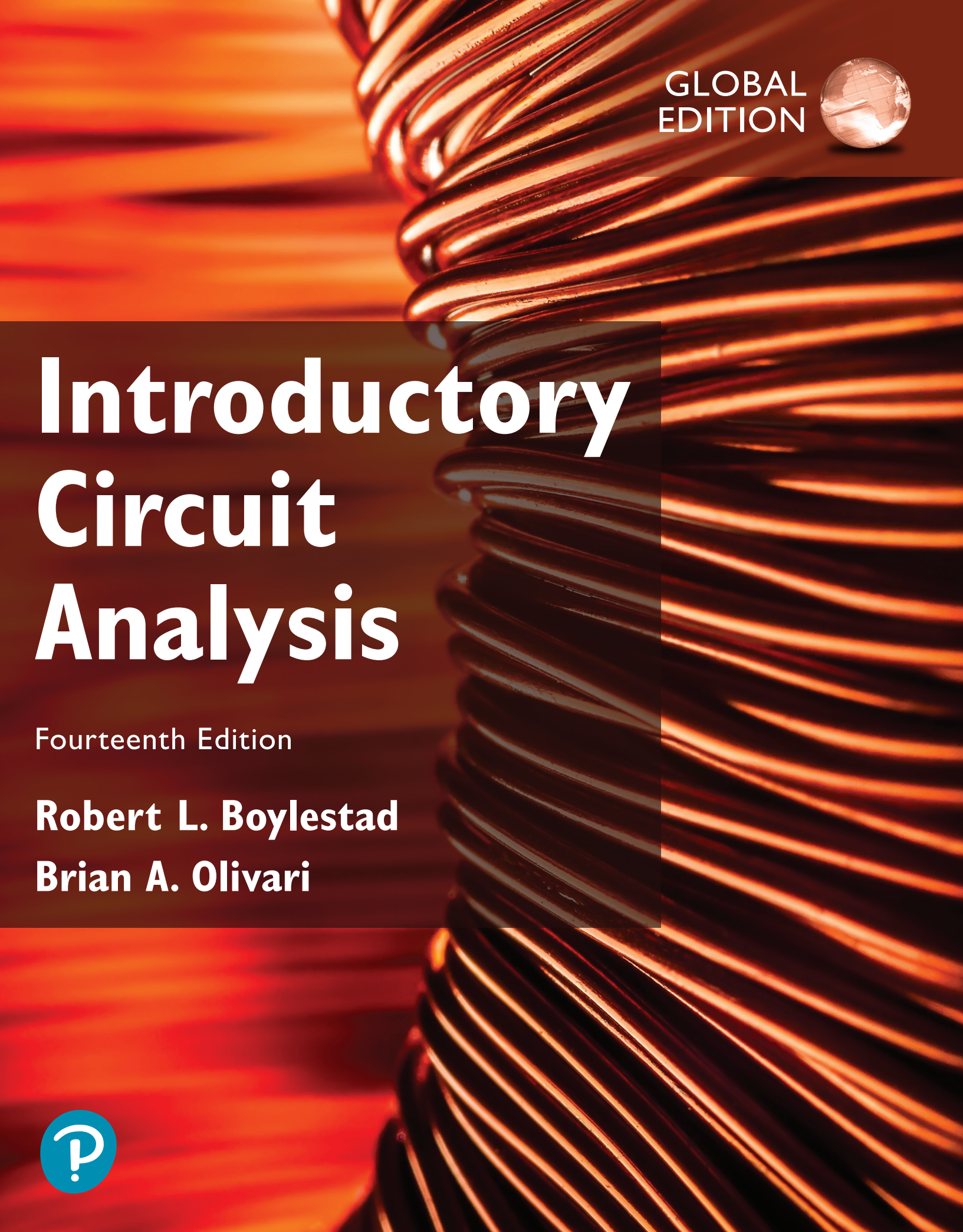
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Robert L. Boylestad
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Summary of Equations to Accompany

INTRODUCTORY CIRCUIT ANALYSIS, Fourteenth Edition, Global Edition

by Robert L. Boylestad/Brian A. Olivari

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ac

Sinusoidal Alternating Waveforms

Sine wave $v = V_m \sin\alpha, \alpha = \omega t = 2\pi ft, f = 1/T, 1 \text{ radian} = 57.3°$, radians $= (\pi/180°) \times$ (degrees), degrees $= (180°/\pi) \times$ (radians)
Identities $\sin(\omega t + 90°) = \cos\omega t, \sin\omega t = \cos(\omega t - (\pi/2))$, $\sin(-\alpha) = -\sin\alpha, \cos(-\alpha) = \cos\alpha$
Average value $G =$ algebraic sum of areas/length of curve
Effective (rms) value $I_{\text{rms}} = 0.707 I_m, I_m = \sqrt{2} I_{\text{rms}}$,

$$I_{\text{rms}} = \sqrt{\text{area}[i(t)]^2/T}$$
$$V_{\text{rms}} = 0.707\, V_m$$
$$V_m = \sqrt{2}\, V_{\text{rms}}$$
$$V_{\text{rms}} = \sqrt{\text{area}[v(t)]^2/T}$$

The Basic Elements and Phasors

***R*:** $I_m = V_m/R$, in phase ***L*:** $X_L = \omega L, v_L$ leads i_L by 90°
***C*:** $X_C = 1/\omega C, i_C$ leads v_C by 90° **Power** $P = (V_m I_m/2)\cos\theta = V_{\text{rms}} I_{\text{rms}} \cos\theta$ ***R*:** $P = V_{\text{rms}} I_{\text{rms}} = I^2_{\text{rms}} R = V^2_{\text{rms}}/R$
Power factor $F_p = \cos\theta = P/V_{\text{rms}} I_{\text{rms}}$ **Rectangular form** $\mathbf{C} = A \pm jB$
Polar form $C = C\angle\theta$ **Conversions** $C = \sqrt{A^2 + B^2}, \theta = \tan^{-1}(B/A), A = C\cos\theta, B = C\sin\theta$ **Operations** $j = \sqrt{-1}$, $j^2 = -1, 1/j = -j, \mathbf{C}_1 \pm \mathbf{C}_2 = (\pm A_1 \pm A_2) + j(\pm B_1 \pm B_2)$, $\mathbf{C}_1 \cdot \mathbf{C}_2 = C_1 C_2 \angle(\theta_1 + \theta_2), \mathbf{C}_1/\mathbf{C}_2 = (C_1/C_2)\angle(\theta_1 - \theta_2)$

Series and Parallel ac Circuits

Elements $R\angle 0°, X_L\angle 90°, X_C\angle -90°$
Series $\mathbf{Z}_T = \mathbf{Z}_1 + \mathbf{Z}_2 + \mathbf{Z}_3 + \cdots + \mathbf{Z}_N, \mathbf{I}_s = \mathbf{E}/\mathbf{Z}_T, F_p = R/Z_T$
Voltage divider rule $\mathbf{V}_X = \mathbf{Z}_X \mathbf{E}/\mathbf{Z}_T$ **Parallel** $\mathbf{Y}_T = \mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \cdots + \mathbf{Y}_N, \mathbf{Z}_T = \mathbf{Z}_1\mathbf{Z}_2/(\mathbf{Z}_1 + \mathbf{Z}_2), G\angle 0°, B_L\angle -90°$, $B_C\angle 90°, F_P = \cos\theta_T = G/Y_T$ **Current divider rule** $\mathbf{I}_1 = \mathbf{Z}_2\mathbf{I}_T/(\mathbf{Z}_1 + \mathbf{Z}_2), \mathbf{I}_2 = \mathbf{Z}_1\mathbf{I}_T/(\mathbf{Z}_1 + \mathbf{Z}_2)$
Equivalent circuits $R_s = R_p X_p^2/(X_p^2 + R_p^2), X_s = R_p^2 X_p/(X_p^2 + R_p^2)$, $R_p = (R_s^2 + X_s^2)/R_s, X_p = (R_s^2 + X_s^2)/X_s$

Series-Parallel ac Networks

Employ block impedances and obtain general solution for reduced network. Then substitute numerical values. General approach similar to that for dc networks.

Methods of Analysis and Selected Topics (ac)

Source conversion $\mathbf{E} = \mathbf{I}Z_p, \mathbf{Z}_S = \mathbf{Z}_p, \mathbf{I} = \mathbf{E}/\mathbf{Z}_S$
Bridge networks $\mathbf{Z}_1/\mathbf{Z}_3 = \mathbf{Z}_2/\mathbf{Z}_4$
Δ-Y, Y-Δ conversions See dc coverage, replacing *R* by *Z*.

Network Theorems (ac)

Review dc content on other side.

Thévenin's theorems (dependent sources) $\mathbf{E}_{OC} = \mathbf{E}_{Th}, \mathbf{Z}_{Th} = \mathbf{E}_{OC}/\mathbf{I}_{SC}, \mathbf{Z}_{Th} = \mathbf{E}_g/\mathbf{I}_g$ **Norton's theorems** (dependent sources) $\mathbf{I}_{SC} = \mathbf{I}_N, \mathbf{Z}_N = \mathbf{E}_{OC}/\mathbf{I}_{SC}, \mathbf{Z}_N = \mathbf{E}_g/\mathbf{I}_g$ **Maximum power transfer theorem** $Z_L = Z_{Th}, \theta_L = -\theta_{Th_Z}, P_{\max} = E^2_{Th}/4R_{Th}$

Power (ac)

R: $P = VI = V_m I_m/2 = I^2R = V^2/R$ **Apparent power** $S = VI$, $P = S\cos\theta, F_p = \cos\theta = P/S$ **Reactive power** $Q = VI\sin\theta$
L: $Q_L = VI = I^2X_L = V^2/X_L$, C: $Q_C = VI = I^2X_C = V^2/X_C$,
$S_T = \sqrt{P_T^2 + Q_T^2}, F_p = P_T/S_T$

Resonances

Series $X_L = X_C, f_S = 1/(2\pi\sqrt{LC}), Z_{TS} = R, Q_l = X_L/R_l, Q_S = X_L/R = (1/R)\sqrt{L/C}$, $V_L = Q_S E, V_{Cs} = Q_S E, P_{\text{HPF}} = (1/2)P_{\max}$, $f_1 = (1/2\pi)[-R/2L + (1/2)\sqrt{(R/L)^2 + 4/LC}], f_2(\text{use} - R/2L)$, $BW = f_2 - f_1 = R/2\pi L = f_S/Q_S$ **Parallel** $X_{Lp} = X_C, X_{Lp} = (R_l^2 + X_L^2)/X_L, f_p = \left[1/\left(2\pi\sqrt{LC}\right)\right]\sqrt{1 - (R_l^2 C/L)}, Z_{TP} = R_s \parallel R_p$, $R_p = (R_l^2 + X_L^2)/R_l, Q_p = (R_s \parallel R_p)/X_{Lp}, BW = f_2 - f_1 = f_p/Q_p$
***Q* ≥ 10:** $Z_{Tp} \cong R_s \parallel Q^2 R_l, X_{Lp} \cong X_L, X_L = X_C, f_p \cong 1/(2\pi\sqrt{LC})$, $Q_p = Q_l, I_L = I_C \cong QI_T, BW = f_p/Q_p = R_l/2\pi L$

Decibels, Filters, and Bode Plots

Logarithms $N = b^x, x = \log_b N, \log_e x = 2.3\log_{10} x, \log_{10} ab = \log_{10} a + \log_{10} b, \log_{10} a/b = \log_{10} a - \log_{10} b, \log_{10} a^n = n\log_{10} a$, $\text{dB} = 10\log_{10} P_2/P_1, \text{dB}_v = 20\log_{10} V_2/V_1$
***R-C* filters** (high-pass) $f_c = 1/(2\pi RC)$,

$$\mathbf{V}_o/\mathbf{V}_i = R\sqrt{R^2 + X_C^2}\angle\tan^{-1}(X_C/R)$$

(low-pass) $f_c = 1/(2\pi RC)$,

$$\mathbf{V}_o/\mathbf{V}_i = X_C/\sqrt{R^2 + X_C^2}\angle -\tan^{-1}\frac{R}{X_C}$$

Octave 2 : 1, 6 dB/octave **Decade** 10 : 1, 20 dB/decade

Transformers

Mutual inductance $M = k\sqrt{L_p L_s}$ **Iron-core** $E_p = 4.44 f N_p \Phi_m$, $E_S = 4.44 f N_S \Phi_m, E_p/E_S = N_p/N_S, a = N_p/N_S, I_p/I_S = N_S/N_p$, $\mathbf{Z}_p = a^2\mathbf{Z}_L, E_p I_p = E_S I_S, P_i = P_O$(ideal)
Air-core $\mathbf{Z}_i = \mathbf{Z}_p + (\omega M)^2/(\mathbf{Z}_S + \mathbf{Z}_L)$

Polyphase Systems

Y-Y system $I_{\phi g} = I_L = I_{\phi L}, V_\phi = E_\phi, E_L = \sqrt{3} V_\phi$ **Y-Δ system** $V_\phi = E_L, I_L = \sqrt{3} I_\phi$ **Δ-Δ system** $V_\phi = E_L = E_\phi, I_L = \sqrt{3} I_\phi$
Δ-Y system $E_L = \sqrt{3} V_\phi, I_\phi = I_L, E_L = E_\phi$ **Power** $P_T = 3P_\phi$, $Q_T = 3Q_\phi, S_T = 3S_\phi = \sqrt{3} E_L I_L, F_p = P_T/S_T$

Pulse Waveforms and the *R-C* Response

% tilt $= [(V_1 - V_2)/V] \times 100\%$ with $V = (V_1 + V_2)/2$
Pulse repetition frequency $(\text{prf}) = 1/T$
Duty cycle $= (t_p/T) \times 100\%$
$V_{\text{av}} = (\text{duty cycle})(\text{peak value}) + (1 - \text{duty cycle}) \times (V_b)$
***R-C* circuits** $v_C = V_i + (V_f - V_i)(1 - e^{-t/RC})$
Compensated attenuator $R_p C_p = R_s C_s$

Nonsinusoidal Circuits

Fourier series $f(\alpha) = A_0 + A_1\sin\omega t + A_2\sin 2\omega t + \cdots + A_n\sin n\omega t + B_1\cos\omega t + B_2\cos 2\omega t + \cdots + B_n\cos n\omega t$
Even function $f(\alpha) = f(-\alpha)$, no B_n terms **Odd function** $f(\alpha) = -f(-\alpha)$, no A_n terms, no odd harmonics if $f(t) = f[(T/2) + t]$, no even harmonics if $f(t) = -f((T/2) + t)$
Effective (rms) value

$$V_{(\text{rms})} = \sqrt{V_0^2 + (V_{m_1}^2 + \cdots + V_{m_n}^2 + V_{m_1}'^2 + \cdots + V_{m_n}'^2)/2}$$

Power $P_T = V_0 I_0 + V_1 I_1 \cos\theta + \cdots + V_n I_n \cos\theta_n = I_{\text{rms}}{}^2 R = V_{\text{rms}}{}^2/R$

Standard Resistor Values

Ohms (Ω)					Kilohms (kΩ)		Megohms (MΩ)	
0.10	**1.0**	**10**	**100**	**1000**	**10**	**100**	**1.0**	**10.0**
0.11	1.1	11	110	1100	11	110	1.1	11.0
0.12	**1.2**	**12**	**120**	**1200**	**12**	**120**	**1.2**	**12.0**
0.13	1.3	13	130	1300	13	130	1.3	13.0
0.15	**1.5**	**15**	**150**	**1500**	**15**	**150**	**1.5**	**15.0**
0.16	1.6	16	160	1600	16	160	1.6	16.0
0.18	**1.8**	**18**	**180**	**1800**	**18**	**180**	**1.8**	**18.0**
0.20	2.0	20	200	2000	20	200	2.0	20.0
0.22	**2.2**	**22**	**220**	**2200**	**22**	**220**	**2.2**	**22.0**
0.24	2.4	24	240	2400	24	240	2.4	
0.27	**2.7**	**27**	**270**	**2700**	**27**	**270**	**2.7**	
0.30	3.0	30	300	3000	30	300	3.0	
0.33	**3.3**	**33**	**330**	**3300**	**33**	**330**	**3.3**	
0.36	3.6	36	360	3600	36	360	3.6	
0.39	**3.9**	**39**	**390**	**3900**	**39**	**390**	**3.9**	
0.43	4.3	43	430	4300	43	430	4.3	
0.47	**4.7**	**47**	**470**	**4700**	**47**	**470**	**4.7**	
0.51	5.1	51	510	5100	51	510	5.1	
0.56	**5.6**	**56**	**560**	**5600**	**56**	**560**	**5.6**	
0.62	6.2	62	620	6200	62	620	6.2	
0.68	**6.8**	**68**	**680**	**6800**	**68**	**680**	**6.8**	
0.75	7.5	75	750	7500	75	750	7.5	
0.82	**8.2**	**82**	**820**	**8200**	**82**	**820**	**8.2**	
0.91	9.1	91	910	9100	91	910	9.1	

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In loving memory of my wife Else
and our children Eric, Alison and Stacey
and our grandchildren Kelcy, Morgan,
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and Aspen.

Brian A. Olivari

To my wife Margie
and our children Jenny, Brittany,
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Preface

Welcome to the fourteenth edition. Over the fifty plus years since the first edition in 1968, the revisions have typically involved adding additional content based on the changes in curriculum. This new fourteenth edition is more about refining and updating content to provide a revision that ensures that the most current and relevant content is provided.

We are also excited about the ways students can purchase this textbook to ensure that they have the most effective and affordable options.

Students can choose from the print book or eText options. With the Pearson eText, students can search the text, use the study tools such as flashcards, make notes online, print out reading assignments that incorporate the notes they take during lectures, and bookmark important passages for later review.

The most notable changes include the following:

- The over 2000 images are as current as possible with many new or modified for this edition.
- The overall design of the text has been updated and enhanced for a more modern, accessible layout.
- The Multisim and PSpice computer material has been removed based on the vast majority of reviewers stating it was not covered. This valuable feedback indicated the importance of covering fundamental theories clearly rather than focusing on the mechanics of applying computer methods.
- Topics requiring a solid understanding of power factor, lead, and lag concepts have been significantly enhanced throughout the text.
- Laboratory experiments and summary of equations to accompany the text have been carefully reviewed for accuracy and changes made where required.
- Problems were carefully reviewed to ensure that they progressed from the simple to the more complex in each section.
- All solutions were checked carefully to ensure accuracy.

The TI 89 Titanium calculator continues to be the choice for this text, and we have provided sufficient detail in the text to perform all the mathematical techniques required without having to refer to the calculator manual provided. In some cases, short-cut methods are introduced that are helpful in what they can perform in the shortest of time. In every respect we feel the TI-89 will serve the student well in their current studies and those to follow.

The feedback we have received from users of the thirteenth edition has been very helpful in defining areas that needed additional explanation and coverage. We always consider the effort to share feedback to be extraordinary since the instructor has so many other obligations in today's teaching environment. The comments we have received directly from users regarding potential errors in the solutions were taken seriously; and we reviewed their comments carefully to ensure that the content is correct and clarified. However, if you have questions about any of the content or solutions, we welcome your comments and will respond to any inquiry as soon as possible.

We realize there is always room for improvement, and while not as obvious as it was in earlier editions, there is always something you can do to take the text one step higher.

Robert L. Boylestad
Brian A. Olivari

SUPPLEMENTS

To enhance the learning process, a full supplements package accompanies this text and is available to instructors using the text for a course.

Instructor Resources

Instructor Resources can be downloaded at www.pearsonglobaleditions.com. If you don't already have a username and password for access, you can request access at www.pearsonglobaleditions.com.

- **Instructor's Resource Manual,** containing text solutions.
- **PowerPoint Lecture Notes.**
- **TestGen,** a computerized test bank.

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About the Authors

ROBERT L. BOYLESTAD

The original contract for *Introductory Circuit Analysis* was signed in 1965 resulting in a publishing date of 1968—a current life history of some 60 years. The first 13 editions were written by me with an average time interval between editions of some 4.5 years. Upon completion of each edition, I felt that I had done all I can to make it the best available. However, as the years passed, there was always something that could withstand some improvement. For the 14th edition, I felt it wise to join hands with Professor Brian Olivari (Maine Maritime Academy) to be sure that I was fully aware of recent trends in the scope and depth of coverage in various subject areas. I feel it has been a wonderful union in developing the content of this edition.

My history in the educational field includes some 45 years at various professorial ranks in the City University, New York. There was also a period of some 10 years as assistant dean at the Thayer School of Engineering at Dartmouth. During my teaching career, I was fortunate enough to find the time to write some seven texts related to the electrical/electronics field. The two most successful are *Introductory Circuit Analysis* and *Electronic Devices and Circuit Theory* (co-authored with Professor Louis Nashelsky). The first one is in its 14th edition now, and the latter is in its 11th edition. Both texts have been translated into foreign languages with the ICA text translated into seven languages: Arabic, Chinese, French, Korean, Portuguese, Spanish, and Taiwanese. In addition to *Introductory Circuit Analysis,* a number of manuals and texts related to computer languages such as *BASIC Applied to Circuit Analysis, Manual for the IBM PC jr.*, and *BASIC for Electronics and Computer Technologies* were also published.

I look forward to any response from users of this 14th edition to ensure that the text remains current in the years to come.

BRIAN A. OLIVARI

I was honored to have been asked by Professor Boylestad to collaborate on the 14th edition of *Introductory Circuit Analysis*. I could never have imagined being co-author on the latest edition when I first used Professor Boylestad's *Electronic Devices and Circuit Theory* textbook as a student back in 1977, and then the *11th edition of Introductory Circuit Analysis* as a professor in 2008.

As a faculty member at Maine Maritime Academy for over 15 years, my teaching has focused on both electrical engineering and mathematics. In engineering, my primary interest has been in circuit analysis and electronics. In mathematics, I have been committed to preparing my math students to be successful at solving engineering problems.

Prior to teaching at Maine Maritime Academy, much of my professional experience came from working in the telecommunications industry at Western Electric, Rochester Telephone, and, most notably, Bell Labs where I was part of a team of engineers (systems, mechanical, electrical, and software) that developed the first-of-its-kind, stored-program-controlled D5 Digital Channel Bank System. Additionally, I served as an associate editor for the IEEE Solid-State Circuits Conference Digest of Technical Papers and taught briefly at Rochester Institute of Technology.

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Introduction

1

Objectives

- *Become aware of the rapid growth of the electrical/electronics industry over the past century.*
- *Understand the importance of applying a unit of measurement to a result or measurement and to ensure that the numerical values substituted into an equation are consistent with the unit of measurement of the various quantities.*
- *Become familiar with the International System of Units (SI) also referred to as the metric system.*
- *Understand the importance of powers of ten and how to work with them in any numerical calculation.*
- *Be able to convert any quantity, in any system of units, to another system with confidence.*

1.1 THE ELECTRICAL/ELECTRONICS INDUSTRY

Over the past few decades, technology has been changing at an ever-increasing rate. The pressure to develop new products, improve the performance and reliability of existing systems, and create new markets will only accelerate that rate. This pressure, however, is also what makes this field so exciting. New ways of storing and manipulating information, manufacturing integrated circuits, and developing software-embedded hardware systems that can "think" on their own based on input data are only a few possibilities.

Change has always been part of the human experience, but in the past, it was gradual. In recent years, however, the rate at which change in the electrical/electronics industry has been taking place is mind-boggling. Just think, for example, it was only a few years ago that "flatscreen" TVs, with wide, flat screens were introduced. Already, these have been eclipsed by much wider 4K ultra high definition (UHD) and 3D models.

Miniaturization has resulted in huge advances in electronic systems. For example, advancement in this technology has allowed cell phones that originally were the size of notebooks to now be smaller than a deck of playing cards. These so-called smartphones (devices), such as an iPhone 12 (2020), provide a multitude of extremely desirable features, in addition to being able to make simple telephone calls. Such features include a multi-touch glass capacitive screen, mp3 music player (iPod capability), web browser, email, text messaging, calendar and contacts, mobile game player, facial recognition (for security purposes), 4K HD video recording, high-resolution camera, video conferencing (FaceTime), GPS, Bluetooth, Wi-Fi, and the ability to run over 2 million software applications "Apps," to name a few. Remarkably, this iPhone can also simultaneously store in its 256 GB memory: 6000 songs, 30,000 photos, as well as 18 hours of 4K video recorded at 30 fps. The Apple Watch, and other "smartwatches," provide smartphone users with the ability to extend some of their devices' capabilities to their wrists. Of course, laptop computers, iPads, and the like, have become ubiquitous in our society, primarily due to rapid technological advances in electronic systems. Nearly invisible and more powerful hearing aids with background noise cancellation features are now available for the hearing impaired. The list of new or improved products

continues to expand because significantly smaller electronic systems have been developed.

Most of us would agree that the computer has revolutionized our daily lives, in ways never imagined not that long ago—and it continues to do so in an accelerated fashion. When we compare the Guidance Computer aboard the Apollo 11 spacecraft, which landed on the moon back in 1969, with a commonly used cell phone in use today (the iPhone), we discover Apollo's computer weighed 70 pounds and offered 2.3 MHz of processing power. Whereas, the performance data for even a much older generation iPhone 6 (2014) is staggering. At 3.36 billion instructions per second, the iPhone 6's clock is 32,600 times faster than the best on board computers of the Apollo era and could perform instructions 120,000,000 times faster. You wouldn't be wrong in saying an iPhone could be used to guide 120,000,000 Apollo-era spacecrafts to the moon, all at the same time. And… the iPhone weighs a mere 4.6 ounces!

Spurred on by the continuing process of miniaturization is a serious and growing interest in **artificial intelligence**, a term first used in 1955, as a drive to replicate the brain's function with a packaged electronic equivalent. Although only about 3 pounds in weight, a size equivalent to about 2.5 pints of liquid with a power drain of about 20 watts (half that of a 40-watt light bulb), the brain contains over 100 billion neurons that have the ability to "fire" 200 times a second. Imagine the number of decisions made per second if all are firing at the same time! This number, however, is undaunting to researchers who feel that an electronic package capable of emulating the human brain is a genuine possibility in the next 10 to 15 years. Of course, including emotional qualities will be the biggest challenge, but otherwise researchers feel the advances of recent years are clear evidence that it is a real possibility. Consider how much of our daily lives is already decided for us with automatic brake control, programmed parallel parking, GPS, Web searching, and so on. The move is obviously strong and on its way. Also, when you consider how far we have come since the development of the first transistor some 67 years ago, who knows what might develop in the next decade or two?

This reduction in size of electronic systems is due primarily to an important innovation introduced in 1958—the **integrated circuit (IC)**. An integrated circuit can now contain features less than 50 nanometers across. The fact that measurements are now being made in nanometers has resulted in the terminology **nanotechnology** to refer to the production of integrated circuits called *nanochips.* To better appreciate the impact of nanometer measurements, consider drawing 100 lines within the boundaries of 1 inch. Then attempt drawing 1000 lines within the same length. Cutting 50-nanometer features would require drawing over 500,000 lines in 1 inch. The integrated circuit shown in Fig. 1.1 is an intel® Core™ i7 6-core processor that has around 3 billion transistors—a number hard to comprehend.

However, before a decision is made on such dramatic reductions in size, the system must be designed and tested to determine if it is worth constructing as an integrated circuit. That design process requires engineers who know the characteristics of each device used in the system, including undesirable characteristics that are part of any electronic element. In other words, there are *no ideal (perfect) elements* in an electronic design. Considering the limitations of each component is necessary

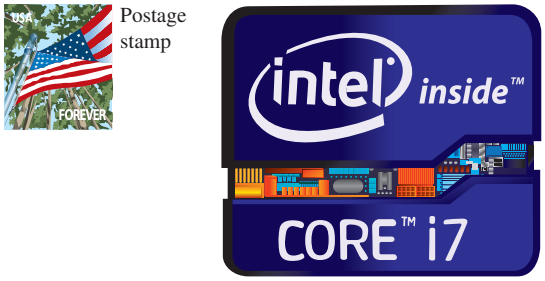

FIG. 1.1
Intel® Core™ i7 6-core processer.

to ensure a reliable response under all conditions of temperature, vibration, and effects of the surrounding environment. To develop this awareness requires time and must begin with understanding the basic characteristics of the device, as covered in this text. One of the objectives of this text is to explain how ideal components work and their function in a network. Another is to explain conditions in which components may not be ideal.

One of the very positive aspects of the learning process associated with electric and electronic circuits is that once a concept or procedure is clearly and correctly understood, it will be useful throughout the career of the individual at any level in the industry. Once a law or equation is understood, it will not be replaced by another equation as the material becomes more advanced and complicated. For instance, one of the first laws to be introduced is Ohm's law. This law provides a relationship between forces and components that will always be true, no matter how complicated the system becomes. In fact, it is an equation that will be applied in various forms throughout the design of the entire system. The use of the basic laws may change, but the laws will not change and will always be applicable.

It is vitally important to understand that the learning process for circuit analysis is sequential. That is, the first few chapters establish the foundation for the remaining chapters. Failure to properly understand the opening chapters will only lead to difficulties understanding the material in the chapters to follow. This first chapter provides a brief history of the field followed by a review of mathematical concepts necessary to understand the rest of the material.

1.2 A BRIEF HISTORY

In the sciences, once a hypothesis is proven and accepted, it becomes one of the building blocks of that area of study, permitting additional investigation and development. Naturally, the more pieces of a puzzle available, the more obvious is the avenue toward a possible solution. In fact, history demonstrates that a single development may provide the key that will result in a mushrooming effect that brings the science to a new plateau of understanding and impact.

If the opportunity presents itself, read one of the many publications reviewing the history of this field. Space requirements are such that only a brief review can be provided here. There are many more contributors

than could be listed, and their efforts have often provided important keys to the solution of some very important concepts.

Throughout history, some periods were characterized by what appeared to be an explosion of interest and development in particular areas. As you will see from the discussion of the late 1700s and the early 1800s, inventions, discoveries, and theories came fast and furiously. Each new concept broadens the possible areas of application until it becomes almost impossible to trace developments without picking a particular area of interest and following it through. In the review, as you read about the development of radio, television, and computers, keep in mind that similar progressive steps were occurring in the areas of the telegraph, the telephone, power generation, the phonograph, appliances, and so on.

There is a tendency when reading about the great scientists, inventors, and innovators to believe that their contribution was a totally individual effort. In many instances, this was not the case. In fact, many of the great contributors had friends or associates who provided support and encouragement in their efforts to investigate various theories. At the very least, they were aware of one another's efforts to the degree possible in the days when a letter was often the best form of communication. In particular, note the closeness of the dates during periods of rapid development. One contributor seemed to spur on the efforts of the others or possibly provided the key needed to continue with the area of interest.

In the early stages, the contributors were not electrical, electronic, or computer engineers as we know them today. In most cases, they were physicists, chemists, mathematicians, or even philosophers. In addition, they were not from one or two communities of the Old World. The home country of many of the major contributors introduced in the paragraphs to follow is provided to show that almost every established community had some impact on the development of the fundamental laws of electrical circuits.

As you proceed through the remaining chapters of the text, you will find that a number of the units of measurement bear the name of major contributors in those areas—*volt* after Count Alessandro Volta, *ampere* after André Ampère, *ohm* after Georg Ohm, and so forth—fitting recognition for their important contributions to the birth of a major field of study.

Time charts indicating a limited number of major developments are provided in Fig. 1.2, primarily to identify specific periods of rapid development and to reveal how far we have come in the last 40 years. In essence, the current state of the art is a result of efforts that began in earnest some 250 years ago, with progress in the last 100 years being almost exponential.

As you read through the following brief review, try to sense the growing interest in the field and the enthusiasm and excitement that must have accompanied each new revelation. Although you may find some of the terms used in the review new and essentially meaningless, the remaining chapters will explain them thoroughly.

The Beginning

The phenomenon of **static electricity** has intrigued scholars throughout history. The Greeks called the fossil resin substance so often used to demonstrate the effects of static electricity *elektron,* but no extensive study was made of the subject until William Gilbert researched the phenomenon in 1600. In the years to follow, there was a continuing investigation of electrostatic charge by many individuals, such as Otto von

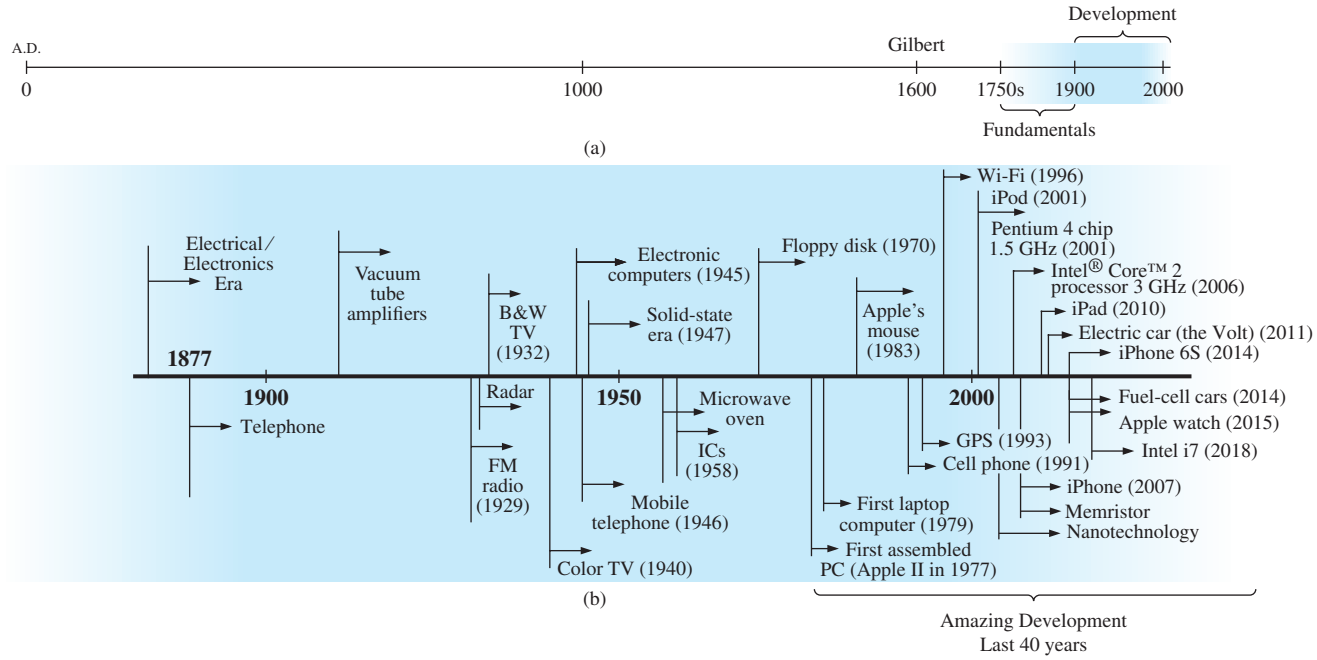

FIG. 1.2
Time charts: (a) long-range, (b) expanded.

Guericke, who developed the first machine to generate large amounts of charge, and Stephen Gray, who was able to transmit electrical charge over long distances on silk threads. Charles DuFay demonstrated that charges either attract or repel each other, leading him to believe that there were two types of charge—a theory we subscribe to today with our defined positive and negative charges.

There are many who believe that the true beginnings of the electrical era lie with the efforts of Pieter van Musschenbroek and Benjamin Franklin. In 1745, van Musschenbroek introduced the **Leyden jar** for the storage of electrical charge (the first capacitor) and demonstrated electrical shock (and therefore the power of this new form of energy). Franklin used the Leyden jar some 7 years later to establish that lightning is simply an electrical discharge, and he expanded on a number of other important theories, including the definition of the two types of charge as *positive* and *negative.* From this point on, new discoveries and theories seemed to occur at an increasing rate as the number of individuals performing research in the area grew.

In 1784, Charles Coulomb demonstrated in Paris that the force between charges is inversely related to the square of the distance between the charges. In 1791, Luigi Galvani, professor of anatomy at the University of Bologna, Italy, performed experiments on the effects of electricity on animal nerves and muscles. The first **voltaic cell**, with its ability to produce electricity through the chemical action of a metal dissolving in an acid, was developed by another Italian, Alessandro Volta, in 1799.

The fever pitch continued into the early 1800s, with Hans Christian Oersted, a Danish professor of physics, announcing in 1820 a relationship between magnetism and electricity that serves as the foundation for the theory of **electromagnetism** as we know it today. In the same year, a French physicist, André Ampère, demonstrated that there are magnetic

effects around every current-carrying conductor and that current-carrying conductors can attract and repel each other just like magnets. In the period 1826 to 1827, a German physicist, Georg Ohm, introduced an important relationship between potential, current, and resistance that we now refer to as *Ohm's law.* In 1831, an English physicist, Michael Faraday, demonstrated his theory of *electromagnetic induction,* whereby a changing current in one coil can induce a changing current in another coil, even though the two coils are not directly connected. Faraday also did extensive work on a storage device he called the condenser, which we refer to today as a *capacitor.* He introduced the idea of adding a dielectric between the plates of a capacitor to increase the storage capacity (Chapter 10). James Clerk Maxwell, a Scottish professor of natural philosophy, performed extensive mathematical analyses to develop what are currently called *Maxwell's equations,* which support the efforts of Faraday linking electric and magnetic effects. Maxwell also developed the *electromagnetic theory of light* in 1862, which, among other things, revealed that electromagnetic waves travel through air at the velocity of light (186,000 miles per second or 3×10^8 meters per second). In 1888, a German physicist, Heinrich Rudolph Hertz, through experimentation with lower-frequency electromagnetic waves (microwaves), substantiated Maxwell's predictions and equations. In the mid-1800s, Gustav Robert Kirchhoff introduced a series of laws of voltages and currents that find application at every level and area of this field (Chapters 5 and 6). In 1895, another German physicist, Wilhelm Röntgen, discovered electromagnetic waves of high frequency, commonly called *X-rays* today.

By the end of the 1800s, a significant number of the fundamental equations, laws, and relationships had been established, and various fields of study, including electricity, electronics, power generation and distribution, and communication systems, started to develop in earnest.

The Age of Electronics

Radio The true beginning of the electronics era is open to debate and is sometimes attributed to efforts by early scientists in applying potentials across evacuated glass envelopes. However, many trace the beginning to Thomas Edison, who added a metallic electrode to the vacuum of the tube and discovered that a current was established between the metal electrode and the filament when a positive voltage was applied to the metal electrode. The phenomenon, demonstrated in 1883, was referred to as the **Edison effect**. In the period to follow, the transmission of radio waves and the development of the radio received widespread attention. In 1887, Heinrich Hertz, in his efforts to verify Maxwell's equations, transmitted radio waves for the first time in his laboratory. In 1896, an Italian scientist, Guglielmo Marconi (often called the father of the radio), demonstrated that telegraph signals could be sent through the air over long distances (2.5 kilometers) using a grounded antenna. In the same year, Aleksandr Popov sent what might have been the first radio message some 300 yards. The message was the name "*Heinrich Hertz*" in respect for Hertz's earlier contributions. In 1901, Marconi established radio communication across the Atlantic.

In 1904, John Ambrose Fleming expanded on the efforts of Edison to develop the first diode, commonly called **Fleming's valve**—actually the first of the *electronic devices.* The device had a profound impact on the design of detectors in the receiving section of radios. In 1906, Lee De Forest added a third element to the vacuum structure and created the

first amplifier, the triode. Shortly thereafter, in 1912, Edwin Armstrong built the first regenerative circuit to improve receiver capabilities and then used the same contribution to develop the first nonmechanical oscillator. By 1915, radio signals were being transmitted across the United States, and in 1918 Armstrong applied for a patent for the superheterodyne circuit employed in virtually every television and radio to permit amplification at one frequency rather than at the full range of incoming signals. The major components of the modern-day radio were now in place, and sales in radios grew from a few million dollars in the early 1920s to over $1 billion by the 1930s. The 1930s were truly the golden years of radio, with a wide range of productions for the listening audience.

Television (TV) The 1930s were also the true beginnings of the television era, although development on the picture tube began in earlier years with Paul Nipkow and his *electrical telescope* in 1884 and John Baird and his long list of successes, including the transmission of television pictures over telephone lines in 1927 and over radio waves in 1928, and simultaneous transmission of pictures and sound in 1930. In 1932, NBC installed the first commercial television antenna on top of the Empire State Building in New York City, and RCA began regular broadcasting in 1939. World War II slowed development and sales, but in the mid-1940s the number of TV sets grew from a few thousand to a few million. Color television became popular in the early 1960s.

Computers The earliest computer system can be traced back to Blaise Pascal in 1642 with his mechanical machine for adding and subtracting numbers. In 1673, Gottfried Wilhelm von Leibniz used the *Leibniz wheel* to add multiplication and division to the range of operations, and in 1823 Charles Babbage developed the **difference engine** to add the mathematical operations of sine, cosine, logarithms, and several others. In the years to follow, improvements were made, but the system remained primarily mechanical until the 1930s when electromechanical systems using components such as relays were introduced. It was not until the 1940s that totally electronic systems became the new wave. It is interesting to note that, even though IBM was formed in 1924, it did not enter the computer industry until 1937. An entirely electronic system known as **ENIAC** was dedicated at the University of Pennsylvania in 1946. It contained 18,000 tubes and weighed 30 tons but was several times faster than most electromechanical systems. Although other vacuum tube systems were built, it was not until the birth of the solid-state era that computer systems experienced a major change in size, speed, and capability.

The Solid-State Era

In 1947, physicists William Shockley, John Bardeen, and Walter H. Brattain of Bell Telephone Laboratories demonstrated the point-contact **transistor** (Fig. 1.3), an amplifier constructed entirely of solid-state materials with no requirement for a vacuum, glass envelope, or heater voltage for the filament. Although reluctant at first due to the vast amount of material available on the design, analysis, and synthesis of tube networks, the industry eventually accepted this new technology as the wave of the future. In 1958, the first **integrated circuit (IC)** chip was developed at Texas Instruments, and in 1961 the first commercial

FIG. 1.3
The first transistor.
SSPL/Getty Images

integrated circuit was manufactured by the Fairchild Corporation. Today some one trillion integrated circuits are manufactured each year.

It is impossible to review properly the entire history of the electrical/electronics field in a few pages. The effort here, both through the discussion and the time graphs in Fig. 1.2, was to reveal the amazing progress of this field in the last 50 years. The growth appears to be truly exponential since the early 1900s, raising the interesting question, Where do we go from here? The time chart suggests that the next few decades will probably contain many important innovative contributions that may cause an even faster growth curve than we are now experiencing.

1.3 UNITS OF MEASUREMENT

One of the most important rules to remember and apply when working in any field of technology is to use the correct units when substituting numbers into an equation. Too often we are so intent on obtaining a numerical solution that we overlook checking the units associated with the numbers being substituted into an equation. Results obtained, therefore, are often meaningless. Consider, for example, the following very fundamental physics equation:

$$\boxed{v = \frac{d}{t}} \qquad \begin{aligned} v &= \text{velocity} \\ d &= \text{distance} \\ t &= \text{time} \end{aligned} \tag{1.1}$$

Assume, for the moment, that the following data are obtained for a moving object:

$$\begin{aligned} d &= 4000 \text{ ft} \\ t &= 1 \text{ min} \end{aligned}$$

and v is desired in miles per hour. Often, without a second thought or consideration, the numerical values are simply substituted into the equation, with the result here that

$$v = \frac{d}{t} = \frac{4000 \text{ ft}}{1 \text{ min}} = \cancel{4000 \text{ mph}}$$

As indicated above, the solution is totally incorrect. If the result is desired in *miles per hour,* the unit of measurement for distance must be *miles,* and that for time, *hours.* In a moment, when the problem is analyzed properly, the extent of the error will demonstrate the importance of ensuring that

the numerical value substituted into an equation must have the unit of measurement specified by the equation.

The next question is normally, How do I convert the distance and time to the proper unit of measurement? A method is presented in Section 1.9 of this chapter, but for now it is given that

$$\begin{aligned} 1 \text{ mi} &= 5280 \text{ ft} \\ 4000 \text{ ft} &= 0.76 \text{ mi} \\ 1 \text{ min} &= \tfrac{1}{60}\text{h} = 0.017 \text{ h} \end{aligned}$$

Substituting into Eq. (1.1), we have

$$v = \frac{d}{t} = \frac{0.76 \text{ mi}}{0.017 \text{ h}} = \mathbf{44.71 \text{ mph}}$$

which is significantly different from the result obtained before.

To complicate the matter further, suppose the distance is given in kilometers, as is now the case on many road signs. First, we must realize that the prefix *kilo* stands for a multiplier of 1000 (to be introduced in Section 1.5), and then we must find the conversion factor between kilometers and miles. If this conversion factor is not readily available, we must be able to make the conversion between units using the conversion factors between meters and feet or inches, as described in Section 1.9.

Before substituting numerical values into an equation, try to mentally establish a reasonable range of solutions for comparison purposes. For instance, if a car travels 4000 ft in 1 min, does it seem reasonable that the speed would be 4000 mph? Obviously not! This self-checking procedure is particularly important in this day of the handheld calculator, when ridiculous results may be accepted simply because they appear on the digital display of the instrument.

Finally,

if a unit of measurement is applicable to a result or piece of data, then it should be applied to the numerical value.

To state that $v = 44.71$ without including the unit of measurement *mph* is meaningless.

Eq. (1.1) is not a difficult one. A simple algebraic manipulation will result in the solution for any one of the three variables. However, in light of the number of questions arising from this equation, the reader may wonder if the difficulty associated with an equation will increase at the same rate as the number of terms in the equation. In the broad sense, this will not be the case. There is, of course, more room for a mathematical error with a more complex equation, but once the proper system of units is chosen and each term properly found in that system, there should be very little added difficulty associated with an equation requiring an increased number of mathematical calculations.

In review, before substituting numerical values into an equation, be absolutely sure of the following:

1. ***Each quantity has the proper unit of measurement as defined by the equation.***
2. ***The proper magnitude of each quantity as determined by the defining equation is substituted.***
3. ***Each quantity is in the same system of units (or as defined by the equation).***
4. ***The magnitude of the result is of a reasonable nature when compared to the level of the substituted quantities.***
5. ***The proper unit of measurement is applied to the result.***

1.4 SYSTEMS OF UNITS

In the past, the *systems of units* most commonly used were the English and metric, as outlined in Table 1.1. Note that while the English system is based on a single standard, the metric is subdivided into two interrelated standards: the **MKS** and the **CGS**. Fundamental quantities of these systems are compared in Table 1.1 along with their abbreviations. The MKS and CGS systems draw their names from the units of measurement used with each system; the MKS system uses *M*eters, *K*ilograms, and *S*econds, while the CGS system uses *C*entimeters, *G*rams, and *S*econds.

TABLE 1.1

Comparison of the English and metric systems of units.

ENGLISH	METRIC		SI
	MKS	CGS	
Length: Yard (yd) (0.914 m)	Meter (m) (39.37 in.) (100 cm)	Centimeter (cm) (2.54 cm = 1 in.)	**Meter (m)**
Mass: **Slug** (14.6 kg)	Kilogram (kg) (1000 g)	Gram (g)	**Kilogram (kg)**
Force: **Pound** (lb) (4.45 N)	Newton (N) (100,000 dynes)	Dyne	**Newton (N)**
Temperature: Fahrenheit (°F) $\left(= \frac{9}{5}°\text{C} + 32\right)$	Celsius or Centigrade (°C) $\left(= \frac{5}{9}(°\text{F} - 32)\right)$	Centigrade (°C)	**Kelvin (K)** $\text{K} = 273.15 + °\text{C}$
Energy: Foot-pound (ft-lb) (1.356 joules)	Newton-meter (N • m) or joule (J) (0.7376 ft-lb)	Dyne-centimeter or erg (1 joule = 10^7 ergs)	**Joule (J)**
Time: Second (s)	Second (s)	Second (s)	**Second (s)**

Understandably, the use of more than one system of units in a world that finds itself continually shrinking in size, due to advanced technical developments in communications and transportation, would introduce unnecessary complications to the basic understanding of any technical data. The need for a standard set of units to be adopted by all nations has become increasingly obvious. The International Bureau of Weights and Measures located at Sèvres, France, has been the host for the General Conference of Weights and Measures, attended by representatives from all nations of the world. In 1960, the General Conference adopted a system called Le Système International d'Unités (International System of Units), which has the international abbreviation **SI**. It was adopted by the Institute of Electrical and Electronic Engineers (IEEE) in 1965 and by the United States of America Standards Institute (USASI) in 1967 as a standard for all scientific and engineering literature.

For comparison, the SI units of measurement and their abbreviations appear in Table 1.1. These abbreviations are those usually applied to each unit of measurement, and they were carefully chosen to be the most effective. Therefore, it is important that they be used whenever applicable to ensure universal understanding. Note the similarities of the SI system to the MKS system. This text uses, whenever possible and practical, all of the major units and abbreviations of the SI system in an effort to support the need for a universal system. Those readers requiring additional information on the SI system should contact the information office of the American Society for Engineering Education (ASEE).*

Fig. 1.4 should help you develop some feeling for the relative magnitudes of the units of measurement of each system of units. Note in the figure the relatively small magnitude of the units of measurement for the CGS system.

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