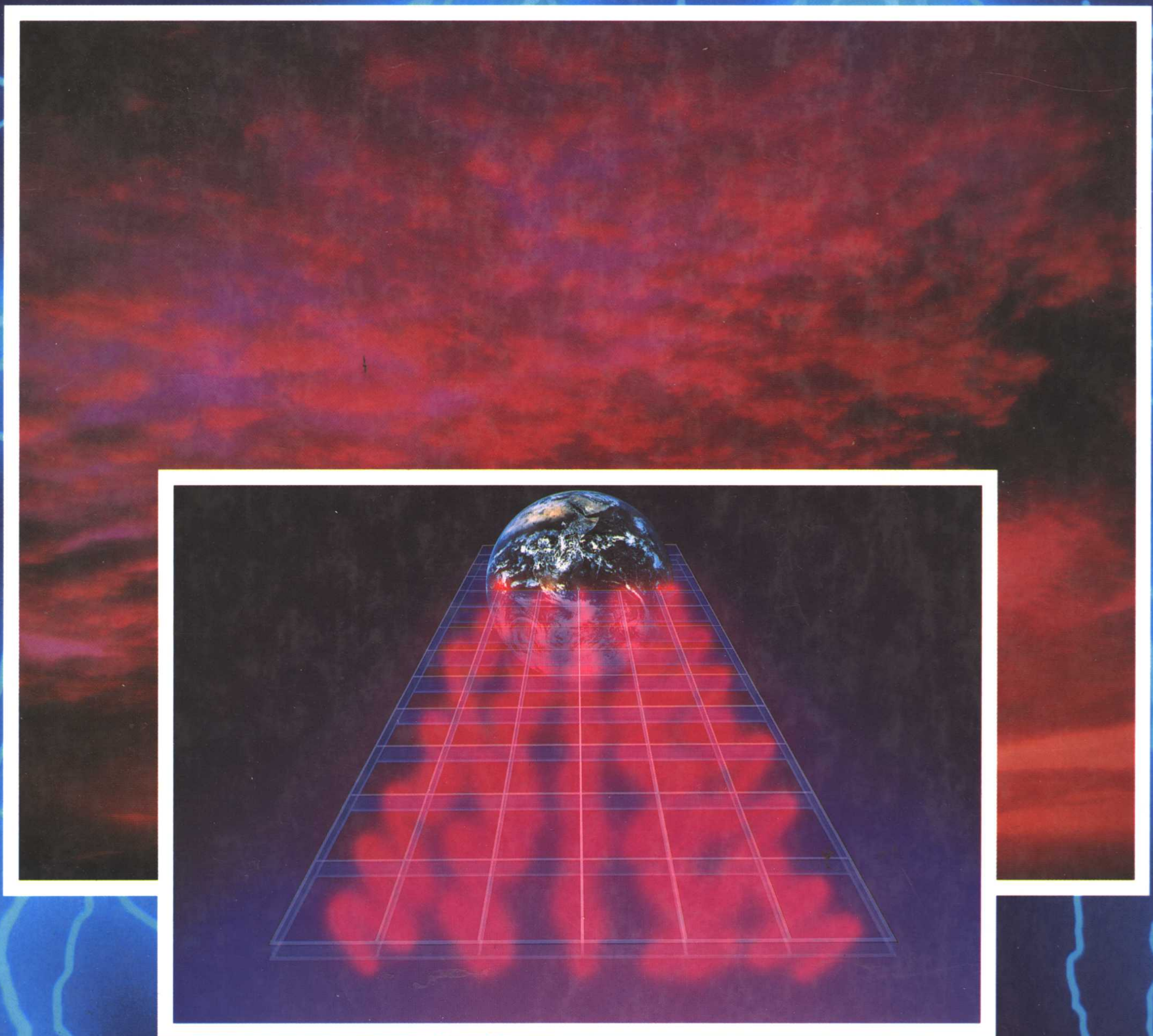
Electric Circuit Analysis

Schuler ▪ Fowler



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Electric Circuit Analysis

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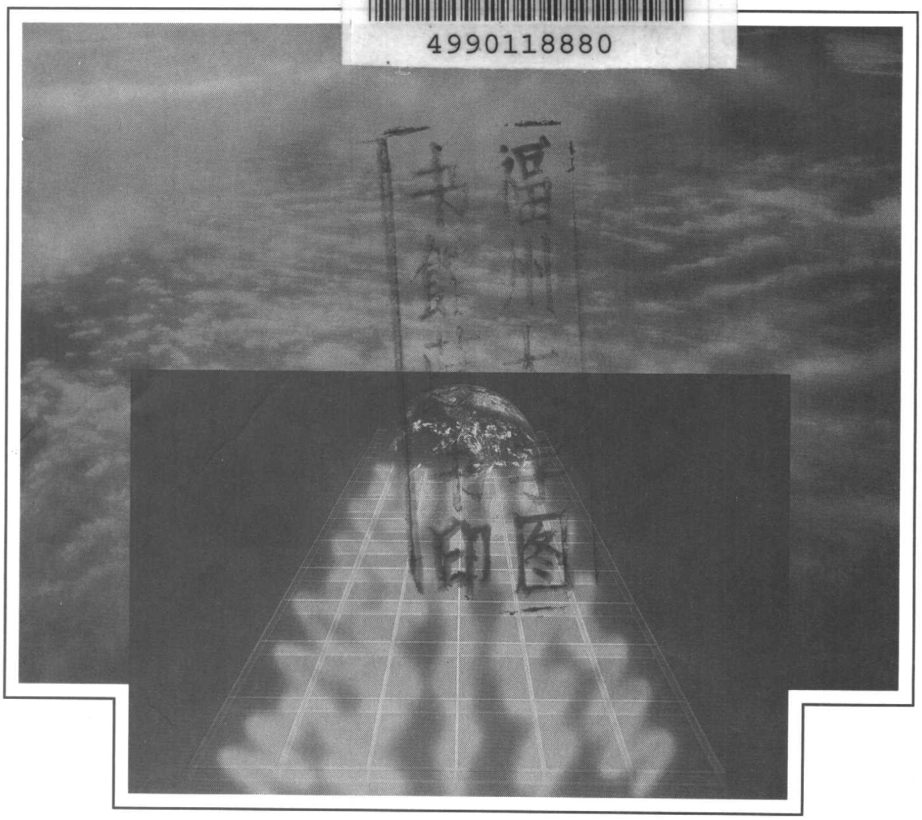

GLENCOE
Macmillan/McGraw-Hill
New York, New York Columbus, Ohio Mission Hills, California Peoria, Illinois

Cover photographs:
Special Effects, Jook Leung/FPG International
Red Sky at Night, Telegraph Colour Library/FPG International
Lightning, Mike and Carol Werner/COMSTOCK, INC.

Library of Congress Cataloging-in-Publication Data

Schuler, Charles A.
Electric circuit analysis / Charles A. Schuler, Richard J. Fowler
; illustrations by Jay D. Helsel.
p. cm.
Rev. ed. of: Basic electricity and electronics.
Includes index.
ISBN 0-02-800442-6
1. Electric engineering. 2. Electronics. 3. Electric circuit
analysis. I. Fowler, Richard J. II. Schuler, Charles A. Basic
electricity and electronics. III. Title.
TK146.S325 1993
621.319'2—dc20 92-22276
CIP

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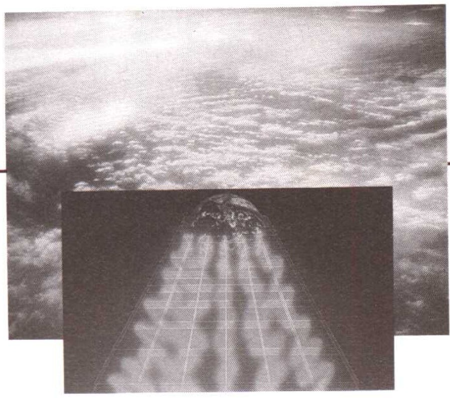
Send all inquiries to:
GLENCOE DIVISION
Macmillan/McGraw-Hill
936 Eastwind Drive
Westerville, OH 43081

ISBN 0-02-800442-6

Printed in the United States of America.

1 2 3 4 5 6 7 8 9 A-HAW 99 98 97 96 95 94 93 92



Preface

This text is designed to be used in introductory courses in electricity and electronics. It provides a thorough coverage of fundamental concepts, dc circuit analysis, and ac circuit analysis. It also introduces both linear and digital electronics. Basic algebra and trigonometry are the only prerequisites.

Students who master dc and ac circuit concepts are in a position to go on to further studies and to enter many technical fields. It is extremely important that beginning students who are preparing for advanced courses and technical careers are exposed to the best possible learning materials.

Electricity is an abstract field. It has its own vocabulary, units of measure, laws, rules, and an ever-expanding myriad of applications. It is often not easy for students to develop a model of how new information applies in a particular case and how the new information relates to what they already have learned. It is essential that the material be presented in a logical format, with smooth transitions from topic to topic. Laws, formulas, and concepts must be carefully intermingled with applications, or they will seem vague to some students and will not be remembered.

The first circuits course is often the most difficult for students. The ideas come too fast, seem to be disconnected, and don't appear to be readily applicable to the student's world. Our job, as authors and teachers, was to make the material as readable, as interesting, and as accurate as possible and to organize it into a logical sequence that was seamless rather than disjointed. Each major topic was carefully developed, with each topic serving as a foundation for subsequent discussions.

Every chapter in this text is divided into major sections, and each of these concludes with a self-test to allow and encourage students to check their progress. The tests reinforce the text material and supports the students' efforts to think about it and apply it.

When techniques are presented, they are immediately followed by illustrative examples that include step-by-step solutions. Each chapter ends with a summary of concepts and equations, review questions, and review problems. A comprehensive glossary appears at the end of the text. Appendix materials are provided with examples of PSpice and MICRO-CAP computer analyses and simulations. An accompanying experiments manual was developed concurrently with this text and is smoothly correlated to it. It provides activities, experiments, and a broad assortment of BASIC programs that can be used and modified by students.

The experiences of many years of classroom teaching are reflected in this work. We have gained much inspiration from the students and colleagues with whom we have been associated over the years. This text is gratefully dedicated to those people. We also wish to acknowledge our families for their support, understanding, and almost infinite patience.

We have taken considerable care to ensure that this text is as error-free and effective as possible. We welcome comments, suggestions, and corrections from both students and instructors.

Charles A. Schuler
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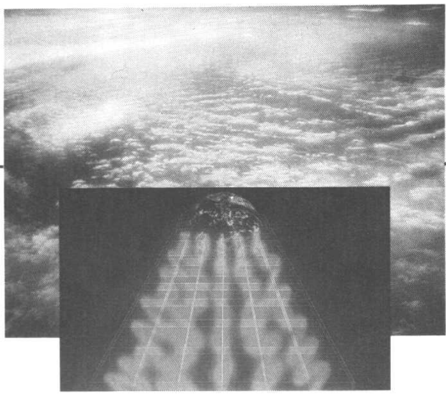

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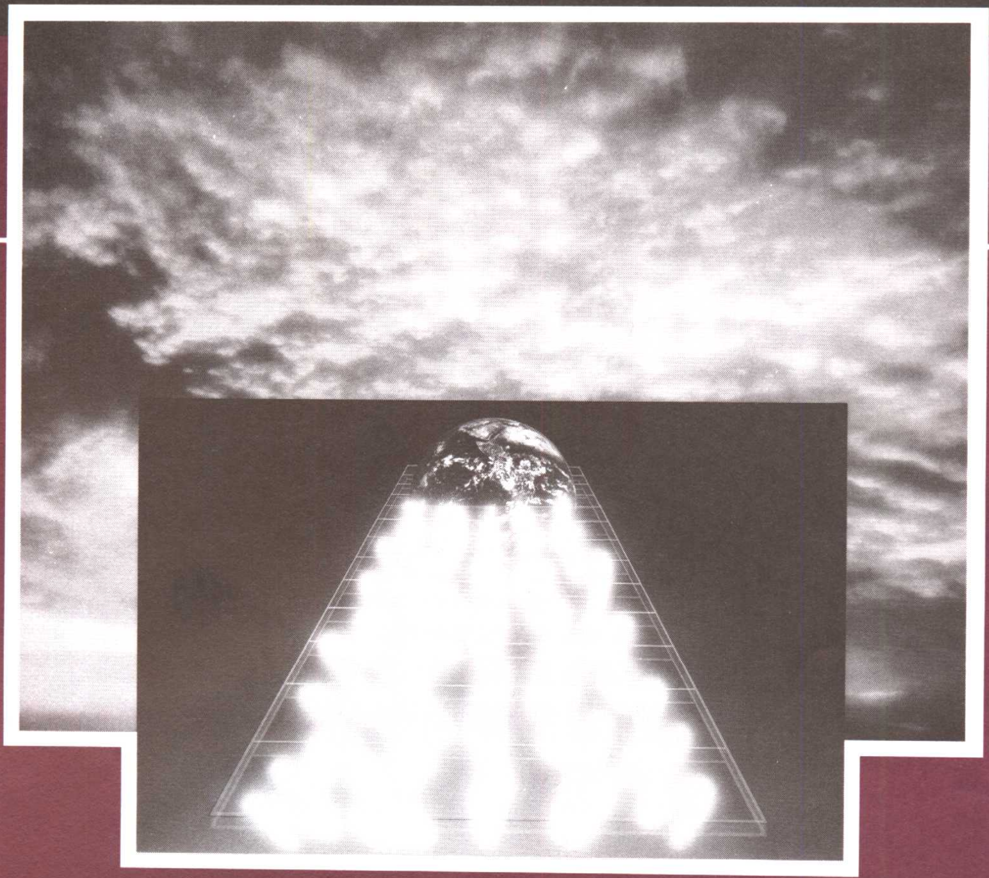

Electricity is a technical subject. As such, it is intimately involved with numbers, equations, calculations, and systems of measurement. This chapter introduces what electricity is and how numbers and measuring units are used to describe its characteristics and behavior.

1-1 SI UNITS

Most of the countries of the world use the metric system of measurement. The metric system offers tremendous advantages because it is almost universal and because the various sized portions of each unit are multiples of 10 when compared to each other and to the base unit. Thus, it is a decimal system and forever eliminates clumsy relationships such as 12 inches (in.) = 1 foot (ft), 3 ft = 1 yard (yd), and 5280 ft = 1 mile (mi).

The international system of units, usually abbreviated SI, was developed from the metric system of measurement in 1960. It is mainly based on the older metric meter-kilogram-second-ampere (mksa) system which uses base units of meters, kilograms, seconds, and amperes. The SI system has become the accepted standard and was officially adopted by the Institute of Electrical and Electronics Engineers (IEEE) in 1965. Therefore, all electrical and electronic measurement should use the SI system. However, there are carryovers from the old English system of measurements. For example, many physical standards used in electronics are derived from the inch. The contacts on an elec-

Chapter 1

Introductory Concepts

tronic component or a circuit board connector are often spaced at inch intervals. Figure 1-1 shows an integrated circuit socket. The contact spacing is based on tenths of inches. Figure 1-2 shows an edge connector for a printed circuit board. The

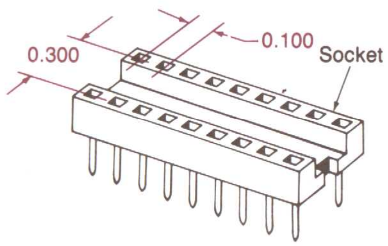

FIGURE 1-1 An integrated circuit socket.

standard contact spacings are specified in inches. It is unreasonable to expect a 100 percent conversion to SI standards in every aspect of electrical and electronic measurements. However, electrical quantities dealing with phenomena such as the flow of electricity, its pressure, and its ability to produce heat are totally based on the SI system.

The SI system is particularly convenient in technical areas where energy calculations are common. This is because only one unit, the joule (J), is used to quantify all types of energy including electric, atomic, chemical, heat, and mechanical. The joule is covered in detail later. Now, thanks to the SI system, electrical specialists can communicate with scientists, mechanical engineers, and chemists without the burden of unique systems of measurements.

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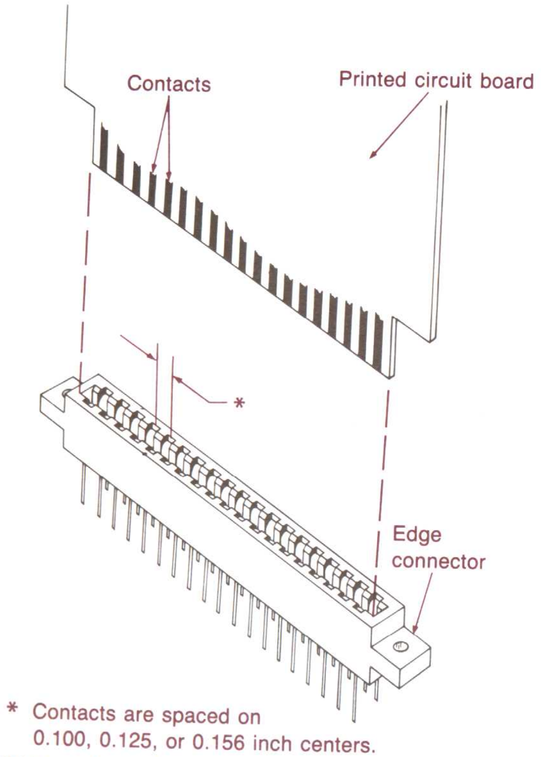

FIGURE 1-2 Printed circuit edge connector.

Table 1-1 is a comparison of the base units among three systems of measurement. The SI system is essentially the same as the metric mksa system, as shown by that column heading. The major difference is that the original mksa system used the Celsius temperature scale. When the SI system was extracted from the mksa system, the Kelvin temperature scale was adopted in favor of the Celsius scale. This deviation from the mksa system is carried into some areas of electricity and electronics. Most manufacturers continue to specify the temperature characteristics of their assemblies and component parts in degrees Celsius even though the IEEE has officially adopted the SI system. On the other hand, the equivalent noise temperature of some electronic devices is specified in degrees Kelvin. The English system is sometimes referred to as the U. S. Customary system. This is because England has officially adopted the SI system as mandatory, while the United States has only recognized the SI system and not officially mandated it. The centimeter-gram-second (cgs) system is also metric. It is convenient for measurements in small-scale systems since it is based on smaller base units of length and mass.

Base units, such as those found in Table 1-1, are the foundation for all measurements. In mechanics, all additional units can be derived from three base units which are length, mass, and time. By adding a base unit for electric current flow, the additional units needed for measurements in electricity can be derived. When the base units of temperature, luminous intensity, and amount of substance are added, any and all scientific and technical units for any type of measurement may be derived.

Table 1-2 shows examples of derived SI units. Area and volume are derived from the base unit of length. Velocity and acceleration are derived from

Table 1-1 A Comparison of Base Units

Quantity	SI, mksa	English (U.S. Customary)	cgs
Length	Meter, m = 100 cm	Foot, ft =0.3048 m	Centimeter, cm 2.54 cm = 1 in
Mass	Kilogram, kg =1000 g	Slug =14.6 kg	Gram, g
Time	Second, s	Second	Second
Electric current	Ampere, A	Ampere	Ampere
Temperature	Kelvin, K =273.15 + °C	Fahrenheit, F $=(\frac{9}{5}\,°C) + 32$	Celsius, C $=\frac{5}{9}\,(°F - 32)$
Luminous intensity	Candela, cd		
Amount of substance	Mole, mol		

Table 1-2 Examples of Derived SI Units

Quantity	Derivation	Units
Area	Length × width	Square meters, m^2
Volume	Length × width × height	Cubic meters, m^3
Velocity	Distance/time	Meters per second, m/s
Acceleration	Distance/time/time	Meters per second per second, m/s^2
Force	Mass × acceleration	Newtons (kilograms × m/s^2), kg × m/s^2
Energy and work	Force × distance	Joules (newtons × meters), N × m
Power	Energy/time	Watts (joules per second), J/s
Pressure	Force/area	Pascals (newtons per m^2), N/m^2
Electric charge	Current × time	Coulombs (amperes × seconds), A × s
Electric potential	Energy/charge	Volts (joules per coulomb), J/C
Electric resistance	Potential/current	Ohms (volts per ampere), V/A
Capacitance	Charge/potential	Farads (coulombs per volt), C/V
Inductance	Potential/current/time	Henrys (volts per ampere per second), V/A/s

the base units of distance (length) and time. Force is derived from mass (a base unit) and from acceleration (a derived unit). Energy (or work) is derived from force and distance. Obviously, derived units can be used to derive additional units. Several of the derived units in Table 1-2 deal with electrical quantities. These units are explained and applied later.

The base units are arbitrary. They have evolved over years of scientific work and investigations into natural phenomena. The meter was originally defined as one ten-millionth of the distance, at sea level, from either pole to the equator. Later, the meter was defined as 1,650,763.73 wavelengths, in a vacuum, of the krypton 86 atom. The most recent definition of the meter is the distance light travels in a vacuum during 1/299,792,458 of a second. Scientific and technical work must be repeatable, even at independent locations. A unified measurement system is one of the key elements for achieving repeatability.

Since the U. S. Customary system of units will likely remain in existence for the foreseeable future, people who work in technical areas will continue to be faced with making conversions from one system to another.

EXAMPLE 1-1

The front panel of an electric control device is 3 in. high and 7.5 in. wide. What are its dimensions in centimeters? What is its area in square centimeters?

Solution

Table 1-1 shows that 1 in. is equal to 2.54 cm. Therefore, the inch dimensions can be converted to centimeter dimensions by multiplying them by 2.54.

$$3 \text{ in.} \times 2.54 \text{ cm/in.} = 7.62 \text{ cm}$$
$$7.5 \text{ in.} \times 2.54 \text{ cm/in.} = 19.05 \text{ cm}$$

Note that the inch units cancel, leaving the answers in centimeter units. The area is now found by

$$7.62 \text{ cm} \times 19.05 \text{ cm} = 145.16 \text{ cm}^2$$

EXAMPLE 1-2

The upper temperature limit of an electronic computer is specified as being 323.15 K. Convert this to degrees Celsius and also to degrees Fahrenheit.

Solution

Table 1-1 shows that the Kelvin temperature is found by adding 273.15 to the Celsius temperature. Therefore, the Celsius temperature may be derived by subtracting 273.15 from the Kelvin value.

$$323.15 - 273.15 = 50° \text{ C}$$

The Fahrenheit temperature can now be found by

$$\left(\frac{9}{5} \times 50\right) + 32 = 122° \text{ F}$$

Self-Test

1. Which system of measurement has been officially adopted by the IEEE?
2. There are carryovers from older systems of measurement. For example, the spacings of component and circuit board connectors are often measured in ______.
3. Identify the two units of temperature measurement most often used in electricity and electronics.
4. Which metric system favors measurements for small-scale systems?
5. Identify the SI base units that are used to derive the additional units needed in electricity.
6. The performance of electronic components is often specified at 25° C. Convert this temperature to degrees Fahrenheit.
7. A circuit board is 12 cm × 8 cm. What are the board's measurements in inches?

1-2 SCIENTIFIC NOTATION

The numbers used in electricity range from very small to very large. It is quite cumbersome to write, speak, and manipulate very small and very large numbers. A *power-of-ten notation system* is widely used to represent such numbers and to greatly lessen the burden of working with them. As the following list shows, 10 is the *base:*

10^{-6} = 0.000001 = one-millionth
10^{-5} = 0.00001 = one hundred-thousandth
10^{-4} = 0.0001 = one ten-thousandth
10^{-3} = 0.001 = one-thousandth
10^{-2} = 0.01 = one-hundredth
10^{-1} = 0.1 = one-tenth
10^{0} = 1 = one
10^{1} = 10 = ten
10^{2} = 100 = hundred
10^{3} = 1000 = thousand
10^{4} = 10,000 = ten thousand
10^{5} = 100,000 = hundred thousand
10^{6} = 1,000,000 = million

Expressing numbers in powers of 10 with one nonzero digit to the left of the decimal point is called *scientific notation.* For example, to convert 0.00000483 to scientific notation, first change the number so that it has one nonzero digit to the left of the decimal point. This involves moving the decimal point six places to the right as shown below (an asterisk is used to mark the original position of the decimal point):

0*000004.83

Now, the number must be multiplied by some power of 10 to restore the number to its original value. When the decimal point is moved to the left, the required power of 10 is positive. When the decimal point is moved to the right, the required power of 10 is negative. The example moved the decimal point six places to the right, so the power of 10 (also called the exponent) is negative 6, producing the scientific notation:

4.83×10^{-6} which is equal to 0.00000483

Suppose we wish to express 483,000 using scientific notation. First, we convert the number so it has one digit to the left of the decimal. This is shown below and again an asterisk is used to show the original location of the decimal point:

4.83000 *

The decimal point had to be moved five places to the left. Therefore, the power of 10 is +5, and the scientific notation for 483,000 is

$4.83 \times 10^{+5}$ or, more commonly, 4.83×10^{5}

Exponents without a minus sign are understood to be positive.

EXAMPLE 1-3

Change the following numbers to scientific notation:

12,720,000
0.000023
628
0.5
13,900
1.83

Solution

$12{,}720{,}000 = 1.272 \times 10^{7}$
$0.000023 = 2.3 \times 10^{-5}$
$628 = 6.28 \times 10^{2}$
$0.5 = 5 \times 10^{-1}$
$13{,}900 = 1.39 \times 10^{4}$
$1.83 = 1.83 \times 10^{0}$ (10^{0} *is not normally used)*
(1.83 is the scientific notation)

EXAMPLE 1-4
Convert the following numbers to standard form:

1×10^9
4.56×10^{-3}
9.871×10^5
3.9×10^{-7}

Solution
To convert from scientific notation, the power of 10 must be eliminated. Move the decimal point to the right for positive exponents and to the left for negative exponents.

$$1 \times 10^9 = 1,000,000,000$$
$$4.56 \times 10^{-3} = 0.00456$$
$$9.871 \times 10^5 = 987,100$$
$$3.9 \times 10^{-7} = 0.00000039$$

The exponents must be handled properly when arithmetic operations are performed with scientific notation. The following rules for exponents apply:

1. To perform addition or subtraction, all numbers must have the same exponent (magnitude and sign). The columns must be aligned according to the decimal points. The sum or the difference will have the same exponent as the numbers being added.
2. To perform multiplication, the exponents are added.
3. To perform division, the exponent of the divisor is subtracted from the exponent of the dividend.
4. To extract a root, the exponent is divided by the root.
5. To raise to a power, the exponent is multiplied by the power.

EXAMPLE 1-5
Add 2.1×10^3, 3.68×10^2, and 4×10^{-1}.

Solution
Make the necessary conversions so that all of the numbers are multiplied by the same power of 10. In this case, it is convenient to use 10^3 since it is the largest power and the answer will be in scientific notation:

$$\begin{array}{r} 2.1 \times 10^3 \\ +0.368 \times 10^3 \\ +0.0004 \times 10^3 \\ \hline 2.4684 \times 10^3 \end{array}$$

Note that the columns are aligned according to the decimal points and that the answer is multiplied by the same power of 10.

EXAMPLE 1-6
Subtract 4.5×10^4 from 1×10^5.

Solution
Once again, we choose the largest power of 10 as the common exponent:

$$\begin{array}{r} 1.00 \times 10^5 \\ -0.45 \times 10^5 \\ \hline 0.55 \times 10^5 \end{array}$$

Notice that the answer is not in scientific notation. It would have been better to use 10^4 as the common exponent. All is not lost, however. It is a simple matter to move the decimal point of the answer one place to the right and make the exponent one digit smaller:

$$0.55 \times 10^5 = 5.5 \times 10^4$$

EXAMPLE 1-7
Perform the following multiplications and express the answers in scientific notation:

$(3.5 \times 10^2) \times (2.1 \times 10^4)$
$(5.1 \times 10^3) \times (4.8 \times 10^{-5})$
$(1.9 \times 10^{-1}) \times (3 \times 10^{-3})$

Solution
For the first multiplication problem, $3.5 \times 2.1 = 7.35$ and the sum of the exponents is 6. Therefore, the answer is 7.35×10^6. For the second problem, $5.1 \times 4.8 = 24.48$ and the sum of the exponents is 10^{-2}. This gives us 24.48×10^{-2}, which is not scientific notation. Shifting the decimal one place to the left and making the exponent one digit larger yields 2.448×10^{-1}. In the last multiplication problem, $1.9 \times 3 = 5.7$ and the sum of the exponents is -4, which produces an answer of 5.7×10^{-4}.

$$3.5 \times 10^2 \times 2.1 \times 10^4 = 7.35 \times 10^6$$
$$5.1 \times 10^3 \times 4.8 \times 10^{-5} = 2.448 \times 10^{-1}$$
$$1.9 \times 10^{-1} \times 3 \times 10^{-3} = 5.7 \times 10^{-4}$$

EXAMPLE 1-8
Perform the following divisions and express the answers using scientific notation:

$$\frac{4.3 \times 10^5}{8.6 \times 10^3}$$

$$\frac{9.9 \times 10^2}{3 \times 10^{-2}}$$

$$\frac{-5 \times 10^{-2}}{2 \times 10^{-3}}$$

Solution
In the first problem, dividing 4.3 by 8.6 gives 0.5, and subtracting the exponent of the divisor from the exponent of the dividend gives 2 for a result of 0.5×10^2, or 5×10^1 in scientific notation. In the second problem, dividing 9.9 by 3 gives 3.3, and subtracting exponents produces a positive 4 since $+2 - (-2) = +4$. The answer is therefore 3.3×10^4. For the last division problem, dividing -5 by 2 yields -2.5, and subtracting the exponents gives $+1$ for an answer of -2.5×10^1.

$$\frac{4.3 \times 10^5}{8.6 \times 10^3} = 5 \times 10^1$$

$$\frac{9.9 \times 10^2}{3 \times 10^{-2}} = 3.3 \times 10^4$$

$$\frac{-5 \times 10^{-2}}{2 \times 10^{-3}} = -2.5 \times 10^1$$

EXAMPLE 1-9
Find the square root of 3.6×10^5.

Solution
To find a square root, it is necessary to divide the exponent by 2. An exponent of 5 will not produce an integer (whole number) result. Therefore, it is best to change the number to an even power of 10. For example, 36×10^4 is equivalent and the exponent is now evenly divisible by 2. The square root of 36 is 6 and $\frac{4}{2} = 2$, which gives an answer of 6×10^2.

EXAMPLE 1-10
Raise 4×10^2 to the third power.

Solution
The example can be written as $4^3 \times (10^2)^3$. $4 \times 4 \times 4 = 64$ and $2 \times 3 = 6$ for a result of 64×10^6. Converting to scientific notation gives 6.4×10^7.

Self-Test

8. Change these numbers to scientific notation:

186,000	0.154
0.0003	1,200,000,000
357.2	0.0000000005

9. Change these numbers to standard form:

4.9×10^2	2×10^{-1}
1.1×10^{-3}	5.5×10^4
5.678×10^5	1.9×10^{-4}

10. Perform the following additions and express the answers using scientific notation:

$(5.5 \times 10^1) + (1.7 \times 10^2)$
$(3.83 \times 10^1) + (2 \times 10^{-1})$
$(2 \times 10^4) + (3 \times 10^3) + (4 \times 10^2)$

11. Perform the following subtractions and express the answers using scientific notation:

$(4.4 \times 10^{-2}) - (4)$
$(7.65 \times 10^3) - (-1.2 \times 10^2)$
$(-4 \times 10^{-5}) - (2.2 \times 10^{-6})$

12. Perform the following multiplications and express the answers using scientific notation:

$(5 \times 10^2) \times (2.6 \times 10^{-3})$
$(3.32 \times 10^{-2}) \times (1 \times 10^3)$
$(4.4 \times 10^6) \times (8 \times 10^5)$

13. Perform the following divisions and express the answers using scientific notation:

$\frac{6.6 \times 10^9}{3 \times 10^6}$ $\frac{1.71 \times 10^5}{4.5 \times 10^{-2}}$

$\frac{9 \times 10^{-6}}{2 \times 10^4}$

14. Take the square root of 8.1×10^3.

15. Raise 2×10^2 to the fourth power.

1-3 PREFIXES

Electrical quantities vary considerably in magnitude. Prefixes are used to modify measuring units by making them multiple or submultiple units. A multiple unit is larger than a nonmodified unit and a submultiple unit is smaller. In the SI system, the prefixes are arranged in increments of three powers of 10 as shown in Table 1-3. The SI system does

Table 1-3 Prefixes

Prefix	Multiple-Submultiple	Power-of-10 Form	SI Symbol
Giga	1,000,000,000	10^9	G
Mega	1,000,000	10^6	M
Kilo	1000	10^3	k
Milli	0.001	10^{-3}	m
Micro	0.000001	10^{-6}	μ
Nano	0.000000001	10^{-9}	n
Pico	0.000000000001	10^{-12}	p

not recognize the older metric prefixes of deca (10^1) and centi (10^{-2}), and these prefixes are not used with electrical units.

If a prefix is added to a unit, a new unit is effectively formed. When a multiple or submultiple unit is raised to a power, the power applies to the new unit and not to the original unit. As an example, a millimeter (mm) is a unit that equals one-thousandth of a meter. The area of a small surface may be measured in square millimeters. Note that $10\ mm^2 = 10\ (mm)^2$ and does not equal $10\ m(m^2)$.

Prefixes can be used to avoid using numbers smaller than 0.1 or greater than 1000. As an example, if a current flow is 0.004 ampere, it is often expressed in terms of *milliamperes* to avoid using a number smaller than 0.1. As another example, a value such as 1500 watts can be expressed in *kilowatts* to avoid the use of a number greater than 1000.

EXAMPLE 1-11

Convert 0.004 ampere to milliamperes and determine how it would be written in abbreviated form. How would it be written using scientific notation?

Solution

Table 1-3 shows that the prefix milli is a submultiple and represents 0.001 or 10^{-3}. When a measurement unit is converted to a submultiple or smaller unit by the use of a prefix, the number must become larger. The relationship in this case is three decimal places. Therefore, amperes are converted to milliamperes by moving the decimal point three places to the right:

$$0.004 \text{ ampere} = 4 \text{ milliamperes}$$

Table 1-3 shows that the prefixes, with the exception of giga and mega, are symbolized with lowercase letters. A current of 4 milliamperes is abbreviated as 4 mA. Using scientific notation, the current would be expressed as 4×10^{-3} ampere or 4×10^{-3} A. Note that abbreviations are not pluralized by adding an "s" even though they are often pronounced or written as plurals. Lowercase "s" is the SI symbol for the second and would cause confusion if used.

EXAMPLE 1-12

Convert 0.000004 ampere to microamperes and to scientific notation.

Solution

Once again, the conversion is from a unit to a submultiple (a smaller unit). In this case, the decimal point must be moved six places to the right:

$$0.000004 \text{ ampere} = 4 \text{ microamperes } (4\ \mu A)$$

Using scientific notation, the current would be expressed as 4×10^{-6} A.

EXAMPLE 1-13

Convert 3400 amperes to kiloamperes and to scientific notation.

Solution

This involves changing from a unit to a multiple unit (to a larger unit). The decimal point must be moved three places to the left.

$$3400 \text{ amperes} = 3.4 \text{ kiloamperes } (3.4\ kA)$$

Using scientific notation, the current would be expressed as 3.4×10^3 A.

Thus far, the examples have produced agreement between scientific notation and the multiple and submultiple units. This is not always the case. For example, a current of 25 μA could be written as 25×10^{-6} A, which is not in scientific notation. It could be converted to 2.5×10^{-5} A, but there is no submultiple unit to represent 10^{-5}. Both representations are correct. However, the method preferred by electrical engineers and technicians is to use the units shown in Table 1-3 when possible. In this system, 25 μA is preferred over 2.5×10^{-5} A. The system of recording values in terms of the multiple units and submultiple units given in Table 1-3 is known as *engineering notation*. As can be seen from this table, engineering notation uses powers

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