department of Electrical and Computer Engineering
Michigan Technological University
arhamble@mtu.edu

Pearson

330 Hudson Street, NY NY 10013

Vice President and Editorial Director, ECS: Marcia J. Horton
Editor-in-Chief: Julian Partridge
Portfolio Manager: Julie Bai
Portfolio Manager Assistant: Michelle Bayman
Acquisitions Editor, Global Edition: Sourabh Maheshwari
Executive Marketing Manager: Tim Galligan
Director of Marketing: Christy Lesko
Field Marketing Manager: Demetrius Hall
Marketing Assistant: Jon Bryant
Managing Content Producer: Scott Disanno
Project Editor, Global Edition: K.K. Neelakantan
Global HE Director of Vendor Sourcing and Procurement: Diane Hynes
Director of Operations: Nick Sklitsis
Operations Specialist: Maura Zaldivar-Garcia
Senior Manufacturing Controller, Global Edition: Angela Hawksbee
Manager, Media Production, Global Edition: Vikram Kumar
Creative Director: Blair Brown
Cover Design: Lumina Datamatics, Inc.
Cover Image: alexfan32 / Shutterstock
Manager, Rights and Permissions: Ben Ferrini
Full-Service Project Management: SPi Global/Shylaja Gattupalli

MATLAB is a registered trademark of The MathWorks, Inc. Company and product names mentioned herein are the trademarks or registered trademarks of their respective owners.

Pearson Education Limited

KAO Two
KAO Park
Harlow
CM17 9NA
United Kingdom

and Associated Companies throughout the world

Visit us on the World Wide Web at: www.pearsonglobaleditions.com

© Pearson Education Limited 2019

The rights of Allan R. Hambley to be identified as the author of this work have been asserted by him in accordance with the Copyright, Designs and Patents Act 1988.

Authorized adaptation from the United States edition, entitled Electrical Engineering: Principles and Applications, 7th Edition, ISBN 978-0-13-448414-3 by Allan R. Hambley, published by Pearson Education © 2018.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without either the prior written permission of the publisher or a license permitting restricted copying in the United Kingdom issued by the Copyright Licensing Agency Ltd, Saffron House, 6–10 Kirby Street, London EC1N 8TS.

All trademarks used herein are the property of their respective owners. The use of any trademark in this text does not vest in the author or publisher any trademark ownership rights in such trademarks, nor does the use of such trademarks imply any affiliation with or endorsement of this book by such owners.

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

10 9 8 7 6 5 4 3 2 1

Typeset by SPi Global®
Printed and bound by Vivar in Malaysia

ISBN 10: 1-292-22312-X
ISBN 13: 978-1-292-22312-4

To my family Judy, Tony, Pam, and Mason
and to my special friend, Carol

Practical Applications of Electrical Engineering Principles

1.1
Using Resistance to Measure Strain *50*

2.1
An Important Engineering Problem: Energy-Storage Systems for Electric Vehicles *122*

3.1
Electronic Photo Flash *170*

4.1
Electronics and the Art of Automotive Maintenance *218*

6.1
Active Noise Cancellation *316*

7.1
Biomedical Engineering Application of Electronics: Cardiac Pacemaker *414*

8.1
Fresh Bread Anyone? *436*

8.2
The Virtual First-Down Line *465*

10.1
Electronic Stud Finder *561*

11.1
Where *Did* Those Trout Go? *605*

12.1
Soup Up Your Automobile by Changing Its Software? *630*

13.1
Mechanical Application of Negative Feedback: Power Steering *677*

15.1
Magnetic Flowmeters, Faraday, and The Hunt for Red October *778*

Contents

Practical Applications of Electrical Engineering Principles 8

Preface 13

1 Introduction 21

1.1 Overview of Electrical Engineering 22
1.2 Circuits, Currents, and Voltages 26
1.3 Power and Energy 33
1.4 Kirchhoff's Current Law 36
1.5 Kirchhoff's Voltage Law 40
1.6 Introduction to Circuit Elements 43
1.7 Introduction to Circuits 51
Summary 55
Problems 56

2 Resistive Circuits 66

2.1 Resistances in Series and Parallel 67
2.2 Network Analysis by Using Series and Parallel Equivalents 71
2.3 Voltage-Divider and Current-Divider Circuits 75
2.4 Node-Voltage Analysis 80
2.5 Mesh-Current Analysis 100
2.6 Thévenin and Norton Equivalent Circuits 110
2.7 Superposition Principle 123
2.8 Wheatstone Bridge 127
Summary 130
Problems 131

3 Inductance and Capacitance 147

3.1 Capacitance 148
3.2 Capacitances in Series and Parallel 155
3.3 Physical Characteristics of Capacitors 158
3.4 Inductance 162
3.5 Inductances in Series and Parallel 167
3.6 Practical Inductors 169
3.7 Mutual Inductance 172
3.8 Symbolic Integration and Differentiation Using MATLAB 173
Summary 177
Problems 178

4 Transients 187

4.1 First-Order *RC* Circuits 188
4.2 DC Steady State 193
4.3 *RL* Circuits 195
4.4 *RC* and *RL* Circuits with General Sources 200
4.5 Second-Order Circuits 206
4.6 Transient Analysis Using the MATLAB Symbolic Toolbox 219
Summary 225
Problems 225

5 Steady-State Sinusoidal Analysis 235

5.1 Sinusoidal Currents and Voltages 236
5.2 Phasors 242
5.3 Complex Impedances 248
5.4 Circuit Analysis with Phasors and Complex Impedances 253
5.5 Power in AC Circuits 259
5.6 Thévenin and Norton Equivalent Circuits 272
5.7 Balanced Three-Phase Circuits 278
5.8 AC Analysis Using MATLAB 290
Summary 294
Problems 295

6
Frequency Response, Bode Plots, and Resonance 307

6.1 Fourier Analysis, Filters, and Transfer Functions 308
6.2 First-Order Lowpass Filters 316
6.3 Decibels, the Cascade Connection, and Logarithmic Frequency Scales 321
6.4 Bode Plots 326
6.5 First-Order Highpass Filters 329
6.6 Series Resonance 333
6.7 Parallel Resonance 338
6.8 Ideal and Second-Order Filters 341
6.9 Bode Plots with MATLAB 348
6.10 Digital Signal Processing 351
Summary 360
Problems 361

7
Logic Circuits 375

7.1 Basic Logic Circuit Concepts 376
7.2 Representation of Numerical Data in Binary Form 379
7.3 Combinatorial Logic Circuits 387
7.4 Synthesis of Logic Circuits 395
7.5 Minimization of Logic Circuits 401
7.6 Sequential Logic Circuits 406
Summary 417
Problems 418

8
Computers, Microcontrollers and Computer-Based Instrumentation Systems 428

8.1 Computer Organization 429
8.2 Memory Types 432
8.3 Digital Process Control 434
8.4 Programming Model for the HCS12/9S12 Family 437
8.5 The Instruction Set and Addressing Modes for the CPU12 441
8.6 Assembly-Language Programming 450
8.7 Measurement Concepts and Sensors 455
8.8 Signal Conditioning 460
8.9 Analog-to-Digital Conversion 467
Summary 470
Problems 472

9
Diodes 479

9.1 Basic Diode Concepts 480
9.2 Load-Line Analysis of Diode Circuits 483
9.3 Zener-Diode Voltage-Regulator Circuits 486
9.4 Ideal-Diode Model 490
9.5 Piecewise-Linear Diode Models 492
9.6 Rectifier Circuits 495
9.7 Wave-Shaping Circuits 500
9.8 Linear Small-Signal Equivalent Circuits 505
Summary 511
Problems 511

10
Amplifiers: Specifications and External Characteristics 523

10.1 Basic Amplifier Concepts 524
10.2 Cascaded Amplifiers 529
10.3 Power Supplies and Efficiency 532
10.4 Additional Amplifier Models 535
10.5 Importance of Amplifier Impedances in Various Applications 538
10.6 Ideal Amplifiers 541
10.7 Frequency Response 542
10.8 Linear Waveform Distortion 547
10.9 Pulse Response 551
10.10 Transfer Characteristic and Nonlinear Distortion 554
10.11 Differential Amplifiers 556
10.12 Offset Voltage, Bias Current, and Offset Current 560
Summary 565
Problems 566

11
Field-Effect Transistors 577

11.1 NMOS and PMOS Transistors 578
11.2 Load-Line Analysis of a Simple NMOS Amplifier 586

11.3 Bias Circuits 588
11.4 Small-Signal Equivalent Circuits 592
11.5 Common-Source Amplifiers 596
11.6 Source Followers 600
11.7 CMOS Logic Gates 605
Summary 610
Problems 611

12
Bipolar Junction Transistors 619
12.1 Current and Voltage Relationships 620
12.2 Common-Emitter Characteristics 623
12.3 Load-Line Analysis of a Common-Emitter Amplifier 624
12.4 *pnp* Bipolar Junction Transistors 630
12.5 Large-Signal DC Circuit Models 632
12.6 Large-Signal DC Analysis of BJT Circuits 635
12.7 Small-Signal Equivalent Circuits 642
12.8 Common-Emitter Amplifiers 645
12.9 Emitter Followers 650
Summary 656
Problems 657

13
Operational Amplifiers 666
13.1 Ideal Operational Amplifiers 667
13.2 Inverting Amplifiers 668
13.3 Noninverting Amplifiers 675
13.4 Design of Simple Amplifiers 678
13.5 Op-Amp Imperfections in the Linear Range of Operation 683
13.6 Nonlinear Limitations 687
13.7 DC Imperfections 692
13.8 Differential and Instrumentation Amplifiers 696
13.9 Integrators and Differentiators 698
13.10 Active Filters 701
Summary 705
Problems 706

14
Magnetic Circuits and Transformers 718
14.1 Magnetic Fields 719
14.2 Magnetic Circuits 728
14.3 Inductance and Mutual Inductance 733
14.4 Magnetic Materials 737
14.5 Ideal Transformers 740
14.6 Real Transformers 748
Summary 753
Problems 753

15
DC Machines 764
15.1 Overview of Motors 765
15.2 Principles of DC Machines 774
15.3 Rotating DC Machines 779
15.4 Shunt-Connected and Separately Excited DC Motors 785
15.5 Series-Connected DC Motors 790
15.6 Speed Control of DC Motors 794
15.7 DC Generators 798
Summary 803
Problems 804

16
AC Machines 814
16.1 Three-Phase Induction Motors 815
16.2 Equivalent-Circuit and Performance Calculations for Induction Motors 823
16.3 Synchronous Machines 832
16.4 Single-Phase Motors 844
16.5 Stepper Motors and Brushless DC Motors 847
Summary 849
Problems 850

APPENDICES

A
Complex Numbers 856
Summary 863
Problems 863

B
Nominal Values and the Color Code for Resistors 865

C
The Fundamentals of Engineering Examination 867

D
Answers for the Practice Tests 868

E
On-Line Student Resources 877

Index 878

Preface

As in the previous editions, my guiding philosophy in writing this book has three elements. The first element is my belief that in the long run students are best served by learning basic concepts in a general setting. Second, I believe that students need to be motivated by seeing how the principles apply to specific and interesting problems in their own fields. The third element of my philosophy is to take every opportunity to make learning free of frustration for the student.

This book covers circuit analysis, digital systems, electronics, and electromechanics at a level appropriate for either electrical-engineering students in an introductory course or nonmajors in a survey course. The only essential prerequisites are basic physics and single-variable calculus. Teaching a course using this book offers opportunities to develop theoretical and experimental skills and experiences in the following areas:

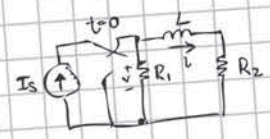
- Basic circuit analysis and measurement
- First- and second-order transients
- Steady-state ac circuits
- Resonance and frequency response
- Digital logic circuits
- Microcontrollers
- Computer-based instrumentation
- Diode circuits
- Electronic amplifiers
- Field-effect and bipolar junction transistors
- Operational amplifiers
- Transformers
- Ac and dc machines
- Computer-aided circuit analysis using MATLAB

While the emphasis of this book is on basic concepts, a key feature is the inclusion of short articles scattered throughout showing how electrical-engineering concepts are applied in other fields. The subjects of these articles include anti-knock signal processing for internal combustion engines, a cardiac pacemaker, active noise control, and the use of RFID tags in fisheries research, among others.

I welcome comments from users of this book. Information on how the book could be improved is especially valuable and will be taken to heart in future revisions. My e-mail address is `arhamble@mtu.edu`

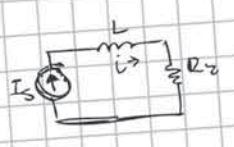
your work...

PART A



Given:
$I_S = 51.0\ mA$
$R_1 = 54.0\ k\Omega$
$R_2 = 51.0\ k\Omega$
$L = 51.0\ mH$

Find:
initial current $i(0^-)$ before break switch



$I_S = i$

$\boxed{i = 51.0\ mA}$

Assume when circuit is in steady state, inductor acts as a short $m \to —$

Use Kirchhoff's current law

$I_S = i + i_R$ $\qquad V = iR$

$I_S = i + \frac{V}{R}$ $\qquad i = \frac{V}{R}$

$I_S = i + \frac{iR_1}{R_2}$

$I_S = i\left(1 + \frac{R_1}{R_2}\right)$

$\frac{I_S}{\left(1 + \frac{R_1}{R_2}\right)} = i$

$i = \frac{51.0\ mA}{\left(1 + \frac{54.1\ k\Omega}{51\ k\Omega}\right)} = \boxed{24.77\ mA}$

your answer specific feedback

Express your answer to three significant figures and include the appropriate units.

Incorrect; Try Again; 5 attempts remaining

Note that elements in series have the same current but the inductor is not in series with the current source. Use Kirchhoff's current law or the current divider to find the initial inductor current.

Express your answer to three significant figures and include the appropriate units.

Incorrect; Try Again; 4 attempts remaining

It appears you have found the current through the resistor, R_1. Find the current through the resistor in series with the inductor.

www.MasteringEngineering®.com

ON-LINE STUDENT RESOURCES

- **MasteringEngineering.** Tutorial homework problems emulate the instructor's office-hour environment, guiding students through engineering concepts with self-paced individualized coaching. These in-depth tutorial homework problems are designed to coach students with feedback specific to their errors and optional hints that break problems down into simpler steps. Access can be purchased bundled with the textbook or online at www.masteringengineering.com.
- **The Companion Website.** Access is included with the purchase of every new book or can be purchased at www.pearsonglobaleditions.com/hambley. The Companion Website includes:
  - Video Solutions that provide complete, step-by-step solution walkthroughs of representative homework problems from each chapter.
  - A Student Solutions Manual. A PDF file for each chapter includes full solutions for the in-chapter exercises, answers for the end-of-chapter problems that are marked with asterisks, and full solutions for the Practice Tests.
  - A MATLAB folder that contains the m-files discussed in the book.

INSTRUCTOR RESOURCES

Resources for instructors include:

- **MasteringEngineering.** This online Tutorial Homework program allows you to integrate dynamic homework with automatic grading and personalized feedback. MasteringEngineering allows you to easily track the performance of your entire class on an assignment-by-assignment basis, or the detailed work of an individual student.
- A complete Instructor's Solutions Manual.
- PowerPoint slides with all the figures from the book.

Instructor Resources are available for download by adopters of this book at the Instructors Resource Center: `www.pearsonglobaleditions.com/hambley`. If you are in need of a login and password, please contact your local Pearson representative.

WHAT'S NEW IN THIS EDITION

- We have continued and added items to the popular Practice Tests that students can use in preparing for course exams at the end of each chapter. Answers for the Practice Tests appear in Appendix D and complete solutions are included in the on-line Student Solutions Manual files.
- New examples have been added in Chapters 1 through 7.
- Approximately half of the end-of-chapter problems have been replaced or modified.
- Coverage of computers, microcontrollers and computer-based instrumentation has been merged from two chapters into Chapter 8 for this edition.
- Appendix C has been modified to keep up with new developments in the Fundamentals of Engineering Exam.

- We have updated the coverage of MATLAB and the Symbolic Toolbox for network analysis in Chapters 2 through 6.
- Relatively minor corrections and improvements appear throughout the book.

PREREQUISITES

The essential prerequisites for a course from this book are basic physics and single-variable calculus. A prior differential equations course would be helpful but is not essential. Differential equations are encountered in Chapter 4 on transient analysis, but the skills needed are developed from basic calculus.

PEDAGOGICAL FEATURES

The book includes various pedagogical features designed with the goal of stimulating student interest, eliminating frustration, and engendering an awareness of the relevance of the material to their chosen profession. These features are:

- Statements of learning objectives open each chapter.
- Comments in the margins emphasize and summarize important points or indicate common pitfalls that students need to avoid.
- Short boxed articles demonstrate how electrical-engineering principles are applied in other fields of engineering. For example, see the articles on active noise cancellation (page 316) and electronic pacemakers (starting on page 414).
- Step-by-step problem solving procedures. For example, see the step-by-step summary of node-voltage analysis (on pages 96–100) or the summary of Thévenin equivalents (on page 272).
- A Practice Test at the end of each chapter gives students a chance to test their knowledge. Answers appear in Appendix D.
- Complete solutions to the in-chapter exercises and Practice Tests, included as PDF files on-line, build student confidence and indicate where additional study is needed.
- Summaries of important points at the end of each chapter provide references for students.
- Key equations are highlighted in the book to draw attention to important results.

MEETING ABET-DIRECTED OUTCOMES

Courses based on this book provide excellent opportunities to meet many of the directed outcomes for accreditation. The Criteria for Accrediting Engineering Programs require that graduates of accredited programs have “an ability to apply knowledge of mathematics, science, and engineering” and “an ability to identify, formulate, and solve engineering problems.” This book, in its entirety, is aimed at developing these abilities.

Furthermore, the criteria require “an ability to function on multi-disciplinary teams” and “an ability to communicate effectively.” Courses based on this book contribute to these abilities by giving nonmajors the knowledge and vocabulary to communicate effectively with electrical engineers. The book also helps to inform

electrical engineers about applications in other fields of engineering. To aid in communication skills, end-of-chapter problems that ask students to explain electrical-engineering concepts in their own words are included.

CONTENT AND ORGANIZATION

Basic Circuit Analysis

Chapter 1 defines current, voltage, power, and energy. Kirchhoff's laws are introduced. Voltage sources, current sources, and resistance are defined.

Chapter 2 treats resistive circuits. Analysis by network reduction, node voltages, and mesh currents is covered. Thévenin equivalents, superposition, and the Wheatstone bridge are treated.

Capacitance, inductance, and mutual inductance are treated in Chapter 3.

Transients in electrical circuits are discussed in Chapter 4. First-order *RL* and *RC* circuits and time constants are covered, followed by a discussion of second-order circuits.

Chapter 5 considers sinusoidal steady-state circuit behavior. (A review of complex arithmetic is included in Appendix A.) Power calculations, ac Thévenin and Norton equivalents, and balanced three-phase circuits are treated.

Chapter 6 covers frequency response, Bode plots, resonance, filters, and digital signal processing. The basic concept of Fourier theory (that signals are composed of sinusoidal components having various amplitudes, phases, and frequencies) is qualitatively discussed.

Digital Systems

Chapter 7 introduces logic gates and the representation of numerical data in binary form. It then proceeds to discuss combinatorial and sequential logic. Boolean algebra, De Morgan's laws, truth tables, Karnaugh maps, coders, decoders, flip-flops, and registers are discussed.

Chapter 8 treats microcomputers with emphasis on embedded systems using the Freescale Semiconductor HCS12/9S12 as the primary example. Computer organization and memory types are discussed. Digital process control using microcontrollers is described in general terms. Selected instructions and addressing modes for the CPU12 are described. Assembly language programming is treated very briefly. Finally, computer-based instrumentation systems including measurement concepts, sensors, signal conditioning, and analog-to-digital conversion are discussed.

Electronic Devices and Circuits

Chapter 9 presents the diode, its various models, load-line analysis, and diode circuits, such as rectifiers, Zener-diode regulators, and wave shapers.

In Chapter 10, the specifications and imperfections of amplifiers that need to be considered in applications are discussed from a users perspective. These include gain, input impedance, output impedance, loading effects, frequency response, pulse response, nonlinear distortion, common-mode rejection, and dc offsets.

Chapter 11 covers the MOS field-effect transistor, its characteristic curves, loadline analysis, large-signal and small-signal models, bias circuits, the common-source amplifier, and the source follower.

Chapter 12 gives a similar treatment for bipolar transistors. If desired, the order of Chapters 11 and 12 can be reversed. Another possibility is to skip most of both chapters so more time can be devoted to other topics.

Chapter 13 treats the operational amplifier and many of its applications. Nonmajors can learn enough from this chapter to design and use op-amp circuits for instrumentation applications in their own fields.

Electromechanics

Chapter 14 reviews basic magnetic field theory, analyzes magnetic circuits, and presents transformers.

DC machines and ac machines are treated in Chapters 15 and 16, respectively. The emphasis is on motors rather than generators because the nonelectrical engineer applies motors much more often than generators. In Chapter 15, an overall view of motors in general is presented before considering DC machines, their equivalent circuits, and performance calculations. The universal motor and its applications are discussed.

Chapter 16 deals with AC motors, starting with the three-phase induction motor. Synchronous motors and their advantages with respect to power-factor correction are analyzed. Small motors including single-phase induction motors are also discussed. A section on stepper motors and brushless dc motors ends the chapter.

ACKNOWLEDGMENTS

I wish to thank my colleagues in the Electrical and Computer Engineering Department at Michigan Technological University, all of whom have given me help and encouragement at one time or another in writing this book and in my other projects.

I have received much excellent advice from professors at other institutions who reviewed the manuscript in various stages over the years. This advice has improved the final result a great deal, and I am grateful for their help.

Current and past reviewers include:

Ibrahim Abdel-Motaled, Northwestern University
William Best, Lehigh University
Steven Bibyk, Ohio State University
D. B. Brumm, Michigan Technological University
Karen Butler-Purry, Texas A&M University
Robert Collin, Case Western University
Joseph A. Coppola, Syracuse University
Norman R. Cox, University of Missouri at Rolla
W. T. Easter, North Carolina State University
Zoran Gajic, Rutgers University
Edwin L. Gerber, Drexel University
Victor Gerez, Montana State University
Walter Green, University of Tennessee
Elmer Grubbs, New Mexico Highlands University
Jasmine Henry, University of Western Australia
Ian Hutchinson, MIT
David Klemer, University of Wisconsin, Milwaukee
Richard S. Marleau, University of Wisconsin

Sunanda Mitra, Texas Tech University
Phil Noe, Texas A&M University
Edgar A. O'Hair, Texas Tech University
John Pavlat, Iowa State University
Clifford Pollock, Cornell University
Michael Reed, Carnegie Mellon University
Gerald F. Reid, Virginia Polytechnic Institute
Selahattin Sayil, Lamar University
William Sayle II, Georgia Institute of Technology
Len Trombetta, University of Houston
John Tyler, Texas A&M University
Belinda B. Wang, University of Toronto
Carl Wells, Washington State University
Al Wicks, Virginia Tech
Edward Yang, Columbia University
Subbaraya Yuvarajan, North Dakota State University
Rodger E. Ziemer, University of Colorado, Colorado Springs

Over the years, many students and faculty using my books at Michigan Technological University and elsewhere have made many excellent suggestions for improving the books and correcting errors. I thank them very much.

I am indebted to Julie Bai, my present and past editors at Pearson, for keeping me pointed in the right direction and for many excellent suggestions that have improved my books a great deal. A very special thank you, also, to Scott Disanno for a great job of managing the production of this and past editions of this book.

Also, I want to thank Tony, Pam, and Mason for their continuing encouragement and valuable insights. I thank Judy, my late wife, for many good things much too extensive to list.

Allan R. Hambley

ACKNOWLEDGMENTS FOR THE GLOBAL EDITION

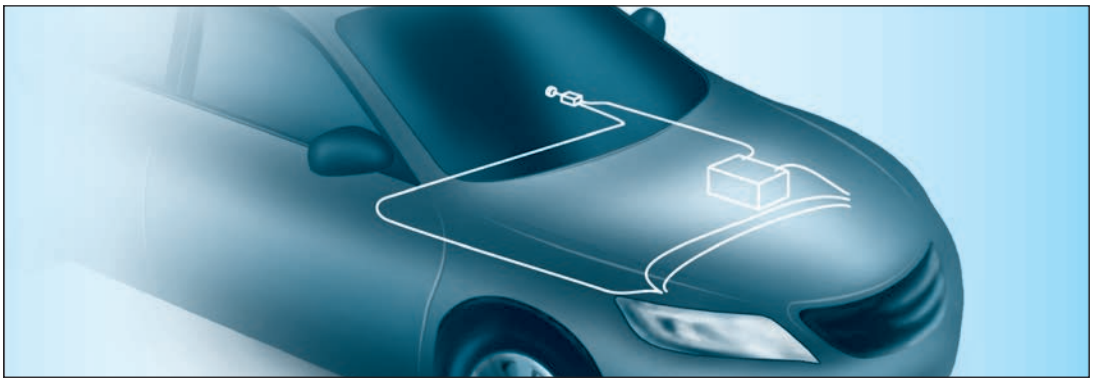
Pearson would like to thank and acknowledge the following people for their work on the Global Edition.

Contributor

Sachin Jain, National Institute of Technology Warangal

Reviewers

Papri Ghosh
Ajay Kumar, Coimbatore Institute of Technology
Nikhil Marriwala, University Institute of Engineering and Technology



Chapter 1

Introduction

Study of this chapter will enable you to:

- Recognize interrelationships between electrical engineering and other fields of science and engineering.
- List the major subfields of electrical engineering.
- List several important reasons for studying electrical engineering.
- Define current, voltage, and power, including their units.
- Calculate power and energy and determine whether energy is supplied or absorbed by a circuit element.
- State and apply Kirchhoff's current and voltage laws.
- Recognize series and parallel connections.
- Identify and describe the characteristics of voltage and current sources.
- State and apply Ohm's law.
- Solve for currents, voltages, and powers in simple circuits.

Introduction to this chapter:

In this chapter, we introduce electrical engineering, define circuit variables (current, voltage, power, and energy), study the laws that these circuit variables obey, and meet several circuit elements (current sources, voltage sources, and resistors).

1.1 OVERVIEW OF ELECTRICAL ENGINEERING

Electrical engineers design systems that have two main objectives:

1. To gather, store, process, transport, and present *information*.
2. To distribute, store, and convert *energy* between various forms.

In many electrical systems, the manipulation of energy and the manipulation of information are interdependent.

For example, numerous aspects of electrical engineering relating to information are applied in weather prediction. Data about cloud cover, precipitation, wind speed, and so on are gathered electronically by weather satellites, by land-based radar stations, and by sensors at numerous weather stations. (Sensors are devices that convert physical measurements to electrical signals.) This information is transported by electronic communication systems and processed by computers to yield forecasts that are disseminated and displayed electronically.

In electrical power plants, energy is converted from various sources to electrical form. Electrical distribution systems transport the energy to virtually every factory, home, and business in the world, where it is converted to a multitude of useful forms, such as mechanical energy, heat, and light.

No doubt you can list scores of electrical engineering applications in your daily life. Increasingly, electrical and electronic features are integrated into new products. Automobiles and trucks provide just one example of this trend. The electronic content of the average automobile is growing rapidly in value. Self-driving vehicles are in rapid development and will eventually become the norm. Auto designers realize that electronic technology is a good way to provide increased functionality at lower cost. Table 1.1 shows some of the applications of electrical engineering in automobiles.

You may find it interesting to search the web for sites related to "mechatronics."

As another example, we note that many common household appliances contain keypads or touch screens for operator control, sensors, electronic displays, and computer chips, as well as more conventional switches, heating elements, and motors. Electronics have become so intimately integrated with mechanical systems that the name **mechatronics** is used for the combination.

Subdivisions of Electrical Engineering

Next, we give you an overall picture of electrical engineering by listing and briefly discussing eight of its major areas.

1. **Communication systems** transport information in electrical form. Cellular phone, radio, satellite television, and the Internet are examples of communication systems. It is possible for virtually any two people (or computers) on the globe to communicate almost instantaneously. A climber on a mountaintop in Nepal can call or send e-mail to friends whether they are hiking in Alaska or sitting in a New York City office. This kind of connectivity affects the way we live, the way we conduct business, and the design of everything we use. For example, communication systems will change the design of highways because traffic and road-condition information collected by roadside sensors can be transmitted to central locations and used to route traffic. When an accident occurs, an electrical signal can be emitted automatically when the airbags deploy, giving the exact location of the vehicle, summoning help, and notifying traffic-control computers.

Computers that are part of products such as appliances and automobiles are called *embedded computers*.

2. **Computer** process and store information in digital form. No doubt you have already encountered computer applications in your own field. Besides the

Table 1.1 Current and Emerging Electronic/Electrical Applications in Automobiles and Trucks

Safety
Antiskid brakes
Inflatable restraints
Collision warning and avoidance
Blind-zone vehicle detection (especially for large trucks)
Infrared night vision systems
Heads-up displays
Automatic accident notification
Rear-view cameras
Communications and entertainment
AM/FM radio
Digital audio broadcasting
CD/DVD player
Cellular phone
Computer/e-mail
Satellite radio
Convenience
Electronic GPS navigation
Personalized seat/mirror/radio settings
Electronic door locks
Emissions, performance, and fuel economy
Vehicle instrumentation
Electronic ignition
Tire inflation sensors
Computerized performance evaluation and maintenance scheduling
Adaptable suspension systems
Alternative propulsion systems
Electric vehicles
Advanced batteries
Hybrid vehicles

computers of which you are aware, there are many in unobvious places, such as household appliances and automobiles. A typical modern automobile contains several dozen special-purpose computers. Chemical processes and railroad switching yards are routinely controlled through computers.

3. **Control systems** gather information with sensors and use electrical energy to control a physical process. A relatively simple control system is the heating/cooling system in a residence. A sensor (thermostat) compares the temperature with the desired value. Control circuits operate the furnace or air conditioner to achieve the desired temperature. In rolling sheet steel, an electrical control system is used to obtain the desired sheet thickness. If the sheet is too thick (or thin), more (or less) force is applied to the rollers. The temperatures and flow rates in chemical processes are controlled in a similar manner. Control systems have even been installed in tall buildings to reduce their movement due to wind.
4. **Electromagnetics** is the study and application of electric and magnetic fields. The device (known as a magnetron) used to produce microwave energy in an oven is one application. Similar devices, but with much higher power levels,

are employed in manufacturing sheets of plywood. Electromagnetic fields heat the glue between layers of wood so that it will set quickly. Cellular phone and television antennas are also examples of electromagnetic devices.

5. **Electronics** is the study and application of materials, devices, and circuits used in amplifying and switching electrical signals. The most important electronic devices are transistors of various kinds. They are used in nearly all places where electrical information or energy is employed. For example, the cardiac pacemaker is an electronic circuit that senses heart beats, and if a beat does not occur when it should, applies a minute electrical stimulus to the heart, forcing a beat. Electronic instrumentation and electrical sensors are found in every field of science and engineering. Many of the aspects of electronic amplifiers studied later in this book have direct application to the instrumentation used in your field of engineering.
6. **Photonics** is an exciting new field of science and engineering that promises to replace conventional computing, signal-processing, sensing, and communication devices based on manipulating electrons with greatly improved products based on manipulating photons. Photonics includes light generation by lasers and light-emitting diodes, transmission of light through optical components, as well as switching, modulation, amplification, detection, and steering light by electrical, acoustical, and photon-based devices. Current applications include readers for DVD disks, holograms, optical signal processors, and fiber-optic communication systems. Future applications include optical computers, holographic memories, and medical devices. Photonics offers tremendous opportunities for nearly all scientists and engineers.
7. **Power systems** convert energy to and from electrical form and transmit energy over long distances. These systems are composed of generators, transformers, distribution lines, motors, and other elements. Mechanical engineers often utilize electrical motors to empower their designs. The selection of a motor having the proper torque speed characteristic for a given mechanical application is another example of how you can apply the information in this book.
8. **Signal processing** is concerned with information-bearing electrical signals. Often, the objective is to extract useful information from electrical signals derived from sensors. An application is machine vision for robots in manufacturing. Another application of signal processing is in controlling ignition systems of internal combustion engines. The timing of the ignition spark is critical in achieving good performance and low levels of pollutants. The optimum ignition point relative to crankshaft rotation depends on fuel quality, air temperature, throttle setting, engine speed, and other factors.

Electronic devices are based on controlling electrons. Photonic devices perform similar functions by controlling photons.

If the ignition point is advanced slightly beyond the point of best performance, *engine knock* occurs. Knock can be heard as a sharp metallic noise that is caused by rapid pressure fluctuations during the spontaneous release of chemical energy in the combustion chamber. A combustion-chamber pressure pulse displaying knock is shown in Figure 1.1. At high levels, knock will destroy an engine in a very short time. Prior to the advent of practical signal-processing electronics for this application, engine timing needed to be adjusted for distinctly suboptimum performance to avoid knock under varying combinations of operating conditions.

By connecting a sensor through a tube to the combustion chamber, an electrical signal proportional to pressure is obtained. Electronic circuits process this signal to determine whether the rapid pressure fluctuations characteristic of knock are present. Then electronic circuits continuously adjust ignition timing for optimum performance while avoiding knock.

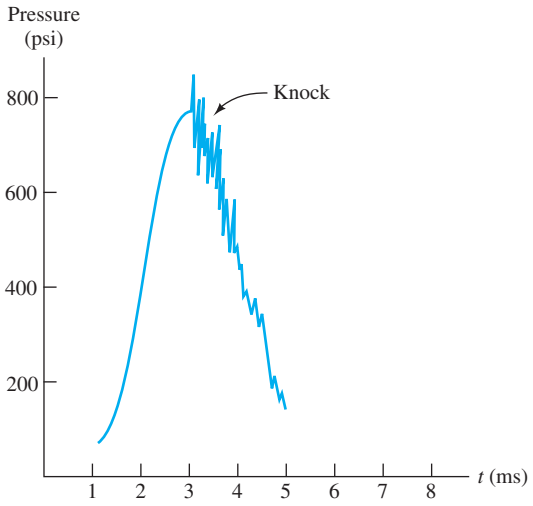


Figure 1.1 Pressure versus time for an internal combustion engine experiencing knock. Sensors convert pressure to an electrical signal that is processed to adjust ignition timing for minimum pollution and good performance.

Why You Need to Study Electrical Engineering

As a reader of this book, you may be majoring in another field of engineering or science and taking a required course in electrical engineering. Your immediate objective is probably to meet the course requirements for a degree in your chosen field. However, there are several other good reasons to learn and retain some basic knowledge of electrical engineering:

1. *To pass the Fundamentals of Engineering (FE) Examination as a first step in becoming a Registered Professional Engineer.* In the United States, before performing engineering services for the public, you will need to become registered as a Professional Engineer (PE). This book gives you the knowledge to answer questions relating to electrical engineering on the registration examinations. Save this book and course notes to review for the FE examination. (See Appendix C for more on the FE exam.)

Save this book and course notes to review for the FE exam.

2. *To have a broad enough knowledge base so that you can lead design projects in your own field.* Increasingly, electrical engineering is interwoven with nearly all scientific experiments and design projects in other fields of engineering. Industry has repeatedly called for engineers who can see the big picture and work effectively in teams. Engineers or scientists who narrow their focus strictly to their own field are destined to be directed by others. (Electrical engineers are somewhat fortunate in this respect because the basics of structures, mechanisms, and chemical processes are familiar from everyday life. On the other hand, electrical engineering concepts are somewhat more abstract and hidden from the casual observer.)
3. *To be able to operate and maintain electrical systems, such as those found in control systems for manufacturing processes.* The vast majority of electrical-circuit malfunctions can be readily solved by the application of basic electrical-engineering principles. You will be a much more versatile and valuable engineer or scientist if you can apply electrical-engineering principles in practical situations.
4. *To be able to communicate with electrical-engineering consultants.* Very likely, you will often need to work closely with electrical engineers in your career. This book will give you the basic knowledge needed to communicate effectively.

Content of This Book

Circuit theory is the electrical engineer's fundamental tool.

Electrical engineering is too vast to cover in one or two courses. Our objective is to introduce the underlying concepts that you are most likely to need. Circuit theory is the electrical engineer's fundamental tool. That is why the first six chapters of this book are devoted to circuits.

Embedded computers, sensors, and electronic circuits will be an increasingly important part of the products you design and the instrumentation you use as an engineer or scientist. Chapters 7 and 8 treat digital systems with emphasis on embedded computers and instrumentation. Chapters 9 through 13 deal with electronic devices and circuits.

As a mechanical, chemical, civil, industrial, or other engineer, you will very likely need to employ energy-conversion devices. The last three chapters relate to electrical energy systems treating transformers, generators, and motors.

Because this book covers many basic concepts, it is also sometimes used in introductory courses for electrical engineers. Just as it is important for other engineers and scientists to see how electrical engineering can be applied to their fields, it is equally important for electrical engineers to be familiar with these applications.

1.2 CIRCUITS, CURRENTS, AND VOLTAGES

Overview of an Electrical Circuit

Before we carefully define the terminology of electrical circuits, let us gain some basic understanding by considering a simple example: the headlight circuit of an automobile. This circuit consists of a battery, a switch, the headlamps, and wires connecting them in a closed path, as illustrated in Figure 1.2.

The battery voltage is a measure of the energy gained by a unit of charge as it moves through the battery.

Chemical forces in the battery cause electrical charge (electrons) to flow through the circuit. The charge gains energy from the chemicals in the battery and delivers energy to the headlamps. The battery voltage (nominally, 12 volts) is a measure of the energy gained by a unit of charge as it moves through the battery.

Electrons readily move through copper but not through plastic insulation.

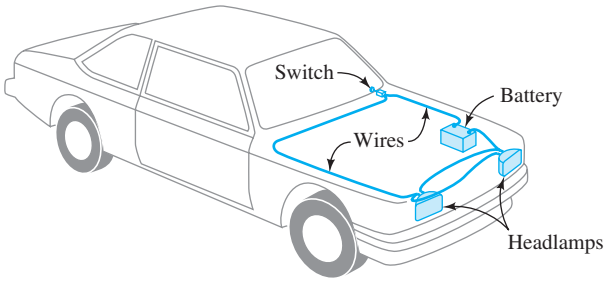
The wires are made of an excellent electrical conductor (copper) and are insulated from one another (and from the metal auto body) by electrical insulation (plastic) coating the wires. Electrons readily move through copper but not through the plastic insulation. Thus, the charge flow (electrical current) is confined to the wires until it reaches the headlamps. Air is also an insulator.

The switch is used to control the flow of current. When the conducting metallic parts of the switch make contact, we say that the switch is **closed** and current flows through the circuit. On the other hand, when the conducting parts of the switch do not make contact, we say that the switch is **open** and current does not flow.

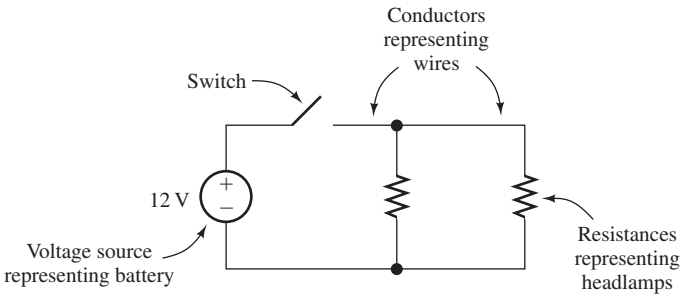
Electrons experience collisions with the atoms of the tungsten wires, resulting in heating of the tungsten.

The headlamps contain special tungsten wires that can withstand high temperatures. Tungsten is not as good an electrical conductor as copper, and the electrons experience collisions with the atoms of the tungsten wires, resulting in heating of the tungsten. We say that the tungsten wires have electrical resistance. Thus, energy is transferred by the chemical action in the battery to the electrons and then to the tungsten, where it appears as heat. The tungsten becomes hot enough so that copious light is emitted. We will see that the power transferred is equal to the product of current (rate of flow of charge) and the voltage (also called electrical potential) applied by the battery.

Energy is transferred by the chemical action in the battery to the electrons and then to the tungsten.



(a) Physical configuration



(b) Circuit diagram

Figure 1.2 The headlight circuit. (a) The actual physical layout of the circuit. (b) The circuit diagram.

(Actually, the simple description of the headlight circuit we have given is most appropriate for older cars. In more modern automobiles, light emitting diodes (LEDs) are used in place of the tungsten filaments. Furthermore, sensors provide information to an embedded computer about the ambient light level, whether or not the ignition is energized, and whether the transmission is in park or drive. The dashboard switch merely inputs a logic level to the computer, indicating the intention of the operator with regard to the headlights. Depending on these inputs, the computer controls the state of an electronic switch in the headlight circuit. When the ignition is turned off and if it is dark, the computer keeps the lights on for a few minutes so the passengers can see to exit and then turns them off to conserve energy in the battery. This is typical of the trend to use highly sophisticated electronic and computer technology to enhance the capabilities of new designs in all fields of engineering.)

Fluid-Flow Analogy

The fluid-flow analogy can be very helpful initially in understanding electrical circuits.

Electrical circuits are analogous to fluid-flow systems. The battery is analogous to a pump, and charge is analogous to the fluid. Conductors (usually copper wires) correspond to frictionless pipes through which the fluid flows. Electrical current is the counterpart of the flow rate of the fluid. Voltage corresponds to the pressure differential between points in the fluid circuit. Switches are analogous to valves. Finally, the electrical resistance of a tungsten headlamp is analogous to a constriction in a fluid system that results in turbulence and conversion of energy to heat. Notice that current is a measure of the flow of charge *through* the cross section of a circuit element, whereas voltage is measured *across* the ends of a circuit element or *between* any other two points in a circuit.

Now that we have gained a basic understanding of a simple electrical circuit, we will define the concepts and terminology more carefully.

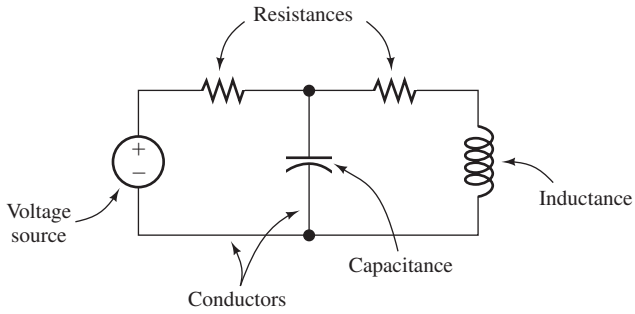


Figure 1.3 An electrical circuit consists of circuit elements, such as voltage sources, resistances, inductances, and capacitances, connected in closed paths by conductors.

Electrical Circuits

An electrical circuit consists of various types of circuit elements connected in closed paths by conductors.

An **electrical circuit** consists of various types of circuit elements connected in closed paths by conductors. An example is illustrated in Figure 1.3. The circuit elements can be resistances, inductances, capacitances, and voltage sources, among others. The symbols for some of these elements are illustrated in the figure. Eventually, we will carefully discuss the characteristics of each type of element.

Charge flows easily through conductors.

Charge flows easily through conductors, which are represented by lines connecting circuit elements. Conductors correspond to connecting wires in physical circuits. Voltage sources create forces that cause charge to flow through the conductors and other circuit elements. As a result, energy is transferred between the circuit elements, resulting in a useful function.

Electrical Current

Current is the time rate of flow of electrical charge. Its units are amperes (A), which are equivalent to coulombs per second (C/s).

Electrical current is the time rate of flow of electrical charge through a conductor or circuit element. The units are amperes (A), which are equivalent to coulombs per second (C/s). (The charge on an electron is -1.602×10^{-19} C.)

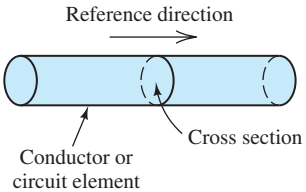


Figure 1.4 Current is the time rate of charge flow through a cross section of a conductor or circuit element.

Conceptually, to find the current for a given circuit element, we first select a cross section of the circuit element roughly perpendicular to the flow of current. Then, we select a **reference direction** along the direction of flow. Thus, the reference direction points from one side of the cross section to the other. This is illustrated in Figure 1.4.

Next, suppose that we keep a record of the net charge flow through the cross section. Positive charge crossing in the reference direction is counted as a positive contribution to net charge. Positive charge crossing opposite to the reference is counted as a negative contribution. Furthermore, negative charge crossing in the reference direction is counted as a negative contribution, and negative charge against the reference direction is a positive contribution to charge.

Thus, in concept, we obtain a record of the net charge in coulombs as a function of time in seconds denoted as $q(t)$. The electrical current flowing through the element in the reference direction is given by

Colored shading is used to indicate key equations throughout this book.

$$i(t) = \frac{dq(t)}{dt} \tag{1.1}$$

A constant current of one ampere means that one coulomb of charge passes through the cross section each second.

To find charge given current, we must integrate. Thus, we have

$$q(t) = \int_{t_0}^{t} i(t)\,dt + q(t_0) \tag{1.2}$$

in which t_0 is some initial time at which the charge is known. (Throughout this book, we assume that time t is in seconds unless stated otherwise.)

Current flow is the same for all cross sections of a circuit element. (We reexamine this statement when we introduce the capacitor in Chapter 3.) The current that enters one end flows through the element and exits through the other end.

Example 1.1 Determining Current Given Charge

Suppose that charge versus time for a given circuit element is given by

$$q(t) = 0 \qquad \text{for } t < 0$$

and

$$q(t) = 2 - 2e^{-100t}\ \text{C} \qquad \text{for } t > 0$$

Sketch $q(t)$ and $i(t)$ to scale versus time.

Solution First we use Equation 1.1 to find an expression for the current:

$$\begin{aligned} i(t) &= \frac{dq(t)}{dt} \\ &= 0 \qquad \text{for } t < 0 \\ &= 200e^{-100t}\ \text{A} \qquad \text{for } t > 0 \end{aligned}$$

Plots of $q(t)$ and $i(t)$ are shown in Figure 1.5. ■

Reference Directions

In analyzing electrical circuits, we may not initially know the *actual direction* of current flow in a particular circuit element. Therefore, we start by assigning current

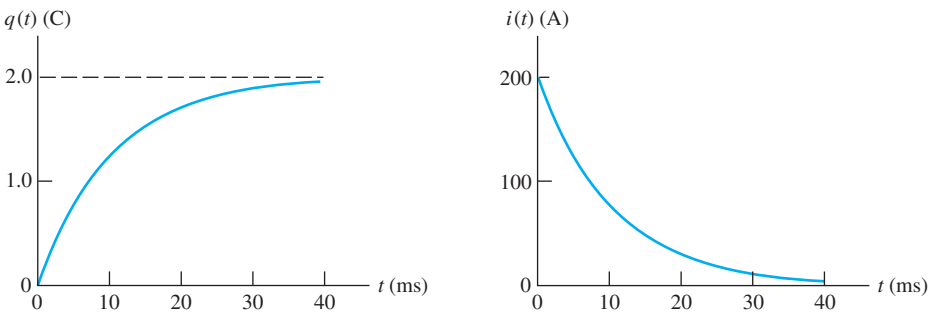


Figure 1.5 Plots of charge and current versus time for Example 1.1. *Note:* The time scale is in milliseconds (ms). One millisecond is equivalent to 10^{-3} seconds.

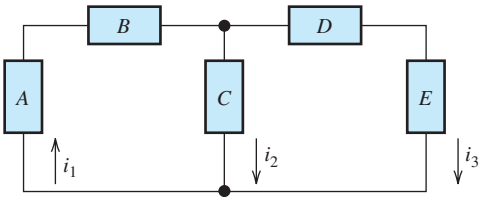


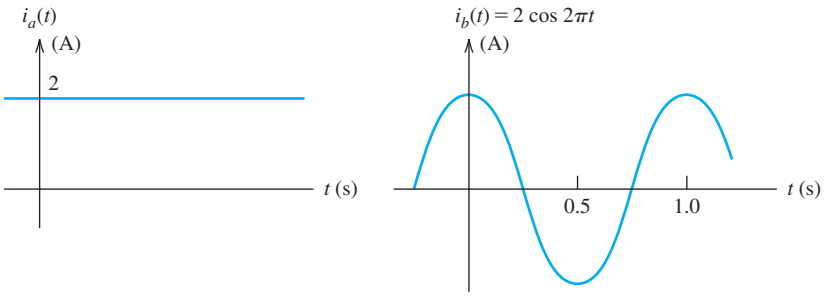
Figure 1.6 In analyzing circuits, we frequently start by assigning current variables i_1, i_2, i_3, and so forth.

variables and arbitrarily selecting a *reference direction* for each current of interest. It is customary to use the letter i for currents and subscripts to distinguish different currents. This is illustrated by the example in Figure 1.6, in which the boxes labeled A, B, and so on represent circuit elements. After we solve for the current values, we may find that some currents have negative values. For example, suppose that $i_1 = -2$ A in the circuit of Figure 1.6. Because i_1 has a negative value, we know that current actually flows in the direction opposite to the reference initially selected for i_1. Thus, the actual current is 2 A flowing downward through element A.

Direct Current and Alternating Current

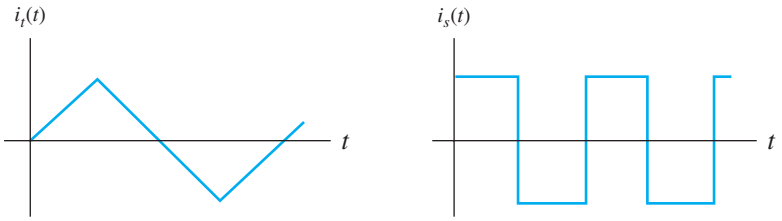
Dc currents are constant with respect to time, whereas ac currents vary with time.

When a current is constant with time, we say that we have **direct current**, abbreviated as dc. On the other hand, a current that varies with time, reversing direction periodically, is called **alternating current**, abbreviated as ac. Figure 1.7 shows the values of a dc current and a sinusoidal ac current versus time. When $i_b(t)$ takes a negative value, the actual current direction is opposite to the reference direction for $i_b(t)$. The designation ac is used for other types of time-varying currents, such as the triangular and square waveforms shown in Figure 1.8.



(a) Dc current (b) Ac current

Figure 1.7 Examples of dc and ac currents versus time.



(a) Triangular waveform (b) Square waveform

Figure 1.8 Ac currents can have various waveforms.