CDC 3C251A

Communications-Computer Systems Control Journeyman

Volume 1. Founding Principles of Communications Electronics

Extension Course Institute

Air Education and Training Command

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Material in this volume is reviewed annually for technical accuracy, adequacy, and currency. For SKT purposes the examinee should check the *Weighted Airman Promotion System Catalog* to determine the correct references to study.

BECAUSE OF its length, the 3C251 CDC is presented as a two-part publication—3C251A and 3C251B. This allows you to pace yourself through the course and better understand the lessons as they are presented. Lessons build on one another to fulfill requirements of the Specialty Training Standard (STS). You need a thorough understanding and knowledge of one lesson before proceeding to the next. This form of instruction also applies as you progress from one volume to the next.

The first volume of CDC 3C251A deals with the mathematical and electronic fundamentals needed by systems controllers. Many of the subjects discussed are a review and expansion of the electronic principles you learned in technical school. As our career field expands to include minor maintenance responsibilities and management and control of functions in Base Central Test Facilities (BCTF) and Base Network Control Centers (BNCC), our electronic foundations must be sound to better identify circuit and network characteristics during troubleshooting activities.

Unit 1 is a review of basic arithmetic operations and the different types of numbering systems used in electronic communications. These fundamentals are used or referred to extensively throughout the remaining volumes of the 3C251A and 3C251B courses.

Units 2 and 3 present material on fundamental electronics and solid-state devices that serves as a foundation for later volumes.

The second volume of 3C251A covers the principles of electronic soldering and the maintenance and care of electrical connectors. The third volume is a study of modulation, multiplexing, and digital signaling techniques. In the fourth volume, we cover the fundamentals of digital communications networks and data processing techniques.

Foldouts 1 through 3 are bound in the back of this volume. Use them as the text directs.

The glossary supplement for the CDC includes terms used in this volume. This allows you to simultaneously refer to terms used throughout the text and reduce the time you might spend skimming for definitions of previously covered items.

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To get an *immediate response* to your questions concerning subject matter in this course, call the author at DSN 597-5161 or E-mail: bearden@kee3b201.kee.aetc.af.mil between 0700 and 1600 (CT), Monday through Friday. Otherwise, write the author at 335 TRS/TTMQEA, ATTN: MSgt Timothy L. Bearden, 600 Hangar Road, to point out technical errors you find in the text, Unit Review Exercises, or Course Examination. Sending subject matter questions to ECI slows the response time.

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This volume is valued at 27 hours (9 points).

NOTE:

In this volume, the subject matter is divided into self-contained units. A unit menu begins each unit, identifying the lesson headings and numbers. After reading the unit menu page and unit introduction, study the section, answer the self-test questions, and compare your answers with those given at the end of the unit. Then do the Unit Review Exercises (UREs).

Unit 1. Relating Mathematics and Communications

Nearly everything going on in today's world has something to do with numbers. Think for a moment how often you use numbers just in normal conversation. What time is it? How far out was he when he shot the three pointer? How much will I have left of my paycheck after the bills are paid? As you can see, numbers are very important to us. If you don't believe it, try going through a checkout stand at a super market without thinking about how much money's in your checking account. You'll find out real quickly how important understanding numbers can be to you. The same goes for communications.

Numbers are what we use to measure how far voice can travel through different types of media, how long it takes to get there, and what is the quality of it once it arrives. Even your home computer or pocket calculator is designed on the basis of logic circuits utilizing certain types of numbering systems.

Many different types of numbering systems are used in electronic-communications and computer systems, but the most common are binary, octal, hexadecimal, and binary coded systems. Some use only one numbering system while others may use a combination of two or more. In this unit, we review some of your basic mathematical skills and learn how to apply them to some of these other types of numbering systems. By the end of this section, you will be able to add, subtract, and perform conversions using any of these numbering systems. You will also learn how to speak with numbers using metric notations and how to apply algebra and logarithms to communications.

1-1. Metric Notation and the Decimal Numbering System

Of all the numbering systems in existence, we are most familiar with the decimal numbering system because we use it every day. Many of its rules and terminology are associated with the other numbering systems we will be studying.

001. Rediscovering the decimal numbering system

In this section, we review decimal fundamentals and use them as a foundation for discussing the other types of numbering systems discussed later in this volume. Metric notation is also covered as it is based upon the decimal system.

Decimal basics. You should recall that the decimal numbering system is comprised of ten different basic symbols (0,1,2,3,4,5,6,7,8, and 9) called digits. When using these digits to represent any number larger than nine, you must employ the use of something called a PLACE VALUE. PLACE simply means the position a digit holds in relation to the decimal point. This position, or PLACE, also determines how many times the digit is multiplied by powers of ten to determine its VALUE. Figure 1-1 gives you a graphical representation of how place value works, using the number 3 as an example. As you can see, progressively moving the PLACE of the digit from right to left has the same effect as multiplying it by the number ten. Hence, in the decimal system, PLACE represents the power of ten by which a digit is multiplied. Let's quickly review POWERS OF TEN.

MILLIONS 10^6	HUNDRED THOUSANDS 10^5	TEN THOUSANDS 10^4	THOUSANDS 10^3	HUNDREDS 10^2	TENS 10^1	UNITS 10^0	
						3	= 3
					3		= 30
				3			= 300
			3				= 3,000
		3					= 30,000
	3						= 300,000

Figure 1-1. Decimal PLACE values.

Powers of ten. The powers of ten are written as 10^0, 10^1, 10^2, 10^4, etc., where: 10^0 is 1, 10^1 is 10x1 or 10, 10^2 is 10x10 or 100, 10^3 is 10x10x10 or 1000, and so forth. In the expression 10^4, the number 10 is referred to as the BASE and the number 4 is called the EXPONENT. The exponent tells you how many times to use the base as a factor. When speaking in powers of ten, the number 10^3 would read as "ten to the third power." Powers of ten are also illustrated in figure 1-1. Another way to expand a number to show PLACE VALUE, and powers of ten is given in the following example:

4321

Where:

$$\begin{array}{lllllll} 1 & = & 1\text{x}10^0 & = & 1\text{x}1 & = & 1 \\ 2 & = & 2\text{x}10^1 & = & 2\text{x}10 & = & 20 \\ 3 & = & 3\text{x}10^2 & = & 3\text{x}100 & = & 300 \\ 4 & = & 4\text{x}10^3 & = & 4\text{x}1000 & = & \underline{+4000} \\ & & & & & = & 4321_{10} \end{array}$$

Not all decimal numbers are whole numbers. Some, like the number 987.64_{10}, have parts on either side of the decimal point. The example, when broken down, would be interpreted like this:

987	=	Integral portion
64	=	Fractional portion
.	=	Decimal point

4	=	LSD (Least significant digit)
9	=	MSD (Most significant digit)
10	=	Radix

The integral portion (987) is to the left of the decimal point; the fractional portion (64) is to the right of the decimal point; the LSD (4) has the least value and the MSD (9) has the greatest value because of their positions in relation to the decimal point. The radix (10) identifies which numbering system is being used and is expressed as a subscript to a number. Normally, the radix is not used with the decimal system because it is generally accepted to be "10" if no radix is given.

The fractional portion is so called because, when broken down, it represents a number less than one. The digits to the right of the decimal point also carry a negative exponent. The decimal fraction PLACE values are better described in the following example:

.654

Where:

$$4 = 4x10^{-3} = 4x\frac{1}{1000} = \frac{4}{1000} = .004 \quad \text{and}$$

$$5 = 5x10^{-2} = 5x\frac{1}{100} = \frac{5}{100} = .050 \quad \text{and}$$

$$6 = 6x10^{-1} = 6x\frac{1}{10} = \frac{6}{10} = \underline{.600}$$

$$.654_{10}$$

As useful as the decimal numbering system is with its place values, exponents, and fractional portions, it would be very cumbersome to write or speak of large decimal numbers with plain language. If you had to say or write the number 1,900,000,000 it would sound and look like, "one billion, nine-hundred million." Or you could try this one, .00006, "six one-hundred-thousandths." This would get awkward after a while, wouldn't it? Luckily, someone came up with the idea of using an easier method called "metric notation", and that's what we're getting into next.

002. Metric notation

Scientific notation lets you keep a fixed decimal point in all of your calculations, regardless of the size of the numbers.

Powers, exponents, and scientific notation. Calculations often consist of unwieldy numbers and decimal fractions that can cause error by misplacing a decimal point, accidentally leaving out a number, or by adding extra zeros. For instance, take a look at the following example:

$$Ratio = \frac{\cancel{0.00}1}{\cancel{0.00}0,000,000,001}$$ 1,000,000,000 x 1 = 1 billion

Narratively speaking, the ratio is a billion to one, or 1,000,000,000:1. Although this particular expression is not too difficult, you can see how easily it would be to add or leave out a zero, thereby changing the intended result. Rather than using all of the zeros, you can write the same problem using scientific notation, like this:

$$Ratio = \frac{1x10^{-3}}{1x10^{-12}} = 1x10^{9}$$

Now, isn't this way a lot easier? It leaves less room for error and makes large numbers easier to handle.

Exponents show the power to which a quantity is raised, or in simpler terms, how many times the quantity (base) is multiplied by itself. For example, 4^3 is read as "four to the third power" and means 4x4x4.

As stated in the first lesson, ten is the most common base number used in calculations. When this is done, the system used is called "powers of ten". In this system, a whole or mixed number is expressed as the product of a factor (usually a number less than ten) and a positive or negative exponent, whichever is appropriate.

Example:

$$0.004 = 4.0x10^{-3}$$

To convert a decimal number to a power of ten expression, first, find the factor by moving the decimal point the required number of places to the left. Then, write the multiplication sign, followed by the number 10 with the exponent. The value of the exponent of 10 is equal to the number of places you moved the decimal point.

Example:

$$300,000,000 = 3.0x10^{8}$$

When you convert a decimal fraction to a power of ten expression, find the factor by moving the decimal point the required number of places to the right, add the multiplication symbol and the number 10 with a negative exponent.

Example:

$$0.000,000,049 = 4.9x10^{-8}$$

You can clearly see the advantages of using exponents, but when you do use them, certain rules must be followed:

- When multiplying numbers, algebraically add the exponents.
- When dividing numbers, algebraically subtract the exponents.

- Using a zero exponent with any base number is always equal to 1.
- A quantity raised to a negative power is equal to the reciprocal of that quantity of the same number, only positive.

That last rule is probably about as clear as mud. To express it as a formula, it would look like:

$$a^{-n} = \frac{1}{a^n}$$

Let's use this rule in a scenario. If a=10 and n=3, then a^{-n} would be 10^{-3}. Now, by applying the rule you get:

$$10^{-3} = \frac{1}{10^3} = \frac{1}{1000} = 0.001$$

It's just that easy as long as you follow the basic rules.

Metric prefixes. Earlier we said powers of ten are multipliers. Writing numbers using powers of ten is a lot easier than writing them without it, but there's an even easier way to do it called "metric notation". In this system, certain prefixes are assigned to numbers to symbolize their meaning. In communications, we use these prefixes with units of measurement to simplify expressions and calculations. For example, instead of saying five million Hertz (5,000,000 Hz), or five times ten to the sixth power Hertz (5×10^6 Hz), we use the metric prefix (mega). In this example, five million Hertz becomes five megahertz or 5 MHz.

If you need to change from one metric multiple to another, you merely move the decimal point left or right and affix the new metric prefix. Thus, you can change 5 MHz to 5,000 kilohertz (5000 kHz).

Table 1-1 is a metric conversion table showing powers of ten as multipliers and their corresponding metric prefixes and symbols. Feel free to refer to it as often as you wish. The more you use metric notation, the easier it gets.

So far we've refreshed our knowledge of the decimal system and some of the easier ways to represent its uses. Our next lessons involve how we use the decimal system to measure values in electronic communications.

MULTIPLIER	PREFIX	SYMBOL	NUMBER		MULTIPLIER
10^{12}	tera	T	1,000,000,000,000	=	10^{12}
10^{11}			100,000,000,000	=	10^{11}
10^{10}			10,000,000,000	=	10^{10}
10^{9}	giga	G	1,000,000,000	=	10^{9}
10^{8}			100,000,000	=	10^{8}
10^{7}			10,000,000	=	10^{7}
10^{6}	mega	M	1,000,000	=	10^{6}
10^{5}			100,000	=	10^{5}
10^{4}	myria	my	10,000	=	10^{4}
10^{3}	kilo	k	1,000	=	10^{3}
10^{2}	hecto	h	100	=	10^{2}
10^{1}	deka	da	10	=	10^{1}
10^{-1}	deci	d	0.1	=	10^{-1}
10^{-2}	centi	c	0.01	=	10^{-2}
10^{-3}	milli	m	0.001	=	10^{-3}
10^{-4}			0.0 001	=	10^{-4}
10^{-5}			0.00 001	=	10^{-5}
10^{-6}	micro	µ	0.000 001	=	10^{-6}
10^{-7}			0.0 000 001	=	10^{-7}
10^{-8}			0.00 000 001	=	10^{-8}
10^{-9}	nano	n	0.000 000 001	=	10^{-9}
10^{-10}			0.0 000 000 001	=	10^{-10}
10^{-11}			0.00 000 000 001	=	10^{-11}
10^{-12}	pico	p	0.000 000 000 001	=	10^{-12}
10^{-15}	femto	f	0.000 000 000 000 001	=	10^{-15}
10^{-18}	atto	a	0.000 000 000 000 000 001	=	10^{-18}

Table 1-1. POWERS OF TEN AND METRIC PREFIXES.

← T – G – M – my – K – h – 0 – da – d – c – m – µ – n – p – f – a →

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

001. Rediscovering the decimal numbering system

1. How many symbols does the decimal numbering system use? What are they?

   10 symbols   0,1,2,3,4,5,6,7,8,9

2. What is meant by PLACE VALUE?
   Place is the position that a digit holds while value is how many times the number is multiplied by 10.

3. What is the purpose of an exponent?

   To show how many times a number is multiplied by itself

4. Using the example, 104.32_{10}, match the characteristics in column B to the parts of the decimal number in column A. Column B items are only used once.

	Column A	*Column B*
D	1. Least significant digit (LSD).	(a) 104
E	2. Most significant digit (MSD).	(b) 32
B	3. Fractional portion.	(c) .
A	4. Integral portion.	(d) 2
C	5. Decimal point.	(e) 1
F	6. Radix.	(f) 10

5. Which portion of a number identifies the type of numbering system being used? How is it expressed within the number? Radix   it is put within parenthesis

6. Why does the fractional portion of a number carry a negative exponent?

002. Metric notation

1. What advantage do you gain by using scientific notation?

2. What is the purpose of an exponent?

3. Which direction do you move the decimal point when you convert whole numbers to powers of ten expressions? Left.

4. When you convert whole numbers to powers of ten expressions, are the exponents positive or negative? Positive

5. Convert the following decimal numbers to their powers of ten expressions: (a) 321, (b) 1046, (c) 47397, (d) 109907, (e) 7333208, (f) 114.35.

6. Which direction do you move the decimal point when you convert decimal fractions to powers of ten expressions? Right

7. When you convert decimal fractions to powers of ten expressions, are the exponents positive or negative? Negative

8. Convert the following decimal numbers to powers of ten expressions: (a) 0.337, (b) 0.4492, (c) 0.098461, (d) 0.0000001, (e) 12.4436, (f) 904.3366.

9. When you multiply powers of ten expressions, what must you do with exponents ?

10. Determine the correct power of ten expression for the following algebraic equations: (a) $10^1 x 10^4 = 10^n$, (b) $10^0 x 10^7 = 10^n$, (c) $10^3 x 10^6 x 10^4 = 10^n$, (d) $10^3 x\ 10^{-3} = 10^n$, (e) $10^{11} x 10^4 x 10^{-7} = 10^n$, (f) $10^{-14} x 10^9 x 10^0 x 10^2 = 10^n$.

11. When you divide powers of ten expressions, what must you do with exponents?

12. What must you remember when you raise any base number to a power of zero?

13. Identify the correct metric prefixes and abbreviations for the following: (a) 1000, (b) 10^6, (c) 1,000,000,000, (d) 10^{-1}, (e) 0.000000001, (f) 10^{-12}.

14. Determine the correct powers of ten expressions for the following:

$$(a)\ \frac{10^4}{10^2}=10^n \qquad (b)\ \frac{10^{-3}}{10^1}=10^n \qquad (c)\ \frac{10^{10}}{10^{-4}}=10^n$$

$$(d)\ \frac{10^{-5}}{10^{-3}}=10^n \qquad (e)\ \frac{10^9 x10^4}{10^3}=10^n \qquad (f)\ \frac{10^2 x10^2 x10^{-3}}{10^1 x10^4}=10^n$$

$$(g)\ \frac{10^5 x10^8 x10^{-13}}{10^{-3} x10^{-7} x10^{-2}}=10^n \qquad (h)\ \frac{10^6}{10^4 x10^{-1}}=10^n \qquad (i)\ \frac{10^1 x10^{-1} x10^1}{10^{-1} x10^1 x10^{-1}}=10^n$$

1-2. Solving Algebraic and Logarithmic Expressions

One of the most important units of measurement you use as a communications-computer systems controller is the decibel. *Decibel* is the common terminology used to describe system and circuit performance standards, characteristics, and test results. It is also a language you must learn and relearn.

The decibel and its uses should be familiar to you from technical school. Unfortunately, many of us who once learned the decibel language do not use and practice it continuously or enough to remain fluent. For this reason, a review of algebra, logarithms, and other items related to the use of the decibel is in order.

003. Adding and subtracting algebraic expressions

Algebra is frequently applied in the study of electronic circuitry. You probably studied algebra before entering the Air Force and certainly used it during electronics training. If your current job requires frequent use of algebra, you probably can easily recall its rules and procedures. Some of us, however, are probably a little "rusty."

A complete review of algebra would require a textbook instead of this CDC and would be a waste of time since your abilities probably fall between the "rusty" and "proficient" extremes. For the purpose of this lesson, we provide only a brief and selective review of algebraic principles.

Algebraic expressions. An algebraic expression is any combination of signs, numerals, and letters used to represent numbers and is written to the rules of algebra. For example; a, -b, M, P, -4, 2b, R_1, and R_2 could all be used as algebraic expressions.

Letters that are used to represent numbers are called *literal numbers*. In the above example, all expressions except the -4 are literal numbers. The numbers to the bottom right of R are called *subscripts*. They are used to show discrete components, functions, or operations of the literal numbers to which they are affixed. Letters can be used as subscripts also, with their identity or meaning usually given along with the expression. A familiar example would be the expression used for Ohm's law for total resistance in a series circuit:

$$R_T = R_1 + R_2 \ldots + R_n$$

Where:

R_T	=	total resistance.
R_1 and R_2	=	discrete values of resistance in the circuit.
R_n	=	value of the last resistor in an unlimited series.

Signs such as (+) or (-) may show that a number is positive or negative; they may also show arithmetical operations. The following signs of operation are used in this course: (+) for addition, (-) for subtraction, (x) for multiplication, and (/) for division. Another thing to remember is that two expressions written together are to be multiplied. For example, 6b means 6xb.

Factors and *coefficients* are terms that express the relationship of numbers to each other. In the expression $x=mn$, m and n are called factors of the product x. For example, if m=5 and n=2 and $x=mn$, then x would be equal to 10. In this case, 5 and 2 are factors of 10.

Each factor of a product is the coefficient of the other factor. In our example, 5 is a coefficient of 2, and vice versa. In the expression 5mn, 5 is called the *numerical coefficient*, and m and n are called *literal coefficients*. Often the word coefficient is restricted to mean only the numerical coefficient.

Numbers without signs (such as 8 volts) show the size or magnitude of a quantity—its absolute value. Because without signs or other qualifying information we can't tell whether 8 volts is positive or negative, in electronics we often apply the appropriate sign for clarity: +8 volts, +3 dBm, or +1 dB. Numbers like these are called *integers*, or whole numbers. Along with positive and negative integers, there are also positive and negative fractions (such as -1/2 or +1/2). Positive and negative integers and fractions are collectively referred to as *signed numbers*.

When you work with signed numbers on paper, you have to be careful not to confuse their signs with arithmetical operation signs. In this course, we use signs of grouping (parentheses, brackets, and braces) to avoid the problem. For instance, the operation of adding -3 to +3 is written (+3)+(-3)=0, which leaves no room for confusion.

Perform algebraic addition and subtraction. In communications electronics, you will most often need to add one signed number to another or subtract one signed number from another. You must adhere to certain rules when you perform these functions. If you haven't used algebra for a while, you may need to brush up in this area. The basic rules for algebraic addition and subtraction (with examples) are provided below for your review.

(1) To add two signed numbers of the same sign, add their absolute values and place the common sign prefixed to the sum.

Example:

$$\begin{aligned}(+2) + (+2) &= 2 + 2 \quad \text{(absolute value)}\\ &= 4 \quad \text{(absolute value)}\\ &= +4 \quad \text{(answer)}\end{aligned}$$

(2) To add two signed numbers of opposite signs, subtract the smaller absolute value from the larger absolute value and place the sign of the larger absolute value prefixed to the difference.

Example:

$$\begin{aligned}(+3) + (-2) &= 3 - 2\\ &= 1\\ &= +1\end{aligned}$$

(3) The process of subtraction is the opposite process of addition. What was that? All this is saying is that when you are doing subtraction, all you're really doing is changing the sign of the number you're subtracting and then adding it to the other number (remembering rules 1 and 2 while you do it).

Example:

$$\begin{aligned}(-4) - (-5) &= (-4) + (+5) \quad \text{(changing signs)}\\ &= 5 - 4 \quad \text{(absolute values)}\\ &= 1 \quad \text{(absolute remainder)}\\ &= +1 \quad \text{(answer)}\end{aligned}$$

Now that you've been refreshed on basic algebraic addition and subtraction, it's time to move on to something a little more challenging—LOGARITHMS!

004. Solving logarithmic expressions

The need to manipulate complex numbers has been evident since ancient times. Without this capability the world would never have had such riches as the great pyramids of Egypt, the magnificent Parthenon of Greece, the Eiffel tower, or our own Empire State Building. Throughout history, mankind has used various methods to perform the necessary computations to accomplish such feats—from carving and counting notches on a stick, to using the ancient abacus, to employing the slide rule, up to relying on modern day calculators and computers to perform the needed calculations. One simple method of working with complex computations requires only a set of common logarithms, a piece of paper, and a pencil. This method allows you to square a number, raise it to any power, and multiply it by another number. It also enables you to find the square root, cube root, or any other root and permits normal division operations. Since the decibel (dB) unit of measurement is a logarithmic function used daily by system controllers, this study of logarithms should also help you understand how the dB scale works.

What is a logarithm? The logarithm (Log) of a certain quantity is the power (exponent) to which a given number (the base) must be raised to equal that quantity. Let's try one! Using the definition of a logarithm, what would the Log of 100_{10} be? To find out, we take the base (10) and calculate how many times we must multiply it by itself to equal 100. Remembering what we've already covered about powers of 10, we know the answer to be 10 times 10, or ten to the first power times ten to the first power, equals one hundred. Next, add the exponents (because you're multiplying powers) and you get the logarithm, which is two (2). This is normally written as $\log_{10} 100=2$.

Logarithm of:

$$
\begin{aligned}
100_{10} &= 10^{n} \\
&= 10^{1} \times 10^{1} \\
&= 10^{2} \\
n &= 2 \qquad \text{or} \\
\text{Log}_{10}\ 100 &= 2
\end{aligned}
$$

Any positive number greater than one may serve as the base, but only two have been selected; resulting in two sets of logarithms. One set uses 2.718 as the base and is called the *natural logarithm system*. The other set uses ten as the base (like the example) and is called the *common logarithm system*. The common system is also used as the basis for the decibel system.

In the common system, logarithms that are exact powers of ten are called integers. You can see this relationship in the following example:

$$
\begin{aligned}
&\text{Log } 100000 = 5, && \textit{since } 10^{5} = 100000 \\
&\text{Log } 10000 = 4, && \textit{since } 10^{4} = 10000 \\
&\text{Log } 1000 = 3, && \textit{since } 10^{3} = 1000 \\
&\text{Log } 100 = 2, && \textit{since } 10^{2} = 100 \\
&\text{Log } 10 = 1, && \textit{since } 10^{1} = 10 \\
&\text{Log } 1 = 0, && \textit{since } 10^{0} = 1
\end{aligned}
$$

Of course, not all logarithms are exact powers of ten. This creates the need for a two-part logarithm. The first part is a whole number (integer), called the *characteristic*, and the second part is a decimal number, called the *mantissa*. Therefore, in the example log 595=2.7745, the number 2 would be the characteristic and 0.7745 would be the mantissa. Characteristics can be found by two different methods, while mantissa are identified using a common logarithm table. Let's take a closer look at this process.

Identifying the characteristic and mantissa. Finding the logarithm of a number is not too difficult as long as you follow certain steps. First, you need to identify the characteristic, and then the mantissa.

Find the characteristic. Before you can determine the characteristic of a logarithm, you must learn these two basic rules:

(1) The characteristic of a logarithm of a number greater than 1 is always positive.

(2) The characteristic of a logarithm of a number less than 1 is always negative.

As we said earlier, there are two ways for finding the characteristic of a logarithm; by the inspection method, and by powers of ten notation. The inspection method is easier to use and easier to remember.

Inspection method. To use the inspection method to identify the characteristic of a logarithm of a number greater than 1, simply count the number of places to the left of the decimal point and subtract 1. For example: to find the characteristic of 672.0, count the number of places to the left of the decimal point (3) and subtract 1, which gives you a characteristic of **2**. To use the inspection method to identify the characteristic of a logarithm of a number less than 1, simply count the number of zeros *immediately* to the right of the decimal point and add 1. Example: the characteristic of 0.672 is -1, the characteristic of 0.0672 is -2, and so forth. Remember, when dealing with numbers less than 1, the characteristic is always negative. That's all there is to the inspection method. Using powers of ten notation to identify the characteristic of a logarithm requires a little more work, but, it's not too difficult either.

Powers of ten notation method. There are two reasons for using the powers of ten notation method. First, the characteristic is automatically exposed (no mental calculation required as in the inspection method), and second, it converts numbers to a range compatible with most common logarithm tables (such as our supplemental foldout 1). Most common logarithm tables have a set range from 1.00 to 99.9; therefore, you could not find the logarithm of the number 595 without converting it to a number within the table's range. The powers of ten notation method does this for you.

To find the characteristic of a logarithm using this method, all you need to do is convert the number to its power of ten expression (previously discussed) and the exponent becomes the characteristic. For example: $595=5.95 \times 10^2$, with 2 being the characteristic. The following examples may illustrate this more clearly. Don't worry about the mantissa in the *Log* column; we'll cover that a little later.

No.	*Powers of Ten*	*Log*
796.0	7.96×10^{2}	2.9009
79.6	7.96×10^{1}	1.9009
7.96	7.96×10^{0}	0.9009
0.796	7.96×10^{-1}	$-1+0.9009$
0.0796	7.96×10^{-2}	$-2+0.9009$

In the above examples, note that the digits in the numbers column are the same and in the same order. The only difference is in the placement of the decimal point. Also, note that in the powers of ten column, all of the digits are exactly the same, except for the exponents. Finally, notice that in the log column, the mantissa (fractional portion of the logarithm) is the same for all of the numbers and only the characteristics have changed.

Well, that's the two methods for identifying the characteristics of logarithms. Either method will work, but you'll find the powers of ten option much easier to use when working with large numbers. There's one more thing you need to know about characteristics, and that is how to display negative characteristics.

When working with negative characteristics, you should never place a minus sign (-) in front of the complete logarithm because *only* the characteristic is negative, not the entire logarithm. There are several ways to label a characteristic as being negative, the first of which is to place a bar over the characteristic indicating only the characteristic is negative.

$$\text{Log } 0.023 = \bar{2}.3617$$

Another method is to display the negative characteristic after the mantissa. For example: 0.3617-2. A third method is to add the base (10 for common logarithms) to the negative characteristic, then show subtraction of the base at the end of the logarithm. This would look like the following:

$$\begin{array}{r} \bar{2}.3617 \\ +10 \\ \hline 8.3617-10 \end{array}$$

There's still one more method available to identify a negative characteristic, and it's the one we use in this text. All you have to do is place a minus sign (-) in front of the characteristic and a plus sign (+) in front of the mantissa. Our logarithm now looks like: -2+0.3617. This method shows that the negative characteristic (-2) is to be added (+) to the mantissa (0.3617). Now that we know how to identify the characteristic portion of a logarithm, let's work on the other part—the mantissa.

Find the mantissa. Recall from earlier in the lesson that the mantissa is the decimal portion of a logarithm; it is always less than 1, always positive, and is identified through the use of a logarithm table. There's one more thing you need to know about the mantissa: numbers having the same digits, in the same order, and differing only in the placement of the decimal point, will always have the same mantissa in their logarithm. For example, the mantissa of 623 is 0.7945, the mantissa of 62.3 is also 0.7945, and the mantissa of 6.23 is 0.7945, too. The reason for this goes back to what we've already learned about decimal (base 10) numbers and the powers of ten. When you convert each of the numbers in our example to a powers of ten expression, you can see that they differ only in their exponential values.

Remember also that the exponents are used to determine the *characteristic* of a logarithm, not the mantissa. When you are identifying the mantissa for all three of these numbers, you are using the same basic value (6.23) to make your calculations. Therefore, the mantissa for each of the numbers will be the same (0.7945).

$$
\begin{aligned}
\text{Log}_{10}\ N &= \textit{characteristic} + \textit{mantissa} \\
\text{Log}_{10}\ 623 &= 6.23\text{x}10^2 + \textit{mantissa of } 6.23 = 2 + 0.7945 = 2.7945 \\
\text{Log}_{10}\ 62.3 &= 6.23\text{x}10^1 + \textit{mantissa of } 6.23 = 1 + 0.7945 = 1.7945 \\
\text{Log}_{10}\ 6.23 &= 6.23\text{x}10^0 + \textit{mantissa of } 6.23 = 0 + 0.7945 = 0.7945
\end{aligned}
$$

Finding the mantissa of a logarithm is really a location process instead of a calculation. The calculations are done to reveal an integer and a decimal number. The mantissa is found by associating this value to a logarithmic table and actually "looking up" the desired mantissa. To do this, you need to know how to use the table. In this case, seeing is believing, so we'll take an example and identify the step-by-step procedures for finding its entire logarithm. Determine the logarithm of the number 987 using Supplemental Foldout 1 (FO-1).

(1) Convert 987 to its powers of ten expression: $987 = 9.87\text{x}10^2$,

(2) The characteristic equals the exponent: characteristic = **2**,

(3) Associate the powers of ten expression to the logarithm table:

- *a.* Locate 9.8 in the numbers (No.) column.
- *b.* Follow horizontally across the table until you reach the "7" column (numbered at the top of the table).
- *c.* The mantissa equals the number where the 9.8 row and the 7 column intersect: **0.9943.**

(4) Add the characteristic to the mantissa: 2+0.9943 = **2.9943.**

(5) Write the logarithmic expression: $\mathbf{Log_{10}\ 987 = 2.9943}$.

$$
\begin{aligned}
\text{Log}\quad N &= \text{characteristic} + \text{mantissa} \\
\text{Log}_{10}\quad 987 &= \left(9.87x10^{2}\right) + \text{mantissa} \\
&= 2 + \text{mantissa of} 9.87 \\
&= 2 + 0.9943 \\
\text{Log}_{10}\quad 987 &= 2.9943
\end{aligned}
$$

See, it's not that difficult, is it? Try a few examples on your own until you get the hang of it.

Of course, you will not always be dealing with three digit numbers. Often, in your job as a systems controller, you will have to work with four-digit numbers which requires the use of another part of the logarithmic table—the "least-means table." Using the steps just covered, let's find the logarithm of the number 6254.

(1) Convert to powers of ten: 6254=6.254x10^3.

(2) Determine the characteristic: 3.

(3) Find and record the mantissa for 6.25: 0.7959.

(4) Continue horizontally across this same row until you reach the "4" column in the least-means difference portion of the table. Where the 6.25 row and the 4 column intersect gives you the least-means value: least-means value = **.0003**.

(5) Add the least-means value to the mantissa value of 6.25 to determine the complete mantissa: 0.7959+0.0003 = 0.7962,

(6) Add the characteristic to the complete mantissa: 0.7962 + 3 = 3.7962,

(7) Write the complete logarithmic expression: **Log$_{10}$ 6254 = 3.7962**.

$$
\begin{aligned}
\text{Log}\quad N &= \text{characteristic} + (\text{mantissa} + \text{least - means difference}) \\
\text{Log}_{10}\quad 6254 &= 6.254x10^{3} + (\text{mantissa} + \text{least - means difference}) \\
&= 3 + (\text{mantissa of } 6.25 + \text{least - means difference}) \\
&= 3 + (0.7959 + \text{least - means difference of } 4) \\
&= 3 + (0.7959 + 0.0003) \\
&= 3 + 0.7962 \\
\text{Log}_{10}\quad 6254 &= 3.7962
\end{aligned}
$$

This works for finding logarithms of mixed decimal numbers, such as 625.4, also. Remember, the mantissa doesn't change in like numbers where the only difference is in the placement of the decimal point. In this instance, only the characteristic would change—giving you a logarithm of 2.7962.

Solving logarithmic expressions is not difficult as long as you understand and follow the rules. We've just demonstrated how easy it really is. But, what do you do if you're given a logarithm and have to convert it to the corresponding decimal number it represents? This process is known as finding the *antilogarithm*, or antilog, and is the reverse process for what we just covered.

Antilogs. As with finding logarithms, determining antilogs is not difficult as long as you follow the steps correctly. Let's see how this is done using the logarithm 3.5502 as an example:

(1) Ignore the characteristic because we work the mantissa first.

(2) Go to the log table and search down the zero (0) column until you find a row beginning with the first two digits of your mantissa (.55). In this instance, you see that it is .5563 which is larger than your mantissa.

(3) Since this number is too large, move up one row and there you'll see it starts with the number .5441. This is the row you will use to convert your mantissa and is labeled to the extreme left as row **3.5**. These are the first two digits in your converted mantissa.

(4) Now move horizontally across this row until you come to the number .5502. Note that this is *exactly* the same as your mantissa.

(5) From this location, follow the column to the top of the table and you will see that it corresponds to the number **5**. This is the third digit of your converted mantissa.

(6) Now that you have all three digits, 3.55, your mantissa has been converted.

(7) Next, you have to retrieve your characteristic, 3, and convert it back to its powers of ten exponent. You should remember from previous lessons that this is 10^3.

(8) Now, multiply your converted mantissa from step 6 by your converted characteristic: $3.55 \times 10^3 = 3.55 \times 1000 = 3550$. Therefore, the antilog of 3.5502 is **3550**.

This completes the process of finding the antilog of the logarithm 3.5502. A picture is worth a thousand words, so look below at the same example in an equation format:

$$
\begin{aligned}
\text{Antilog } N &= \text{converted mantissa } \times \text{ converted characteristic} \\
\text{Alog } 3.5502 &= \text{converted mantissa of } 0.5502 \times \text{ converted characteristic of } 3 \\
&= 3.55 \times \text{ converted characteristic of } 3 \\
&= 3.55 \times 10^3 \\
&= 3.55 \times 1000 \\
N &= 3550 \text{ (antilog)}
\end{aligned}
$$

As with logarithms, when you are solving for antilogs you will not always find the exact number listed in the table as we did in the above step number 4. When this happens, you once again employ the use of the least-means difference table. Let's say, for example, we are solving for the antilog of 3.5508. Here we would follow the same steps as we did in the previous example until we come to step number 6. Since we cannot locate the exact mantissa, we move across the 3.5 row to the closest number less than our mantissa (0.5502), and record the number at the top of that column (5). Now we subtract this mantissa value from our mantissa to find the least-means difference (LMD) value (0.5508-0.5502=0.0006). Move across the row to the least-means difference portion of the table to the number 6. Follow to the top of the column to determine the corresponding number (5). Finally, put all of the identified digits together and you get the mantissa value of 3.555. From this point, continue the process with step 7 and you will find that the antilog of 3.5508 equals 3.555×10^3 or 3555. The equation format would be:

$$
\begin{aligned}
\text{Alog}_{10}\ N &= (\text{converted mantissa} + \text{converted LMD}) \text{ x converted characteristic} \\
\text{Alog } 3.5508 &= (\text{converted mantissa of } 0.5502 + \text{converted LMD}) \text{ x converted characteristic} \\
&= [3.55 + (0.5508 - 0.5502)] \text{ x converted characteristic} \\
&= (3.55 + 0.005) \text{ x converted characteristic} \\
&= 3.555 \times 10^3 \\
&= 3.555 \times 1000 \\
N &= 3555 \ \text{(antilog)}
\end{aligned}
$$

Hopefully, this lesson has provided sufficient review of logarithms and antilogarithms for you to solve log and antilog expressions. Figure 1-2 summarizes these same processes and should be referred to until such time as you feel comfortable working with them. You will be using what you've learned here in upcoming lessons. Now that we've completed our review of the decimal numbering system, it's time to tackle our next subject, the binary numbering system.

HOW TO FIND THE LOGARITHM OF A NUMBER

Determine the characteristic of the number by inspection.
Find the mantissa from the tables.

PARTS OF A LOGARITHM

For numbers not exact powers of ten, the logarithm has two parts: an integral part (whole number), and a decimal part. The integral part is called the characteristic and the decimal part is called the mantissa.

For numbers greater than one-the characteristic is positive and is one less than the number of digits to the left of the decimal point.

For numbers less than one-the characteristic is negative and is equal to one more than the number of zeros immediately to the right of the decimal point.

For all numbers-the mantissa is positive.

For like numbers-numbers which have the same figures in the same order and differ only in position of the decimal point, have the same mantissa.

FOUR-PLACE LOGARITHM TABLES

The first column in the table contains the first two digits of the numbers whose mantissas are given in the table, and the top row contains the third digit. Thus, to find the mantissa of 595, find 59 in the left-hand column and 5 at the top. In the column under 5, and opposite 59, we find 7745, the mantissa. The logarithm of 595, then, is 2.7745.

EXAMPLES

Number	Logarithm
57	1.7559
570	2.7559
12.2	1.0864
3.56	0.5514

Figure 1-2. Steps for finding logarithms.

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

003. Adding and subtracting algebraic expressions

1. Match the statements in column A with their associated terms in column B. Items in column B may be used once, more than once, or not at all.

Column A	*Column B*
___ (1) Any combination of signs, numerals, and letters used to represent numbers and written to the rules of algebra.	a. Algebraic expressions.
___ (2) Symbols used to show discrete components, functions, or operations of literal numbers.	b. Literal numbers.
___ (3) A collective term used to describe positive and negative integers and fractions.	c. Signed numbers.
___ (4) Symbols used to express the condition of a number or arithmetical operation.	d. Coefficients.
___ (5) Terms used to express the relationship of numbers in a product.	e. Subscripts.
___ (6) Letters that are used to represent numbers.	f. Integers.
___ (7) Term used to express whole numbers.	g. Factors.
	h. Signs.

2. How do you add signed numbers of the same sign?

3. How do you add signed numbers of opposite signs?

4. Compare the process of subtraction to the process of addition.

5. Add the following algebraic expressions: (a) $+2+(+8)+(+6)=n$, (b) $+19+(+11)+(+10)=n$, (c) $-1+(-14)+(-4)=n$, (d) $-23+(-4)+(-14)=n$, (e) $4+(-3)+7=n$, (f) $-2.6+12.4+(-6)=n$.

6. Subtract the following algebraic expressions: (a) +2-(+8)-(+6)=n, (b) +19-(+11)-(+10)=n, (c) -1-(-14)-(-4)=n, (d) -23-(-4)-(-14)=n, (e) 4-3-7=n, (f) -22.6-12.4-(-6)=n.

004. Solving logarithmic expressions

1. What is a logarithm?

2. Without using the log table, what is the log of 10? 100? 1000?

3. Which set of logarithms uses ten as its base?

4. Name and describe the two parts of a logarithm.

5. As you determine the logarithm of a number, which part do you identify first?

6. Are all characteristics of logarithms positive, or are they negative?

7. What are the two methods used to identify characteristics of logarithms?

8. How would you use the inspection method to identify the characteristic of a logarithm for a number greater than 1?

9. How would you use the inspection method to identify the characteristic of a logarithm for a number less than 1?

10. Why might you prefer to use the powers of ten method to identify the characteristic of a logarithm instead of the inspection method?

11. How do you identify the characteristic of a logarithm using the powers of ten notation method?

12. If the characteristic of a logarithm for a number is negative, does the entire logarithm become negative?

13. Why is the mantissa of the logarithm for 6.990, 69.90, and 6990 the same?

14. Which portion of a common logarithm table is used to identify the least-means value of a mantissa for the logarithm of a number?

15. Determine the logarithm for the following numbers using supplemental foldout 1: (a) 17, (b) 32, (c) 76.4, (d) 227, (e) 834.5, (f) 2333.

16. What is an antilogarithm?

17. How do you determine the antilog of a logarithm?

18. Determine the antilogarithms for the following logarithms using supplemental foldout 1: (a) 3.4900, (b) 1.9186, (c) 4.8768, (d) 8.4138, (e) 3.6611, (f) 2.5045.

1-3. Principles of the Binary Numbering System

Many modern computers operate using the binary numbering system because of its simplicity; it uses only two symbols, 0 and 1. Since only these two symbols are used, only two conditions are needed to represent them, i.e., on or off, yes or no. This greatly simplifies computer design and enhances accuracy.

005. Binary basics

As a communications-computer systems controller, you work with computers on a daily basis, and you use the binary numbering system for other applications as well. Suffice to say, a thorough knowledge of this numbering system is vital to your success as a controller and your ability to provide quality service to our users.

Binary and decimal system comparison. Recall from a previous lesson about the decimal numbering system that it uses the symbols 0 through 9 to represent digits and is also based on the powers of ten. The binary numbering system is very similar in operation, but only has the two symbols (0 and 1) and is based on powers of two. Zeros are used as PLACEHOLDERs and ones represent 1s. You can write any number of the decimal or other numbering system using just these two symbols. To express numbers other than 0 and 1 in the binary system, the symbols are arranged in a specified sequence. The PLACE of each symbol within the sequence determines its VALUE based on the powers of two. Don't you agree this sounds a lot like the decimal system you just finished reviewing?

The easiest way to understand the binary system is to relate it to the decimal system. Remember from the study of the powers of ten that $10^0=1$, $10^1=10x1=10$, $10^2=10x10=100$, $10^3=10x10x10=1000$, etc. The same principle applies to the binary system. For example: $2^0=1$, $2^1=2x1=2$, $2^2=2x2=4$, $2^3=2x2x2=8$, and so forth. Other than differences in the base (radix) and in the symbols used to represent numeric values, the binary numbering system is quite similar to the decimal system. For instance, 123_{10} and 1111011_2 both equal the same number, but they use different symbols to mean the same value. The following example shows how this is done:

$$
\begin{array}{lllllll}
123_{10} & = 3x10^0 & = 3x1 & & & = & 3 \\
 & = 2x10^1 & = 2x10 & & & = & 20 \\
 & = 1x10^2 & = 1x(10x10) & = & 1x100 & = & \underline{+100} \\
 & & & & & = & 123_{10}
\end{array}
$$

and

$$
\begin{array}{lllll}
1111011_2 & = 1x2^0 & = 1x1 & & = 1 \\
 & = 1x2^1 & = 1x2 & & = 2 \\
 & = 0x2^2 & = 0x(2x2) & = 0x4 & = 0 \\
 & = 1x2^3 & = 1x(2x2x2) & = 1x8 & = 8 \\
 & = 1x2^4 & = 1x(2x2x2x2) & = 1x16 & = 16 \\
 & = 1x2^5 & = 1x(2x2x2x2x2) & = 1x32 & = 32 \\
 & = 1x2^6 & = 1x(2x2x2x2x2x2) & = 1x64 & = \underline{+64} \\
 & & & & = 123_{10}
\end{array}
$$

As you can see from this example, the PLACE of each digit in a binary number determines its VALUE just like in the decimal system. Note, however, that in the binary system, as the exponent increases by one, the power doubles. This is inherent only to the binary numbering system. The example shown above is derived from using what is known as a place value chart.

PLACE value charts. PLACE value charts are the key to understanding any numbering system. A correctly constructed chart not only provides a visual representation of the value of each digit of a number, but it also can be used to convert from one numbering system to another (fig. 1-4). Should you choose to build your own place value chart, you must follow the basic rules listed below:

(1) *Base (radix) line.* The first base entry should always be made at the far right and should be the base with an exponent of (^{0}). Base columns proceed from there to the left, increasing in power, for as many columns as are needed.

(2) *Power line.* This line also starts at the right. The power indicates the value of any digits in the column below that power. The first entry is *always* "1." The second entry, under the base with an exponent of (^{1}), is *always* equal to the base. All entries after that are equal to the power of the previous power entry multiplied by the base.

(3) *Number line.* The digits on this line represent the total numerical value of each particular column. Looking at figure 1-3, note there is a 1 in the 2^3 column. This digit represents the numerical value of 8. The most significant digit (MSD) is always the digit on the far left, while the least significant digit (LSD) is the digit on the far right.

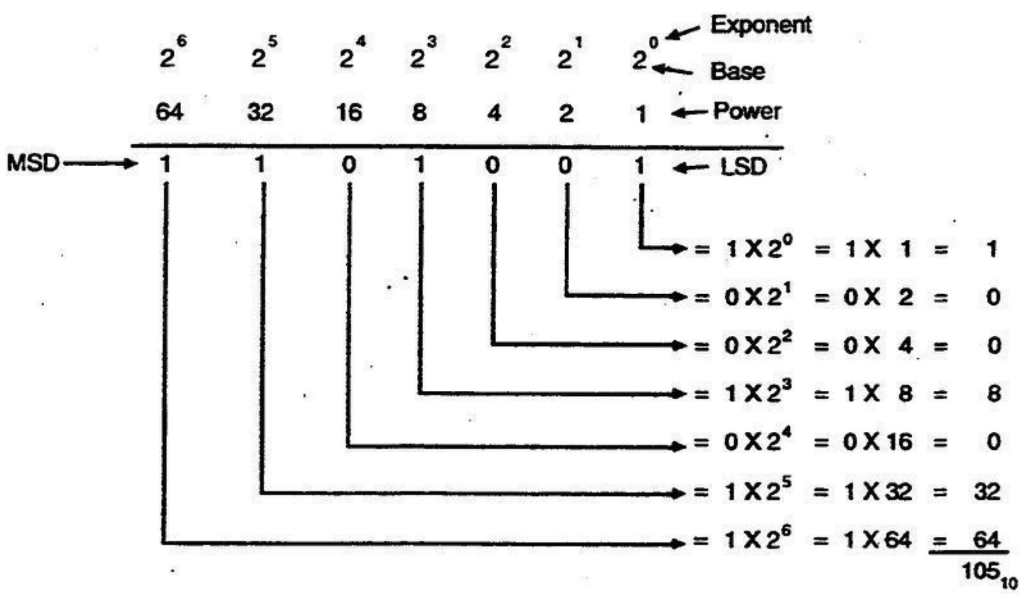


Figure 1-3. Binary PLACE value.

006. Perform decimal-to-binary-to-decimal conversions

You've seen the many similarities between the decimal and binary numbering systems. Now, let's see how their likeness enable us to convert from one system to the other.

Decimal-to-binary conversion. When we used the powers of two in our previous lesson, we were actually converting our binary numbers to their decimal equivalents. This method of conversion works for any binary number. A PLACE value chart such as figures 1–3 and 1–4 can also be used to perform these conversions. Let's use figure 1–4 to convert 142_{10} to its binary equivalent using the following steps:

	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0	← EXPONENT ← BASE
	256	128	64	32	16	8	4	2	1	← POWER
MSD →		1	0	0	0	1	1	1	0	← LSD

$$142_{10} = \begin{array}{r} 142 \\ -128 \\ \hline 14 \\ -8 \\ \hline 6 \\ -4 \\ \hline 2 \\ -2 \\ \hline 0 \end{array}$$

$$= 10001110_2$$

Figure 1–4. Decimal to binary conversion.

(1) First, in the power line, find the most significant power value which can be subtracted from the decimal number we are trying to convert. We find in the 2^7 column that 128 is the largest number that can be subtracted from 142. We place a 1 under that column on the number line and subtract 128 from 142, resulting in a remainder of 14.

(2) Next, we move to the 2^6 column and find that 64 cannot be subtracted from our remainder and so place a 0 under it on the number line.

(3) Then we move to the 2^5 column and find that 32 cannot be subtracted either, and place a 0 under it on the number line.

(4) We find that 16 in the 2^4 column won't subtract and place a 0 under it, also.

(5) The 8 in the 2^3 column will subtract and leave a remainder of 6, so place a 1 under it on the number line.

(6) Under the 2^2 column, we find that 4 will subtract from our remainder, leaving 2; place a 1 under it on the number line.

(7) The 2 in the 2^1 will subtract leaving no remainder, so place a 1 under it on the number line.

(8) Finally, the 1 in the 2^0 column cannot be subtracted from our 0 remainder so we place a 0 under it on the number line.

(9) Reading our binary number from the left (MSD) toward the right (LSD), we find we have converted 142_{10} to its binary equivalent of 10001110_2.

Binary-to-decimal conversion. Converting binary numbers to decimal numbers is even simpler than converting decimal to binary. One method is to take your binary number and convert it using powers of two.

$$
\begin{array}{lclclcr}
11011101_2 & = & 1\text{x}2^0 & = & 1\text{x}1 & = & 1 \\
 & = & 0\text{x}2^1 & = & 0\text{x}2 & = & 0 \\
 & = & 1\text{x}2^2 & = & 1\text{x}4 & = & 4 \\
 & = & 1\text{x}2^3 & = & 1\text{x}8 & = & 8 \\
 & = & 1\text{x}2^4 & = & 1\text{x}16 & = & 16 \\
 & = & 0\text{x}2^5 & = & 0\text{x}32 & = & 0 \\
 & = & 1\text{x}2^6 & = & 1\text{x}64 & = & \underline{+64} \\
 & & & & & = & 93_{10}
\end{array}
$$

Another method is to build yourself a PLACE value chart like the one in figure 1-4 and apply your binary number to the number line. Then, all you have to do is add all the power values for the columns containing a binary 1. Try it using the same binary number as in the previous example.

007. Perform binary addition and subtraction

Besides being able to convert binary numbers, you must also know how to perform simple binary mathematical operations. Later, we cover how to add and subtract numbers using the binary system.

Binary addition. Binary addition is easy since we deal only with 0s and 1s. Easy, that is, if you follow the rules. This time there's only three to remember:

(1) When adding a column of even numbers of 1, the sum will always be 0.

(2) When adding a column of uneven numbers of 1, the sum will always be 1.

(3) For every two 1s added in a column, a 1 is carried to the next column.

Figure 1–5 is a binary addition truth table stating the same principles.

0	+	0	=	0	&	CARRY 0
0	+	1	=	1	&	CARRY 0
1	+	0	=	1	&	CARRY 0
1	+	1	=	0	&	CARRY 1

Figure 1–5. Truth table for binary addition.

Using these rules, let's add 1011_2 and 1110_2.

Steps: Begin at the right-hand column (LSD) and work to the left (MSD).

a) 1+0=**1**, with no carry.

b) 1+1=**0**, with 1 carry.

c) 0+1+1(carry from previous column)=**0**, carry 1.

d) 1+1+1(carry from previous column)=**1**, carry 1.

e) Bring the carry down from the previous column, **1**, which becomes the MSD.

The binary sum equals 11001_2.

Figure 1–6 illustrates these same steps. Another, less preferred method would be to convert each binary number to its decimal equivalent, perform the addition, and convert the sum back to a binary number.

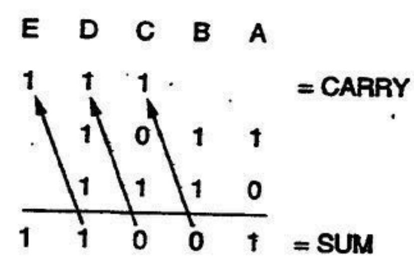


Figure 1–6. Steps for binary addition.

$$\begin{array}{rcl} 1011_2 & & 11_{10} \\ \underline{+1110_2} & = & \underline{+14_{10}} \\ & & 25_{10} \quad = \quad 11001_2 \end{array}$$

Below are several practice examples. Study them closely to make sure you understand binary addition. *Caution:* The most common mistake when you add binary numbers is to forget to add in the carries, or to add them incorrectly.

Addition Examples:

(1)	1	(2)	0	(3)	0	(4)	1
	0		1		0		1
	1		1		0		10
(5)	11	(6)	10	(7)	11	(8)	11
	00		01		01		11
	11		11		100		110
(9)	101	(10)	111	(11)	1111	(12)	1111
	010		11		0101		1111
	111		1010		10100		11110

Enough of binary addition. After reviewing the practice problems, let's move on to binary subtraction.

Binary subtraction. Binary subtraction is just the reverse of binary addition with its own set of rules:

(1) 0-0=0, no borrow.

(2) 0-1=1, borrow 1.

(3) 1-0=1, no borrow.

(4) 1-1=0, no borrow.

These same rules are depicted in figure 1–7, binary subtraction truth table.

0	–	0	=	0	NO BORROW
0	–	1	=	1	BORROW 1
1	–	0	=	1	NO BORROW
1	–	1	=	0	NO BORROW

Figure 1–7. Truth table for binary subtraction.

Using these rules, let's subtract 1010_2 from 10110_2:

(1) Starting with the right-hand column and moving left; 0-0=**0**, no borrow.

(2) 1-1=**0**, no borrow.

(3) 1-0=**1**, no borrow.

(4) 0-1=**1**, borrow 1.

(5) 0-0=**0**, no borrow.

The binary difference equals 1100_2. The following example shows the same steps in column format.

Example :

02	borrow (equal to the radix)
10110	minuend
$\underline{-1010}$	subtrahend
1100	

NOTE: When borrowing from a column, you are actually borrowing from the next higher power in a powers of two system. In the above example, when you borrowed the MSD from the minuend, you were actually borrowing what that digit represents, $1x2^4$ (16). You then added that to the next lower column, $0x2^3$ (0), making it 16. Then you were able to subtract the MSD of the subtrahend $1x2^3$ (8) with a remainder of 8 ($1x2^3$), represented by the binary 1. This may sound complicated, but it's not when viewed from a powers of two perspective.

Example :

$$\begin{array}{lcccccc}
10110 & = & 1x2^4 & 0x2^3 & 1x2^2 & 1x2^1 & 0x2^0 \\
\underline{-1010} & = & \underline{-0x2^4} & \underline{-1x2^3} & \underline{-0x2^2} & \underline{-1x2^1} & \underline{-0x2^0} \\
 & & & & & & \\
 & = & 0x2^4 & 2x2^3 & 1x2^2 & 1x2^1 & 0x2^0 \\
 & & \underline{-0x2^4} & \underline{-1x2^3} & \underline{-0x2^2} & \underline{-1x2^1} & \underline{-0x2^0} \\
 & & 0 & 1 & 1 & 0 & 0
\end{array}$$

Perhaps the easiest way to perform binary subtraction is to subtract as you would in the decimal system— that is, by treating the binary digits as decimal digits. When a borrow is necessary, its value *always equals* the radix (in this case, 2). This is true for any numbering system. The borrow is then added decimally to the minuend digit of that particular column, and the subtrahend is subtracted decimally.

Example :

02	borrow (equal to the radix)
10	minuend
$\underline{-1}$	subtrahend
1	

Review the following examples to make certain you understand the principles of binary subtraction.

Subtraction Examples:

(1) 1	(2) 0	(3) 10	(4) 11
−1	−0	−01	−1
0	0	01	10
(5) 111	(6) 111	(7) 110	(8) 1110
−010	−110	−011	−0111
101	001	011	0111

That's it for the binary system and this portion of unit one of the CDC. You've seen it compared and converted to the decimal system, as a powers of two system, and you've learned how to perform binary addition and subtraction. Make sure you complete and understand all of the Self-Test Questions before continuing. We use what you've learned up to this point to tackle the next numbering system, the octal numbering system.

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

005. Binary basics

1. What symbols are used to represent numbers in the binary numbering system?

2. What radix is used in the binary numbering system?

3. What determines the decimal value of a binary digit in the binary numbering system?

4. In the binary numbering system, what happens to the power of a digit as the exponent increases by 1?

5. What is the advantage to using a correctly constructed PLACE value chart when you work with numbering systems?

6. Match the statements concerning PLACE value charts in column A with their associated elements in column B. Items in column B may be used once or more than once.

Column A

___ (1) The first entry on this line is always 1.

___ (2) The second entry on this line is always equal to the radix.

___ (3) The first entry on this line should always carry an exponent of 0.

___ (4) The first entry on this line should always be made at the far right.

___ (5) The most significant digit (MSD) is entered to the far left on this line.

___ (6) The least significant digit (LSD) is entered to the far right on this line.

___ (7) The entries on this line indicate the decimal value of any digits entered directly below them.

___ (8) Digits entered on this line represent the total numerical value of each particular column.

___ (9) A column entry on this line is equal to the power of the previous column entry multiplied by the base.

Column B

a. Power line.

b. Number line.

c. Radix (base) line.

006. Perform decimal-to-binary-to-decimal conversions

1. When you convert decimal numbers to binary numbers, which binary digit do you identify first?

2. What is the general process used to convert decimal numbers to binary numbers?

3. During decimal-to-binary conversion, what symbol is assigned as a binary digit for a power of two that will not divide into the decimal number?

4. After you convert a decimal number to its binary equivalent, how is the new binary number correctly displayed?

5. Convert the following decimal numbers to their binary equivalents: (a) 5, (b) 17, (c) 40, (d) 68, (e) 108, (f) 321, (g) 543, (h) 1018, (i) 2222.

6. What two methods are used to convert binary numbers to decimal numbers?

7. Briefly describe the process for converting binary numbers to decimal numbers using the powers of two method.

8. Briefly describe the process for converting binary numbers to decimal numbers using the PLACE value chart method.

9. Convert the following binary numbers to their decimal equivalents: (a) 10_2, (b) 011_2, (c) 1110_2, (d) 10100_2, (e) 11101_2, (f) 1100010_2, (g) 1111001_2, (h) 10101010_2, (i) 101111011_2.

007. Perform binary addition and subtraction

1. What does the sum of a column that contains an even number of binary 1s always equal?

2. What does the sum of a column that contains an odd number of binary 1s always equal?

3. Describe what takes place during binary addition when two binary 1s are added together.

4. When you perform binary addition with multiple columns of numbers, which column must you add first? Why?

5. Add the following binary numbers:

(*a*)	(*b*)	(*c*)	(*d*)	(*e*)	(*f*)
111	1011	11011	1110101	10010011	1111111
100	1100	1000	111101	10100101	1000100
+11	+1011	+1111	+100010	+11101100	+1011010

6. During binary subtraction, what condition would require you to borrow from the next higher column of numbers?

7. What is the value of a borrow that is used during binary subtraction?

8. Subtract the following binary numbers:

(*a*)	(*b*)	(*c*)	(*d*)	(*e*)	(*f*)
101	1101	11011	111111	1000101	100100101
−10	−111	−1010	−10111	−100110	−11110010

1-4. Principles of the Octal Numbering System

The octal numbering system is also used in many computers because it takes a fewer amount of digits to represent large numbers. You've already seen the advantages the binary system has over the decimal system in this respect. Octal numbering has the same advantages over binary numbering. In this section, you will receive an understanding of how the octal numbering system works and its relationship to the other two numbering systems we've already covered. You will learn how to convert from octal numbering to binary and decimal and vice versa. By the time we complete this section, you will also be able to perform octal mathematics. Ready, set, go!

008. Octal basics

Remember from our previous discussion that the binary system is used in computer calculations because it requires only two digits, 0 and 1. Unfortunately, a binary number requires three to four times as many digits in a row to represent a number as does the decimal system ($111011_2=59_{10}$). The more digits you have to work with, the greater is your chance for error. In comparison, the octal numbering system uses only one-third the number of digits as does the binary system. Another advantage of the octal system is that it is much easier to convert to binary than is the decimal system.

Octal, binary, and decimal systems comparison. You'll also recall from previous lessons that the decimal system uses 10 symbols (0,1,2,3,4,5,6,7,8,9) and is a base ten system; the binary system uses two symbols (0,1) and is a base two system. The octal numbering system uses eight symbols (0,1,2,3,4,5,6,7) and is a base eight system. Where decimals can be written as powers of ten and binary numbers can be written as powers of two, likewise, octal numbers can be written as powers of eight. As in other systems, the exponents in octal numbers tell how many times the base (8) is used as a factor. The value of a digit in an octal number is equal to the digit multiplied by the power of the PLACE it occupies. This should sound familiar to you because all of the numbering systems we've covered up to this point follow the same basic principles.

PLACE value charts. Place value charts are very useful when we work with octal numbers. They follow the same rules we discussed earlier as far as having a *base line*, *power line*, and a *number line*. Figure 1–8 is an octal PLACE value chart. You can see that it looks almost identical to a binary chart except for the numbers used. The base line shows the powers of eight: 8^0, 8^1, 8^2, 8^3, etc.; the power line shows the value of how many times the base is multiplied by itself for each exponent column: 8x0=1, 8x1=8, 8x8=64, 8x8x8=512, etc.; and the number line shows how many times each power of eight column is used: $7x8^0=7x1=7$, $0x8^1=0x8=0$, $2x8^2=2x(8x8)=2x64=128$, $1x8^3=1x(8x8x8)=1x512=512$. PLACE value charts provide a quick reference for viewing the powers of eight.

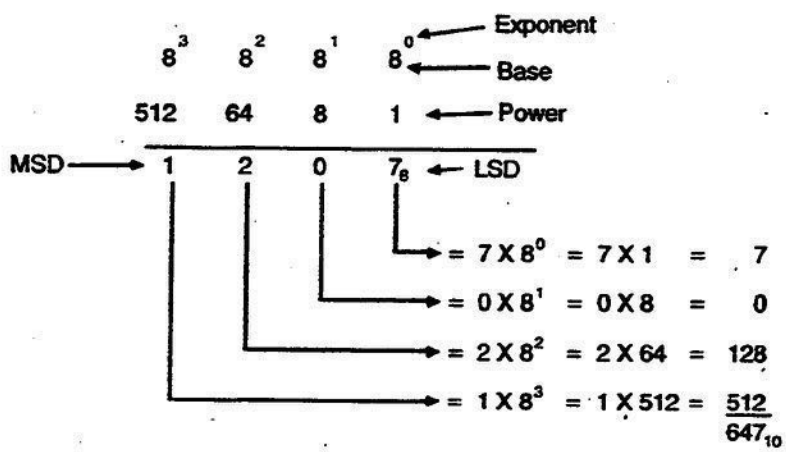


Figure 1–8. Octal PLACE value.

Working with octal numbers is no more difficult than any other numbering system as long as you understand and follow the rules. Yes, we keep repeating this statement, but that is because it is so important. If you understood how to work with binary numbers, then you already know how to apply the rules to the octal system.

009. Perform octal numbering conversions

So much for the basics. Now let's convert octal numbers to other numbering systems. It's not hard. As a matter of fact, you just did it in the previous paragraph!

Octal-to-decimal-to-octal conversion. When you build a PLACE value chart for the octal system, you are actually performing octal-to-decimal conversion. The steps for doing this are few and simple:

(1) Convert the octal number to a series of powers of eight expressions.

(2) Decimally add the results.

(3) Write the sum as a base ten number.

Let's try one. Following the above steps, convert 202_8 to its decimal equivalent.

$$
\begin{array}{rclclclcr}
202_8 & = & N_{10} & & & & & & \\
 & = & 2x8^0 & = & 2x1 & & & = & 2_{10} \\
 & & 0x8^1 & = & 0x8 & & & = & 0_{10} \\
 & & \underline{+2x8^2} & = & 2x(8x8) & = & 2x64 & = & \underline{+128_{10}} \\
 & & & & & & & & 130_{10}
\end{array}
$$

$$N = 130$$

Converting decimal numbers to octal numbers is almost the same as converting decimal to binary—only one more step is added. The steps to converting decimal to octal are as follows:

(1) Using a PLACE value chart, determine the largest power of eight value that can be subtracted from the decimal number. (NOTE: To identify the powers of eight required to complete the conversion, you may need to extend the octal place value chart in figure 1–8 or create your own.)

(2) Divide this power of eight value into the decimal number to determine how many times this power of eight can be used as a multiple (Don't worry if it doesn't come out even.) This multiple becomes your MSD.

(3) Next compute the product of your power of eight value and your multiple.

(4) Subtract the product in step 3 from your decimal number to get a remainder.

(5) Repeat the above steps until you get a remainder of zero, recording each multiple from step 2 as your next octal digit.

(6) The last octal digit becomes your LSD.

(7) Write your result as a base eight number.

NOTE: At no point should any of your octal digits exceed the number 7. If this happens, you've identified the wrong product and should proceed to the next higher power of eight.

Let's follow the above steps and convert 32671_{10} to its octal equivalent:

$$
\begin{aligned}
32671_{10} &= N_8 \\
&= 4096\overline{)32671} &&= 7.98 &&= \{7\} \quad (MSD) \\
&= 32671-(4096x7) &&= 32671-28672 &&= 3999 \\
&= 512\overline{)3999} &&= 7.81 &&= \{7\} \\
&= 3999-(512x7) &&= 3999-3584 &&= 415 \\
&= 64\overline{)415} &&= 6.48 &&= \{6\} \\
&= 415-(64x6) &&= 415-384 &&= 31 \\
&= 8\overline{)31} &&= 3.89 &&= \{3\} \\
&= 31-(8x3) &&= 31-24 &&= 7 \\
&= 1\overline{)7} &&= 7.0 &&= \{7\} \quad (LSD) \\
&= 7-(1x7) &&= 7-7 &&= 0 \\
N &= 77637_8
\end{aligned}
$$

Now let's verify our computation by converting our octal number to its decimal equivalent:

$$
\begin{aligned}
77637_8 &= N_{10} \\
&= 7x8^0 &&= 7x1 &&= 7 \quad \text{(LSD)} \\
& +3x8^1 &&= 3x8 &&= 24 \\
& +6x8^2 &&= 6x64 &&= 384 \\
& +7x8^3 &&= 7x512 &&= 3584 \\
& \underline{+7x8^4} &&= 7x4096 &&= \underline{+28672} \quad \text{(MSD)} \\
& && && 32671
\end{aligned}
$$

$$N = 32671_{10}$$

Converting octal and decimal numbers may require a few steps to accomplish correctly, but it's not difficult once you've done it a few times. You may want to practice some on your own before proceeding with the next part of our lesson—octal-to-binary conversion.

Octal-to-binary-to-octal conversion. Converting octal and binary numbers is done by a simple substitution process thanks to a natural relationship between binary and octal numbers. The base of the octal system is 8; the base of the binary system is 2, and 2^3 equals 8. Therefore, one octal digit can be expressed as three binary digits. Let's take a closer look at this relationship by counting to 7 in each system:

Octal No.	*Binary No.*	*Octal No.*	*Binary No.*
0	000	4	100
1	001	5	101
2	010	6	110
3	011	7	111

Since the largest number used in the octal system is 7, you can see that this direct substitution method is possible. Using this method, let's convert octal numbers to binary numbers.

Octal-to-binary. The steps to converting octal numbers to binary numbers are:

(*1*) Starting with the MSD, replace each octal digit with its three-digit binary equivalent.

(*2*) Combine the binary digits as a serial number and apply the new radix.

Sounds simple doesn't it? It is. Let's try one; convert the number 44765_8 to its binary equivalent:

$$
\begin{aligned}
44765_8 &= N_2 \\
&= 4_8 = 100_2 \quad \textit{and}, \\
& 4_8 = 100_2 \quad \textit{and}, \\
& 7_8 = 111_2 \quad \textit{and}, \\
& 6_8 = 110_2 \quad \textit{and}, \\
& 5_8 = 101_2 \quad \textit{therefore}, \\
44765_8 &= 100_2 100_2 111_2 110_2 101_2 \\
N &= 100100111110101_2
\end{aligned}
$$

This can be verified by converting both the octal number and binary number to their decimal equivalents. You'll find they both equal 18933_{10}. Converting binary to octal is almost as simple.

Binary-to-octal. When converting binary numbers to octal numbers, you must work with a binary number whose total number of digits are divisible by three. To get the required number of binary digits, you simply add zeros to the extreme left until you get a total number of digits divisible by three. Then, you use direct substitution to perform the conversion. Use the following steps:

(*1*) Add the required number of zeros to get a total divisible by three.

(*2*) Substitute the octal equivalent for each consecutive set of three binary digits.

(*3*) Serially combine the octal digits.

(4) Write the new octal number with a radix of 8.

Think you've got it? Let's try an example.

$$
\begin{aligned}
10110110101_2 &= N_8 \\
&= 10 \quad 110 \quad 110 \quad 101 \\
&= 010 \quad 110 \quad 110 \quad 101 \\
&= 2_8 \quad 6_8 \quad 6_8 \quad 5_8 \\
N &= 2665_8
\end{aligned}
$$

Converting the octal numbering system to its decimal and binary equivalents involves simple processes—one by a powers of ten conversion, the other by substitution. Our next lesson concentrates on performing math operations using the octal system.

010. Perform octal addition and subtraction

Octal addition is performed using a sum-and-carry technique. Octal subtraction is done in much the same manner as decimal and binary subtraction. Let's tackle the addition process first.

Octal addition. The process for adding octal numbers is the same as that of the decimal and binary systems. The only difference is the limit imposed by the radix. Remember, the highest digit in the octal numbering system is 7. Therefore, whenever this limit is exceeded for any column of numbers, it results in a carry to the next higher order column. For example: in the decimal system $9_{10}+1_{10}=10_{10}$; in the binary system $1_2+1_2=10_2$; and in the octal system $7_8+1_8=10_8$. Working with these different numbering systems may get a little confusing after a while, but a matrix table such as the one in figure 1–9 can help.

0	1	2	3	4	5	6	7
1	2	3	4	5	6	7	10
2	3	4	5	6	7	10	11
3	4	5	6	7	10	11	12
4	5	6	7	10	11	12	13
5	6	7	10	11	12	13	14
6	7	10	11	12	13	14	15
7	10	11	12	13	14	15	16

Figure 1–9. Octal addition matrix.

To use the table, locate your first number in the left margin, locate your other number in the top margin, then project a line from each until they intersect. Where the lines meet is the sum of your two numbers.

Example: A line from 3 on the left and a line from 6 on the top intersect at the number 11; therefore, the sum of 3_8 and 6_8 equals 11_8. Study the following examples until the process becomes familiar to you:

Examples:

(1) $\begin{array}{r} 7 \\ \underline{1} \\ 10 \end{array}$ (2) $\begin{array}{r} 5 \\ \underline{3} \\ 10 \end{array}$ (3) $\begin{array}{r} 6 \\ \underline{4} \\ 12 \end{array}$ (4) $\begin{array}{r} 7 \\ \underline{6} \\ 15 \end{array}$

(5) $\begin{array}{r} 2 \\ \underline{7} \\ 11 \end{array}$ (6) $\begin{array}{r} 7654 \\ \underline{1426} \\ 11302 \end{array}$ (7) $\begin{array}{r} 1234567 \\ \underline{7273747} \\ 10530536 \end{array}$

As you can see, the only difference between adding octal numbers and other numbering systems is the radix used. You shouldn't rely on the use of a matrix table too much; octal addition is a simple process, and you should be able to work without it. Now, let's learn how to subtract octal numbers.

Octal subtraction. Subtraction in the octal system is performed the same as for the decimal and binary systems. When you borrow from a column, your borrow equals the radix; 10 for decimal, 2 for binary, and 8 for octal.

Example :

$$73_8 - 24_8 = N$$

$$= \begin{array}{r} 73 \\ \underline{-24} \end{array}$$

$$= \begin{array}{rr} \mathbf{6} & \mathbf{11} \\ 7 & 3 \\ \underline{-2} & \underline{4} \\ 4 & 7 \end{array} \quad (\textit{borrow } 8)$$

$$N = 47_8$$

Now let's try it with larger octal numbers:

Example:

$$
\begin{array}{lcccccl}
4627_8 - 3764_8 & = & N & & & & \\
 & = & 4 & 6 & 2 & 7 & \\
 & & \underline{-3} & \underline{7} & \underline{6} & \underline{4} & \\
 & & & & & & \\
 & = & & \mathbf{13} & & & \text{(borrow 8)} \\
 & & \mathbf{3} & \mathbf{5} & \mathbf{10} & & \text{(borrow 8)} \\
 & & 4 & 6 & 2 & 7 & \\
 & & \underline{-3} & \underline{7} & \underline{6} & \underline{4} & \\
 & & 0 & 6 & 4 & 3 &
\end{array}
$$

$$N = 643_8$$

In this lesson, we found that the octal numbering system is used in computers to represent binary numbers because it uses three times less the number of digits. It is also used because it's easier to convert to binary than it is the decimal system. We also found that performing octal math operations is very similar to working with decimal and binary numbering systems. So far in this unit, we've covered base ten numbers, base two numbers, and base eight numbers. Now we're going to take a look at base sixteen numbers, also known as the hexadecimal numbering system.

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

008. Octal basics

1. How many binary digits are required to represent a number as compared to the number of decimal digits it takes to represent that same number?

2. How many octal digits are required to represent a number as compared to the number of binary digits it takes to represent that same number?

3. Is it easier to convert decimal numbers to binary numbers or octal numbers to binary numbers?

4. What symbols does the octal numbering system use to represent numbers?

5. What is the base, or radix, of the octal numbering system?

6. What determines the value of a single digit in an octal number?

009. Perform octal numbering conversions

1. Briefly describe the process for converting octal numbers to decimal numbers.

2. Convert the following octal numbers to their decimal equivalents: (a) 73_8, (b) 460_8, (c) 1045_8, (d) 1724_8, (e) 4304_8, (f) 11762_8.

3. Which octal digit do you identify first when you convert decimal numbers to octal numbers? Which do you identify last?

4. Describe the general procedures for converting decimal numbers to octal numbers.

5. Convert the following decimal numbers to their octal equivalents: (a) 17_{10}, (b) 42_{10}, (c) 133_{10}, (d) 449_{10}, (e) 1680_{10}, (f) 19688_{10}.

6. What type of process is used to convert octal numbers to binary numbers?

7. Describe the relationship that exists between the binary numbering system and the octal numbering system which allows for ease in converting one system to the other.

8. Briefly describe the process for converting octal numbers to binary numbers.

9. Convert the following octal numbers to their binary equivalents: (a) 101_8, (b) 736_8, (c) 1062_8, (d) 1154_8, (e) 2031_8, (f) 6664_8.

10. What total number of digits must a binary number contain before it can be converted to its octal number equivalent?

11. How do you ensure a binary number contains the required number of digits to be converted to its octal equivalent?

12. How is binary-to-octal conversion similar to octal-to-binary conversion?

13. Briefly describe the process of converting binary numbers to octal numbers.

14. Convert the following binary numbers to their octal equivalents: (a) 1101_2, (b) 100100_2, (c) 11101010_2, (d) 11111111_2, (e) 100010111_2, (f) 100100111101_2.

010. Perform octal addition and subtraction

1. What technique is used to add octal numbers?

2. At what point during octal addition is a carry created?

3. What other technique can you use to add octal numbers besides the sum-and-carry technique?

4. Add the following octal numbers:

(*a*) 10	(*b*) 321	(*c*) 111	(*d*) 7654	(*e*) 4147	(*f*) 67215
+23	+76	+425	1316	2730	17451
			+402	+1651	+5363

5. When you perform octal subtraction, what is the value of a borrow?

6. Subtract the following octal numbers:

(*a*) 73	(*b*) 146	(*c*) 3426	(*d*) 4321	(*e*) 30716	(*f*) 12147
–21	–17	–517	–1476	–1325	–10655

1–5. Principles of the Hexadecimal Numbering System

Like the octal numbering system, the hexadecimal numbering system requires fewer digits to represent binary numbers than does the decimal system. As a matter of fact, it also requires only one-fourth as many digits as the binary system, making it very advantageous for use in microprocessors. This section discusses the basics of the hexadecimal (HEX) system, its conversion techniques for the decimal and binary systems, and hexadecimal mathematical operations.

011. Hexadecimal basics

As stated in previous sections of this volume, the binary numbering system is very useful in computer operations because of its simplicity. Unfortunately, it requires a large number of 1s and 0s to represent a numerical value. In the hexadecimal numbering system, one HEX digit can represent the same value as up to four binary digits, thereby decreasing the chances for error when you work with large numbers.

Hexadecimal, binary, and decimal systems comparison. The HEX system is very similar to the other numbering systems we have covered, differing mainly in the size of the radix. It uses 16 symbols (0,1,2,3,4,5,6,7,8,9,A,B,C,D,E, and F) to represent numbers and, therefore, has a base of 16. HEX values start with zero through nine (just like the decimal system) with the last six values represented by alphabetical characters. The decimal numbers 10 through 15 are represented by A through F, respectively.

HEX numbers are written like the other numbering systems we've discussed—the digits are arranged followed with a base number ($_{16}$) subscript—for example, $AF94_{16}$. They can also be written using a HEX symbol, "X", followed by the HEX characters and a prime mark—example: X'AF94'. AF94 is the HEX number and X' identifies it as being a base 16 number.

The HEX numbering system has the same characteristics as the other numbering systems we've discussed—a number's value is determined by digit size and placement, with each position in a number representing a different power of the base. Our next lesson illustrates the processes we use to convert the hexadecimal numbering system to other types of numbering systems. First up is decimal-to-hexadecimal conversion.

012. Perform hexadecimal numbering conversions

The processes for converting HEX numbers are very similar to the numbering conversions we've already covered. This lesson concentrates on converting the HEX system to the decimal and binary systems.

Hexadecimal-to-decimal-to-hexadecimal. Begin by converting HEX numbers to decimal numbers.

Hexadecimal-to-decimal. The process for converting HEX numbers to decimal numbers is the same as the conversion process used in the other systems we've studied. Begin by building yourself a PLACE value chart as we discussed earlier. Next, multiply the numerical value of your HEX digits times the powers of sixteen positions each digit occupies. Then, decimally add the results and write the new number with a base ten subscript. For example, let's convert $A9364_{16}$ to its decimal equivalent:

Example :

$$
\begin{array}{lcrcrcr}
A9364_{16} & = & N_{10} & & & & \\
 & = & 4\text{x}16^0 & = & 4\text{x}1 & = & 4 \\
 & & 6\text{x}16^1 & = & 6\text{x}16 & = & 96 \\
 & & 3\text{x}16^2 & = & 3\text{x}256 & = & 768 \\
 & & 9\text{x}16^3 & = & 9\text{x}4096 & = & 36864 \\
 & & \underline{+A\text{x}16^4} & = & 10\text{x}65536 & = & \underline{+655360} \\
 & & & & & = & 693092
\end{array}
$$

$$N = 693092_{10}$$

Figure 1–10 gives you another example. Notice that the PLACE value chart elements and the conversion process are the same for the HEX system as for the previous numbering systems we discussed. This is an important fact to remember when you convert any numbering system to the decimal numbering system. Now let's convert a decimal number to a hexadecimal number.

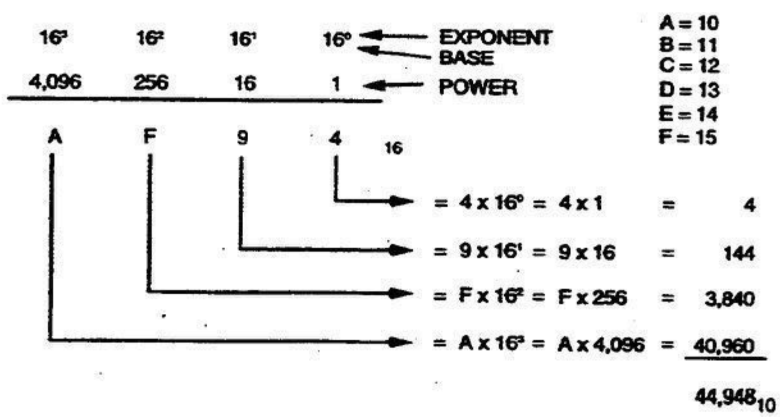


Figure 1–10. Hexadecimal PLACE value.

Decimal-to-hexadecimal. The process for converting decimal numbers to HEX numbers is quite different from the other methods we've studied. This is accomplished by DIVIDING the decimal number SUCCESSIVELY BY THE BASE of the HEX system. The steps for converting decimal numbers to HEX numbers are:

(1) Divide the decimal number by 16 and record the remainder.

(2) Next, divide the quotient from step 1 by 16 and record the remainder.

(3) Repeat step 2 until the quotient equals zero, recording the remainder each time.

(4) The FIRST remainder you recorded is the LSD and the LAST remainder you recorded is the MSD. Your intermediate remainders fall between the LSD and MSD in reverse order.

(5) Using HEX symbols A through F, where appropriate, write the new number with the HEX subscript base.

Let's convert 77235_{10} to its HEX equivalent using these steps:

Example : Convert 77235_{10} to its HEX equivalent .

Step 1.	$16\overline{)77235}$	=	4827,	*remainder*	3	=	[3]	=	LSD
Step 2.	$16\overline{)4827}$	=	301,	*remainder*	11	=	[B]	=	*intermediate digit*
Step 3.	$16\overline{)301}$	=	18,	*remainder*	13	=	[D]	=	*intermediate digit*
Step 4.	$16\overline{)18}$	=	1,	*remainder*	2	=	[2]	=	*intermediate digit*
Step 5.	$16\overline{)1}$	=	0,	*remainder*	1	=	[1]	=	MSD
Step 6.	77235_{10}	=	$12DB3_{16}$						

Now, let's check our result by converting our HEX number back to a decimal number:

Convert $12DB3_{16}$ to its decimal equivalent.

$$
\begin{aligned}
12DB3_{16} &= N \\
&= 3\text{x}16^0 = 3\text{x}16 = 3 \\
&\quad \text{B}\text{x}16^1 = 11\text{x}16 = 176 \\
&\quad \text{D}\text{x}16^2 = 13\text{x}256 = 3328 \\
&\quad 2\text{x}16^3 = 2\text{x}4096 = 8192 \\
&\quad \underline{+1\text{x}16^4} = 1\text{x}65536 = \underline{+65536} \\
&\quad = 77235
\end{aligned}
$$

$$N = 77235_{10}$$

Performing decimal-to-hexadecimal conversion is a little more complicated than binary and octal, but it is still a simple process as long as you follow the steps. Now, let's convert HEX numbers to binary numbers.

Binary-to-hexadecimal-to-binary. Conversion of binary numbers to HEX numbers is accomplished by a substitution method similar to that used to convert binary to octal (lesson 009). A number whose radix is a power of 2 can be directly converted to its equivalent value in another numbering system whose radix is also a power of 2. Since the HEX system has a radix of 16, or 2^4, we can use one HEX digit to represent four binary digits. Look at the following example: 1110_2 equals 14_{10}; E_{16} equals 14_{10}; therefore, 1110_2 equals E_{16}. Let's look at some more examples:

<u>BINARY NUMBER</u>	=	1111	1011	1101	0101
HEXADECIMAL NUMBER		F	B	D	5

Binary-to-hexadecimal. When converting binary numbers to HEX numbers, you must work with a binary number whose total number of digits are divisible by four. To get the required number of binary digits, you simply add zeros to the extreme left until you get a total number of digits divisible by four. If you're converting a binary number with a fractional portion, you may have to add zeros to the extreme left of the integer portion and/or to the extreme right of the fractional portion. The integer portion and the fractional portion must contain a number of digits divisible by four. Then, you use direct substitution to perform the conversion. Follow these steps:

(1) Add the required number of zeros to the binary number to get a total number of digits divisible by four.

(2) Substitute the HEX equivalent for each consecutive set of four binary digits. Use the HEX symbols for numbers above 9, where appropriate.

(3) Serially combine the HEX digits.

(4) Write the new HEX number with a subscript radix of 16.

Using the above steps, let's convert 1110110111010_2 to its HEX equivalent:

Example :

$$
\begin{aligned}
1110110111010_2 &= N_{16} \\
&= 1 \quad 1101 \quad 1011 \quad 1010 \\
&= 0001 \quad 1101 \quad 1011 \quad 1010 \\
&= 1_{16} \quad D_{16} \quad B_{16} \quad A_{16} \\
N &= 1DBA_{16}
\end{aligned}
$$

You can verify your results by converting both the binary number and the HEX number to decimal numbers and you will see they both equal 7610_{10}. Converting HEX numbers to binary numbers is just as easy.

Hexadecimal-to-binary. To convert a HEX number to a binary number, you simply substitute the four-digit binary numbers (adding placeholder zeros if necessary) for each of the HEX digits, join them serially, and apply the binary subscript radix. Let's try converting $3C4D_{16}$ to its binary equivalent:

$$\begin{aligned} 3C4D_{16} &= N_2 \\ &= 3_{16} \quad C_{16} \quad 4_{16} \quad D_{16} \\ &= 0011_2 \quad 1100_2 \quad 0100_2 \quad 1101_2 \\ N &= 11110001001101_2 \end{aligned}$$

Again, if you check the calculation for the above example by converting both numbers to their decimal equivalents, you'll see they both equal 15437_{10}. Besides converting HEX numbers, you also need to be able to perform HEX math operations. Next, we explain how to add and subtract hexadecimal numbers.

013. Perform hexadecimal addition and subtraction

Addition and subtraction in the HEX system is a little different than the other numbering systems we've studied, but it is performed using the same basic rules. First, let's look at HEX addition.

Hexadecimal addition. Hexadecimal addition uses the same sum-and-carry method as other numbering systems. A carry is generated any time a sum exceeds a number equal to the radix (16). The steps for adding HEX numbers are as follows:

(1) Add the LSD column as you would in the decimal system.

(2) Divide the total by 16. The quotient becomes a carry to the next column and the remainder becomes the sum of the LSD column.

(3) Repeat steps 1 and 2 for all columns until the addition is complete.

(4) The sum of the last column becomes your MSD.

Now, using these steps, let's add 9C2A, 342B, and 77F1:

1. A+B+1=10+11+1=22. 22/16=1, remainder 6. **6** is the LSD; carry the 1 to the next column.
2. 1 (carry from LSD column) +2+2+F=1+2+2+15=20. 20/16=1, remainder 4. **4** is the next significant digit; carry 1 to the next column.
3. 1 (carry from the previous column) +C+4+7=1+12+4+7=24. 24/16=1, remainder 8. **8** is the next significant digit; carry 1 to the next column.
4. 1 (carry from the previous column) +9+3+7=20. 20/16=1, remainder 4. **4** is the next significant digit; carry 1 to the next column.
5. 1 (carry from the previous column) +0=1; **1** becomes the MSD.

$9C2A+342B+77F1=N_{16}$

$$\begin{array}{lcrrrrcrrrrrl}
 & & & & & & & 1 & 1 & 1 & 1 & & \text{(carries)} \\
9C2A & = & 9 & 12 & 2 & 10 & = & & 9 & 12 & 2 & 10 & \\
342B & = & 3 & 4 & 2 & 11 & = & & 3 & 4 & 2 & 11 & \\
\underline{+77F1} & = & \underline{+7} & \underline{7} & \underline{15} & \underline{1} & = & & \underline{+7} & \underline{7} & \underline{15} & \underline{1} & \\
 & & & & & & & 1 & 4 & 8 & 4 & 6 &
\end{array}$$

$N = 14846_{16}$

You can verify your addition by converting each of the HEX numbers to its decimal equivalent, adding them up, and converting the sum back to HEX. You will find they are the same. As you can see, HEX addition is performed the same as any other numbering system. Try a few more examples on your own and then we'll move on to HEX subtraction.

Hexadecimal subtraction. The basic rules for subtraction are the same, regardless of the type of numbering system used. When a borrow is necessary to complete a subtraction, the borrow value is equal to the radix of that numbering system. In the HEX system, this is, of course, 16. The rules of subtraction for the HEX system are:

(1) Beginning with the LSD column, subtract the subtrahend digit from the minuend digit if the minuend digit is equal to or larger than the subtrahend digit.

(2) If the minuend digit is smaller, borrow 16 (BASE) from the next higher column that contains a significant digit. Reduce the value of the digit you borrowed from by 1.

(3) Add the borrowed value to your minuend digit.

(4) Now, you can subtract the subtrahend digit from the minuend digit.

(5) Repeat steps 1 through 4 for each column until the subtraction is complete.

Let's subtract 4D3B from CA47 using the above rules:

Example:

$$\begin{array}{lclllll}
CA47-4D3B & = & N & & & & \\
 & & B & 26 & 3 & 23 & \text{(borrows equal to the radix)} \\
CA47 & = & C & A & 4 & 7 & \text{minuend} \\
\underline{-4D3B} & = & \underline{-4} & \underline{D} & \underline{3} & \underline{B} & \text{subtrahend} \\
 & & 7 & D & 0 & C &
\end{array}$$

$N = 7D0C_{16}$

You can verify your results by converting the HEX numbers to another numbering system, such as decimal or binary, performing the subtraction, and converting the result back to hexadecimal.

You've seen from these lessons that the hexadecimal numbering system requires much fewer digits to represent large numbers than does either decimal, binary, or octal. We've shown that converting decimal numbers to HEX numbers requires the use of a division process; converting from HEX to decimal is performed by powers of sixteen notations; and binary-hexadecimal-binary conversion is accomplished through direct substitution. Finally, you've found that HEX addition and subtraction is performed by the same sum-and-carry and borrow-equal-to-radix methods used in all numbering systems. Next, you apply what you've learned about the various numbering systems to develop an understanding of commonly used number *coding* systems.

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

011. Hexadecimal basics

1. What symbols are used to represent numbers in the hexadecimal (HEX) numbering system?

2. What is the base, or radix, of the hexadecimal numbering system?

3. Define the decimal values for the hexadecimal alphabetical symbols.

4. What determines the value of a HEX digit?

012. Perform hexadecimal numbering conversions

1. Briefly describe the process for converting HEX numbers to their decimal equivalents.

2. Why are PLACE value charts useful when you convert HEX numbers to decimal numbers?

3. Convert the following hexadecimal numbers to their decimal equivalents: (a) 23_{16}, (b) 94_{16}, (c) $3A7_{16}$, (d) $CF85_{16}$, (e) $34DA_{16}$, (f) $F2CB1_{16}$.

4. Briefly describe the process for converting decimal numbers to hexadecimal numbers.

5. Which hexadecimal digit do you identify first when you convert decimal numbers to hexadecimal numbers? Which is the last hexadecimal digit you identify?

6. During decimal-to-hexadecimal conversion, in what order do you identify the intermediate hexadecimal digits?

7. Convert the following decimal numbers to their hexadecimal equivalents: (a) 40_{10}, (b) 176_{10}, (c) 435_{10}, (d) 1866_{10}, (e) 11734_{10}, (f) 1062991_{10}.

8. What method do you use to convert binary numbers to HEX numbers? What makes this possible?

9. How many digits must a binary number contain before you can convert it to a hexadecimal number?

10. Briefly describe the process for converting binary numbers to hexadecimal numbers.

11. Convert the following binary numbers to their hexadecimal equivalents: (a) 1101_2, (b) 11110_2, (c) 1010110_2, (d) 10011001_2, (e) 1111110110_2, (f) 11011001110_2.

12. What method do you use to convert hexadecimal numbers to binary numbers?

13. Briefly describe the process for converting hexadecimal numbers to binary numbers.

14. Convert the following hexadecimal numbers to their binary number equivalents: (a) C_{16}, (b) 24_{16}, (c) $D13_{16}$, (d) $2F51_{16}$, (e) $AF02_{16}$, (f) $3CBA_{16}$.

013. Perform hexadecimal addition and subtraction

1. What method do you use to add hexadecimal numbers?

2. Briefly describe the hexadecimal addition process.

3. Add the following hexadecimal numbers:

(*a*)	123	(*b*)	9C4A	(*c*)	AD7A	(*d*)	2D06	(*e*)	77D2	(*f*)	CDE4
	+456		+3FC6		+758B		+33F1		+9BAC		+B96F

4. What is the value of a *borrow* in hexadecimal subtraction?

5. Briefly describe the rules for hexadecimal subtraction.

6. Of the decimal, binary, octal, or hexadecimal numbering systems, which requires fewer digits to represent large numbers?

7. Subtract the following hexadecimal numbers:

(*a*)	1CD	(*b*)	400	(*c*)	D29	(*d*)	1B44	(*e*)	2857	(*f*)	38A2
	–143		–240		–C5		–115A		–441		–2BD0

1–6. Principles of Binary Coded Numbering Systems

Some computer systems do not use the numbering systems we discussed in previous sections of this volume. Instead, they use number coding techniques to represent the numerical values needed to complete their operations. This section covers two of the most common coding systems—the binary-coded decimal system and the gray code system.

014. Principles of the binary-coded decimal (BCD) numbering system

The binary-coded decimal (BCD) system is designed with the same basic principles as the numbering systems we've already learned. It is a PLACE value system with its own unique radix (N_{BCD}) that is used to represent decimal number values in a format more suitable for computer operations.

BCD basics. BCD uses a four-digit binary number to represent each of the ten decimal digits, 0 through 9. However, it does not use the same radix as the binary system and cannot represent or be converted to binary values. Also, the highest decimal value of one four-digit BCD number cannot exceed 9. The PLACE value of BCD digits are the same as the first four PLACE values of the binary system (8,4,2, and 1). Since the highest decimal value cannot exceed the number 9, the largest BCD digit will be 1001. This is because:

$$
\begin{aligned}
1001_{BCD} &= N_{10} \\
&= \quad 1xBCD^0 = 1x1 = 1 \\
&\quad +0xBCD^1 = 0x2 = 0 \\
&\quad +0xBCD^2 = 0x4 = 0 \\
&\quad \underline{+1xBCD^3} = \underline{1x8} = \underline{8} \\
&\qquad\qquad\qquad\qquad\quad 9 \\
N &= 9_{10}
\end{aligned}
$$

BCD, decimal, and binary systems comparison. To fully understand the BCD PLACE values, you need to create a chart or weight table showing the relationship between BCD and its decimal and binary equivalents:

Decimal		Binary Coded Decimal		Binary
0	=	0000	=	0000
1	=	0001	=	0001

Decimal		Binary Coded Decimal		Binary
2	=	0010	=	0010
3	=	0011	=	0011
4	=	0100	=	0100
5	=	0101	=	0101
6	=	0110	=	0110
7	=	0111	=	0111
8	=	1000	=	1000
9	=	1001	=	1001
10	=	0001 0000	=	1010
11	=	0001 0001	=	1011
14	=	0001 0100	=	1110
18	=	0001 1000	=	10010

You can see from looking at the chart that binary numbers and binary-coded decimal numbers are not the same for values beyond the decimal number 9. This is why the BCD system cannot be directly converted to the binary system. However, decimal numbers can be easily converted to BCD and vice versa.

015. Perform BCD numbering conversions

Due to the type of radix BCD uses, conversion techniques are limited to the decimal system only. Therefore, when you convert numbering systems other than decimals to BCD, convert them to their decimal equivalent FIRST. Then, convert the decimal number to its BCD equivalent. Decimal-to-BCD conversion is accomplished through simple substitution.

Decimal-to-BCD conversion. To convert a decimal value to its BCD equivalent, start with the least significant digit and work outwards. The steps for converting decimal numbers to BCD numbers are as follows:

(1) Write down the 8421 code for each decimal digit.

(2) Assign a four digit binary weight for each BCD digit code.

(3) Serially combine the binary digits and apply the BCD subscript radix.

Example: *Convert* 1806_{10} to its BCD equivalent.

Step 1.

1	8	0	6	Decimal number
8421	8421	8421	8421	BCD bit position weights

Step 2.

1	8	0	6	Decimal number
8421	8421	8421	8421	BCD bit position weights
0001	1000	0000	0110	BCD number

Step 3.

$$1086_{10} = 1100000000110_{BCD}$$

Converting decimal numbers to BCD numbers is a simple process as long as you understand the decimal system, the binary system, and the general rules for conversion. Next, we'll explore how to convert BCD numbers to decimal numbers.

BCD-to-decimal conversion. You have to remember that each group of BCD digits can only represent the decimal numbers 0 through 9 when you convert BCD numbers to decimals. Other than this, the process for conversion is just the reverse of the decimal-to-BCD process you just learned. The steps for this type of conversion are:

(1) Separate the BCD digits into groups of four, adding zeros where necessary and appropriate.

(2) Write down the BCD code for each group of binary digits.

(3) Substitute the decimal value for each of the BCD groups (use the value chart, if necessary).

(4) Serially combine the decimal digits and apply the decimal subscript radix.

Example: Convert 10000110001001_{BCD} to its decimal equivalent.

Step 1.

0010	0001	1000	1001	BCD *number*

Step 2.

8421	8421	8421	8421	BCD *bit position weights*
0010	0001	1000	1001	BCD *number*

Step 3.

8421	8421	8421	8421	BCD *bit position weights*
0010	0001	1000	1001	BCD *number*
2	1	8	9	*Decimal equivalent of* BCD *number*

Step 4.

$$10000110001001_{BCD} = 2189_{10}$$

The 8421 BCD code is just one of an infinite number of possible codes. When working with the BCD system, you must know the type code used in order to interpret it. This ends our discussion of the binary-coded decimal system.

016. Principles of the gray code number coding system

Take a moment to review the basic principles and conversion techniques before we continue on to our final lesson on number coding systems— the GRAY CODE system.

Gray code basics. The gray code is a cyclic number coding system. Within a cyclic code, only one digit changes value as it proceeds from one number to the next. This type of system is useful for binary counters and analog-to-digital converters used in some computers.

Perform gray code numbering conversions. The number conversion techniques used for the gray code system are simple variations of binary addition.

Binary-to-gray code conversion. Binary numbers are easily converted to gray code numbers using the following steps (refer to figure 1–11):

(1) Bring down the MSD of the binary number. This becomes the MSD of your gray code number.

(2) Beginning with the binary MSD, laterally add the binary digits two at a time and drop the carry (if any). The sum of the two digits (without the carry) becomes your next significant digit.

(3) Repeat step 2 for each additional digit, with the sum of the final two digits becoming the LSD of your gray code number.

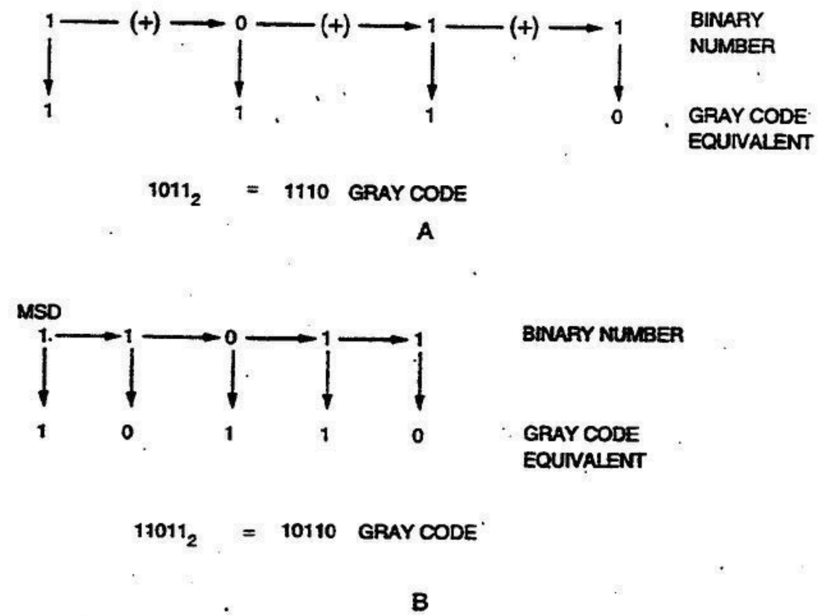


Figure 1–11. Binary to GRAY CODE conversion.

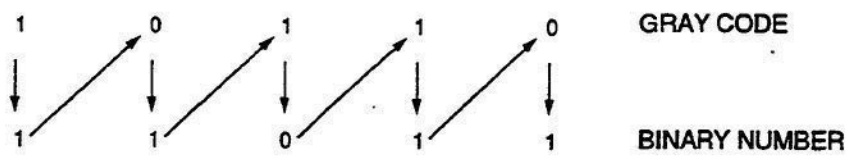
Converting gray code numbers to binary numbers is accomplished by applying a slight variation of this same binary addition technique.

Gray code-to-binary conversion. The process for converting gray code numbers to binary numbers is almost the same as converting binary numbers to gray code numbers except, instead of adding two successive binary numbers together, you add binary and gray code numbers together. The steps for converting gray code numbers to binary are as follows (refer to figure 1–12):

(1) Bring down the MSD of the gray code number. This becomes the MSD of your binary number.

(2) Add the binary MSD to the next gray code digit and drop the carry (if any). The sum of these two digits (without the carry) becomes the next significant digit of your binary number.

(3) Repeat step 2 for each successive binary number and gray code number, with the sum of the last two digits becoming the LSD of your binary number.



10110 GRAY CODE = 11011_2

Figure 1–12. GRAY CODE to binary conversion.

Gray code conversions are simple as long as you keep track of which type of conversion you're trying to do, gray code to binary, or binary to gray code.

This brings us to the end of this section on number coding systems as well as to the end of our first unit. Remember our discussions on algebra, the metric system, all of the different numbering systems (decimal, binary, octal, and hexadecimal), and the binary-coded decimal and gray code numbering systems. Practice the mathematical operations and conversion techniques for each until you're completely confident in your ability to handle them. Once in a while, come back and review this section because you'll soon find out that if you don't *use* what you learned here, you'll soon *lose* your ability to work with these skills. All you've learned here will be applied later as we study FUNDAMENTAL ELECTRONICS.

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

014. Principles of the binary-coded decimal (BCD) numbering system

1. What symbol represents the radix of the binary-coded decimal numbering system?

2. What comprises a single BCD digit?

3. What is the largest decimal value a single BCD digit can represent?

4. List all single BCD digits in ascending order of value.

5. List the BCD equivalents for the decimal values 10 through 20.

6. Why can't BCD numbers be directly converted to binary numbers?

7. Can BCD numbers be converted directly to decimal numbers?

015. Perform BCD numbering conversions

1. What is the only numbering system to which the binary-coded decimal system can be directly converted?

2. What must be accomplished before you can convert a binary-coded decimal number to any numbering system other than the decimal numbering system?

3. What conversion method do you use to convert decimal numbers to their BCD equivalents?

4. Briefly describe the steps for converting decimal numbers to binary-coded decimal numbers.

5. Convert the following decimal numbers to their BCD equivalents using the 8421 binary-coded decimal code: (a) 7, (b) 11, (c) 33, (d) 50, (e) 102, (f) 1679.

6. What conversion method do you use to convert BCD numbers to their decimal equivalents?

7. Briefly describe the process for converting BCD numbers to decimal numbers.

8. What information must be given before a binary-coded decimal system can be interpreted? Why?

9. Convert the following 8421 binary-coded decimal numbers to their decimal equivalents: (a) 10110_{BCD}, (b) 110101_{BCD}, (c) 10011001_{BCD}, (d) 100100110101_{BCD}, (e) 11010100000110_{BCD}, (f) 11000010101100001_{BCD}.

016. Principles of the gray code number coding system

1. What type of number coding system is the gray code? Explain.

2. Name two popular telecommunication uses for the gray code number coding system.

3. What method do you use for gray code conversion?

4. When you convert binary numbers to gray code numbers, what determines the most significant (MSD) digit of the converted gray code number?

5. Briefly describe the process for converting binary numbers to gray code numbers.

6. Convert the following binary numbers to their gray code number equivalents: (a) 111_2, (b) 0010_2, (c) 10101_2, (d) 111010_2, (e) 100101111_2, (f) 111111111_2.

7. Explain the major difference between binary-to-gray code conversion and gray code-to-binary conversion.

8. How is the binary number's most significant digit (MSD) determined when you perform gray code-to-binary conversion?

9. Briefly describe the process for converting gray code numbers to their binary number equivalents.

10. Convert the following gray code numbers to their binary equivalents: (a) 101 GRAY CODE, (b) 1001 GRAY CODE, (c) 11011 GRAY CODE, (d) 110110 GRAY CODE, (e) 11101101 GRAY CODE, (f) 10010110011 GRAY CODE.

Answers to Self-Test Questions

001

1. Ten. They are: 0,1,2,3,4,5,6,7,8,9.
2. PLACE refers to the position a digit holds in relation to the decimal point. It determines how many times the digit is multiplied by powers of ten to determine its VALUE.
3. The exponent tells how many times the base is used as a factor.
4. (1) d, (2) e, (3) b, (4) a, (5) c, (6) f.
5. The radix identifies the type of numbering system represented. It is expressed as a subscript to the number.
6. The fractional portion of a number carries a negative exponent because it represents a number less than one.

002

1. Scientific notation allows you to keep a fixed decimal point in your calculations, regardless of the size of the numbers. It leaves less room for error and makes large numbers easier to handle.
2. The exponent is used to show the power to which a quantity is raised, or how many times the quantity is multiplied by itself.
3. Move the decimal point to the left when you convert whole numbers to powers of ten expressions.
4. Powers of ten expressions of whole numbers carry a positive exponent.
5. (a) 3.21×10^2, (b) 1.046×10^3, (c) 4.7397×10^4, (d) 1.09907×10^5, (e) 7.333208×10^6, (f) 1.1435×10^2.
6. Move the decimal point to the right when converting decimal fractions to powers of ten expressions.
7. Decimal fractions carry a negative exponent when converted to powers of ten expressions.
8. (a) 3.37×10^{-1}, (b) 4.492×10^{-1}, (c) 9.8461×10^{-2}, (d) 1.0×10^{-7}, (e) 1.24436×10^{1}, (f) 9.043366×10^{2}.
9. You add the exponents when you multiply powers of ten expressions.
10. (a) 10^5, (b) 10^7, (c) 10^{13}, (d) 10^0, (e) 10^8, (f) 10^{-3}.
11. You must subtract the exponents when you divide powers of ten expressions.
12. Any number raised to a power of zero will always equal one.
13. (a) kilo/k, (b) mega/M, (c) giga/G, (d) deci/d, (e) nano/n, (f) pico/p.
14. (a) 10^2, (b) 10^{-4}, (c) 10^{14}, (d) 10^{-2}, (e) 10^{10}, (f) 10^{-4}, (g) 10^{12}, (h) 10^3, (i) 10^2.

003

1. (1) a, (2) e, (3) c, (4) h, (5) d,g, (6) b, (7) f.

2. To add two signed numbers of the same sign, add their absolute values and place the common sign prefixed to the sum.
3. To add two signed numbers of opposite signs, subtract the smaller absolute value from the larger absolute value and place the sign of the larger absolute value prefixed to the difference.
4. The process of subtraction is opposite the process of addition. When you perform subtraction, you're changing the sign of the number you are subtracting and then adding it to the other number.
5. (a) n=+16, (b) n=+40, (c) n=-19, (d) n=-41, (e) n=+8, (f) n=+3.8.
6. (a) n=-12, (b) n=-2, (c) n=+17, (d) n=-5, (e) n=-6, (f) n=-29.

004

1. The logarithm of a number is the power to which the base must be raised to equal that number.
2. 1,2,3.
3. The common logarithm system uses base ten.
4. The first part is a whole number (integer), called the characteristic. The second part is a decimal number, called the mantissa.
5. You identify the characteristic first, then the mantissa.
6. The characteristics of logarithms of numbers greater than one are always positive. The characteristics of logarithms of numbers less than one are always negative.
7. Characteristics of logarithms are identified by inspection or by powers of ten notation.
8. To use the inspection method to identify the characteristic of a logarithm of a number greater than 1, simply count the number of places to the left of the decimal point and subtract 1.
9. To use the inspection method to identify the characteristic of a logarithm of a number less than 1, simply count the number of zeros immediately to the right of the decimal point and add 1.
10. The characteristic of a logarithm is automatically exposed when using the powers of ten notation method, requiring no mental calculation as does the inspection method. Also, the powers of ten notation method converts numbers to a range compatible with most common logarithm tables.
11. You identify the characteristic of a logarithm for a number by converting the number to its powers of ten notation. The exponent within the expression becomes the characteristic of the number's logarithm.
12. No. Only the characteristic of a logarithm can be negative.
13. When converted to their powers of ten expressions, the fractional portion of all three numbers are the same, and it is this portion that is used to identify the mantissa of a logarithm for a number.
14. The least-means difference portion of a common logarithm table is used to identify the least-means value of a mantissa for the logarithm of a number.
15. (a) 1.2304, (b) 1.5051, (c) 1.8831, (d) 2.3560, (e) 2.9215, (f) 3.3680.
16. An antilogarithm is the decimal number corresponding to a logarithm.
17. First, you identify the fractional portion of the antilog by locating the mantissa of the logarithm within the log table and following it backwards to its decimal value on the number line. Next, you convert the characteristic of the log to its powers of ten expression. Finally, you multiply the two portions together to get the antilogarithm.

18. (a) 3090, (b) 82.9, (c) 75300, (d) 259400000, (e) 4582, (f) 319.5.

005

1. The symbols, 0 and 1, are used to represent numbers in the binary numbering system.
2. The binary numbering system is a base two numbering system.
3. The decimal value of a binary digit is determined by its placement within the number sequence, based on the powers of two.
4. As the exponent increases in the binary numbering system, the power doubles itself.
5. A correctly constructed PLACE value chart provides a visual representation of the value of each digit of a number and can be used to convert one numbering system to another.
6. (1) a, (2) a, (3) c, (4) a,c, (5) b, (6) b, (7) a, (8) b, (9) a.

006

1. The most significant digit is the first position you identify when you convert decimal numbers to binary numbers.
2. The general process for converting decimal numbers to binary numbers is to successively divide the decimal number by powers of two values until the remainder is reduced to zero, recording the divisor from each step as successive binary digits.
3. During decimal-to-binary conversion, a PLACEHOLDER (0) is assigned as the binary digit for a power of two that will not divide into the decimal number.
4. The correct method for displaying a binary number is with the MSD to the far left, the LSD to the far right, with successive digits falling between the two, and the subscript base affixed to the LSD.
5. (a) 101_2, (b) 10001_2, (c) 101000_2, (d) 1000100_2, (e) 1101100_2, (f) 101000001_2, (g) 1000011111_2, (h) 1111111010_2, (i) 100010101110_2.
6. The two methods for converting binary numbers to decimal numbers are the powers of two method and conversion using a PLACE value chart method.
7. To convert a binary number to its decimal equivalent using the powers of two method, you simply multiply each binary digit by its power of two place value, decimally add all of the products, and affix the decimal radix.
8. To convert a binary number to its decimal equivalent using the PLACE value chart method, you apply your binary number to the chart's number line, decimally add all the power values for the columns containing a binary 1 digit, and affix the decimal radix.
9. (a) 2_{10}, (b) 3_{10}, (c) 14_{10}, (d) 20_{10}, (e) 29_{10}, (f) 98_{10}, (g) 121_{10}, (h) 170_{10}, (i) 379_{10}.

007

1. The sum of a column containing an even number of binary 1s always equals 0.
2. The sum of a column containing an odd number of binary 1s always equals 1.
3. Whenever two binary 1s are added together during binary addition, a value of 0 is recorded and a binary 1 is carried to the next column of numbers.
4. The right-hand column of numbers is always added first during binary addition because its sum becomes the least significant digit of the total sum. Also, if carries are created from the addition process, they are carried to the next higher column, not the next lower column.
5. (a) 1110, (b) 100010, (c) 110010, (d) 11010100, (e) 1000100100, (f) 100011101.

6. In binary subtraction, you must borrow from the next higher column of numbers any time you're required to subtract 1 from 0.
7. A borrow is equal to the place value of the column it comes from, if viewed from a decimal system perspective. A borrow is always equal to the radix of the numbering system used, if viewed from the numbering system's base perspective.
8. (a) 11, (b) 110, (c) 10001, (d) 101000, (e) 11111, (f) 110011.

008

1. It takes three to four times as many binary digits to represent a number than it does to represent that same number in the decimal numbering system.
2. It only requires one-third the number of digits to represent a number in the octal numbering system as it does in the binary numbering system.
3. It is much easier to convert octal numbers to binary numbers than it is to convert decimal numbers to binary numbers.
4. The octal numbering system uses the symbols 0,1,2,3,4,5,6, and 7 to represent numbers.
5. The octal numbering system is a base 8 numbering system.
6. The value of a digit in an octal number is equal to the digit multiplied by the power of the PLACE it occupies.

009

1. To convert octal numbers to decimal numbers, you convert your octal digits to powers of eight expressions, decimally add the results, and affix the decimal subscript radix.
2. (a) 59_{10}, (b) 304_{10}, (c) 549_{10}, (d) 980_{10}, (e) 2244_{10}, (f) 5106_{10}.
3. When you convert decimal numbers to their octal equivalents, the first octal digit you identify is the most significant digit and the last you identify is the least significant digit.
4. To convert a decimal number to its octal equivalent; you successively divide the highest possible power of eight into the decimal number, determine how many times that power of eight will divide into the decimal number, retain this multiple as your octal digit, and continue the process until the remainder is reduced to zero. The first octal digit identified is your MSD, the last octal digit identified is your LSD, and the intermediate octal digits fall between in the order they are identified.
5. (a) 21_8, (b) 52_8, (c) 205_8, (d) 701_8, (e) 3220_8, (f) 46350_8.
6. A substitution process is used to convert octal numbers to binary numbers.
7. The base of the octal system is 8; the base of the binary system is 2, and 2^3 equals 8. Therefore, one octal digit can be expressed as three binary digits.
8. To convert octal numbers to binary numbers; substitute the three-digit binary number equivalent for each octal digit (starting with the octal MSD), serially combine the binary digits, and apply the binary subscript radix.
9. (a) 1000001_2, (b) 111011110_2, (c) 1000110010_2, (d) 1001101100_2, (e) 10000011001_2, (f) 110110110100_2.
10. Before a binary number can be converted to its octal equivalent, it must contain a total number of digits that is divisible by three.
11. To condition a binary number for conversion to its octal equivalent, you must add placeholder zeros to the extreme left of the integer portion and to the extreme right of the fractional portion (if any) until the total number of binary digits is divisible by three.

12. Binary-to-octal conversion and octal-to-binary conversion are both accomplished using a substitution process.

13. To convert a binary number to its octal equivalent; you add enough placeholder zeros to get a total number of binary digits which is divisible by three, substitute one octal digit equivalent for each consecutive group of three binary digits, then serially combine the octal digits and affix the appropriate radix.

14. (a) 15_8, (b) 44_8, (c) 352_8, (d) 377_8, (e) 427_8, (f) 4475_8.

010

1. The sum-and-carry technique is used to add octal numbers.
2. A carry is created during the octal addition process any time a sum exceeds the number 7.
3. An octal matrix table may be used to perform octal addition; however, this is not the preferred method.
4. (a) 33_8, (b) 417_8, (c) 536_8, (d) 11574_8, (e) 10750_8, (f) 114251_8.
5. If a borrow is necessary when performing octal subtraction, the value of the borrow is equal to the radix, or 8.
6. (a) 52_8, (b) 127_8, (c) 2707_8, (d) 2623_8, (e) 27371_8, (f) 1272_8.

011

1. The hexadecimal numbering system uses the symbols 0,1,2,3,4,5,6,7,8,9,A,B,C,D,E, and F to represent numbers.
2. The hexadecimal numbering system is a base 16 numbering system.
3. Hexadecimal alphabetical symbols A through F have a decimal value of 10 through 15, respectively.
4. The value of a HEX digit is determined by its size, placement, and power of sixteen position within the HEX number.

012

1. To convert a HEX number to its decimal equivalent; multiply the numerical value of each HEX digit by the power of sixteen position each digit occupies, then decimally add the values together and affix the subscript base ten radix.
2. PLACE value charts, when constructed correctly, provide a visual representation of the conversion process.
3. (a) 35_{10}, (b) 148_{10}, (c) 935_{10}, (d) 53125_{10}, (e) 13530_{10}, (f) 994481_{10}.
4. To convert decimal numbers to hexadecimal numbers, you; divide 16 into the decimal number and record the remainder as a hexadecimal digit, divide the resulting quotient by 16 and record the remainder as a hexadecimal digit, successively divide the quotients by 16 until the final quotient is reduced to zero, and record each remainder as a hexadecimal digit.
5. During the conversion of decimal numbers to hexadecimal numbers, the least significant digit (LSD) is the first HEX digit identified and the most significant digit (MSD) is the last HEX digit identified.
6. During the decimal-to-hexadecimal conversion process, the intermediate HEX digits are identified in reverse order.
7. (a) 28_{16}, (b) $B0_{16}$, (c) $1B3_{16}$, (d) $74A_{16}$, (e) $2DD6_{16}$, (f) $10384F_{16}$.

8. Binary-to-hexadecimal conversion is accomplished by a substitution process. This is possible due to the relationship between the base two and base sixteen where four binary digits can represent one HEX digit.
9. For a binary number to be converted to a hexadecimal number, it must contain a total number if digits that is divisible by four.
10. To convert a binary number to its hexadecimal equivalent, you; add the required number of placeholder zeros to have a total number of binary digits that is divisible by four, substitute one HEX digit equivalent for each group of four consecutive binary digits, serially combine the HEX digits and affix the appropriate radix.
11. (a) D_{16}, (b) $1E_{16}$, (c) 56_{16}, (d) 99_{16}, (e) $3F6_{16}$, (f) $6CE_{16}$.
12. Hexadecimal-to-binary conversion is accomplished by using a substitution process.
13. To convert HEX numbers to binary numbers, you substitute four-digit binary number equivalents (adding placeholder zeros if necessary) for each HEX digit, serially combine the binary digits, and affix the appropriate radix.
14. (a) 1100_2, (b) 100100_2, (c) 110100010011_2, (d) 10111101010001_2, (e) 1010111100000010_2, (f) 11110010111010_2.

013

1. The hexadecimal numbering system uses the sum-and-carry method to add HEX numbers.
2. To add hexadecimal numbers, begin by adding the numbers in the LSD column as you would for the decimal system. Next, divide the total by 16, recording the remainder as the sum of the column and the quotient as a carry to the next column. Repeat for the remaining columns.
3. (a) 579_{16}, (b) $DC10_{16}$, (c) 12305_{16}, (d) $60F7_{16}$, (e) $1137E_{16}$, (f) 18753_{16}.
4. A borrow in any numbering system is equal to the radix of that system; in the hexadecimal system, a borrow is equal to 16.
5. Beginning with the LSD column, subtract the subtrahend digit from the minuend digit. If the minuend is smaller than the subtrahend, borrow from the next column, then perform the subtraction. Repeat for the remaining columns.
6. The hexadecimal numbering system requires fewer digits to represent large numbers than does the decimal system, binary system, or octal system.
7. (a) 8A, (b) 1C0, (c) C64, (d) 9EA, (e) 2416, (f) CD2.

014

1. The symbol used to represent the radix of the binary-coded decimal numbering system is a subscript BCD (N_{BCD}).
2. A BCD digit is comprised of a four-digit binary number.
3. The largest decimal value a single BCD digit can represent is 9.
4. The single BCD digits in ascending order of value are: 0000_{BCD}, 0001_{BCD}, 0010_{BCD}, 0011_{BCD}, 0100_{BCD}, 0101_{BCD}, 0110_{BCD}, 0111_{BCD}, 1000_{BCD}, and 1001_{BCD}.
5. The BCD equivalents for decimal values 10 through 20 are: 10000_{BCD}, 10001_{BCD}, 10010_{BCD}, 10011_{BCD}, 10100_{BCD}, 10101_{BCD}, 10110_{BCD}, 10111_{BCD}, 11000_{BCD}, 11001_{BCD}, and 100000_{BCD} respectively.
6. BCD numbers cannot be directly converted to binary numbers because they are not the same for values beyond the value of 1001_2.
7. BCD numbers can easily be converted to decimal numbers and vice versa.

015

1. The binary-coded decimal system can only be directly converted to the decimal numbering system.
2. Before a BCD number can be converted to something other than a decimal number, it must first be converted to its decimal equivalent, then the decimal number can be converted to other numbering systems.
3. Decimal numbers are converted to their BCD equivalents using a simple substitution process.
4. To convert decimal numbers to BCD numbers, you write the 8421 code for each decimal digit, assign a four-digit binary weight for each BCD digit code, then serially combine the binary digits and apply the BCD subscript radix.
5. (a) 111_{BCD}, (b) 10001_{BCD}, (c) 110011_{BCD}, (d) 1010000_{BCD}, (e) 100000010_{BCD}, (f) 1011001111001_{BCD}.
6. BCD numbers are converted to their decimal equivalents using a substitution process.
7. To convert BCD numbers to decimal numbers, you: separate the BCD number into groups of four binary digits (adding placeholder zeros where appropriate), apply BCD position weights for each group, substitute the decimal equivalent for each group, then serially combine the decimal digits and affix the subscript decimal radix.
8. The type of code being used must be known before a BCD system can be interpreted because the 8421 code is just one of an infinite number of possible codes available.
9. (a) 16_{10}, (b) 35_{10}, (c) 99_{10}, (d) 935_{10}, (e) 3506_{10}, (f) 18561_{10}.

016

1. The gray code number coding system is a cyclic code in which only one digit changes value when proceeding from one number to the next.
2. The gray code number coding system is used in some binary counters and analog-to-digital signal converters.
3. Gray code conversion is accomplished using a variation of binary addition.
4. A gray code's MSD is always the same as the binary number's MSD when converting a binary number to its gray code equivalent.
5. To convert a binary number to its gray code equivalent: first, bring down the MSD of the binary number as the MSD of your gray code number. Then, beginning with the MSD, laterally add the binary digits two at a time and drop the carry; the sum of which becomes the gray code number's next significant digit. Continue adding in this manner for the remaining binary digits, with the sum of the last two digits to be used as the gray code number's LSD.
6. (a) 100 GRAY CODE, (b) 0011 GRAY CODE, (c) 11111 GRAY CODE, (d) 100111 GRAY CODE, (e) 110111000 GRAY CODE, (f) 100000000 GRAY CODE.
7. Converting gray code numbers to binary numbers is almost the same as converting binary numbers to gray code numbers except, instead of adding two binary digits together at a time, you add a binary digit and a gray code digit.
8. When converting gray code numbers to their binary equivalents, the binary number's MSD is always the same as the gray code number's MSD.
9. To convert a gray code number to a binary number: first, bring down the gray code number's MSD to use as the binary number's MSD. Next, add the binary MSD to the next gray code digit and drop the carry to determine the binary number's next significant digit. Repeat for the

remaining binary and gray code digits with the sum of the last two digits to be used as the binary number's LSD.

10. (a) 110_2, (b) 1110_2, (c) 10010_2, (d) 100100_2, (e) 101101110_2, (f) 11100100010_2.

Do the Unit Review Exercises (URE) before going to the next unit.

Unit Review Exercises

Note to Student: Consider all choices carefully, select the *best* answer to each question, and *circle* the corresponding letter. When you have completed all unit review exercises, transfer your answers to ECI Form 34, Field Scoring Answer Sheet.

Do not return your answer sheet to ECI.

1. (001) In the number 13467_{10}, the number 7 is the
   a. most significant digit.
   b. least significant digit.
   c. equivalent of $10x7^0$.
   d. equivalent of $7x10^1$.

2. (001) In the number 12_{10}, the 10 is the
   a. most significant digit (MSD).
   b. least significant digit (LSD).
   c. exponent.
   d. radix.

3. (002) What is the correct scientific notation for 6,870,000?
   a. 0.687×10^4.
   b. 6.87×10^5.
   c. 6.87×10^6.
   d. 687×10^7.

4. (002) The algebraic expression for the product of $10^6$and 10^{-12} is
   a. 10^6.
   b. 10^{-6}.
   c. 10^{18}.
   d. 10^{-18}.

5. (002) What is the correct scientific notation for 0.005 mW?
   a. 5×10^{-3}.
   b. 5×10^{-4}.
   c. 5×10^{-5}.
   d. 5×10^{-6}.

6. (003) Add (-14) + (-7).
   a. -7.
   b. -14.
   c. -21.
   d. -28.

7. (003) Subtract the following: 60-(+3)-30-14
   a. -13.
   b. 13.
   c. 19.
   d. 73.

8. (004) What is the logarithm of 1000_{10}?
   a. 1.
   b. 3.
   c. 4.
   d. 10.

9. (004) What is the logarithm of 3.43?
   a. 0.5353.
   b. 0.8189.
   c. 1.2673.
   d. 1.7899.

10. (004) What number is represented by the logarithm 1.5740?
    a. 86.7.
    b. 74.6.
    c. 52.3.
    d. 37.5.

11. (005) A zero in any binary number performs the function of
    a. a divider.
    b. an expander.
    c. a multiplier.
    d. a placeholder.

12. (006) Convert 104_{10} to its binary equivalent.
   a. 1001001_2.
   b. 1011100_2.
   c. 1101000_2.
   d. 1110010_2.

13. (006) Convert 110110_2 to its decimal equivalent.
   a. 88.
   b. 64.
   c. 54.
   d. 28.

14. (007) Add the following binary numbers:

$$\begin{array}{r} 1011011 \\ 10111 \\ 100001 \\ \underline{+101111} \end{array}$$

   a. 11001110.
   b. 10111110.
   c. 11000010.
   d. 10001110.

15. (007) Subtract 1011_2 from 11001_2.
   a. 1001_2.
   b. 1011_2.
   c. 1100_2.
   d. 1110_2.

16. (008) The value of a digit in an octal number is equal to the digit multiplied by
   a. itself.
   b. the octal base.
   c. the decimal number, 8.
   d. the power of the place it occupies.

17. (009) Convert 2371_8 to its equivalent decimal number.
   a. 1017_{10}.
   b. 1267_{10}.
   c. 1273_{10}.
   d. 1274.

18. (009) What is the octal equivalent of 54_{10}?
   a. 12_8.
   b. 44_8.
   c. 66_8.
   d. 72_8.

19. (009) What is the octal number for 101101_2?
   a. 53_8.
   b. 55_8.
   c. 66_8.
   d. 67_8.

20. (010) Add 46_8 and 43_8.
   a. 89_8.
   b. 97_8.
   c. 111_8.
   d. 121_8.

21. (010) Subtract 37_8 from 124_8.
   a. 65_8.
   b. 77_8.
   c. 87_8.
   d. 93_8.

22. (011) How do you compute the place value of the number 3 in 132_{16}?
   a. Multiply 3 times 16^0.
   b. Multiply 3 times 16^1.
   c. Divide 3 into 16.
   d. Divide 16 into 32.

23. (012) Convert $7CB_{16}$ to its decimal equivalent.
    a. 1995_{10}.
    b. 2763_{10}.
    c. 6372_{10}.
    d. 9719_{10}.

24. (012) Convert $EF58_{16}$ to its binary equivalent.
    a. 1110111101011000_2.
    b. 1111110101001000_2.
    c. 1100100101100010_2.
    d. 1101111101100010_2.

25. (013) Add these hexadecimal numbers:

```
 1F2B
 3CEF
+2594
```

a. 2839.
b. 6237.
c. 80AF.
d. 81AE.

26. (013) Subtract these hexadecimal numbers:

```
 8B5D4F
–5A3218
```

a. 421A37.
b. 412C37.
c. 321A28.
d. 312B37.

27. (014) One binary coded decimal number *cannot* exceed a decimal value greater than
   a. 15.
   b. 9.
   c. 7.
   d. 1.

28. (015) Convert 1590_{10} to BCD.
   a. 100010001000_{BCD}.
   b. 110010001000_{BCD}.
   c. 1010110010000_{BCD}.
   d. 10010110010000_{BCD}.

29. (015) Convert 100110000111_{BCD} to its decimal equivalent.
   a. 987_{10}.
   b. 789_{10}.
   c. 601_{10}.
   d. 106_{10}

30. (016) Convert $11111_{GRAY\ CODE}$ to its binary equivalent.
   a. 10000_2.
   b. 10001_2.
   c. 10010_2.
   d. 10101_2.

Please read the unit menu for Unit 2 and continue. ➔

Unit 2. Fundamental Electronics

Page

Our career field has changed drastically in recent years. As major new communications systems are installed and older systems are digitized, the need to maintain a higher degree of knowledge in fundamental electronics has become necessary. One of the prime benefactors of this knowledge is the technical controllers working in base central test facilities (BCTFs).

Most of the information in this unit is based on the *theory* surrounding the elements of electricity. A theory is merely an idea or a line of reasoning believed to be correct. Theories are stated to explain the phenomena and facts found during experiments. Many theories that at first appeared to be valid are later discarded or revised as new discoveries are made. This has been especially true in the field of electricity. In this unit, we discuss the elements of electricity, fundamentals of DC, magnetism, and fundamentals of AC.

2–1. Elements of Electricity

We begin this section with an elementary discussion of the nature of matter and structure of the atom. We then explain the concept of electrical current flow as a drift of millions of negatively charged particles called electrons. We discuss the devices for producing current flow and define many basic electrical units and describe how they are used.

017. The structure of matter

Matter is anything that occupies space and has weight; that is, the weight and dimensions of matter can be measured. Examples of matter are air, water, automobiles, clothing, and our own bodies. Matter may be found as a solid, liquid, or gas.

Elements. An element is a substance that cannot be reduced to a simpler substance by chemical means. Examples of elements that you have contact with everyday are iron, gold, silver, copper, and oxygen. There are now known to be 103 elements; all the different substances we know about are composed of one or more of these elements.

When two or more elements are chemically combined, the resulting substance is called a *compound.* A compound is a chemical combination of elements that can be separated by chemical, but *not* by physical means. Examples of common compounds are water, which consists of the elements hydrogen and oxygen, and table salt, which consists of sodium and chlorine. A *mixture,* on the other hand, is a combination of elements or compounds, not chemically combined, that *can* be separated by physical means. Examples of mixtures are air (which is made up of nitrogen, oxygen, carbon dioxide, and small amounts of several rare gases) and sea water (which consists chiefly of sa... and water).

Molecules. A molecule is the smallest particle of a compound that has all the characteristics of the compound. Matter is made up of molecules.

Consider water, for example. Water is matter since it occupies space and has weight. Depending on the temperature, it may exist as a liquid, a solid, or a gas under the common names of water, ice, or steam. Regardless of the temperature, it still has the same composition. If we start with a quantity of water, divide it and pour out one-half, divide the remainder and pour out one-half, and continue this process a sufficient number of times, we eventually end up with a quantity of water that cannot be further divided without ceasing to be water. This quantity is called a molecule of water. If this molecule of water is divided, instead of there being two parts of water, there will be one part of oxygen and two parts of hydrogen (H_2O). Hydrogen and oxygen are both gases at normal temperature and pressure.

Atoms. Molecules are made up of smaller particles called *atoms*. An atom is the smallest particle of an element that retains the characteristics of that element. The atoms of one element, however, differ from the atoms of all other elements. Since there are approximately 103 known elements, there must be 103 different atoms, or a *different* atom for each element. Just as thousands of words can be made by combining the proper letters of the alphabet, so thousands of different materials can be made by chemically combining the proper atoms.

Any particle that is a chemical combination of two or more atoms is a *molecule*. The oxygen molecule consists of two atoms of oxygen, and the hydrogen molecule consists of two atoms of hydrogen. Sugar, on the other hand, is a compound composed of atoms of carbon, hydrogen, and oxygen. These atoms are combined into sugar molecules. Since a sugar molecule can be broken down by chemical means into smaller and simpler units, we cannot have sugar atoms.

The atoms of each element are made up of *electrons, protons,* and in most atoms, *neutrons;* which collectively are called *subatomic particles*. Furthermore, the electrons, protons, and neutrons of one element are identical to those of any other element. There are different kinds of elements because the number and arrangement of the electrons and protons within an atom are different in the different elements.

An electron is a small negative charge of electricity. A proton has a positive charge of electricity equal in charge, but of opposite polarity, to the charge of the electron. Scientists have measured the mass and size of electrons and protons and know how much charge each possesses. Although electrons and protons have the same quantity of charge, the mass of a proton is approximately 1,837 times that of an electron.

In some atoms, there exists a neutral particle called a *neutron*. A neutron has a mass approximately equal to that of a proton, but has no electrical charge. According to popular theory, the electrons, protons, and neutrons of atoms are thought to be arranged in a manner similar to a miniature solar system. The protons and neutrons form a heavy nucleus with a positive charge around which the very light electrons revolve. The exact nature of these orbits is somewhat hazy, but an electron is believed to have several motions that complicate its behavior.

Hydrogen and helium atoms (fig. 2–1) have a relatively simple structure. A hydrogen atom has only one proton in its nucleus, with one electron rotating about it. A helium atom is a little more complex. It has a nucleus made up of two protons and two neutrons with two electrons rotating about the nucleus. Atoms of sulfur and copper are still more complex, as shown in figure 2–2.

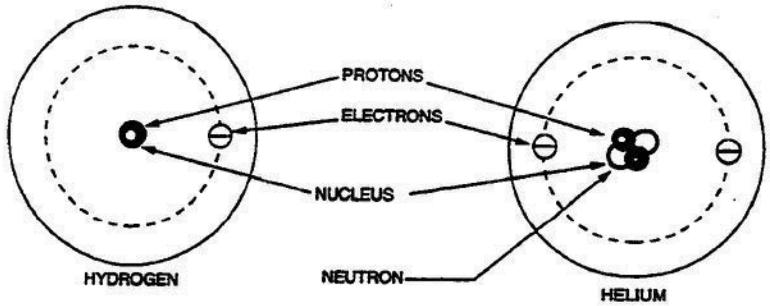


Figure 2–1. Structure of simple atoms.

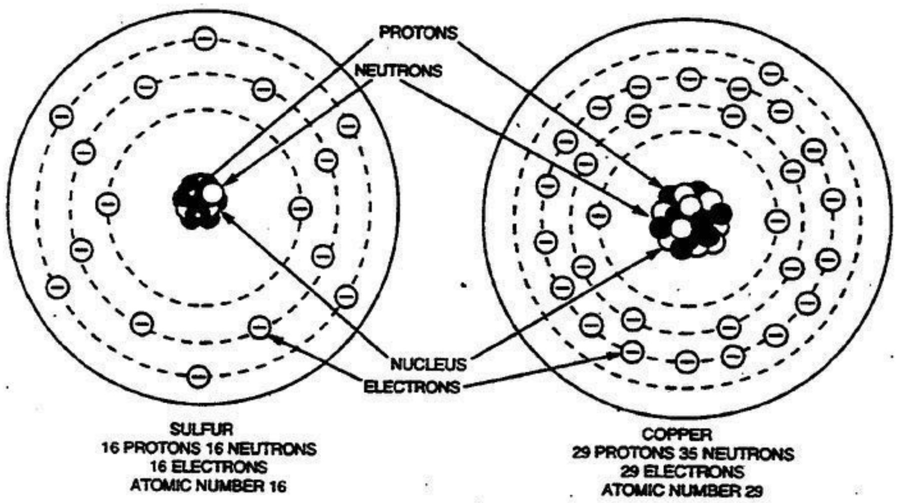


Figure 2–2. Structure of complex atoms.

The atoms of the elements are classified numerically by their complexity; the atomic number of hydrogen is 1; helium is 2; etc. In figure 2–2, notice the relationship between the atomic number of sulfur and copper and the number of protons. The atomic number of an atom is the same as the number of protons in the nucleus of the atom.

The structures of the different atoms cause the elements to have different properties. The physical and chemical properties, as well as the electrical properties of matter, are determined by the structure of its atoms, the way in which the atoms combine to form molecules, and the state (gas, liquid, or solid) in which the matter exists.

The influence of the nucleus of an atom on the electrons orbiting about it depends upon the diameter of the orbits. The electrons that orbit around the nucleus do not travel in a random way. Each electron travels in a specific *shell* and is confined to that shell. Electrons in the inner shell, those near the nucleus, are bound tightly in the atom. Electrons in the outer shells are rather loosely bound and, when influenced by some outside force, may be torn away from the atom. This leaves the atom with a deficiency of electrons. The atom is then positively charged and is a *positive ion.* The electrons that are loosely bound to the nucleus are sometimes called *free* electrons. They are not exactly free, but they tend to move from one atom to another, exchanging places continuously with other free electrons. Some materials contain many more of these so-called free electrons than do others. In general, metals contain many more free electrons than do substances like rubber and glass.

Valence. The number of electrons in the outermost shell determines the *valence* of an atom. For this reason, the outer shell of an atom is called the *valence shell;* and the electrons contained in that shell are called *valence electrons.* The valence of an atom determines its ability to gain or lose an electron, which, in turn, determines the chemical and electrical properties of the atom. An atom having a relatively small number of electrons in its outer shell, in comparison to the number of electrons required to fill the shell, easily loses its valence electrons.

"Valence shell" always refers to the outermost shell, whether it be a major shell or a subshell. Copper and sodium atoms each have one electron in the outermost shell. Even though the atomic weights and atomic numbers of copper and sodium are quite different, the atoms are similar in that they both contain one valence electron.

Ions and ionization. We mentioned previously that ions are atoms which have assumed a charge and stated that there are positive and negative ions. Following, we discuss the process whereby an atom acquires a charge.

It is possible to drive one or more electrons out of any of the shells surrounding a nucleus. In the case of incomplete shells, it is also possible to cause one or more additional electrons to become attached to an atom. In either case, whether an atom loses or gains electrons, it is said to be *ionized.* For ionization to take place, there must be a transfer of energy that results in a change in the internal energy of the atom.

An atom having more than its normal number of electrons acquires a negative charge and is called a *negative ion.* Conversely, an atom having less than its normal number of electrons is left with less negative than positive charges and is called a *positive ion.* Thus, ionization is the process by which an atom loses or gains electrons.

To drive electrons out of the shells of an atom requires raising the internal energy of the atom. This energy may be obtained through bombardment by photons and phonons (light energy) or by subjecting the atom to electric fields. The amount of energy required to free electrons from an individual atom is called the *ionization potential.*

The ionization potential necessary to free an electron from an inner shell is much greater than that required to free an electron from an outer shell. Also, more energy is required to remove an electron from a complete shell than from an unfilled shell.

018. The characteristics of static electricity

Among the pecularities of nature is the phenomenon known as static electricity. Man has long been fascinated and frustrated by the occurrence of static electricity.

Static electricity. It has been known for a long time that a comb, when rubbed with a cloth or run through your hair, attracts light pieces of paper. The early Greeks were familiar with this phenomenon and, without realizing it, discovered the type of electricity that today is known as *static electricity.* The Greeks knew that when they rubbed a piece of amber, which they called *electron,* with a piece of cloth, it attracted other objects such as bits of cloth or pith. From the Greek word for amber are derived the English words *electron* and *electricity.* Originally, static electricity was considered electricity at rest, as the name *static* implies. Since electrons are continually in motion within an atom, however, static electricity is now more commonly associated with charged bodies.

Charged bodies. Remember that an electrically *charged body* is one that has more or less than the normal number of electrons. It may be either positively or negatively charged. A *positively* charged body is one in which some of the electrons have been removed from the atoms so that there is a deficiency of electrons; that is, there are fewer electrons than protons. A *negatively* charged body is one in which there is more than the normal number of electrons in each atom; that is, there are more electrons than protons. A body in which there is an equal number of electrons and protons in each atom is an uncharged, or *neutral* body.

Removing electrons from a body involves physically attaching them to another body and then moving the other body some distance away. The second body has an excess of electrons, and thus, is negatively charged. The first body has a deficiency of electrons, and thus, is positively charged. This can be illustrated by rubbing glass with silk and then separating the two. Some of the electrons are rubbed off the glass onto the silk. This leaves the glass with a positive charge (deficiency of electrons) and the silk with a negative charge (excess of electrons). If the two bodies, the silk and the glass, are not brought into contact, they will retain the charges for a long period of time; the charges will eventually leak off to surrounding objects. When the silk and the glass are allowed to touch, however, the surplus of electrons on the silk will move onto the glass and neutralize the charges on the two bodies.

When a rubber rod is briskly rubbed with a piece of woolen cloth, a number of electrons from the cloth adhere to the rubber rod. If the two objects are separated immediately, there will be an excess of electrons on the rubber rod. In other words, the rubber rod will be negatively charged. Note that a glass rod rubbed with wool has a negative charge.

A simple experiment can be performed to show the effects of these two different charges. Suppose that two small balls of pith, or any light material, are suspended by a thread so they hang freely, as shown in figure 2–3, A. If both balls are touched with the negatively charged rubber rod, they become negatively charged and will swing away from each other, as shown in figure 2–3, B. If both balls are touched with the positively charged glass rod, the same thing happens (fig. 2–3, C). In other words, when both pith balls are charged the same way, they repel each other. If one ball is touched with the positively charged glass rod and the other with the negatively charged rubber rod, they have unlike charges and will swing toward each other, as shown in figure 2–3, D. In other words, when the two balls have unlike charges, they attract each other. This attraction shows that a force is present and that a field of force has been established. The field may be called an *electric* field, a *dielectric* field, or an *electrostatic* field.

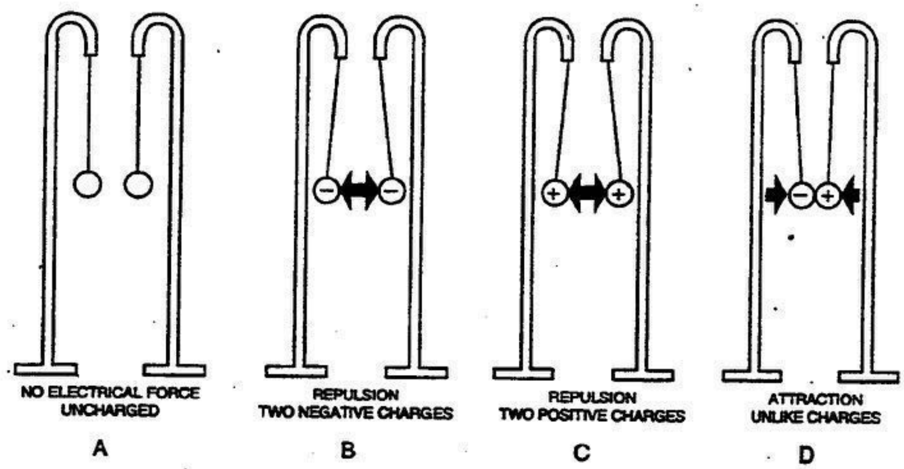


Figure 2–3. An experiment with electrical charges.

This experiment demonstrates one of the fundamental laws of electricity—like charges repel each other and unlike charges attract.

If one negatively charged pith ball is isolated and the negatively charged rubber rod is brought toward it from any direction, a force of repulsion is present. If the pith ball is positively charged, there is a force of attraction, no matter from which direction you bring the negatively charged rod toward the pith ball. The conclusion, then, is that a dielectric field entirely surrounds a charged body.

Representing a field of force. In diagrams, lines are used to represent the direction and intensity of the field of force. The intensity (field strength) is indicated by the density (number of lines per unit area). The direction of the field is indicated by arrowheads on these lines. The direction of the field of force is the direction a small positive test charge moves or tends to move when acted upon by the field of force. Arbitrarily, it is agreed that a small positive charge will be used when we are determining the direction of an electric field. This is unfortunate in one respect because similar arrowheads are commonly used in electrical circuit diagrams to indicate the direction that electrons travel.

You must remember that the direction of the field of force around a charged body is represented as the direction that a unit *positive* charge moves, or tends to move, when placed in a field. This shows that the direction of the field about an isolated positive charge is always away from that charge—that is, a positive test charge is repelled. The direction about an isolated negative charge is *toward* the charge—that is, a positive test charge is attracted. Thus, the direction of the field of force between a positive and a negative charge is from positive to negative. Figure 2–4 shows the direction of the field of force about both types of charges; an isolated negatively charged body, as in figure 2–4, A, and an isolated positively charged body, as in figure 2–4, B.

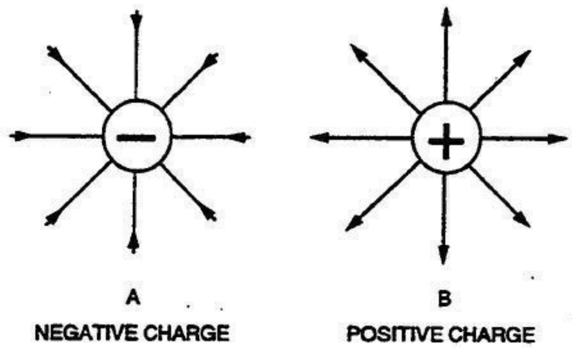


Figure 2–4. Fields about isolated charges.

Figure 2–5 shows the field of force about two unlike charges. Notice that the lines of force are continuous from positive to negative; thus, the charges are attracted. Even though they are in the same direction, the lines of force between the charges are not parallel. They bulge out at the center because lines of force in the same direction repel each other.

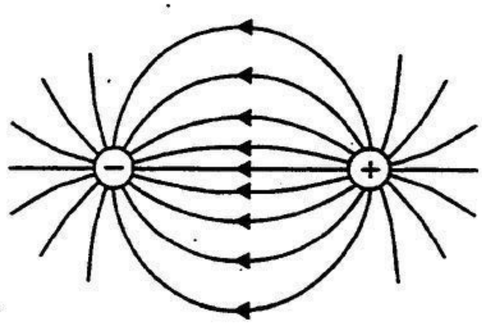


Figure 2–5. Electrical lines of force about unlike charges.

Figure 2–6 shows the field of force about like charges. The lines of force between the charge are not continuous from positive to positive, and the charges repel each other.

The dielectric, or electric field, requires no physical or mechanical connecting link, but can be applied through air or a vacuum. In general, the fields of force permeate (pass through) the space surrounding charged objects and diminish in proportion to the square of the distance from their origin. Electrons revolve at tremendous velocities around the positive nucleus of an atom, but they do not fly off on a tangent because there is a field of force between them and the positive protons of the nucleus.

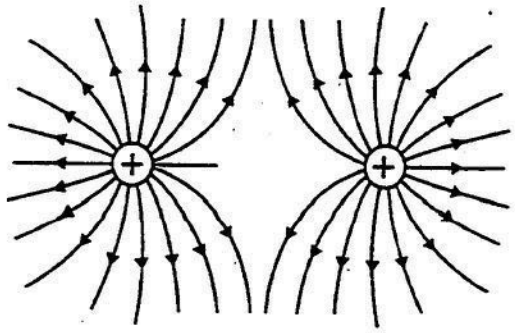


Figure 2–6. Electrical lines of force about like charges.

The field of force between the electrons and protons in an atom is the same as the dielectric or electrostatic field associated with charged bodies. However, any discussion of electric, dielectric, or electrostatic fields is understood to mean the external fields about the charged bodies, unless specific reference is made to the field within the atom.

Determining the force between charged bodies. Experimentally, it has been shown that charged bodies act upon each other with a force of attraction when they have unlike charges and act upon each other with a force of repulsion when they have like charges. Similar experiments show that the forces of attraction or repulsion change with the magnitude of the charges and also with the distances between them. This relationship is defined by Coulomb's law, which states that charged bodies attract or repel each other with a force that is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. Mathematically, Coulomb's law is expressed as:

$$F = \frac{q^{\circ}q'}{d^2}$$

Where q° and q' represent the charges and d^2 represents the distance separating them.

The charge of one electron or one proton might be used as the unit of electrical charge, but it would not be practical because of its extremely small magnitude. Generally, the practical unit of charge used is the *coulomb,* which is equal to a charge of 6,280,000,000,000,000,000, or 6.28×10^{18} electrons.

019. The electrical conductivity of matter

In the study of electronics, the association of matter and electricity is of paramount importance. Since every electronic device is constructed of parts made from ordinary matter, the effects of electricity on matter must be well understood.

Conductors, insulators, and semiconductors. As a means of accomplishing this, all the elements of which matter is made may be placed into one of three categories: conductors, insulators, and semiconductors. Conductors are elements such as copper and silver which conduct a flow of electricity very readily. Due to their good conducting abilities, they are formed into wire and used whenever it is desired to transfer electrical energy from one point to another. Insulators (nonconductors), on the other hand, do not conduct electricity to any great degree and are used when it is desirable to prevent a flow of electricity. Elements and compounds such as sulfur, rubber, and glass are good insulators. Materials such as germanium and silicon are not good conductors, but cannot be used as insulators either. Since their electrical characteristics fall between those of conductors and insulators, they are classified as semiconductors. The electrical conductivity of matter is ultimately dependent upon the energy levels of the atoms of which the material is constructed.

Materials containing many free electrons permit a large current to flow in response to a relatively low electrical pressure. The metals belong to this group of materials. Such materials are called *conductors.*

Materials containing very few free electrons permit relatively little current flow in response to an electrical pressure. Glass, plastics, porcelain, and rubber are examples of materials in this category. Such materials are called *insulators.*

Resistance. Actually, no material is a perfect insulator. All materials have some free electrons that flow as an electrical current. Neither are there any materials that act as perfect conductors. Even the best conductors available have some opposition to current flow. This opposition to current flow is called *resistance,* a very important electrical property.

All materials may be classified as having some resistance. Some materials are good conductors; others are poor conductors. From an electrical point of view, however, it is convenient to classify materials as conductors (those having many free electrons) or as insulators (those having very few free electrons). Materials between these two extremes are called *resistance materials,* or *semiconductors.* The amount of current flow under a given set of conditions depends on the type of material used and on the physical dimensions of the conductor.

The unit of resistance is the ohm and is defined later in the study of Ohm's law. The symbol, or abbreviation, for resistance is R. The unit of measurement of resistance is the ohm, which is usually expressed by the Greek letter "Ω" (omega).

Physical factors affecting the resistance of conductors were first studied by George Simon Ohm, who showed that the resistance of a given conductor of uniform cross section varies directly as its length and inversely as the area of its cross section. He also showed that resistance depends upon the material of which the conductor is composed. For a given material at a fixed temperature, doubling the length causes the resistance to double, while doubling the cross-sectional area causes the resistance to be just one-half as great.

As stated previously, the amount of opposition that a conductor offers to current flow depends upon the chemical structure of the conductor; that is, upon the way atoms are bound together. In order to compare different types of materials as to their ability to conduct or oppose current flow, you must have some type of standard. *Resistivity* is a term we use to describe the relative opposition that various materials offer to current flow. Some texts define resistivity as the amount of resistance offered per cubic centimeter. For example, copper, at 20°C, has a resistivity of approximately 0.0000017 unit (ohm) of resistance per cubic centimeter. Iron has a resistivity of approximately 0.00001. This means that the resistance of iron is approximately 100/17, or six times as great as that of copper.

The resistance of a substance changes as its temperature changes. In general, the resistance of a metal increases as its temperature rises. The resistance of most liquid, gaseous, and nonmetallic conductors decreases with an increase in temperature. The amount of change in resistance per ohm per degree is called the *temperature coefficient*. In simple terms, this means that as the temperature of a conductor changes, its resistance changes proportionately.

A metal conductor has a positive temperature coefficient; that is, its resistance increases as its temperature increases. Since the resistance of most nonmetallic conductors decreases as temperature increases, these conductors have a negative temperature coefficient. That is, the resistance changes in the opposite direction, or inversely, to changes in temperature.

In electrical circuits, it is normally desirable to have materials whose resistance does not change with a change in temperature—that is, materials that have a temperature coefficient of zero. There are certain alloys that, for all practical purposes, have this characteristic. Their resistance changes very slightly with a considerable change in operating temperature. Such materials are particularly suitable for use in measuring instruments because any change in the resistance of the components within such instruments may cause a considerable error in the accuracy of the measurement.

Conductance. *Conductance* is an electrical property of matter and the opposite of resistance. The conductance of a material is its ability to conduct electrical current. Although it is not absolutely necessary to use the unit of conductance in the solution of electrical circuit problems, you should be familiar with the term.

The ability of matter to conduct electricity is measured to find whether it has a high or low amount of resistance to a circuit. The greater its ability to conduct (conductance), the less resistance it has. Conversely, the less the material's ability to conduct, the higher is the resistance value of the material. Resistance and conductance have essentially the same overall effect on a circuit and differ only by how a problem is approached.

The unit of conductance is the *mho* (ohm spelled backward) and the symbol is G. The conductance of a material is the reciprocal of resistance. The relation of conductance and resistance can be expressed as follows:

$$G = \frac{1}{R} \quad \textit{or} \quad R = \frac{1}{G}$$

For example, if a resistor has a resistance of 2 ohms, it has a conductance of 1/2 mho.

Copper is used as a conducting material to a greater extent than any other material—not only because of its high conductivity (ability to conduct as compared with a standard) and comparatively low cost, but also because of the excellence of its physical characteristics in general. It has high tensile strength, is easily bent and formed, is relatively free from atmospheric corrosion, and is easily soldered.

Aluminum is the principal competitor of copper in high-voltage transmission lines. If a conductor of copper and one of aluminum have the same physical dimensions, the aluminum conductor has a resistance of about one and one-half times that of the copper conductor; that is, aluminum has higher resistivity, but the weight of the aluminum conductor is only about one-third that of the copper.

020. Let's talk about current flow

A basic in our discussion of electronics is the movement of electrons, or current flow, within the various circuits we monitor.

Electric current. Electric current is commonly defined as the flow, or drift, of electrons through a conductor. In your study of the atom, you learned that electrons in the outer shells of an atom may be torn away from that atom by some external force. You also learned that metals generally contain more so-called *free* electrons than do other materials. There is evidence to show that the electrons of metal are circulating between atoms; that is, the outer electrons of atoms are continuously exchanging places with similar electrons from adjacent atoms. In a metal such as copper, according to theory, there are clouds of these free electrons drifting among the atoms. They are not bound to any single atom but are constantly drifting, first in one direction and then in another.

Suppose that a copper wire is used to connect two charged bodies, as shown in figure 2–7. One body is positively charged, and the other is negatively charged. This means that the *positive* body has a deficiency of electrons, and the *negative* body has an excess of electrons. When the wire is connected between these points, there is a movement of the free electrons along the copper wire, as indicated by the arrows. This movement is from the *negative* toward the *positive* body.

This movement is explained by the theory that an electrical pressure exists between any two points when one has a greater number of electrons than the other. The greater the difference in the number of electrons, the greater is the electrical pressure. The greater the electrical pressure, the greater is the movement of electrons along the wire. Likewise, the less the difference in the number of electrons, the less is the pressure and the amount of electron flow. Electrons continue to flow through the wire until the bodies become equally charged. This action constitutes an electrical current flow.

This theory of how electrons move through a conductor may not be complete in all details, but it does satisfactorily explain general electrical phenomena. The positively charged body may attract the free electrons from atoms in its vicinity, which leaves these atoms positively charged; they, in turn, attract electrons from

Figure 2–7. Current flow.

adjacent atoms. This action continues until some of the electrons from the negatively charged bodies are used to supply the missing electrons from nearby positively charged atoms.

The electron drift may also be considered a result of the repelling action of the negatively charged body. In this case, electrons are forced onto nearby atoms, causing these atoms to become negatively charged; they, in turn, force electrons onto adjoining atoms that have a deficiency of electrons.

Experiments show that the relatively heavy positive nucleus of an atom does not move through a conductor. Only the free electrons, those not tightly bound to a given atom, travel along the conductor as electrical force may dictate. The relative number of free electrons in a material has a definite bearing on the amount of current flow through this material.

The points to remember are that the electron flow is from negative to positive and that this current continues to flow until the two bodies become equally charged.

Potential difference. Remember that we said a body was negatively or positively charged, contrasting it with its normal or uncharged state. Now let us go a step further. If we connect a copper wire between two metallic spheres, A and B, both charged negatively, but with A charged more negatively than B (having a greater number of excess electrons than B), electrons will flow along the wire from A to B, continuing to do so until the number of excess electrons on both spheres is equal.

Now assume that two spheres, x and y, are charged positively, with x charged more positively than y. If these two spheres are connected by a wire, electrons will flow along the wire from y to x. The reason they flow that way is that x, having a higher positive charge than y, has been deprived of more electrons than y. As with A and B, the electrons will flow from y to x until both spheres have equal charges.

In general, electrons flow momentarily along a connecting wire between two charged bodies if the bodies are charged either with different amounts of the same charge or with any amount of different charges. The only requirement is that one body has a charge of greater intensity than the other. The difference in electrical pressure caused by these charges is known as *potential difference*. The difference in potential between two points is measured in *volts*.

To find a point at absolute zero potential, it would be necessary to go an infinite distance from all charges in order to get out of their electric fields. It can, therefore, be seen that absolute zero potential has no practical meaning; since there can be a positive and a negative potential, there should be some point that we refer to as being at zero potential.

Earth has been selected to represent zero potential. To put some object at the potential of the Earth *(zero potential),* a good connection must be made to the soil moisture by connecting to a large water pipe system or to a large amount of buried conducting material. This is referred to as *ground* by practical electricians. Most electrical installations are grounded at some place. (Later in the course, you learn that the term *ground* is also used to mean a common connection for several electrical circuits—not necessarily the Earth).

Electromotive force (EMF). The only electrical pressure that we have considered to this point is that developed as a static charge (by rubbing a glass rod with silk, or a rubber rod with wool). Under these conditions, current flows only until the two charged bodies become equally charged. In electrical circuits, it is necessary to have current flowing continuously. Thus, it is necessary to have a source that maintains two points at different pressures so that current continues to flow. This type of source is commonly referred to as an *electromotive force.*

Electromotive force is defined as any force that causes electrons to move through a conductor. Since electrons move, electromotive force (EMF) might be called electron-moving force, which is nothing more than an electric field of force that exists between points of different potential. Hence, a potential difference and an EMF represent the same thing.

In the early days, electricity was thought to act like a fluid that flowed through wires, as water flowed through a pipe. According to this idea, a pressure was required—hence the term *electrical pressure.* This term is still used, and it represents the same condition as potential difference, or EMF. Potential, force, and pressure usually are not measured in the same units. It may seem strange that the volt can be used as a unit of force as well as a unit of pressure. Academically speaking, the volt is not the proper unit for force or pressure, but, in practice, the potential difference, EMF, and electrical pressure all represent the same set of conditions. Therefore, the same unit suffices.

The symbol most often used to represent voltage potential difference, EMF, or electrical pressure, is E. The abbreviation for volt is V.

Current flow. As explained previously, an electric current is said to flow when electrons drift or move along a conductor. This current is a direct result of an electromotive force, or difference of potential, and continues to flow so long as the difference of potential exists along the conductor. This idea is illustrated in figure 2–8. Electrons are flowing through the conductor and the lamp, from the negative (-) terminal to the positive (+) terminal of the source of EMF. These terminals are maintained negative and positive, respectively, by the action within the source of EMF (the battery in this case). As electrons leave the negative terminal, the source causes additional electrons to be supplied at the negative terminal by taking them from the positive terminal and transferring them to the negative terminal. This action ensures that the negative and positive terminals are kept at the same respective potential difference, regardless of the number of electrons moving along the conductor.

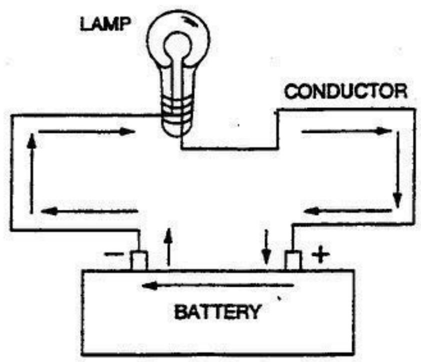


Figure 2–8. The direction of electron flow from a source of EMF.

At this point, it is important to clear up any confusion you may have regarding the direction of current flow. Remember from our study of fields of force that lines of force move from a positively charged body to a negatively charged one. Looking again at figure 2–8, you can see that electron movement *within* the EMF source is from positive to negative. It is only through the conductor that you see current flow from negative to positive. Thus, there is no contradiction here.

Velocity of electron flow. The velocity of electron motion is not particularly important at this point, but it will be important later in the course to understand the motional (drift) velocity with which electrons move through a conductor. The rate at which an electron moves from the negative terminal through a conductor to the positive terminal is relatively slow. The electrons move at extremely high speeds within the orbits of the atoms, however, and the electron movement from one atom to another is very fast. If it were not for the constant changes in direction, the speed at which electrons drift through conductors would be many millions of times greater.

Although the drift of an individual electron along a conductor is relatively slow, an electrical impulse resulting from this motion is transmitted along the conductor at a very rapid rate. This is similar to the motion of a starting freight train. The jerk of the engine is transmitted along the lines of cars very rapidly, but the starting speed of the train as a whole is very slow. The transmission of an electrical impulse is also similar to that illustrated by the balls in the pipe of figure 2–9. If some force is applied to ball A, as indicated by the arrow, this force is

Figure 2–9. An analogy of the transmission of an electrical impulse.

transmitted to the remainder of the balls in the pipe almost instantly. In other words, when ball A moves a fraction of an inch, all the balls in the pipe move the same distance as a result of the force applied to A.

In the case of electrical motion, the electrical impulse is transmitted at approximately the speed of light (approximately 186,000 miles per second).

The unit of current flow. The rate at which electrons pass a given point in a conductor is a measure of the amount of current flowing. The rate of current flow is 1 unit when a specific number of electrons pass a point in a conductor in a given amount of time; that is, current is 1 unit when 1 coulomb of electrons passes a certain point in 1 second. A similar measure would be the rate at which water flows through a pipe. The unit of current is called the *ampere.* If the coulomb (6.28×10^{18} electrons) of charge passes a given point on a conductor in 1 second, then 1 ampere of current is said to flow.

For example, if 1/10 coulomb of electricity passes a point in 1/10 second, the rate of current flow is 1 ampere; if 2 coulombs of electricity pass a given point in 2 seconds, the rate of current flow is 1 ampere; if 60 coulombs of electricity pass a given point in 60 seconds, the rate of current flow is 1 ampere. Therefore, the measure of current flow is independent of the length of time that current actually flows, but is determined by the rate of flow at any given time. The symbol that is usually used to represent electrical current is I, which represents the intensity of current flow. The abbreviation used for the ampere is amp or A.

Devices for producing an electromotive force. There are several devices for obtaining a difference of potential of an electromotive force. The methods most commonly encountered in the study of electricity and electronics are the chemical cell and the mechanical generator. Other methods, having more limited application, are thermoelectric, photovoltaic, and piezoelectric.

The chemical cell. An electromotive force is produced when chemical energy is converted into electrical energy. The chemical energy is the result of chemical action on two dissimilar metallic plates.

The dry cell. This is a familiar device for producing an EMF by chemical means. The construction of a dry cell is shown in figure 2–10. The positive electrode or anode of the dry cell is a carbon rod located in the center of the zinc container that forms the negative electrode or cathode. Each dry cell has an EMF of about 1.5 volts, regardless of its physical size. A 6-volt dry-cell battery consists of four cells connected in series. To increase the current, one must connect the cells in parallel.

The lead-acid cell. One of the most common uses of the lead-acid cell is in aircraft and automobile storage batteries. Each lead-acid cell, regardless of size, generates approximately 2.2 volts. An automobile battery rated at 12 volts has 6 cells in series (6 x 2.2 volts). Although this indicates that the total voltage of the cells in series is greater than the voltage at which the battery is rated, this is true only when the battery is fully charged and not connected in a circuit.

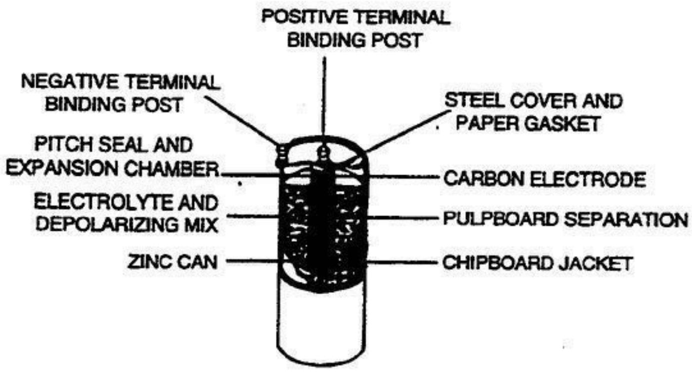


Figure 2–10. Construction of a dry cell.

Mechanical generators. Another common method of developing an electromotive force is by converting mechanical energy into electrical energy. The mechanical energy is used to rotate a conductor through a magnetic field. The most common type of mechanical generator is the type used in a car or aircraft. Other types are the emergency power units for hospitals and hydroelectric installations.

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

017. The structure of matter

1. What is matter?

2. What is an element?

3. What is a compound?

4. What is a mixture?

5. What is a molecule?

6. What is an atom?

7. What are the components of an atom?

8. What is a valence shell?

9. What determines an atom's ability to gain or lose electrons?

10. Describe the difference between negative and positive ions.

11. Define ionization.

018. The characteristics of static electricity

1. What is meant by an electrically charged body?

2. What are the fundamental laws of electrical charges?

3. What do we use as the unit of electrical charge?

019. The electrical conductivity of matter

1. What are the three categories of matter?

2. What is the difference between conductors and insulators?

3. Define resistance.

4. What is the unit of resistance? What is its symbol?

5. Briefly describe the relationship between a conductor's length and its resistance, as discovered by George Ohm. Between its cross-sectional area and resistance?

6. What term do we use to describe a material's ability to oppose current flow?

7. Generally, what effect does an increase in temperature have on the resistance of metallic and nonmetallic conductors?

8. What is a negative temperature coefficient?

9. Define conductance.

10. What is the unit of measurement for conductance? What is the symbol for conductance?

11. Describe the relationship between resistance and conductance.

12. Why is copper used as a conducting material more than other materials?

020. Let's talk about current flow

1. Define electric current.

2. What determines the conductivity of a material?

3. Point *x* on a conductor is more positive than point *y*. What is the direction of current flow?

4. What do we call the difference in electrical pressure caused by two charged bodies with different amounts of the same charge, and what is its unit of measurement?

5. Define electromotive force (EMF).

6. Define current flow.

7. What is the symbol we use for current flow?

8. What is the unit of measurement for current flow? What is its abbreviation and symbol?

9. What are the two most common methods of producing EMF?

10. What is the potential of the following:

    a) one dry cell?

    b) one lead-acid cell?

2–2. Fundamentals of Direct Current (DC)

Throughout your career as a technical controller, you will be required to maintain many electronic systems. Although we are not actually electronic systems repairmen, our duties have evolved to the point where we must have a better understanding of electronic fundamentals.

021. DC circuit terminology—components, symbols, and value expressions

In this section, we discuss fundamentals of direct current (DC), resistance, and basic circuit symbols and components.

The basic components and symbols of a practical circuit. You have seen how current flow is present when a conductor is connected between two charged bodies such as the two terminals of a battery shown in figure 2–11. However, the connection shown in the figure is not a practical basic circuit since the two terminals neutralize the battery in a short period of time and render it useless. Thus, some means must be employed to prevent this useless draining of the power source. Any electronic device that offers resistance to current flow may be used.

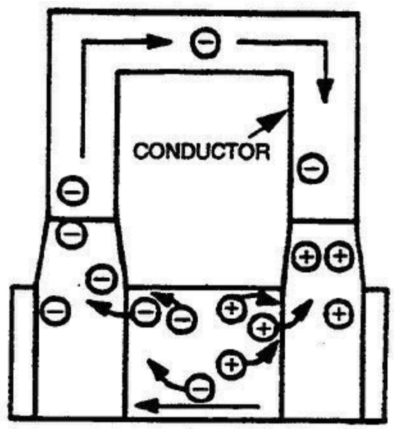


Figure 2–11. Battery connected to a conductor.

Essentially, the three requirements of a practical circuit are (a) EMF source, (b) conductor, and (c) resistance of some power dissipating device (resistor, bell, lamp, etc.).

Figure 2–12 is a schematic representation of such a circuit. Notice that symbols rather than pictures are used to represent the electronic components. All electronic components have a symbol, and you must be able to recognize the symbol and relate it to the proper components.

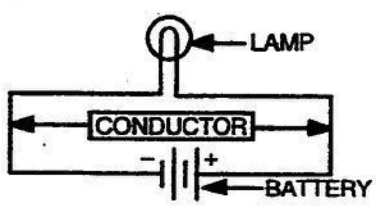


Figure 2–12. Basic DC circuit.

Let us examine a few basic circuit *symbols*. Refer to the symbols in figure 2–13 as we describe each component.

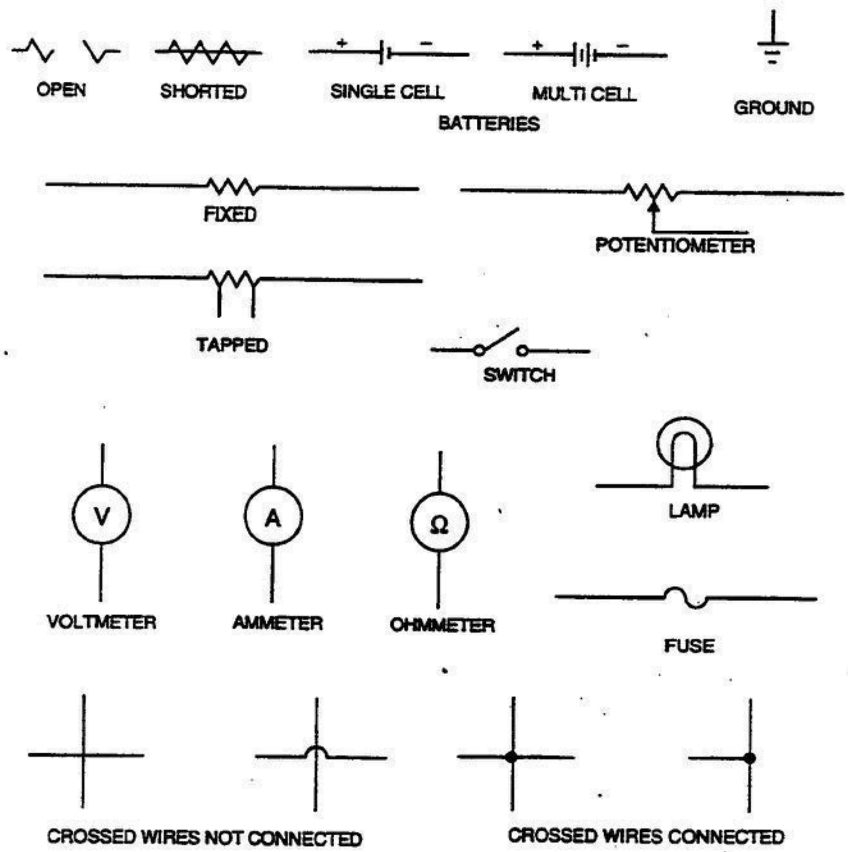


Figure 2–13. Basic electronic symbols.

Resistors. A good conductor introduces very little resistance; however, a component to which a conductor is connected may offer a lot of resistance. One of these high-resistance components is called a *resistor*. The purpose of a resistor is to control the amount of current flow in the circuit. In technical controls, we often use 600Ω or 900Ω resistors in termination plugs to temporarily correct a level problem.

There are three varieties of resistors you encounter in the field: wire wound, precision wire wound, and composition. Some have a fixed-resistance value and others are variable. Resistors are made of resistive wire, metal film, or carbon. They are used to control large amounts of current. Wire-wound resistors are constructed by winding resistance wire on a porcelain base. The ends of the wire are attached to metal terminals. A coating is applied to the wire to protect it and to conduct heat away from the metal terminals.

Two types of wire-wound resistors are shown in the upper portion of figure 2–14. Notice that one type has a slider and the other has fixed taps. These two arrangements allow the effective resistance to be changed.

Precision wire-wound resistors are illustrated in the lower left portion of figure 2–14. These types of resistors are used when the resistance value must be very accurate, such as in test instruments.

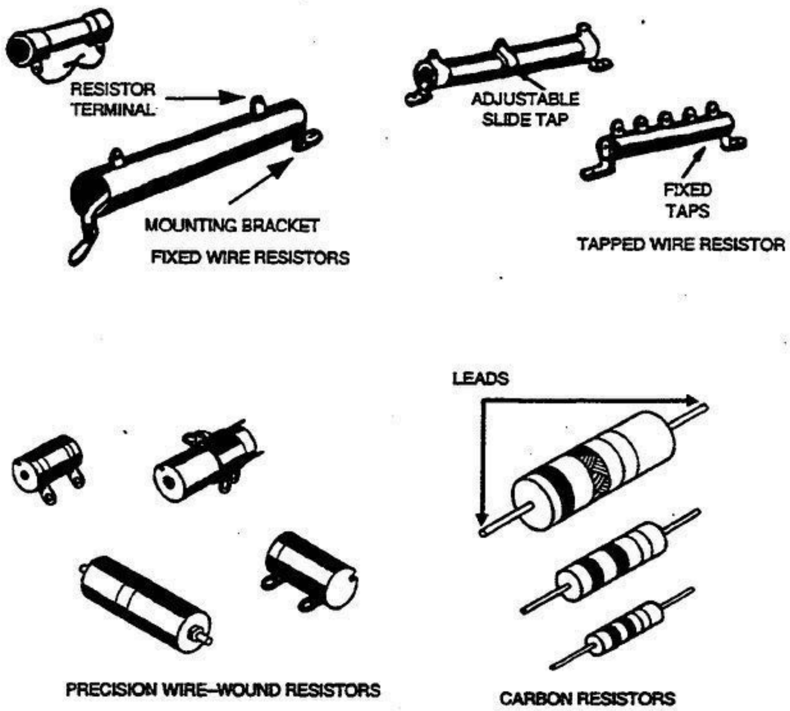


Figure 2–14. Resistors used in electronic circuits.

Composition resistors are shown in the lower right portion of figure 2–14. The most common of these are carbon resistors, which are constructed of a rod of compressed graphite and a binding material. Wire leads are attached to each end of the rod. The rod is then covered with an insulating material.

The schematic symbols for these resistors are shown in figure 2–13. The first resistor is the most common and comes in a wide range of ohmic values. The rheostat is a type of variable resistor. It is usually wire wound and is available in only low-ohmic values. Another wire-wound device is the tapped resistor. Different amounts of opposition are sensed at its various taps. The potentiometer is either made of carbon or wire wound. This variable resistor is also available in a wide range of ohmic values.

Battery. A battery is a device that converts chemical energy to electrical energy. In the single and multicell batteries shown in figure 2–13, the short lines represent the negative terminal. The negative terminal of one cell is connected to the positive terminal of another cell, and so on.

Ground. A ground is a point in a circuit used as a common reference point from which voltages are measured. Voltages may be either positive or negative with respect to ground. You are probably familiar with the electrical ground on an automobile; the chassis is the common reference point.

Voltmeter. This component is used to measure voltage in volts.

Ammeter. An ammeter is used to measure current flow in amps.

Ohmmeter. An ohmmeter is used to measure resistance in ohms.

Rotating machines. A generator is used to convert mechanical energy to electrical energy. A motor is used to convert electrical energy to mechanical energy.

Switches. A switch is used as a circuit controlling device or, simply, as a means of turning the circuit power on and off. There are numerous switch combinations to learn by association.

Lamp. A lamp can be used in a circuit as a loading device or to indicate a circuit condition.

Fuse. A fuse is used as a protective device for the circuit in which it is located.

Crossed wires. Connected wires are shown by placing a dot at the junction where the wires cross. If there is no dot at the junction where wires cross, there is no connection. Some schematics still use the older system of "hooking" one wire over the other to indicate the lack of a connection.

Polarized connectors. These units are used with DC or AC circuits. In either case, the large terminal on the male plug, or the larger opening in the female plug, is always the grounded terminal.

Electronic value expressions. Earlier in this CDC, we discussed some mathematical concepts relating to communications electronics. In this lesson, we expand on those areas so you can apply the techniques and concepts of electronics.

You became acquainted with the electrical terms resistance, voltage, and current in previous discussions. Other terms you see often are *inductance, capacitance, power,* and *frequency*. All of these terms refer to electrical values.

Since these electrical values range from much less than unity to much greater than unity, specific *prefixes* and *symbols* are used to simplify expressing their values. This is where powers of ten come into use.

Electronics technicians use certain powers of ten so often that special names and symbols have come into use. The names are prefixed to the standard unit. For instance, a thousand is a very common multiple. The symbol for a thousand is "k", and its prefix is kilo. One thousand volts is referred to as 1 kilovolt and is expressed as 1 kV. One thousand ohms is 1 kilo-ohm and is expressed as 1 kΩ. Quite often the symbol for kilo is typewritten using lowercase k. For example, 1000 volts may appear as 1 kV; 1000 ohms may appear as 1 kΩ.

Because prefixes represent specific powers of ten, they are very convenient to use. For example, kilo may be substituted for 10^3 in any numerical value.

Therefore:

$$5 \times 10^3 = 5 \text{ kilometers}$$
$$10 \times 10^3 = 10 \text{ kilowatts}$$
$$38 \times 10^3 = 38 \text{ kilowatts}$$

Milli is equal to 10^{-3}. Therefore:

$$5 \times 10^{-3} = 5 \text{ milliamps}$$
$$430 \times 10^{-3} = 430 \text{ millivolts}$$
$$6 \times 10^{-3} = 6 \text{ milliwatts}$$

Refer to table 1–1 which is a conversion chart you should memorize for working with electronics problems.

022. DC circuit operation

DC components are combined and connected together to form circuits. There are several means of connecting these components, and each has its own characteristics.

Series DC circuits. The most basic circuit in electronics is the series circuit. No matter how complex a circuit gets, it still boils down to a collection of interconnected series circuits. Therefore, it is essential that you have a thorough understanding of what makes up a series direct current circuit, how current flows in the circuit, and what factors affect current flow. This knowledge will be a tremendous asset as you study more complicated parallel and series-parallel DC circuits.

Circuit requirements. Figure 2–15, A, shows a DC circuit. It is a series circuit because there is only one possible path for current to flow. It contains the three basic requirements for any circuit: a source of power (battery), a load device (resistor), and a conductor (wire).

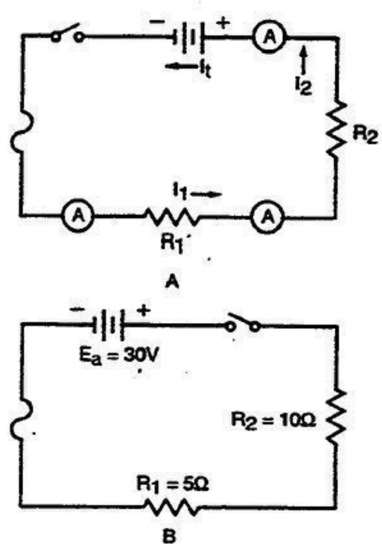


Figure 2–15. Series DC circuits.

Most practical circuits also contain a safety device (fuse) and a control device (switch).

circuit. All the ammeters will read the same amount of current. This is the first important thing to remember about a series circuit—current is the same at all points throughout a series circuit.

Voltage. Now, let us discuss voltage in a series circuit. The sum of the voltages dropped across each component of series circuit is equal to the applied voltage. Changing the applied voltage has a definite effect on the circuit.

Resistance. Now consider what effect a change in resistance has on current flow. For example, when voltage remains constant and the resistance is doubled, current is reduced to one-half of its original value. On the other hand, if the voltage remains constant and the resistance is reduced to one-half of its original value, the current doubles its original value.

Parallel DC circuits. It is often necessary to connect electrical devices so the entire source of voltage is across each device. A circuit in which two or more devices are connected across the same voltage source is a parallel circuit. Refer to the circuit in figure 2–16. Note that points A, B, C, and D are connected together and are one point electrically when the circuit is closed as shown. Similarly, points E, F, G, and H comprise another electrical point. Since the applied voltage appears between points A and E, the same voltage appears between points B and F, between C and G, and between points D and H. We can conclude that when resistors are connected in parallel across a voltage source, each resistor has the same voltage applied to it, although the currents may differ depending on the values of resistance.

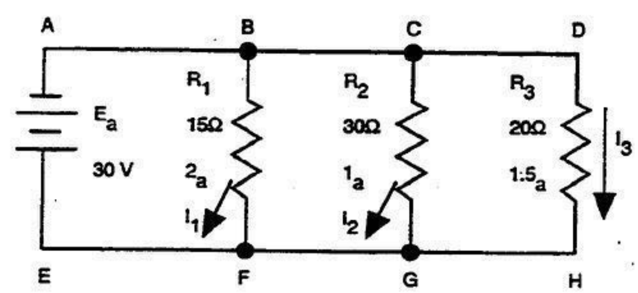


Figure 2–16. Basic parallel DC circuit.

Voltage. The sum of the voltage drops in a closed loop are equal to the applied voltage.

Current. The total current divides proportionally among the branches in a parallel circuit in a manner depending on the resistance of each branch. Branches in a parallel circuit with low resistance draw more current than branches with high resistance.

Resistance. The total resistance of any number of equal resistors connected in parallel is equal to the resistance of one resistor divided by the number of resistors.

Series-parallel DC circuits. A series-parallel circuit appears to be very complex for a beginner in electronics. However, by applying the same laws and rules we have learned for series and parallel circuits, series-parallel circuits are not as complex as they appear. A series-parallel circuit consists of groups of parallel resistance in series with other resistances. An example is shown in part A of figure 2–17.

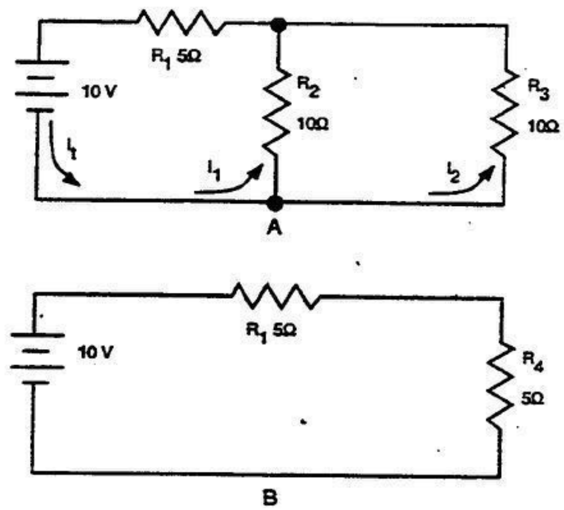


Figure 2–17. Series-parallel DC circuits.

Voltage divider circuits, rheostats, and potentiometers. Unlike your home, where practically all electrical appliances operate at the same voltage, our devices require many different values of voltage. It is impractical to have a separate power source for each voltage value, so we divide voltages.

Voltage dividers. A device that makes it possible to obtain more than one voltage from a single power source is a voltage divider. Voltage dividers are used in many applications. A simple voltage divider is composed of a number of resistors in

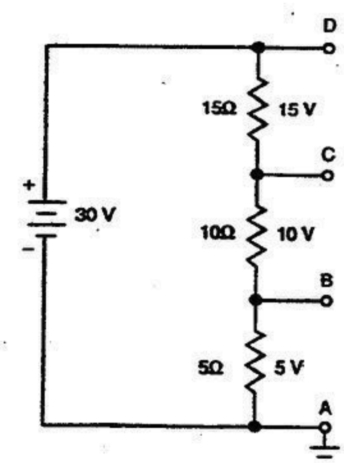


Figure 2–18. Simple voltage divider.

series with a power source, as shown in figure 2–18. This circuit is simply a series circuit consisting of three resistors connected across a source of voltage. Taps are provided and identified as A, B, C, and D. In addition to taps, a ground reference point has been added to the circuit. The design location of this ground is a very important factor for analysis of the circuit. You will see why a little later.

Variable resistors. In our study of voltage dividers, we used fixed resistors in the circuit. Quite often a voltage divider network makes use of a variable resistor. There are basically two types. One is called a rheostat and the other is called a potentiometer. There is a slight difference between them. Rheostats have two connections, one for the fixed resistance element and one for the variable wiper arm. A potentiometer has three connections, two for the elements and one for the wiper arm. Potentiometers may be used as rheostats by using only two connections, one for the element and one for the wiper arm.

Generally, rheostats have a limited range of values and a high-current handling capability. A potentiometer has a wide range of values, but it has a limited current handling capability.

Rheostats. A rheostat is a variable resistor that may be used as a control to vary the amount of current that flows through a voltage divider. A typical circuit in which a rheostat is used is shown in figure 2–19. Since the rheostat controls the current, it determines the voltage drop between point X and ground.

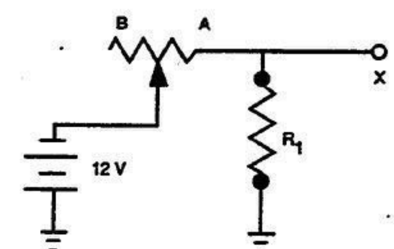


Figure 2–19. Rheostat as a voltage divider.

Examine the figure to see how the rheostat performs its function. As the slider arm is moved from A toward B, the amount of rheostat resistance in the circuit is increased. Since the rheostat resistance and the fixed resistance are in series, the total resistance of the circuit also increases. The total current in the circuit, therefore, decreases. By a similar analysis, as the slider arm is moved toward A, total resistance decreases and current increases.

Potentiometers. Another type of variable resistor is the potentiometer. A potentiometer is a control used to vary the amount of voltage applied to an electrical device or circuit. A typical circuit in which a potentiometer is used is shown in figure 2–20.

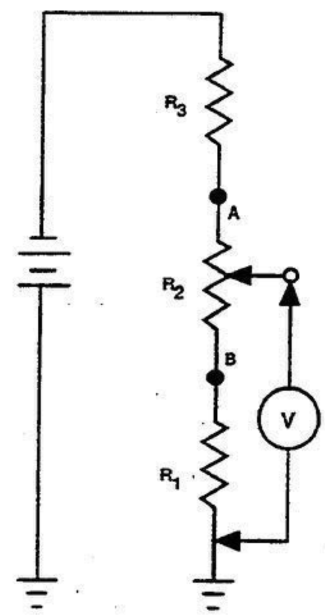


Figure 2–20. Potentiometer as a voltage divider.

Examine the figure to see how the potentiometer performs its function. As the slider arm of R_2 is moved from A to B or B to A, the amount of resistance does not change, and the current will not change. However, if a voltmeter is connected in the circuit, as shown, a change in voltage is noted as the arm is moved.

Using a potentiometer in a voltage divider network provides us with a means of obtaining a variable voltage from a fixed voltage source. The potentiometer is one of the most common controls found in electronic applications. In choosing a potentiometer for a given purpose, follow the same rules as for a resistor. Select the proper ohmic value and power rating.

Resistive bridge circuits. Bridge circuits are frequently used in electronics where a signal from a "detecting" device is used to drive or connect an operational device. Some bridge circuits have fixed components while others contain adjustable components. With a variable component, a bridge circuit may be used as a very accurate piece of test equipment.

023. Perform DC circuit calculations

Many times it is necessary for you, the technician, to determine the characteristics of a circuit. You then have to fall back on the math formulas we are about to cover.

Calculate voltage, current, and resistance in a series DC circuit. The series DC circuit is the most basic of all electronic circuits. Learning the simple steps for calculating operational and component values for these type circuits empowers you with the ability to solve more complex circuitry. Here we introduce the procedures for determining current, resistance, voltage, and power.

In our discussion on the electrical conductivity of matter, we introduced the theories of George Ohm. We use the mathematical formulas he and others developed to calculate the various values contained in electronic circuits. First, let's solve for current values.

Current flow. If we close the switch in figure 2–21,A, current flows. The three ammeters show how much current is flowing at various points in the circuit. From what we've already learned, we know that in a series circuit, current is the same at all points throughout the circuit. Therefore, all the ammeters read the same value.

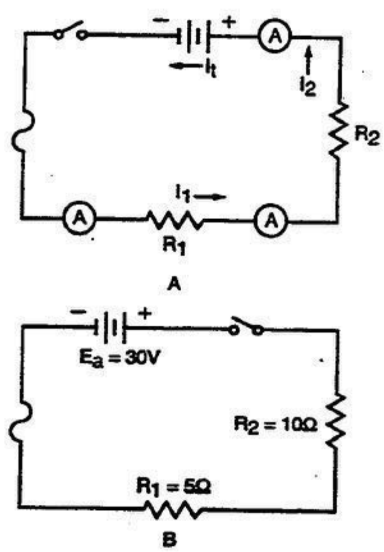


Figure 2–21. Series DC circuits.

Notice, we have not said how much current is flowing. We have merely said that whatever the current is, it is the same everywhere in the circuit. Let us solve the simple circuit shown in the B portion of figure 2–21. In order to find the total current (I_t), we must first find the total resistance. Total resistance (R_t) in a series circuit equals the sum of the individual resistances.

$$R_t = R_1 + R_2 + R_3 + \dots R_n \dots$$

In our sample circuit,

$$\begin{aligned} R_t &= R_1 + R_2 \\ &= 5\Omega + 10\Omega \\ &= 15\Omega \end{aligned}$$

The resistance of the battery, switch, and fuse is negligible in this circuit. However, in highly critical circuits, the battery, switch, and fuse resistance must be considered. Now let us use Ohm's law to determine the current flow in the circuit. There are three Ohm's law formulas:

$$I = \frac{E}{R}$$
$$R = \frac{E}{I}$$
$$E = IR$$

We use the following Ohm's law formula (where I=current, E=voltage, and R=resistance):

$$I = \frac{E}{R}$$

Our battery voltage (E_a) is 30 volts and total resistance (R_t) is 15Ω, so we can substitute:

$$I_t = \frac{E_a}{R_t} \quad or \quad I_t = \frac{30\,V}{15} \quad or \quad I_t = 2 \text{ amps}$$

Current is 2 amps, the series flow of electrons everywhere in the circuit.

Resistance. Now consider what effect a change in resistance has on current flow. For example, when voltage remains constant and the resistance is doubled, current is reduced to one-half of its original value. Let us assume that the resistance of our circuit in section B is 30 ohms. Since the voltage remains constant:

$$I_t = \frac{E_a}{R_1} \quad or \quad I_t = \frac{30\,V}{30\Omega} \quad or \quad I_t = 1 \text{ amp}$$

On the other hand, if the voltage remains constant, and the resistance is reduced to one-half of its original value, the current doubles its original value.

Voltage. Now, let us discuss voltage in a series circuit. The sum of the voltages dropped across each component of series circuit is equal to the applied voltage. This is expressed as follows:

$$E_a = E_{R_1} + E_{R_2} + \ldots$$

In our simple circuit of figure 2–21, we know that E_a is 30 volts. Thus, the voltage dropped across R_1 and the voltage dropped across R_2 add up to 30 volts. By using Ohm's law, we can find the exact voltage drop across each resistor.

We know I_t is 2 amps, and we know that:

$$I_1 = I_{R_1}$$
$$I_{R_1} = 2 \text{ amps}$$
$$\textit{and } I_{R_2} = 2 \text{ amps}$$

With this information, we can calculate the voltage dropped across each resistor:

$$\begin{aligned} E_{R_1} &= I_{R_1} \text{ x } R_1 \\ &= 2\,A \text{ x } 5\Omega \\ &= 10\,V \end{aligned}$$

$$\begin{aligned} E_{R_2} &= I_{R_2} \text{ x } R_2 \\ &= 2\,A \text{ x } 10\Omega \\ &= 20\,V \end{aligned}$$

If we add the voltages dropped across the two resistors (10V + 20V), we get 30 volts, the same as our battery.

Changing the applied voltage has a definite effect on the circuit. By using Ohm's law, you can see a direct relationship between voltage and current. Taking our simple circuit in figure 2–21 again, assume the voltage is doubled and resistance is held constant:

$$I_t = \frac{E_a}{R_t} \quad \textit{or} \quad I_t = \frac{60\,V}{15\Omega} \quad \textit{or} \quad I_t = 4 \text{ amps}$$

If the voltage is reduced to one-half its original value and the resistance held constant, the current decreases to one-half of its original value:

$$I_t = \frac{E_a}{R_t} \quad \textit{or} \quad I_t = \frac{15\,V}{15\Omega} \quad \textit{or} \quad I_t = 1 \text{ amp}$$

You will run into other types of problems that require a little mental flexibility on your part. Before making false starts, always examine the circuit to see what is known. Remember, anytime we have two known values of Ohm's Law, we can always solve for the unknown value.

Up to this point in our analysis of series circuits, we have been mentioning only Ohm's law. Before going on, we need to introduce another law.

Kirchhoff's Laws. In 1847, a German physicist, Gustav Richard Kirchhoff, developed what is known as Kirchhoff's laws for current and voltage. These laws may be stated as follows:

- The algebraic sum of the currents at any junction of conductors is zero. This means that the sum of all currents flowing to a point must be equal to the sum of all currents flowing away from that point.
- The algebraic sum of the applied voltage and the voltage drops around any closed circuit is zero. This means that in any closed circuit, the applied voltage is equal to the sum of the voltage drops around the circuit.

In our previous analysis of series DC circuits, you found that the current is equal through each resistor, regardless of the size or number of resistors. Therefore, current is the same throughout the circuit. This is a direct application of Kirchhoff's first law. We discuss further applications of this law later as we deal with parallel DC circuits.

Kirchhoff's second law states that the applied voltage is equal to the sum of the individual voltage drops in a closed circuit. Refer to our discussion for figure 2–21 and find the application of Kirchhoff's second law. The applied voltage was 30 volts. We found the voltage drop across R_1 to be 10 volts and the voltage drop across R_2 to be 20 volts. The total voltage drop, then, was 30 volts, the same as the applied voltage.

Now, let us solve a problem when the applied voltage is the unknown quantity. We use both Kirchhoff's and Ohm's laws to check our solution.

Refer to figure 2–22. Since the current through R_1 is known (2 amps), the total current of the circuit is known (Kirchhoff's first law). By using the total resistance equation, we can determine total resistance (30 ohms). Now calculate the applied voltage using Ohm's law (E = IR). Then, solve for the applied voltages using Kirchhoff's law by taking the sum of the voltage drops in the loop and see if our answers are the same.

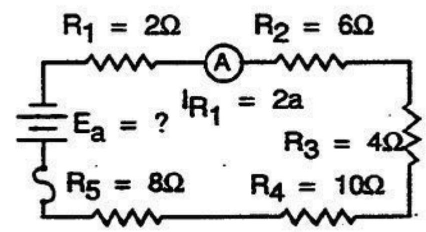


Figure 2–22. Application of Kirchoff's and Ohm's laws.

Solving with Ohm's law, E = IR, first determine total resistance.

$$\begin{aligned} R_t &= R_1 + R_2 + R_3 + R_4 + R_5 \\ &= 2\Omega + 6\Omega + 4\Omega + 10\Omega + 8\Omega \\ &= 30\Omega \end{aligned}$$

$$\textit{since } I_t = 2 \text{ amps}$$

$$\begin{aligned} \textit{and } E_a &= I_t R_t \\ &= 2\,A \times 30\Omega \\ &= 60\,V \end{aligned}$$

Before applying Kirchhoff's second law, you must first use Ohm's law (E = IR) to find the individual voltage drops. Using this formula, you find the voltage drops across the resistors to be as follows:

$$\text{Voltage drop across } R_1 \left(E_{R_1}\right) = 4 \text{ volts}$$
$$\text{Voltage drop across } R_2 \left(E_{R_2}\right) = 12 \text{ volts}$$
$$\text{Voltage drop across } R_3 \left(E_{R_3}\right) = 8 \text{ volts}$$
$$\text{Voltage drop across } R_4 \left(E_{R_4}\right) = 20 \text{ volts}$$
$$\text{Voltage drop across } R_5 \left(E_{R_5}\right) = 16 \text{ volts}$$

Applying Kirchhoff's second law as follows (where E_a equals the applied voltage):

$$\begin{aligned} E_a &= E_{R_1} + E_{R_2} + E_{R_3} + E_{R_4} + E_{R_5} \\ &= 4\,V + 12\,V + 8\,V + 20\,V + 16\,V \\ &= 60\,V \end{aligned}$$

Power dissipation in series circuits. Power is the rate of doing work per unit of time. Work results from a force acting on a mass over a distance. The operation of electrical circuits involves a force (voltage) acting on a mass (electrons) over a distance. The amount of time required to perform a given amount of work determines the energy expended. Since energy is the capacity to do work, power can also be defined as the time rate of developing or expending energy. In electrical circuits, electrical energy is transformed into heat energy. Following the law of conservation of energy, the heat energy will be equal in value to the electrical energy causing it. Therefore, by measuring the amount of heat energy given off by an electrical circuit in a given amount of time, you can calculate the amount of electrical power consumed in the circuit.

Joule's Law on electrical power. An experiment measuring the heat given off by an electric circuit was performed by an English physicist, James Joule, in 1843. He experimentally proved that the amount of heat produced by an electrical circuit was dependent upon current and resistance. This proportional relationship is known as Joule's law, and is stated as follows: "The amount of heat produced by a circuit element is directly proportional to resistance, the square of the current, and time." The equation for the law is as follows:

$$\text{Heat} = I^2R = \text{Power}$$

By substituting Ohm's law values into the power formula developed from Joule's law, we can derive the following equation:

Substituting	$I = \frac{E}{R}$ (Ohm's law)
into	$P = I^2R$
then	$P = \frac{E^2R}{R}$
or	$P = \frac{E^2R}{R^2}$
and	$P = \frac{E^2}{R}$

The resultant equation is useful when the resistance and voltages are known.

The power formula can also be expressed as an equation in terms of current and voltage as follows:

Substituting	$R = \frac{E}{I}$ (Ohm's law)
into	$P = I^2R$
then	$P = I^2\frac{E}{I}$
and	$P = IE$

The unit of measure of electrical power is the "watt." The watt represents the rate at any given instant at which work is being done in moving electrons through a circuit.

The previous examples demonstrate that any form of the power formula may be used to find power in a circuit. Likewise, if you know the power dissipated in a simple circuit and the value of any one of the other circuit quantities (E, I, or R), you can find the value of the remaining quantities. To see how this is done, first calculate for voltages.

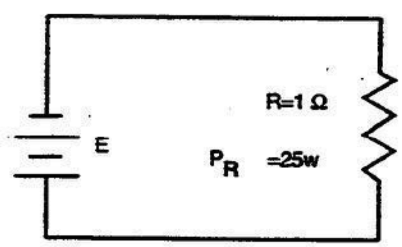


Figure 2–23. Power in a series DC circuit.

The power dissipated by the 1-ohm resistor in figure 2–23 is 25 watts. Calculate voltage in the circuit as follows:

$$P = \frac{E^2}{R}$$
$$E^2 = PR$$
$$E = \sqrt{PR}$$
$$E = \sqrt{25\text{ (watts) x 1W}}$$
$$E = \sqrt{25\text{ volts}}$$
$$E = 5\text{ volts}$$

Now, calculate for current:

$$P = I^2R$$
$$\frac{P}{R} = \frac{I^2R}{R}$$
$$\frac{P}{R} = I^2$$
$$I = \sqrt{\frac{P}{R}}$$
$$I = \sqrt{\frac{25\text{ (watts)}}{1W}}$$
$$I = \sqrt{25\text{ amps}}$$
$$I = 5\text{ amps}$$

This illustrates how the solution of a simple circuit can be found when any two values are known. Circuits having known values of power and current, or power and resistance, can be solved using Joule's law and Ohm's law correctly. Always begin a circuit analysis by knowing what is given and choosing a formula with two known values and the unknown you wish to find.

Electrical components are often given a power rating. The power rating in watts indicates the rate at which the device converts electrical energy into another form of energy, such as light, heat, or motion. Common examples of devices rated in this manner are soldering irons and small electric motors.

In some electrical devices, the wattage rating indicates the maximum power the device is designed to dissipate, rather than the normal operating power. A 150-watt lamp, for example, dissipates 150 watts when operated at the rated voltage printed on the bulb. In contrast, a device such as a resistor is not normally rated in terms of voltage or current. Resistors are given a power rating in watts and can be operated at any combination of voltage and current as long as the power rating is not exceeded. In most circuits, the actual power dissipated by a resistor is considerably less than the resistor's power rating. In well-designed circuits, a safety factor of 100 percent or more is allowed between the actual power dissipation of the resistor in the circuit and the power rating listed by the manufacturer. The wattage rating listed is the rate at which the resistor can dissipate power without damage from overheating.

Resistors of the same resistance value are available in different wattage values. Carbon resistors, for example, are commonly made in wattage ratings of 1/8, 1/4, 1/2, 1, and 2 watts. The larger the physical size of a carbon resistor, the higher is its wattage rating since a larger amount of material radiates heat more easily. When you need resistors of wattage ratings greater than 2 watts, you normally use wire-wound resistors. Wire-wound resistors are made in sizes between 5 and 200 watts, with special types being used for power in excess of 200 watts.

Calculate values in DC parallel circuits. It is often necessary to connect electrical devices so the entire source of voltage is across each device. A circuit in which two or more devices are connected across the same voltage source is a parallel circuit. Refer to the circuit in figure 2–24. Note that points A, B, C, and D are connected together and are one point electrically when the circuit is closed as shown. Similarly, points E, F, G, and H comprise another electrical point. Since the applied voltage appears between points A and E, the same voltage appears between points B and F, between C and G, and between points D and H. We conclude that when resistors are connected in parallel across a voltage source, each resistor has the same voltage applied to it, although the currents may differ depending on the values of resistance. Let us discuss these points more thoroughly.

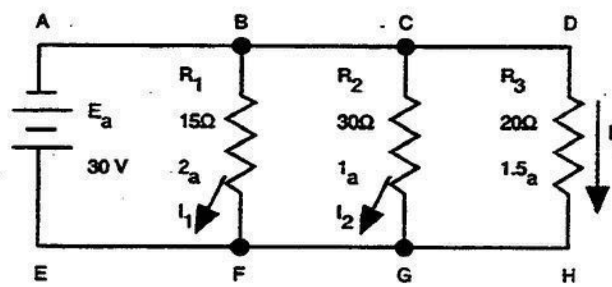


Figure 2–24. Voltage in a parallel DC circuit.

Calculating voltage. Kirchhoff's law states that the sum of the voltage drops in a closed loop are equal to the applied voltage. Let us prove this by calculating the voltage drop across each of the resistors in figure 2–24. In the circuit shown, R_1, R_2, and R_3 form three parallel closed loops with 30 volts applied. If we find the voltage drop across any one of the resistors, we should have the applied voltage. Let us calculate the voltage drop of R_1 by using Ohm's law and the indicated values of resistance and branch current:

$$\begin{aligned} E_{R_1} &= I_1 R_1 \\ &= 2\text{A} \times 15\Omega \\ &= 30 \text{ volts} \end{aligned}$$

Now, by using the same form of Ohm's law and the indicated branch values of current and resistance, we calculate the voltage drops of R_2 and R_3:

$$E_{R_2} = I_2 R_2$$
$$= 1A \; x \; 30\Omega$$
$$= 30 \; volts$$
$$E_{R_3} = I_3 R_3$$
$$= 1.5A \; x \; 20\Omega$$
$$= 30 \; volts$$
$$E_a = E_{R_1} = E_{R_2} = E_{R3}$$

We have now proven that voltage drops across each resistor or branch loops are equal to the applied voltage.

Calculating current. The total current divides proportionally among the branches in a parallel circuit in a manner depending on the resistance of each branch. Branches in a parallel circuit with low resistance draw more current than branches with high resistance. The current flow in the circuit may be expressed mathematically as follows:

$$I_t = I_1 + I_2 + I_3$$

Thus, to calculate the total current, simply add up the individual branch currents. Of course, before we calculate total current, it is necessary to calculate the individual branch currents by using Ohm's law. This is done by dividing the applied voltage by the resistance of the individual resistors.

Calculating resistance. The total resistance of any number of equal resistors connected in parallel is equal to the resistance of one resistor divided by the number of resistors. Expressed mathematically:

$$R_t = \frac{R}{N}$$

Where R_t is the total resistance, R is the resistance of one resistor, and N is the number of resistors.

The equivalent resistance of any two resistors in parallel is equal to the product of the two resistors divided by their sum. This is found by using the following formula:

$$R_t = \frac{R_1 R_2}{R_1 + R_2}$$

For example, the circuit in figure 2–25 contains a 20-ohm and a 30-ohm resistor in parallel. The calculation of their equivalent resistance is as follows:

$$R_t = \frac{20x30}{20+30} = \frac{600}{50} = 12 \text{ ohms}$$

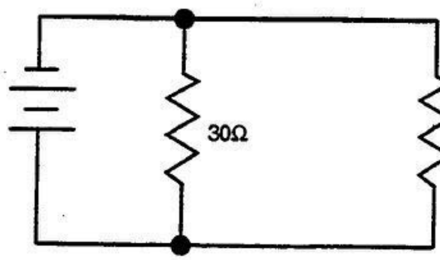


Figure 2–25. Parallel DC circuit with two unequal resistors.

Now let us discuss a little more difficult circuit that has more than two unequal resistors in parallel. Using the circuit in figure 2–26, let us solve for individual branch resistances. By Kirchhoff's law, we know that the voltage drop across each resistor is equal to the applied voltage. By using Ohm's law, the resistance of each branch can be calculated as follows:

$$R_1 = \frac{E_a}{I_1}$$

$$= \frac{28\text{V}}{2_a}$$

$$= 14 \text{ ohms}$$

$$R_2 = \frac{E_a}{I_2}$$

$$= \frac{28\text{V}}{.5_a}$$

$$= 56 \text{ ohms}$$

$$R_3 = \frac{E_a}{I_3}$$

$$= \frac{28\text{V}}{I_a}$$

$$= 28 \text{ ohms}$$

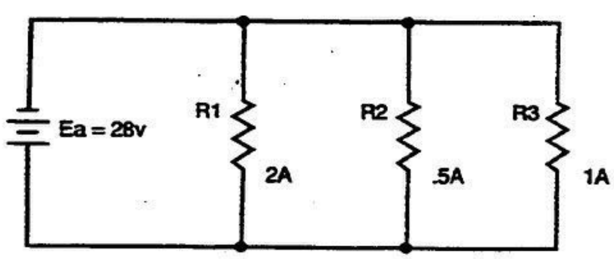


Figure 2–26. Parallel DC circuit (individual branch resistance).

Since the resistors are of unequal value and the circuit contains more than two parallel resistors, we must use the following general formula to solve for total resistance:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

This reciprocal formula can be written as:

$$R_t = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Then by substituting our calculated values:

$$R_t = \frac{1}{\frac{1}{14} + \frac{1}{56} + \frac{1}{28}}$$
$$= \frac{1}{.125}$$
$$= 8 \text{ ohms}$$

Calculating power. Using the circuit in figure 2–26, let us determine the power dissipated by the circuit. When we are given the voltage and the individual branch currents, the power formula can be used in this form: P = IE. The power dissipated by each resistor is equal to the current flowing through it times the voltage drop across it. Thus, the power dissipated by the three resistors is as follows:

$$P_{R_1} = 56 \text{ watts}$$
$$P_{R_2} = 14 \text{ watts}$$
$$P_{R_3} = 28 \text{ watts}$$

The total power P_t dissipated by any circuit is always equal to the sum of the power dissipated by the individual resistors. Thus, P_t for the circuit shown in figure 2–26 is 98 watts.

Total power can also be calculated by multiplying total current times the applied voltage:

$$P_t = I_t E_a$$

The power formula has two other forms. If the total current and total resistance are known, but voltage is unknown, we can use the following form of the basic formula:

$$P_t = I_t^2 R_t$$

If the applied voltage and the total resistance are known, we can use this form of the basic formula:

$$P_t = \frac{E_a^{\,2}}{R_t}$$

Calculate values in series-parallel circuits. A series-parallel circuit appears to be very complex for a beginner in electronics. However, by applying the same laws and rules we learned for series and parallel circuits, series-parallel circuits are not as complex as they appear. A series-parallel circuit consists of groups of parallel resistance in series with other resistances. An example is shown in part A of figure 2–27.

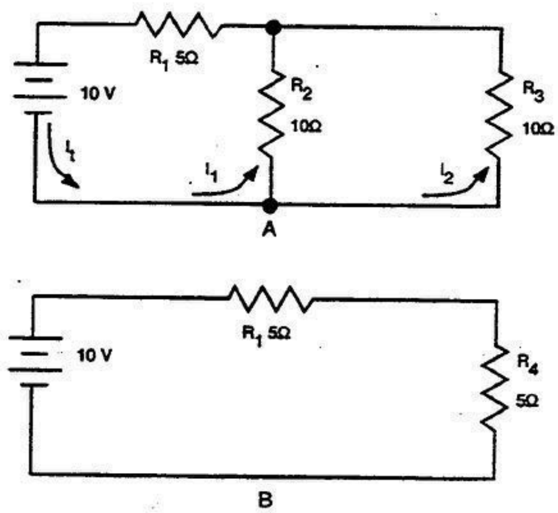


Figure 2–27. Series-parallel DC circuits.

Perhaps the easiest method for working with series-parallel circuits is to break them down and redraw them as equivalent series circuits. The first step in redrawing the circuit is to reduce the two parallel resistances, R_2 and R_3, to an equivalent single resistance. We call this single equivalent resistance R_4. We can solve for R_4 by using the "product over the sum" formula:

$$\begin{aligned} R_4 &= \frac{R_2 R_3}{R_2 + R_3} \\ &= \frac{10\text{x}10}{10+10} \\ &= 5 \text{ ohms} \end{aligned}$$

Thus, in place of the two 10-ohm resistors, we could insert into the circuit a single 5-ohm resistor without altering the total current in the circuit. At this time, we can redraw the circuit as shown in part B of figure 2–27.

The total resistance of the circuit is equal to R_1 plus R_4, or 10 ohms. Knowing this, we calculate the total current for the entire circuit by means of Ohm's law.

$$I_t = \frac{E_a}{R_t}$$
$$= \frac{10V}{10\Omega}$$
$$= 1 \text{ amp}$$

This 1 amp is the total current of the circuit. Thus, the voltage drop across each resistor is 5 volts. The power dissipated by each resistor and the total power can now be calculated by using any convenient power formula you studied earlier.

Now, let us look at part A of figure 2–28 and find the simple series equivalent circuit, total resistance, total current, branch currents, individual voltage drops, and total power dissipated by the circuit.

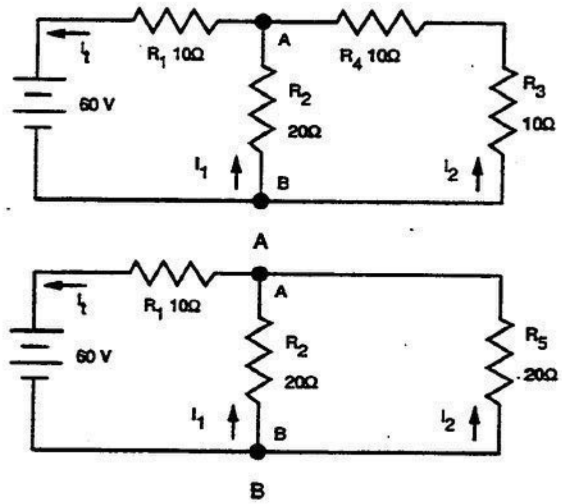


Figure 2–28. Series-parallel/series equivalent DC circuits.

To begin, add the series resistances R_3 and R_4 to get the equivalent resistance R_5 as shown in part B of the figure.

R_2 and R_5 in part B are in parallel and of equal value—20 ohms each. Thus, the total resistance of R_2 and R_5 is 10 ohms. If R_2 and R_5 are replaced by a series 10-ohm resistor, we can add that equivalant resistance to the resistance of R_1, 10 ohms. The circuit then appears as a simple series circuit having a total resistance of 20 ohms. The total current flow, then, would be 3 amps. Since the total current flow is 3 amps, the voltage drop across R_1 is 30 volts ($E = IR$). Thus, the voltage drop from point A to B is 30 volts.

Now, let us go back to part A of figure 2–28. We know the voltage across the parallel network, point A to point B, is 30 volts. This 30 volts is across R_2 and the series combination (R_5) of R_3 and R_4. Knowing the voltage across each branch in the network, you can now calculate branch current by using Ohm's law formula for each resistor:

$$I = \frac{E}{R}$$

Your calculations should show that the current flow through each branch is 1.5 amps, or a total current flow of 3 amps. You can determine total power dissipated by the circuit by using the power formula P = IE.

Let us consider another series-parallel circuit (fig. 2-29) and find the simple series equivalent circuit and total resistance. The first thing to do with the circuit is to reduce each group of parallel resistors to a single equivalent resistor. The first parallel group is R_2 and R_3. Using the formula:

$$R_a = \frac{R_2 R_3}{R_2 + R_3}$$

You find the equivalent resistance is 30 ohms.

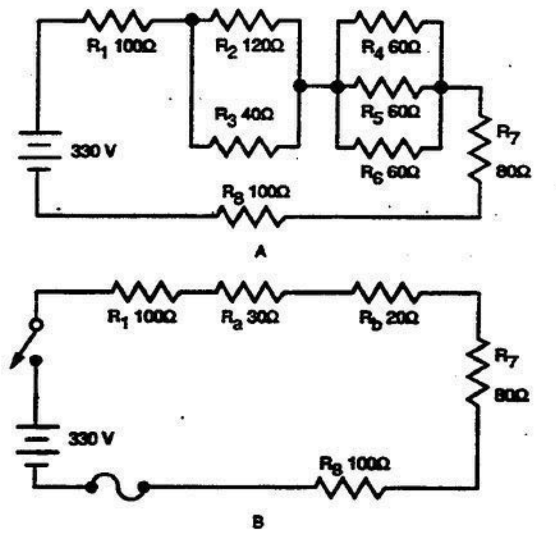


Figure 2–29. Complex series-parallel DC circuits.

The next step is to find the equivalent resistance of the parallel combination of R_4, R_5, and R_6. Since all are of equal value, the total is 20 ohms.

The two parallel combinations can be redrawn as single 30-ohm and 20-ohm resistors as shown in part B of figure 2–29.

Now, we have an equivalent series circuit in which the total resistance can be found very easily by adding all the resistance values. Your calculation should show the total resistance to be 330 ohms.

With total resistance and applied voltage known, it is simple to determine that the circuit current flow is 1 amp.

Find voltage drops across each resistor by applying the formula E = IR. Determine the power dissipated by each resistor by applying the formula P = IE.

Calculate values in voltage dividers. Since much of our work involves the presence of resistive circuits that are connected together to form voltage dividers, let's take a close look at these devices.

Simple voltage divider circuits. As stated earlier, a voltage divider is used to obtain more than one voltage from a single power source. Let's calculate the electronic values for a common voltage divider such as the one depicted in figure 2–30.

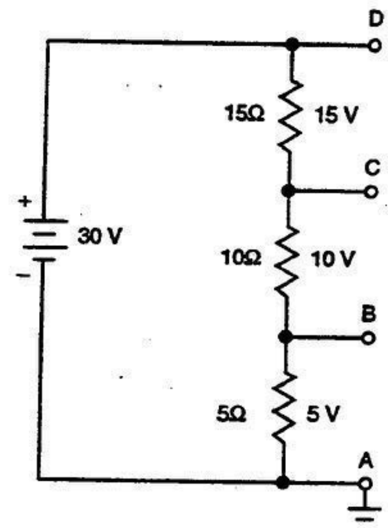


Figure 2–30. Simple voltage divider circuit.

With the values shown in figure 2–30, it is easy to see that we have a total resistance of 30 ohms. The applied voltage is 30 volts. By using Ohm's law ($E = IR$), we find 1 amp of current develops a voltage of 5 volts across the 5-ohm resistor, 10 volts across the 10-ohm resistor, and 15 volts across the 15-ohm resistor. The voltage present at tap A with respect to ground is 0 volts. The voltage at tap B with respect to ground is 5 volts. The voltage at tap C with respect to ground is 15 volts (5V + 10V). The voltage at tap D with respect to ground is 30 volts (5V + 10V + 15V). Note the voltage at point D is also equal to the applied voltage. Thus, from one common power source, it is possible to obtain several different values of voltage.

Up to this point, we have discussed a voltage divider circuit that has one side of the power supply grounded. Now, see what happens when we move the ground from one side of the power supply to some other point in our voltage divider (fig. 2–31). By adding resistor values, the total resistance is 200 ohms. With a 100-volt power supply, current is 0.5 amps. By using Ohm's law, we find the voltage drops across the resistors to be as follows: R_1 = 20 volts; R_2 = 3 volts; and R_3 = 50 volts.

Since the tap at point A is connected to the negative side of the battery with respect to ground, the voltage at point A is negative 20 volts. Resistors R_2 and R_3 are connected to the positive side of the battery with respect to ground. Thus, the voltages at points C and D are positive with respect to ground. The voltage drop across R_2 is 30 volts. Since R_2 is connected between point C and ground, the voltage at point C is positive 30 volts. The voltage at point D is equal to the voltage drop across R_3 and R_2, or positive 80 volts with respect to ground.

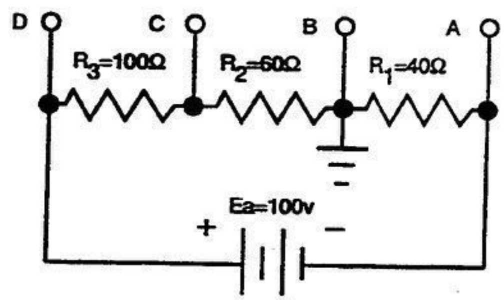


Figure 2–31. Voltage divider circuit with a negative voltage potential.

In our discussion so far, we have only been concerned with a ground reference point. Quite often in electronic equipment, the ground symbol not only represents the reference point, but it also denotes the metal chassis. Using the metal chassis for ground is valuable when you consider economy, ease of circuit construction, and ease of making electrical measurements. When each electrical circuit is completed, common points are connected directly to the metal chassis; current flows through the metal chassis (conductor) to reach other points of the circuit.

Loaded voltage divider circuits. So far you've learned that a voltage divider resembles a simple series circuit. Now we discuss what happens when load devices are connected to a simple voltage divider.

A load device is any component, mechanical or electrical, that consumes power as it performs its function. A resistor is often used as a load device. We must distinguish between the terms "load device" and "load." "Load" means current. When we speak of a light load, we mean that a low value of current is being drawn from the power source or battery. When we speak of a heavy load, we mean that a high value of current is being drawn from the power source or battery. It stands to reason, then, that the ohmic value of the load device determines the amount of load placed on a given voltage source. By placing the load device across a voltage divider, we have a loaded voltage divider circuit.

Figure 2–32 illustrates a loaded voltage divider circuit with four different load devices: R_5, between point D and ground; R_6, between point C and ground; R_7, between point B and ground; and R_8, between point A and ground. Careful inspection of this loaded voltage divider circuit shows it to be a complex series-parallel circuit.

To calculate the current and voltage drops within a voltage divider, use Kirchoff's laws. The current law states that the sum of the currents entering any point in a circuit equals the sum of the currents leaving that point. The voltage law states that the sum of the voltage drops around a closed loop is equal to the applied voltage. Keep these laws in mind while you work with voltage dividers.

The current drawn from the power source divides between the voltage divider and load devices; it combines again as it returns to the power source. The voltage divider, with the power supply, forms a closed loop and the sum of the voltage drops along the divider equals the applied voltage. The voltage across the various

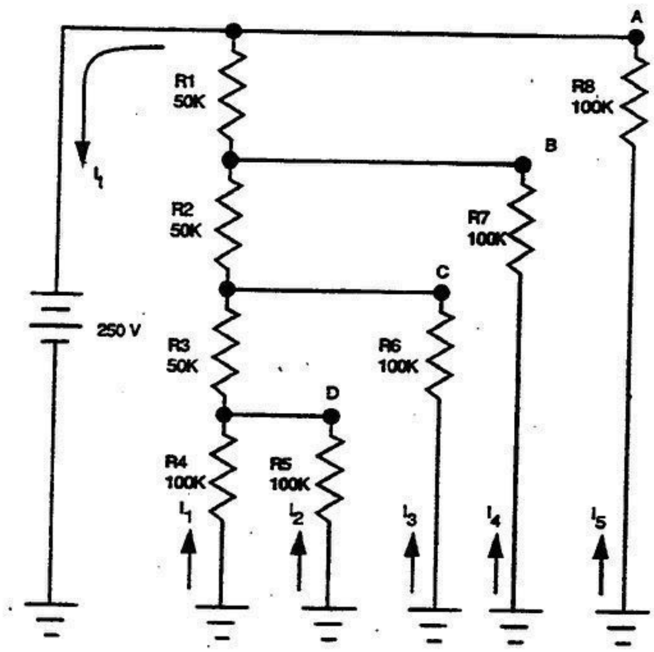


Figure 2–32. Voltage divider circuit (solving for voltage).

load devices equals the voltage present at the tap on the divider. The voltage dropped across R_4 is the voltage present at point D with respect to ground. Now, let us solve for total resistance, total current, and voltage at each point.

Solving for resistance. The combined effect of the individual load resistors and the voltage divider resistors in the circuit can be solved if you start at the inside of the circuit and work out. We use the equivalent circuits shown in figure 2–33 for our discussion. Refer to the corresponding figure identified by step numbers to review each of the following steps in computing the resistance.

Step 1:

$$\begin{aligned} R_{e1} &= \frac{R_4 \, x \, R_5}{R_4 + R_5} \\ &= \frac{100k \, x \, 100k}{100k + 100k} \\ &= 50k\Omega \end{aligned}$$

NOTE: R_{e1} is defined as "resistance Equivalent1."

Step 2:

$$\begin{aligned} R_{e1} &= \frac{(R_{e1} + R_3) \, x \, R_6}{(R_{e1} + R_3) + R_6} \\ &= \frac{(50k + 50k) \, x \, 100k}{(50k + 50k) + 100k} \\ &= 50kW \end{aligned}$$

Step 3:

$$\begin{aligned} R_{e2} &= \frac{(R_{e2} + R_2) \, x \, R_7}{(R_{e2} + R_2) + R_7} \\ &= \frac{(50k + 50k) \, x \, 100k}{(50k + 50k) + 100k} \\ &= 50kW \end{aligned}$$

Step 4:

$$\begin{aligned} R_t &= \frac{(R_{e3} + R_1) \, x \, R_8}{(R_{e3} + R_1) + R_8} \\ &= \frac{(50k + 50k) \, x \, 100k}{(50k + 50k) + 100k} \\ &= 50kW \end{aligned}$$

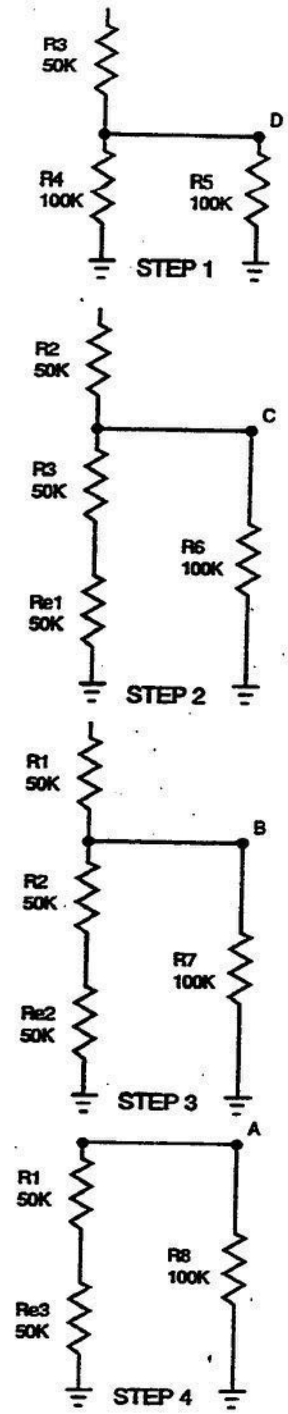


Figure 2–33. Voltage divider circuits (solving for resistance).

Solving for current and voltage. With the total resistance of 50k ohms known, the load (total current) placed on the voltage source by the divider can be calculated by the following Ohm's law formula:

$$I_t = \frac{E_A}{R_t} = \frac{250\text{V}}{50\text{k}\Omega} = \frac{250\text{V}}{50\text{x}10^{-3}\,\Omega}$$
$$= 5\text{x}10^{-3} \text{ amps}$$
$$= 5\text{mA}$$

With the total current known, we can apply Kirchhoff's law and Ohm's law to solve for individual branch currents and the voltage at each point along the divider with respect to ground. Figure 2–34 shows the individual paths of current through the divider circuit. The total current in the circuit is equal to the sum of the individual branch currents or

$$I_t = I_1 + I_2 + I_3 + I_4 + I_5$$

The current through R_1 is equal to I_t - I_5.

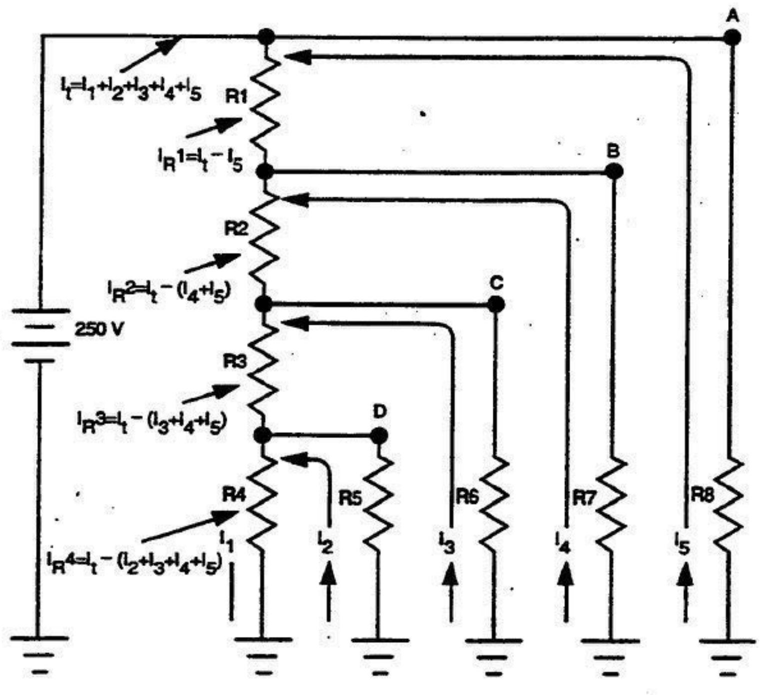


Figure 2–34. Voltage divider circuit (individual paths of current flow).

In the same manner:

$$I_{R_2} = I_t - (I_4 + I_5)$$
$$I_{R_3} = I_t - (I_3 + I_4 + I_5)$$
$$I_{R_4} = I_t - (I_2 + I_3 + I_4 + I_5)$$

When we determined network resistance, we worked from the inside. To determine voltages and branch currents, let us start with the outermost load device in figure 2–34. The voltage across R_8 (point A with respect to ground) is the source voltage. We can, therefore, use Ohm's law to find the current through R_8.

The following steps are shown in progressive order as a method of determining the voltage at each point along the divider and the individual branch currents. Use figures 2–34 and 2–35 as aids.

Step 1:

$$E_A = \text{source voltage } E_a,\ 250V$$
$$I_5 = \frac{E_A}{R_8} = \frac{250V}{100k\Omega} = 2.5mA$$

Step 2:

$$I_{R_1} = I_t - I_5 = 5mA - 2.5mA = 2.5mA$$
$$E_{R_1} = I_{R_1} R_1$$
$$= 2.5mA \text{ x } 50k\Omega$$
$$= 125V$$
$$E_B = E_A - E_{R_1}$$
$$= 250V - 125V = 125V$$
$$I_4 = \frac{E_B}{R_7} = \frac{125V}{100k\Omega} = .625mA$$

Step 3:

$$I_{R_2} = I_t - (I_4 + I_5)$$
$$= 5mA - (1.25mA + 2.5mA)$$
$$= 1.25mA$$
$$E_{R_2} = I_{R_2} R_2$$
$$= 1.25mA \text{ x } 50kW = 62.5V$$
$$E_C = E_A - (E_{R_1} + E_{R_2})$$
$$= 250V - (125V + 62.5V)$$
$$= 62.5V$$
$$I_3 = \frac{E_C}{R_6} = \frac{62.5V}{100kW} = .625mA$$

Step 4:

$$
\begin{aligned}
I_{R_3} &= I_t - (I_3 + I_4 + I_5) \\
&= 5\text{mA} - (.625\text{mA} + 1.25\text{mA} + 2.5\text{mA}) \\
&= .625\text{mA}
\end{aligned}
$$

$$
E_{R_3} = I_{R_3} R_3 = .625\text{mA x } 50\text{kW} = 31.25\text{V}
$$

$$
\begin{aligned}
E_D &= E_A - (E_{R_1} + E_{R_2} + E_{R_3}) \\
&= 250\text{V} - (125\text{V} + 62.5\text{V} + 31.25\text{V}) \\
&= 31.25\text{V}
\end{aligned}
$$

$$
I_2 = \frac{E_D}{R_5} = \frac{31.25\text{V}}{100\text{kW}} = .3125\text{mA}
$$

$$
I_1 = \frac{E_D}{R_4} = \frac{31.25\text{V}}{100\text{kW}} = .3125\text{mA}
$$

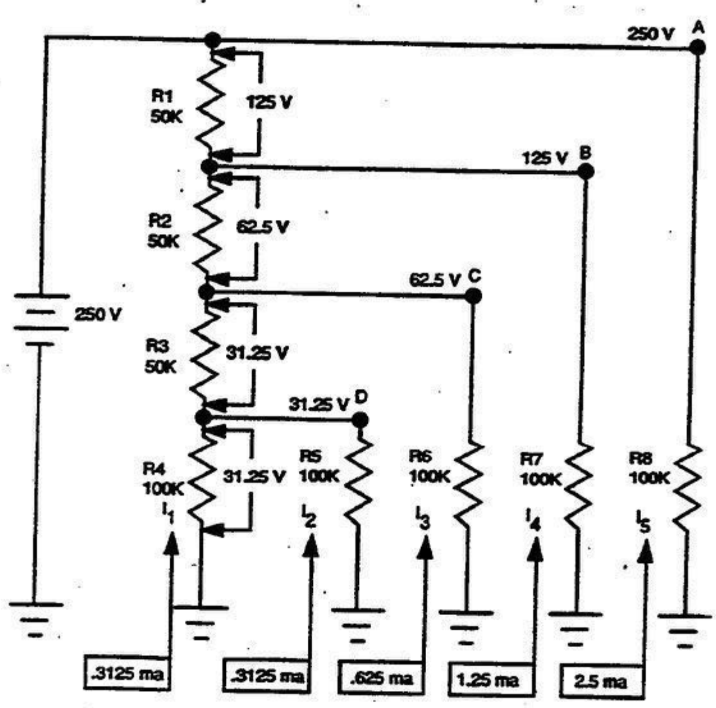


Figure 2–35. Voltage divider circuit (solving for individual currents).

Now analyze the voltage divider circuit shown in figure 2–36. The load resistor, R3, is connected through switch S1 to point Y on the voltage divider. First, calculate the voltage at point Y with the switch open, under a no-load condition. Second, calculate the voltage at point Y with the switch closed, a loaded condition.

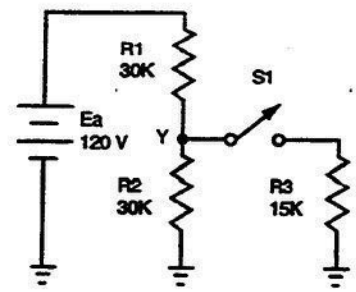


Figure 2–36. Voltage divider circuit (calculating voltage under load and no-load conditions).

Switch open:

$$R_t = R_1 + R_2 = 30k + 30k = 60k\Omega$$
$$I_t = \frac{E_a}{R_t} = \frac{120V}{60k\Omega} = 2mA$$
$$E_{R_1} = I_t \text{ x } R_1 = 2mA \text{ x } 30k = 60V$$
$$E_{R_2} = E_a - E_{R_1} = 120V - 60V = 60V$$
$$E_Y = E_{R_2} = 60V$$

The voltage at point Y without the load device connected to the divider is 60 volts. Total resistance of the circuit is 60 kΩ and total current is 2 mA.

Switch closed:

$$R_e = \frac{R_2 \text{ x } R_3}{R_2 + R_3} = \frac{30k \text{ x } 15k}{30k + 15k} = 10k\Omega$$
$$R_t = R_1 + R_e = 30k + 10k = 40k\Omega$$
$$I_t = \frac{E_a}{R_t} = \frac{120V}{40k\Omega} = 3mA$$
$$E_{R_1} = I_t \text{ x } R_1 = 3mA \text{ x } 30k\Omega = 90V$$
$$E_{R_2} = E_{R_3} = E_a - E_{R_1} = 120V - 90V = 30V$$
$$E_Y = E_{R_2} = E_{R_3} = .30V$$

The voltage at point Y with the load device connected to the divider is 30 volts. Total resistance of the circuit is 40 kΩ and total current is 3 mA. Reviewing our calculations, we can make the following conclusions concerning a load device connected to a voltage divider:

- Total circuit resistance decreases.
- Total circuit current increases; that is, the load on the voltage portion of the divider decreases.
- The voltage drop across the series resistor increases.

All voltages obtained in the previous explanations are positive in polarity. In every case, the negative terminal of the battery is grounded. This makes all other points in the circuit positive with reference to ground.

Recall that voltage dividers can supply negative voltages when the positive battery terminal is grounded. With the most positive point grounded, all other points in the circuit are negative with reference to that point.

When you studied unloaded voltage dividers, you learned that both positive and negative voltages may be obtained from a single voltage divider. This happens if some point of the resistive network is grounded. This point *cannot* be one of the battery terminals, but must be in the resistance network of the voltage divider. Calculations for these circuits are the same as for the examples just shown. Just keep in mind that ground is merely a reference point.

Balanced and unbalanced resistive bridge circuits. Bridge circuits are frequently used in electronics where a signal from a "detecting" device is used to drive or connect an operational device. Some bridge circuits have fixed components while others contain adjustable components. With a variable component, a bridge circuit may be used as a very accurate piece of test equipment.

Part A of figure 2–37 shows a regular parallel circuit with which we are already familiar. It has two paths for current flow. Note that we have inserted two identifying points on the circuit: point A, between R_1 and R_2, and point B, between R_3 and R_4. Suppose we take points A and B and stretch the circuit. The result is a diamond shape. To make a bridge circuit out of this diamond shape, some type of resistive load (the detecting device) must be connected between points A and B.

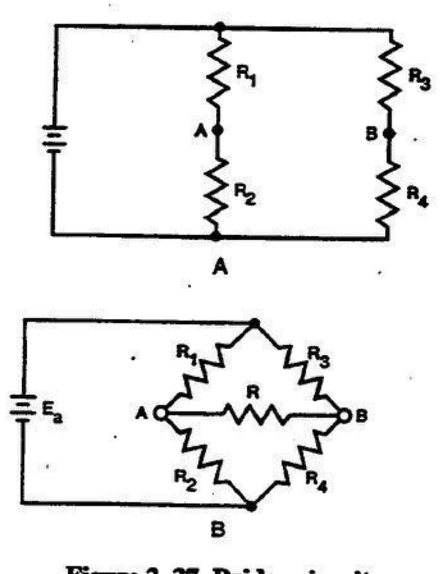


Figure 2–37. Bridge circuit.

Balanced bridge circuits. Perhaps you can see a relationship in the circuit already. If there is a difference of potential between points A and B of the bridge circuit, current will flow through the load device (R). The direction of current flow is determined by the polarity of voltage present at point A with respect to point B. On the other hand, if there is no difference of potential between points A and B, no current will flow through the load device. During this no flow condition, the bridge circuit is said to be balanced. Quite often when a bridge circuit is used in a test instrument, the load device is a very sensitive meter movement such as a galvanometer. Figure 2–38 shows a galvanometer, which indicates direction and amount of current flow, connected into a bridge circuit.

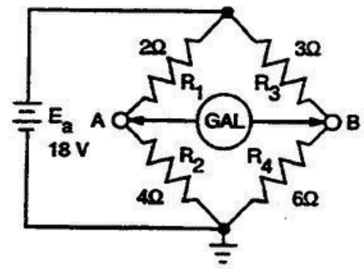


Figure 2–38. Balanced bridge circuit.

To determine the potential difference between points A and B, we can connect a voltmeter between them. Instead, let us find the answer by using Ohm's law. In a parallel circuit, the applied voltage (E_a) is the same in all branches. Add the resistance in each branch: branch A = 6 ohms; branch B = 9 ohms.

Now find the current through the two branches by using the following Ohm's law formula:

$$I = \frac{E}{R}$$

You found that 3 amps flow through branch A and 2 amps through branch B. You are now ready to compute the potential at points A and B. Notice that a ground reference point has been added to the circuit. With ground at this point, the potential at points A and B is positive with respect to ground.

Branch A at point A

$$\begin{aligned} E &= I_A \times R_2 \\ &= 3_a \times 4\Omega \\ &= 12 \text{ volts} \end{aligned}$$

Branch B at point B

$$\begin{aligned} E &= I_B \times R_4 \\ &= 2_a \times 6\Omega \\ &= 12 \text{ volts} \end{aligned}$$

To find the potential difference between points A and B, you subtract the smaller voltage from the larger. In our case, this is zero volts. With 0 volts existing between the two points, no current flows through the galvanometer. This is the condition of a balanced bridge.

Let us examine figure 2–38 a little closer. Note the relation of the value of R_1 (2Ω) to the value of R_2 (4Ω). The ohmic value of R_2 is twice that of R_1. You see the same relationship between R_3 (3Ω) and R_4 (6Ω). This relationship can be expressed in mathematical form as follows:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \quad \text{or} \quad \frac{2\Omega}{4\Omega} = \frac{3\Omega}{6\Omega}$$

This ratio is stated: R_1 is to R_2 as R_3 is to R_4. Cross-multiplying numerators and denominators yields the result, 12 ohms equals 12 ohms. The bridge is balanced.

Also note that a relationship exists with R_1 to R_3 and R_2 to R_4.

$$\frac{R_1}{R_3} = \frac{R_2}{R_4} \quad \text{or} \quad \frac{2\Omega}{3\Omega} = \frac{4\Omega}{6\Omega}$$

These relationships between any two resistors in the vertical or horizontal plane exist in any bridge circuit. If the ratios are equal, the circuit is balanced.

Unbalanced bridge circuits. In the examples above, we worked with a balanced bridge circuit. Let us now examine the characteristics of an unbalanced bridge circuit. The bridge circuit shown in figure 2–39 is an unbalanced bridge circuit. With your understanding of balanced bridge circuits, you can already see, by looking at the value of the resistors, the bridge is in an unbalanced condition. A more positive way to determine whether the bridge is balanced or unbalanced is to use the ratio formula:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \quad \text{or} \quad \frac{7\Omega}{14\Omega} = \frac{3\Omega}{4\Omega}$$

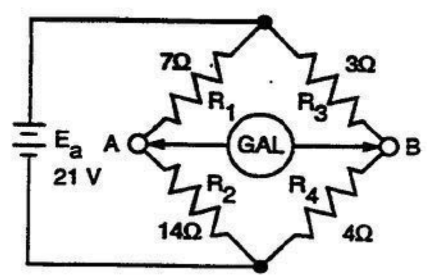


Figure 2–39. Unbalanced bridge circuit.

With the bridge unbalanced, a potential difference exists between points A and B. You can determine this potential difference by Ohm's law. Your calculation should show that 1 amp flows through branch A and 3 amps through branch B. Using the current flows and the resistance of R_2 and R_4, determine the voltage at points A and B. Your calculation should show that the voltage at point A is 14 volts and at point B is 12 volts. The potential difference between points A and B is 2 volts. Since point A is more positive than point B, current flows from point B toward point A through the galvanometer. To balance this bridge circuit, the size of R_1, R_2, R_3, or R_4 must change. Let us assume that we want to change R_4. We can use the ratio.

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \quad \text{or} \quad \frac{7\Omega}{14\Omega} = \frac{3\Omega}{R_4}$$

Solve for the unknown (R_4) by cross-multiplying.

$$7\Omega \times R_4 = 14\Omega \times 3\Omega$$
$$7\Omega \times R_4 = 42$$
$$R_4 = 6\Omega$$

We could replace R_4 with a 6-ohm resistor and have a balanced bridge. No potential difference would exist between points A and B and the galvanometer would read zero.

024. Troubleshooting DC circuits

We have studied how components work and interact with each other in series, parallel, and series-parallel DC circuits. Ideally, every circuit we encounter works properly. This is not always the case. We as tech controllers should be able to identify the characteristics of faulty components within a DC circuit.

Multimeters. To actually troubleshoot a circuit, you need to be able to make measurements of the different electrical values. Measurements of current, voltage, and resistance are easily accomplished with a multimeter.

Most multimeters have two selector switches on their front. One switch is for the function to be performed (such as: measure resistance) and the other selects the range in which the measurement is made. For the specifics on the use of any particular multimeter, it is best to refer to the commercial manual that accompanies the meter.

Circuit defects. The conditions that may exist in a DC circuit, other than normal, are either a shorted or opened resistor. There is a systematic procedure by which we can isolate such faulty components. Before troubleshooting these defects, let us first briefly discuss what these defects are.

An *open* resistor is one where no current can flow through it, much in the same manner that no cars can cross an opened drawbridge. A broken resistive element or an interior lead separation are possible causes for an open resistor.

A *shorted* resistor is one that offers no opposition to current flow. If you imagine a resistor as a dam that holds back water, then a shorted resistor is like the dam crumbling and allowing all the water that was held back to flow freely. Causes for this are interior leads making contact, possibly due to vibrations or to maintenance work being done in the area.

When troubleshooting, it is imperative to remember that an absence of current indicates an open resistor, whereas an excessive amount of current indicates a shorted resistor.

Series circuit troubleshooting. By comparing the circuits in figures 2–40, 2–41, and 2–42, it is apparent that, even though they are designed the same, something is wrong. The same values have been assigned to all the components, but when we make the various measurements, we obtain different values.

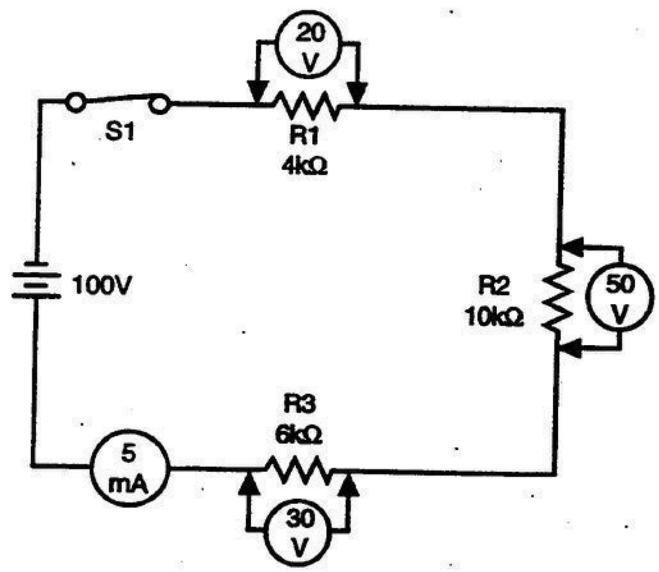


Figure 2–40. Normal series DC circuit.

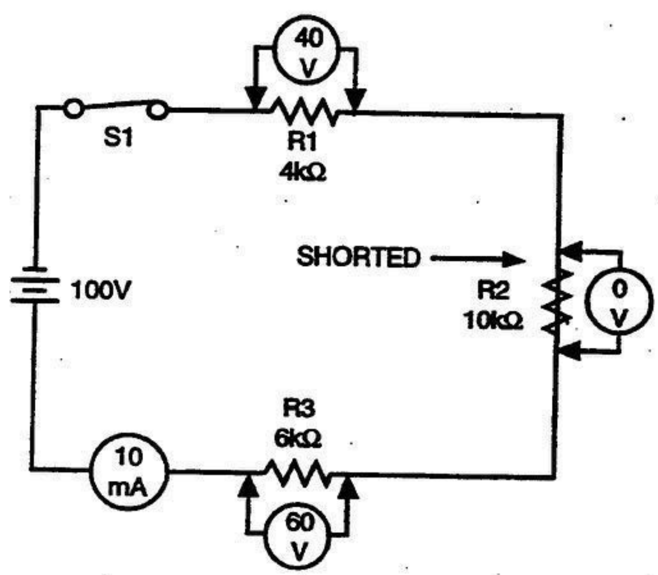


Figure 2–41. Shorted series DC circuit.

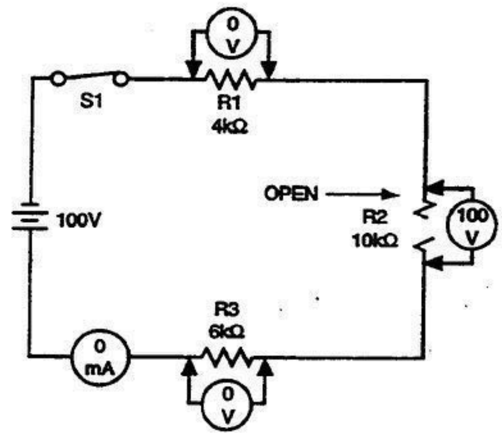


Figure 2–42. Opened series DC circuit.

It is easy to troubleshoot a circuit if you recognize the different values as symptoms of a faulty circuit.

Symptom	*Possible Trouble*
Excessive Current	Shorted Resistor
No Current	Open Resistor
E_a Across One Resistor	Open Resistor
No E Across One Resistor	Shorted Resistor

By changing the values of the components in figure 2–40 and using Ohm's law, a faulty component can be isolated. Let us assume that E_a is 50 volts, R_1 is 5 kΩ, R_2 is 7 kΩ, and R_3 is 13 kΩ. Total resistance is the sum of the resistance value (or 25 kΩ) of all components. Total current is the result of E_a/R_t according to Ohm's law or 2 mA.

If we check the current with a multimeter and find it to be at 4.2 mA, we know that there probably is a shorted resistor in the circuit due to excessive current. We can isolate it either with a voltmeter or mathematically. Knowing that a shorted resistor offers no resistance makes the mathematical task easier. Add the values of the resistors in the circuit for a new total resistance, leaving out one of the resistors each time. If R_1's value is left out, R_t is 20 kΩ. If R_2's value is left out, R_t is 18 kΩ. If R_3's value is left out, R_t is 12 kΩ. Using these new values in the current formula, I_t equals E_a/R_t, we can obtain the three current values of 2.5 mA, 2.8 mA, and 4.2 mA respectively. This shows that the resistor that is shorted is R_3.

This method of isolation can be applied throughout the troubleshooting section. Use it with future examples.

By using Ohm's law, we can mathematically solve for unknowns in a DC circuit with faulty components, but the realities of the situation dictate using a multimeter to isolate the defective component.

Parallel circuit troubleshooting. If we compare the different diagrams of the same parallel circuit, shown in figures 2–43, 2–44, and 2–45, we can readily see that something is not right.

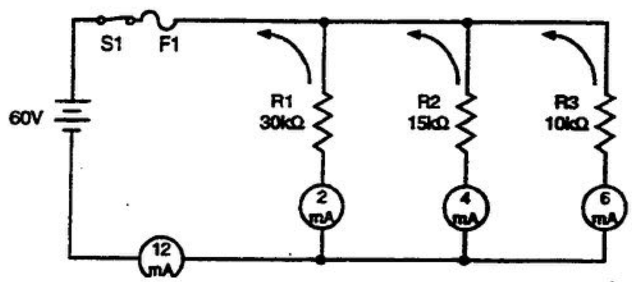


Figure 2–43. Normal parallel DC circuit.

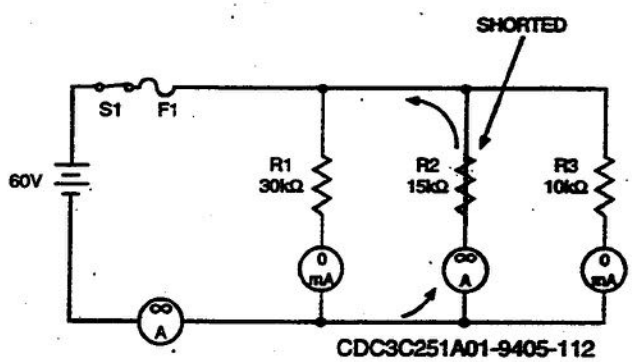


Figure 2–44. Shorted parallel DC circuit.

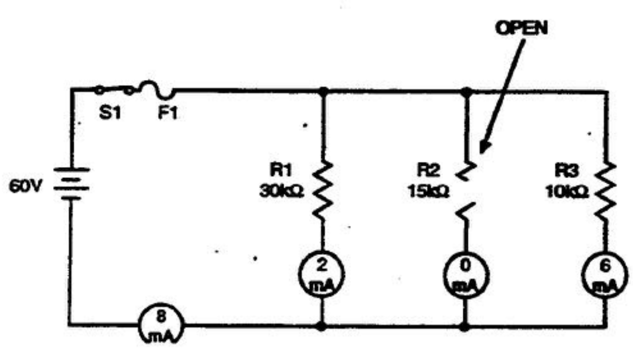


Figure 2–45. Opened parallel DC circuit.

Remembering a few rules helps you to isolate what is wrong within a parallel circuit. Figure 2–44 represents a circuit immediately after R_2 shorted out. In practical application, since the branch with the shorted resistor offers no resistance and has excessive current flowing through the circuit, the fuse will blow. Remember the following when troubleshooting:

Shorted Parallel Resistor

a. The power will be off due to a blown fuse.

b. A voltmeter cannot be used to isolate the component.

c. Measuring the resistance of (Ohming out) the shorted component will show zero ohms.

Figure 2–45 has an open in the circuit. Remember that an open acts like a dam in the branch where it is located. Remember the following when troubleshooting:

Open Parallel Resistor

a. There will be a reduction in total current.

b. No current will flow through the open resistor.

c. A voltmeter cannot be used to isolate the component.

d. Ohming out the faulty resistor will show infinite ohms.

e. Ohm's law can be used to isolate the faulty component.

Series-parallel circuit troubleshooting. Series-parallel troubleshooting is an application of concepts learned in the troubleshooting of either a series or a parallel circuit. When these concepts are used in a systematic approach, it is easy to isolate faulty components. We break series-parallel troubleshooting down into two parts. What happens with an open or shorted resistor in the (a) series portion of a circuit; (b) in the parallel portion of the circuit? Use figures 2–46, 2–47, and 2–48 with the discussion on faults in the *series* portion of a circuit.

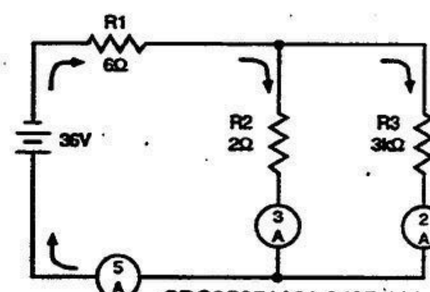


Figure 2–46. Normal series-parallel DC circuit.

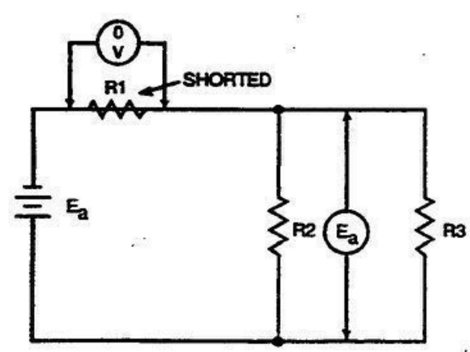


Figure 2–47. Short in series portion of a series-parallel DC circuit.

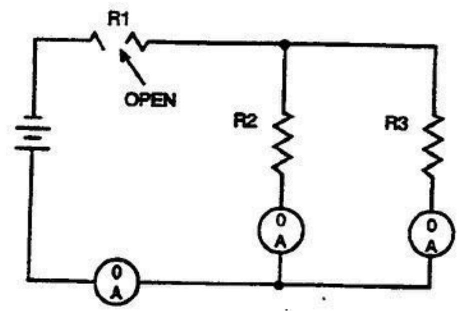


Figure 2–48. Open in series portion of a series-parallel DC circuit.

When a resistor in the *series* portion of a series-parallel circuit becomes open, the following symptoms occur:

a. No current flow through the circuit.

b. Applied voltage dropped across the open resistor.

c. No voltage dropped across the parallel portion of the circuit.

When a resistor in the *series* portion of a series-parallel circuit becomes shorted, the following symptoms occur:

a. Increased current flow through the circuit.

b. Zero volts dropped across the shorted resistor.

c. Applied voltage dropped across the parallel portion of the circuit.

Use figures 2–46, 2–49, and 2–50 with the discussion on the faults in the *parallel* portion of a circuit.

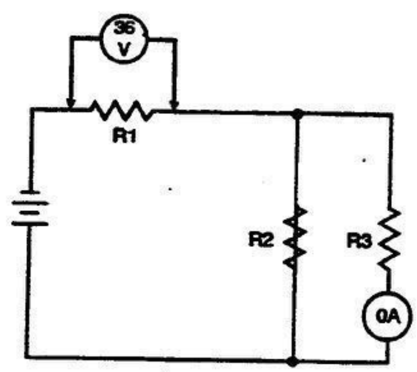


Figure 2–49. Short in parallel portion of a series-parallel DC circuit.

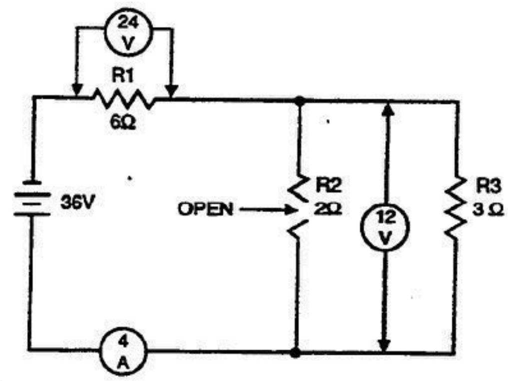


Figure 2–50. Open in parallel portion of a series-parallel DC circuit.

When a resistor in the *parallel* portion of a series-parallel circuit becomes open, the following symptoms occur:

a. A decrease in total current.

b. Voltage across the series portion of the circuit decreases.

c. Voltage across the parallel portion of the circuit increases.

When a resistor in the *parallel* portion of a series-parallel circuit becomes shorted, the following symptoms occur:

a. An increase in total current.

b. Applied voltage dropped across the series portion of the circuit.

c. Zero volts dropped across the parallel portion of the circuit.

When you troubleshoot a series-parallel circuit, you can see by the different symptoms that the problem is not always obvious. For example, if E_a is dropped across the series portion of the circuit, the fault can either be an open in the series portion or a short in the parallel portion. Because of the nature of series-parallel circuits, it is necessary to isolate components from the circuit and ohm them out to be certain which component failed.

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

021. DC circuit terminology--components, symbols and value expressions

1. Name the three basic requirements for a practical circuit.

2. Draw these schematic symbols:

(a) ground.

(b) rheostat.

(c) ammeter.

(d) battery.

(e) crossed wires not connected.

(f) lamp.

3. What is the purpose of resistors?

4. Name three varieties of resistors.

5. What is a battery?

6. Define "ground" as it applies to electronics.

7. Match the electronic terms in Column B with the associated statements in Column A. Items in column B may be used once, more than once, or not at all.

Column A	*Column B*
___(1) Used to provide circuit protection.	(a) Battery.
___(2) Used to measure current flow.	(b) Ground.
___(3) Converts chemical energy to electrical energy.	(c) Voltmeter.
___(4) Used as a circuit loading device or to indicate circuit condition.	(d) Ammeter.
___(5) Used to measure voltage.	(e) Ohmmeter.
___(6) Common reference point from which voltages are measured.	(f) Rotating machine.
___(7) Converts electrical energy to mechanical energy.	(g) Switch.
___(8) Used to control power to a circuit.	(h) Lamp.
___(9) Used to measure resistance.	(i) Fuse.

8. Convert the following values as directed. Example: Change 0.006 amps to mA = 6 mA.

(a) 3000 ohms to k ohms.

(b) 60 kV to volts.

(c) 2 mA to A.

(d) 0.600A to mA.

(e) 150 mW to kilowatts.

(f) 10 Mega ohms to ohms.

(g) 5 amps to μ amps.

(h) 100 ohms to K ohms.

(i) 0.002 mA to amps.

022. DC circuit operation

1. How many paths for current flow can a series DC circuit contain?

2. Name the required components of a basic series DC circuit.

3. Name two components, other than those required, that are normally included in most practical circuits.

4. What should you keep in mind when you measure for current at various test points in a series circuit?

5. If you add the voltages dropped across all components in a series circuit, what should the total equal?

6. What happens to current in a series DC circuit when voltage remains constant and resistance is doubled?

7. Define a parallel DC circuit.

8. Explain how current is divided in a parallel DC circuit.

9. State the relationship of total resistance to the number of resistors connected in a parallel DC circuit when all resistors have the same value.

10. What does a series-parallel DC circuit consist of?

11. What is the purpose of a voltage divider?

12. Name two types of variable resistors used in voltage dividers.

13. How many active terminals does a rheostat have?

14. How many active terminals does a potentiometer have?

15. What is the purpose of a rheostat?

16. What effect does increasing rheostat resistance in a voltage divider have on the circuit's total resistance and current?

17. What is the purpose of a potentiometer?

18. What purpose do bridge circuits serve in electronics?

023. Perform DC circuit calculations

1. Give the Ohm's law formulas for computing the following values in a series DC circuit:

   (a) current.

   (b) resistance.

   (c) voltage.

2. Using the circuit in figure 2–51, calculate the unknown values. Record your calculations here.

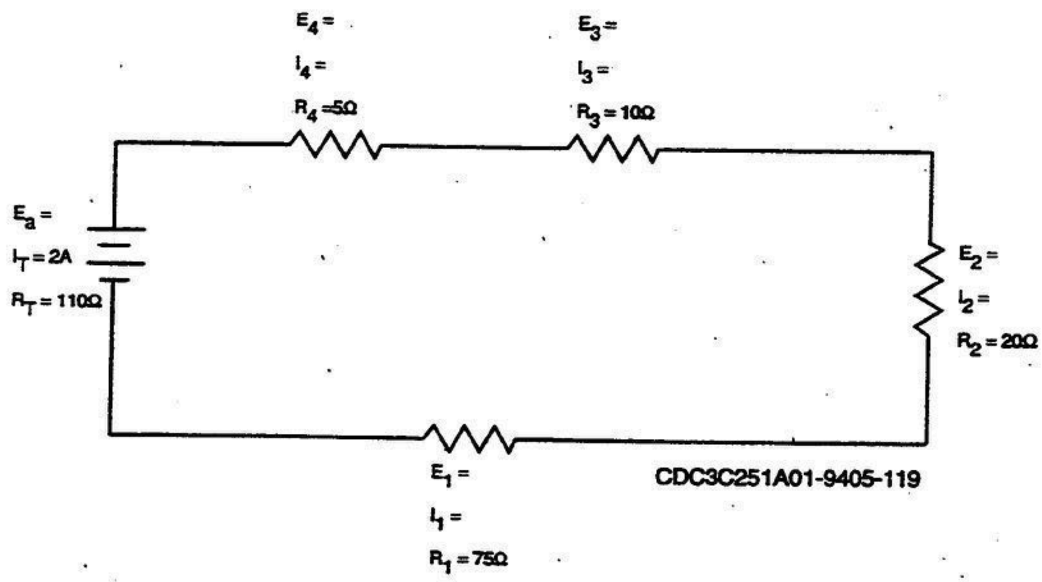


Figure 2–51. Lesson 023, self-test question 2.

3. Briefly state Kirchhoff's law on current.

4. Briefly state Kirchhoff's law on voltage.

5. What is Joule's law formula for computing total power in a series circuit when only total current and resistance are known?

6. Using the circuit in figure 2–52, calculate for the unknown values. Record your calculations here.

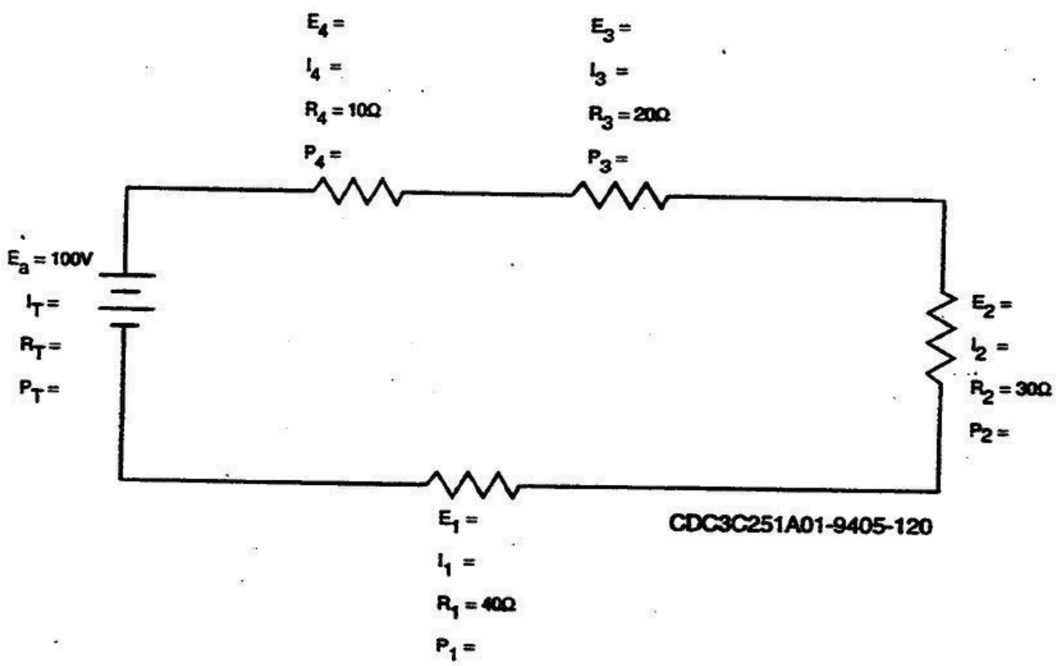


Figure 2–52. Lesson 023, self-test question 6.

7. How do you determine total current in a parallel DC circuit when you know only the individual branch currents?

8. What formula would you use to determine total resistance in a parallel DC circuit that consists of four unequal resistors?

9. What formula would you use to determine total power in a parallel DC circuit when you know only total current and applied voltage?

10. Using the circuit in figure 2-53, calculate for the unknown values.

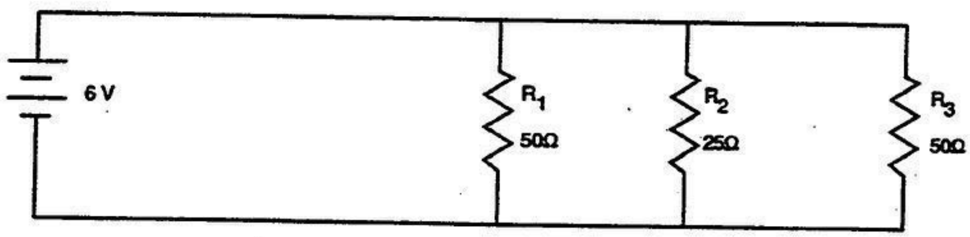


Figure 2-53. Lesson 023, self-test question 10.

E_a =

I_t =

R_t =

P_t =

11. What is the first step you take when you prepare to calculate values in a series-parallel DC circuit?

12. Using the circuit in figure 2-54, calculate the unknown values.

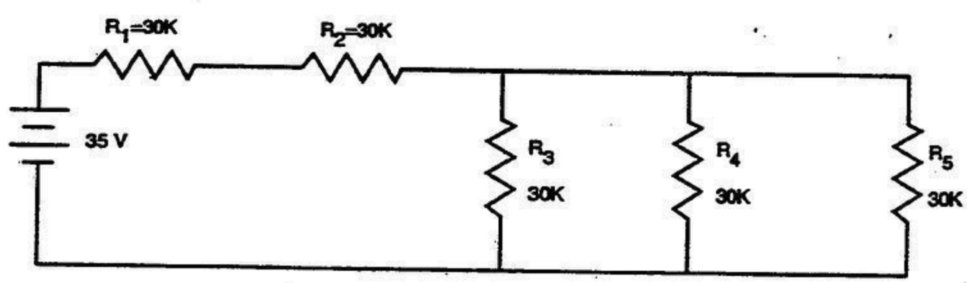


Figure 2-54. Lesson 023, self-test question 12.

E_a =

$R_T =$

$I_T =$

$P_T =$

13. What is meant by a loaded voltage divider?

14. How many paths are there for current flow in the loaded voltage divider depicted in figure 2–55?

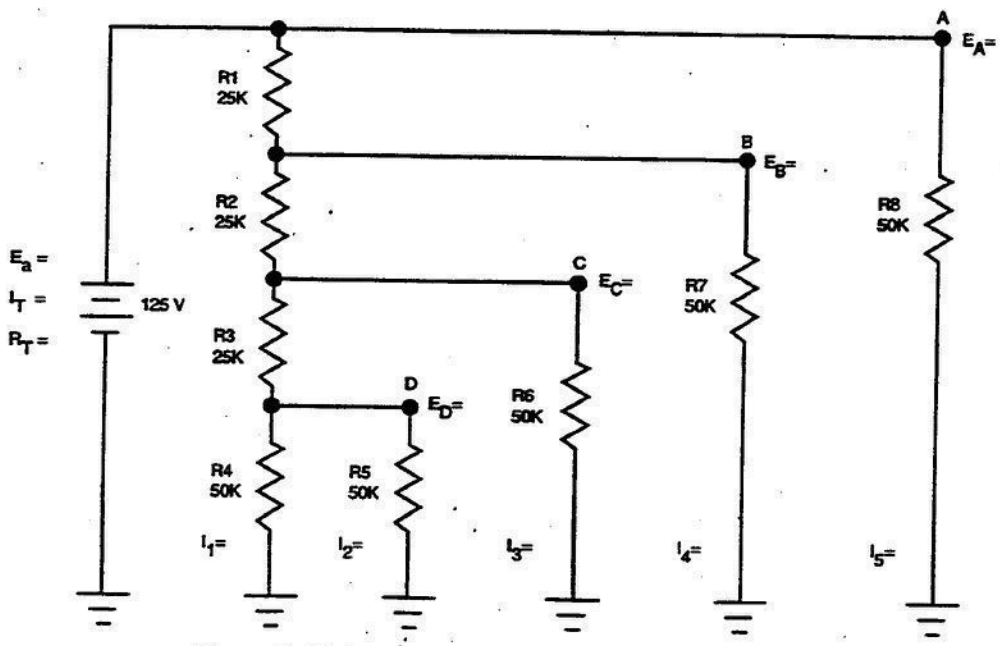


Figure 2–55. Lesson 023, self-test question 14 and 17.

15. What does the term "load" mean?

16. When a load device is placed across a voltage divider, what happens to total circuit resistance, total circuit current, and the voltage drop across the series resistor?

17. Using the circuit in figure 2–55, calculate the unknown values.

18. Explain the difference between a balanced resistive bridge circuit and an unbalanced resistive bridge circuit.

024. Troubleshooting DC circuits

1. What is the condition of a resistor that does not let current flow through?

2. If no voltage is dropped across one resistor in a series circuit, what is probably the resistor's condition?

3. What does the excessive current in a parallel circuit with a shorted resistor probably cause?

4. What type of test equipment *cannot* be used to troubleshoot a shorted or open resistor in a parallel DC circuit?

5. What is the measured ohmic value of a shorted resistor in a parallel DC circuit?

6. What is the measured ohmic value of an open resistor in a parallel DC circuit?

7. What is the total current value of a series-parallel DC circuit that contains an open resistor in its series portion?

8. What is the probable fault in a series-parallel DC circuit in which no voltage is dropped across its parallel portion?

9. What is the probable fault in a series-parallel DC circuit in which voltage measured across the series portion is equal to the applied voltage?

2–3. Fundamentals of Alternating Current (AC)

Over the years, certain disadvantages in the use of direct current have become apparent. In a direct current system, the supply voltage must be generated at the level required by the load. To operate a 220-volt lamp, for example, the generator must deliver 220 volts. A 110-volt lamp cannot operate from this generator by any convenient means, but a resistor can be placed in series with the 110-volt lamp to drop the extra 110 volts. The resistor, however, wastes an amount of power equal to that consumed by the lamp.

Another disadvantage of the direct current system is the large amount of power lost due to the resistance of the transmission wires used to carry current from the generating station to the consumer. This loss can be greatly reduced by operating transmission lines at very high voltages and low current. This is not a practical solution in a DC system since the load also has to operate at high voltage.

As a result of the difficulties encountered with high current, practically all modern power distribution systems use a type of current known as *alternating current (AC)*. In an alternating-current system, the current flows first in one direction, then reverses and flows in the opposite direction. Unlike DC voltage, AC voltage can be stepped up or down by a device called a *transformer*. A transformer permits transmission lines to be operated at high voltage and low current for maximum efficiency. At the consumer end, the voltage is stepped down to whatever value the load requires by using a transformer. Due to its inherent advantages and versatility, alternating current has replaced direct current in all but a few commercial power distribution systems.

025. The basic concepts of AC

In the following lessons, we review some of the basic concepts of AC and some of the properties of electrical circuits that affect the constantly changing current encountered in AC circuits.

Current and voltage development. Many other types of current and voltage exist in addition to direct current and voltage. If a graph is constructed showing the magnitude of DC voltage across the terminals of a battery with respect to time, it appears as in figure 2–56, A. The DC voltage is shown to have a constant amplitude. Some voltages go through periodic changes in amplitude like those shown in figure 2–56, B. The pattern that results when these changes in amplitude are plotted on graph paper is known as a *waveform.*

Induction. Electromagnetic induction occurs any time a conductor is passed through a magnetic field in such a way as to cut the lines of force. In figure 2–57, a conductor is passed upward through a magnetic field in a direction perpendicular to the direction of the flux lines. As the conductor cuts through the flux lines, the magnetic field exerts a force on the free electrons within the conductor. This force causes the free electrons to leave one end of the conductor and pile up on the other, creating a difference of potential across the conductor. The direction of this electron displacement and the resulting polarity of induced voltage can be determined by the use of the *left-hand rule for generators* stated as: With the thumb, forefinger, and middle finger on the left hand held perpendicular to each other, point the forefinger in the direction of the magnetic field and the thumb in the direction of motion of the conductor; the middle finger then points in the direction of electron displacement (negative end of conductor). The application of this rule is demonstrated in figure 2–57. Notice that the middle finger points to the end of the conductor, which assumes a negative charge as a result of the electron displacement.

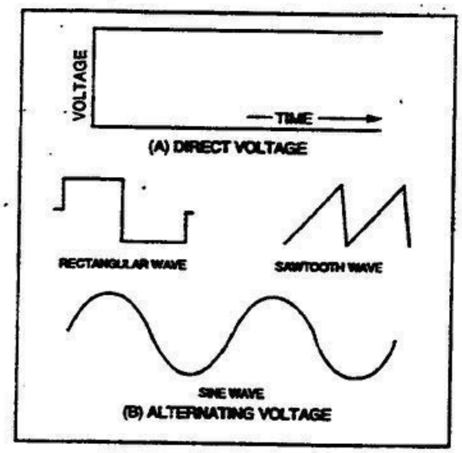


Figure 2–56. Voltage waveforms.

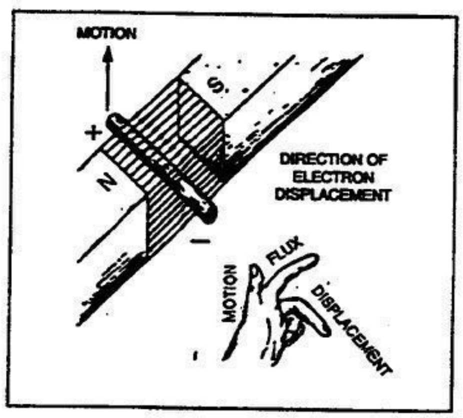


Figure 2–57. Left-hand rule for induced EMF.

Magnitude of induced voltage. The amount of voltage induced into a conductor cutting a magnetic field is dependent on the number of lines cut per unit of time. This is determined by the following four basic factors:

(1) The speed of relative motion between the field and the conductor.

(2) The strength of the magnetic field.

(3) The length of the conductor within the field.

(4) The angle at which the conductor cuts the field.

If the speed at which the conductor cuts the lines of force is increased, the force on the free electrons within the conductor is greater and the generated voltage is increased.

Increasing the strength of the magnetic field also increases the force on the electrons, thereby increasing the induced voltage. The induced voltage is directly proportional to the strength of the field.

The length of the conductor within a field affects the amount of induced voltage. A longer conductor permits the magnetic field to perform more work on the free electrons. A long conductor consists of a number of short conductors connected in series. The individual induced voltages in each of the short sections add to produce a large total voltage across the long conductor. For this reason, practical generators use long conductors which are formed into coils to conserve space. The angle at which the conductor cuts the lines of force affects the number of lines cut per unit of time and, therefore, the amount of induced voltage.

Simple alternator. The construction of a simple, two-pole alternator is shown in figure 2–58. Notice that the conductor has been formed into a loop within the magnetic field. The rotating loop and its supporting structure is called an *armature.* The free ends of the loop are attached to cylindrical pieces of metal called *slip rings* which rotate along with the loop. As the loop rotates, the induced voltage appears at the slip rings. In order to connect the stationary load to the rotating loop without the possibility of the leads twisting as the loop rotates, sliding contacts, called *brushes,* are used. These are generally made of carbon and press against the slip rings to form a rotating contact. Any voltage present on the rings is transferred to the stationary brushes and hence to the load.

Induced voltage. To analyze the operation of a simple alternator, refer to figure 2–59. In this drawing, the loop of wire is rotating counterclockwise within the magnetic field. At the instant of time illustrated, the section of the loop from A to B is passing downward though the magnetic field. Application of the left-hand rule for generators to this side of the loop shows the electrons being forced from A toward B as indicated by the arrow on the left-hand side of the loops. Since the electrons are leaving A and being concentrated at B, end A assumes a positive charge while end B takes on a negative charge.

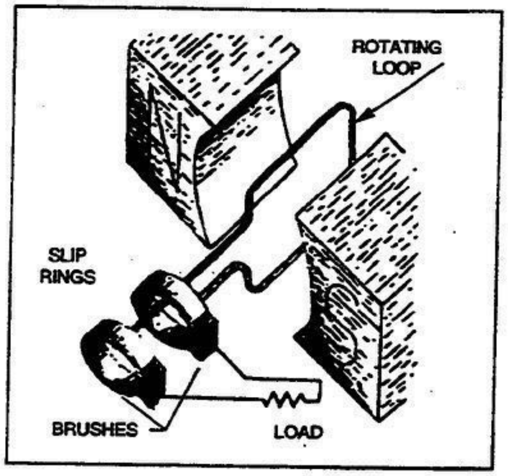


Figure 2–58. Simple alternator.

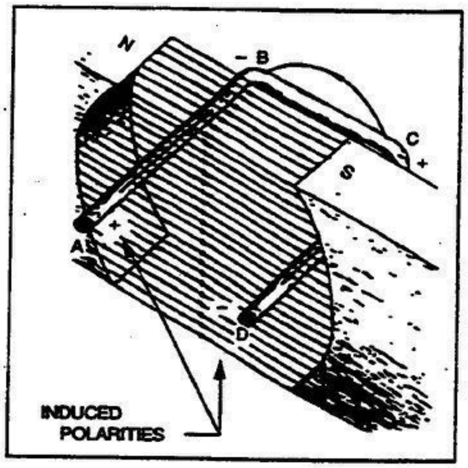


Figure 2–59. Polarity of induced voltage.

While the left-hand side of the loop is passing downward through the magnetic field, the right-hand side of the loop is traveling upward through the field. Since the direction of motion of side CD is opposite to the direction of motion of side AB, the voltages induced into these two sides are of opposite polarity. Application of the left-hand rule to side CD shows the electrons to be displaced from C to D. This displacement current, shown by the arrow, leaves C positive and makes D negative. Notice that in tracing around the wire loop, the voltages induced in the two sides are *series aiding*. The voltage that appears between the ends of the loop (A-D) is, therefore, equal to the *sum* of the voltages in each side. This total voltage is present at the brushes and can be applied to an external load.

A complete cycle. If the loop of wire in the simple alternator is rotated at a constant speed, a voltage is generated that varies in amplitude and periodically reverses polarity. To show how this waveform of voltage is generated, the amplitude of the voltage induced into the loop is plotted for each 45° of rotation (fig. 2–60).

As in the previous explanation, the loop of wire is assumed to rotate in a counterclockwise direction. The illustration represents a cross-sectional view in which the end view of one side of the loop is shown; the other side of the loop is omitted for simplicity.

At the start of the revolution (time 0), the loop is traveling parallel to the lines of force. Since no lines of force are cut by the conductor, no voltage is induced in the loop.

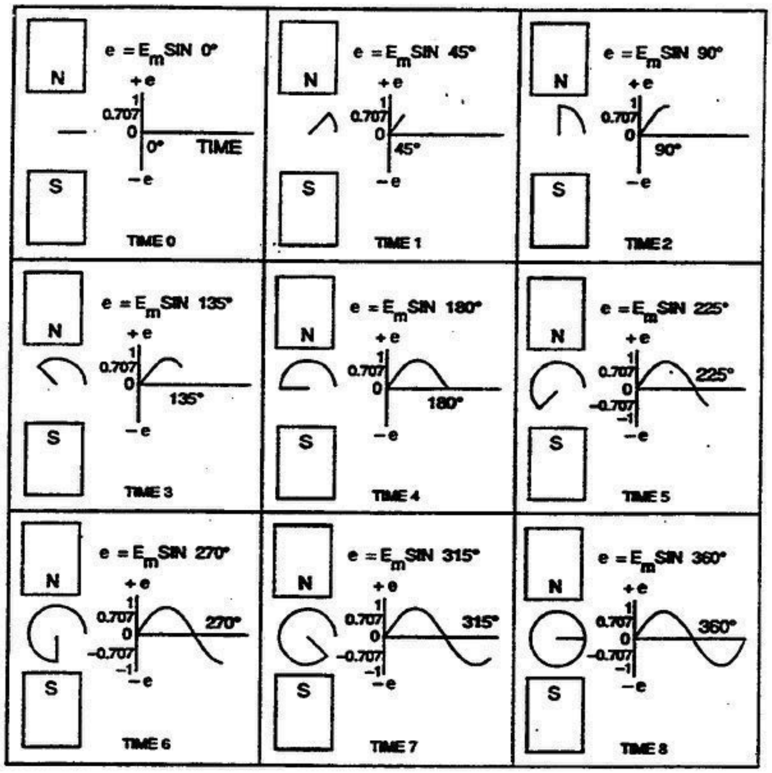


Figure 2–60. Generation of a sine wave.

At time 1, the conductor advances 45° to the position shown. Since the angle at which the conductor cuts the lines of force is known, the equation below can be used to compute the voltage induced into the conductor in terms of the maximum possible induced voltage. Assuming that the maximum voltage (E_m) that can be induced in the loop is 1 volt (when the conductor cuts the lines at right angles), the instantaneous voltage (e) induced at an angle of 45° will be:

$$
\begin{aligned}
e &= E_m \text{ x } \sin\theta \\
&= E_m \text{ x } \sin 45° = 1 \text{ x } 0.707 \\
&= 0.707 \text{ volt}
\end{aligned}
$$

Thus, the instantaneous induced voltage at 45° of rotation is 0.707 volt.

By the time the conductor reaches 90° at time 2, it is cutting perpendicular to the lines of force, and the instantaneous voltage is:

$$
\begin{aligned}
e &= E_m \text{ x } \sin\theta \\
&= 1.0 \text{ x } \sin 90° \\
&= 1.0 \text{ x } 1.0 \\
&= 1.0 \text{ volt}
\end{aligned}
$$

The induced voltage at 90° is, therefore, 1 volt.

As the conductor rotates another 45° to 135° at time 3, the induced voltage is reduced from its maximum to the same value that was developed at 45° or 0.707 volt.

At 180° of rotation (time 4), the conductor is again traveling parallel to the lines of force, and no voltage is induced. At this instant, the conductor has rotated 180 mechanical degrees and the induced voltage has varied from zero to its maximum positive value and back to zero.

As the conductor passes 180°, it once again begins to cut lines of force. Notice, however, that the conductor is cutting the lines of force in a direction *opposite* to the direction of travel during the first 180°. Since the direction of cutting has reversed, the voltage induced into the conductor is of the *opposite polarity*. Thus, at time 5, the voltage induced into the conductor is a *negative* 0.707 volt.

At 270° of rotation (time 6), the conductor is once again cutting the lines of force at right angles and the induced voltage is at its maximum negative value (-1.0 volt).

In traveling from 270° through 315° to 360°, the amount of induced voltage decreases and becomes zero at 360° when the conductor is again traveling parallel to the lines of force. At this point, the conductor is back at the starting position, and one complete *cycle* of events has occurred. Should the conductor continue rotating, additional cycles are generated identical to the one just completed. Since the instantaneous amplitude of the generated waveform is proportional to the sine of the angle of cutting, this waveform is called a *sine wave*.

026. The peak, effective, and average voltage of selected waveforms

In working with AC voltages, we tend to discuss several different types of voltages, each with its own characteristics and rules.

Waveforms. As stated in the previous lesson, a plot of voltage or current versus time is called a *waveform*. If we plot direct current versus time, we end up with a straight line. However, when we plot alternating current, a current that periodically changes polarity, we arrive at a variety of shapes. Some of the more common waveshapes are the square, rectangular, sawtooth, and pulse. These waveshapes are used for triggering, timing, and computing circuits.

The sine wave shown in figure 2–61 results from a plot of the instantaneous current output of a generator due to the rotation of its armature. The length of the horizontal line represents the time of one rotation of such an armature. We have noted specific points of rotation of this line in both degrees and radians (a term that also represents the amount of angular rotation).

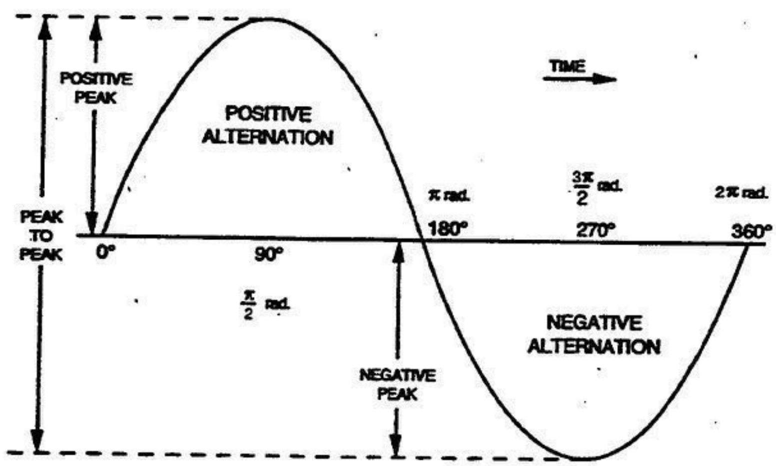


Figure 2–61. AC sine wave.

What is a radian? Remember that the circumference of a circle is equal to 2π times its radius. We can describe a circle or any portion of its arc in terms of its radius. Look back to figure 2–60 and notice the relationship of the sine wave phase and the armature location. A full circle is, therefore, 2π radians, or 360°; a half circle is π radians, or 180°; a quarter circle is $\pi/2$ radians, or 90°, etc. The time of one rotation or one generation of a sine wave represents its period.

Peak voltage. Notice that the horizontal line in figure 2–61 divides the sine wave into two equal parts—one above the line and the other below it. The portion above the line represents the positive alternation and the portion below represents the negative alternation. Notice that the wave reaches its maximum swing from zero at 90° and 270°. Each of these points is called the *peak* of the sine wave.

When we speak of the peak amplitude of a sine wave, we mean the maximum swing, or the height of one of the alternations at its peak. These terms apply to either current or voltage and are important to remember because you use them throughout your career. For example, suppose you have a sine wave with an amplitude of four units; that is, the peak of the sine wave is four graphic units (on the scope screen) from the zero reference line. Also, suppose each unit represents 10 volts. With that information, you can find the amplitude of the voltage the sine wave represents by multiplying the number of units by the value of voltage each represents. Thus, the peak amplitude is 40 volts (4 x 10 = 40).

Another value of importance is the peak-to-peak value. This term, as shown in figure 2–61, represents the difference in value between the positive and negative peaks of a sine wave. Of course, this is equal to twice the peak value. Why is this term so important? Suppose you want to find the amplitude (voltage) of a sine wave as you did previously; however, this time there is no zero reference. By using the peak-to-peak value and dividing it by two, you can obtain an accurate peak amplitude. Assume that each graphic unit on the scope represents 10 volts and there are 8 units between the peak-to-peak of the sine wave. The peak-to-peak value then is 80 volts. The peak value is 40 volts.

Effective voltage. A more useful value in dealing with AC is the effective value, the value that produces the same heating effect as an equal value of DC. Since the heating effect of a quantity of current is proportional to the square of the current, we can calculate the effective value by squaring the instantaneous values of all points on a sine wave, taking the average of these values, and extracting the square root. The effective value is, thus, the root of the mean (average) square of these values. This value is known as the root-mean-square, or RMS value. When we speak of a voltage as having a value of 110 volts, we mean that it has an effective or RMS value of 110 volts. Unless otherwise stated, the AC voltage or current is expressed as the effective value.

We can derive a mathematical expression for an RMS value for one alternation of a sine wave by restating our definition as follows:

$$\text{RMS} = \sqrt{\frac{\text{area under the } I^2 \text{ curve (one loop)}}{\text{length of one alternation}}}$$

The area under the I^2 curve is analogous to that of a triangle, or equal to one-half the base times the height, or 1/2 (πrad)(I^2 peak). Dividing this area by the length of one alternation (πrad) gives us the mean or average value. Our formula is now:

$$\text{RMS} = \sqrt{\frac{p/2\,(I^2\text{peak})}{p}}$$

solving

$$\text{RMS} = \sqrt{\frac{I^2\text{peak}}{2}}$$

Now suppose we have a sine wave that represents a current with a peak value of one unit. By substituting this value in our formula, it becomes:

$$I_{RMS} = \sqrt{\frac{(1)^2}{2}}$$

$$= \sqrt{\frac{1}{2}}$$

$$= \frac{1}{\sqrt{2}} = \frac{1}{1.414}$$

$$= .707$$

The effective value of one unit of AC is therefore equal to 0.707 of its peak value.

Similarly, a sine wave of voltage whose peak value is 1 volt has the same heating value as 0.707 volts of DC. Therefore, to find the effective value of AC, multiply 0.707 times the maximum or peak value.

The reciprocal of 0.707 is 1.414. Now, since you know the effective value, you can obtain the peak value by multiplying the effective value by 1.414.

Average voltage. It is also important to know the average value in a sine wave. The average value is the average of the instantaneous values of all points in a single alternation. The average of a complete sine wave is zero. The average of a sine function can be defined as the area under one alternation divided by the base of the alternation. The base of one alternation, as in figure 2–61, is π radians. Unlike our computation of area under the I^2 curve, the area under a curved surface such as a sine wave is very complex. To save us a lot of math, accept the fact that the area of one alternation is equivalent to two times its peak value (voltage or current). The average value may then be defined by the following expression:

$$\text{Average value} = \frac{2\ (\text{peak value})}{(\text{length of base})}$$

or

$$\text{Average value} = \frac{2\ (\text{peak value})}{p}$$

If a sine wave represented a value of 1 volt, we can say:

$$E_{AVE} = \frac{2(1)}{p}$$

Dividing the numerator and denominator by 2 yields:

$$E_{AVE} = \frac{1}{\pi/2}$$

or

$$= 1\frac{2}{\pi}$$

$$= .637$$

The average height of a single alternation (positive or negative) is 0.636 times the peak value. The relationship between the average, effective, and peak values can be determined mathematically and is shown in the following formulas:

- Average value = 0.636 peak value = 0.9 effective value.
- Effective value = 0.707 peak value = 1.11 average value.
- Peak value = 1.414 effective value = 1.57 average value.

027. Terms and symbols related to AC

As we stated before, alternating current is constantly reversing direction. We call two consecutive alternations—one positive and one negative—a full cycle. We often refer to the positive and negative alternations as half-cycles. The number of cycles that occur in a given time is the frequency. The universally used unit of frequency is the hertz. Instead of saying, "60 cycles per second," we say, "60 hertz."

In electronics, however, 60 hertz is a relatively low frequency. We often talk of frequencies in the thousands and millions. When we speak of frequencies in the thousands, we use the term "kilohertz." When we speak of frequencies in the millions, we use the term "megahertz."

There are two other terms we use—"millisecond" and "microsecond." Assume that the time or period of one cycle is one thousandth of a second. Then, the frequency is referred to as one millisecond. If the time of one cycle is one millionth of a second, the frequency is one microsecond.

We have said that current or voltage may occur as sine waves. Since voltage is used to produce current, let us compare the sine waves in a different way than we have before. Figure 2–62 shows three sine waves. The top wave represents voltage. The other two waves represent current.

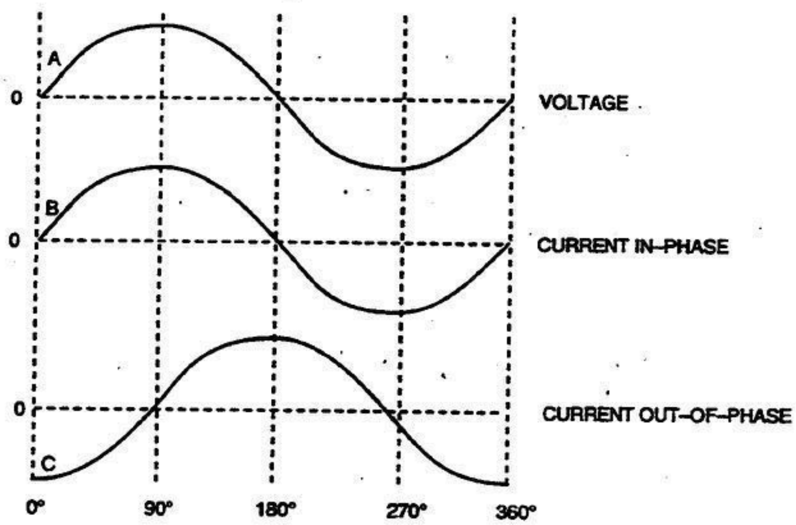


Figure 2–62. Phase relationship.

Notice that the voltage sine wave A and current sine wave B move together. Since the two sine waves go through all phases of the cycle together, they are in phase. We do not limit use of the term "in phase" to just the voltage and current produced by the voltage. Two alternating voltages or currents that rise and fall together are "in phase."

Current is in phase with the voltage only in circuits that are purely resistive. You will find that there are electrical components that affect the voltage and current phase relationships in AC circuits. Whenever one of these components is included in a circuit, an out-of-phase relationship exists between current and voltage.

An out-of-phase relationship exists any time waves do not move simultaneously. This out-of-phase relationship can be seen by comparing sine waves A and C in figure 2–62. The current sine wave is maximum negative when the voltage sine wave is zero (at the start of its positive half-cycle). To describe this relationship, we say that the current lags the voltage by 90°. If the action of the current sine wave occurs before that of the voltage, we say that the current leads the voltage.

028. What is inductance?

There are several components that are used in AC circuits. Chief among these are the inductor and the capacitor. Let's start off by looking at the inductor.

Inductance in electrical circuits. We define inductance as a property of a circuit that opposes any change in current flow. All circuits have this property. The opposition, however, takes place only when there is a change in current flow. The inductance does not oppose current flow; it only opposes a change in current flow. Where current is constantly changing, as in an AC circuit, opposition caused by inductance is always present. The symbol for inductance is the capital letter "L."

Before we continue with our discussion of inductance, let us review counter-electromotive force (CEMF). In motors, CEMF is voltage that is induced in the armature as rotating armature coils cut through the magnetic lines of a field. This CEMF is directly proportional to the speed of the armature. In other words, CEMF is directly proportional to the number of lines of force that are cut per second.

Remember, there are three basic requirements for inductance. They are: a magnetic field, a conductor, and relative motion. Look at figure 2–63 and see how alternating current fulfills these three requirements.

In figure 2–63, A, you see a conductor with an alternating current applied from a generator. At time T0, in part B of the figure, the current waveform is at zero, representing no current flow in the conductor, and there is no magnetic field. From T0 to T1, current is increasing and is flowing from A to B. This increase in current flow produces an expanding (or moving) magnetic field around the conductor, as indicated by the arrows in part C. We now have a conductor, a magnetic field, and the relative motion necessary for induction.

When the current decreases from maximum to zero (during the interval T1 to T2), the magnetic field collapses and cuts the conductor in the opposite direction, as shown in part D of the figure. We again have a conductor, a magnetic field, and relative motion. The same sequence of events occurs during the interval T2 to T4, except the current in the conductor flows from B to A and produces an opposite polarity of magnetic field, as shown in parts E and F. This causes the polarities of the induced voltage to oppose the change in current flow.

To increase the property of inductance, the conductor is formed into a loop or coil. Assume you have a conductor that forms $2\frac{1}{2}$ loops or turns. Current flow through one loop produces a magnetic field that encircles that one loop in one direction.

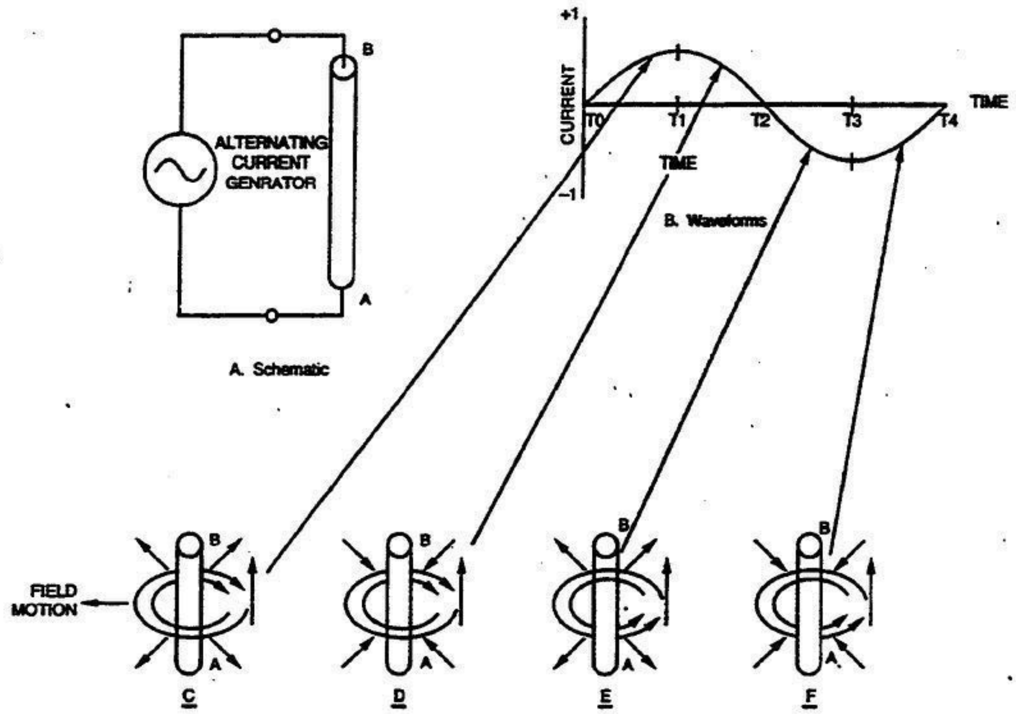


Figure 2–63. Using an alternating field for induction.

As current increases, the magnetic field expands and cuts all the loops. The current in every loop affects all other loops. The field cutting other loops has the effect of increasing the opposition to a current change.

When current is increasing, energy from the alternating current generator builds up the magnetic field. When the current is decreasing, the magnetic field collapses and returns its energy to the circuit.

Self-inductance. Another term you will encounter in dealing with inductance is self-induction. Self-induction is defined as the process by which the magnetic field of a conductor induces a CEMF in the conductor itself. The symbol for self-induction is the same as that for inductance; that is, the letter "L."

Mutual induction. Another type of induction is mutual induction. This is the action of inducing a voltage in one circuit by varying the current in some other circuit. Mutual inductance, then, is the common property of two associated electric circuits that determines, for a given rate of change of current in one of the circuits, the electromotive force induced in the other. The symbol for mutual induction is the letter "M."

To illustrate mutual induction, imagine placing two coils close to each other. Apply power to one coil with an AC generator and connect a voltmeter to the other. There is no physical connection between the two coils. As alternating current flows through one coil, it produces a magnetic field that is alternately expanding and collapsing. Each time the magnetic field builds up or collapses, it cuts across the other coil. Again, you have the three requirements for induction—a magnetic field, a conductor, and a relative motion.

You can see that a voltage is induced in the other coil. This voltage has one polarity when the magnetic field is expanding and the opposite polarity when the field is collapsing. This alternating voltage causes current to flow through the voltmeter. The voltage induced into the second coil by a varying current in the first coil is an application of mutual induction.

The unit of measure for inductance is the "henry." A henry is defined as the inductance in a circuit that induces an EMF of 1 volt when the current is changing at a rate of 1 ampere per second. The symbol for henry is the small letter "h."

Flux linkage. Flux linkage is defined as the interlocking of magnetic lines of force around one coil or wire that link another coil or wire. The ratio of the flux lines (originating in one coil that cuts a second coil) to the total number of lines developing around the first coil gives you a new term called coefficient of coupling.

Factors affecting inductance. The four physical factors that affect the inductance of a single-layer coil are the number of turns in the coil, its diameter, its length, and the type of material used for the core.

Number of turns in a coil. First, notice how the number of turns affects the inductance of a coil. Increasing the number of turns in a coil has the same effect as increasing the number of conductors in the field of a basic generator. In a basic generator, it increases the output; in a coil, it increases the CEMF, the force caused by induction that opposes current change. Doubling the number of turns increases the inductance of a coil by a factor of approximately four.

Coil diameter. The second factor is coil diameter. Assume that you have two coils with the same number of turns and the same diameter of conductors. The cores of each coil are the same length; however, the diameter of one core is much larger than that of the other. The larger core provides an easier path for magnetic flux than the core with the smaller cross-sectional area. Again, this has the effect of increasing the strength of a magnetic field and, in turn, increasing the inductance of the coil. The inductance of a coil increases directly as the cross-sectional area of the core increases. Doubling the radius of a coil increases the inductance by a factor of four.

Length of the coil. The third factor that affects the inductance of a coil is its length. This time, assume we have two coils with the same number of turns and the same size conductor. Also, the core has the same cross-sectional area. However, one core is much longer than the other and the turns of the conductor are spaced farther apart. The coil with the longer core has few flux linkages due to the space between each turn, and, therefore, low inductance. The other coil has the same number of turns, but they are closely spaced, making a relatively short coil.

This close spacing increases the flux linkage which increases the inductance of the coil. A coil with twice the length of another has half the inductance.

Type of core material. The fourth physical factor is the type of core material. A soft-iron magnetic core provides a better path for magnetic lines of force than a non-magnetic core (such as air). The soft-iron magnetic core's high permeability has less reluctance in the magnetic flux, resulting in more magnetic lines of force. This increase in the magnetic field increases the number of lines of force cutting each loop of the coil and, thus, increases the inductance of the coil.

An additional factor is the type of coil winding used. Assume we have a coil with close spacing and wound in layers. This has the effect of obtaining maximum flux linkage. Thus, a layer-wound coil has larger inductance values than the same size single-layer wound coils.

029. Calculating total inductance and inductive reactance

As we use inductors, we find that they produce inductance that, in turn, produces inductive reactance.

Calculating inductance. The unit of inductance (L) of a coil is the henry (h). A coil that develops a CEMF of 1 volt when the current is changing at the rate of 1 ampere per second has an inductance of one henry. From the above physical factors that affect the inductance of a coil, we can develop an expression that approximates the unit of inductance.

$$L = \frac{N^2 \mu A}{l}$$

where:

L = inductance

N = number of turns

A = cross – sectional area of the core

μ = permeability of the core material

l = length of coil

Multiply the above expression by a constant to make a practical formula. This constant depends upon the following:

- Units of linear measurement (inches or centimeters).
- Units of inductance (henries, millihenries, or microhenries). Coil construction (single or multi-layered).
- Ratio of the length to the diameter of the coil.
- Percent of flux linkage.

Many times you come across circuits with several inductors in them. These inductors may be connected either in series or parallel. The rules for computing the total inductance in a series or parallel inductance circuit are similar to the rules for computing total resistance in a series or parallel resistive circuit.

Visualize three coils connected in series in an AC circuit. The first coil introduces a certain amount of inductance, the second adds to this inductance, and, finally, the third adds to the total of the other two coils. In order to find the total inductance in a series circuit, you must add the inductance of all the coils. So the formula for total inductance of coils connected in series is as follows:

$$L_t = L_1 + L_2 + L_3 + \ldots$$

What happens when three coils are in parallel? The coils provide three paths for current. The current that goes through the first coil is opposed only by the inductance of that coil. The same is true of the current going through the other two coils. The formula for computing the total inductance of a parallel circuit, therefore, is as follows:

$$L_t = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots}$$

Inductive reactance. You learned that the current in a purely inductive circuit lags the voltage by 90°. The reason for this lag is the opposition to alternating current offered by inductance. Alternating current is constantly changing and the effects which the magnetic fields have is that voltage continuously opposes the circuit's current. The magnetic field expands and collapses; thus, it reacts and dissipates no power. For this reason, we call the opposition *reactance* and use the symbol X. The reactance of a coil, L is called inductive reactance, is symbolized X_L, and is defined as the opposition to current flow offered by the inductance of a circuit. You can calculate the inductive reactance of a circuit by using the following formula:

$$X_L = 2\pi fl$$

where:

X_L = inductive reactance in ohms (dissipates no power)

2p = 6.28

f = frequency in hertz

l = inductance in henries

As you can see by the formula, there are two variables that affect inductive reactance— the inductance and the frequency of the circuit. Frequency is directly proportional to the amount of opposition or reactance a circuit experiences. This critical variable greatly affects quality control tests such as envelope delay and frequency response. Since inductive reactance is opposition to current flow, we use the same unit of measure as for resistance—ohms.

Inductors are used to store energy in a magnetic field. An opened or shorted inductor is useless because it will not store energy. An ohmmeter can be used to measure the DC resistance of an inductor to locate open or shorted windings. The resistance of a good inductor is normally low.

All inductors can be checked for opens. Audio and power inductors can be checked for shorts. Some RF inductors cannot be checked for shorts because the windings have few turns of large size wire and a normal resistance of zero ohms. Before you check the ohmic value of an inductor, disconnect it from the circuit.

030. Phase relationships in pure inductors

Because inductors oppose the changes in current, they affect the phase relationships of current and voltage. Let's see how.

Voltage and current relationship in inductors. We have said that an inductor opposes a change in current flow. By knowing this, you can see that an inductor has very little effect on direct current. A sine wave of alternating current, however, is continually changing. This means that the magnetic field in an AC circuit is continually changing, generating a CEMF that continually opposes the change in current. Let us analyze the effects of an inductor in a circuit with an AC source.

Inductors connected to an alternating current source. In figure 2–64, we show an inductor (coil) connected to an AC source. The graph shows the relationship that exists between the current (I) and the voltage (E) developed across an inductor with respect to time. The solid line of the graph represents the current across the inductor and the dotted line represents the voltage across the inductor. This voltage is actually a CEMF developed as the current's magnetic field expands and collapses. At time T0, the initial rate of change is maximum and the voltage is maximum. As the rate of change of current gradually decreases, from T0 to T1, the induced voltage decreases. At T1, the current stops increasing. At that time, we have zero rate of change and the induced voltage is zero. As the current flow decreases (T1 to T2), its magnetic field collapses and the polarity of the voltage induced across the inductor reverses. Notice that at T1, with zero rate of change, E = 0. As the rate of change of current increases to maximum at T2, where even the direction of current flow changes, E = maximum with reversed polarity from T0 (–4 units).

Notice that maximum rate of change of current takes place when current passes though zero at T0, T2, and T4. As the current decreases to zero and reverses its direction, the induced voltage reaches its peak and then starts decreasing. When the rate of change of current decreases to zero, at T1 and T3, there is no change in flux and, therefore, zero voltage is induced in the coil.

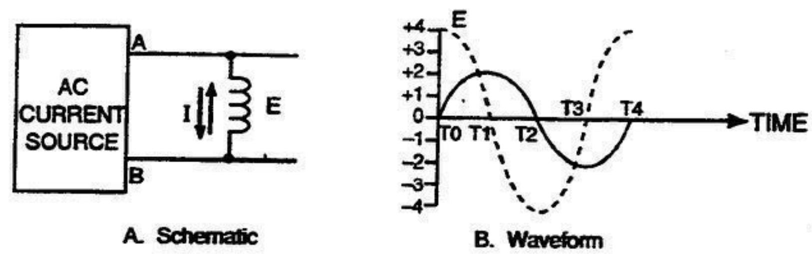


Figure 2–64. Inductor with a sine wave applied.

In all cases, the amplitude of the induced voltage is determined by the rate of change of current flow. The polarity of the induced voltage is determined by two factors, the direction of current flow and whether it is increasing or decreasing. The induced voltage opposes any change in current flow. If current is increasing, induced voltage opposes the increase; if current is decreasing, induced voltage opposes the decrease. Of special interest is the fact that for the sine wave of current, there is a sine wave of voltage. The current and voltage waveforms are 90° out of phase.

Inductors connected to an alternating voltage source. Now apply an AC voltage source to the inductor to see what happens. Imagine a circuit with an AC voltage source, conductors, a coil, and that has no opposition to current flow except from inductance. This is a circuit without resistance, a purely inductive circuit. The AC voltage applied to the inductance encounters an equal and opposite voltage induced in the coil and zero current flows. As you know, this circuit can only exist in theory; a real circuit must have some resistance. Therefore, assume the minimum amount of resistance. The CEMF still takes place because of the inductance, but current lags the applied voltage by 90°.

Inductor power losses. Power loss is defined as energy dissipated without accomplishing work. Let us discuss three types of power loss in inductors and methods used to reduce them.

Copper loss. Copper loss results from the resistance of the conductor used to wind a coil. It is a heat loss that can be reduced by increasing the size of the conductor, thus reducing its resistance, or by using a material of lower resistance for the inductor. Normally, copper loss is reduced by increasing conductor size. The conductor material frequently used that has less resistance than copper is silver. Gold has the best conductivity quality, but there are obvious cost limitations involved.

Hysteresis loss. The second inductor loss is hysteresis loss. As you know, the core of a coil is magnetized whenever a current is flowing through it. If AC is applied, the core is magnetized first in one direction and then in the other. When a material is magnetized, the molecules of the material align themselves with the magnetic field. Every time the magnetic field reverses, the molecules realign themselves. This constant reversal of the molecules causes molecular friction, thereby producing heat called hysteresis loss. Hysteresis loss is reduced by using a material with a high permeability for the core. The higher the permeability of the material the less molecular friction exists.

Eddy current loss. The third inductor loss is caused by eddy currents. These are currents that are induced in the core of the inductor. Remember our requirements for inducing a voltage: a conductor, a magnetic field, and relative motion. In this case, the core is the conductor that is cut by the expanding and collapsing fields of the coil, inducing current in it. Eddy currents cause excessive heat in a soft-iron core.

Eddy currents are reduced by laminating the core. A laminated core is one made of thin sheets of metal that are electrically insulated from one another. The insulation does not oppose the magnetic flux, but it does reduce the eddy current by limiting the paths for current flow.

031. The types and uses of transformers and relays

Now that we have covered the basic principles of induction, we want to relate this to an area of systems control. Transformers and relays are two of the most common devices used throughout electronics that utilize these principles.

A transformer does just what the word implies—transfers electrical energy from one circuit to another. It does this by mutual induction, a term we discussed earlier. Relays are used to control or switch electrical circuits, usually from a remote location.

Transformer construction. A transformer is a device that uses inductance to transfer electrical energy from one circuit or winding to another. A simple transformer consists of two coils of wire placed on some type of core. These coils are called windings. The winding that is connected to the source is the primary winding. The winding that supplies energy to the load is called the secondary winding. Frequently, additional connections are made to a transformer winding between the end connections. These additional connections are called *taps*. A tap placed at the center of a winding is called a *center tap*.

Transformers use various materials for their cores. An air-core transformer is commonly used in circuits carrying radio-frequency energy. Radio-frequency transformers also use powdered iron, brass, and aluminum cores. Transformers used in low-frequency circuits require a core of low-reluctance magnetic material to concentrate the field about the windings. This type of transformer is called an *iron-core transformer*.

Audio and power transformers are of the iron-core type. Iron cores are often fabricated from a number of thin silicon steel strips (laminations) covered with an insulating varnish before they are assembled.

Types of transformers. In general, there are four types of transformers: autotransformers, power transformers, audio transformers, and RF transformers.

Autotransformers. An autotransformer consists of a single winding with one or more taps. The entire winding may act as the primary with only part of the winding acting as the secondary (step down) or part of the winding may act as the primary while the entire winding acts as the secondary winding (step up).

Autotransformers are normally used in power circuits; however, they may be designed for audio or RF (radio frequency) use. Figure 2–65 shows the symbol for audio transformers and several hookups for different output voltages. The symbol for an RF autotransformer is the same except that it may not indicate an iron core. RF autotransformers have an air core.

PRIMARY	SECONDARY	
	STEP UP	STEP DOWN
1–2	1–3	2–3
1–3	–	1–2 2–3
2–3	1–3 1–2	

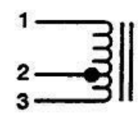


Figure 2–65. Chart and symbol for power and audio autotransformer.

Power transformers. Power transformers are often constructed with two or more secondary windings. Thus, one transformer can provide several voltage level outputs. The secondaries provide a wide selection of voltages and currents. Power transformers are designed to operate on the common power line frequencies (50 to 60 Hz) and to handle relatively large amounts of power.

Audio transformers. An audio transformer resembles a power transformer in appearance; however, it has several internal refinements. The core material is carefully selected and special techniques are used to fabricate the windings. Audio transformers are designed to operate over the audio range of 20–20,000 Hz. Audio transformers are available with multiple primaries or secondaries.

RF transformers. This type of transformer is designed to operate in ranges from 10 kHz to 300,000 MHz.

Step-up and step-down turns ratios. The ratio of the number of turns in the primary to the turns in the secondary is called the turns ratio.

If an input voltage is applied to the primary winding and no load is connected to the secondary winding, the primary acts as a simple inductor. The current flowing in the primary depends on the applied voltage (amplitude and frequency) and the inductive reactance of the primary. This current produces a magnetic field that cuts the primary and secondary as it expands and collapses. This produces a CEMF in the primary (self-inductance) that nearly equals the applied voltage and it induces a voltage in the secondary (mutual inductance). The amplitude of the voltage induced into each turn of the secondary is identical to the CEMF produced in each turn of the primary.

When 10 volts are applied across 10 turns of the primary, a CEMF of nearly 1 volt per turn develops. A two-turn secondary, then, has an induced voltage of 2 volts (1 volt per turn). Thus, a turns ratio of 10 (primary) to 2 (secondary), or 5 to 1, produces a step-down in voltage, from 10 volts (primary) to 2 volts (secondary). The transformer is then described as having a step-down turns ratio.

With a transformer having a step-up turns ratio of 1:4, an input of 10 volts applied to the primary produces 40 volts in the secondary. The turns ratio equals the voltage ratio in all cases. We can express this as an equation:

$$\frac{N_p}{N_s} = \frac{E_p}{E_s}$$

where:

N_p = number of turns in the primary
N_s = number of turns in the secondary
E_p = voltage of the primary
E_s = voltage of the secondary

The extent to which magnetic lines of the primary cut across the secondary is expressed as a "coefficient of coupling." If we say a transformer has a coefficient of coupling of 1, this means that all of the magnetic lines of the primary link the secondary. That is, 100 percent of the flux lines produced by the primary winding cut the secondary winding. A coefficient of coupling of 0.9 indicates that 90 percent of the flux lines produced by the primary cut the secondary. A coefficient of coupling less than 1 reduces the voltage induced in the secondary.

Transformer operation with loaded secondary. Up to now, our discussion of transformer action has been with no load on the secondary; we considered induced voltage only. When a load is connected to the secondary winding of a transformer, current flows in the secondary. The magnetic field produced by the current in the secondary interacts with the primary field. This interaction is truly mutual inductance, where both the primary and secondary current are in direct opposition to the primary magnetic field and cancel some of the primary field. This reduces CEMF, and, as a result, primary current increases to nearly reestablish the primary field. To summarize, as current increases (with increased load) in the secondary, primary current increases.

Total power available from a transformer secondary must come from the source that supplied the primary. Remember, a transformer does not generate power; it merely transfers power from a primary circuit to a secondary circuit. If the transformer is 100 percent efficient, total primary power equals secondary power.

If a 100Ω load is connected to the secondary of a transformer with a step-up turns ratio of 1:10, 10 volts applied to the primary produces 100 volts in the secondary. Current through the 100Ω load is 1 amp. Power consumed in the load is 100 watts (P = I x E). With 10 volts applied to the primary winding of 10Ω, the primary current is 10 amps. Applying the power formula to the primary circuit yields 100 watts. Notice there is a step-up in voltage (1:10) and a step-down in current (10:1). Power supplied to the load comes from the source, and we have no losses in the coupling. This transformer is 100 percent efficient because output power equals input power.

Practical transformers, although highly efficient, are not perfect devices. They range from 80 to 98 percent efficient. Primary power must be slightly greater than secondary power to offset the decrease in efficiency. The losses associated with transformers are the same as the losses for inductors. Efficiency can be computed by dividing transformer output power by input power. Another area dependent on the principles of induction is the use of relay circuits.

Relays. Many electrical devices use the magnetic attraction of an electromagnet. An important use of this action is in devices, called relays, that are used for controlling or switching electrical circuits from some remote location. These devices are constructed in many different sizes and shapes and are used for many different purposes. However, all electromagnetic relays operate on the principle that iron is attracted toward an electromagnet.

Electromagnet relays. A relay is basically a coil with an iron core and a movable iron bar. When current flows through the coil, electromagnetic force pulls the movable bar toward the iron core. The movement of the bar can operate contacts that turn electrical circuits ON or OFF.

Figure 2–66 shows a basic relay and relay circuit. The relay itself consists of five main parts: an iron core, coil, armature, contacts, and spring. When the switch S1 is closed, current flows through the coil and causes the core to become a strong electrical magnet. The magnetic attraction pulls the iron armature toward the core, causing the contact points to close. This completes a path for current in the lamp circuit and the lamp glows. When switch S1 is opened, the field around the electromagnet collapses and the spring pulls the armature contacts apart, stopping current flow to the lamp circuit.

Electromagnetic relays are represented by the schematic symbols shown in figure 2–67. Figure 2–67, A represents a single-pole, single-throw (SPST) relay with the contacts normally open (NO). When current flows through the coil, the contacts

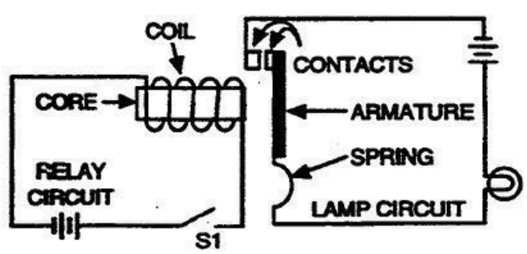


Figure 2–66. Basic relay.

close. Figure 2–67, B shows a SPST relay with the contacts normally closed (NC). When current flows through the coil, the contacts open. Figure 2–67, C shows a single-pole, double-throw (SPDT) relay with one contact NC and one NO. This type of relay is used to transfer current from one circuit to another. A single relay may have multiple poles with any combination of opened or closed contacts (fig. 2–67, D).

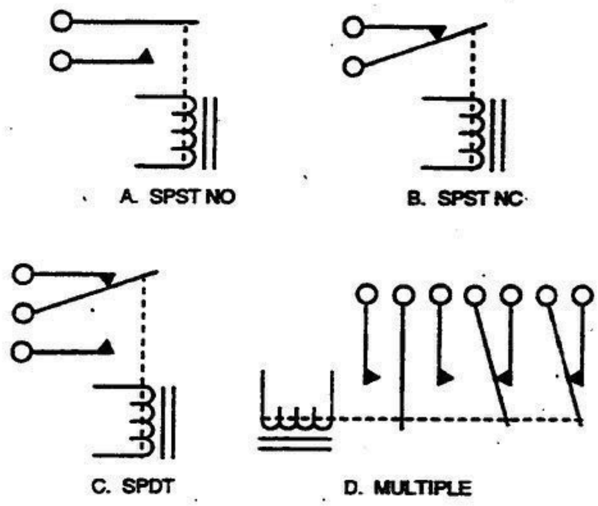


Figure 2–67. Schematic symbols.

The relays shown in figure 2–67 are in a de-energized (unmagnetized) condition; no current is flowing through the coils. In all schematic diagrams, the relays are shown de-energized unless otherwise stated.

Relay circuits. Figure 2–68 shows a *holding relay*. Switches S1 and S2 are spring loaded switches that return to their original positions as soon as they are released. S1 is NC and S2 is NO. Momentarily closing S2 permits current to flow through coil C and the lamp. With current applied, the armature is attracted toward the electromagnet, thus closing the circuit at point A. This provides an additional path for current through coil C and the lamp. Releasing contact A keeps or holds the circuit closed. In order to stop current, switch S1 must be temporarily opened. Opening S1 causes the relay to de-energize and open contact A. Releasing or closing S1 does not re-establish current. S2 must once again be closed to turn on the lamp and energize the relay. S2 is sometimes marked ON and S1 marked OFF.

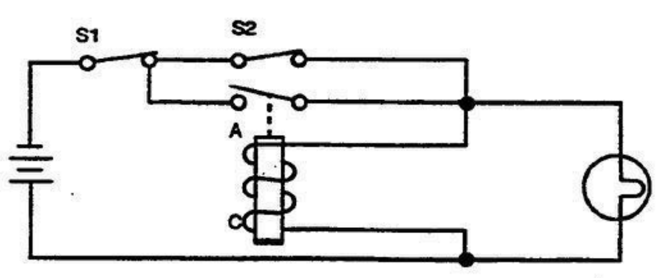


Figure 2–68. Holding relay.

Starting relay. A common use of this relay is in an automobile starter circuit. The ignition switch activates a relay that, upon closing, permits a large current to flow in the starter motor circuit. Figure 2–69 illustrates the starting relay circuit.

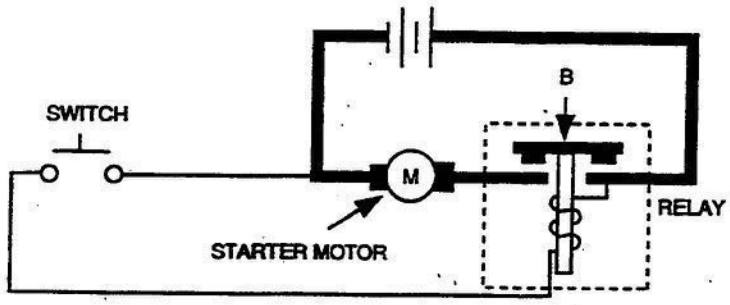


Figure 2–69. Starting relay.

When the ignition switch is moved to the START position, its contacts close and current flows through the relay coil. This causes an electromagnetic force that pulls the iron bar B toward the coil and closes the starter motor circuit. Note that the conductors in this circuit are short, heavy cables. A small current in the relay coil circuit controls a very large current in the starter circuit. The relay remains energized until the ignition switch is released.

Intermittent relay. A relay can also be connected to cause the armature to vibrate. The simple door bell or buzzer is an example of using a SPST relay with NC contacts to produce sound. When the switch is closed, current flows through the relay coil and through the contacts. As a magnetic field builds up around the coil, it attracts the armature downward. Once the armature moves downward to the other side of the contact, the circuit is broken and current can no longer flow through the coil. The magnetic field surrounding the coil then collapses, allowing the armature to return to its original position. Once it returns to this position, current again flows through the coil and the action repeats itself. This vibrating action of the armature continues until the switch is opened.

Overload relay. Another application of an electromagnetic relay is its use as a protective device similar to a fuse. Figure 2–70 shows an example of the overload relay circuit. When switch S1 is closed, current flows through the relay coil and load resistor R_L. Assume the normal circuit current is 10 mA, but the relay coil requires 20 mA of current to move the armature. The relay is de-energized with a normal current of 10 mA. If the load resistor becomes shorted, the circuit current exceeds 20 mA, the relay is energized, and the path for current is opened. A mechanical latch locks the armature in the open position. After the trouble is corrected, the reset button must be pushed to release the armature so that it returns to its NC position. The action of the overload relay described here is that of a fuse or circuit breaker with manual reset.

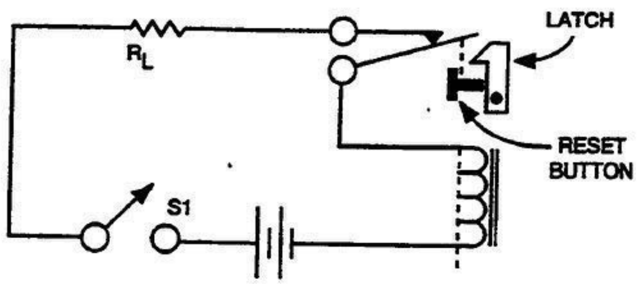


Figure 2–70. Overload relay.

This ends our discussion of relay circuits. Remember that there are various types suited for different applications, ranging from simple circuit switching to overload protection.

032. Capacitors and factors that affect them

We have been studying inductance that opposes a change in current. This characteristic can have a major impact on circuitry passing through a technical control or base central test facility, especially those on-base subscribers. Another property that must be considered is capacitance. In this lesson, we learn that capacitance opposes a change in voltage. We begin with a study of the factors that affect capacitor operation and then discuss capacitive reactance and the method for determining capacitive reactance.

Factors affecting capacitor operation. A simplified diagram of a capacitor is shown in figure 2–71. To understand what happens within a capacitor, you must use the principles of electrostatics. In the uncharged condition, the atoms that make up the dielectric of a capacitor are in their normal, or neutral, state. That is, the electrons of each atom are revolving around their nucleus in normal orbital paths. Figure 2–71 shows only three atoms (greatly enlarged) of the millions that make up the dielectric.

Electrical factor. When a voltage is applied to the capacitor, the plates become charged. Assuming the polarity as indicated in figure 2–71, electron flow from the applied voltage (E_a) is toward plate A and away from plate B.

The atoms within the dielectric now become affected by the repelling force of the field. The electrostatic field places a strain on the atoms and their orbits become

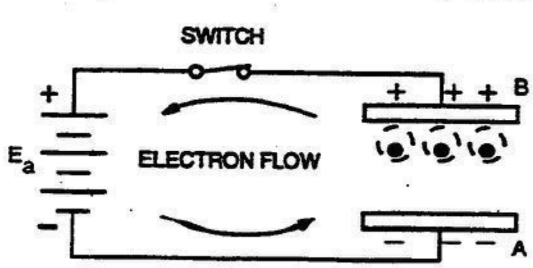


Figure 2–71. Electron flow in a capacitor circuit.

distorted. The electrons that are repelled by plate A and forced to orbit closer to plate B force electrons to leave plate B to return to E_a. Thus, plate A has a negative charge and B has a positive charge. The changes in the potential on plate A are passed to plate B through the dielectric; the force exerted on one side is passed to the other without physical contact. There may be some electrons that pass through, due to leakage and other causes, but we do not discuss them at this time.

When stress is placed on the dielectric, energy is stored in the form of orbital strain. The many thousands of dielectric atoms have their orbits distorted by the electrostatic field, and they develop a force equal and opposite to the applied force (E_a). When this happens, the capacitor is charged and electron flow ceases. The charged capacitor thus offers infinite resistance to DC—it blocks DC.

If the applied voltage is removed by opening the switch, the electrons on plate A are trapped, the deficiency of electrons on plate B continues, and the electrons of the dielectric remain in a charged condition. The charge on the capacitor can be removed by completing a path for the electrons to flow from plate A to plate B. Then, the capacitor can discharge, thus equalizing the difference of potential between the plates.

The amount of charge stored in a capacitor is directly proportional to the applied voltage and the capacity of the capacitor. In other words, for a given capacitor, the ratio of charge to the applied voltage is a measure of the capacitor action called *capacitance* (C). The unit of measure of capacitance is the farad, which we represent by f. A farad is defined as the capacity of a capacitor to charge to one coulomb (6.28×10^{18} electrons) with a difference of 1-volt potential across the plates. The physical size needed to produce 1 farad is beyond practical use. The unit in practical use is one millionth or one million-millionth of a farad. A millionth part of a farad is a microfarad (10^{-6} farads) and is abbreviated µf. One million-millionth of a farad is called a picofarad (10^{-12} farads), abbreviated pf.

Physical factors. Three physical factors determine the capacitance of a capacitor; they are plate surface area, dielectric thickness or plate spacing, and dielectric material.

1. The *plate surface area* controls the number of free electrons available to enter and leave the capacitor when a voltage is applied. A large plate area accepts a larger charging current and maintains a larger charge potential. Therefore, the plate area has a direct bearing on the quantity of energy that can be applied or stored in the capacitor.
2. The *dielectric thickness* or spacing between the plates is inversely proportional to the capacitance of a capacitor. Increasing the distance between the plates decreases the force of the repelling electron and, therefore, decreases the amount of charge.
3. The *dielectric material* used in the construction of a capacitor determines the amount of voltage that may be applied and the quantity of energy

stored. The dielectric materials have different atomic structures and present different quantities of atoms to the electrostatic field.

Working voltage. In addition to its measure of capacity, every capacitor has a working voltage rating. The amount of voltage that can be applied is determined by the dielectric material. The working voltage refers to the maximum DC value that can be applied to a capacitor continuously. A capacitor marked 600 VDC should withstand a continuous application of 600 VDC without damage. This working voltage is largely dependent on the dielectric material of which the capacitor is constructed.

Current and voltage phase relationship. In figure 2–72, A, a capacitor is connected to an AC voltage source that develops a pure sine wave output. The graph in figure 2–72, B shows the relationship that exists between the voltage across the capacitor and the current that charges the capacitor. The solid line represents voltage (E_c) and the dotted line represents current (I_c). This current charges the capacitor so that, in turn, the capacitor has a voltage that opposes any change in voltage. At the instant voltage is applied by the AC source, the minimum charge across the capacitor (zero volts) allows maximum current (I_c) to flow. This, in turn, allows the capacitor to charge.

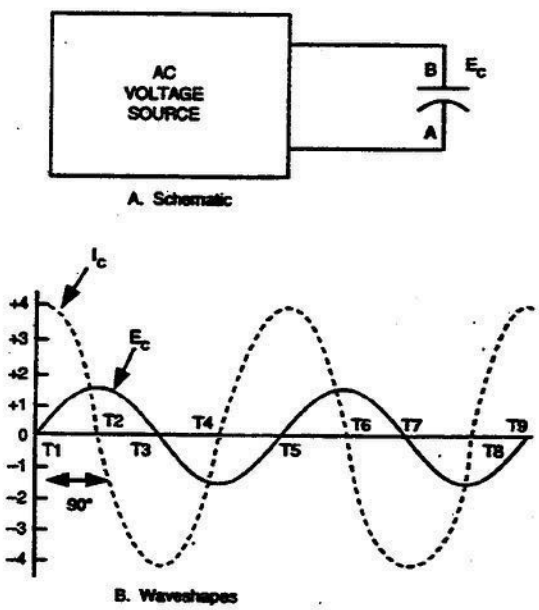


Figure 2–72. A capacitor connected across an AC source.

As the applied voltage increases during the time period from T1 to T2, the electrons accumulate on plate A and leave plate B of the capacitor. This develops an opposing voltage, etc. When the peak positive potential on E_c reaches maximum at T2, the capacitor's current decreases to zero. As the applied voltage decreases from its peak positive value to zero, the voltage across the capacitor decreases to zero, with maximum discharge current at T3. From T3 to T4, the polarity of the applied voltage reverses the direction of current. This allows the capacitor to charge with a reverse polarity. From T4 to T6, the direction of capacitor current is just the opposite of current flow from T2 to T4.

An important thing for you to see at this point is that with a sine wave of voltage applied, the capacitor has its peak voltage charge when current is zero (T2 to T4). Also, with zero voltage on the capacitor, maximum rate of change of applied voltage causes maximum capacitor current. The capacitor current is directly proportional to the rate of change of voltage across the capacitor; however, capacitor current leads capacitor voltage by 90°.

Look at the first 90° of the sine wave (T1 to T2) and try to realize that electrons must flow into one plate and away from the other plate of a capacitor before there can be a voltage across the capacitors. If you can understand this, you can understand that capacitors store energy during voltage rise and discharge energy as the applied voltage decreases. Keep in mind, though, that current does not flow through the capacitor; the charging and discharging of the two capacitor plates cause the current to flow in the circuit. Capacitors do not consume energy. They only store it. Therefore, a pure capacitor dissipates no power.

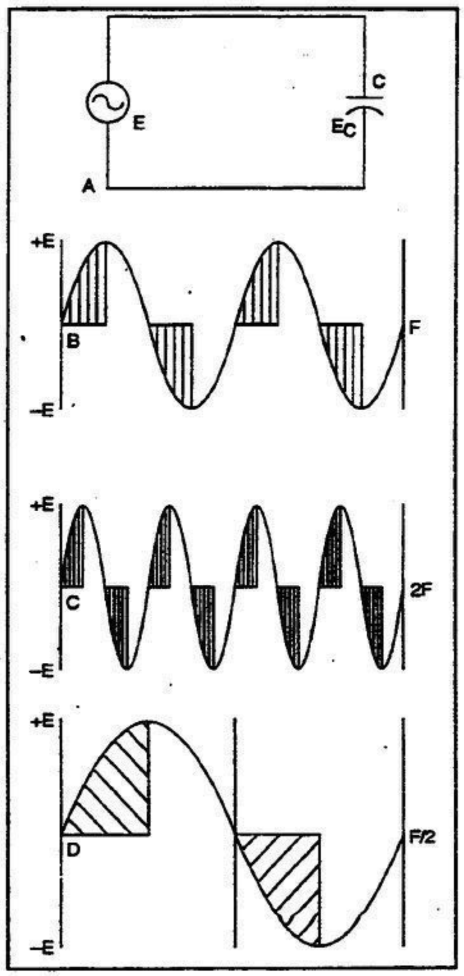


Figure 2–73. A capacitor connected in a series circuit.

Calculating capacitive reactance. The opposition of a capacitor to the flow of current is called *capacitive reactance*, X_C. Let us see what factors determine this reactance. Refer to figure 2–73, A, which shows a capacitor in series with an alternating-voltage source. The capacitor stores an amount of energy equal to its capacity times the voltage. This amount of energy is actually stored twice (+E and -E) in each cycle of applied voltage (fig. 2–73, B). The time allowed for charging depends on the frequency $\left(f = \frac{1}{t}\right)$. If the frequency is doubled with no change in C or E, the same energy (Q) is stored in half the time. When the frequency is doubled (fig. 2–73, C), the capacitor charges to the peak voltage twice as many times, using twice the current. If the frequency is cut in half (fig. 2–73, D), one-half the current flows in the same time.

where:

X_c = capacitive reactance in ohms

$2\pi = 6.28$

f = frequency

C = capacitance in farads

Now we know there are two variables that affect capacitive reactance. They are the size of the capacitor and the frequency of the circuit. Since the formula for X_c always involves $\frac{1}{2\pi}$, which is $\frac{1}{6.28}$, we can save time later if we divide 6.28 into 1. We obtain 0.159, and the formula can now be written as:

$$X_c = \frac{.159}{fC}$$

Also, by transposing, you can quickly change the formula to determine capacitance when X_c and f are known:

$$C = \frac{.159}{fX_c}$$

or we can solve for an unknown frequency when X_c and C are known:

$$f = \frac{.159}{CX_c}$$

Notice there is a similarity in the calculation of total capacitance to the calculation of total resistance. Capacitors add in parallel. This is easy to see when you recall that capacitance is directly proportional to plate surface area. If two or more capacitors are connected in parallel, you find the equivalent capacitance by adding their values.

$$C_t = C_1 + C_2 + C_3 + \ldots$$

Capacitors in series must be treated like resistors in parallel to determine the equivalent capacitance. In effect, the thickness of the dielectric material increases and the distance between the plates combines to produce an equivalent capacitor smaller than any one of the series capacitors.

With two capacitors, use the formula:

$$C_t = \frac{C_1 \times C_2}{C_1 + C_2}$$

For any number of series-connected capacitors of equal value, the total series capacitance is equal to their total value divided by the number of capacitors (as with equal resistors in parallel):

$$C = \frac{C}{N}$$

For more than two unequal capacitors in series:

$$C_t = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

In using the formula for capacitors in series, the total capacitance is smaller than the smallest capacitor. The combination of capacitors in series results in an equivalent capacitor that has a smaller value and withstands a higher circuit voltage than any one of the series capacitors.

When the capacitive reactance (X_c) for a capacitor is known, the value is expressed in ohms. In circuits that contain capacitors in series and parallel and capacitive reactance values are given, treat the values as resistance. Remember that if the values are in ohms, treat them as you do resistors.

In a series circuit, the total capacitive reactance is expressed:

$$X_c\ total = X_{c_1} + X_{c_2} + X_{c_3} + \ldots$$

In a parallel branch, use the formulas for resistors in parallel: Three or more reactances:

$$X_{c_t} = \frac{1}{\frac{1}{X_{c_1}} + \frac{1}{X_{c_2}} + \frac{1}{X_{c_3}}}$$

Two reactances:

$$X_{c_t} = \frac{X_{c_1} X_{c_2}}{X_{c_1} + X_{c_2}}$$

Any number all the same value:

$$X_{c_t} = \frac{X_c}{N}$$

In solving for capacitor voltage, current, or reactance, use Ohm's law as follows:

$$E_c = I_c X_c$$

$$I_c = \frac{E_c}{X_c}$$

$$X_c = \frac{E_c}{I_c}$$

A good capacitor stores a charge. A capacitor that is open or shorted is useless because it will not store or hold a charge. Capacitors having values greater than 0.001 µF can be checked for opens or shorts using an ohmmeter. Before you check a capacitor with an ohmmeter, ensure that it is fully discharged and disconnected from the circuit.

In Unit 2, we have covered many of the electronics fundamentals you studied at technical school. These *basics* of electronics are sometimes boring, sometimes difficult to grasp, and quite often, hard to relate to. They are, however, essential knowledges. You may find it necessary to relate back a few of the lessons you have just completed as you proceed.

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

025. The basic concepts of AC

1. What rule is used to determine direction of induced current?

2. Is induced voltage directly or indirectly proportional to the strength of the field?

3. What is used in an alternator to make contact with the slip rings?

4. As a conductor is rotated to the magnetic field, when is maximum voltage induced into it?

5. What is the complete wave (360°) of induced voltage called?

026. The peak, effective, and average voltage of selected waveforms

1. Define waveform.

2. Describe four common waveform shapes.

3. Define peak voltage.

4. Define peak-to-peak voltage.

5. Define effective voltage.

6. Define average voltage.

7. Calculate the peak, effective, and average voltage of a 200V peak-to-peak sine wave.

8. Calculate the peak and average voltage from a 110 effective voltage.

027. Terms and symbols related to AC

1. What constitutes a full cycle of alternating current?

2. What constitutes a half cycle of alternating current?

3. Define these terms:

   a. Kilohertz.

   b. Megahertz.

   c. Millisecond.

   d. Microsecond.

4. What is an out-of-phase relationship?

028. What is inductance?

1. Define inductance and give its symbol.

2. What are the basic requirements for inductance?

3. Define mutual induction and give its symbol.

4. Define the term "henry" and give its symbol.

5. List the four primary physical factors that affect the inductance of a single-layer coil.

6. Which type of core, air or soft iron, has the least reluctance to inductance?

029. Calculating total inductance and inductive reactance

1. What is the total inductance of a circuit having coils of 15 henries, 6 henries, and 12 henries connected in series?

2. Compute the total inductance of a circuit containing coils of 10 henries, 20 henries, and 30 henries connected in parallel.

3. Define inductive reactance and give its unit of measurement.

4. Given the following information, calculate for X_L:

   a. 400 Hz, 6 henries.

   b. 6 kHz, 3 millihenries.

   c. 20,000 Hz, 7 millihenries.

5. The frequency applied to an inductive circuit changes from 60 Hz to 120 Hz. What happens to the inductive reactance of the circuit?

030. Phase relationships in pure inductors

1. When current flow is present in a coil, what determines the amplitude and polarity of the induced voltage?

2. What is the phase relationship of voltage and current though an inductor?

3. Define inductor power loss.

4. How can copper losses in an inductor be reduced?

5. How can you reduce inductor power loss caused by the molecular friction of the core?

6. Explain how a laminated core reduces eddy current losses in inductors.

031. The types and uses of transformers and relays

1. In a transformer, which windings are connected to the source voltage? Which ones are connected to the load side of the transformer?

2. Name the four types of transformers.

3. What type of turns ratio does a transformer have if, when we apply 10 volts to the primary, the voltage read across the secondary is 2 volts?

4. Assume that a transformer has a coefficient of coupling of 75.9. What does this mean?

5. What does "a transformer is 100 percent efficient" mean?

6. What electrical device is used to control or switch electrical circuits from a remote location?

7. Name the five main components of a relay.

8. Which type of relay circuit is used to energize automobile starter motors?

9. Which type of relay circuit does a common household doorbell system use?

10. Which type of relay does an electrical circuit breaker represent?

032. Capacitors and factors that affect them

1. What does capacitance oppose?

2. What effect does a charged capacitor have on direct current?

3. What is the symbol for capacitance? What is its unit of measure? What symbol represents the unit of measure?

4. What are the physical factors that determine the capacitance of a capacitor?

5. Explain the "working voltage" rating. On what physical factor is it based?

6. When is a capacitor said to be fully charged?

7. Define capacitive reactance.

8. Solve for X_c in the following problems:

Frequency	*Capacitor Value*
a. 1 kHz	0.5 µf
b. 400 Hz	0.01 µf
c. 20 kHz	0.05 pf

9. Solve for total capacitance:

   a. Three 0.05 µf capacitors connected in parallel.

   b. Three 0.05 µf capacitors connected in series.

   c. Three parallel capacitor legs, one leg a 0.05 µf capacitor, the other two legs are 0.1 µf capacitors each.

Answers to Self-Test Questions

017

1. Matter is anything that occupies space and has weight.
2. A substance that cannot be reduced to a simpler substance by chemical action.
3. A compound is the resultant substance formed from the chemical combination of two or more elements which cannot be separated by physical means.
4. A mixture is a combination of elements or compounds that are not chemically combined and can be separated by physical means.
5. The smallest particle of a compound that has all the characteristics of the compound.
6. The smallest particle of an element that retains the characteristics of that element.
7. Protons, neutrons, and electrons.
8. The outermost shell of an atom.

9. The valence of an atom determines its ability to gain or lose electrons.

10. Negative ions are atoms which have more than their normal number of electrons and carry a negative charge and positive ions are atoms which have less than their normal number of electrons and carry a positive charge.

11. The process by which an atom gains or loses electrons.

018

1. One that has more or less than the normal number of electrons.
2. Like charges repel each other; unlike charges attract each other.
3. The coulomb.

019

1. Conductors, semiconductors, and insulators.
2. Conductors have many free electrons; insulators have very few free electrons.
3. The opposition to current flow.
4. Ohm; omega (Ω).
5. A conductor's resistance doubles as its length is doubled, however, doubling its cross-sectional area only increases its resistance by one-half its original value.
6. Resistivity is a term we use to describe the relative opposition that various materials offer to current flow.
7. An increase in temperature causes the resistance of metallic conductors to increase and the resistance of nonmetallic conductors to decrease.
8. When the resistance of a conductor decreases as its temperature increases.
9. The ability of a material to conduct an electrical current.
10. The unit of measurement for conductance is the "mho" and its symbol is "G."
11. A material's conductance is the reciprocal of its resistance, and vice versa.
12. Because of its high conductivity, comparatively low cost, and its physical characteristics.

020

1. The flow of electrons through a conductor.
2. The relative number of free electrons in a material.
3. Point y to point x.
4. Potential difference; volts.
5. Force that causes electrons to move through a conductor.
6. The rate at which electrons pass a given point in a conductor.
7. The symbol used to represent current is "I."
8. The unit of measurement for current flow is the "ampere", or amp, and its symbol is "A."
9. Chemical cell and mechanical generator.
10. (a) 1.5V.

    (b) 2.2V.

021

1. EMF source, a conductor, and a resistor or other power dissipating devices (bell, lamp, etc.).
2. Refer to figure 2-13 to check your answers.
3. The purpose of resistors is to control the amount of current flow in a circuit.
4. Three varieties of resistors are wire wound, precision wire wound, and composition.
5. A battery is a device that converts chemical energy into electrical energy.
6. Ground is a point in a circuit used as a common reference point from which voltages are measured.
7. (1) i, (2) d, (3) a, (4) h, (5) c, (6) b, (7) f, (8) g, (9) e.
8. (a) 3K; (b) 60,000V; (c) 0.002A; (d) 600 mA; (e) 0.00015 kW; (f) 10,000,000Ω; (g) 5,000,000 μamps; (h) 0.1 kΩ; (i) 0.000002 amps.

022

1. A series DC circuit has only one possible path for current flow.
2. A source of power (battery), a load device (resistor), a conductor (wire).
3. Most practical circuits also contain a fuse and a switch.
4. Current should be the same at all points throughout a series circuit.
5. The sum of the voltages dropped across each component of series circuit should equal that of the applied voltage.
6. Current is reduced to one-half its original value.
7. A parallel DC circuit is one in which two or more devices are connected across the same voltage source.
8. In a parallel DC circuit, the total current divides proportionally among the branches in a manner depending on the resistance of each branch, with those having lower resistance drawing more current than those with higher resistance.
9. The total resistance of any number of equal resistors connected in parallel is equal to the resistance of one resistor divided by the number of resistors.
10. A series-parallel circuit consists of groups of parallel resistance in series with other resistances.
11. A device which makes it possible to obtain more than one voltage from a single power source and whose purpose is to provide voltage values other than the source voltage.
12. Two types of variable resistors used in voltage dividers are rheostats and potentiometers.
13. Two.
14. Three.
15. To vary current.
16. Increasing the amount of rheostat resistance in a voltage divider circuit causes an increase in the circuit's total resistance and a decrease in the circuit's total current.
17. To vary voltage.
18. Bridge circuits are frequently used in electronics where a signal from a detection device is used to drive or connect an operational device.

023

1. (a) I=E/R; (b) R=E/I; (c) E=IR.
2. (a) $E_a = 220V$; (b) $E_1 = 150V$; (c) $I_1 = 2A$; (d) $E_2 = 40V$; (e) $I_2 = 2A$; (f) $E_3 = 20V$; (g) $I_3 = 2A$; (h) $E_4 = 10V$; and (i) $I_4 = 2A$.
3. The algebraic sum of the currents at any junction of conductors is zero. This means that the sum of all currents flowing to a point must be equal to the sum of currents flowing away from that point.
4. The algebraic sum of the applied voltage and the voltage drops around any closed circuit is zero. This means that in any closed circuit, the applied voltage is equal to the sum of the voltage drops around the circuit.
5. $P=I^2R$
6. (a) $I_t = 1A$; (b) $R_t = 100\Omega$; (c) $P_t = 100W$; (d) $E_1 = 40V$; (e) $I_1 = 1A$; (f) $P_1 = 40W$; (g) $E_2 = 30V$; (h) $I_2 = 1A$; (i) $P_2 = 30W$; (j) $E_3 = 20V$; (k) $I_3 = 1A$; (l) $P_3 = 20W$; (m) $E_4 = 10V$; (n) $I_4 = 1A$; (o) $P_4 = 10W$.
7. The total current can be determined by adding all branch currents together.
8. $R_t = \dfrac{1}{\dfrac{1}{R_1}+\dfrac{1}{R_2}+\dfrac{1}{R_3}+\dfrac{1}{R_4}}$
9. $P_t=I_tE_a$.
10. (a) $E_a = 6V$; (b) $I_T = 0.48A$; (c) $R_T = 12.5\Omega$; (d) $P_T = 2.9W$.
11. Break the series-parallel circuit down and redraw it as equivalent series circuits.
12. (a) $E_a = 35V$; (b) $R_T = 70\ k\Omega$; (c) $I_T = 0.5\ mA$; (d) $P_T = 17.5\ mW$.
13. A voltage divider that has been loaded with an electronic component or circuit that draws current from the source.
14. Five.
15. Current.
16. Total circuit resistance decreases, total circuit current increases, and the voltage drop across the series resistor increases.
17. (a) $E_a = 125V$; (b) $I_T = 5\ mA$; (c) $R_T = 25\ k\Omega$; (d) $E_A = 125V$; (e) $I_5 = 2.5\ mA$; (f) $E_B = 62.5V$; (g) $I_4 = 1.25\ mA$; (h) $E_C = 31.25V$; (i) $I_3 = 0.625\ mA$; (j) $E_D = 15.625V$; (k) $I_2 = 0.3125\ mA$; and (l) $I_1 = 0.3125\ mA$.
18. A balanced resistive bridge circuit is one in which individual branch potentials are equal. An unbalanced resistive bridge circuit is one in which individual branch potentials are unequal.

024

1. Open.
2. Shorted.
3. Blown fuse.
4. A voltmeter cannot be used to troubleshoot shorted or open resistors in parallel DC circuits.
5. 0Ω.
6. Infinite ohms.

7. 0 amps.
8. The series portion contains an open resistor.
9. The circuit contains either an open resistor in the series portion of the circuit or a shorted resistor in the parallel portion.

025

1. Left-hand rule for generators.
2. Directly.
3. Brushes.
4. When it is cutting perpendicular to the lines of force.
5. Sine wave.

026

1. A waveform is a graphic representation of voltage or current versus time.
2. Square, rectangular, sawtooth, and pulse.
3. The value, in volts, of the maximum height of one alternation of a sine wave.
4. The difference, in volts, between the positive and negative peaks of a sine wave.
5. The value, in volts, of a sine wave that produces the same heating effect as an equal value of direct current.
6. The value, in volts, of the average of the instantaneous values of all points in a single alternation of a sine wave.
7. (a) $E_{PK} = 100V$; (b) $E_{eff} = 70.7V$; (c) $E_{AVE} = 63.6V$.
8. (a) $E_{PK} = 155.5V$; (b) $E_{AVE} = 99V$.

027

1. Two consecutive alternations of an AC sine wave.
2. One positive or negative alternation of an AC sine wave.
3. (a) A thousand cycles per second.
   (b) A million cycles per second.
   (c) The time of one cycle in one thousandth of a second.
   (d) The time of one cycle in one millionth of a second.
4. When voltage and current of a waveform are not moving simultaneously.

028

1. The property of a circuit that opposes any change in current flow. The symbol is the letter "L."
2. A magnetic field, a conductor, and relative motion.
3. The action of inducing a voltage in one circuit by varying the current in some other circuit. The symbol is the letter "M."
4. The inductance in a circuit that induces an EMF of 1 volt when the current is changing at a rate of 1 ampere per second. The symbol is the letter "h."
5. The number of turns, the diameter, the length, and the type of material used for the core.

6. Soft-iron.

029

1. $L_t = 33$ henries.
2. $L_t = 5.4$ henries.
3. The opposition to current flow offered by the inductance of a circuit. Ohms.
4. (a) 15.072 kΩ; (b) 113.04Ω; (c) 879.2Ω.
5. It doubles.

030

1. The amplitude is determined by the rate of change of current flow. Polarity is determined by the direction of current flow through the coil and whether the current flow is increasing or decreasing.
2. Voltage leads current by 90°.
3. Energy dissipated without accomplishing work.
4. Increase the size of the conductor, thus reducing heat and resistance.
5. Use a core material with a high permeability.
6. A laminated core is made up of sheets of metal, electrically insulated from each other. The insulation does not oppose the magnetic flux but reduces eddy currents by limiting the paths for current flow.

031

1. Primary; secondary.
2. Autotransformer, power transformer, audio transformer, and RF transformer.
3. It has a 5 to 1 ratio, or a step-down turns ratio.
4. That 75.9 percent of the lines of flux of the primary winding are cutting the secondary winding.
5. That the total primary power equals secondary power. The primary means a decrease in current and vice versa.
6. Relays are used to control or switch electrical circuits from remote locations.
7. The main components of relays are the: iron core, coil, armature, contacts, and spring.
8. Starting relays are used in automobile ignition systems.
9. Doorbells use intermittent relays to produce sound.
10. Circuit breakers are comprised of overload relay devices.

032

1. A change in voltage.
2. A charged capacitor offers infinite resistance to DC, effectively blocking DC.
3. C, farad, f.
4. The plate surface area, the dielectric thickness or plate spacing, and the dielectric material.
5. "Working voltage" is the maximum DC value that can be applied to a capacitor continuously. It depends largely on the dielectric material of the capacitor.
6. When it contains a potential equal to and opposite the charging source.

7. The opposition of a capacitor to the flow of current.
8. (a) 318Ω; (b) 39.750 kΩ; (c) 159 MΩ.
9. (a) $C_t = 0.15$ µf; (b) $C_t = 0.0167$ µf; (c) $C_t = 0.25$ µf.

Do the Unit Review Exercises (URE) before going to the next unit.

Unit Review Exercises

Note to Student: Consider all choices carefully, select the *best* answer to each question, and *circle* the corresponding letter.

31. (017) When two or more elements are chemically combined, what is the resulting substance called?
    a. An atom.
    b. A mixture.
    c. A molecule.
    d. A compound.

32. (017) Electrons in the outer shell of atoms are called
    a. photons.
    b. neutrons.
    c. valence electrons.
    d. ionized electrons.

33. (018) A body of matter that has an equal number of protons and electrons in each atom is
    a. ionized.
    b. uncharged.
    c. positively charged.
    d. negatively charged.

34. (018) Which of the following diminishes in proportion to the square of the distance from a charged body?
    a. Fields of force.
    b. Number of protons.
    c. Number of electrons.
    d. Directivity of the charges.

35. (019) What is the unit of resistance?
    a. Amp.
    b. Ohm.
    c. Volt.
    d. Henry.

36. (019) What affects the resistance of a conductor?
    a. The cross-sectional area of the conductor.
    b. The resistivity of the material.
    c. The length of the conductor.
    d. All of the above.

37. (019) The unit of conductance is the
    a. farad.
    b. henry.
    c. mho.
    d. ohm.

38. (020) Which of these materials has the *most* free electrons?
    a. Iron.
    b. Wood.
    c. Glass.
    d. Rubber.

39. (020) Define electromotive force (EMF).
    a. A difference of potential.
    b. The amount of current flow.
    c. The force between two neutral bodies.
    d. An opposition to the flow of electrons.

40. (020) Which of the following are *most* often used to produce an electromotive force (EMF)?
    a. Chemical cell and mechanical generator.
    b. Chemical cell and piezoelectric crystal.
    c. Photoelectric cell and piezoelectric crystal.
    d. Thermoelectric cell and mechanical generator.

41. (022) The most basic electronic circuit is the
    a. series circuit.
    b. bridge circuit.
    c. parallel circuit.
    d. series-parallel circuit.

42. (022) The current through a branch of a parallel network is
    a. inversely proportional to the amount of resistance of the branch.
    b. directly proportional to the amount of resistance of the branch.
    c. inversely proportional to the amount of resistance of the network.
    d. directly proportional to the amount of resistance of the network.

43. (022) A rheostat is a variable resistor that may be used as a control to vary
    a. resistance.
    b. voltage.
    c. current.
    d. power.

44. (023) If 10 amps of current are flowing toward a 10-ohm resistor in a series DC circuit, how many amps of current are flowing away from that resistor?
    a. 1.
    b. 5.
    c. 10.
    d. 20.

45. (023) If a series circuit dissipates 2 watts of power across a 2-ohm resistor, the value of the voltage is
    a. 2V.
    b. 4V.
    c. 6V.
    d. 8V.

46. (023) The applied voltage in a parallel DC circuit is calculated by
    a. finding any voltage drop in the circuit.
    b. dividing total resistance by total current.
    c. dividing total current by total resistance.
    d. multiplying total inductance by total reactance.

47. (023) If a 20-ohm resistor is in series with a parallel circuit containing branches of 30, 30, and 30 ohms, with 10 volts total applied, what is the total current draw of the circuit in amperes to the nearest tenth?
    a. 0.3.
    b. 0.5.
    c. 3.3.
    d. 11.0.

48. (023) The ground reference point in a series voltage divider is important because it
    a. determines the polarities of tapped voltages.
    b. is economical and eases circuit construction.
    c. determines the allowable number of tapped voltages.
    d. allows current flow through the chassis to other points of the circuit.

49. (023) Which statement is *true* about total circuit resistance and the load on the voltage portion of the divider when a load device is connected to a voltage divider?
    a. Resistance decreases; the load decreases.
    b. Resistance decreases; the load increases.
    c. Resistance increases; the load decreases.
    d. Resistance increases; the load increases.

50. (023) Which statement is *true* of a resistive balanced bridge circuit's ohmic values?
    a. If all the resistances are within 10 percent of each other, it is balanced.
    b. If the ratios are equal between resistors in only the horizontal plane, it is balanced.
    c. If the ratios are equal between any two resistors in the horizontal or vertical planes, it is balanced.
    d. If the resistances are not equal between planes but can be equaled by the center load, it is balanced.

51. (024) An open resistor
    a. restricts current flow.
    b. does not oppose current flow.
    c. is caused by interior leads touching.
    d. is indicated by excessive current flow.

52. (024) To identify an open resistor in a parallel DC circuit, you would test for
    a. zero resistance.
    b. reversed polarity.
    c. excessive current.
    d. infinite resistance.

53. (024) To troubleshoot a series-parallel DC circuit for an open parallel resistor, you would test for
   a. a decrease in total current.
   b. an increase in total current.
   c. zero voltage dropped across the parallel portion of the circuit.
   d. applied voltage dropped across the series portion of the circuit.

54. (025) In a simple, two-pole alternator, the rotating loop and its supporting structure form the
   a. brushes.
   b. armature.
   c. generator.
   d. slip rings.

55. (025) If the *maximum* induced voltage in a given alternator is 20 volts, what is the induced voltage at 45°?
   a. 10 volts.
   b. 13.7 volts.
   c. 14.14 volts.
   d. 28.28 volts.

56. (026) Calculate the peak voltage of an AC sinewave which has a peak-to-peak voltage of 2 volts.
   a. 4 volts.
   b. 1 volt.
   c. 1.414 volts.
   d. 0.707 volts.

57. (026) The peak value of AC has what relationship to effective value? To average value?
   a. 0.636; 0.707.
   b. 0.707; 0.636.
   c. 1.414; 1.57.
   d. 1.57; 1.414.

58. (027) What type of circuit has voltage and current in phase with each other?
   a. Resistive.
   b. Inductive.
   c. Capacitive.
   d. No circuit.

59. (028) All of the following factors have an effect on the inductance of a coil *except* the
    a. type of current.
    b. number of turns.
    c. ratio of diameter to length.
    d. material used in the conductor.

60. (029) What is the total inductance of a series circuit containing coils of 5 henries, 10 henries, and 15 henries?
    a. 30 henries.
    b. 15 henries.
    c. 10 henries.
    d. 3.3 henries.

61. (029) What is the unit of measure for inductive reactance?
    a. Ohm.
    b. Mho.
    c. Farad.
    d. Henry.

62. (029) Before you troubleshoot an inductor,
    a. apply power.
    b. calculate total circuit current.
    c. disconnected it from the circuit.
    d. test all other circuit components.

63. (030) What is the phase relationship between current and voltage in an actual inductance circuit with minimum resistance?
    a. Current lags voltage by 90°.
    b. Current leads voltage by 90°.
    c. Current lags voltage by 45°.
    d. Current leads voltage by 45°.

64. (030) What are the three types of power losses in an inductor?
    a. Eddy currents, inductance, and hysteresis.
    b. Resistance, lamination, and inductance.
    c. Hysteresis, copper, and eddy currents.
    d. Copper, resistance, and inductance.

65. (031) Transformers used in low-frequency circuits require
   a. an air core.
   b. a turn's ratio of at least 10:1.
   c. a core of low-reluctance magnetic material.
   d. a core of high-reluctance magnetic material.

66. (031) What type of transformer often provides several voltage level outputs, and how are they achieved?
   a. Power; two or more secondaries.
   b. RF; two or more secondaries.
   c. Power; numerous taps.
   d. RF; numerous taps.

67. (031) Relay circuits operate on the principle of
   a. proton displacement.
   b. current amplification.
   c. electron displacement.
   d. electromagnetic attraction.

68. (031) Which type of relay is used to protect a piece of equipment from excessive current flow?
   a. Intermittent.
   b. Overload.
   c. Starting.
   d. Holding.

69. (032) A capacitor rating of "600 VDC" refers to the capacitor's
   a. inductance.
   b. capacitance.
   c. working voltage.
   d. dielectric thickness.

70. (032) As the frequency applied to a parallel capacitive branch is increased, the
   a. branch current decreases.
   b. branch current increases.
   c. total capacitance increases.
   d. total capacitive reactance increases.

71. (032) What is the approximate capacitive reactance of a circuit with an input frequency of 2 kHz and total capacitance of 10 pf?
    a. 800 kilohms.
    b. 1,256 kilohms.
    c. 8 megohms.
    d. 12.56 megohms.

72. (032) Before you test a suspected faulty capacitor,
    a. energize it.
    b. calculate total circuit resistance.
    c. test all other circuit components.
    d. fully discharge it and disconnect it.

Please read the unit menu for Unit 3 and continue. ➔

STUDENT NOTES

Unit 3. Solid-State Devices

Page

Previously, we reviewed basic mathematical concepts and discussed simple electronic principles. You learned at technical school that three basic circuit arrangements make up almost all electronic devices: rectifiers, amplifiers, and oscillators. As you know, it is the arrangement of the components within an electronic device that makes the device operate. In this unit, we discuss another aspect of the electronics environment—solid-state devices. From your studies of electronics, you realize that solid-state devices are used in many circuits because of their small size, reliability, durability, and low power requirements. Transistors add one more advantage to the list—the ability to amplify.

3–1. Fundamentals of Solid-State Devices

Before proceeding with the material in this unit, you may wish to review the section on electron theory. This theory, as you know, applies to all electronic devices. Your knowledge of electron theory, including atomic structure, gives you the basis for understanding the application of the solid-state devices we discuss in this unit.

033. Atomic structure in solid-state components

The conduction of an atom depends on its ability to take on, give up, or share the electrons in its outer shell. If electrons are removed, the atom becomes a positively charged ion. When the atoms of an element give up or take on electrons easily, we say the material is a good conductor of electricity. Copper, silver, and gold, which have only one electron in their outer shells, are good conductors.

When donor atoms, such as arsenic, phosphorus, or antimony are added as impurities, only four of the five valence electrons can pair up with an electron of an adjacent atom. Therefore, the crystal formed contains one free electron for each donor atom added. These atoms have a tendency to give up or donate their extra electron. At normal room temperature, the free valence electrons gain enough energy to break their electrical bond and wander throughout the crystal material. The crystal is called N-type material because it contains these free electrons. The electrons are negatively charged particles that came from donor atoms.

When acceptor atoms such as aluminum, gallium, boron, or indium are used as impurities, there are only three valence electrons that pair up with electrons of adjacent atoms. This means that one electron of the adjacent atoms is not paired. We refer to the position in the crystal where there is no electron as a "hole." We consider the hole as positive, even though it has no charge, because it exhibits characteristics of a positively charged particle—that is, it attracts or accepts an electron to fill it.

Just as in N-type material, some electrons in the crystal made with acceptor impurities gain enough energy to break away from their atom. This is particularly true in atoms that are adjacent to acceptor atoms because the electrons have a tendency to fill the holes in the acceptor atoms. When the electron leaves an atom to fill a hole in the crystal material, it leaves a vacancy in the atom it just left. We might say that the hole moved from one atom to another. Since the atom with the hole is now a positive ion, it attracts an electron from an adjacent atom. This action causes a random movement of holes throughout the crystal. This type of crystal is called P-type material because it contains acceptor atoms, and the holes in the material have characteristics similar to those possessed by positively charged particles.

PN junction diode. An important phenomenon occurs when P-type and N-type materials are found together. This phenomenon permits the use of semiconductors as current control devices in much the same way that vacuum tubes are used. In the region near the junction, free valence electrons in the N-type material and holes in the P-type material are attracted to each other and, therefore, move toward each other and combine. That is, electrons cross the junction and assume a place in the structure of the molecule that contained a hole. This satisfies the valence force of the two molecules of both materials, N-type material losing one of its free electrons and P-type material gaining a desired electron. Both molecules now share eight electrons in their valence shells. You might think that all of the free electrons in the N-type material would cross the junction to fill the holes in the P-type material, but this is not so. Only a region near the junction is affected. Figure 3–1 illustrates this action.

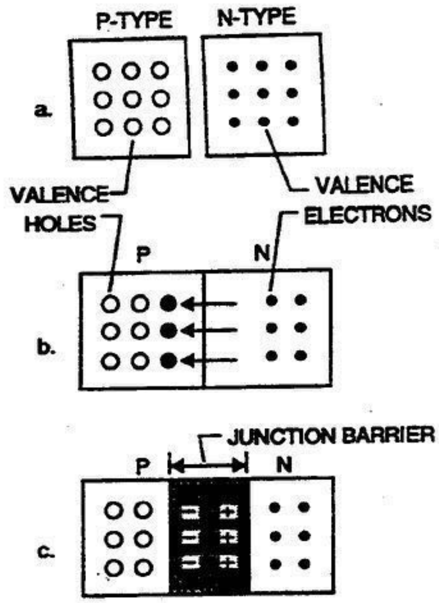


Figure 3–1. PN junction.

In part "a" of figure 3–1, dots represent the valence electrons in the N-type material and small circles represent the valence holes in the P-type material. Both the electrons and the holes are shown equally distributed in their respective materials. In part "b," which shows the two materials fused together, the electrons near the junction have passed through the junction to fill holes in the P-type material. This movement, remember, is caused by the valence force of impurity atoms in both materials. The valence force of each pair of atoms that gives up and receives an electron is eliminated but a new force, an *electrostatic force,* is created.

When electrons in the N-type material cross the junction to fill holes in the P-type material, the ratio of electrons to protons increases in the P-type material and decreases in the N-type material. That is, negative ions are created in the N-type material. An EMF is thus created across the junction. The region near the junction, therefore, may be compared to a battery with the polarities indicated in part "c" of figure 3–1. When the charge of this region reaches a certain potential, the region acts as a barrier to valence electrons attempting to cross the junction. It is, therefore, sometimes called the *junction barrier.*

The reason a PN junction acts as a barrier to valence electrons can be understood by studying figure 3–1, c. The force of the negative ions formed in the P-type material near the junction repels the valence electrons in the N-type material. These valence electrons try to cross the barrier to fill valence holes in the P-type material. The force of the positive ions formed in the N-type material near the junction repels the holes in the P-type material. These holes tend to move toward the junction. As a result, the region near the junction is depleted of current carriers because there are no current-carrying free electrons in the N-type material near the junction and no current-carrying holes in the P-type material near the junction.

The region near the junction, therefore, is called the *depletion region.* The width of this depletion region is determined by the amount of impurities in the crystal material. The width of the region can be changed by applying an external EMF, called *bias*, to the PN junction.

Forward bias. If we attach a battery with the polarities shown in figure 3–2, the potentials we apply forward bias the PN junction. In addition, the depletion region decreases the barrier, battery voltages aid each other, and the diode conducts. The potential of the battery causes both the holes and free electrons to move toward the barrier. For each electron entering the N-type material, one combines with a hole at the junction. As each hole is filled, an electron is removed from the P-type material and returns to the battery. As the potential of the battery is increased, the depletion region decreases until the diode exhibits only the natural resistance of the semiconductor material.

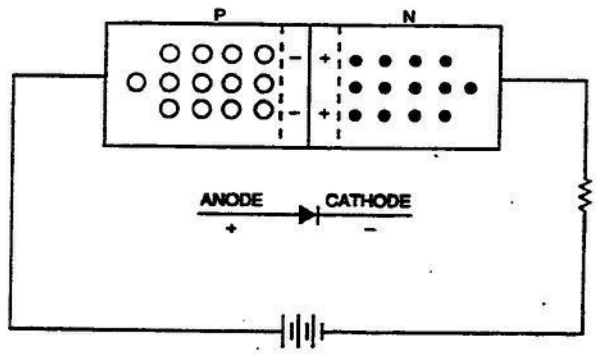


Figure 3–2. Forward-biased PN junction.

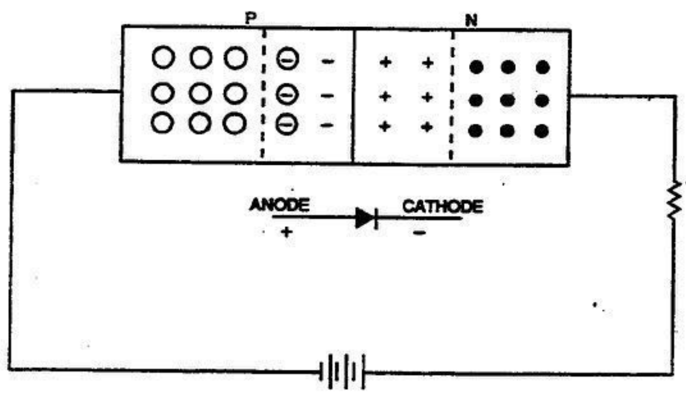


Figure 3–3. Reverse-biased PN junction.

When used in electronic circuits, a diode allows maximum current flow when the electron movement is from the cathode (negative) to the anode (positive) in a forward-biased state. Virtually all current flow is blocked when the diode is reverse biased and the current attempts to flow from the anode to the cathode.

Many types of semiconductor diodes are available. They vary from the size of a pinhead, used in subminiature circuitry, to large diodes used in high-power circuits. The cathode lead of a diode is identified by a distinctive marking (color dot or band and sign) or by its unusual shape (raised edge or tapes).

Reverse bias. When an external EMF is applied to a PN junction with the negative polarity connected to the P-type material and the positive polarity connected to the N-type material, the junction is reverse biased. This action increases the width of the depletion region. Let us follow the action in figure 3–3, which shows the electrical symbol for a diode just below the PN junction.

Electrons from the negative terminal of the battery flow to the diode and fill holes in the P-type material. Other electrons are driven to the next holes. This action continues until electrons fill the holes adjacent to the original depletion area. This last action is depicted by the minus signs inside the circles. At the same time, the positive potential of the battery attracts electrons that entered the P-type material and are extracted from the N-type material. The electrons, except for a small leakage current, cannot pass through the depletion region. Therefore, this region increases until the barrier voltage (the voltage drop across the barrier) becomes equal to the battery voltage.

If the battery voltage is increased until all of the free valence electrons and holes are eliminated, any further increase in voltage normally breaks down the crystal structure. The crystal acts only as a resistor, dissipates heat, and may be destroyed. As you can see, with no current carriers available, the current consists of electrons that are bound in the molecular structure of the crystal. If too many of these electrons are used as current, the molecular structure disintegrates. There are special diodes designed for this type of operation called *Zener diodes*. They are used as regulating devices because they offer a certain opposition to the flow of current until the applied EMF reaches a certain value, then they conduct.

Transistors. The fact that a PN junction exhibits low resistance when forward biased and high resistance when reverse biased makes it possible to produce a device that can amplify current by making a device with two PN junctions. By introducing a signal into the forward-biased junction and extracting the result from the reverse-biased junction, a power gain can be produced in an external circuit. This device, which transfers the signal current from a low-resistance circuit, is called a *transistor*. The name was derived by contracting the two terms *transfer* and *resistor*.

Types. There are two types of transistors—PNP and NPN. The PNP type is made by fusing N-type material between two pieces of P-type material. NPN-type transistors are made by fusing P-type material between two N-type materials. The upper part of figure 3–4 shows a pictorial representation of a transistor. The lower part of the figure shows the electrical symbols for both types of transistors.

Notice the names given to each of the three crystals: "emitter," "base," and "collector." In this type of transistor presentation, the crystals are usually identified by the letter of the type of material used. In the electrical symbol, the emitter is identified by an arrow; the base is represented by a T-shaped figure similar to the plate of a vacuum-tube symbol; the collector is shown as a slanted line. Both the emitter and collector touch the base.

Notice that the arrow points in the opposite direction in an NPN-type transistor from where it points in the PNP-type transistor. This arrow may be used to identify the type of transistor when found in a schematic diagram. If the arrow points in, the transistor is a PNP type. If the arrow points out, it is an NPN type. An easy way to remember how to use the arrow when determining the type of transistor is to think of the arrow as pointing or not pointing in. The similarity of the words "pointing in" and the letters PN gives us a clue that this is a PNP-type transistor. Likewise, the similarity of the words "not pointing in" and the letters NPN tells us that the transistor is an NPN type. It is also useful to remember that, in a schematic diagram, current flow is always against the arrow.

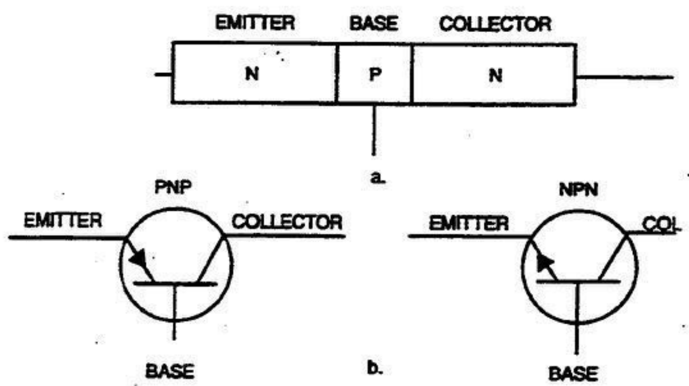


Figure 3–4. Pictorial and schematic transistor symbols.

Operation. The bias applied to each PN junction of a transistor determines the current flow through the transistor. The emitter-base junction is forward biased and the base-collector junction is reverse biased. Figure 3–5 shows the connections needed to bias an NPN-type transistor using two batteries. The figure also shows two external resistors, R1 and R2; the natural resistance of the N-type material, R_n; and the junction barrier voltages represented by battery symbols. Use this diagram to follow the various current flows in the transistor circuit.

First, consider current flow as if the collector circuit were open. As a negative potential is applied to the emitter and a positive potential is applied to the base, the emitter-base junction is forward biased. That is, the battery voltage and the junction barrier voltage are in series and are aiding each other. The only opposition to current flow in the circuit is the resistance of R1 and the natural resistance of the emitter material (R_n). Current flows from the negative side of battery C, through R1, through the emitter, across the emitter-base junction, through the base, and back to the opposite side of the battery.

Now, consider the collector circuit with the emitter circuit open. Battery B applies a negative potential to the base and a positive potential to the collector. This biases the base-collector junction in a reverse direction because the battery

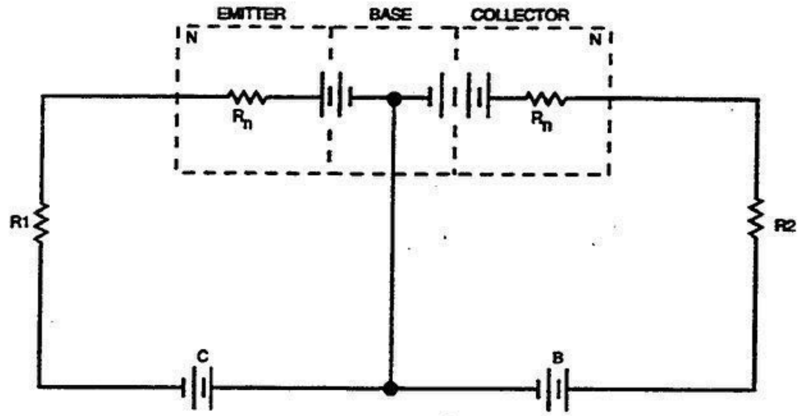


Figure 3–5. Transistor circuit operation.

potential is in series with the barrier voltage, but in opposition to its current potential. As a result, no current flows in this circuit.

With both the emitter-base and base-collector circuits connected as in figure 3–5, the amount of forward bias determines the amount of current flow in the collector circuit. Between 92 and 99 percent of the emitter current flows through the collector. Notice in the diagram that batteries B and C are in series with each other in the emitter-collector circuit. Therefore, the electrons traveling through the emitter are attracted by the potential of the positive terminal of battery B, as well as the positive ions in the collector material. Another reason the electrons take this path instead of through the base circuit is the thickness of the base material. The base of a transistor is much thinner than the emitter or collector and, therefore, contains an insufficient amount of current-carrying holes to handle the large amount of electrons coming from the emitter. Most of the electrons, therefore, diffuse through the base and penetrate the base-collector depletion region where they are attracted by the positive potential of battery B.

A small change in forward bias causes a large change in collector current. If the bias is increased, the increase in the amount of electrons in the base circuit cancels out more of the base-collector barrier voltage, permitting a greater flow of electrons through the collector. If the forward bias is reduced, the base-collector barrier increases, which reduces the amount of collector current. Another way of looking at it is that a decrease in forward bias causes an increase in emitter-base resistance and a proportionally larger increase in base-collector resistance. Thus, a transfer of resistance is accomplished. The ability of a small base-emitter voltage to control a large emitter-collector current makes the transistor an ideal variable resistor and amplifier.

Collector current changed by varying the forward bias can be restored to its original value by varying the reverse bias inversely. The amount of reverse-bias change, however, must be much greater than the change in forward bias. The ratio of the change in reverse bias to the change in forward bias, which is necessary to maintain the same current flow, may be compared to the amplification factor of a vacuum tube.

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

033. Atomic structure in solid-state components

1. What prevents excessive valence electron movement in a PN junction?

2. What does forward bias on a PN junction narrow?

3. Describe the movement of electrons in a forward-biased diode.

4. Define the term "transistor."

5. Explain the structural differences between the two types of transistors.

6. What type of transistor is represented by a transistor schematic symbol in which the arrow on the emitter points towards the base?

7. What type of transistor is represented by a transistor schematic symbol in which the arrow on the emitter *does not* point towards the base?

8. Is the emitter-base junction of a NPN transistor always forward-biased or reverse-biased?

9. Is the base-collector junction of a NPN transistor always forward biased or reverse biased?

10. What effect does a change in forward bias on the emitter of a transistor have on its collector current?

3–2. Solid-State Rectifiers and Power Supply Filters

Many electronic circuits use both alternating current (AC) and direct current (DC) voltages. Since it is impractical to provide separate voltage sources to a circuit, AC voltage is converted to the needed DC voltage. An alternating current flows in one direction for one-half of the cycle and reverses direction for the second half of the cycle. A direct current flows in one direction only, from negative to positive.

As the first step in changing AC to DC, one half-cycle of AC must be extracted, or rectified, from the source voltage. Since a diode allows maximum current flow through itself in one direction and virtually blocks current in the opposite direction, it becomes the primary component in a rectifier circuit.

A rectifier converts an AC source voltage to a "pulsating DC" voltage, as shown in the first step of the power supply block diagram in figure 3–6. This train of pulses can be viewed as a DC voltage with an AC component. The AC component is removed by the following filter circuit and then, if required, a voltage regulator supplies the desired amount of DC to the operating circuit.

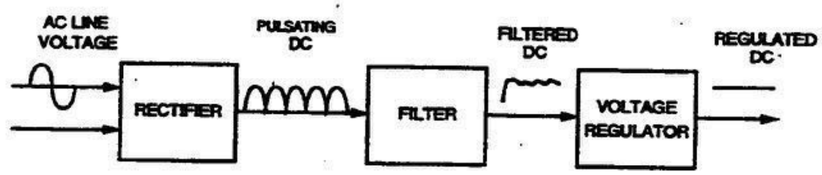


Figure 3–6. Power supply block diagram.

034. Half-wave, full-wave, and bridge rectifier circuits

Rectifiers appear in several different configurations. Among the most popular are the half-wave, full-wave, and the bridge. Let's take a look at each.

Half-wave. A diode, in series with a resistor, has the ability to select one alternation of an applied AC voltage as usable DC voltage. The selected alternation may be either positive or negative, depending upon the rectifier configuration.

Figure 3–7 shows a diode and a resistor in series with the secondary coil of a transformer. During the positive alternation of the input AC voltage, current flow forward biases the diode (cathode to anode) and it offers almost no opposition to the flow. The figure shows that, at this time, the peak voltage is dropped across the resistor. During the negative alternation, the diode is reverse biased and offers many times the opposition of the resistor. On this alternation, virtually no voltage is dissipated by the resistor, resulting in the pulsating DC output shown.

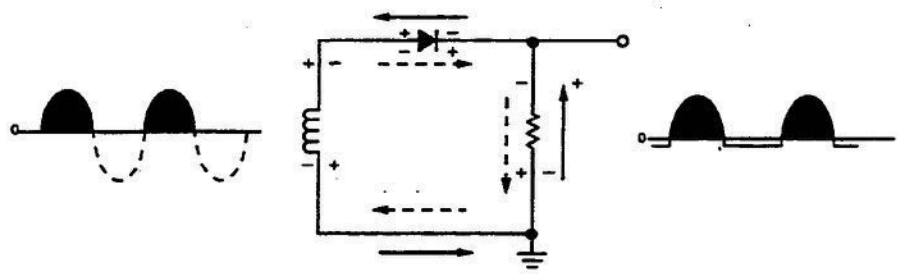


Figure 3–7. Positive half-wave rectifier.

Many circuits require a DC voltage that is negative to a reference. By reversing the position of the diode in the circuit, a negative output voltage is obtained. Figure 3–8 shows this configuration and the output voltage obtained.

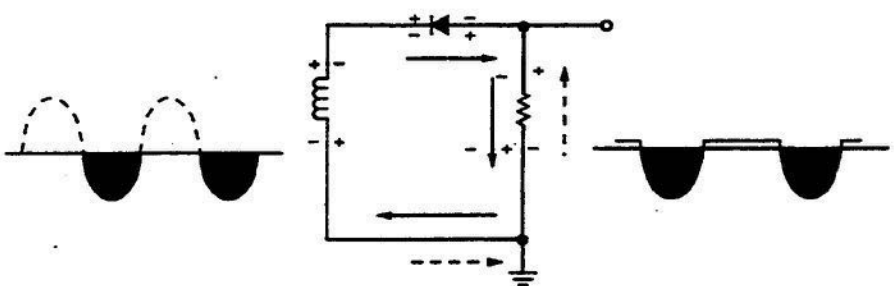


Figure 3–8. Negative half-wave rectifier.

A study of the two figures of half-wave rectifiers reveals that they are easy to distinguish from one another. Maximum current flow is against the arrow, from cathode to anode, in the diode. Therefore, the position of the anode in relation to the polarity of the input coil determines the polarity of the voltage obtainable across the load resistor.

The diode in a half-wave rectifier must carry the full load current and also must be rated for at least the maximum load current to be encountered. Also, the full peak voltage of the secondary winding appears across the diode when it is reverse biased. Therefore, the peak inverse voltage (PIV) rating of the diode must exceed the highest peak voltage of the secondary.

A half-wave rectifier has only a few advantages; among the advantages are fewer parts and, consequently, lower cost. The disadvantages of a half-wave rectifier are many. It draws power from the input power source during only half of the input cycle. For that reason, it is limited in the amount of current it can supply to the load. A half-wave rectifier is used only in applications that require a relatively small current drain.

Another disadvantage is that the current flow through the secondary of the power transformer is always in the same direction. This unidirectional current flow causes the molecules in the iron core to become oriented in one direction (magnetized). This effect, called DC *core saturation*, reduces the efficiency of the transformer. As a result, an overly large transformer is needed for half-wave rectification.

The biggest disadvantage of the half-wave rectifier is the difficulty in filtering the output into steady DC voltage. This is because the output pulses are widely spaced with periods of zero output between them. Thus, a half-wave rectifier has poor voltage regulation with a varying load.

Because of the number of disadvantages, the half-wave rectifier circuit is seldom used except in cases where the advantage of low cost outweighs the disadvantages.

Full-wave. The disadvantages of half-wave rectifiers can be overcome by using a full-wave rectifier. In a full-wave rectifier, two diodes are connected so that each conducts during alternate half-cycles of the AC input. The two diodes have a common load and the current flows through this load, always in the same direction (fig. 3–9). Note the two dots over the transformer. This indicates that instantaneous polarities are the same at this point. In other words, there is no phase shift between the primary and secondary in this circuit.

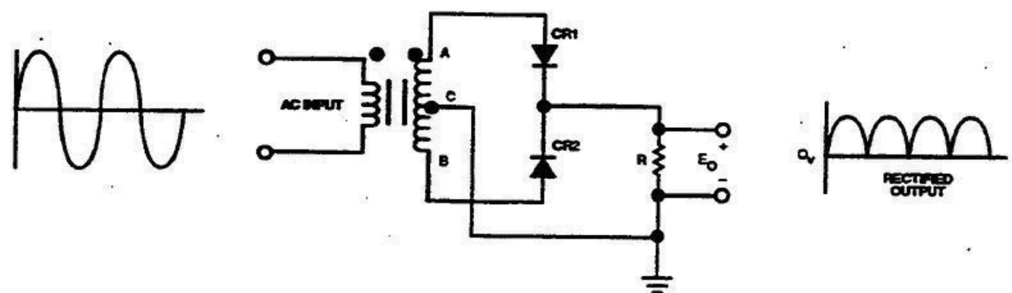


Figure 3–9. Positive full-wave rectifier.

A full-wave rectifier uses two diodes with the anodes of the diodes connected to opposite ends of the transformer secondary. A common cathode resistor is connected between the two cathodes and the center tap on the secondary winding of the transformer. When an AC input voltage is applied to the transformer primary, it appears as a stepped-up voltage across the entire transformer secondary (points A and B). Since point C is the electrical center of the secondary, half the induced voltage exists between points A and C, and half between B and C. Since these two voltages are measured with respect to the common reference point C, they are always 180° out of phase. The voltage between A and C is applied between the anode and cathode of diode CR1 and the voltage between B and C is applied to CR2.

The two 180° out-of-phase voltages developed across the secondary of the center-tapped transformer cause the two diodes of the full-wave rectifier to conduct on alternate half-cycles of the AC input (fig. 3–10).

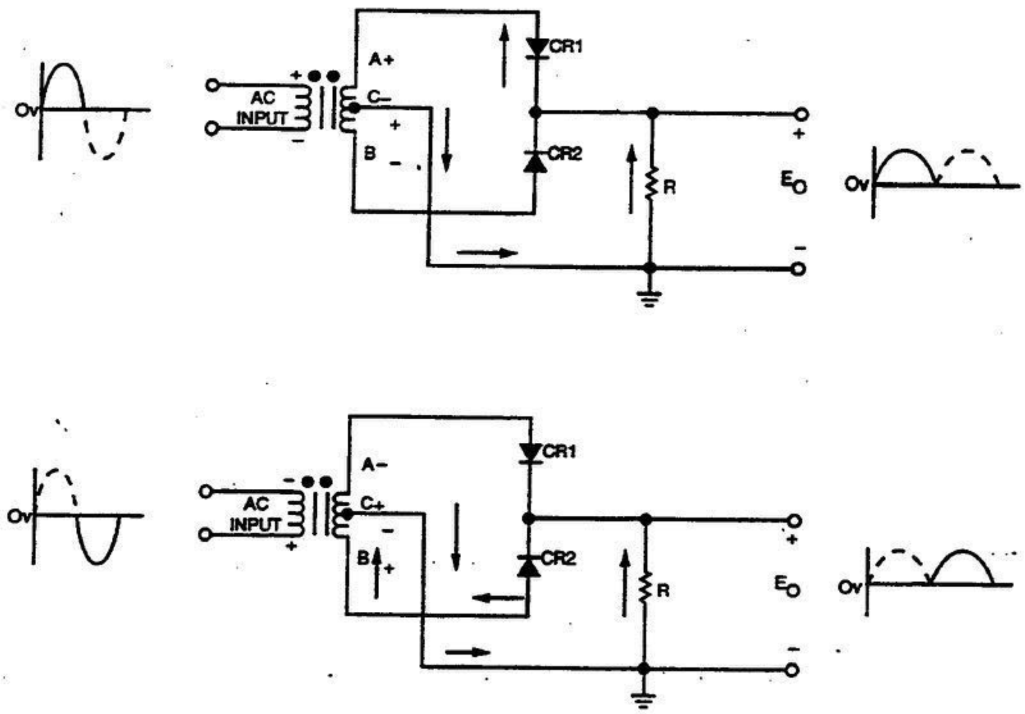


Figure 3–10. Positive full-wave rectifier, current flow and output voltage.

During each positive half-cycle of the AC input, shown in the top part of figure 3–10, the end of the secondary winding connected to diode CR1 is positive and the end connected to CR2 is cut off. The current path for CR1 is from point C up through the load resistor, through CR1, and back to point "A" of the transformer. The voltage developed across the resistor has a waveshape similar to the half-cycle of the AC input and a polarity as shown in the top part of the figure.

During each negative half-cycle of the input, the voltage polarity across the transformer secondary reverses. Now the anode of CR2 is positive with respect to its cathode and the anode of CR1 is negative with respect to its cathode. CR2 conducts and CR1 is cut off. The current path as CR2 conducts is shown in the bottom part of figure 3–10. The polarity of the output pulse developed across the load resistor is the same as that produced by a positive half-cycle of the AC input. Each half-cycle of the AC input, therefore, produces output pulses across the resistor of the same polarity.

By using a center-tap transformer, only half of the input potential is developed across the load. The loss in voltage is partially made up because both alternations of the input are developed, resulting in an increase in the current supplied to the load.

Figure 3–11 shows the configuration of a negative full-wave rectifier. The diodes have been reversed in the circuit and the cathodes are now closest to the tops of the transformer.

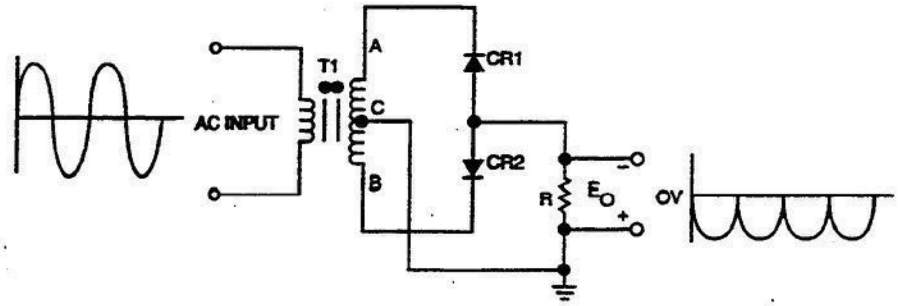


Figure 3–11. Negative full-wave rectifier.

Bridge. The most efficient of rectifiers is a bridge rectifier circuit (fig. 3–12). It provides the high voltage of a half-wave rectifier and its high-current capabilities are comparable to a full-wave rectifier because each alternation of the input is reproduced in the output. A bridge rectifier is made up of four diodes wired into a circuit to provide two separate paths for current flow to a load resistor. AC is applied to two separate corners on alternate half-cycles and the rectified peak output is taken between the other two corners.

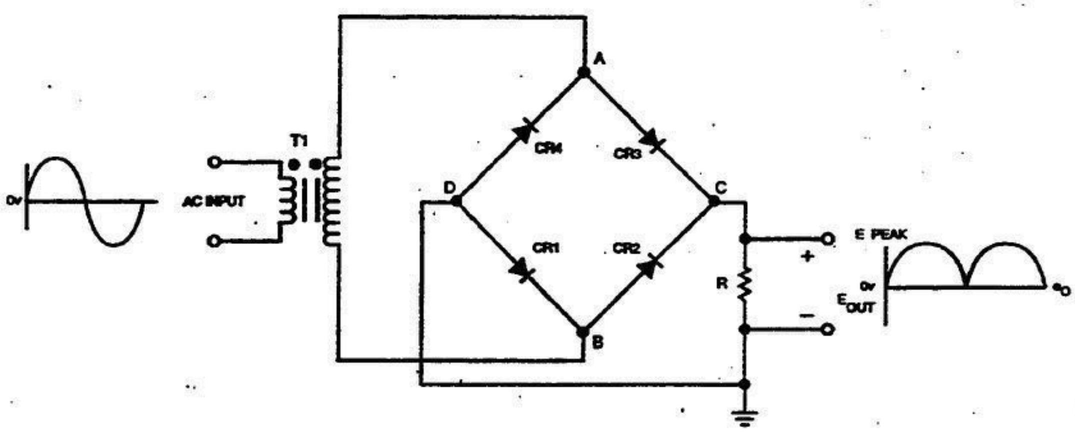


Figure 3–12. Positive bridge rectifier, input and output voltages.

The current flow paths are shown in figure 3–13. During the positive input alternation, current flows from the bottom of the secondary through CR1, up through R and CR3 to the top of the secondary.

On the negative half-cycle of the AC input, the bottom of the transformer secondary is positive and the top is negative. Diodes CR1 and CR3 cannot conduct because the polarity of the voltage causes them to cut off. Diodes CR2 and CR4, being forward biased, can now conduct. The current path, therefore, is from the top of the transformer, through diode CR4, through the load resistor, through diode CR2, and back to the bottom of the secondary.

Observe that the direction of current flow through R is the same for both the positive and negative half-cycles of the AC input. The output voltage developed across R is a rectified version of the AC input voltage. Figure 3–12 shows the complete output waveshape from the bridge rectifier. With a given power

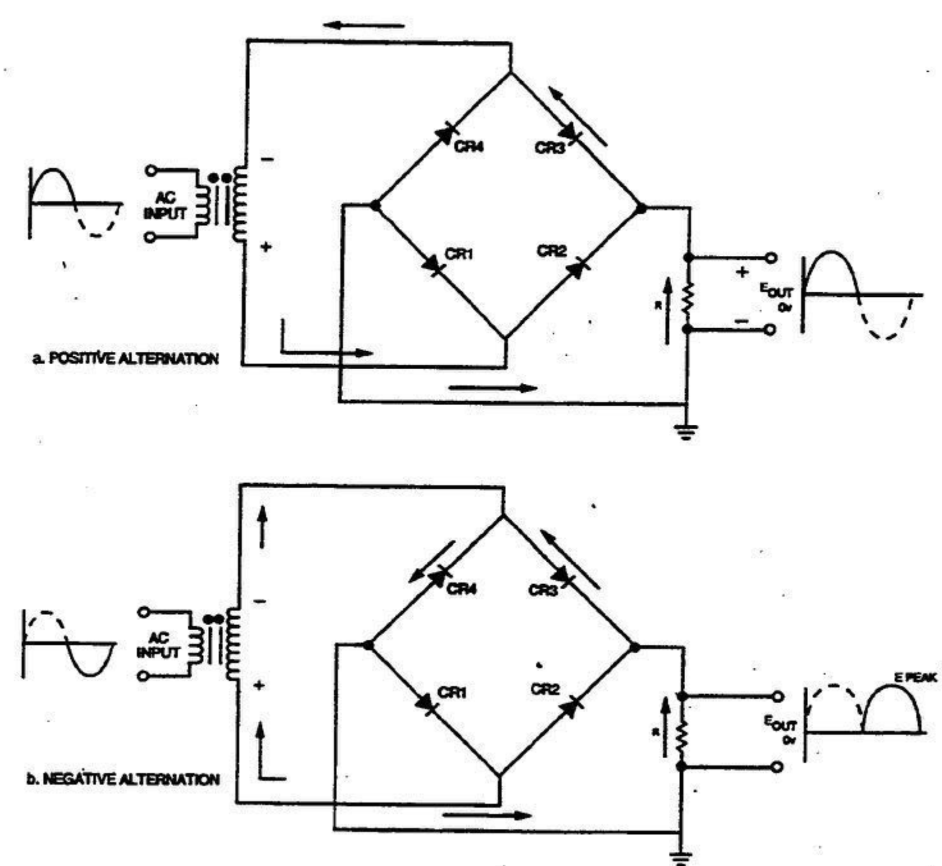


Figure 3–13. Positive bridge rectifier with input and output.

Observe that the direction of current flow through R is the same for both the positive and negative half-cycles of the AC input. The output voltage developed across R is a rectified version of the AC input voltage. Figure 3–12 shows the complete output waveshape from the bridge rectifier. With a given power transformer, a bridge rectifier produces an output voltage nearly twice as large as that produced by a conventional full-wave rectifier. This is because the entire secondary of the transformer is applied across the diode pairs.

The output of a bridge rectifier is developed across the load resistor. The amplitude of the output voltage depends upon the current flowing through the load. The polarity of the output voltage may be positive or negative.

To obtain a negative output from a bridge rectifier, simply reverse all diode connections. Now the current pulses during each half-cycle of input voltage flow downward through the load resistor, thus giving a negative output voltage. Figure 3–14 shows the path for current flow for a half-cycle of operation.

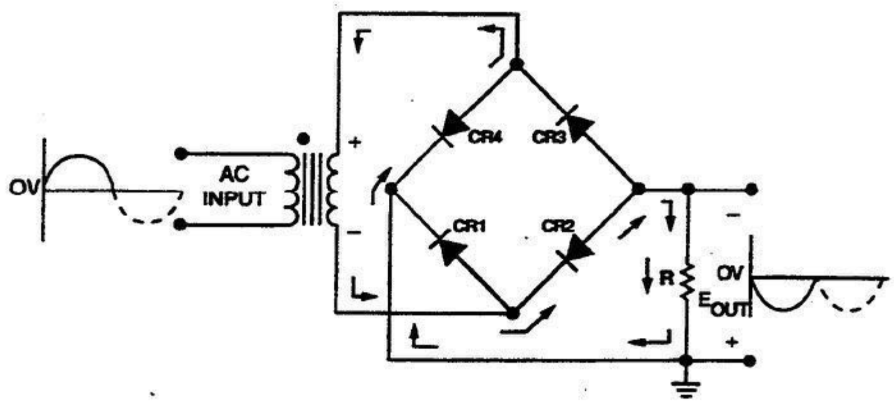


Figure 3–14. Negative bridge rectifier and current flow path.

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

034. Half-wave, full-wave, and bridge rectifier circuits

1. What is the function of a half-wave rectifier?

2. What advantage does a half-wave rectifier have over other types?

3. What is the greatest disadvantage of half-wave rectifiers?

4. To produce a negative pulsating DC output from a full-wave rectifier, how must the current flow? Refer to figure 3–11.

5. On the positive alternation of the input cycle (fig. 3–9), which CR is conducting and which is reverse biased?

6. Which rectifier circuit configuration produces the highest voltage and current output?

7. On the negative alternation of the input cycle (fig. 3–12), which two diodes are conducting?

3–3. Basic Solid-State Amplifiers and Frequency Sensitive Filters

Transistors and diodes by themselves are interesting, but of little practical use to us. For this reason, we must now study a practical application of the transistor and we must take a look at how we can eliminate the fluctuating peaks associated with simple rectifiers.

035. The three basic amplifier configurations.

For a better understanding of more complex circuits in later studies, a thorough understanding of basic circuit operation is necessary. In this section, we discuss the operation and characteristics of three basic amplifier configurations—the *common base* (CB), *common emitter* (CE), and *common collector* (CC). Unless otherwise specified, all considerations made with NPN transistors are identical to those made with PNP types, if bias polarities are reversed.

Common base. Figure 3–15 illustrates the common-base configuration. Both types of transistors—NPN and PNP—are shown; polarities of the source voltages are the only difference between the two. DC voltages are used at this time to establish the basic operating conditions of the amplifiers.

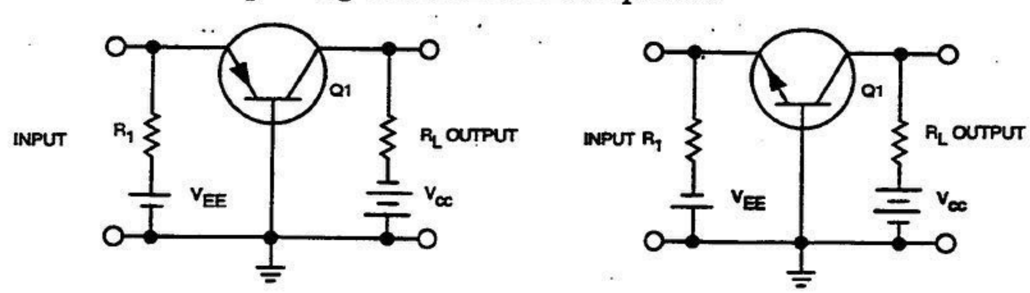


Figure 3–15. Common-base (CB) amplifier.

An input signal is applied to the emitter-base junction and the output is taken from the collector-base junction. Since the base is common to both the input and output circuit, this arrangement is referred to as a common-base (CB) amplifier. It is also referred to as a grounded-base amplifier.

With the emitter-base junction forward biased and the collector-base junction reverse biased, current flows. Using the NPN transistor illustrated in figure 3–16, notice that the collector current is 95 percent of the emitter current, with the remaining 5 percent flowing in the base circuit as a result of electrons from the emitter combining with holes in the P-type base.

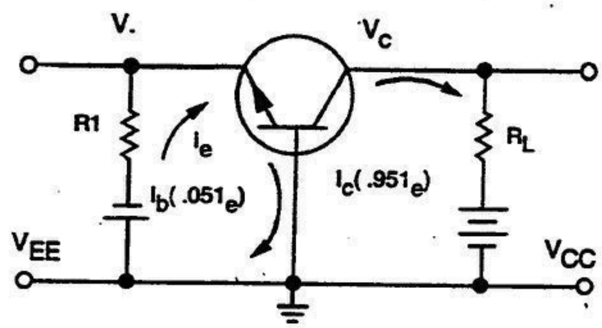


Figure 3–16. Common-base currents.

With no signal input, a certain collector current flows, producing a voltage drop across the load resistor (R_L). This voltage drop is in opposition to the collector battery voltage, V_{CC}, and places the collector voltage, V_c, at some value lower than the battery voltage. With no signal applied, the emitter, base, and collector circuits are constant. The presence of this constant bias current is necessary for the proper operation of a transistor. That is, no-signal, or quiescent bias current, in a transistor presents an average current to which the signal current either adds or subtracts. It is important that this quiescent current is of the proper magnitude so that equal positive and negative alternations of the input signals produce equal positive and negative alternations of the output current above and below the average value. An incorrect quiescent bias current may cause one or more forms of distortion in the output signal.

In the quiescent condition, a small DC reference voltage is dropped across R_L. With a PNP-type transistor, current flows from the bottom of R_L to the top. This causes the polarity of the quiescent collector voltage to be less negative than the supply. With the NPN type, current flows from the top of R_L to the bottom. This causes the polarity of the quiescent collector voltage to be less positive than the supply. This NPN quiescent voltage condition is shown in the output scale in figure 3–16 with an assumed 6 VDC being dropped across R_L.

By injecting a signal into the emitter-base junction of figure 3–17—assuming that the first half-cycle is positive going and the second half-cycle is negative going—the emitter, which is negative with respect to the base, becomes less negative. In other words, the positive-going input signal opposes the negative bias voltage. With a reduction in forward bias, the emitter current decreases, resulting in a reduction of the collector current. Since the collector current decreases, the voltage drop across R_L decreases. We said that the collector voltage, V_c, is equal to the battery voltage, V_{CC}, minus the voltage drop across R_L. Thus, since the voltage drop across R_L decreases, the collector becomes more positive. Therefore, as the input signal varies through its positive half-cycle, the output signal developed at the collector also varies through a positive half-cycle.

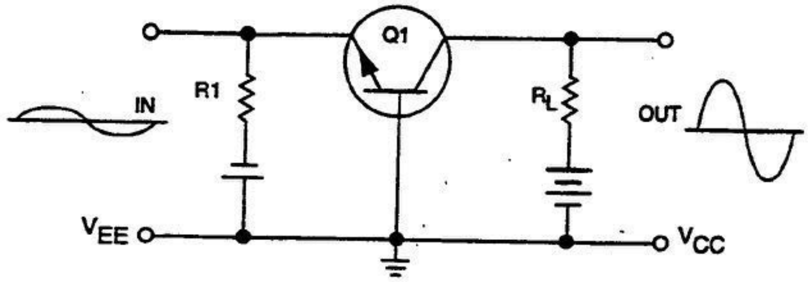


Figure 3–17. Signal voltage.

When the input signal goes through its negative half-cycle, the emitter becomes more negative with respect to the base. This reaction causes the forward bias to increase, the emitter current to increase, the collector current to increase, and the voltage drop across R_L to increase. Since the voltage drop across R_L opposes the positive potential of V_{CC}, the collector goes more negative (less positive). The conclusions drawn from this discussion are that in the common-base amplifier, the input and output voltages are in phase.

The operation of a PNP-type common-base amplifier is an almost identical process as just discussed, except that the battery connections and direction of current flow are reversed.

Usually, you see common-base amplifier configurations as shown in figure 3–18. Capacitor C_c serves to isolate the DC reference bias of the transistor circuit from the input circuit and vice versa. R1 is a bias resistor and, in conjunction with battery V_{EE}, establishes the proper forward bias for the emitter-base junction. Resistor R_L is the load resistor, and, in conjunction with battery V_{CC}, establishes the proper reverse bias for the base-collector junction. In some cases, you find another coupling capacitor in the output circuit of an amplifier. It serves to isolate the DC reference voltage from the next stage and vice versa.

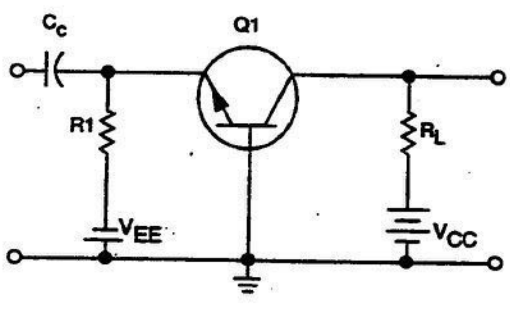


Figure 3–18. DC reference bias isolation.

Common-base amplifiers have a very low input impedance (resistance) of from 30 to 160 ohms and a very high output impedance of 300 to 500 kilohms. Since approximately the same current flows in the emitter and collector circuits, a very high load resistance can be placed in the collector output circuit to produce a considerable voltage gain. Actually, voltage gains up to 1500 are not unusual in this circuit arrangement.

As was shown in figure 3–16, the collector current is less than the emitter current (92 to 98 percent). Therefore, the current gain of this circuit is less than unity; that is, less than one.

Power gain is considered moderate and may go up to 1,000 times. A common-base amplifier is used in many high-frequency applications because of its good frequency response (good fidelity or ability to reproduce an exact input signal at the output). Since virtually the same current flows in both the emitter and collector circuits, a transistor is not subject to a condition called thermal runaway. This makes the thermal stability very good.

Common emitter. Figure 3–19 shows the widely used common (grounded) emitter circuit configuration. The input is applied between the base and emitter and the output is taken from the collector to emitter. Thus, in this circuit, the emitter is common to both the input and output circuits.

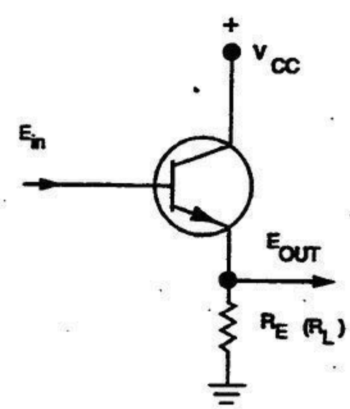


Figure 3–19. Common-emitter circuit.

Using figure 3–19, trace a signal through the amplifier circuit assuming that the input is on a positive alternation. The bias polarity is in the forward, low-resistance direction for the EB junction. As the input signal goes positive, the effective emitter-base voltage (forward bias) increases. This increase in forward bias decreases the emitter-base junction resistance. As the junction resistance decreases, the collector current through R_L increases. The voltage drop across R_L also increases, making the collector side of R_L less positive, and, therefore, negative going.

When the input signal goes negative, forward bias decreases. This decrease in forward bias increases the emitter-base junction resistance. As a result, the collector current through R_L decreases, making the collector side of R_L less negative and, therefore, positive going. From the above discussion of signal flow, you can see that input and output signals are 180° out of phase.

A common-emitter amplifier provides very high power gains of up to 10,000 times. Can you see why the CE configuration is termed "widely used"? The common-emitter circuit does, though, have the disadvantages of low-frequency response and poor thermal stability with respect to the other two amplifier configurations.

Common collector. A third configuration, the common-collector circuit, is unique since voltage amplification does *not* take place. This configuration has a voltage gain of less than one.

The reason for the low-voltage gain of a common-collector configuration can easily be explained with the aid of figure 3–20. The input signal is represented by an AC generator. The AC input voltage is impressed across the resistor. Since R_G parallels the transistor emitter-base junction and the emitter resistor R_L, the input voltage is also felt across emitter-base resistance in series with R_L. The input circuit is in parallel with the resistances provided by the emitter-base junction and the load resistor. Figure 3–21 shows an equivalent circuit.

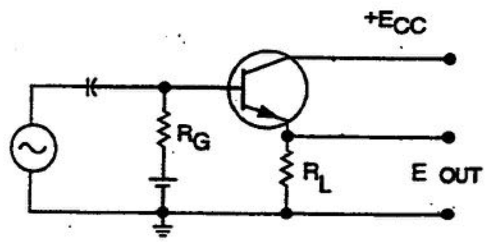


Figure 3–20. Common-collector.

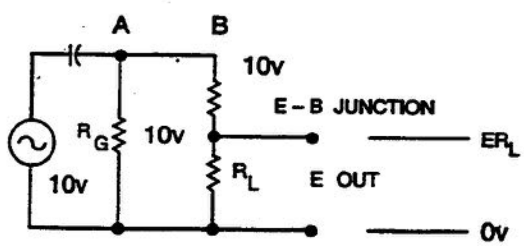


Figure 3–21. CC equivalent circuit.

In the figure, the input voltage of 10 volts is also the voltage at points A and B (voltage is the same across parallel branches). Since the emitter-base junction is in series with the load resistor, the entire 10 volts cannot be dropped across the load resistor. The output voltage is taken across the load resistor and must be less than the input. Since the output cannot be equal to the input, it cannot be unity and must be less than one.

Figure 3–22 shows a typical common-collector circuit. The circuit appears to be very similar to the common-emitter configuration. A capacitor is placed parallel to the battery which places the collector at AC ground because it acts as an AC short. The input is applied between the base and ground. Since the collector is at AC ground, the input is actually applied between the base and collector. The output is from emitter to ground, across the emitter resistor. Remember that the collector is at AC ground.

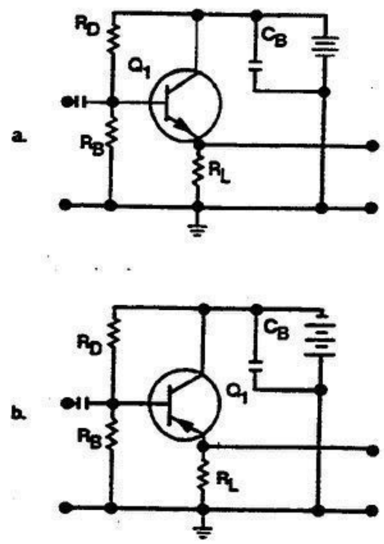


Figure 3–22. Common-collector (NPN and PNP) circuit.

As the positive half-cycle appears at the input, the forward bias increases which causes an increase in circuit current. This, in turn, creates an increase in voltage across the emitter resistor. The negative half of the input causes a decrease in bias, a decrease in current, and a decrease in output voltage. You can see from the previous discussion that the input and output signals are in phase. The emitter follows the base.

As in the common-emitter configurations, the quiescent, or DC reference voltage output, of an NPN common collector is positive; and for a PNP, the DC reference voltage is negative.

A study of the two configurations of figure 3–22 shows you why this is true. The emitter of the NPN common collector is connected to ground as is the negative terminal of the battery. The output is taken between ground and the top of R_L, which, of course, is the load resistor. Since the output is taken above ground, the output is positive with respect to ground.

In the PNP common-collector, the positive battery terminal connects to ground. The output is taken from a point below ground potential and the DC reference voltage is accordingly negative with respect to ground.

The battery bypass capacitor, C_B, places the collector at AC ground. R_D establishes the base-collector bias. Base-emitter bias is established by the R_D - R_B voltage divider. A negative to positive bias exists at the base due to the voltage drop across the emitter-base junction. The top of R_B and the base are at the same potential. R_B also has two other purposes: it provides a degree of stabilization and develops the input signal. Stabilization is achieved by R_B providing a leak-off path for minority carriers. R_L is the output resistor and develops the output signal.

We stated earlier that the common collector was not actually a voltage amplifier. Usually, it is used to match the impedance of two different types of circuits.

Applications. Because the three basic configurations have different characteristics, each is utilized in only those applications that take advantage of its characteristics.

The common-base configuration is not generally used in circuitry where power gain is a primary consideration because it always produces a current gain less than unity and because of the tremendous difference in its input and output resistances. The only practical way to couple common base (CB) stages together is with transformers. Otherwise, there is such a mismatch between the high-resistance output of one stage and the low-resistance input of the next that it is unprofitable to cascade stages. CB configurations are used often in high-frequency amplifiers, oscillators, and switches because of their high cutoff frequency. The CB arrangement also is applicable in circuitry subjected to abnormal changes in ambient temperature because of its excellent thermal stability. Finally, CB stages are useful for impedance-matching high-resistance circuits to low-resistance circuits.

The common-emitter configuration is used primarily in voltage or power amplifier circuitry. This makes the CE circuit prevalent in about 90 percent of all transistor circuit applications. This configuration also exhibits the closest match between input and output resistance, which permits cascading stages (connecting the output of a first stage to the input of the next stage) with all conventional types of coupling. Offsetting these advantages are the low cutoff frequencies and poor thermal stability. Although these deficiencies can be reduced to some extent by proper circuit design, they invariably lower the effectiveness of all CE configurations.

The common-collector configuration is largely used as an isolation stage and impedance matching of high- to low-impedance circuits. Because of the loss in the input circuit caused by the emitter load resistor, it can accept relatively large input signals and deliver distortion-free output signals. It delivers a less-than-unity voltage gain and has a moderate frequency response usage. Its use in impedance matching is primarily due to the power gain that can be obtained.

Figure 3–23 contains a complete listing of comparisons between the three configurations. You should be able to justify each of the characteristics listed in the chart.

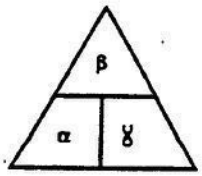
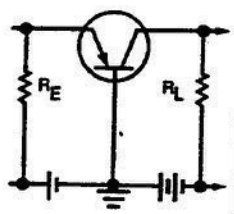
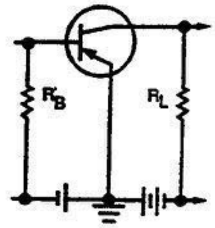
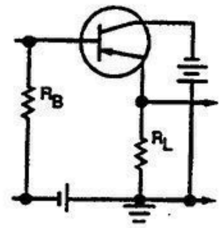
	 COMMON BASE	 COMMON EMITTER	 COMMON COLLECTOR
CURRENT AMPLIFICATION FACTOR	$\alpha = \frac{\Delta I_C}{\Delta I_E}$ VCB = K	$\beta = \frac{\Delta I_C}{\Delta I_B}$ VCE = K	$\gamma = \frac{\Delta I_E}{\Delta I_B}$ VEC = K
INPUT IMPEDANCE	LOW (30 - 150Ω) r_{ib}	MODERATE (500 - 1500Ω) r_{ie}	HIGH (20K - 500KΩ) r_{ic}
OUTPUT IMPEDANCE	HIGH (300K - 500KΩ) r_{ob}	MODERATE (30K - 50KΩ) r_{oe}	LOW (50 - 1KΩ) r_{oc}
VOLTAGE GAIN $\frac{V\ OUT}{V\ IN}$	HIGH (500 - 1500) AVB	MODERATE-HIGH (300 - 1000) AVE	LOW LESS THAN ONE AVC
CURRENT GAIN $\frac{I\ OUT}{I\ IN}$	LOW (.90 - .99) LESS THAN ONE	MODERATE-HIGH (10 - 150)	MODERATE-HIGH (10 - 150)
POWER GAIN $\frac{P\ OUT}{P\ IN}$	MODERATE (1000) APB	HIGH (10,000) APE	LOW-MODERATE (100) APC
PHASE RELATIONSHIP	OUTPUT AND INPUT VOLTAGE IN PHASE	OUTPUT AND INPUT VOLTAGE 180° OUT-OF-PHASE	OUTPUT AND INPUT VOLTAGE IN PHASE EMITTER FOLLOWS BASE
FREQUENCY RESPONSE	HIGH (50KC - 1MC)	LOW (5KC - 50KC)	MODERATE (20KC - 500KC)
THERMAL STABILITY	GOOD (1)	POOR (10)	FAIR (100 - 5)

Figure 3–23. Comparison of configurations.

036. What are the gain characteristics of amplifiers?

The basic purpose of a transistor circuit is to amplify current, voltage, or power. In the previous section, you learned that the three basic amplifier configurations yielded current or voltage gains in varying amounts. These gains can be calculated using a chart (which is published by the manufacturer) of the particular transistor being used in the circuit. These charts are called static characteristic curves and are similar to the common-emitter (CE) NPN chart shown in figure 3–24. The curves plot collector current against collector voltage with the base current at a fixed value. The horizontal axis in the figure represents the output voltage, V_{CE} (the collector-emitter voltage). The vertical axis represents the collector current, I_C. The curves on the chart represent various input currents, I_B (the base current in a CE amplifier).

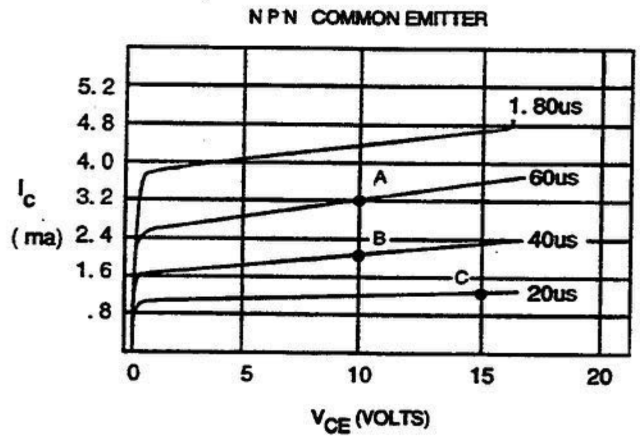


Figure 3–24. CD (NPN) characteristic curves.

Gain versus load. The load impedance of an amplifier is usually resistive throughout most of its operating range. As is the case with all amplifiers, gain is a function of load. The plots in figure 3–25 are representative of the curves of gain for the three transistor configurations we have been discussing. Noteworthy are the following facts:

a. The *highest current gains* (A_I) are obtained for low values of load resistance. (Common-emitter and common-collector amplifiers yield substantial current gains. For a common-base amplifier, it is always less than one.)

b. The *highest voltage gains* (A_V) are obtained for high values of load resistance. (Common-base and common-emitter amplifiers produce appreciable voltage gains. For a common-collector amplifier, it is always less than one.)

c. The *highest power gain* occurs when the product of the current voltage gain is greatest. Since the common-emitter amplifier has both high current gains and high voltage gains, its power gain is necessarily the highest.

A study of the curves in figure 3–25 gives you an appreciation of the advantages offered by each configuration. Notice in figure 3–26 that the input impedance is also a function of load impedance. This is expected since we know that the input is not independent of the output for transistor amplifiers. Note how greatly the input resistance of the common-collector amplifier varies with load resistance. Obviously, then, the load is an important factor in amplifier operation.

Load lines. The effects of load upon gain can be readily shown by load lines. From load lines, gains can be visualized and computed. Moreover, load lines reveal the limits of operation, the extent of nonlinear (amplitude) distortion, and the class of operation for the amplifiers they represent. Aside from their usefulness for design purposes, they contribute much to the understanding of amplifier performance.

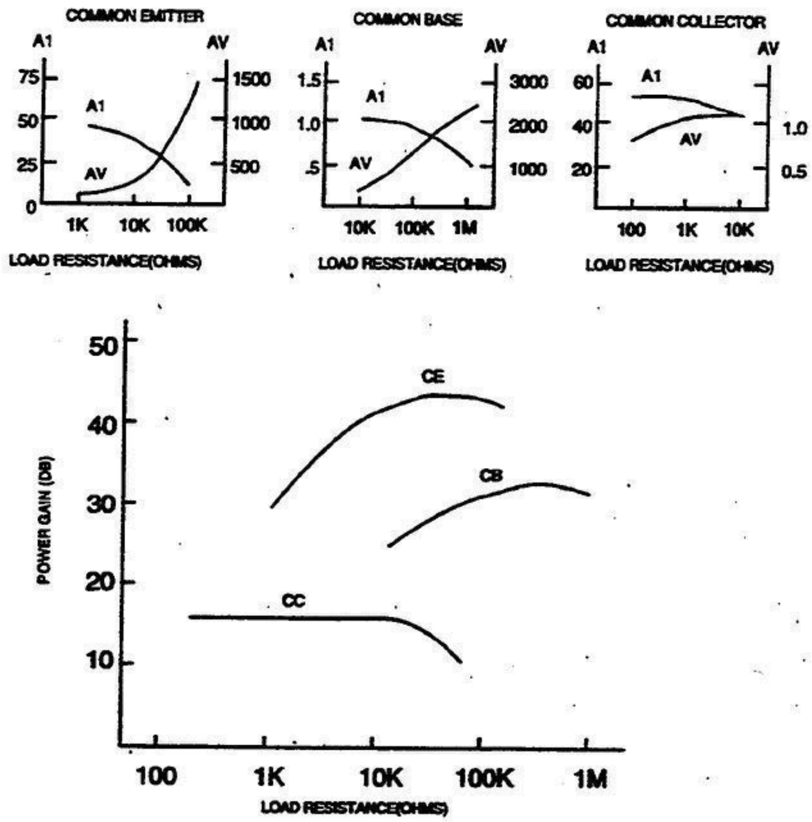


Figure 3–25. Gain versus load resistance curves.

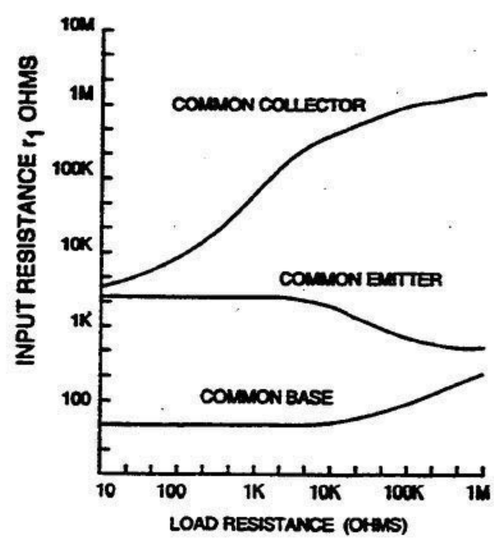


Figure 3–26. Input resistance versus load resistance curves.

What is a load line? Quite simply, a load line is a plot of current versus voltage from a no-load (zero current) to a full-load (maximum current) condition for a specific load impedance (fig. 3–27, A).

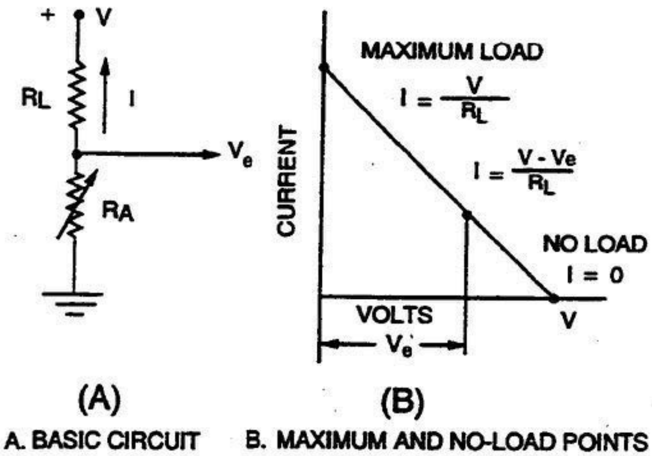


Figure 3–27. Load-line plot.

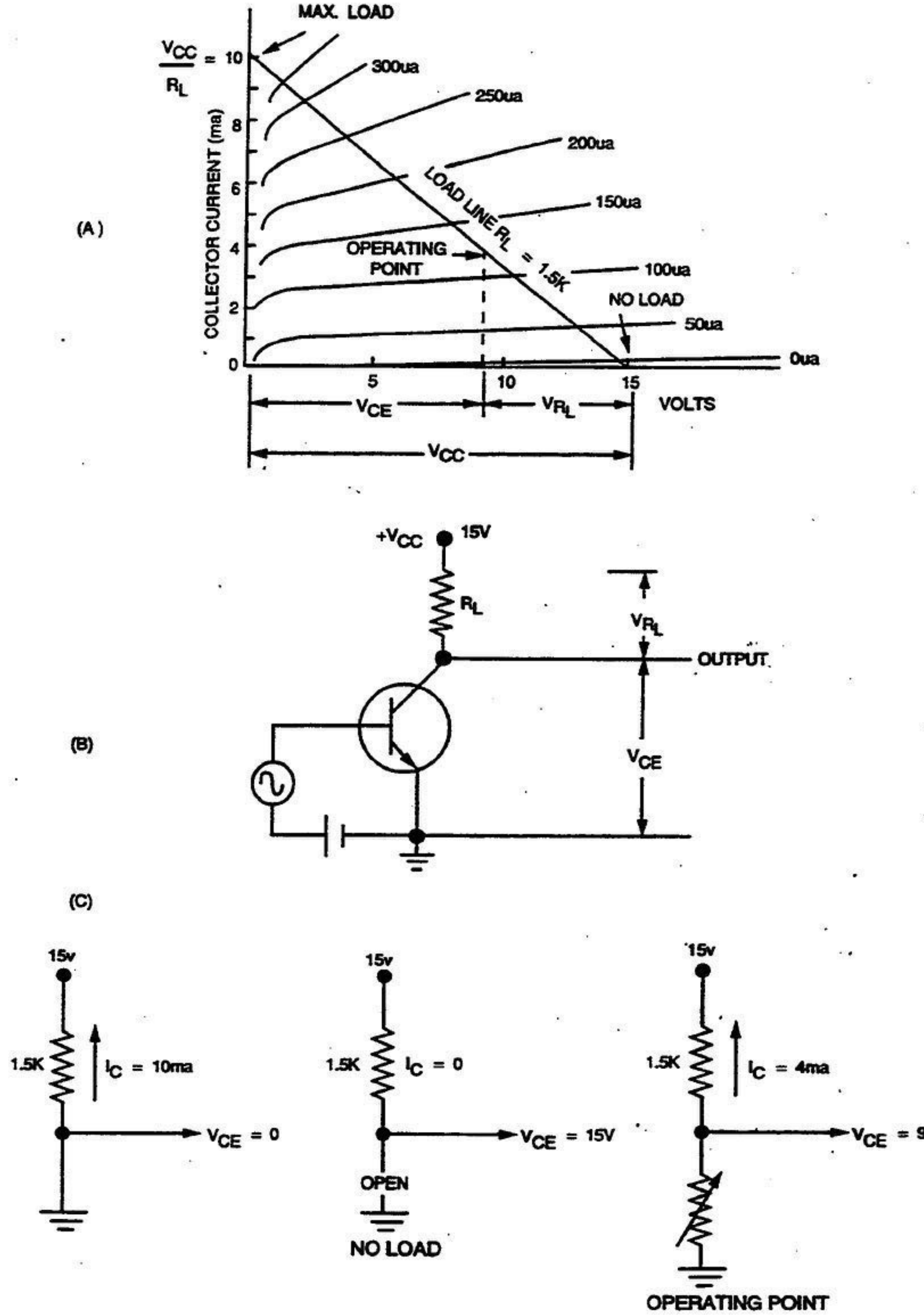
The load resistance is R_L. Assuming that R_A can be varied from a zero resistance (short-circuited state) to an infinite resistance (open-circuit state), the load current (I) goes from a maximum value, V_{RL} (full-load condition), to zero (no-load condition). Since R_L is a linear impedance of fixed value, any load between no-load and full-load necessarily lies on a straight line connecting these two conditions (fig. 3–27, B). The circuit behaves as a voltage divider and can be analyzed accordingly. Load current (I) varies directly with the voltage ($V - V_O$) across R_L in accordance with Ohm's law.

In figure 3–28, A; the load line is drawn for the common-emitter characteristic curves of a transistor. This gives us a load-line diagram for the circuit in figure 3–28, B. V_{CC} is the DC voltage applied.

Maximum load is obtained by considering the transistor short-circuited (fig. 3–28, C). No-load (zero current) is obtained by considering the transistor open-circuited (cut off). If the transistor is biased so that I = 125 microamps, the operating point is established on the load line as shown in figure 3–28, A. From the same diagram, the values of V_{CC} and I_C are read to be 9V and 4 mA, respectively, at the operating point (fig. 3–28, C).

In this brief discussion, we have sought to bring out the useful aspects of load-line diagrams in illustrating transistor amplifier gain with respect to input, output, and bias conditions. When characteristic curves and load lines are available for a particular application of transistor amplifiers, a great deal can be learned about their behavior and output. Two things we can learn about them are:

- Gain is readily determined for resistance loads.
- Operational limits and bias conditions can be quickly determined.



A. CHARACTERISTIC CURVE LOAD-LINE PLOT B. BASIC CIRCUIT C. CIRCUIT CONDITIONS AT SIGNIFICANT POINTS

Figure 3–28. Load line for transistor amplifier (common-emitter configuration).

037. The four basic frequency sensitive filters

It is often necessary to eliminate or suppress frequencies that are unnecessary or that hinder the transmission of a particular message. For example, in the output of a balanced-bridge modulator, although there are many frequency components, transmission of only one component is desired. The frequencies that are eliminated or suppressed are said to be attenuated. A circuit that gives a higher loss to some frequencies than to others is called an electrical filter, or, more commonly, simply a filter. There are four types of filters: low-pass, high-pass, band-pass, and band-reject.

Since losses within filters vary with frequency, filters that are specifically designed to cause loss to certain frequencies must consist of elements (inductors, capacitors, etc.) that have impedance values that vary with frequency. Combinations of inductive and capacitive reactances fulfill this requirement. Recall that the formula for inductive reactance, $X_L = 2\pi fL$, shows that as frequency increases so does inductive reactance, which causes a greater opposition to the flow of alternating current. The formula for capacitive reactance, $X_C = 1/2\pi fC$, shows that as frequency increases, capacitive reactance decreases. This causes a smaller opposition to the flow of an alternating current. It is these two factors that determine the arrangement of the various elements of the four frequency sensitive filters.

Low-pass filters. A *low-pass* filter permits the passage of frequencies from zero up to a predetermined frequency, but attenuates all others. Figure 3–29 shows the frequency characteristic of a low-pass filter. Attenuation (loss) is plotted vertically, and frequency is plotted horizontally. The *pass region* (from zero to the cutoff frequency, f_C) is the range of frequencies for which there is no attenuation. Actually, the attenuation in the pass region is not zero, but rather a small, negligible amount. The cutoff frequency, f_C, is the frequency at which the attenuation starts to increase rapidly. The *attenuation region* (from the cutoff frequency to infinite frequencies) is the range of frequencies for which the attenuation is appreciable.

High-pass filters. A *high-pass* filter permits the passage of frequencies from a predetermined frequency (not zero) up to infinite frequencies, but attenuates all others. Figure 3–30 shows the frequency characteristics of a high-pass filter. Attenuation is plotted vertically and frequency is plotted horizontally. The attenuation region is from zero to the cutoff frequency, f_C; the pass region is from the cutoff frequency to infinite frequencies. As with a low-pass filter, the attenuation in the pass region is not actually zero, but a small, negligible amount.

Band-pass filters. A *band-pass* filter permits the passage of a band of frequencies lying between two predetermined frequencies, but attenuates all others. To obtain a pass region between two frequencies, neither of which is zero or infinite, use is made of a low-pass filter in cascade (series) with a high-pass filter. Figure 3–31 shows the desired pass band (pass region) of a band-pass filter. Attenuation is

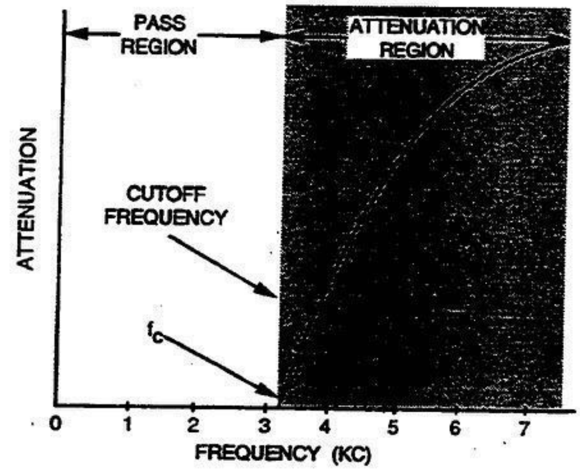


Figure 3–29. Low-pass filter characteristics.

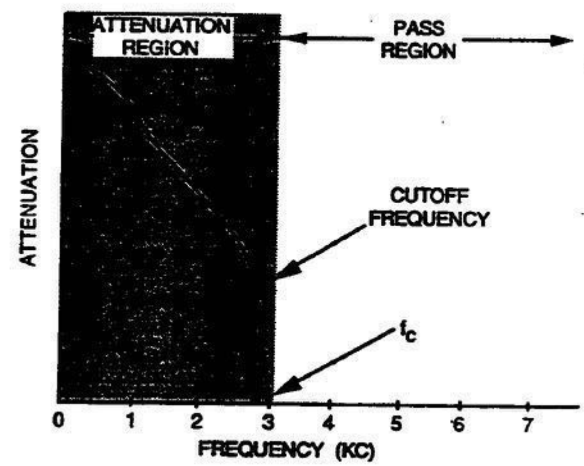


Figure 3–30. High-pass filter characteristics.

plotted vertically and frequency is plotted horizontally. The two attenuation regions are separated by the pass band. One attenuation region ranges from zero to the cutoff frequency, f_1; the pass band lies between cutoff frequencies f_1 and f_2; and the other attenuation region ranges from cutoff frequency f_2 to infinite frequencies.

To obtain this result, a low-pass and high-pass filter, which have overlapping cutoff frequencies, are arranged in cascade; that is, the cutoff frequency of the low-pass filter is greater than that of the high-pass filter. Only the range of frequencies between the two cutoff frequencies is in the pass region of both filters. All other frequencies are in the attenuation region of either the low-pass or the high-pass filter. As with low- and high-pass filters, the attenuation in the pass region is not actually zero, but rather a small, negligible amount.

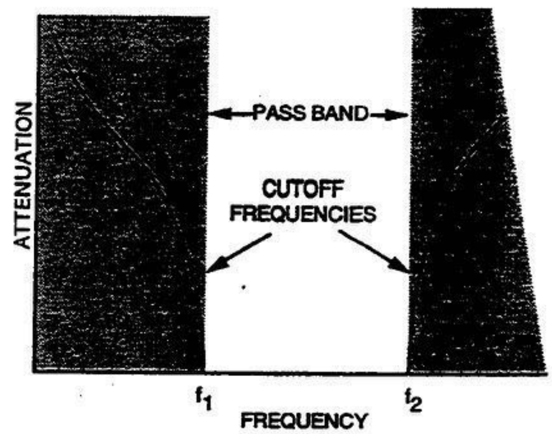


Figure 3–31. Band-pass filter characteristics.

Band-reject filters. A *band-reject* filter attenuates all frequencies within a specified band, but passes all frequencies above or below that band. The cutoff frequencies in figure 3–32 (f_1 and f_2) represent the attenuation region for a band-reject filter. If we assume that it is desired to reject all frequencies from 3,000 to 6,000 Hz, this would be the frequency range represented by f_1 and f_2. Band-reject filters are often referred to as band-stop, band-elimination, or wave-trap filters.

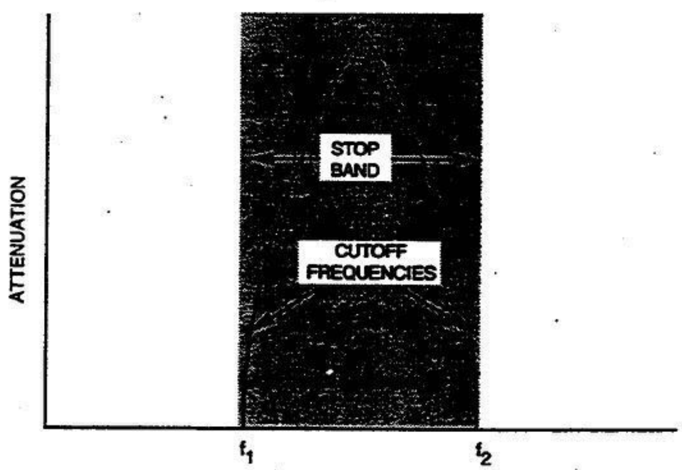


Figure 3–32. Band-reject filter characteristics.

It should be apparent from our discussion on low-pass, high-pass, band-pass, and band-reject filters that these simple filters greatly enhance the capabilities of communications and test equipment. As a Systems Controller, you find different variations of these filters engineered into the communications circuitry with which you work. Study their design characteristics carefully. It is easy to tell if they are performing the task they are supposed to through the daily diagnostics that apply to your Technical Control Facility (TCF).

Self-Test Questions

After you complete these questions, you may check your answers at the end of the unit.

035. The three basic amplifier configurations

1. In which amplifier is the input applied to the emitter and the output taken from the collector?

2. In a CB amplifier, are the output and input in phase or out of phase with each other?

3. Which type of amplifier has a very low input impedance, a very high output impedance, and a current gain less than unity?

4. Does a CB amplifier have a current gain greater than or less than unity?

5. For what type frequency applications is a CB amplifier used mainly?

6. What can be said about the frequency response and thermal stability characteristics of a CB amplifier?

7. Which amplifier has a 180° phase shift between input and output signals?

8. Which type of amplifier provides very high power gains?

9. What type of thermal stability does a CE amplifier have?

10. What is the voltage gain for a CC amplifier?

11. Does a CC amplifier have a current gain greater or less than unity?

12. Are CC amplifier input and output signals in or out of phase?

13. What is the usual use for CC amplifiers?

036. What are the gain characteristics of amplifiers?

1. What is the basic purpose of transistor circuits?

2. Explain the purpose of static characteristic curves.

3. For a common-base amplifier, what is the numerical ratio for current gain?

4. Which transistor amplifier has the highest power gain?

5. Describe a load line.

6. In respect to what three conditions are load-line diagrams useful in illustrating transistor amplifier gain?

037. The four basic frequency sensitive filters

1. What is an electrical filter?

2. State the filtering characteristics of each of the following frequency sensitive filters.

   (a) Low-pass filter.

(b) High-pass filter.

(c) Band-pass filter.

(d) Band-reject filter.

Answers to Self-Test Questions

033

1. The junction barrier.
2. The depletion region.
3. Cathode to anode.
4. A transistor is an electronic device which transfers signal current from a low-resistance circuit.
5. PNP transistors have N-type material fused between two pieces of P-type material. NPN transistors have P-type material fused between two pieces of N-type material.
6. The type represented is a PNP transistor.
7. The type represented is a NPN transistor.
8. The emitter-base junction of a NPN transistor is always forward-biased.
9. The base-collector junction of a NPN transistor is always reverse-biased.
10. An increase in forward bias effects an increase in collector current and a decrease in forward bias effects a decrease in collector current.

034

1. A half-wave rectifier converts one alternation of an AC voltage into usable DC voltage.
2. A half-wave rectifier consists of fewer parts and costs less.
3. Half-wave rectifiers have poor voltage regulation when used with varying loads.
4. From the source through the resistor to the ground.
5. One is conducting; two is reverse biased.
6. Bridge rectifier.
7. Two and four.

035

1. A common-base amplifier has its input applied to the emitter and its output taken from the collector.
2. The input and output of common-base amplifiers are in phase.
3. Common-base amplifiers have these characteristics.
4. Common-base amplifiers have current gains less than unity.
5. Common-base amplifiers are mainly used in high frequency applications.

6. High-frequency response and good thermal stability.
7. Common-emmiter amplifiers have input and output signals which are 180° out of phase.
8. Common-emitter amplifiers provide power gains up to 10,000 times.
9. Common-collector amplifiers have poor thermal stability.
10. Common-collector amplifiers have voltage gains of less than one.
11. Common-collector amplifiers have current gains of less than unity.
12. Common-collector amplifier's input and output signals are in phase.
13. Common-collector amplifiers are usually used for circuit impedance matching purposes.

036

1. The basic purpose of transistor circuits is to amplify current, voltage, or power.
2. Static characteristic curves are used to calculate gain values for transistors.
3. The numerical ratio for current gain for a common-base amplifier is less than one.
4. Common-emitter amplifiers have the highest power gain.
5. A load line is a graphic plot of current versus voltage for a specific load on a transistor.
6. Load-line diagrams are useful in illustrating transistor amplifier gain with respect to input, output, and bias.

037

1. A circuit that attenuates some frequencies more than others is called an electrical filter.
2. (a) Passes frequencies from zero up to a predetermined frequency and attenuates all those above that frequency.

   (b) Passes frequencies from a predetermined frequency up to infinite frequencies and attenuates all those below that predetermined frequency.

   (c) Passes frequencies in a predetermined band and attenuates all those above and below that band.

   (d) Attenuates all frequencies in a predetermined band and passes all those above and below that band.

Unit Review Exercises

Note to Student: Consider all choices carefully, select the *best* answer to each question, and *circle* the corresponding letter. When you have completed all unit review exercises, transfer your answers to ECI Form 34, Field Scoring Answer Sheet.

Do not return your answer sheet to ECI.

73. (033) Electrons in a forward-biased diode move from the
   a. cathode to the anode.
   b. anode to the cathode.
   c. cathode to ground.
   d. anode to ground.

74. (033) Current flow through a transistor is determined by the
   a. current flow into the collector.
   b. bias applied to each PN junction.
   c. voltage at the emitter-base junction.
   d. resistance of the emitter-base junction.

75. (034) A power rectifier that operates on the principle of converting one alternation of an AC voltage to DC voltage is the
   a. full-wave rectifier.
   b. half-wave rectifier.
   c. Zener diode rectifier.
   d. full-wave bridge rectifier.

76. (034) The output voltage polarity of a bridge rectifier may be reversed by
   a. changing the input polarity.
   b. reversing the transformer leads.
   c. reversing all diode connections.
   d. reversing half the diode connections.

77. (035) For what type of frequency application are common-base amplifiers *mainly* used?
   a. Low.
   b. Moderate.
   c. High.
   d. Frequencies less than 5 kHz.

78. (036) The gain, limit of operation, and class of operation for a transistor amplifier can *best* be shown by using
    a. a load-line chart.
    b. an amplitude vs. frequency chart.
    c. an input vs. output voltage graph.
    d. an input vs. output resistance graph.

79. (037) Which frequency sensitive filter is used to pass frequencies from zero to a predetermined point and attenuate all others?
    a. Low-pass.
    b. High-pass.
    c. Bandpass.
    d. Band reject.

80. (037) Which frequency sensitive filter attenuates all frequencies above and below a given frequency band?
    a. Low-pass.
    b. High-pass.
    c. Band-pass.
    d. Band-reject.

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No.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
1.0	.0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
1.1	.0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
1.2	.0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
1.3	.1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
1.4	.1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
1.5	.1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
1.6	.2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
1.7	.2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
1.8	.2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
1.9	.2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
2.0	.3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
2.1	.3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
2.2	.3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
2.3	.3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
2.4	.3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
2.5	.3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
2.6	.4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
2.7	.4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
2.8	.4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
2.9	.4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
3.0	.4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
3.1	.4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
3.2	.5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
3.3	.5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
3.4	.5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
3.5	.5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
3.6	.5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
3.7	.5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
3.8	.5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
3.9	.5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
4.0	.6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
4.1	.6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
4.2	.6232	6243	6253	6263	6274	6234	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
4.3	.6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
4.4	.6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
4.5	.6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
4.6	.6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
4.7	.6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
4.8	.6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
4.9	.6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
5.0	.6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
5.1	.7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
5.2	.7100	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
5.3	.7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
5.4	.7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7

No.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
5.5	.7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
5.6	.7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
5.7	.7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
5.8	.7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
5.9	.7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
6.0	.7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
6.1	.7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
6.2	.7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
6.3	.7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
6.4	.8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
6.5	.8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
6.6	.8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
6.7	.8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
6.8	.8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
6.9	.8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
7.0	.8451	8457	8463	8470	8476	8482	8436	8494	8500	8506	1	1	2	2	3	4	4	5	6
7.1	.8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
7.2	.8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
7.3	.8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
7.4	.8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
7.5	.8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
7.6	.8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
7.7	.8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
7.8	.8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
7.9	.8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
8.0	.9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
8.1	.9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
8.2	.9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
8.3	.9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
8.4	.9243	9248	9253	[illegible]	[illegible]	9269	9274	9279	9284	9289	1	1	2	2	3	3	[illegible]	[illegible]	[illegible]
8.5	.9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
8.6	.9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
8.7	.9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
8.8	.9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
8.9	.9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
9.0	.9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
9.1	.9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
9.2	.9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
9.3	.9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
9.4	.9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
9.5	.9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
9.6	.9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
9.7	.9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
9.8	.9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
9.9	.9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

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Foldout 1. Table of common logarithms.

THE TABLE

• The Logarithm table is broken down into columns and additional parts of the basic number. Under the column designated "No." we would find the two digit number for which the mantissa is required. As in the case of 1.9, the mantissa would be read under the column designated "0." This means that there is only one significant digit to the right of the decimal poin .

- Let us assume that we have a number such as 1.95 for which the mantissa is required. To find the mantissa, we would find 1.9 under the column "No.," then move to the right across the table until we arrive at the column under the large "5." This would produce the mantissa .2900 for the number 1.95. The first 9 columns, under the heading numbers 1 thru 9, are for numbers which have three significant digits. In our example we would find the mantissa for 1.91 through 1.99 in these columns corresponding to the line 1.9 under the "No" column.

- If our number has a fourth significant digit for which the mantissa is required, the means difference table would be used to determine the complete mantissa. The last 9 columns of the log table are the means difference table. Since there is not enough room to write the entire mantissa, only the difference is given. This difference should be added to the mantissa given for the three significant digit number.

- As in our previous example, let us assume the number for which the mantissa is required is 1.955 as opposed to 1.95. This would require us to determine the mantissa for 1.95 as we did above. Then, look under the column in the means difference section which is numbered correspondingly to our fourth significant digit. In this case, 1.95 and 5. The means difference is 11, and should be added to the mantissa given for 1.95 or .2900.

This would be, .2900 + .0011 = 2911
Therefore the mantissa for 1.955 = .2911
Although not indicated, all means differences are added to the right most numbers of the mantissa given for the three digit number.
For example, the mantissa for 1.95 is .2900 and not 2900.
In adding the means difference, you would add as follows,

$$\begin{array}{r} .2900 \\ \underline{11} \\ .2911 \end{array}$$

The 11 is assumed to be .0011 when adding.
In the case of single number means differences such as 1, 2, 3, 4, . . . 9, it is assumed that these numbers are preceded by three zeros.
For example, if the means difference in the column = 4, it is assumed to be .0004, and so on.

• Review of Material. Let us briefly review what we have covered.

- The log is the exponent which indicates the power a base number must be raised to 9 to equal the number which the log represents.

- The log consists of a characteristic (whole part) and a mantissa (fractional part).

- The value of a characteristic is determined through inspection of the number for which the log is required. It is positive and one less than the total number of significant digits to the left of the decimal point for numbers greater than 1. It is negative and one more than the number of zeros immediately to the right of the decimal point for numbers less than one. For numbers between 1 and 9 it is zero.

- The mantissa is the fractional part of the log, and is derived through higher mathematical processes involving the series and distribution of numbers. Mantissas are normally derived for numbers from 1.000 through 9.999 for the base number used in the log system and the results are compiled in a Table of Logarithms.

- The log to the base 10 is written log $_{10}$, but in practice the 10 is understood, thus generally it is written, log *n*.

- Tables of Logarithms are constructed in different ways. Most tables provide only the mantissas of logs for numbers from 1.0 through 9.9. Other tables are constructed to provide the characteristic and mantissa for numbers running as high as 9999. Log tables can be obtained that enable us to determine the mantissa of the log with an accuracy of from four significant digits to ten significant digits. In the electronics communications field, four place or four digit accuracy is more than adequate. An example of a four and ten digit mantissa is given below.

Mantissa for log 5 = .6990 to four places, and,
Mantissa for log 5 = .6989700041 to ten places.

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Foldout 2. How to find logarithms.

FINDING LOGs

NOTE: For numbers which are not exact powers of ten, the common log will consist of two parts, an integral part (whole number) called the characteristic, and a decimal part (fractional) called the mantissa. These are addressed below.

1. Characteristic. The characteristic of a common log is determined by inspection of the number for which the log is desired. Two rules may be used to determine the characteristic as follows:

- Rule I: The characteristic of a log of a number greater than 1 is positive and is one less than the number of digits to the left of the decimal point. For example, the characteristic of the following numbers are,

555.5 = 2
55.55 = 1
5.555 = 0, and so on

- Rule II: The characteristic of a log of a number less than 1 is negative, and is equal to one more than the number of zeros immediately to the right of the decimal point. For example, the characteristic of the following numbers are,

0.5555 = -1
0.0555 = -2
0.0055 = -3, and so on.

2. The Mantissa. As previously stated, the mantissa is the fractional or decimal part of the log. In nearly all practical numbers encountered when using logs, we will be required to use the mantissa.

- The mantissa is derived through the use of higher mathmatical processes for the base number in question. It would serve no purpose to discuss these processes here, other than to say that their results are compiled into a Table of Logarithms. The table which accompanies this foldout is one of them, giving mantissa for numbers from 1.000 through 9.999. The characteristic is not given, as it is determined through inspection of the number, as stated above.

- The mantissa for a number is the same regardless of the number of significant digits to the right or left of the decimal point.

For example, the mantissa for the following numbers is the same,

550000. = .7404
550.00 = .7404
55.000 = .7404
5.5 = .7404, and so on.

In the above examples, only the characteristic would change.

- Mantissas can also be derived using a log-log, or deci-log slide rule, or many of the current state-of-the-art scientific electronic calculators. Techniques and procedures for obtaining the common log mantissa are provided in the user instructions when purchasing these devices.

- The most common method for obtaining the mantissa is using the Table of Common Logs. As previously discussed, these tables are derived through higher mathematical processes that are of no concern to this discussion. They vary in construction and provide from four to ten significant digits in the mantissa. The most common table used is a four-place table, which gives the mantissa to four significant digits. The number for which the log is desired should first be converted to its scientific notation expressed as a power of 10. In the case of 1900, this would be expressed in scientific notation as 1.9×10^3. The 1.9 would then be the number for which the mantissa would be found in the log table. 10^3 automatically tells you that the characteristic is 3. Using the table, we find that the mantissa for 1.9 is .2788. Therefore, the common log of 1900 would be 3.2788, or

log 1900 = 3.2788, (since $\log_{10}$ is understood).

BACKGROUND

Invention of the logarithm is attributed to a Scottish mathematician, John Napier, who published the first table of natural logarithms in the year 1614. These logarithms or logs, were eventually named after their inventor. Other great philosophers and mathematicians of that era also contributed greatly to the development and use of logs. Henry Briggs published the first table of Common Logs in 1624. Other significant contributions were made by Burgi and the distinguished Karl Gauss. Initially looked upon as the "toy" of the mathematician and astronomer, the log has taken on an important role in our scientific and engineering endeavors. Technicians should have a working knowledge of their use, and how they are applied to terms in the communications field.

THE BASE

1. The Base. The Logarithm is the exponent to which a fixed number (the base) must be raised to equal a given number.

For example, the quantity $3^2 = 9$, the exponent 2 is called the logarithm of 9 to the base 3. Further, $2^2 = 4$. Here the exponent 2 is called the logarithm of 4 to the base 2. The logarithmic relationships outlined in the two examples above would normally be written, $\log_3 9 = 2$, and $\log_2 4 = 2$.

- Any positive number greater than 1 can be used as the base. The development of logarithms briefly outlined above has resulted in the selection of two numbers which are used as bases. The Napierian or Natural log uses the number 2.718281828 as the base, ano best describes mathematical functions to which it applies. The Briggsian logarithm or Common Log uses 10 as the base number and finds better applicability to those electronic terms used in the communications field. Expressions for voltage, current, power gains and losses, or referenced measurements use Common Logs. The log to the base 10 is generally called the Common Logarithm.

- The base which the log is calculated to is written in the form of a subscript to the lower right of the term "log." For the base 10 or common log, it would be written,

$$\log_{10}$$

- In the Natural system of logs, the Greek letter epsilon (ε) has been used to identify the log to the base 2.718281828, or,

$$\log_{\varepsilon}$$

2. Common Log. In the Common system of logs, the base 10 subscript is usually omitted when written. For example, log 100 = 2 is assumed to be $\log_{10} 100 = 2$.

X	0.0001	0.001	0.01	0.1	1	10	100	1000	10000
log X	-4	-3	-2	-1	0	1	2	3	4

Partial Table of Logs to Base 10

- As previously stated, the log is the exponent to which the base number must be raised to equal the number which the log is to represent.

- In the table above, we find that the common log for 1000 is 3. This means that the base number 10 must be raised to the third power to equal 1000. By the same token, the common log of 0.001 is -3. This means that the base number 10 must be raised to the -3 power to equal the number 0.001 and so on.

- The above table of common logs is more than adequate as long as we deal with exact powers of ten.

TABLE OF LOGARITHMS
(FOUR-PLACE MANTISSAS)

No.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3638	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	[illegible]	11	12	14	[illegible]
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7100	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7
No.	0	1	2	3	4	5	6	7	8	9									

No.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	2	3	[illegible]	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4
No.	0	1	2	3	4	5	6	7	8	9									

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Foldout 3. Table of logarithms (four-place mantissas).

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