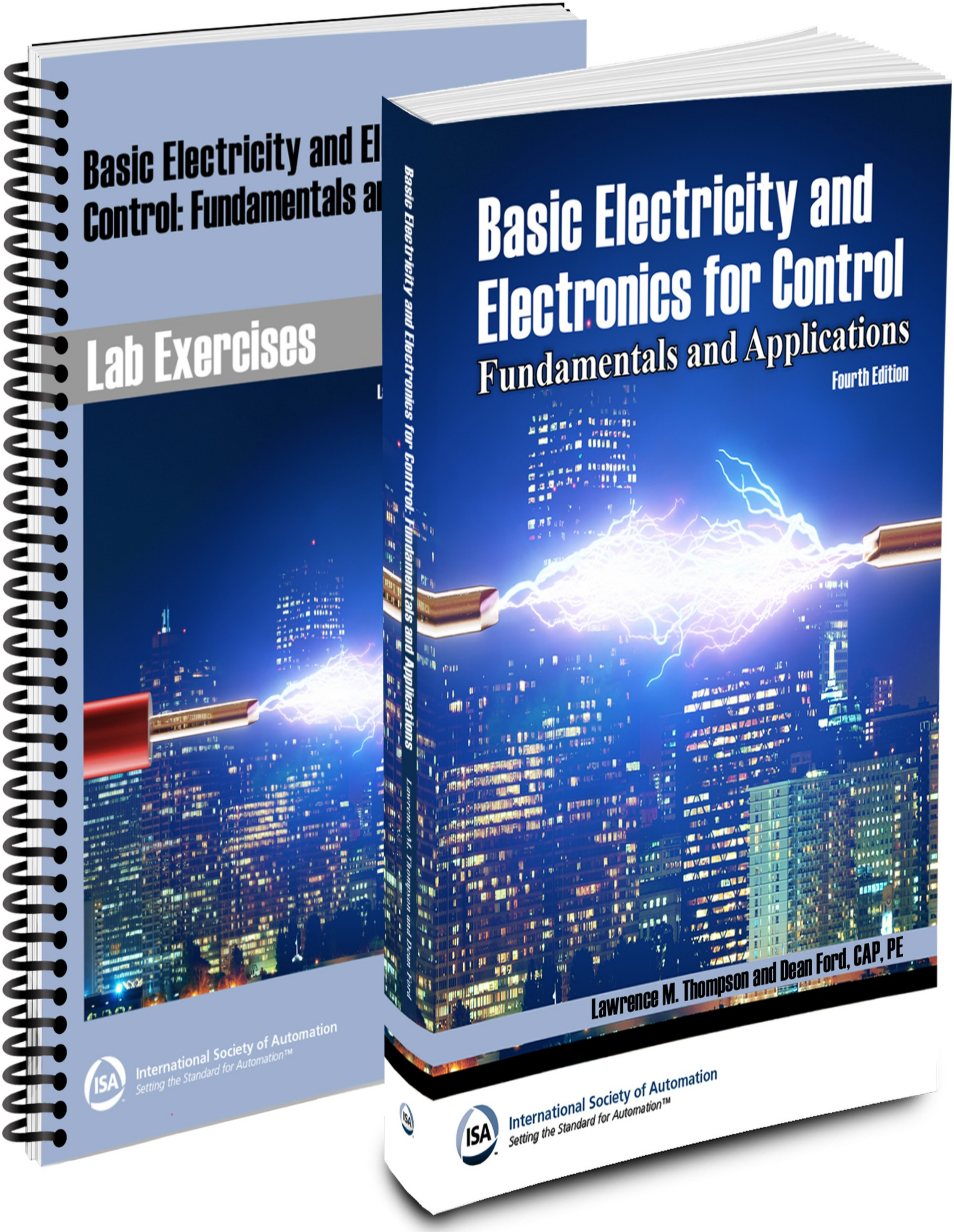
Basic Electricity and
Control: Fundamentals
Lab Exercises
International Society of Automation
Setting the Standard for Automation™
Basic Electricity and Electronics for Control
Fundamentals and Applications
Fourth Edition
Basic Electricity and Electronics for Control: Fundamentals and Applications
Lawrence M. Thompson and Dean Ford
Lawrence M. Thompson and Dean Ford, CAP, PE
ISA
International Society of Automation
Setting the Standard for Automation™

Basic Electricity and Electronics for Control

Fundamentals and Applications

Fourth Edition

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Lawrence M. Thompson
Dean Ford, CAP, PE

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In January 2020, ISA and the world of automation and control lost a passionate and dedicated innovator, educator, and author, as well as a funny, kind, and caring man of great faith. Larry Thompson was dedicated to helping others succeed and expanding the profession. Larry's legacy will continue as those he taught share their knowledge with the next generation of automation professionals, and the books he authored continue to be essential resources.

Contents

A Note from Larry Thompson

This text started out many years ago as a lab-based text, one of the first such published by the International Society of Automation (ISA)—titled *Basic Electrical Measurements and Calibration*—in 1978, nearly 45 years ago. Many things in the electrical/electronics industry have changed since the first edition was published.

In the years following publication, digital instrumentation has become affordable, widespread, and has almost totally displaced analog devices in automation. While analog instruments have not completely disappeared, they are no longer the technology of choice for current automation installations. With the plethora of commercial, affordable, and readily available large-scale integrated circuits, ubiquitous microprocessors, and memory, digital devices have become the low maintenance and easy-to-use form of industrial equipment currently used in measurement and control.

In order to be effective in teaching the simple basics of electricity and electronics, it became apparent that while the text has undergone two previous revisions, the amended text would have to be further revised to remain current. While this has been accomplished in this edition, the focus is no longer on calibration but on learning the basics of electricity and electronics from a behavior-oriented perspective using (supplied) generic labs, which required an information and text configuration change to reflect the book's purpose and intent more accurately. All of the test procedures and generic overviews required updating, in view of the fact that many of the maintenance philosophies, procedures, and test equipment have dramatically changed since that first book was written.

As before, the text is easy to read and behavior-based, and it makes use of repeatable observations. As there is a multitude of equipment that could be used to successfully accomplish lab exercises to reinforce the text, it is left to the reader to select his or her choice based on their reading of the text, and the availability and affordability of the equipment. A good place to start is with the lab exercise equipment lists included in the Lab Workbook.

It was necessary to completely revise most chapters to make relevant the discussion of basic electrics, measurements, reactive devices, analog/digital conversions, and contemporary circuitry. In the end, this revision (the fourth) became a somewhat different work. Sadly, some material from the original had to be left out due to irrelevance to modern settings.

As stated before, this is basically a behavior-based text, *not a design-oriented or math-based course*, and it references equipment and circuitry found in most industrial and commercial facilities. It is intended as a primer for technical and nontechnical people interested in the electronic and measurement areas. The examples used in the text attempt to approximate "real-life" applications rather than prove a text-based passage. This text is applicable to the vocational, industrial, and occupational areas.

In most places, this text is not rigorously mathematical; in some areas where precision in mathematics is necessary, those points are elaborated upon. Where technical sophistication exists, as opposed to ease of understanding, understanding prevails. This is *not an engineering text*, but a basic and practical course in electrics and electronics. It is not intended as a substitute for a technical education nor is it a pre-engineering text.

For proper use and good practice, and to ensure the reader's ability to work safely, a prior knowledge of standard workplace safety procedures and techniques is required. A rudimentary knowledge of measurements and experience in the proper use of typical test equipment will be of great benefit when reading this text.

I hope this new version will be as enthusiastically accepted as a teaching tool and learning medium as the previous editions, as it is designed to give readers a significant background in topics needed for most technical occupations.

Lawrence (Larry) M. Thompson Sr.
CAP (Certified Automation Professional)
January 2020

Acknowledgments

The book was originally dedicated to my wife, Gavina, for sharing her time with me so that work on the book could proceed in a timely manner; the work on this revision has the same compelling sharing of the time resource. Additionally, I would like to acknowledge the many people who helped this version come to fruition; various reviewers who pointed me in the right direction and those involved in the production process—particularly Liegh Elrod—for their patience and ability to change my writing into some semblance of prose.

About the Authors

Lawrence M. Thompson

Lawrence (Larry) M. Thompson was the owner and general manager of ESdat Co. (Electronic Systems: development and training company), a consulting firm specializing in industrial data communications. Throughout his distinguished career, Thompson served as a technician, technical trainer, and course developer in electronics, measurement/control, and computer networking. A 20-year veteran of the US Air Force, Thompson specialized in maintaining electronic encryption equipment during his service. His post-military industrial experience included positions as a technician, test engineer, and test engineering supervisor for numerous companies.

Thompson held a bachelor's degree in applied arts and science from Tarleton State University and worked on a master's degree in computer science at the University of Texas. He retired from his role as Department Chair for E-Commerce Technology at Texas State Technical College to run his own consulting business full time. He served as an adjunct instructor for the International Society of Automation (ISA) for more than 35 years. He wrote several books, including ISA's *Industrial Data Communications* and *Basic Electrics/Electronics for Control*, and was a Certified Automation Professional (CAP).

Dean Ford

Dean Ford, CAP, PE, is the Managing Principal Engineer at Luminary Automation and Engineering, LLC, a firm he cofounded. His entire 25-plus year career has involved automation systems engineering and consulting. Initially stumbling into the profession via a co-op opportunity at Anheuser-Busch in 1994, he fell in love with the automation. The ability to see how things are made and learn the science and processes behind automation energize him.

Ford develops and leads a dedicated and passionate staff of automation professionals. He is a licensed Control Systems Engineer in 24 states and a Certified Automation Professional (CAP). Ford is a senior member of the International Society of Automation (ISA), and he participates in many industry standards committees. He is an active member of many industry groups including the American Water Works Association (AWWA), Water Environment Federation (WEF), and Smart Water Networks Forum

(SWAN). He serves on the Government Relations and Workforce Development committees for the Automation Federation, educating the public and policy makers about the critical role automation plays in the future. Ford also serves as the chair of the AWWA Water Utility Technology and Automation Committee (WUTAC).

Ford's current mission is to build a diverse and revolutionary automation and engineering firm that treats people as assets and enables them to succeed. He educates utility and manufacturing clients to take advantage of their investments in technology and to evolve their thinking toward automation as being a long-term investment. Applying lessons and experience from private industry to the public sector, Ford brings a unique perspective to utility operations and automation users.

He holds a BS in electrical engineering from the Missouri University of Science and Technology and an Executive MBA from the Robert H. Smith School of Business at the University of Maryland. He is a passionate and lifelong learner, always looking to learn something new and apply it to the real world.

Ford was presented with the opportunity to continue the legacy of Larry Thompson's work after Thompson passed in 2020. He is honored to continue the work Thompson started and to continue teaching automation professionals the foundational skills required to make them well-rounded automation professionals.

A Note from Dean Ford

It has been a pleasure developing this content for automation professionals who are just beginning their careers and experienced professionals who want to gain a deeper understanding of how the tools of our trade work under the hood. It is the authors' belief that to be a well-rounded automation professional, one must have a basic knowledge of how electricity flows through the devices we use and what makes programs and human-machine interface (HMI) devices interact with physical devices in the field.

The automation profession is unique. We use computers and programming to make devices do things. We connect the digital world to the physical world, unlike any other profession. It is a powerful responsibility we must take seriously. Without an understanding of how devices work under the hood, incorrect devices can be applied or correct devices can be misconfigured. These relatively simple situations can cause catastrophic failures leading to property damage, lost production, wasted resources, or even the loss of life.

In the pages of this book and the companion lab workbook, we hope to provide the reader with a foundational understanding of how and why the physical devices we use work the way they do. To accomplish this, we must educate the reader on the basic physics of electricity and electronics: why does a transistor perform the way it does, how do magnets work, and so on. In many of these cases, we must educate the reader on some foundational principles before we can explain how a device works. For example, to understand how an analog-to-digital converter functions, one must first understand how transistors and amplifiers work, as well as number systems such as binary and hexadecimal.

In today's world in which one has the ability to instantly find a video or tutorial on just about anything, this book provides a foundation that you can build on with the information you find and that enables you to apply what you learn to your profession. It is far too easy to rely on a vendor or the Internet to specify and purchase a device without the proper understanding of how it works and its correct application.We hope the information in this book assists you in understanding how to improve the process of specifying, applying, programing, and configuring these devices and the systems that use them.

How to Use this Book

Due to the complex nature of the topics in this book and how they build on each other, we think it best to take smaller chunks and master them before moving to the next module. Because we learn better with practice, review questions and answers are included throughout the book, and the accompanying lab workbook contains hands-on exercises. We recommend having access to a lab or the equipment and materials outlined in the lab workbook to best learn the concepts.

Note

Multiplication Symbol

Depending on your background, the use of this symbol may not be familiar. It is common practice in engineering and scientific fields to use a dot to represent multiplication. For example:

$5 \times 6 = 30$ will typically be represented as $5 \bullet 6 = 30$.

Prologue

This introductory course on electricity and electronics provides the expected behaviors but not the design concepts. If this course has provided all you ever wanted to know about the subject, that is fantastic. If this course has caused you to question one facet or another more deeply, or the whole subject, we recommend completing more comprehensive courses in mathematics and electrical engineering. The original author worked and learned in this area for more than 40 years and continued to learn new ideas, concepts, and applications throughout his career. The science and natural laws form the foundations of electricity and don't change over time, but the applications certainly do. The foundations presented in this book are a set of rules and behaviors that, given a certain set of conditions and a certain device, determine the result. If during your work, you don't get the same result, it will not have been due to a sudden change in the laws of physics. It is important to look inward and review the material and connections to find the error in your setup. Larry Thompson (the original author) wished you a continuing success in your endeavors with electricity and electronics.

With the honor of continuing his work, Dean Ford has attempted to modernize the content, accounting for the applications most control engineers experience today. His goal was to provide updated material that today's automation professionals can learn from to become stronger and more prepared resources who make better decisions in their day-to-day jobs.

We welcome your feedback. If you feel that a section of this book could be presented in a clearer manner, if you think a topic (or topics) has been omitted that should be included, and/or if you found information that you think should not be included in the book, please contact the International Society of Automation (ISA, info@isa.org).

Introduction

This text is concerned with electrical measurement practices. It is assumed that the reader is either acquainted with or wishes to become acquainted with the basics of electricity. Even if the reader has previous knowledge, there is a wide variance among readers in the depth of understanding, length of time since studies (if any) of electrical phenomena, and how well the basic electrical facts were absorbed.

To make this text as useful to as wide a variety of readers as possible on the plethora of devices presently employed to access information (PCs, tablets, phones, etc.), it is broken into modules. The information in each module is explained from a practical point of view (intuitive learning), and the corresponding lab exercises in the accompanying *Lab Workbook* are devoted to hands-on learning. The intention of this book is to discuss design and troubleshooting at the technical level and tasks of a more practical nature. Each learning module employs a limited use of mathematics (mostly arithmetic) in the explanations. However, the exercises in the *Lab Workbook* are designed to be learn-by-experience, practical applications. One may learn through the practical approach or the formal approach, or some combination of both; it only matters that learning takes place.

Because electricity cannot be seen and there are different and increasingly complex explanations for electrical phenomena, the text will look only at electrical behavior and use simple descriptions and mathematical models.

The equipment required for each exercise in the *Lab Workbook*, and the specifications for that equipment, is listed at the beginning of the exercise. The equipment may be purchased from the reader's preferred source.

1
Electrical Basics

This module discusses the basics of electrical current flow and the laws governing the relationship between potential measured in voltage, resistance measured in ohms, and the resulting energy transfer called *current* measured in amperes (colloquially, *amps)*.

Module 1: Objectives

After successfully completing this module, you will be able to:

- Demonstrate that there must be a potential difference for work to be done (or cu flow).
- Determine if there is a complete path to and from the source for current to flow.
- Define and determine the three most commonly measured electrical values: volts and ohms.
- Learn how to convert very large and very small numbers into a significant form.
- Explain Kirchhoff's first and second laws and Ohm's law, and solve circui problems requiring knowledge of those laws.
- Determine total resistance values for series and parallel circuits.

Module 1A: Energy

Simply stated, for any work to be performed, there must be sufficient energy to accomplish the work. What is energy? Physics tells us that work is described as "force through a distance." An electric current can transfer energy; that is, the "source" of energy can be physically separated from the point where the work is to be performed. An electric current will transfer energy from the *source* (where the energy is located) to accomplish work at the *load*. The energy in an electric current will perform the work as well as transfer the energy from some distance.

But how do we define *electrical energy*?

Potential

For there to be energy for work to be performed, there must be a difference in the levels of energy at the point where the work is to be performed. This is a commonsense or an intuitive concept. Water will not flow unless the source water is at a higher level. In fact, the water analogy was the first to be used for electric concepts.

If there is no water in the tower, then there will be no water pressure. The height of a water column determines the pressure exerted at the bottom of the column. In the case of Figure 1-1, this pressure causes a flow of water through the water wheel. The pressure at the bottom of the drain is the lowest pressure in the system. Energy has been transferred from the water tower through the water wheel because of the difference in pressure between the water tower and at the drain. This is the first of a series of important observations: *If there is no pressure difference, there is no energy to be transferred or transformed*. Because of the difference in energy, fluid will flow in the piping, operate the water wheel, and exhaust at the drain. *The pressure difference itself did not power the water wheel; the flow did. But there would be no flow without the difference in pressure*. Pressure itself is *potential* energy. *Pressure* is defined as force over an area (e.g., pounds per square inch). Potential energy does not perform work but has the potential to perform work. When a fluid is in motion, some of the pressure is transformed into *kinetic* energy. Kinetic energy is force in motion. It does the work; it is the *force acting through a distance*. Because the discoverers of electricity could not see current and could not conceive of it, they merely observed and recorded its behavior. For an intuitive (as opposed to mathematical) explanation, we will perform the same procedure.

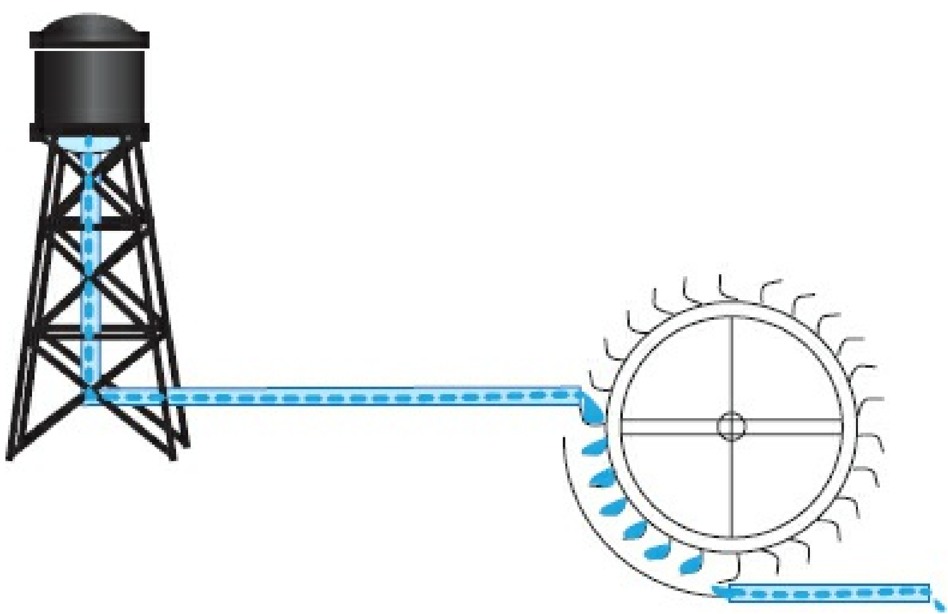

Figure 1-1. Water tower, wheel, and drain.

Charge and Current

Because the early discoverers of electricity could not visualize it, they equated it to water flow. They called electrical flow *current*. Not terribly original, but it gets the point across. If there is no electrical pressure difference, there will be no electric current flow. An electric current performs the work. Although there are many explanations of how current flow is constituted, the concept we will use is that an electrical current is “a movement of charge.” There are two (and only two) types of charges: *negative* and *positive.* (Although studies in quantum behavior indicate partial charges might exist, this text reflects classic physics.) Whether an item has a net negative or net positive charge depends on who is observing it and what their net charge might be. Figure 1-2 illustrates this fact.

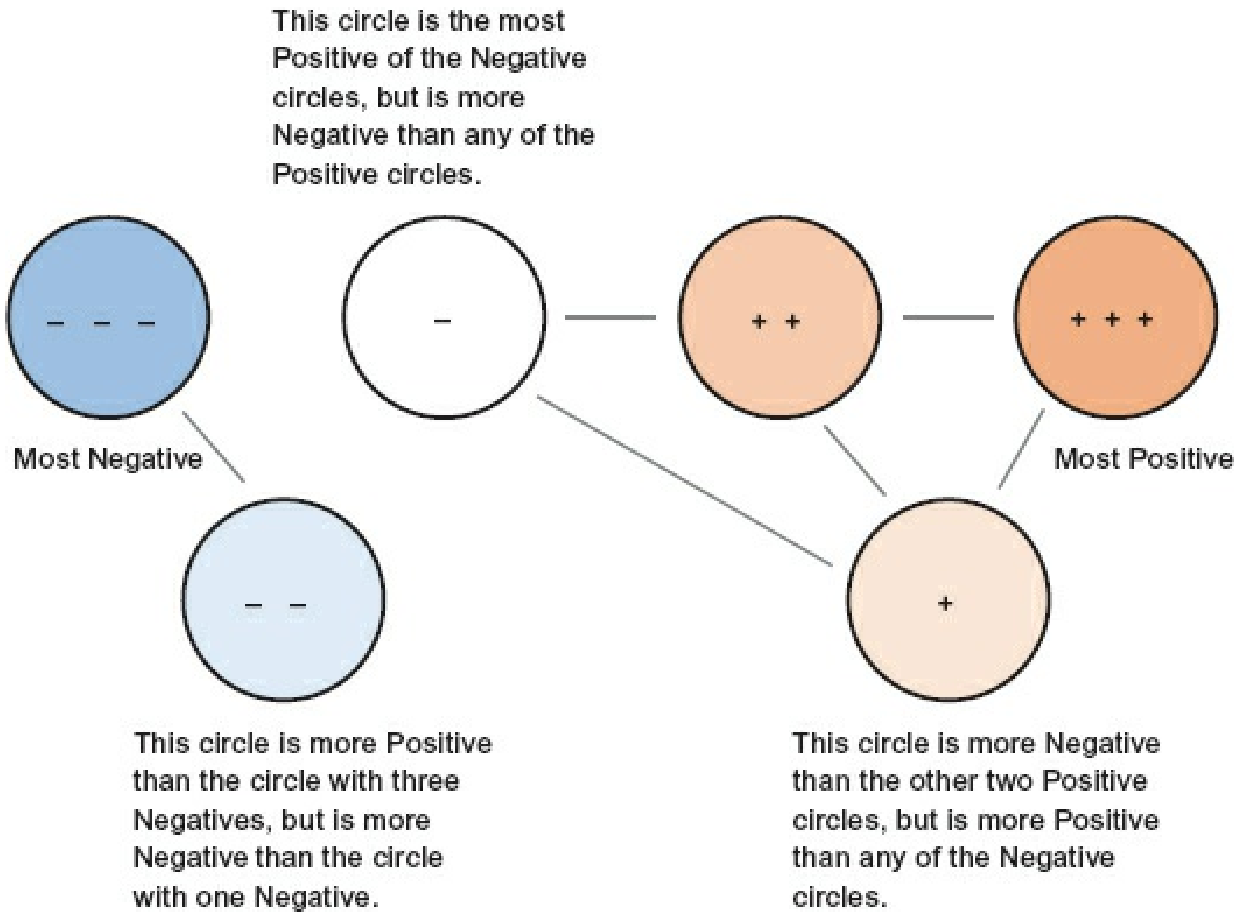

Figure 1-2. Difference in charge.

In Figure 1-2, it is easy to see that the circles with the negatives and positives will have a difference in charge between them, and that if you observe a negative circle from any positive circle, it is indeed negative. Similarly, if you observe positive circles from any negative one, they are indeed positive. But what about observing from the more and less positive circles? If you use the less positive circle as your reference, then the one with more positives will be positive. However, if you observe the less positive circle using a more positive circle as your reference, it will appear to be negative. But they are both positive, right? The observation that both are positive could only come from an independent observer, one with a different (and presumably more negative) reference relative to the two positive objects. *All charge is relative*. This point is critical to remember throughout measurement. You must establish a *reference* or *zero point*. Although the reference might appear to be charged when observed from an independent location, the reference is our measurement's zero, so we may only determine the charge differences relative to our reference.

Complete Path

For an electrical current to flow, there must be a complete path from the point of high pressure to the point of low pressure. This concept is different from the water tower analogy, yet it is still easy to grasp. To conduct electricity, conductors are used. These are the pipes in the water tower analogy. *Conductors* are made of materials that easily pass electrical charges. *Insulators* are made of materials that do not easily conduct electricity. Conductors, such as wires, are usually made of metals like copper or aluminum. Insulators are made of materials such as rubber, plastic, and some ceramics. Insulated wires (the most common kind) have an insulator wrapped around the wire to keep the charges from contacting the environment. Kirchhoff[1] stated that "no more charge could leave a point than arrived at that point," meaning that for a circuit to work, it must return a charge to the source for every charge the source emits into the circuit. This means there must be a complete circuit from the source's negative lead to the source's positive lead, that is, a complete path. Figure 1-3 illustrates a complete conductive path. Note that the charge emitted by the negative post returning to the positive post must also be performed internally in the battery from the positive post to the negative post to have a complete path. In lead acid batteries, this process is performed by the chemical interaction between the electrolyte and the lead plate.

The source develops the electric pressure or potential (difference in charge). This source could be a battery, a generator, or any method of generating a difference in charge. Again, this difference in charge is known as *potential* or, more formally, *electromotive force* (E). It is the electrical pressure that will cause current to flow in the conductors (drawn as connecting lines in Figure 1-3). There must be a conductive path from the negative side, through the load, to the positive side of the source. If there is no conductive path, there will be no way to equalize the difference in charge, and nothing to relate one terminal to the other. If you are at the positive terminal and measure the difference along the conductor to the positive end of the load, there will be no difference in charge. (*Note:* This may not be precisely true depending on the measuring equipment, as explained in later sections, but for our purposes at this time, any difference will not be significant.) The same can be said for the negative terminal of the source through the conductor to the negative terminal of the load. Notice in Figure 1-3 that the entire battery potential is across the load as the conductors extend the battery connections to the load.

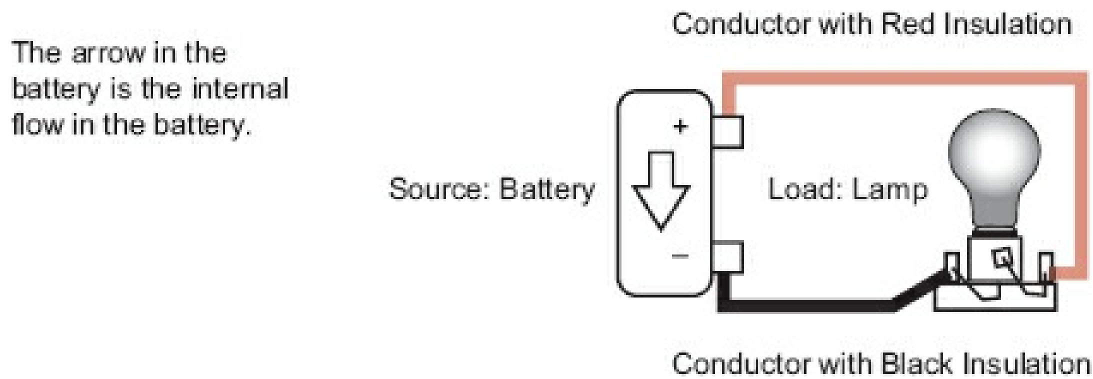

Figure 1-3. The complete conductive path.

Now the potential can force work to be done. Whatever the load is (heating a resistance, turning a motor, lighting a lamp, etc.), energy will be used. This is work. There is one hard-and-fast rule for energy: “there is no free lunch.” In other words, moving, heating, cooling, or changing something in any way generally involves work, and the energy to perform that work must be provided.

Module 1A: Summary 1

- For work to be performed, there must be the energy difference available to perfo work. For an electric current to flow, there first must be a potential differenc electromotive force.
- Electromotive force can move charges through conductors.
- Conductors pass charges easily; insulators do not.
- For a potential to cause an electric current, there must be a complete conducti between the negative (cathode) and positive (anode) terminals of the source of er

Electrical Units

The big picture has been discussed, so now some of the fine details must be explained. Standard units of measurement are used so that independent measurements can be related and have the same meaning. Three of these units will be used throughout electrical measurement: the *volt*, a measure of the electrical pressure; the *amp* (ampere), a measure of electrical current; and the *ohm*, a measure of electrical resistance. The following terms are also important and are the foundation of electric energy.

Joule

The basic unit of energy is the *joule* (J). This is a very small unit of energy; several hundred thousand joules are required to operate an incandescent lamp for over an hour or so. Note that the energy required to do work and the amount of work performed are one and the same. If it takes 250,000 J / h to power an incandescent lamp, then the energy required was 250,000 J / h and the work performed was 250,000 J / h. If all this energy was converted to light, the lamp would be 100% efficient. It is not, however, so the total energy required is the work required to light the lamp plus the work wasted (usually as heat).

Coulomb

The basic unit of electrical charge is the *coulomb* (C). A coulomb is defined as a number of electrons. The electron is an entity that has one negative charge, the smallest amount of charge measurable. For our purposes, this amount of charge is indivisible; there are no half electron charges. A coulomb is the amount of charge represented by 6,250,000,000,000,000,000 electrons. While this may seem large, it is not because electrons and their charges are quite small.

Charge: A Formal Definition

Charge (Q) is measured in coulombs. Stated in arithmetic, for example, if Q = 15 C, the amount of charge is 15 coulombs.

Current: A Formal Definition

The actual electrical flow (movement of charges) is defined as 1 C past a point in 1 s and is called an *ampere* (named after André-Marie Ampère). Contemporary usage has shortened that term to *amp*. The symbol for current is I, which stands for *intensity of electrical current*. Current is measured in amperes (A). Stated arithmetically, if I = 5 A, the current is 5 A. It is important to note that *time* has become one of the variables. Amperes are stated in coulombs per second. So, it could be stated arithmetically: I = Q/time, where Q is charge in coulombs and time is in seconds.

Electromotive Force: A Formal Definition

The pressure that causes current to flow is called *electromotive force* (E), which is measured in volts (V, named after Alessandro Volta). Because we must determine (by use of the volt) the amount of "potential" energy in a difference of charge, the terms already used will suffice. The joule is the basic unit of energy, the coulomb is the basic unit of charge, and because electrical pressure is the energy in a difference of charge, it may be stated arithmetically as:

$$V = \text{energy (in joules)} / \text{charge (in coulombs)}$$

Or in words: A 10 V battery means that each coulomb of charge provides 10 J of energy (or work). By rearranging the relationship to show work (or energy), it becomes:

$$\text{work} = \text{volts (V)} \bullet \text{charge}$$

Watts

Because we use the joule as the basic unit of energy, joules per second is an appropriate measure of the energy required of an electrical current. Joules per second are known as *watts* (W, named after James Watt). A watt is a measure of power. Arithmetically stated:

$$P \text{ (power)} = \text{energy (work)} / \text{time (seconds)}$$

If we combine our previous work, I is Q (charge in coulombs) per second, and E (symbol E, measured in volts) = work / charge or work / Q. Therefore:

$$V = J / Q$$

$$I \text{ (amps)} = Q / \text{seconds}$$

$$W \text{ (power)} = J / Q \bullet Q / \text{seconds or } W \text{ (power)} = \text{joules/second}$$

All this means that power in an electrical circuit is determined by:

$$W = E \text{ (volts)} \bullet I \text{ (amps)}$$

Resistance

Charges go easily through conductors, but there is some opposition. When it comes to insulators, charges are presented with a very large task, a great opposition, to flow through the material. The opposition to current flow is known as *resistance*. All conductors have resistance, and all insulators have resistance. The only substances that don't have resistance are superconductors, and they are not covered in this text. The ease with which a charge may pass energy in a conductor is called *conductance*. Resistance is its reciprocal. The unit of resistance is the ohm (Ω), named after Georg Ohm. In the past, the unit of conductance was called the *mho*. (There is no Georg Mho, but what is mho spelled backward? And you thought scientists didn't have a sense of humor.) Increasing global standardization has changed the measure of conductance; it is now measured in siemens (or micro siemens). A conductor has very few ohms of resistance, in many cases so few as to be negligible. A good insulator has millions of ohms of resistance. Therefore, a conductor has few ohms, an insulator has many. Consequently, a conductor will easily pass electrical current whereas an insulator will not.

Module 1A: Summary 2

- The three quantities most used in electrical measurements are
  - the volt (V), the unit of electrical pressure;
  - the amp (A), the unit of electrical current; and
  - the ohm (Ω), the unit of opposition to current flow.
- A path with very few ohms will easily pass electrical current.
- A path with many ohms will pass little electrical current.
- Power (as measured in watts) is equal to pressure (volts) times current (amps).

Be careful. If you follow these guidelines, you will avoid the majority of problems:

1. *Know* the potentials involved and where they are present, and know the e properties in question and how to measure them.

2. *Do not* allow your skin to contact any current-carrying conductor.

3. *Do not* attempt to measure high or unknown potentials unless you have rece appropriate training and have the appropriate safety equipment.

4. *Consider* any circuit as active unless you *personally* have *disconnected* the circuit' sources, tagged it as such, and locked it in a manner so that no one but you ma on again.

Other precautionary measures are explained throughout the text.

Remember that *you have the ultimate responsibility* to know what is on, what is off, what the potentials are, and what the safe procedures are. After all, *it is your life*.

Module 1A: Review 1

See Appendix B for the answers.

1. Who has the ultimate responsibility for *your* safety?

____

2. If you are given a voltmeter, can you assume this meter can safely measure ar potentials in your area?

____

3. Disrespect for electricity will eventually result in a(n) __________.

Electrical Units Continued

Volts, Amps, and Ohms

Recall that volts are the measure of the potential (electrical pressure) existing between two points, whereas amps are the measure of the amount of current (charge) that the potential can push through the resistance (measured in ohms) of a complete path for current flow. A circuit is one or more paths of current flow designed to accomplish a particular function.

Steady Voltage

If a potential is held steady (kept at the same value) for a complete path, a certain amount of current will flow. If the resistance in the path is increased (more ohms) and the pressure is the same, the current will decrease (less amps). Figure 1-4 illustrates a circuit (one complete path of current flow in this case).

Assume the source is 12.6 V (just like the battery in your car). Assume the load resistance is 12.6 Ω. The amount of current in the circuit is 1 A. If the source remains the same (12.6 V) and the resistance is increased (doubled) to 25.2 Ω, the current will be cut in half to ½ A. If the resistance is cut in half to 6.3 Ω, then with the source remaining steady (at 12.6 V), the current will increase to 2 A. To summarize:

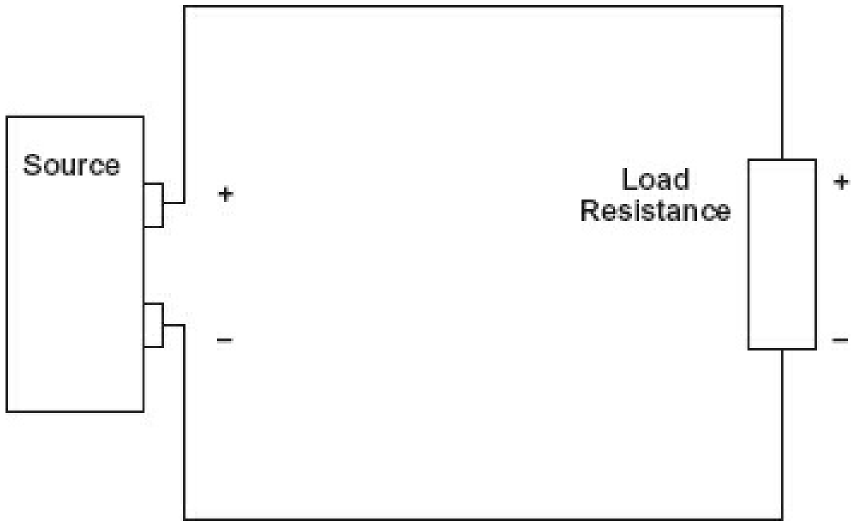

Figure 1-4. A complete circuit.

- If the voltage is held steady and the *circuit resistance increases*, the current in the decreases.
- If the voltage is held steady and the *circuit resistance decreases*, the current in the increases.

Ohm

An ohm is described as that resistance through which 1 V will push 1 A.

In circuits that pass large currents, there will be very few ohms, perhaps even fractional ohms. In those circuits where small currents are used (as is the case in most electronics), the resistance varies from a few ohms to many millions of ohms.

To make the volt, amp, and ohm usable (i.e., not too many zeros, and certainly not too many zeros after a decimal point), the following prefixes are used.

Unit Prefixes

In the electrical world, values range from the very, very large to the very, very small. To prevent us from making errors counting zeros before and after the decimal point, an easier and more exact method has been developed. The International System of Units (SI) uses a common and standard set of prefixes incorporating the decimal numbering system or the power of 10. Other names for this are Scientific Notation and Engineering Notation. This is a method by which we replace zeros with a power of 10 nomenclature. For example, one million (1,000,000) is represented as 1×10^6.

This method relies on the concept of significant digits. A *significant digit* is a number that holds some meaning other than a decimal placeholder like six zeros in a row. An entire chapter could be written on the methods used to identify significant digits and the scientific notation. Suffice it to say that we only need to concern ourselves with a basic knowledge of these prefixes and how to convert from one to another. We will also follow the norm of limiting the number of digits to four significant digits. Unit prefixes commonly used are listed in Table 1-1:

Table 1-1. Number prefixes.

Prefix	Power of 10	Symbol	Arithmetic
giga	$1 \cdot 10^{9}$	G	(1 • 1,000,000,000)
mega	$1 \cdot 10^{6}$	M	(1 • 1,000,000)
kilo	$1 \cdot 10^{3}$	k	(1 • 1000)
milli	$1 \cdot 10^{-3}$	m	(1 • 1/1000)
micro	$1 \cdot 10^{-6}$	μ	(1 • 1/1,000,000)
nano	$1 \cdot 10^{-9}$	n	(1 • 1/1,000,000,000)
pico	$1 \cdot 10^{-12}$	p	(1 • 1/1,000,000,000,000) (pico was formerly *micro-micro*)

Unit Conversions

The prefixes described above are nothing more than units. To convert from one unit to another, we follow a simple method called the factor-label method. It can be used to convert any unit into any other unit so long as they are the same unit type (length, volume, volts, amps, etc.). This method uses a fraction technique where the units are canceled out until the desired units remain. This is best described by actually doing it so let's convert 65 mph (miles per hour) to kph (kilometers per hour). First, we determine the number of meters in 1 mile (1 mile = 1609.344 meters), and we set that up as a fraction (1609.344 meters/1 mile). Next we set up the factors and cancel out the units we don't want.

$$\frac{65\text{ miles}}{1\text{ hour}} \bullet \frac{1609.344\text{ meters}}{1\text{ mile}} \bullet \frac{1\text{ kilometer}}{1000\text{ meters}}$$

$$\frac{65 \bullet 1609.344 \bullet 1}{1 \bullet 1 \bullet 100} \; \frac{\text{kilometer}}{\text{hour}}$$

$$\frac{104607.36}{1000} \; \frac{\text{kilometer}}{\text{hour}}$$

$$104.6 \; \frac{\text{kilometer}}{\text{hour}}$$

1. Use the following equation to convert from volts (V) to kilovolts (kV); there a volts in 1 kilovolt.

   XXXX. V • (1 kV / 1000 V) = X.XXX kV

   1230 V • (1 kV / 1000 V) = 1230 / 1000 kV = 1.23 kV

2. Use the following equation to convert from volts to millivolts (mV); there a millivolts in 1 volt.

0.XXXX volts • (1000 mV / 1 V) = XXX mV

0.123V • (1000 mV / 1 V) = 0.123 • 1000 mV = 123 mV

3. Use the equation below to convert from volts to microvolts (µV); there are 1 microvolts in 1 volt.

   0.XXXXXX V • (1,000,000 µV/ 1 V) = XXXXXX µV

   0.00123 V • (1,000,000 µV / 1 V) = 0.00123 • 1,000,000 µV = 1230 µV

4. There are two ways to convert from millivolts to microvolts. For illustration, le the long way and then the short way. There are 1000 millivolts in 1 volt and 1 microvolts in 1 volt.

   0.XXX mV • (1 V / 1000 mV) • (1,000,000 µV / 1 V) = 0.XXX • (1,000,000 / 1000) µV = 0.XXX • 1000 µV = XXX µV

5. Use the equation below to convert from microvolts to millivolts; there a microvolts in 1 millivolt.

   XXXX.X µV • (1 mV / 1000 µV) = X.XXX µV

   1230 µV • (1 mV / 1000 µV) = 1230 / 1000 mV = 1.23 mV

6. Use the equation below to convert from millivolts to volts; there are 1000 milliv volt.

   XXXX.X mV • (1 V / 1000 mV) = X.XXX V

   123 mV • (1 V / 1000 mV) = 123 / 1000 V = 0.123 V

7. Use the equation below to convert from kilovolts to volts; there are 1000 vo kilovolt.

   XXXX.X kV • (1000 V / 1 kV) = X,XXX V

   0.123 kV • (1000 V / 1 kV) = 0.123 • 1000 V = 1,230 V

8. Use the equation below to convert from milliamps to amps; there are 1000 milli 1 amp.

   XXXX.X mA • (1 A / 1000 mA) = X.XXX A

   1230 mA • (1 A / 1000 mA) = 1230 / 1000 A = 1.23 A

9. Use the equation below to convert from amps to milliamps; there are 1000 milli 1 amp.

   XXXX.X A • (1000 mA / 1 A) = X.XXX mA

   0.123 A • (1000 mA / 1 A) = 0.123 • 1000 mA = 1230 mA

10. Use the equation below to convert from kilohms to ohms; there are 1000 ohn kilohm.

X.XXX kΩ • (1000 Ω / 1 kΩ) = XXX.X Ω

1.23 kΩ • (1000 Ω / 1 kΩ) = 1.23 • 1000 Ω = 1230 Ω

11. Use the equation below to convert from megohms to ohms; there are 1000 ohn kilohm and 1000 kilohms in a megohm.

XXXX.X MΩ • (1000 Ω / 1 kΩ) • (1000 kΩ / 1 MΩ) = XXX.X • 1000 • 1000 Ω = X,XXX,XXX Ω

1.123 MΩ • (1000 Ω / 1 kΩ) • (1000 kΩ / 1 MΩ) = 0.123 • 1000 • 1000 Ω = 1,230,000 Ω

	A	mA	μA
120.0			
2		380	
3			40
45.18			
5		7570	
6			43,000
7		12.6	
8			951

	MΩ	kΩ	Ω
1	2.0		
2		280	
3			40
40.520			
5		3530	
6			43,000
7		10.6	
8			951

Module 1A: Summary 3

- Safety is an implicit part of electrical measurement.
- For current to flow, there must be a difference in potential and a complete path.
- The most measured electrical variables are
  - electromotive force (E) in *volts,*
  - current in *amps, and*
  - resistance in *ohms.*
- There is a relationship between the potential (volts), the current flowing (amps), resistance (ohms) in an electrical circuit.
  - Value prefixes are used to keep the significant numbers to less than four.

Module 1A: Review 2

See Appendix B for the answers.

1. Electromotive force is another name for electrical __________.

2. For electrical current to flow in a circuit, two things are necessary. Select essential components from the following list:

   A. Source potential
   B. Load
   C. Complete path
   D. High resistance

   ____

3. An insulator will conduct (*more* or *less*) current than a conductor.

   ____

4. A zero reference is necessary to determine how much __________ exists be charged object and the reference.

5. Which performs the work, electromotive force or current?

   ____

6. If you have a 10 V source and a 5 Ω load, how much current will flow in a c circuit?

7. If you change the load to 10 Ω, will more or less current flow?

   ____

8. If you again change the load to 2 Ω, will more or less current flow than in questi

   ____

9. Given a 230 V source and a 70 A load, what is the power being used?

   ____

10. If an incandescent lamp is rated at 100 W for 120 V, what is the current requ operate the lamp (disregard inefficiency)?

    ____

Module 1B: Measurement of Electrical Values

Measurements are as old as recorded history. This book deals with basic electrical/electronic units of measurement. Of course, the fundamental units—volt, ohm, ampere—are measured and explained, but other units applicable to electrical and electronic technologies are also discussed. These are frequency, time, henrys, farads, and impedance. Before you can begin to measure, you must understand the measurement vocabulary. It is important that you develop a complete understanding of this module because the language and concepts defined will be used throughout this text.

Accuracy and Precision

Scientifically, an absolutely accurate measurement does not exist. All measurements are approximations of the "true" value. When the accuracy of a measurement or set of measurements is stated, it is stated in terms of inaccuracy, or a range about the true measurement where the given measurement may be found. *Accuracy*, *precision*, and *resolution* are terms associated with a measurement. There are many other terms describing measurement conditions, but these three are components of any measurement, even simple measurements. As an example, use the measure of a simple line segment, as in Figure 1-5.

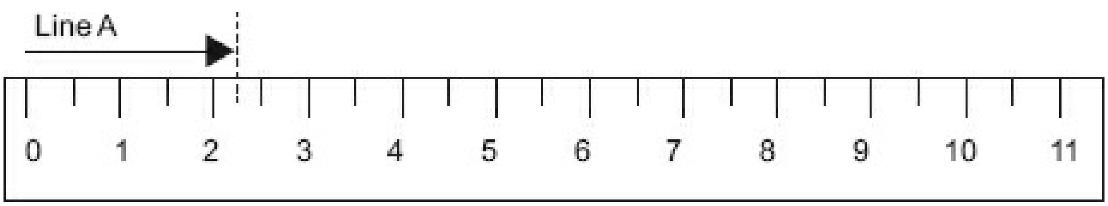

Figure 1-5. Ruler scale.

Accuracy is how closely you approximate the true value. The measurement shown in Figure 1-5 falls between 2 in and 2½ in. If the desired accuracy were measurements to the nearest inch, this would be an accurate estimate. However, if you wanted accuracy to 1/16 in, then the given ruler does not have the scale accuracy to measure to that degree of accuracy. You can only approximate to ½ in with the given scale and no better. Guessing any closer to the value would be just that, guessing.

Precision, particularly in instrumentation, means repeatability. You cannot have repeatable accuracy without a high degree of precision. Repeatability means that each time you make a measurement of the same real value, you arrive within a given range near the previous readings.

Each time you measure Line A with the ruler in Figure 1-5, you interpolate (make an educated guess) that line A is 2 in long. Each time you take the measurement, you arrive at the same conclusion (assuming you are consistent). Therefore, the precision of the scale in Figure 1-5 is ½ in, that being the closest approximation you can realistically make for this measurement.

Resolution is the smallest change (or interval) that can be measured by a particular measurement reading scale. For the ruler in Figure 1-6, the resolution depends on the viewer's ability to approximate a change in the two measured lines. Line A is 2¼ in, Line B is 2⅛ in. The difference in length is hard to see, particularly if only one line is evident. If you add ¼-inch scaling marks as in Figure 1-7, it is far easier to detect the small change and measure it.

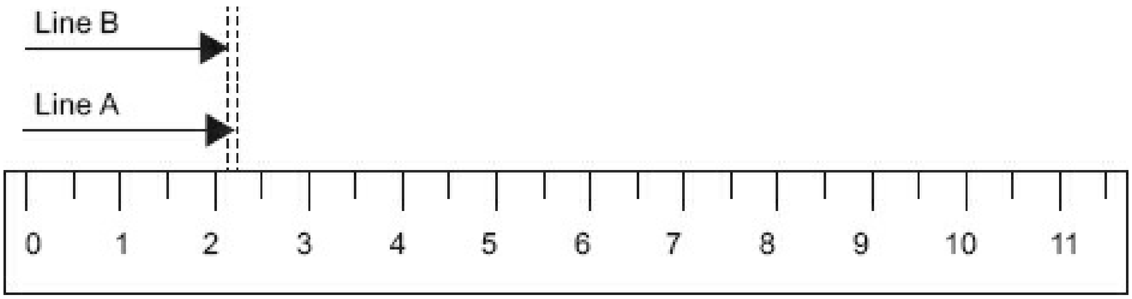

Figure 1-6. Comparison at ½ in.

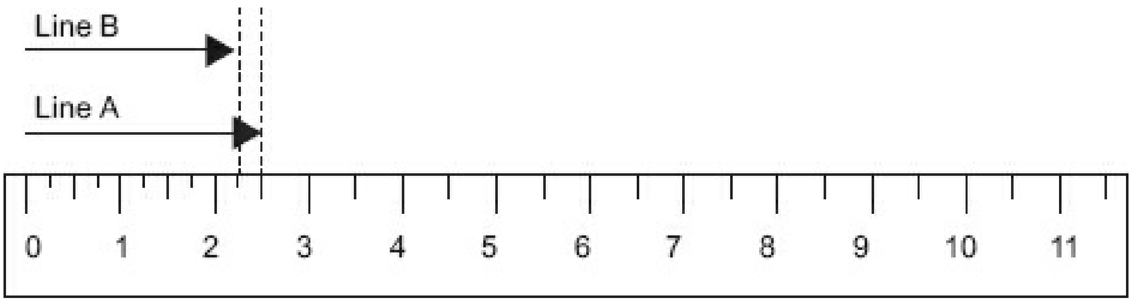

Figure 1-7. Comparison at ¼ in.

By adding the ¼-inch scale, you have improved the accuracy by getting closer approximations of the real value. You have also improved the precision because the likelihood of making the same, more accurate reading each time has increased. This is a direct result of increasing the resolution of the scale.

- Question: Can you have accuracy without precision?

  Answer: No, accuracy refers to how close the measurement value is to the actual value. To be accurate, each measurement of the same quantity should be within the stated accuracy about the true value. Precision is the ability to repeat the same measurement with the same reading, so you must have the necessary precision for the accuracy of the instrument.

- Question: Can you have precision without accuracy?

  Answer: Yes, you may be precisely wrong. If you obtain the same measurement value each time a real value is measured, then you have a high degree of precision. If, for example, using the ruler in Figure 1-7, the scale 0 is offset from the line by ½ in, your readings may be precise, but reading the wrong value gives the wrong value each time.

Least Count

Suppose you took four measurements and recorded the readings as shown in Table 1-2.

Table 1-2. Example readings.

Reading	Actual	Deviation

Value		
2.25 in	2.25 in	0.00
2.30 in	2.25 in	0.05
2.20 in	2.25 in	–0.05
2.25 in	2.25 in	0.00

The difference between readings is ±0.05 in. No further resolution is available, so 0.05 in is the *least count* for this set of measurements. The determination of least count is tied directly to resolution, and thereby to scale divisions. The smaller the least count, the greater number of scale divisions for a given interval.

When using a digital readout, least count is easier to determine. Digital meters are usually identified by the number of digits in the reading, such as 3½ digits. This indicates that there will be three decimal numerals in the reading, and the half indicates that the most significant digit is a 1 or a 0. Generally, the leading 0 is blanked (rendered not visible electronically). As an example, for a 3½ digit instrument with a 2.0 V scale, the least count is 0.001 (and the smallest interval between readings is 0.001 V). The upper value is indicated by 1.999 V. An overrange condition will be 2 V.

Digital or Analog

In measurement, there are differences in terminologies and the way specifications are stated. Let us begin by defining some terms.

- **Upper range value (URV**) – The highest value in this scale.
- **Lower range value (LRV**) – The lowest value in this scale.
- **Range** – Always stated as "from the lower range value (LRV) to the upper rang (URV)." As an example, from 0 VDC to 15 VDC.
- **Span** – The difference between the upper range value and lower range value, st one value. In the previous example of the range from 0 to 15 VDC, the s measurement is 15 VDC.
- **Analog** – Where the measured value may be any value between the upper anc range values. In other words, the scale is continuous (at least until you rea resolution of the instrument). Think of a light dimmer, which creates varied le luminance from off to full on.
- **Digital** – Where all measurements between the upper and lower range values discrete (stand-alone) points with no value existing between the discrete poin digital measurement, the value is a one or a zero; these values are combined to larger numbers using numbering systems like binary. The familiar decimal sy digital. Only 10 numbers exist (0 through 9), and all representations of values a with those basic 10 numbers.
- **Zero** – The lower range value. In electrical/electronic voltage measurement,

usually (but not always) the reference voltage known as *common* or *ground*, and value of 0 V.

- **Full scale** – This is the zero value plus the span. If the meter measures 0 to 15 V, V is full scale (or 100% of span).

Accuracy is always stated in percent of inaccuracy (or measurement error). Accuracy may be determined by several different approaches. One formula for determining accuracy is:

$$\frac{\textit{measured value} - \textit{true value}}{\textit{true value}} \bullet 100 = \textit{percent reading}$$

or

$$\frac{\textit{measured value} - \textit{true value}}{\textit{full scale value}} \bullet 100 = \textit{percent full scale}$$

To avoid specmanship,[2] the first formula will be used throughout this text in the following forms:

$$\frac{\textit{measured value} - \textit{actual value}}{\textit{actual value}} \bullet 100 = \textit{percent of accuracy}$$

or

$$\frac{\textit{measurement \#2} - \textit{measurement \#1}}{\textit{measurement \#1}} \bullet 100 = \textit{percent of difference}$$

Example VOM Specifications

These are the specifications from a (now obsolete) analog volt-ohm meter (VOM) on the DC voltage ranges:

Ranges: 1, 2.5, 10, 50, 250, 1000 V

Sensitivity: 20,000 Ω/V

Accuracy: ±3% of full-scale reading

Sensitivity is the smallest input change the device can detect. This is a typical example of specifications found in a catalog. First, here are the ranges.

Ranges:

- 0 to 1 V
- 0 to 2.5 V
- 0 to 10 V
- 0 to 50 V
- 0 to 250 V

- 0 to 1000 V

The accuracy is a *full-scale* statement which, as explained later, is the best the meter can do. That is, when measuring 10 V on the 10 V scale (a full-scale reading), the actual value may vary from 9.7 to 10.3 V; ±0.3 V. Measurement on this scale of any values lower than 10 V will give a worse accuracy, as the ±0.3 V is constant for any reading on the scale.

A typical digital multimeter (DMM) has specifications for the DC range similar to the voltage ranges in the following example.

Example DMM Specifications

4½ digit meter. *Note:* Most modern digital meters in industrial use are autoranging, meaning they pick the range that gives the best reading. However, if you prefer, you may select the range.

Ranges: 200 mV, 2 V, 20 V, 200 V, 1000 V

Resolution: 10 μV, 1 mV, 10 mV, 100 mV, 1V

Accuracy: ±0.05%

Note that the difference between the full-scale value (such as 2 V) and the actual range value (1.999 V) is the scale resolution. For the 2 V scale, the resolution is 1 mV or 0.001 V. Add that to the 1.999 V actual range, and the result is 2 V. This value specified as resolution in typical catalogs is really the least significant digit value. Most shop-type DMMs have this arrangement. More expensive models may offer 5½, 6, 6½, 7½, or even more digits.

The accuracy of a digital meter is usually stated in terms of the percentage reading. In the case of a typical meter, the stated accuracy is 0.05%, accurate enough for most shop measurements. However, a more accurate measurement can be had for a higher cost. In contemporary use, accuracy of 0.1% of measured value is standard (and generally achieved only by digital instruments if cost is a constraint).

As mentioned earlier, for an analog meter with full-scale accuracy specifications, the reading at full scale is the best the meter can do. Why?

As an example, the meter reading in Figure 1-8 is exactly 10.0 V. If the stated accuracy of this meter is ±2%, what range would contain the real value? Because 2% = 0.02 and the meter reading is 10.0, the meter reading times the stated accuracy will give the range 10.0 • ±0.02 = ±0.2 V, so the true voltage lies between 9.8 V and 10.2 V. This is not saying that for all values between 9.8 V and 10.2 V the meter will read 10.0 V. It means that the voltage that causes the meter to read 10.0 V is somewhere in the range of 9.8 to 10.2 V; it could just as easily be 10.0 V as any other value in the range.

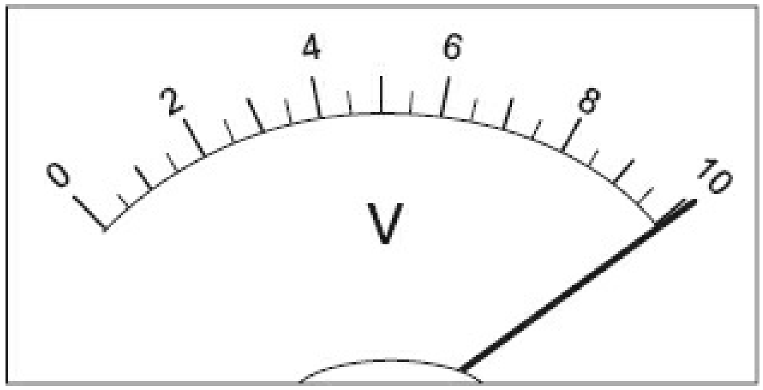

Figure 1-8. Analog 10 V scale.

If the actual voltage does not change, and each time you measure this voltage you get exactly 10.0 V, then your meter is precise to a 0.20 of a volt. However, that is not the way precision should be stated. The resolution of the scale in Figure 1-8 is 0.2 V. If the meter is at its stated accuracy and you made 10 readings that varied about 10 V within the ±0.2 V range, you could state that within the scope of your testing, the meter was precise to 0.2 V.

If you were to measure an exact 5.0 V with this meter, and you use the 0 to 10 V range for the measurement, how accurate would your reading be? Because a meter with an accuracy stated at full scale is at its best accuracy at that point, it stands to reason that the meter will be less accurate in other parts of its scale.

The reason is that the ±0.2 V is constant throughout the range. In the case of 10.0 V, it had an "uncertainty" of +0.2 V. For 5 V, the ±0.2 V range remains, so when the meter reads exactly 5.0 V, the actual voltage is in the range of 4.8 to 5.2 V. This is an inaccuracy of 0.4%. If you read exactly 1.0 V on the 10 V scale, the actual voltage would be between 0.8 and 1.2 V, which is a 20% error. This is why those who use an analog meter are always instructed to make measurements in the upper one-third of the scale.

There are ways to obtain a better approximation of the actual voltage with an analog meter; however, analog meters are seldom used for industrial calibrations today, so further discussion is not necessary. For now, we will go back and look at Figure 1-7, which is drawn here as Figure 1-9. Even with this simple measurement, several types of error could creep into our measurement.

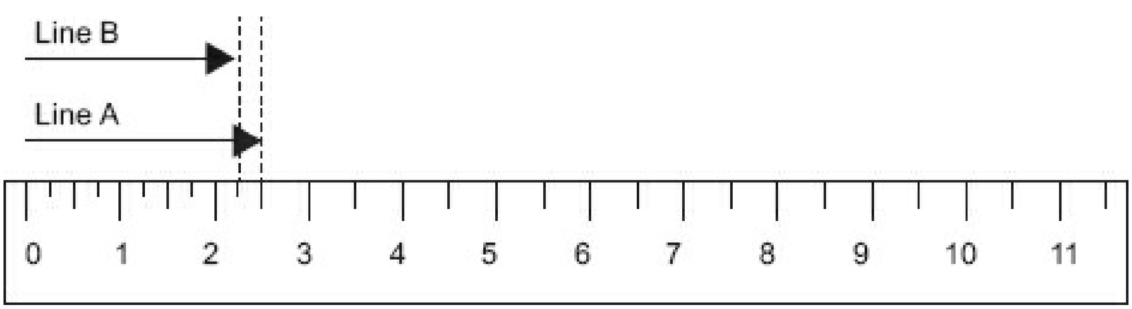

Figure 1-9. Reprinted Figure 1-7.

Error

Error is the amount the measurement differs from the actual or real value. There are different sources of errors. If the error in Figure 1-9 is attributable to the scale, for example, because the embossing is inaccurate or the ruler is warped, this is *systematic* error. If the error is caused by a person reading the wrong scale mark, then it is a human error, commonly called a *gross* error.

Errors that occur periodically (at a predictable frequency) are called *recurring* errors, whereas errors that occur without apparent reason are called *random* errors. Module 3E will explain error and how to compensate for error in greater detail.

Standard

Measurements usually refer to some reference value, usually called a *standard*. The unit of length now used in all scientific and technical fields is the meter (approximately 39 in). A standard meter is based on a certain number of radiated wavelengths of krypton (Superman had better look out); this standard and its measuring devices are kept in Paris, France. This definition is an international standard. These standards are the fundamental units of measurement and are not derived from any other unit. (The meter is measured directly and not derived from inch measurements or other nondirect methods). Standards are discussed in greater detail in Module 3D.

All countries, of course, keep their own standards. As a rule, they are compared to the international standards but are independently derived using the same methodology and technology. These standards are known as *primary standards*. A calibration shop keeps standards that are occasionally compared to the primary standards and are in all cases traceable to the primary standard. These are called *secondary standards*. *Shop standard*s or *working standards* are the ones you generally see in application. Most shops and manufacturing facilities have shop or working standards.

Module 1B: Summary

- Accuracy is a relative measurement.
- Precision refers to the repeatability of measurement.
- Resolution is determined as the smallest measurable change the measurement can display.
- Gross errors are errors made by people.
- Systematic errors are equipment errors.
- Random errors are not predictable.

Module 1B: Review

See Appendix B for the answers.

1. Define each of the following as concisely and accurately as possible:

   A. Accuracy

   ____

   B. Precision

   ____

   C. Measurement uncertainty

   ____

   D. Resolution

   ____

   E. Least count

   ____

   F. Primary standard

   ____

   G. Secondary standard

   ____

   H. Shop standard

   ____

Module 1C: Kirchhoff's and Ohm's Laws

The Circuit Laws

Kirchhoff's Current Law (KCL), Also Known as Kirchhoff's First Law

The current entering any junction is equal to the current leaving that junction.

$$i_2 + i_3 = i_1 + i_4$$

At any node (i.e., junction) in a one path (series) electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node. This means that in a one-path (series) complete circuit, current is the same at any place in the circuit.

Kirchhoff's Voltage Law (KVL), Also Known as Kirchhoff's Second Law

The sum of all the voltages around a loop is equal to zero.

$$V_1 + V_2 + V_3 - V_4 = 0$$

The sum of the Es in any closed loop is equivalent to the sum of the potential drops in that loop. This means that the sum of the voltage drops around a closed loop will equal the applied voltage.

Ohm's Law

Ohm's law states that the current through a resistance between two points is directly proportional to the voltage across the two points. This means that if you hold the resistance (R, measured in ohms) constant, then the current (I for intensity, measured in amps) will vary directly proportional to the E (measured in volts) across the resistance.

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

a. b. c.

Figure 1-10. Ohm's law.

The definition of Ohm's law is illustrated in Figure 1-10a. By simple algebraic movement, it is also represented by the 10b. and 10c. ratios.

Connecting a Complete Circuit

A circuit is made up of components. Illustrated in Figure 1-11 are three of the many components that make up an electrical circuit.

A resistor, as the name says, offers a certain amount of resistance to current flow. Figure 1-11 shows a real resistor and its schematic symbol. Resistors make up the load of many electronic circuits.

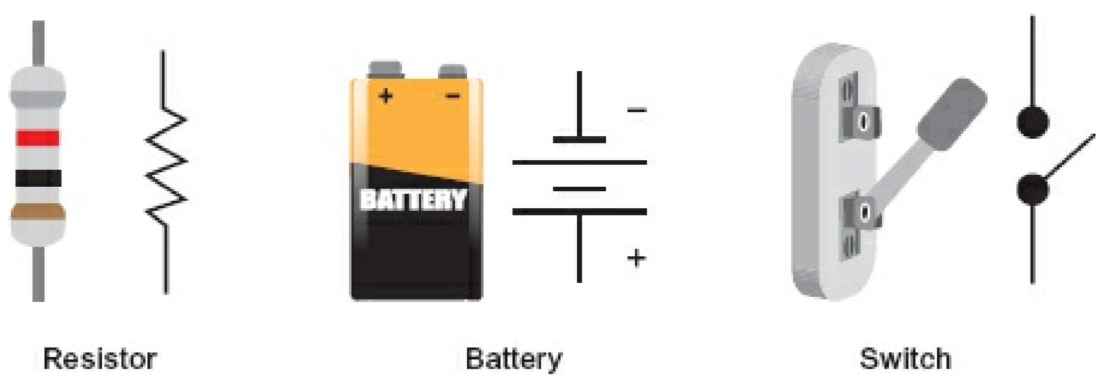

Figure 1-11. Circuit components.

A battery is an electro-chemical means of producing a potential, E. In order to interrupt the complete circuit, we have a switch. A knife switch is shown as well as its schematic symbol which bears a striking resemblance to the real thing.

Figure 1-12 is the pictorial of a complete circuit, while Figure 1-13 is the schematic representation of the same circuit.

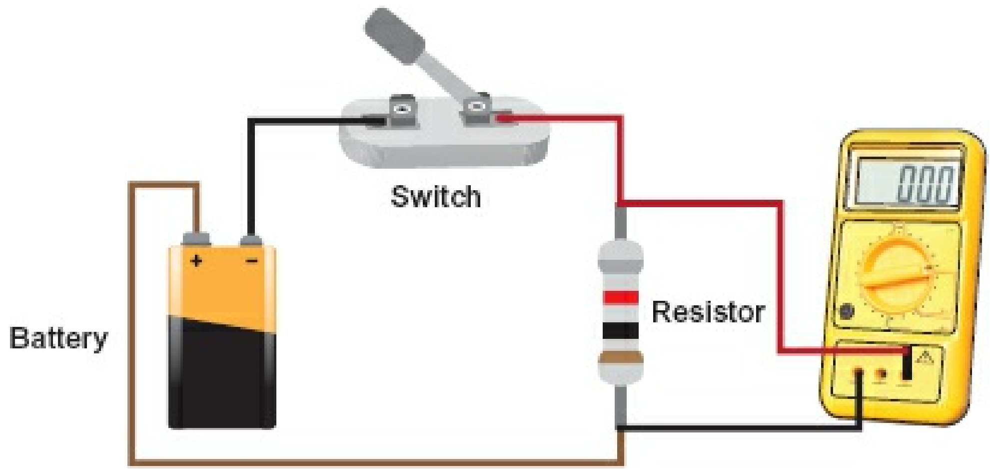

Figure 1-12. Complete circuit pictorial.

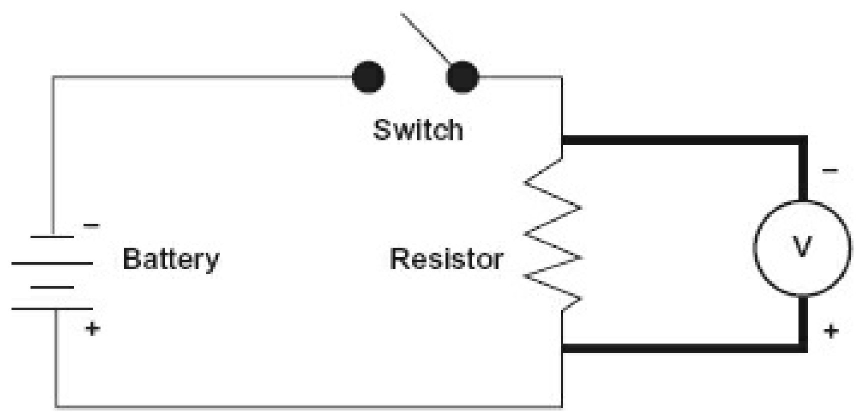

Figure 1-13. Complete circuit schematic.

Figures 1-12 and 1-13 show that if the switch completes the circuit, you have a complete path from the negative terminal (–) of the battery to the positive (+) terminal of the battery.

When the switch is open, there is no current flow (no complete path from – to +).

This means that the entire battery voltage measured across the switch as the voltage drops (open switch) must equal the applied (battery) voltage.

The voltmeter is connected to measure across the resistor (not the switch). If there is no current flow, there will be no voltage drop across the resistor.

Now close the switch. All the current is now flowing through the resistor. The resistor is a 1 kΩ (1000 Ω) resistor. This value was determined by the color code on the resistor. This method of identifying resistor values is fast disappearing (due to surface-mount and product printers), so it will not be elaborated on in this text.

Assume the battery is 10 V. What voltage will the voltmeter measure? The answer is 10 V, as it is the only voltage drop in the circuit now that the switch is closed. What is the current through the resistor? Use Ohm's law: I = E/R or 10/1000 = 0.01 A or 10 mA. An easy way to remember Ohm's law is to use the Ohm's law circle (see Figure 1-

14).

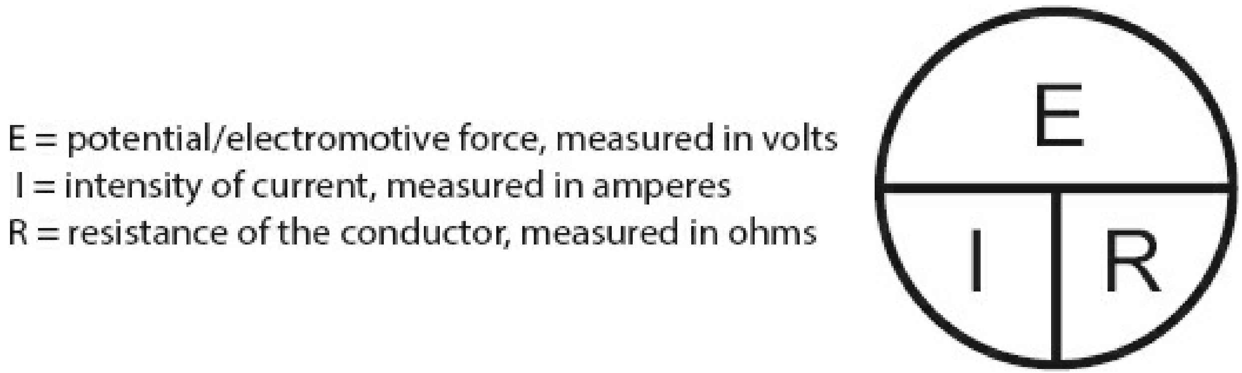

Figure 1-14. Ohm's law circle.

Ohm's law circle is a useful tool for determining equations. Simply use a finger to cover the value you need, and the uncovered area gives you a makeshift view of the required equation.

In Figures 1-15 and 1-16, we will double the resistance in the circuit. What do you estimate the voltage across each resistor to be when the switch is closed?

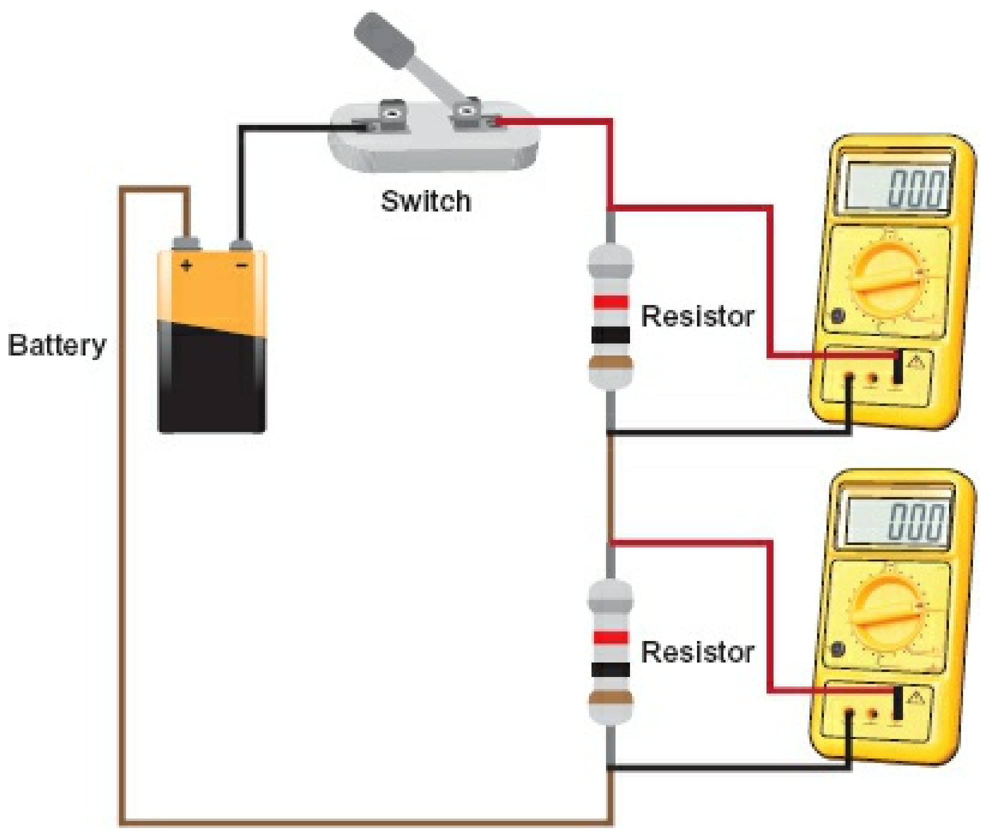

Figure 1-15. Double the resistance pictorial.

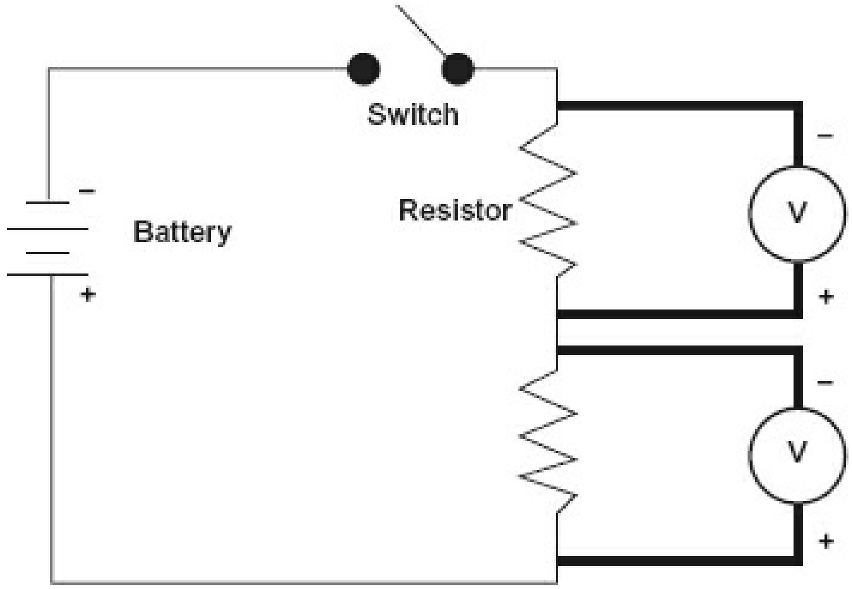

Figure 1-16. Double the resistance schematic.

You must remember Kirchhoff's laws for a simple solution, although we will follow up and show how you also can use Ohm's law. Using KCL, we know that the current (in a single branch or series circuit) is the same throughout, so the same current flows through each resistor. Because they are identical resistors, they have the same voltage drop. According to KVL, we know the sum of the voltage drops must equal the applied voltage.

In the previous example, we assumed the battery was 10 V, and we will do the same here for consistency. That means there should be 5 V across each resistor (because 5 + 5 = 10).

Using Ohm's law, we must first determine a total resistance. Because the resistors are in series (one current path), the resistances must be added. Therefore, 1 kΩ plus 1 kΩ equals 2 kΩ. To determine total current flow (using your circle solving for I), the equation will be 10 V divided by 2 kΩ which equals 0.005 A or 5 mA.

To determine E across the resistor, multiply the current, 0.005 A, by the resistance, which gives you 5 V.

The steps are summarized below:

1. Calculate total R: R (upper) + R (lower) = 2 kΩ
2. Calculate total I: Divide the applied voltage (10 V) by the total resistance (2 kΩ equals 0.005 A (5 mA).
3. Calculate R drop: Multiply each resistor (1 kΩ) by the total current (0.005 A gives you 5 V across each resistor as they are both 1 kΩ.

As observed previously, if you hold the applied voltage at the same value and increase the resistance, the current will decrease. In our case with 1 kΩ total resistance and 10 V applied, the current was 10 mA (0.010 A). When R was increased by 1 kΩ to a total of 2 kΩ, the current with 10 V applied was half, or in our case 5 mA.

Module 1C: Summary

- **Kirchhoff's first law (KCL)** – No more current can enter a point than leaves tha that is, current is the same throughout a series loop.
- **Kirchhoff's second law (KVL)** – The sum of all the voltages around a loop is e zero; that is, the sum of the voltage drops in a series circuit equals the applied vo
- **Ohm's law** – If the voltage is held steady and the resistance is increased, the will decrease in a series loop; that is, E = I • R.

Module 1D: Parallel Circuits

A simple two-branch parallel (multipath) circuit is illustrated in Figure 1-17 (pictorial) and Figure 1-18 (schematic).

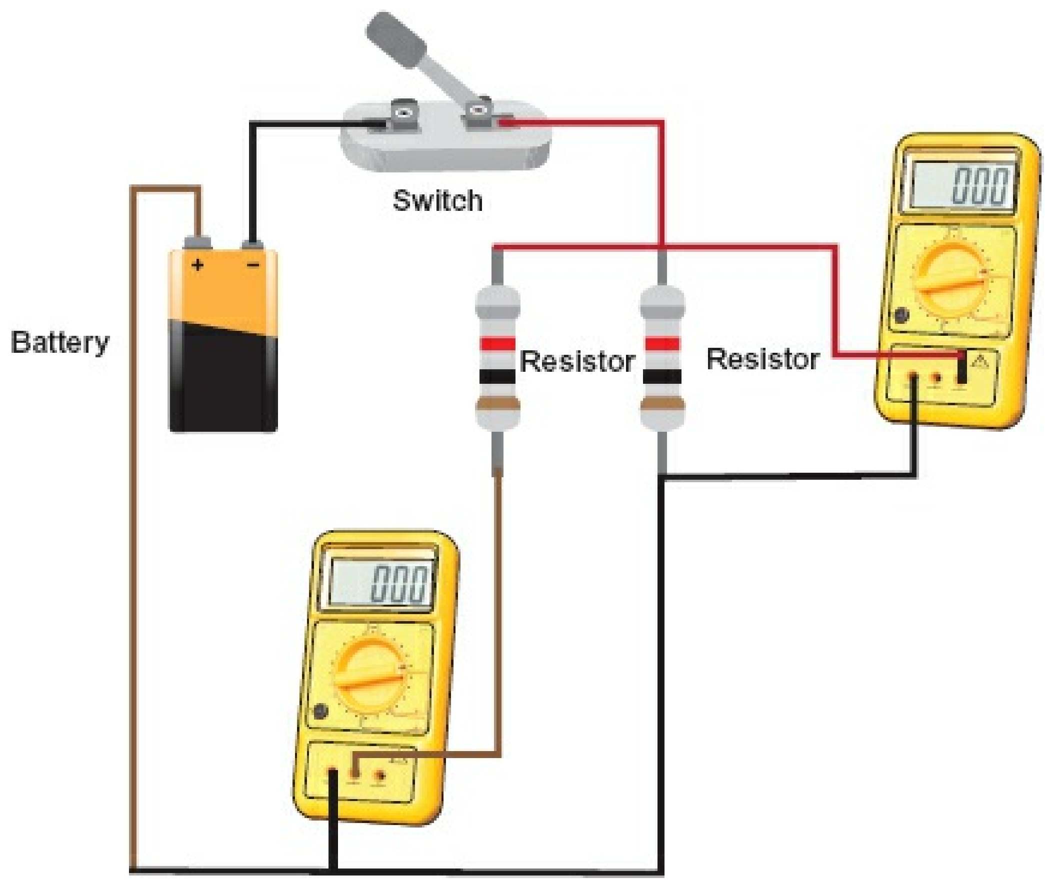

Figure 1-17. A simple parallel circuit pictorial.

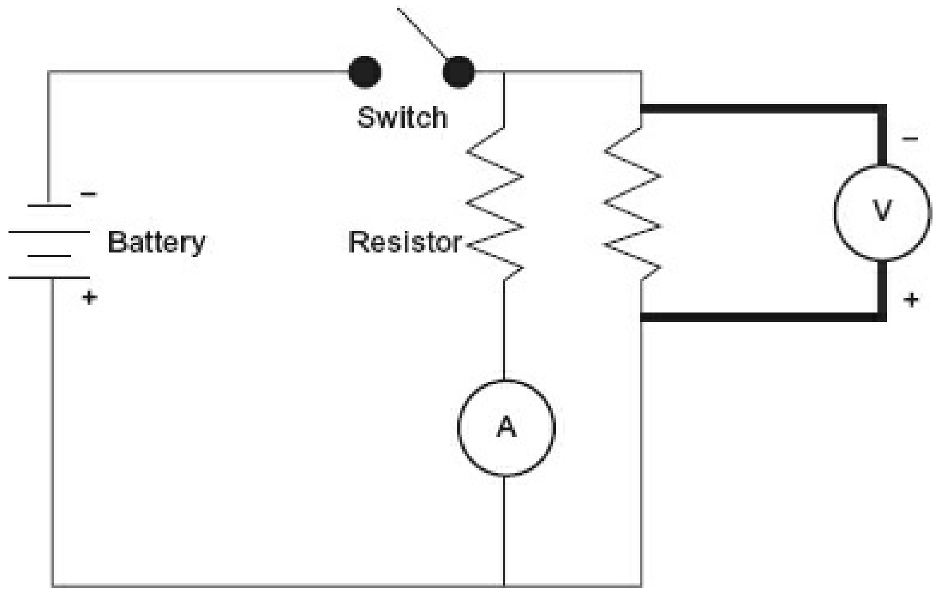

Figure 1-18. A simple parallel circuit schematic.

As shown, the applied voltage is the same across both resistors, meaning they will each draw the amount of current dependent on the applied voltage and their resistance. Because there is more than one path, the total current will be the sum of the branch currents, while the voltage drop is the same across each branch. This means the total resistance is less than the lowest resistance.

If we use the same values for applied voltage (10 V) and resistor values (1 kV), we could easily make some assumptions. Because the resistances are the same, we can safely assume that each branch will have the same current flow, and therefore the same voltage drop across each resistor. This is true in a parallel circuit regardless of the resistor size provided the resistor is not so small as to cause the full ampacity of the battery (a short circuit) to flow through that branch.

Parallel Current Paths

Figure 1-19 illustrates a parallel circuit. Note that the potential across each branch is the same, as the conductors go from each resistor to the source. Because the voltage is the same across each path, called a *branch*, the current flowing in each branch depends on the resistance of each branch. If all the branch currents are added together, the result will be the total current flow in the circuit from (or to) the battery.

Examples

Battery = 10 V, R_1 = 10 Ω, R_2 = 10 Ω

What is the current flow through each branch (I_{R1} and I_{R2}), and what is the total current flow (I_t)? Using Ohm's law, determine the current through each resistor. 10 V / 10 Ω = 1 A. So, each branch has 1 A. Because the "no free lunch" rule still applies, that current has to come from somewhere. There is a total of 2 A, so that is the current flow from and to the battery.

Battery = 10 V, R_1 = 15 Ω, R_2 = 5 Ω

What is the current flow through each branch (I_{R1} and I_{R2}) and what is the total current flow (I_t)? Using Ohm's

Law, determine the current through each resistor. For R_1, 10 V / 15 Ω = 0.67 A. For R_2, 10 V / 5 Ω = 2 A. Total current is 2.67 A.

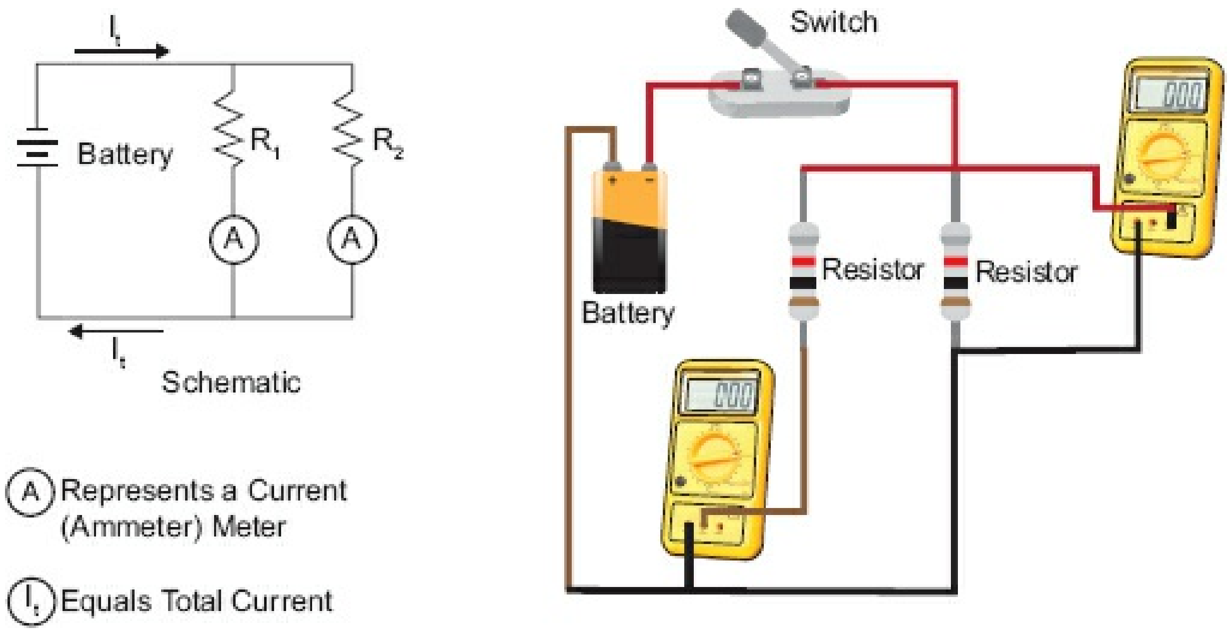

Figure 1-19. Parallel circuit.

In both of these examples, we have determined the total current flow. With that value we could determine the resistance that the source (in our examples, the battery) sees, that is, the value equivalent to a single resistance connected to the source. This is known as the *total resistance* (or R_t). In the first example, with two 10 Ω resistors in parallel, the total current was 2 A. The source was 10 V, so by Ohm's law the total resistance is 10 V / 2 A = 5 Ω. *Hint:* Because equal resistors always pass the same current when the same potential is across them, the total resistance will be half of the resistor value for two resistors. Can you prove that it would be one third for three resistors of equal value? One quarter for four resistors of equal value?

To make a long story short, the source "sees" only the total resistance, not how it is developed, constructed, or connected. All methods of determining resistance try to identify that *equivalent total resistance*.

Assumed Voltage Method (Preferred)

Using the same method as before, we can determine the total resistance of a three-branch circuit (Figure 1-20).

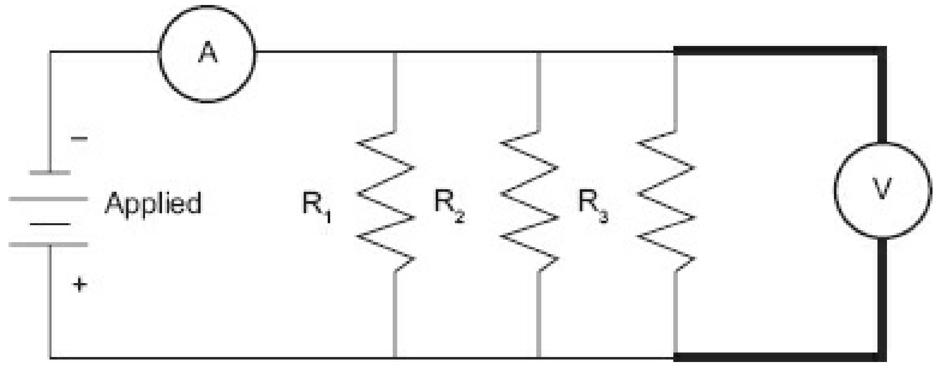

Figure 1-20. Three-branch resistive circuit.

Where applied voltage is 10 V:

$R_1 = 10\ \Omega$

$R_2 = 15\ \Omega$

$R_3 = 5\ \Omega$

You know the total resistance must be less than 5 Ω.

Step 1: Assume a voltage, preferably one that each resistor can go into evenly. In this case, we assume 30 V. This is not so easy with values like 4.7 kΩ, 3.3 kΩ, and 1.5 kΩ; however, a calculator soothes the pain.

Step 2: With this applied voltage, determine the current through each branch:

$I_{R_1} = 30\ V\ /\ 10\ \Omega = 3\ A$

$I_{R_2} = 30\ V\ /\ 15\ \Omega = 2\ A$

$I_{R_3} = 30\ V\ /\ 5 = 6\ A$

Step 3: Add the currents:

$I_{R_1} + I_{R_2} + I_{R_3} = 11\ A$

Step 4: Divide the total current into the assumed voltage:

Total resistance = 30 V / 11 A = 2.73 Ω

This method assumes knowledge of Ohm's law and parallel circuits only.

Reciprocal Method

The assumed voltage method is nothing more than a verbal way of expressing the computational (reciprocal) method.

Using the sum of the reciprocals method:

$$\text{Total Resistance} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} ... + \frac{1}{R_n}}$$

$$\text{Total Resistance} = \frac{1}{\frac{(R_2 + R_n) + (R_1 + R_n) + (R_1 + R_2)}{R_1 \bullet R_2 \bullet R_n}}$$

If there are only two resistors (which is a special case), total resistance can be determined by:

$$\text{Total Resistance} = \frac{R_1 \bullet R_2}{R_1 + R_2}$$

For example: 75 / 20 = 3.75 Ω

For our purposes, the assumed voltage method (if the actual voltage is not known) works best as it uses Ohm's law and does not require formulas.

Note that a formula is a model of reality. The more closely the formula conforms to real-world experience, the better the model. In the previous case, because you are performing the same arithmetic processes (determine an assumed voltage or determine the lowest common denominator), the answers are the same. Because the assumed voltage method came before the reciprocals method, it is merely the formula proving the natural fact method.

Module 1D: Summary

- In a parallel circuit, each branch draws a portion of the total current.
- The source sees only the total resistance, not any branches.
- Using the assumed voltage method, you assume an applied voltage, determ individual branch currents and total them, and then divide the current total i assumed voltage.
- In a parallel circuit, the total resistance is always less than the lowest branch resis

Module 1D: Review

See Appendix B for the answers.

1. For the circuit shown in Figure R1-1, identify the points you should use to mea voltage of:

A. R_1 ____________
B. R_2 ____________

C. The applied voltage ___________

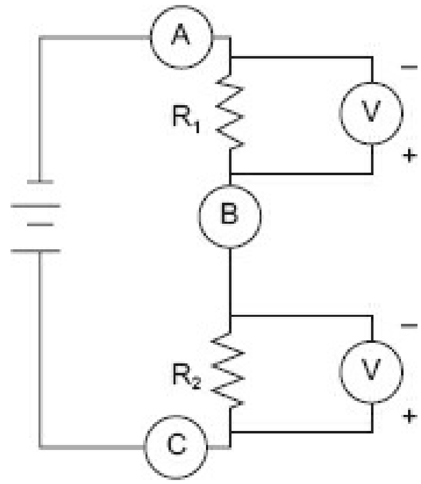

Figure R1-1.

2. In Figure R1-1, if you were to measure current, where would you insert your me

____

3. If you have a 12.0 V source and two 1200 Ω resistors in series, what will be the:

A. Total current flow? ___________
B. Total resistance? ___________

4. If you measure 10 mA (10/1000 A or 0.01 A) and it passes through an 1800 Ω what is the voltage across the resistor? _________________________________

5. If you have a 100 V source and the total current measured is 2 A, what is t resistance? ___________________________________

6. If you wish to see a 5 V drop across a resistor for 20 mA current flow, what val that resistor have? ____________________________________

7. For safe measurement, voltage is always measured _______ ____.

8. For safe measurement, current is measured in ___________. However, a sa would be to measure voltage across a ___________ and use Ohm's law to de current.

9. The primary safety consideration for measuring resistance is to ensure that the p the component under test is ___________.

10. Determine the requested values in problems A through C based on Figure R1-2.

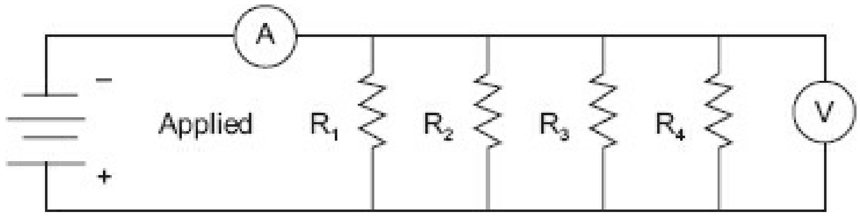

Figure R1-2.

A. Determine total current (I) when:

Applied = 100 V, R_1 = 100, R_2 = 250, R_3 = 50, and R_4 = 500

B. Determine the total resistance for problem A.

____

C. What is the voltage drop across R_1, R_2, R_3, and R_4 when the applied voltage is 5

R_1: __________ R_2: __________

R_3: __________ R_4: __________

Conclusion

You have reached the end of Module 1. Please reread the module objectives. If you have met these objectives, continue to the next module. If you are having difficulty, please reread the text. If the difficulty persists, locate a peer, mentor, supervisor, or someone who has technical knowledge of these topics and ask them to assist you.

---

1 Gustav Kirchoff (1824–1887) was a German physicist credited with developing circuit laws that form the fundamental components of rules that explain how electricity works.

2 *Specmanship* is using specifications or measurement results to establish a supposed or commonly accepted superiority of one entity over another, generally when no such superiority exists.

2 Basic Electric Characteristics

In the previous module, basic direct current circuits were demonstrated, both parallel and serial. In this module, the terminologies are similar and measurements are made the same way.

Module 2: Objectives

After successfully completing this module, you will be able to:

- Define, describe, and determine alternating current (AC) characteristics.
- Define and describe magnetism, electromagnetism, field, and sinusoidal.
- Define and describe AC values: rms, peak, peak-to-peak, period, and frequency.
- Describe and determine capacitance values: capacitance, working voltage, die and electrolytic capacitors.
- Determine resistor-capacitor (RC) time constants.
- Determine the value of capacitive reactance (X_C) when given specific capacitiv resistive values.
- Define and describe an inductor's characteristics, including the resistor-inductc time constant and inductive kick.
- Determine the value of inductive reactance (X_L) when given specific inductanc resistive values.
- Define resonance and the behavior of resistor-capacitor-inductor (RCL) circuits serial and parallel.
- Define, describe, and determine circuit impedance.

Module 2A: Alternating Current

Although direct current (DC) is used in most electronic devices, alternating current (AC) is the most commonly occurring type of electric current. You could think of DC as a special form of AC.

If you have a fair grasp of DC from the previous module, then the concept of AC is relatively easy to comprehend. It is *essential* that you understand AC behaviors; most of our modern world uses these behaviors to run industry, to provide information, for medical therapies, and more. The list of uses is endless. To understand AC is to understand the *why* of modern technology. First, we will define both types of current.

Direct Current Defined

DC is defined as an electrical current that maintains the polarity of the source and (generally) does not change in amplitude (magnitude) continuously. The output of the 9 V battery in Module 1 was 9 V; the positive terminal was positive and the negative terminal was negative, and it does not change. Batteries are one source of DC.

Alternating Current Defined

Alternating current (AC) is defined as an electrical current that continuously changes amplitude (magnitude) and periodically changes polarity. A little investigation will show that most of the concepts of AC have already been discussed in Module 1. AC still obeys Ohm's law (for the *instantaneous voltage* it exhibits at any selected moment).

Understanding AC requires only a modification of what the reader has already learned. Although the following explanation is simplistic, it is also quite true. We can simulate AC (a *switched* or *square wave* is the result, but it meets our definition for *periodically changing polarity*).

Figure 2-1 illustrates how to mechanically generate a form of AC (pulsating DC; in this case, a square wave) using two batteries and a switch. The waveform is the voltage across the resistor due to the present switch condition plus each switch condition prior to this condition. As a result, we can create a histogram that represents the value over time. The waveform is a graphic (a graph) of the voltage across the resistor for a period and, in our case, several different switch conditions.

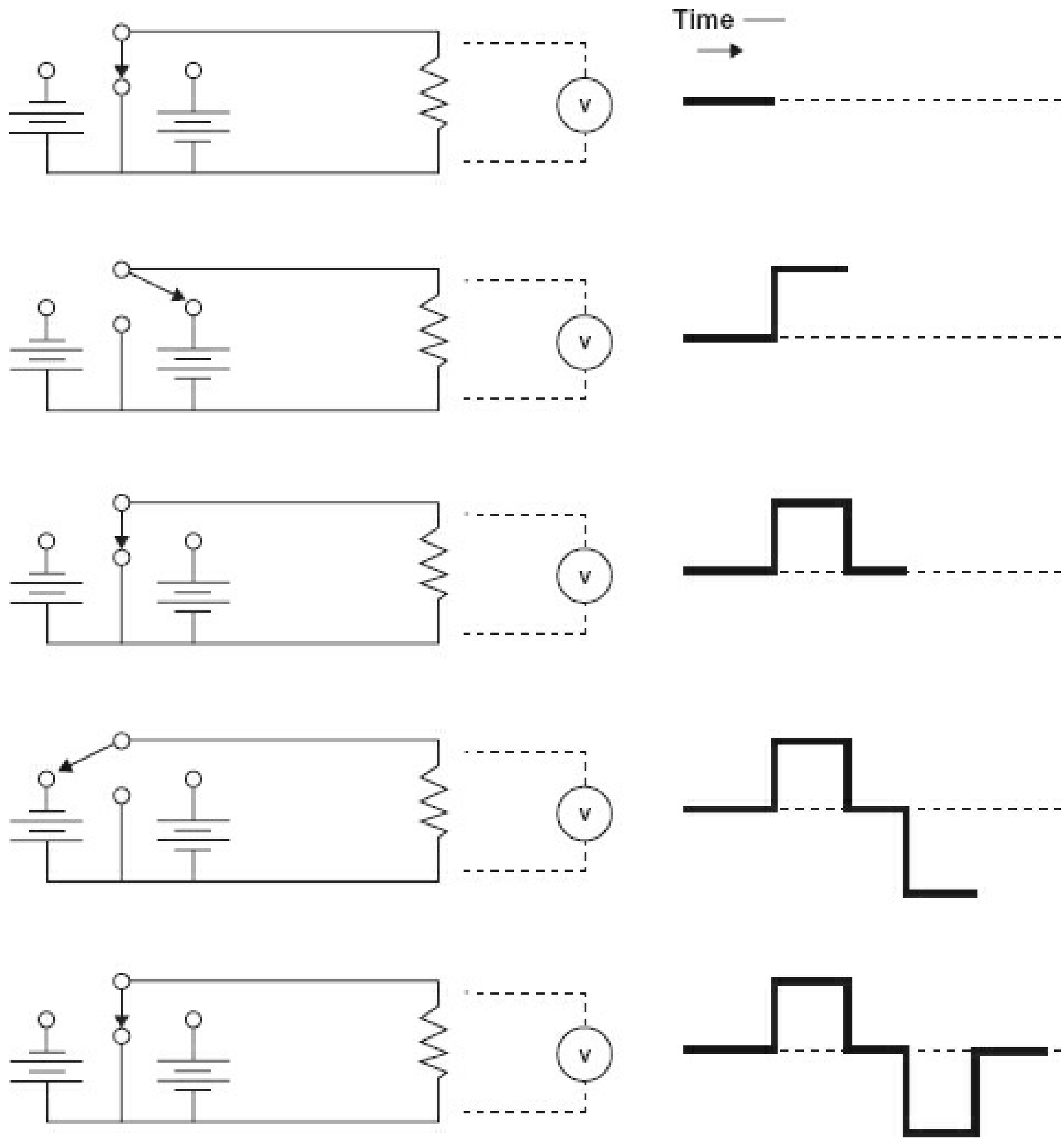

Figure 2-1. Switched waveforms.

Note that the switched waveform almost fits the description of AC if the switch is being moved between positions at a periodic rate. That is, if the waveforms are continuously changing in amplitude (except at plateaus) and periodically changing polarity. *Amplitude* is the magnitude of positive or negative current (or voltage). *Polarity* is the direction of current or the direction the voltage would push current. The time it took for the current to be switched from zero to positive, zero to negative, and back to zero (the time it took for our switch conditions to be completed) is known as the *period*. It is measured in time. If you were operating the switch and decided to switch it faster and faster, the period of time would decrease, and the number of positive and negative alternations would increase. We call the complete zero-to-positive-to-zero-to-negative-to-zero a *cycle. A cycle contains one positive and one negative alternation*. The number of cycles in one second is expressed as hertz (Hz), or in many cases as pulses per minute (ppm) if is not symmetrical.

To summarize, the time it takes to complete one cycle (a positive and negative alternation) is known as the period, and the number of complete cycles in 1 s is known as hertz. The period is a time measurement.

This is probably not how you pictured AC. You might have in your vision a sinusoidal waveshape. It is true that most AC is of the sinusoidal variety.

Electromagnetism

A sinusoidal waveform is easily generated mechanically. However, first you must understand magnetism and its effect on conductors. One of the earliest noticed behaviors of electricity was that there was a magnetic field around a conductor carrying current. This was proven by placing a compass next to a wire carrying DC (in a complete circuit, of course), which is illustrated in Figure 2-2.

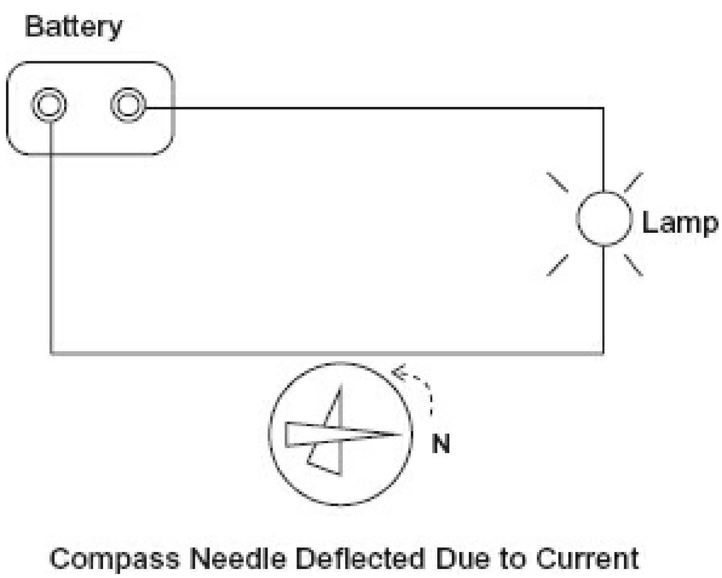

Figure 2-2. Magnetism and electric current.

When the current was switched on, the magnet would deflect; when the power was removed, the magnet would deflect in the opposite direction and then return to its normal position. The greater the current, the greater the deflection. Winding the wire in a coil amplified the effect (coiling the conductor concentrates the magnetic field). Placing an iron core in the center of this coil greatly enhanced the power of this field. (A ferrous core further concentrates the magnetic field.) This is an electromagnetic field. *Electro* because it is caused by an electric current, *magnetic* because the result is a magnet just like a permanent (natural) magnet. *Any conductor carrying current has a magnetic field*.

Field

The best description of a field (any kind of field, *magnetic, electrostatic, gravitational,* *ether*) the author remembers came from *The Radio Amateurs Handbook by the American Radio Relay League (ARRL)* circa 1953. Roughly paraphrased, it states:

> If an event occurs at A, that causes an event to occur at B, and there is no visible or physical connection, we say they are in the same field.

Engineers describe fields as *areas of influence*. The exact mechanism is not known, but the behavior is well modeled, meaning we can predict quite reliably the effects of a magnetic field . To visualize a field, imaginary lines of force are drawn depicting the field strength in the area of influence. You might have seen simulations of these lines when iron filings are placed on a glass above a magnet (or paper or cloth); see Figure 2-3. For magnetic fields, the lines are drawn from the south to the north pole; they never cross as they are always parallel to each other. The more of these imaginary lines of force in an area, the stronger the field.

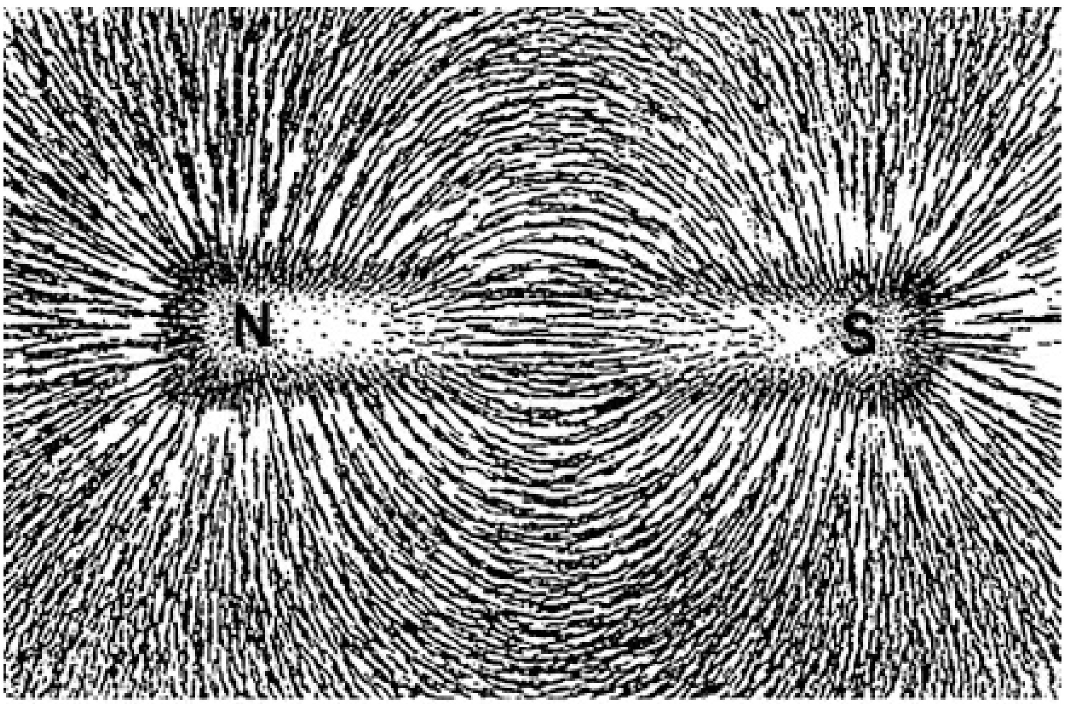

Figure 2-3. Magnetic lines of force.

By coiling the conductor, we concentrate the lines of force within the coil area. Placing an iron core in the center of the coil causes the lines of force to concentrate because iron is a magnetic substance through which the lines of force travel easily. These imaginary lines of force are anything but imaginary in real life. They power electric motors, bring power into businesses and homes, generate the spark for your gasoline engine, and perform countless other chores, many of which will be described later in this text.

Michael Faraday (1791–1867) is credited with the study of electromagnetism and the development of many of the principles we use today. Faraday's law of induction states that if a conductor cuts across a magnetic field or the magnetic field cuts across the conductor, and there is relative motion (one or both are moving), an electric current will be induced in the conductor. The amount of current will depend on the

- strength of the field,
- number of conductors cutting the field,
- geography of the conductors (wound in a coil?), and
- speed of the relative motion.

For this discussion, there is only one conductor. Figure 2-4 illustrates how a coil that is placed in a magnetic field and rotated will generate an electromotive force, or E (voltage), in accordance with Faraday's law of induction. If the circuit is completed (closed), the voltage will force a current through the circuit. The arrow points to the portion of the curve generated by movement to that position from the previous position.

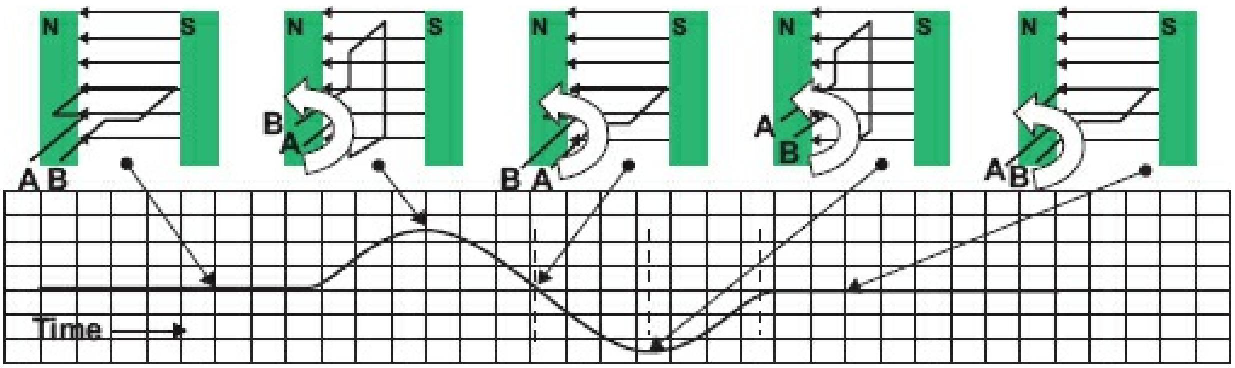

Figure 2-4. Generating an alternating current.

Sinusoidal Waveshape

Figure 2-5 illustrates why this is called a *sine wave*. With the radius as the amount of voltage generated by a single coil (seen previously in Figure 2-4), start at 0° rotation and rotate the radius counterclockwise 360° so it aligns with where it started, just as shown in Figure 2-4. The radius for the circle in Figure 2-5 is 1. The voltage generated will be the sine (sin) of the angle of the radius relative to where it started (0°) during rotation.

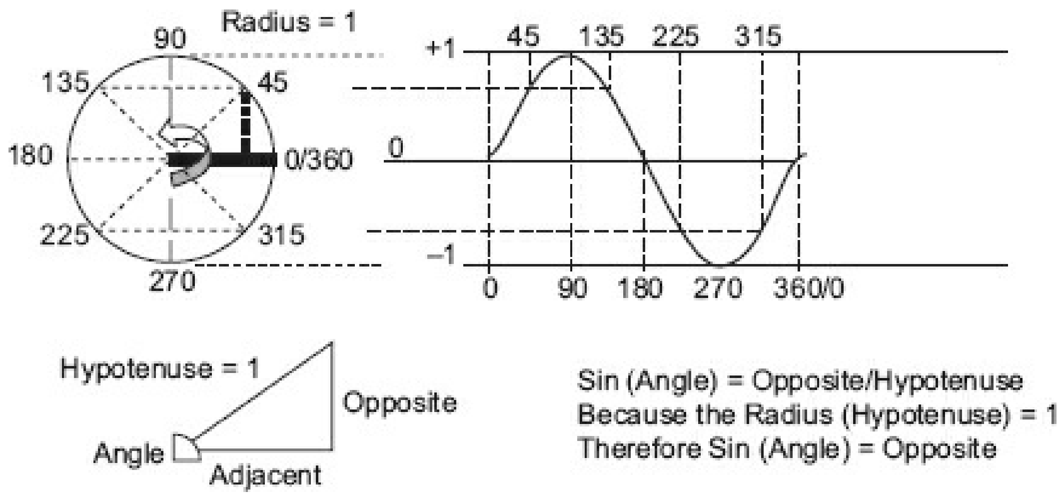

Figure 2-5. Sine wave.

Because the sine of an angle is equal to the ratio of the opposite side (in this case, the amplitude) divided by the hypotenuse, which is 1, the amplitude of this waveshape is described as tracing the sine of the rotating radius. If you can remember your high school geometry, you will recall that the circumference of a circle (the length of the line starting at 0° and tracing the outer boundary of the circle to 360°) is 2πr (pronounced "two pie r") where π ≅ 3.14. This means if you stretched a piece of string around the circle shown, it would be 6.34 in long. A sine wave is mathematically known as 2πf, where f is the number of waveshapes appearing in 1 s. Sine waves have some fascinating properties; many will be discussed in this module.

Alternating Voltage and Current

One must visualize this sine wave along with the switching system to see what is taking place. Ohm's law is not (and will not be) repealed. Let us use the drawing in Figure 2-6 and define a few terms.

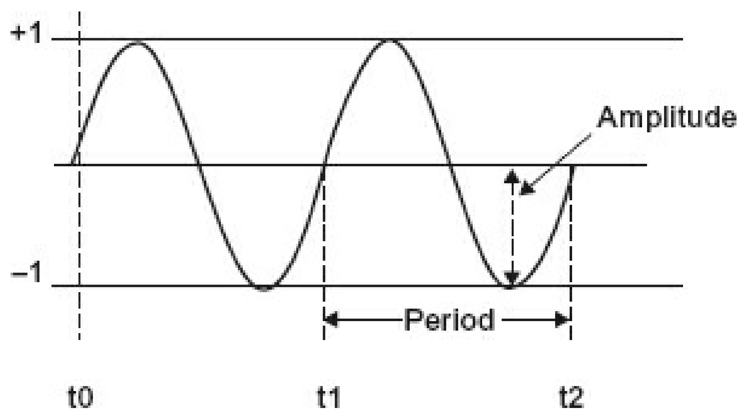

Figure 2-6. A sinusoidal waveform.

- **Peak-to-peak value** – This is measured from the positive most voltage excursion negative most voltage excursion. In Figure 2-6, the peak-to-peak value is 2.0 mea from either the negative-most or the positive-most excursion to the peak value opposite excursion.

- **Peak voltage** – The peak value for either the negative or the positive excursi
Figure 2-6, the peak value is 1.0.

- **Root-mean-square (rms)** – Also called the *effective* value. Practically speaking, thi
value of an AC sinusoidal waveform that produces the same heating effect as a
this value. For example, 0.707 V rms will produce the same heating effect as 0.707
Most alternating voltage/current values are rms. In Figure 2-6, the rms value is
To calculate the rms value from the peak voltage, multiply the peak voltage by 0.7
calculate the peak voltage from the rms value, multiply the rms value by 1.414. (
want to know why, 1.414 is the reciprocal of 0.707.)

- **Frequency** – The number of occurrences in a specified time period (identified in
2-6), usually 1 s. Frequency is measured from one point on a recurrent waveform
same point on the following waveform. In Figure 2-5, 0° is one point and 360°
other end of the complete waveform. It is called a *cycle* because it completes 360°
period and then repeats. The number of cycles per second was formerly expres
"cycles per second," but this has been changed to hertz. It is incorrect to say "he
second" unless you are talking about the change in frequency per second. Frec
may be determined by dividing the time of the period into 1 s.

- **Period** – If the frequency is known, the period may be calculated by dividing 1 s
frequency.

- **Phase** – The angular position of a waveshape from its starting (0°) location point.

- **Phase difference** – The number of degrees two signals of the same frequen
separated. This is illustrated in Figure 2-7. Which one is leading the other and
one is lagging depends on which one is the reference.

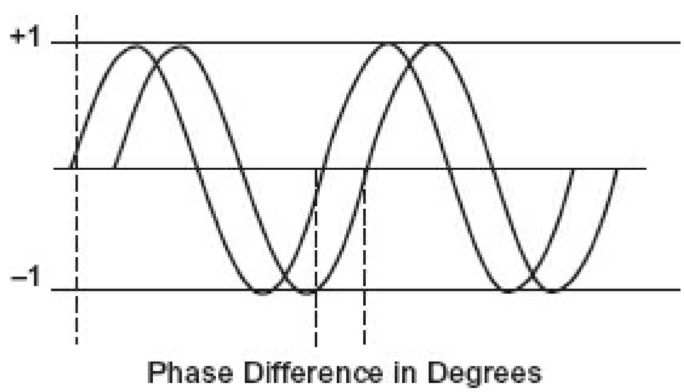

Figure 2-7. Phase difference.

Both signals have the same frequency and amplitude; they are separated by 90°, which is the phase difference. Note that a continuing change of phase in one direction will cause a change in frequency. *Phase* and *frequency* are related and are called the *angular* components of a sinusoidal waveshape.

Module 2A: Summary

- A sinusoidal waveshape is described by amplitude, frequency, and phase.
- Root-mean-square (rms) is the AC equivalent to DC in terms of heating power.
- If you know one amplitude measurement, others may be calculated.
- Frequency is the number of occurrences in a period of time, usually 1 s.
- Frequency is determined by dividing the period of time into one (1).
- Phase is the angular position of a waveshape from its (0°) starting point.
- Phase difference is the number of degrees two signals of the same frequency are a

Module 2B: Alternating Current Values

Other than looking at the waveshape of AC, you must understand the relationships between voltage and current with this sinusoidal waveshape. As stated before, Ohm's law has not been repealed, and it still takes voltage (potential) to push current (flow) through the resistance (opposition).

Figure 2-8 illustrates a complete AC circuit. We will use this circuit to calculate the power (in watts) for an AC circuit with a 10 V rms source (marked AC in Figure 2-8). The sinusoidal waveform in the diagram is that of current. Recall that this would be 1 A if 10 VDC was applied.

Use Table 2-1 to determine values of current and power.

$$\text{Power: } P \text{ (watts)} = E \bullet I$$

If we do a little algebraic magic (called *substitution*),

$$E = I \bullet R \text{ (Ohm's law)}$$

And place that representation in the power formula:

$$P = I \bullet R \bullet I \text{ or } P = I^2 \bullet R$$

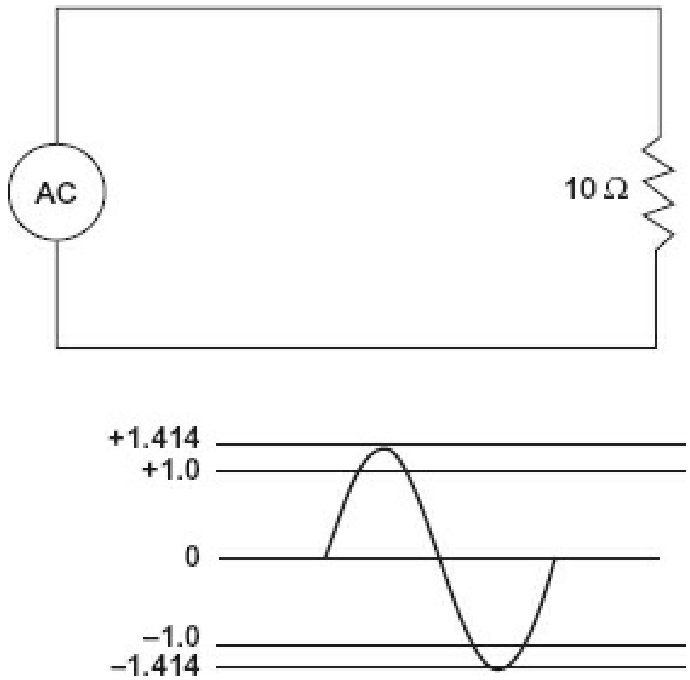

Figure 2-8. Basic AC circuit.

Table 2-1. Instantaneous AC values.

Degrees	I	I^2	P (watts)
0	0.000	0.000	0.000
10	0.245	0.060	0.600
20	0.486	0.236	2.36
30	0.707	0.500	5.00
40	0.909	0.826	8.26
50	1.083	1.173	11.73
60	1.225	1.500	15.00
70	1.329	1.766	17.66
80	1.393	1.940	19.40
90	1.414	2.000	20.00

Root-Mean-Square Energy

Notice that at times the resistor is dissipating 20 W, which means 1.4 A are flowing through it but the actual DC power equivalent is only 10 W. This is determined by multiplying the peak voltage by 0.707 (1.414 • 0.707 = 1). With AC, an old but important parameter has come back into our measurements—time. Since the start of this discussion of electricity, it was claimed that current really does not flow; rather, this was a way for the early investigators of electrical phenomena to understand and visualize electricity. With AC, current would "flow" one way for a period of time and then "flow" the other way for an equal amount of time (for a sine wave). The average current then would be zero if you were counting polarity and current really did flow. But if you consider electricity as energy being transferred, and to transfer the effect from DC to AC you choose heating a resistor, then it is apparent that work will be done by the AC. In Table 2-1, note that in half of a cycle (any 90° section), different amounts of energy are expended at different times. That is why the table is titled "Instantaneous

AC values.” Polarity is not a factor in resistive heating.

The amount of energy dissipated in the resistor over the time it was dissipated must be determined. True, 2.0 A is flowing at the negative and the positive peak, but those peaks exist only for a short period compared to the waveshape as a whole. The average energy dissipated over one cycle will equal 10 W (just what Ohm’s law says it should be). This mathematical process, averaging over a period of time, is called *integration.* It is used to calculate the area under the curve, or the energy over time. Anyone who has ever calculated their average speed when traveling from one city to another has averaged over time or, technically, performed integration.

Example

You travel from Waco, Texas, to Austin, Texas, and the mileage between your start and your arrival is 100 mi. The drive took you 2.0 h. What was your average speed? Simply divide the mileage by the time, and the result is 50 mph. Were you always traveling 50 mph? No, sometimes it was 0 mph and other times it was 75 mph.

Example

You are told that the voltage available at the wall socket of your residence is 120 VAC. What does this mean?

It means that the voltage available will heat a resistor the same amount as a DC voltage of that amount (120 VDC). It also means that the peak voltage (the highest voltage in either a positive or a negative direction) will be almost 170 V. It is determined by multiplying the rms value, 120, by 1.414 to obtain the peak.

Power

The figures in Table 2-1 illustrate several things regarding the power of an AC. Note that the instantaneous power is actually twice the rms power; however, it only lasts an instant (pun intended). The half power point is at 30 where the current is 0.707 (of its rms value), which gives the power as 0.500.

The following conversions should be committed to memory:

- If you have the *peak voltage*, multiply by 0.707 to obtain the *rms* (effective) value.
- If you have the *effective* (rms) value, multiply by 1.414 to obtain the *peak voltage*.

In a sinusoidal or symmetrical waveshape, peak-to-peak voltage is twice the peak voltage. Note too, that for heating the resistor, voltage and current are in phase; that is, the greater the voltage, the greater the current—just like Mr. Ohm told us.

Figure 2-9 illustrates the previous statement that voltage and current are in phase through a resistive circuit.

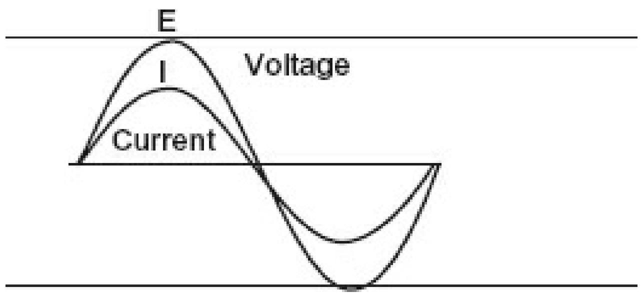

Figure 2-9. Relationships between E and I in a resistive circuit.

Figure 2-9 illustrates that through a resistive circuit, time does not enter into the calculations except when trying to determine the instantaneous values of voltage, current, or power. Those values depend on the source power waveform. Voltage and current are in phase (peaks are at the same time, and zero crossings are at the same time).

Electromagnetic Wave

When energy is cyclic, that is, it is an alternating voltage or current, it carries with it certain phenomena. (Phenomena are things we can observe, measure, and predict but cannot explain well). Fact 1: A difference in potential creates an electrostatic field; this is the potential difference that pushes current. Its *area of influence* is between two points of different charge. (This also creates an arc when the potential overcomes the resistance of the insulator between the charged bodies.) If a difference of potential can cause a current to flow, then the current will vary as the potential (Ohm's law). Fact 2: Current flowing through a conductor sets up an electromagnetic field. The strength of this field is determined by the amount of current (among other parameters).

A wavelength is the distance a field can move at the speed of light (approximately 3.00×10^8 m/s or 186,000 mi/s) *in one cycle*. At about one-sixth of the wavelength, the magnetic field, if it is dominant (usually low-voltage, high-current environments), will create an electrostatic field at right angles to it and the direction of travel. Or, the electrostatic field, if it is dominant (usually high-voltage, low-current environments), will create an electromagnetic field at right angles to itself and the direction of travel. In either case, one will make the other and they are self-perpetuating (propagating) after that, and this leads to radiated energy. The key is that they must be alternating fields to cause this to happen. DC does not alternate. The higher the frequency of the alternations (and the shorter the wavelength), the easier it is to propagate. Table 2-2 lists ACs in order of their frequency and name.

Table 2-2. Electromagnetic spectrum.

Frequency Range	Wavelength (m)	Common Designator
0 to 20 Hz	Infinity to 10,000,000	Sub audio
20 Hz to 10 kHz	10,000,000 to 300,000	Audio
10 kHz to 30 kHz	300,000 to 10,000	Very low frequency (VLF)
30 kHz to 300	10,000 to 1000	Low frequency (LF)

kHz		
300 kHz to 3 MHz	1000 to 100	Medium frequency (MF)
3 MHz to 30 MHz	100 to 10	High frequency (HF)
30 MHz to 300 MHz	10 to 1	Very high frequency (VHF)
300 MHz to 3 GHz	1 to 0.1	Ultra high frequency (UHF)
3 GHz to 30 GHz	0.1 to 0.01	Super high frequency (SHF)
30 GHz to 300 GHz	0.01 to 0.001	Extra high frequency (EHF)
	1 mm to 700 nm	Infrared
	700 nm to 310 nm	Visible light
	310 nm to 10 nm	Ultraviolet
	10 nm to smaller	Cosmic rays

As indicated by Table 2-2, almost all energy is of the AC variety; that is, it has a frequency. Of course, at higher frequencies, the characteristics of propagation differ.

Module 2B: Summary

- AC changes amplitude continuously and polarity periodically.
- The rms value is the transfer value; that is, the rms value will provide the same h effect as a DC voltage of that value.
- To determine the peak voltage or current, multiply the rms (effective) value by 1.4
- To determine the rms (effective) value, multiply the peak voltage by 0.707.
- 1.414 is the reciprocal of 0.707; that is, 1/1.414 = 0.707, and 1/0.707 = 1.414.

Module 2B: Review

See Appendix B for the answers.

1. Answer questions A through E based on Figure R2-1.

   A. What is the peak-to-peak amplitude of this signal? ____________ V

   B. What is the peak amplitude of this signal? ____________ V

   C. What is the rms value of this signal? ____________ V

   D. What is the period (in seconds) of this signal? ____________ s

   E. What is the frequency of this signal? ____________ Hz

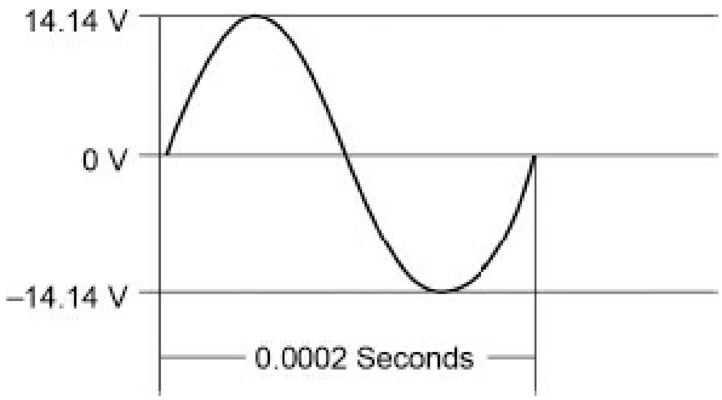

Figure R2-1.

2. An AC signal has an effective value of 12.6 V and a period of 16.67 ms (0.01667 s).

   A. What is the peak voltage? ____________________ V

   B. What is the frequency? ____________________ Hz

3. A sinusoidal AC signal has a peak-to-peak voltage of 35.6 V and a frequency of 1 (1000 Hz).

   A. What is the peak voltage ____________________ V?

   B. What is the effective voltage ____________________ V?

   C. What is the period of one cycle ____________________ s?

4. What is the peak instantaneous power dissipated by a 10 Ω resistor if 15 W is dissip by the effective value?

____

____

____

____

5. Voltage and current are ____________________ phase in a resistive circuit.

   A. in
   B. out of
   C. neither of the above

____

6. You have observed a 100 V peak-to-peak signal with a period of 0.000025 s in a s circuit with a 47 Ω resistor. What are the:

A. Effective voltage ________________ V

B. Frequency ________________ kHz

C. Effective power dissipated ________________ W

D. Peak power dissipated ________________ W

Module 2C: Capacitors

Until this point, electric current has been measured in terms of DC and Ohm's law. AC is somewhat different in its operations. There is still no free lunch; measurements are not always what they appear to be. Two components of any electrical circuit that come into play only when there is a change (and of course AC is always changing) are capacitance and inductance.

Capacitance

There is a capacitance between any two conductors separated by an insulator. So almost all circuitry has capacitance. If there is a *difference in potential* between the two conductors, then there will be an electrostatic field between the two through the insulator. Figure 2-10 illustrates this concept.

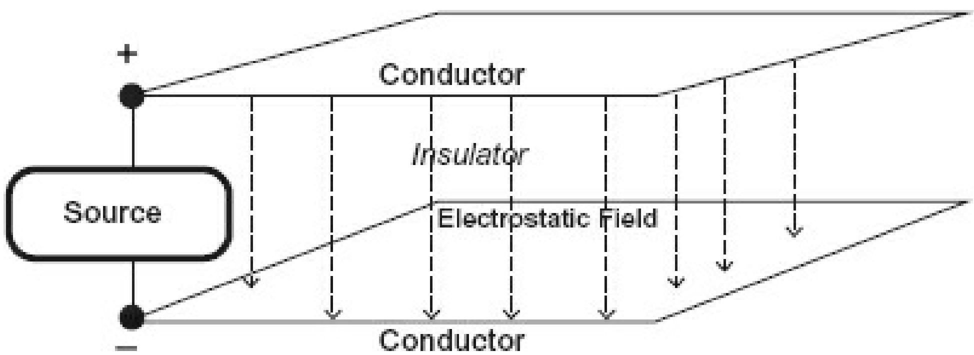

Figure 2-10. Electrostatic field.

The greater the difference in potential, the stronger the field. Remember that the electrostatic field is caused by the difference in the number of charges between the conductors. If we move the two conductors closer together, the field strength will be stronger because field strength is determined by the square of the distance. For a certain strength field, the closer together the two conductors are, the stronger the field per unit area. Another way to increase the strength of the electrostatic field is to increase the size of the conductors; this exposes more area to each conductor, resulting in more charges over a larger area and therefore a stronger field.

If we could find a fairly good insulator, such as glass or mica, and use it to fill the area between our two conductors, this would cause the lines of force to concentrate (much like an iron core does for a magnetic field) and we would have an even stronger field.

In summary, we can increase the strength of an electrostatic field between two conductors by moving them physically closer together, making their exposed surfaces larger, or by changing the insulator between them to one with the ability to concentrate the electrostatic lines of force. Manufactured devices that have these specified properties are called capacitors.

So how did those charges get there? If the charges were in motion (energy was transferred), then work was performed. We can look at Figure 2-10 and intuitively understand that the source potential is going to be all along each conductor, so where and when was the work done? Look at Figure 2-11. It is a schematic of a source, a resistor (representing the resistance of the conductors), a capacitor, and a switch.

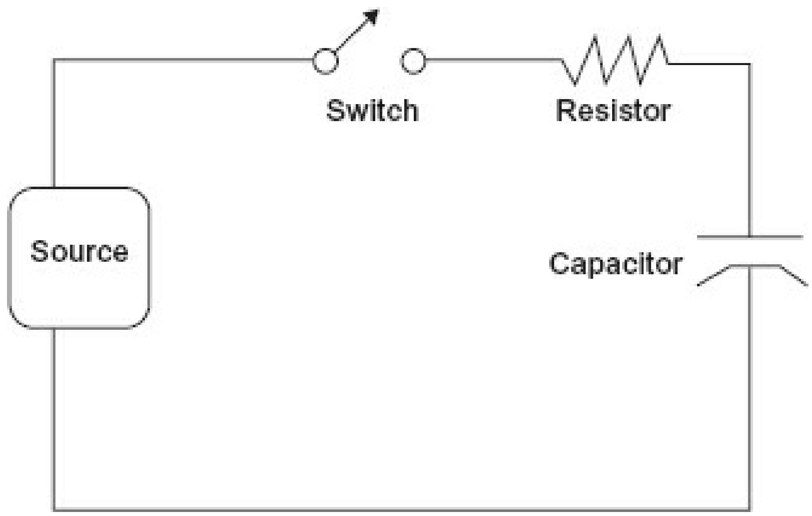

Figure 2-11. Capacitor in circuit.

When the switch is open, and assuming it has never been closed before, there is no difference in potential across the capacitor. Close the switch. Charges must now be transported to the capacitor so the potential difference supplied by the source can be across the capacitor. These are charges in motion, so this is a current. As soon as the charges across the capacitor equal the applied (source) voltage, there will be no more current flow.

If you open the switch, the charges just stay there (ideally). Close the switch again, and because the capacitor is already charged and equals the applied voltage, no current flows.

One consideration is that this charging current had to flow through the resistor. The bigger the resistor, the more it limits the amount of charge that can flow, so the longer it will take to charge the capacitor up to the source voltage.

You might consider a capacitor analogous to a tire on your car. If the tire is flat (and you have repaired the leak), when you apply air pressure to it, the tire will fill up until the pressure in the tire is the same as the pressure applied. Note that the tire did not fill up immediately but was restricted by the size of the supply tube, valve stem, and pressure applied. Remove the pressure and the tire remains pressurized (assuming the valve is OK). The tire has a certain air capacity. Bicycle tires can be at the same pressure as a car tire but hold much less air. It is a question of capacity. The same is true of capacitors. They come in many different capacities and can withstand many different pressures. Only, instead of air, we are filling them with charges, and the pressure across them is measured not in pounds per square inch, but in volts.

Before going any deeper into the whys and wherefores of capacitors, we will examine their physical construction and how they are identified.

Capacitor Voltage Rating

All capacitors are defined by their capacitance and a voltage rating. Because capacitance increases the closer the conductors are placed together, it is reasonable to assume that capacitors will be manufactured with the conductors as close as possible. The problem is that the fields become quite strong the closer the conductors are placed together. At some point, this electrical pressure will overcome the resistance of the insulator. With enough potential, anything will conduct electricity. Therefore, capacitors are designed to withstand a specified amount of pressure based on the strength of the insulator, which is called a *dielectric* when used in a capacitor. This design voltage is normally derated to include tolerances and a safety factor, and this is the capacitor maximum voltage rating. This voltage must not be exceeded. To do so is to ask for a catastrophic failure. And remember this is not the average or rms voltage we are referring to, but the peak voltage under any circumstance.

Dielectric

Capacitors are often named for their dielectric. This is a primary determinant in how much capacity a given physical design can have. Table 2-3 lists the properties of some common dielectric materials compared to air. Air has a dielectric constant of nearly 1, the same as a vacuum. What the constant means is that for a given size and spacing of the conductors, replacement of air by the dielectric material would give you that many more times capacitance.

Table 2-3. Dielectric materials.

Material	Constant
Vacuum	1.0000
Air	1.0006
Paraffin paper	3.5
Glass	5 to 10
Mica	3 to 6
Petroleum	2
Pure water	81

Most capacitors use some form of synthetic, generally plastic, as a dielectric. These have a constant from 3 to 10.

Electrolytic Capacitors

To achieve an even higher capacitance for a given area, electrolytic capacitors are manufactured. In these capacitors, a liquid, paste, or solid dielectric is placed between the conductors and a current is passed through them. This will coat one plate with a thin (very thin) insulating film. These conductors will be very close, and they will have a high capacitance for their physical size. There is a penalty to pay, though. These are directional capacitors. In other words, they are polarized and they must be connected correctly in a circuit where current cannot pass through them in a reverse direction. Installing electrolytic capacitors in the reverse polarity will typically make them develop strong leakage currents, which, after a time, may generate enough vapors (or steam) inside the capacitor to cause a small, yet dangerous explosion. Polarity in electrolytic capacitors should be carefully observed to avoid accidents.

Almost all electrolytic capacitors have some leakage current; therefore, if you charge an electrolytic capacitor at the end of a working day, the next morning the voltage across the capacitor will be near zero volts.

⚠ WARNING

Capacitors store energy. When the charging circuit is no longer available (you have turned the circuit off), if there is no discharge path, the capacitors will retain their charge, perhaps for a long time depending on environmental conditions. You should always check that power supply capacitors have been discharged by measuring the potential across them using your meter (on the appropriate range). High-voltage capacitors that do not have an engineered discharge path may require the use of a shorting stick; as this may result in an arc flash condition, please consult the local procedures prior to proceeding. Follow those procedures exactly—the energy stored could be lethal.

Due to those unwanted characteristics, sometimes it is better to avoid the use of electrolytic capacitors and replace them with other dielectric material capacitors, when feasible. Electrolytic capacitors are generally favored for their size and cost, whereas other technologies are favored for their life span and “no leakage” characteristic.

Capacitor Values

Capacitance is measured in farads (named for Michael Faraday). One farad (F) is a very large unit. Two plates 10 ft high, 10 ft apart, and parallel for 40 mi would approximate 1 F. For a more realistic example, the capacity of a typical 12 V car battery is about 1 F. The general use measurement of a capacitor will be one millionth (1/1,000,000) of a farad, or 1 microfarad (µF). Even that is a large unit, so the basic unit of capacitance is the picofarad (pF), that is, a millionth of a millionth (1/1,000,000,000,000) of a farad.

Although capacitors have a color code much like resistors have, the colors were primarily used in a time when components were large enough to see. Most modern capacitors have the value written on them, which is often a three-number code. The first two numbers are values, the third is the number of zeros. If units are not identified, they are almost always in picofarads. Other units will be identified.

Module 2C: Summary 1

- Capacitors store charge.
- Capacitors have a maximum working voltage that should not be exceeded.
- Capacitors have a basic value of the picofarad, which is 1 millionth of 1 million

farad.

- Electrolytic capacitors are directional and must be inserted in the circuit in the c polarity.

Parallel Capacitors

Connecting capacitors in parallel, as shown in Figure 2-14, results in increasing the area exposed to each conductor. Simple addition of the values will give the resulting capacity. Remember, the working voltage rating will be the lowest rating of any one of the capacitors.

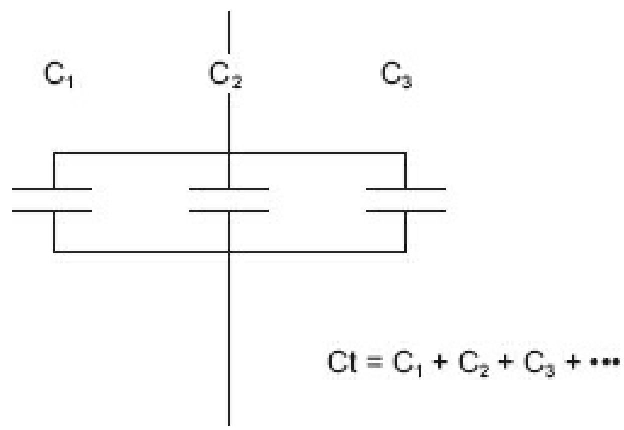

Figure 2-12. Capacitors in parallel.

Series Capacitances

As Figure 2-13 illustrates, capacitors in series present a more difficult concept than those in parallel.

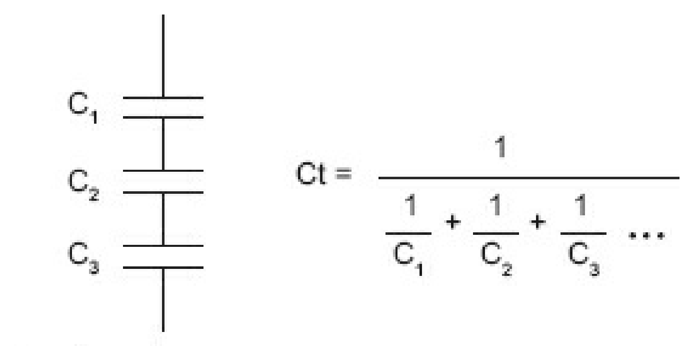

Figure 2-13. Capacitors in series.

In this case, you are separating the top plate of C_1 and the lower plate of C_3. This will reduce the capacitance. How much less? Less than the lowest-capacity capacitor in the series. The amount of charge that can be stored between the lower plate of C_3 and the upper plate of C_1 depends on the capacity of those conductors (plates) in between.

You may have two, three, or as many capacitors as you want in series. Three are chosen here as an illustration, but the concept extends to as many as are in series.

Theoretically, the working voltage becomes the sum of all the working voltages, but it is not a good idea to use a series of capacitors to get a higher working voltage because the distribution of voltage drop depends on the capacitive values and the circuit application, and if one should fail by passing current, the other(s) will also fail.

RC Time Constant

Let us revisit the circuit in Figure 2-11, redrawn here as Figure 2-14.

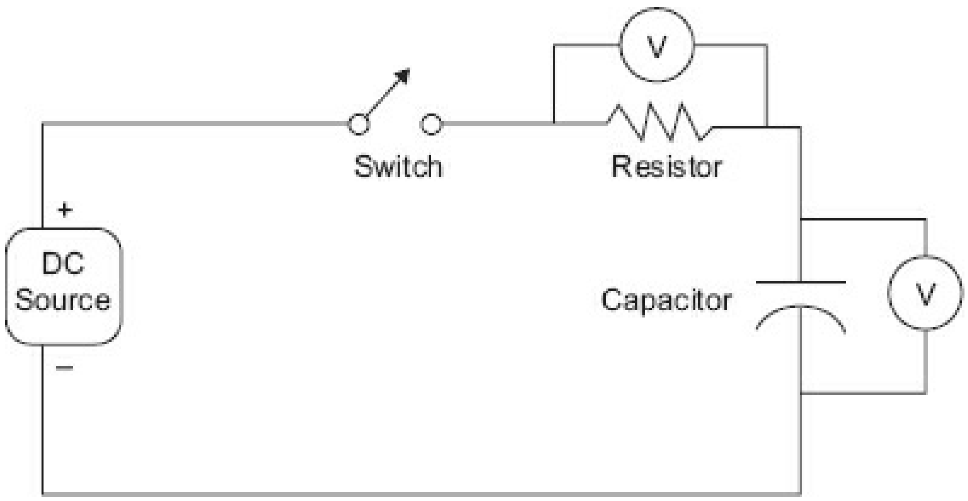

Figure 2-14. RC circuit.

The circuit in Figure 2-14 is called an *RC circuit* because it contains a resistor (R) and a capacitor (C). Assume the source at 10 VDC and that the switch has not been previously closed. The voltmeters will both read 0 V because no charges are in motion in the circuit. It does not provide a complete path for current flow. Assume the resistor is 1 megohm (MΩ; 1,000,000 Ω) and the capacitor is 1 µF. What happens when the switch is closed?

1. The instant the switch closes, the maximum amount of charges will move conductors (plates) of the capacitor.

2. After this instantaneous rush, all other movement of charge will be less beca charges will start to build up on the plates of the capacitor, lessening the p difference between the source and the capacitor and the push to the charges.

3. For the values given in the preceding paragraph, the readings and the time elap shown in Table 2-4.

Table 2-4. RC time readings.

Time	V resistor	V capacitor
1 s	3.72	6.28
2 s	1.35	8.65
3 s	0.50	9.50
4 s	0.20	9.80
5 s	0.00	10.00

Notice that after 5 s, when the capacitor has the same charge across it as does the source, no current will flow. How do you know this? Because the only time you can have a voltage drop across a resistor is when current is flowing through it (remember Ohm's law?). It will make no difference if the switch is opened or closed as long as the charge remains on the capacitor and the source voltage does not change. Figure 2-15 is a graph of the voltage across the capacitor. The numbers inside are the percentage of charge.

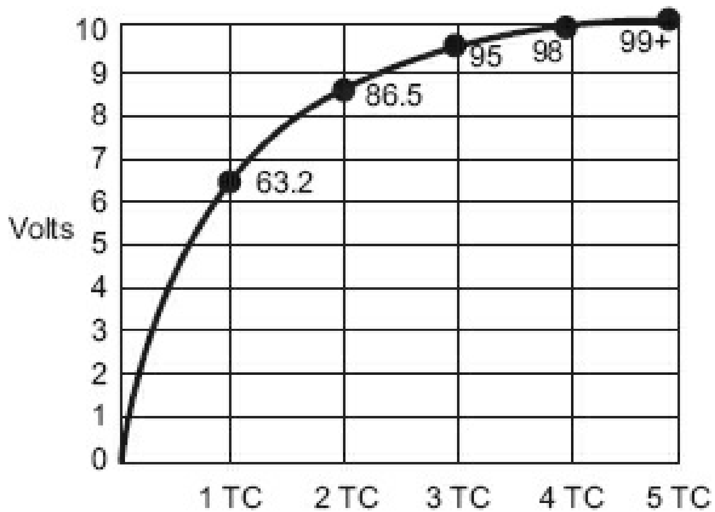

Figure 2-15. RC charging time constant curve.

This curve, called a *time constant curve*, is universal in nature. Nothing in the universe is instantaneous, so there is a time constant curve for every change. Note the key word here is *change*. Capacitors are often described as blocking DC, that is, not letting DC pass. That is not exactly true. Once charged, if there are no changes (and many applications of DC are steady voltages for some period of time), no current will flow in a circuit like the one in Figure 2-16. The other key word here is *time*. Previously, our discussions were about DC and resistance, where any change had a proportional effect on the circuit constants. With the reactive components, time is a key variable to the effect the reactive components will have on circuit operation. Components that react in a time-based manner to change are known as *reactive components*; the capacitor is one of them, but the resistor is not. However, the inductor is also a reactive component. There are two reactive components (capacitance and inductance) and one passive component (the resistor).

As you may ascertain from the previous discussion, there is a proportion that applies to the value of R and C as to how long it will take to completely charge the capacitor. It is quite simple:

1 TC (time constant) = R (ohms) • C (farads)

Or, to be more useful:

1 TC (time constant) = R (megohms) • C (microfarads)

It takes 5 TC to completely charge the capacitor, and it takes 1 TC for the capacitor to charge to 63.2% of its total charge. Each following time constant will be 63.2% of the remainder.

Example

Using the values in the previous discussion, 1 MΩ for the resistor, 1 μF for the capacitor:

1 TC = 1 MΩ (1,000,000 Ω) • 1 μF (1/1,000,000 farad) = 1 s

In 1 s, the voltage across the capacitor will be 63.2% of the total 10 V, or 6.33 V. This leaves 3.67 V remaining for total charge.

During the second time constant, the capacitor will charge up an additional 63.2% of 3.67 V, 2.32 V for a total of 8.65 V.

During the third time constant, the capacitor will charge up an additional 63.2% of 2.32 V, and so on.

If you do this with a calculator, you will find that you equal 10 V at about the third time constant. This results from the rounding of the constant and percentages. That is why some industrial vendors use three time constants rather than five for the 100% point.

Those of you with mathematical training might think, "Whoa, it will never be completely charged because there will always be only 63.2% of the remainder to charge left." Maybe so, but for all intents and purposes, the capacitor is completely charged in five time constants.

Figure 2-16 illustrates a modification of our basic circuit. In this circuit, we can charge the capacitor through R, and we can discharge the capacitor through R. When the switch is thrown so the resistor returns to the other side of the capacitor rather than the battery, the capacitor will discharge. How long will it take to discharge? As long as it took to charge. Figure 2-17 illustrates the discharge graph.

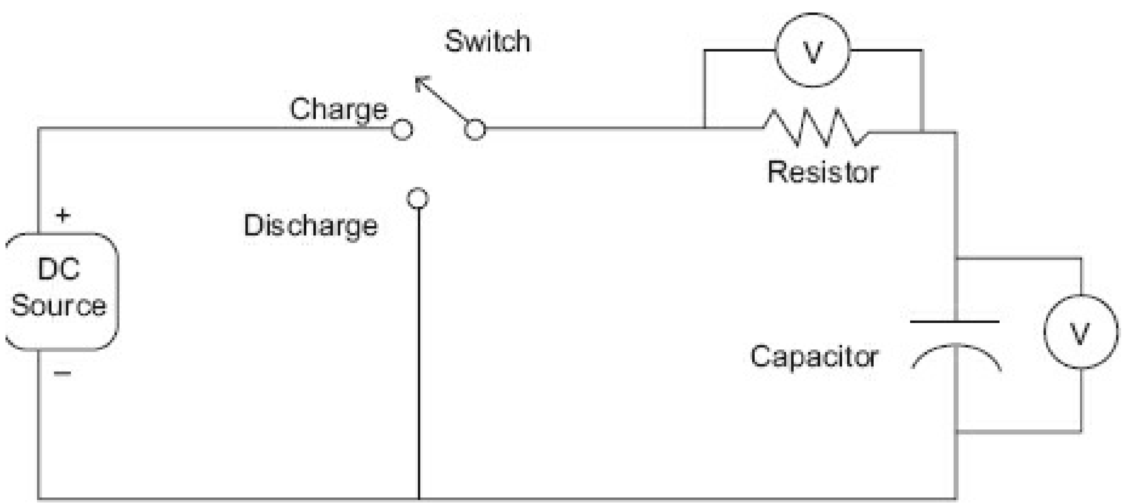

Figure 2-16. Modified RC circuit.

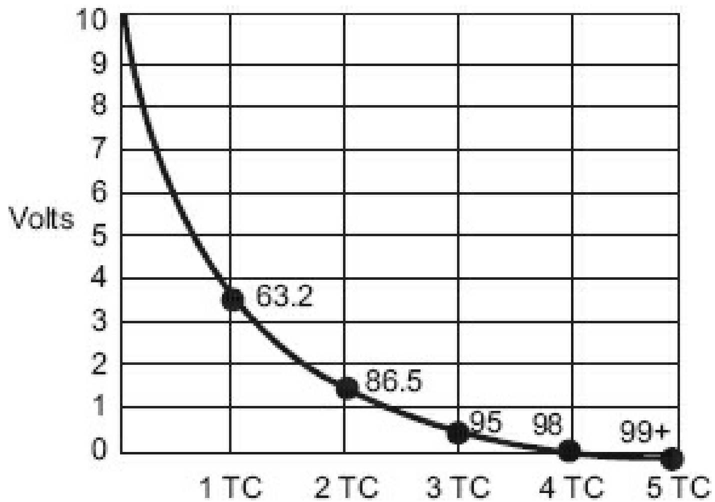

Figure 2-17. RC discharging time constant curve.

Figure 2-17 is the reverse image of the charge chart. Here the capacitor will discharge 63.2% of its total charge in 1 TC, becoming fully discharged in 5 TC.

One aspect of reactive components that is often overlooked is that they do not dissipate power. They store energy and release it. The losses come about due to the resistance of conductors, impurity of insulators, and other factors. Referring to the circuit in Figure 2-16, the resistor will dissipate the power and the capacitor uses none; it merely stores and returns a charge when the circuitry is correct.

Module 2C: Summary 2

- A capacitor takes a finite time to charge, that is, it is not instantaneous.
- A resistor will limit the amount of charges (current) available to the capacitor wh charging; therefore, the larger the resistor, the longer the period of time to charge.
- The larger the resistor, the longer it will take a capacitor to discharge.
- The relationship between time and values is expressed as:

  1 TC = R (ohms) • C (farads), or more usefully as:

  1 TC = R (megohms) • C (microfarads)

- It takes 5 TC to fully charge or discharge.
- Before a capacitor affects a circuit, there must be a voltage (potential) chang defined period of time; otherwise, it acts as an open circuit for DC once charged.

Module 2C: Review

See Appendix B for the answers.

1. A capacitor has a value of 0.047 µF. What is its value in picofarads?

___

2. A capacitor has a value of 27,000 pF. What is its value in microfarads?

___

3. A capacitor has a value of 0.01 µF. What is its value in picofarads?

___

4. A capacitor has a value of 680 pF. What is its value in microfarads?

___

5. A capacitor has a value of 0.15 µF. What is its value in picofarads?

___

6. A capacitor has a value of 1000 pF. What is its value in microfarads?

___

7. A capacitor has a value of 10 µF. What is its value in picofarads?

___

8. A capacitor has a value of 5600 pF. What is its value in microfarads?

___

9. Determine the time constant (TC) for the following values:

   A. 47 kΩ, 15 µF ___

   B. 1.2 MΩ, 0.001 µF ___

   C. 1200 Ω, 150 µF ___

   D. 2.2 MΩ, 2200 µF ___

   E. 390 kΩ, 2200 pF ___

10. If a circuit has 450 kΩ resistance and 0.015 µF capacitance, how long will it take charge this circuit from a 100 VDC source? To fully discharge it?

___

Module 2D: X_C – Capacitive Reactance

Look back at the two curves for the circuit in Figure 2-16, charge (Figure 2-15) and discharge (Figure 2-17). What would be the effect of the following: waiting 5 TC with the switch in charge, throwing the switch to discharge, waiting another 5 TC for it to discharge, returning the switch to charge, and repeating this process each time the circuit is fully discharged or fully charged? This action would appear to allow the entire current (in either direction) through the capacitor. Suppose the switch was thrown after 1 TC? Using the values of the original example, where 1 TC equals 1 s, you would find that current is always moving in this circuit. To the source, it would appear as if it had to supply current at 1 s intervals. How much current? After the initial charge, the source would have to supply exactly as much current as the RC circuit discharged in that time period.

To illustrate the impact of time, the circuit in Figure 2-18 substitutes an AC source for the DC one shown in Figure 2-16.

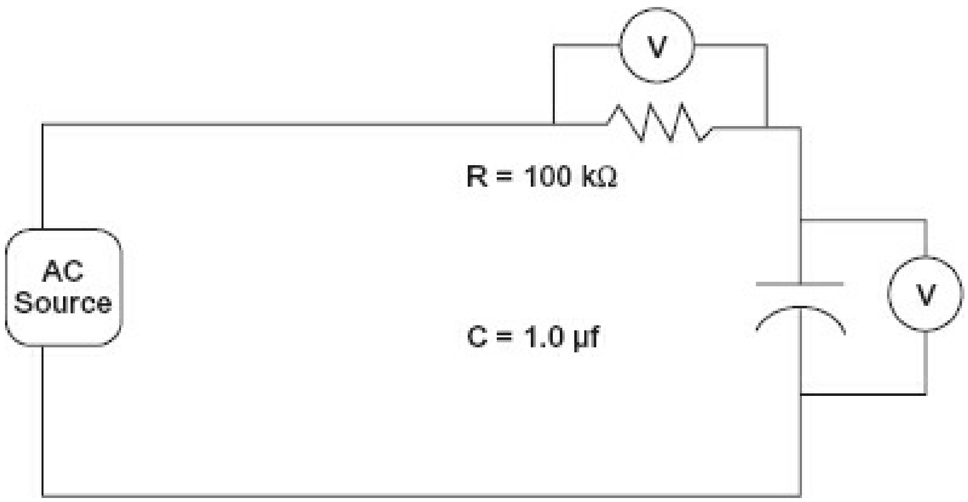

Figure 2-18. AC source for RC circuit.

Integration and Differentiation with an RC Circuit

Note that when a square wave is driving an RC connection (Figure 2-19), the output will depend on the configuration of the RC combination. Of course, correct values and such must be observed, but note that both integration (averaging the waveform change over time) and differentiation (determining the greatest rate of waveform change) are possible depending on how the R and C are connected.

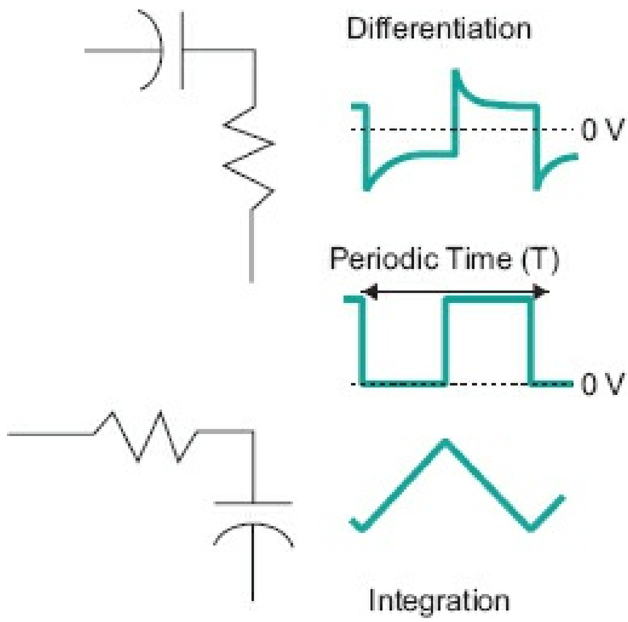

Figure 2-19. DC source (square wave) for RC circuit.

Example

Determine the capacitive reactance of a 1.0 μF capacitor at various frequencies.

Table 2-5. Capacitive reactance.

Frequency (Hz)	X_C
0	infinity (∞)
1	159 kΩ
10	15.9 kΩ
100	1.6 kΩ
1000	0.16 kΩ
10,000	16 Ω
100,000	1.6 Ωs

As you can see, when the frequency goes up, the opposition goes down. At 1.59 Hz for the 1 μF capacitor, the X_C will equal 100 kΩ. This is the amount of R in the Figure 2-20 circuit. In a circuit where the X_C is equal to the R, the voltage drops across both will be equal.

Use an AC source that has a ±10 V output (P–P). This means that when the AC waveform is rising positive, the capacitor will charge in that direction. When the AC waveform is going negative, the capacitor will charge in that direction. The time constant for the circuit is 0.1 s. If the period of the waveform is less than 0.01 s (1/10 the time constant). you can readily see that there will be AC current flow through the resistor. In fact, the resistor will probably drop almost all of the source voltage, because the capacitor is never able to even reach 1 TC before the potential across it reverses direction. This is the portion of the time constant curve that is near maximum current flow. It would appear to the AC source that the capacitor is offering little opposition to AC. That is not quite a true statement. If you decreased the frequency of the AC, then the current would start to fall off according to the time constant curve and it would become apparent that the capacitor was being alternately charged and discharged. If you reduced the frequency low enough, you of course come to DC (0 Hz), and other than the initial change that is limited by the time constant, no current would flow.

The opposition a capacitor offers to AC depends on the value of the capacitance, the frequency of the AC, and the other circuit components. If a capacitor was connected alone across a DC potential, its effect would only be noticeable on voltage changes. There is a relationship defined for the amount of opposition a capacitor exhibits to AC. As you would expect, this opposition goes down as the frequency goes up. The opposition has a name: *capacitive reactance*. Its symbol is X_C, and it is in ohms. The relationship is:

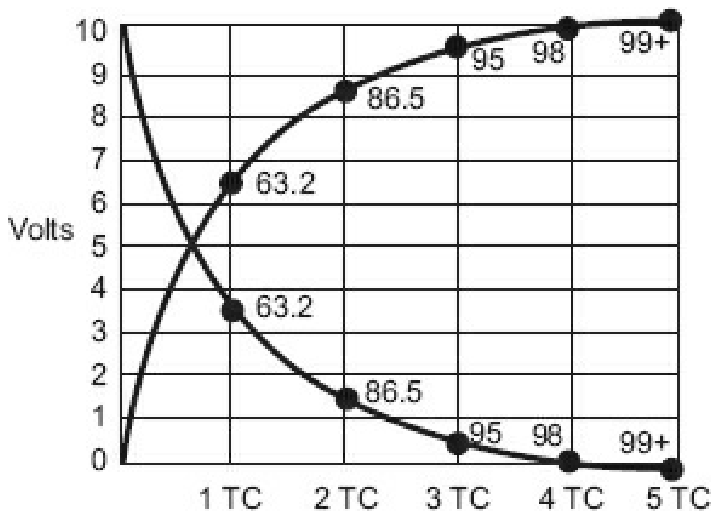

Figure 2-20. RC charge curves.

$$X_C = \frac{1}{2\pi fC}$$

where C is in farads, f is in Hz (or f is in MHz and C is in µF).

If you may recall, the 2π describes a sine wave and the f stands for the number of sine waves in a second (Hz). Let us apply this relationship to the circuit in Figure 2-18.

Phase in an RC Circuit

We now come to a problem that is difficult to place in words. While mathematics makes it easy to express, mathematics, like any language, requires training and practice. This text was designed for those with little of either in mathematics, so the reader who has a math background will have to bear with the author while the phase relationships in a capacitive circuit are explained.

In the circuits discussed, particularly the DC charge circuit, notice that when the current is at its maximum, the voltage drop across the capacitor is at its minimum. When the capacitor is fully charged, current is at its minimum and voltage is at its maximum. The current can be represented by the voltage drop across the resistor—the more the current, the greater the voltage drop across the resistor. This gives us a way to examine what happens in an RC circuit. If we take the circuit in Figure 2-17, and we plot the voltage across the resistor and the capacitor for a charge, it would be similar to Figure 2-20.

If we alternate between charge and discharge, here is a definite phase relationship between the two components, voltage and current through a capacitor. Before you begin to believe that Mr. Ohm has been prevaricating, remember that the voltage we are talking about is the voltage *across* the capacitor; the *current is still pushed* by the *source*! Note too that when a capacitor is going to discharge, the maximum voltage across the capacitor will cause the maximum current to flow. *It is the measurement across a capacitor in an AC circuit that is the problem*. Because the maximum voltage drop does not occur until the capacitor is charged, we say that current leads voltage through a capacitor. A convenient way to remember this is the acronym *ICE*: *I* for current, *C* for capacitor, and *E* for voltage. I leads E through C.

In a purely capacitive circuit (there is no such thing; they all have resistance), the current would always lead the voltage by 90°, that is, if you plotted the current through a capacitor by the voltage drop across it, the two waveforms would be like those shown in Figure 2-21.

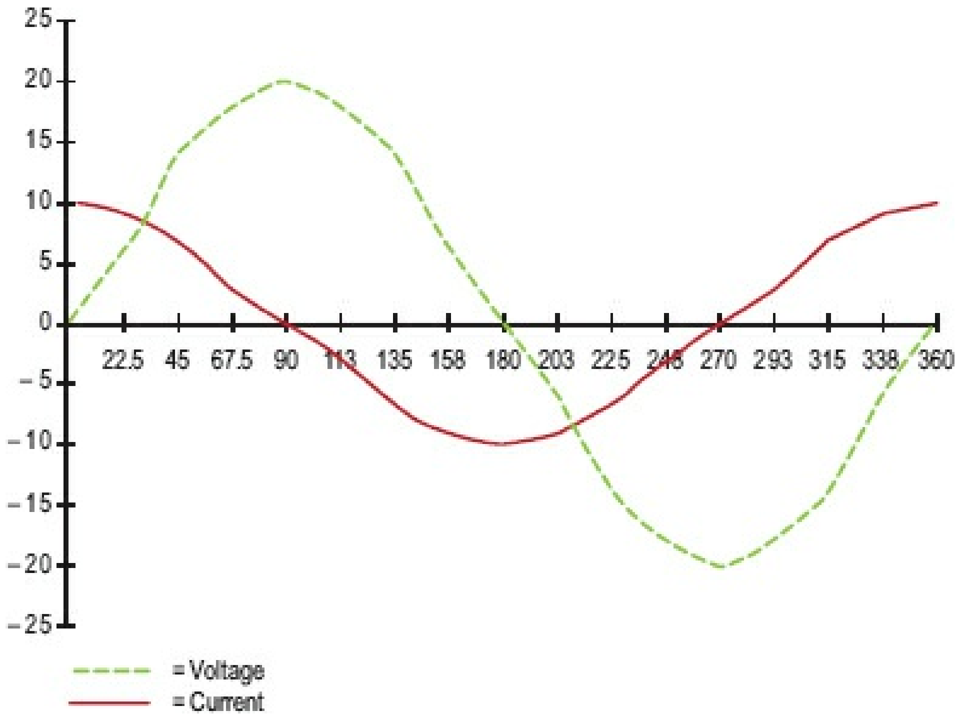

Figure 2-21. Phase relationship E and I through C.

In Figure 2-21, the voltage waveform was made twice the amplitude of the current waveform for better visibility. Note that this is for a pure capacitance circuit. In effect, it tells you that the maximum power will be at the point where the product of E and I is the greatest. Although a detailed discussion is beyond the scope of this module, note that in a purely capacitive circuit, the maximum power will occur where the two lines cross (approximately 45°, 135°, 225°, and 315°, with 0 power at 90°, 180°, 270°, and

360°). Minimum power occurs when there is no current. This relationship is not pursued further here because there are few purely capacitive circuits found in practice.

When you add resistance to the circuit, the phase difference between the voltage and current becomes less. This is easy to visualize. There is no phase difference through a resistor; there is a phase difference of 90° through a pure capacitor. The more the resistance, the more the circuit acts as a resistance. Normally, the phase difference is a design effort and not necessarily a concern of those taking basic measurements. Yet when making measurements in an AC circuit that has capacitance, you must realize that when measuring an AC voltage across a capacitor, the voltage read *cannot be used in any circuit determinations without allowing for the phase difference*.

Application

Calculate the X_C of an unknown capacitor by measurement. You have determined that the capacitor is somewhere between 0.01 and 1 µF by its size and construction.

1. Obtain a function generator as an AC source and a 20 kΩ potentiometer, and (them in the circuit shown in Figure 2-22.

2. Select a frequency range from 10 to 200 Hz and start at 100 Hz.

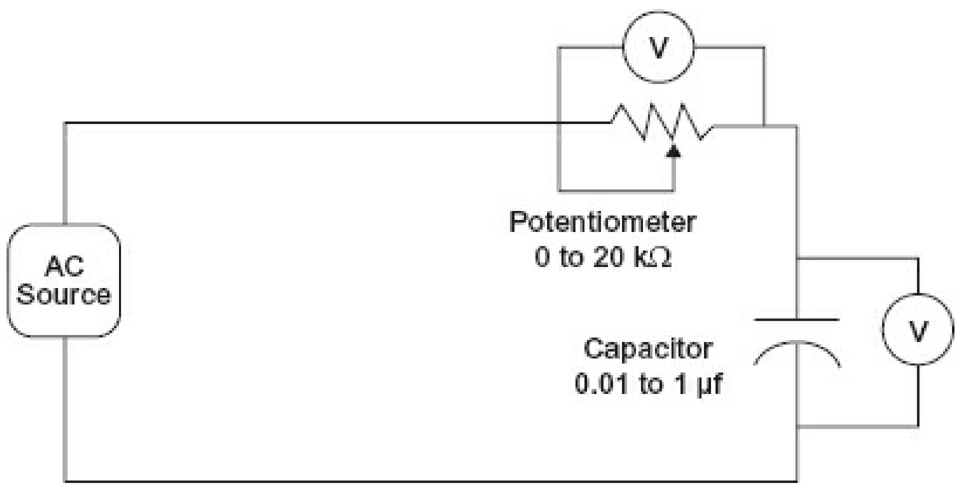

Figure 2-22. Determining X_C.

3. Apply a magnitude of AC that enables easy measurement but does not exc ratings of the capacitor or the potentiometer.

4. Adjust the potentiometer until the voltage drop across the resistor and the capac equal. If this cannot be obtained, try a different frequency range. If you guessed on the range of the capacitor, you will have to try a larger potentiometer. Assum Hz you were able to reach equal voltage drops across the resistor and capacitor. point, the phase angle will be 45°, and the resistance of the potentiometer and equal.

5. Remove the potentiometer from the circuit and measure its value. The measu

will be the approximate value of X_c for that capacitor depending on the toleranc resistor and the accuracy of the meters involved. Also, the source frequency sho be so high as to render the meters inaccurate. Assume in our application the v resistance measured is 15.9 kΩ.

6. Use the formula for X_c rearranged to obtain the capacitor's value.

$$C = \frac{1}{2\pi f X_c}$$

7. Obtain the value, which with our example numbers is 0.1 µF.

If a better measurement of a capacitance is desired, there are many instruments that are capable of accurate measurement.

Module 2D: Summary

- Changing voltage across a capacitor will cause the charge current to change.
- The opposition to a change in voltage by a capacitor is called reactance.
- Reactance varies with the R and C values and the applied frequency.
- The formula for X_C is:

$$X_C = \frac{1}{2\pi f C}$$

- Remember ICE (ELI the ICEman, where *I* stands for current, *C* stands for capac stands for voltage, and *L* stands for inductance) current leads voltage thro capacitor.

Module 2D: Review

See Appendix B for the answers.

1. Determine the capacitive reactance (Xc) of the following capacitors at the frequency.

   A. 100 kHz, 0.015 µF ____________________

   B. 60 Hz, 2200 µF ____________________

   C. 1 MHz, 680 pF ____________________

   D. 25 kHz, 1.5 µF ____________________

   E. 300 kHz, 0.002 µF ____________________

Module 2E: Inductive Reactance

The other reactive component is inductance. Electromagnetism was discussed earlier, and we will continue that discussion. As stated earlier, an electric current flowing through a conductor creates a magnetic field at right angles to its direction of travel, and a conductor moving through a magnetic field at right angles to the field will have a current induced in the conductor.

Now, let's coil the conductor to concentrate the magnetic field. This magnetic field, which is now in motion, cuts across the conductors of its own coil inducing a voltage.

The voltage induced in the coil creates a current flow in the opposite direction from the current causing it. The greater the change, the greater the opposition. This is illustrated in Figure 2-23.

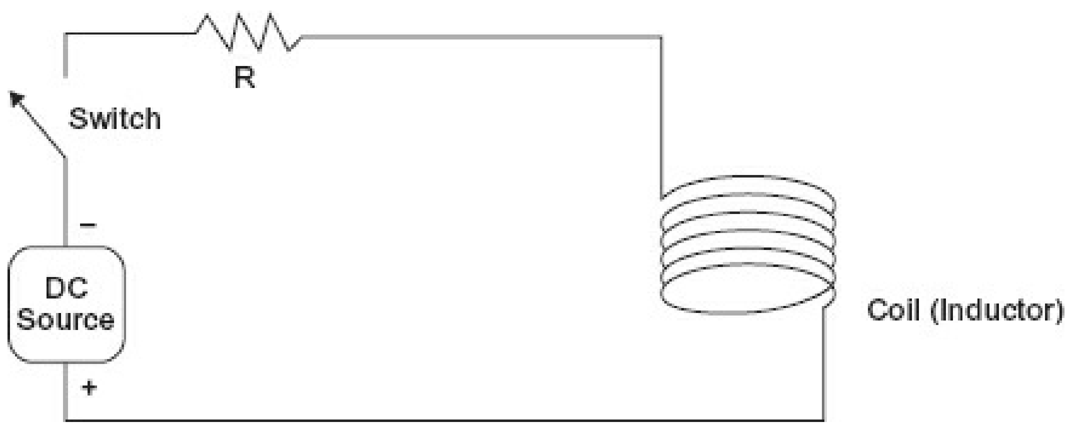

Figure 2-23. An R-L circuit.

When the switch is open, it is obvious that no current flows. It is also apparent that after the switch is closed and has remained closed for some time (more than 5 TC), maximum current will flow. The only limit to current will be R, which might represent the resistance of the windings of the coil, or an external resistance, or both. In any case, the resistance of the coil is included in R.

But what about the moment when the switch is closed? At the time of closure, the rate of change of current in the circuit is at its maximum; anytime you go from zero to something in a small increment of time, the rate of change is rapid. Current attempts to flow through the coil. Because of the rapid rate of change, a large current is induced in the opposition direction as the current tries to set up a magnetic field. As time elapses, the rate of change—which is the amount of change divided by the time in which the change takes place—becomes less and less, causing more and more current to flow and the magnetic field to increase, until eventually the amount of current limited by the source potential and the resistance of the circuit is flowing and the magnetic field is at its maximum. Figure 2-24 illustrates the concept.

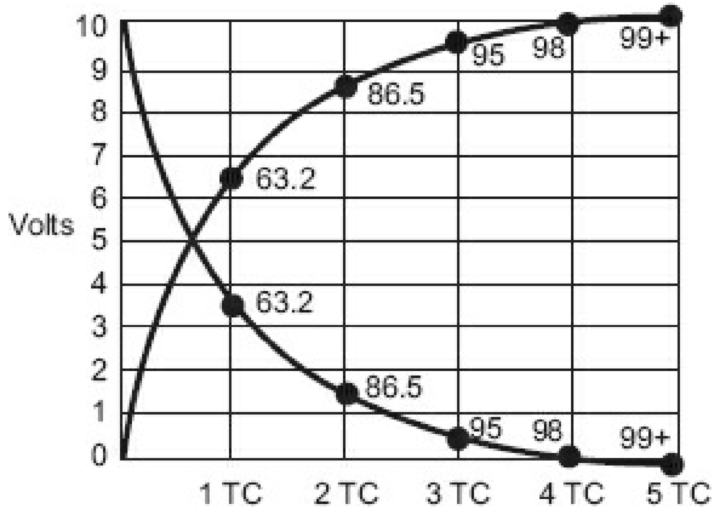

Figure 2-24. L-R circuit curves.

These curves represent a series R-L circuit with a resistance of 10 Ω and a supply voltage of 10 VDC. The upward rising curve represents the voltage drop across the resistor, while the decreasing line represents the voltage drop across the coil.

You might think those curves look a lot like those for a capacitor, only reversed. You are absolutely right. Time constants apply here as well as for the capacitor. Because 1 TC is equal to R (in ohms) times C (in farads) for a capacitor, and because the inductor behavior is opposite of that of a capacitor, 1 TC for an inductive circuit is L (in henries) divided by R (in ohms), shown in Figure 2-25.

$$TC = \frac{L}{R}$$

Figure 2-25. Inductive time constant.

Practically, we see the ratio means the lower the amount of resistance to the amount of inductance, the greater the time constant. Because less resistance means less opposition to current flow, the initial rate of change will be greater and take longer to overcome.

The energy produced by the opposition current is called *counter electromotive force (CEMF*). The magnetic field contains energy. It takes energy to produce this field, and the energy is not lost nor dissipated as heat. The CEMF is the *opposition to setting up this field*. Just like charging a capacitor requires a *change in voltage* to cause charges to be put into motion (current), inductance requires a *change in current* to create (or discharge) a magnetic field and the resultant CEMF (*back voltage*, as it is sometimes called).

Inductance (and inductive reactance) is common to all conductors. Its unit of measurement is the henry (H). The henry is defined as: 1 hour is the *inductance* that will cause *a change of 1 A per second to produce 1 V CEMF*.

Module 2E: Summary 1

- All conductors have inductance.

- An inductance produces a CEMF that counteracts current changes.
- There is no energy lost in a magnetic field, but it takes energy to set up.
- The greater the rate of change, the greater the CEMF.
- An R-L circuit's time constant is determined as 1 TC = L (henries) **/** R (ohms).
- Remember ELI (ELI the ICEman), where voltage leads current through an inductc

Discharging the Magnetic Field

Refer to Figure 2-26.

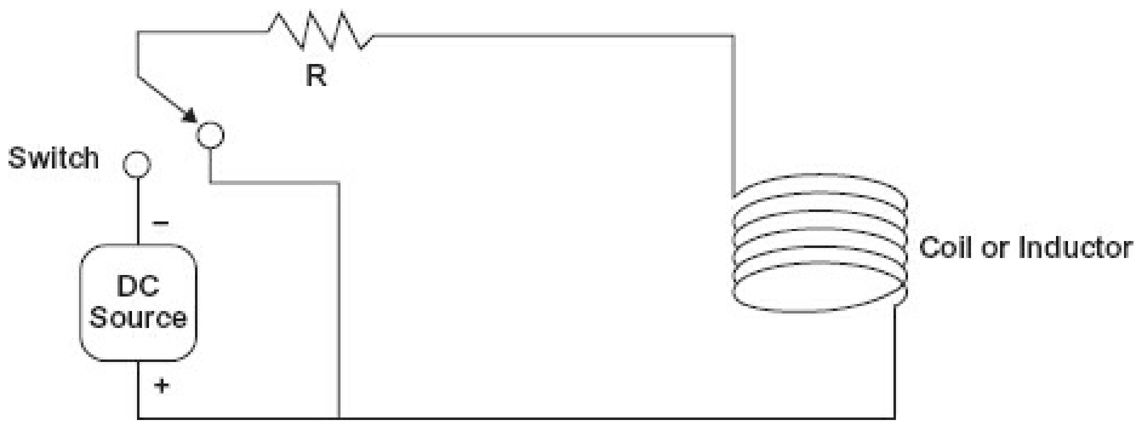

Figure 2-26. Discharge of R-L circuit.

When the switch is thrown to the position shown, the magnetic field will collapse. All the energy stored will be released by the collapse of the field. As the field collapses, the magnetic lines of force cut across the conductors, inducing into the conductor a current that will oppose the change. When the circuit charged, the counter E was in opposition, so the polarity would have been where the end of the coil next to the source negative was negative. When discharging, this end of the coil is positive, causing current to flow in the same direction as the charge current (opposing the decrease change).

What if the discharge path was not there? Suppose you just decided to open the switch. Recall the concept of power. There is instantaneous power, but the power we are most interested in is the average power. To average, you must have time. It took the coil some finite time to charge as determined by L / R. That was the power it took to set up the magnetic field. Now, no power is lost in the field; it is stored in the field, and then you open the switch. You are asking for the circuit to make an extremely rapid rate of change. Although it took some amount of time to charge, you wish the coil to discharge instantly. True, the coil will collapse rapidly; this will set up a rather large voltage. How large? Large enough to ionize the air around the switch as you are opening it and arc the field energy across the switch contacts. Remember that power is equal to (E • I) / Time. For example, making power a fixed number, the amount of power it took to set up the field is 1 W over 1 s. This could mean 10 V at 0.1 A would give 1 W/s. Now you are trying to discharge the circuit in, say, 1/10,000 of a second. That means the product of E • I must be 10,000 to make the same amount of power in the reduced interval of time. As a result, you could have 50,000 V at 0.2 A for 1/10,000 of a second. You are not getting something for nothing; rather, it is like saving $50 a month for 10 years ($6000) and then going to Las Vegas and spending it all in one night. Same amount of money, just over a different period.

⚠ CAUTION
This principle that the voltage will rise to any level to dissipate the energy stored in the collapsing field is known as inductive kick. It is the principle used to develop the 50,000 V spark plugs required by a car's 12 VDC battery. Inductive kick must be considered. Failing to do so could be hazardous. Large inductive loads on DC circuits must have some means of discharging the field energy other than the switch. The arcs developed could cause severe burns and even fatality. Even small inductive loads store energy and are responsible for destroying many switch contacts and semiconductor outputs.

Inductors

All conductors have inductance. However, special devices have been developed that have specified amounts of inductance. They are called *inductors*. Coils and transformers all have inductance, and it is an effect that must be considered. Inductors are designed for the frequency range over which they will operate. Types of inductors range from those with ferrous cores (relatively low frequency) to those with air cores (generally higher frequencies). The general classification of inductors is by their core.

Ferrous core inductors may have a solid ferrous core, a laminated ferrous core, or a powdered/ferrite core. The reason for the different cores is to prevent currents from being set up in the core, which would dissipate their energy as heat and cause the coil to be inefficient.

Inductors designed for audio and radio frequencies are sometimes called *chokes* due to their ability to impede high frequency currents. Laminated core chokes are most often used at power frequencies because they provide a large amount of inductance without a core-induced current problem.

Toroidal inductors are those formed as a doughnut of powdered iron (see Figure 2-27). They have a very high inductance for their size. Ferrite cores are toroids of a certain length that are slipped over conductors to provide the effect of a choke.

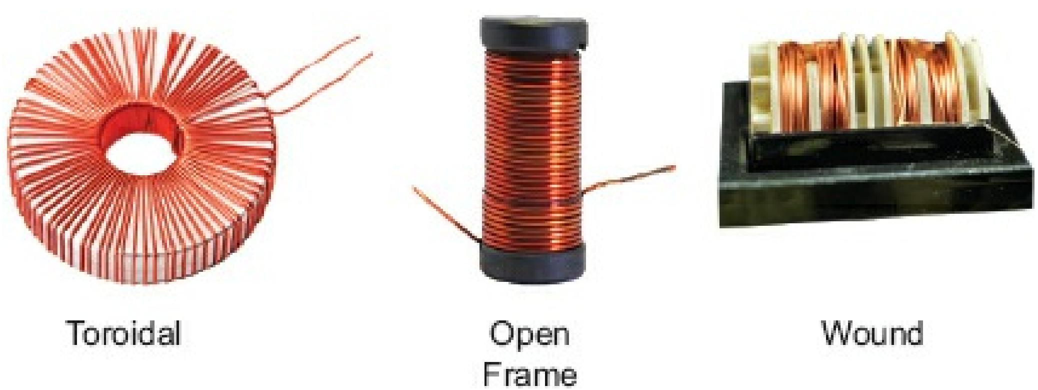

Figure 2-27. Various inductors.

Other than the amount of inductance given in henries (H) or millihenries (mH), the only rating of concern for inductors is voltage. This is the maximum amount of voltage the insulation around the conductors can withstand. It should not be exceeded.

Inductive Reactance

As with the capacitor, the opposition an inductor offers AC depends on frequency. This opposition is called *inductive reactance*, or X_L. L is the symbol attached to inductors. It is easy to see that the more rapid the change, the more opposition an inductor offers to the change in current. Therefore, the inductive reactance rises with frequency. The relationship between frequency, inductance, and reactance is shown in Figure 2-28.

$$X_L = 2\pi fL$$

where

X_L = inductive reactance

$2\pi f$ = sine wave at f frequency

L = inductance in henries

Figure 2-28. Inductive reactance.

Module 2E: Summary 2

- When an electromagnetic field collapses, the energy will be dissipated either th intended paths or through arcing.
- The ability of an inductor to raise the CEMF to the value that is necessary to dis the energy is known as inductive kick.
- Inductors come in different sizes and shapes and are generally identified as air c ferrous core.
- Inductive reactance is identified as X_L.
- Inductive reactance is expressed as $X_L = 2\pi fL$.

Inductive Phase Relationships

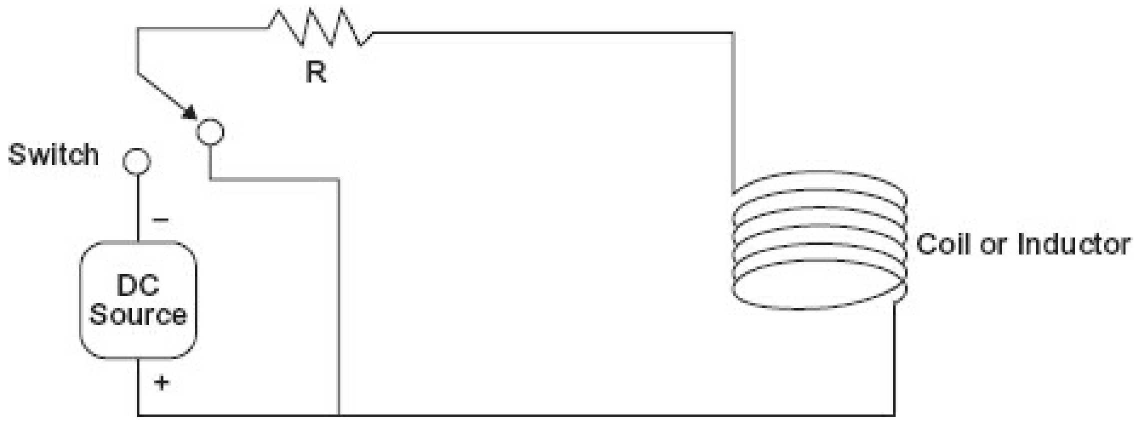

Figure 2-29. Switched RL circuit.

As with capacitors, phase relationships come into play when inductors are in a circuit. In Figure 2-29, when the switch is closed to charge the coil, there will be minimum current and maximum voltage drop across the coil. When the fifth time constant has passed, there will be minimum voltage drop across the coil, but maximum current through the coil. It appears to be the opposite of a capacitor, and indeed it is. Where current led voltage through a capacitor, voltage leads current through an inductor. The mnemonic for this is *ELI*, where *E* stands for voltage, *L* stands for inductance, and *I* stands for current. Together these memory tags can be remembered as ELI the ICEman. You will have to ask your grandparents what an iceman was.

A graph of the relationships between voltage and current for an inductor is shown in Figure 2-30.

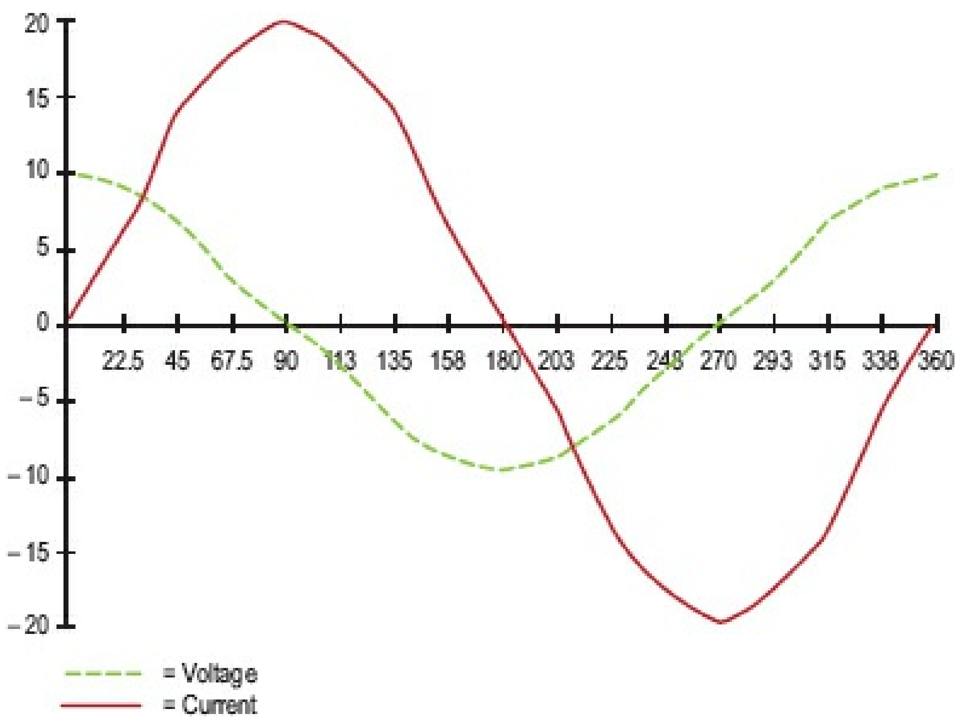

Figure 2-30. Phase relationships in an RL circuit.

Here the voltage is represented by the line that starts at 10, and the current starts at 0. In this graph, the current is twice the amplitude of the voltage to increase visibility.

This graph is only good for the theoretical idea of an inductor with no resistance. Perhaps in the superconducting mode this is possible, but not in the normal world at this time. All inductors have resistance themselves, plus the resistance in the circuit. This will reduce the phase difference. As before, phase difference is a design effort, and other than knowledge that it exists and its effects on measurement and the behavior of circuits, no greater investigation into the phase difference will be undertaken in this text.

Module 2E: Summary 3

- There is a phase difference between current through a transformer and the v across the transformer.
- In a pure inductive circuit, the phase difference between voltage and current is 90
- Voltage leads current through an inductor—ELI.

Module 2E: Review

1. Determine the TC for the following RL circuits:

   A. 12 H, 1.2 kΩ ____________________

   B. 1.5 H, 10 Ω ____________________

   C. 7 H, 25 Ω ____________________

   D. 450 mH (millihenry), 4.7 kΩ ____________________

   E. 180 mH, 120 Ω ____________________

Module 2F: RCL Circuits

Figure 2-31 illustrates a series resister-capacitor-inductor (RCL) circuit.

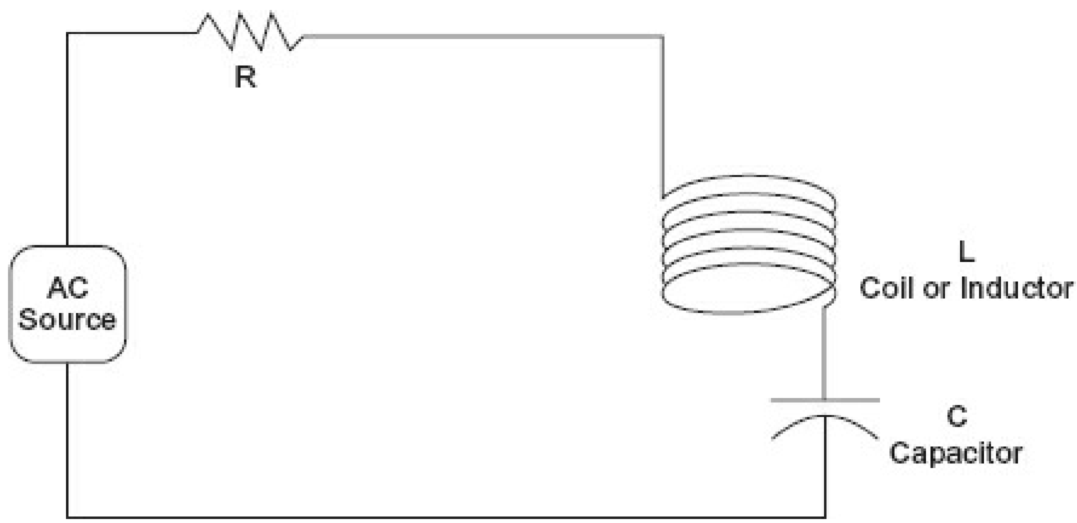

Figure 2-31. Series RCL circuit.

What is the behavior of this circuit? Let us list what we know about RL and RC circuits. First, they behave in an opposite manner. Current leads voltage in the capacitor, voltage leads current in the inductor, and both are in phase in the resistor. The inductor and the capacitor actions both depend on frequency.

If we adjust the frequency so that both C and L drop the same voltage, then their reactances are equal. Because they are opposite in effect, they cancel at this point and only the resistance is left. This condition, where X_L and X_C are equal, is called *resonance*. The frequency at which this occurs is called the *resonant frequency*. In this case, the smaller the R, the greater the amount of current that may flow. At higher or lower frequencies, either the inductive (at higher frequency) or the capacitive (at lower frequency) will offer more opposition, so the minimum opposition this circuit offers is at resonance, at the resonant frequency.

Impedance

The total opposition an RL, RC, or RCL circuit offers to AC is called *impedance*; its symbol is Z, and it is measured in ohms. Remember that reactance is offered by the capacitor or inductor by itself, without resistance. Because there are few uses of an inductor or capacitor by itself, they are generally used together with resistances in practical applications.

Resistance is considered the *real* part of the impedance equation. Inductive and capacitive reactance have phase shifts and are called *imaginary* (or mathematical) components of the total impedance. Take no heed of the word—their effects are real and extremely useful, just hard to determine at times. Impedance can (and will) vary if the frequency of interest varies because it determines the imaginary components, the inductive and capacitive reactances. The formula for impedance is shown in Figure 2-32.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Figure 2-32. Impedance formula.

Of particular note, the resonant condition is when $X_L = X_C$. The square root of R squared is R. This is just what we said earlier. If there is just inductive reactance or just capacitive reactance, then it is just that term, as shown in Figure 2-33.

$$Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{R^2 + X_L^2}$$

Figure 2-33. Inductive/capacitive reactance and impedance formulas.

Parallel RCL Circuit

Figure 2-34 illustrates a parallel RCL circuit.

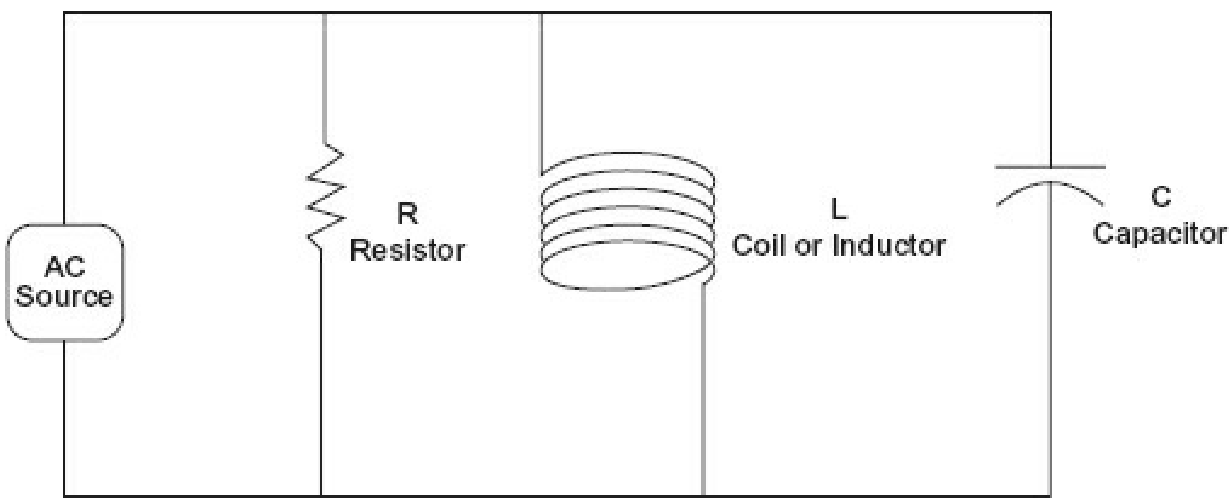

Figure 2-34. Parallel RCL circuit.

At some frequency, the inductive reactance and the capacitive reactance will become equal, leaving only the R in the circuit. In this case, R will be the maximum opposition to current flow. At lower frequencies, the inductor will offer less opposition. At higher frequencies, the capacitor will offer less opposition. Only at resonance will you obtain the *maximum resistance and voltage drop, and least amount of current*.

Application

In your radio or TV, there must be a means of selecting the station you wish over all the others available. Typically, a parallel RCL circuit is used with a variable capacitor or inductor. You tune the resonance of the RCL circuit to the carrier frequency (the frequency by which the station is identified) by varying a reactive component. Only that frequency will produce a significant voltage; all others are shunted by the capacitive or inductive branch. The signal is then amplified and detected for your listening enjoyment.

Module 2F: Summary

- Resonance is the frequency at which the inductive and capacitive reactances are e
- Impedance is the total opposition a circuit offers to AC and is measured in ohms.
- The formula for the impedance of a series RL circuit is:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

- Using a serial resonant circuit, the current drawn by the circuit will be at its ma at resonance.
- Using a parallel resonant circuit, the line current will be at its minimum while a current will circulate between the L and C components.

Module 2F: Review

See Appendix B for the answers.

1. Determine the resonant frequency for a 1 µF capacitor and a 0.10 H inductor.
2. Determine the impedance of the following circuits at the frequency given.

A. 1 kHz, 1 H, 2 kΩ ____________________

B. 12 kHz, 0.15 µF, 3.3 kΩ ____________________

C. 330 kHz, 360 pF, 1 mH, 5 kΩ ____________________

Module 2G: Transformers

A transformer is a special kind of inductor. Up to now, we have been dealing with self-induction, calling the result CEMF. If we put two (or more) coils in the same moving magnetic field, both will have a current induced in them. We call this effect *mutual induction*, and it too is measured in henries. One hour of mutual induction is where 1 V is induced in a coil by a change in current of 1 A per second in another coil in the same magnetic field. Figure 2-35 illustrates various types of transformer schematics. We use transformers for several primary reasons:

- Change voltage levels
- Match impedances
- Provide isolation

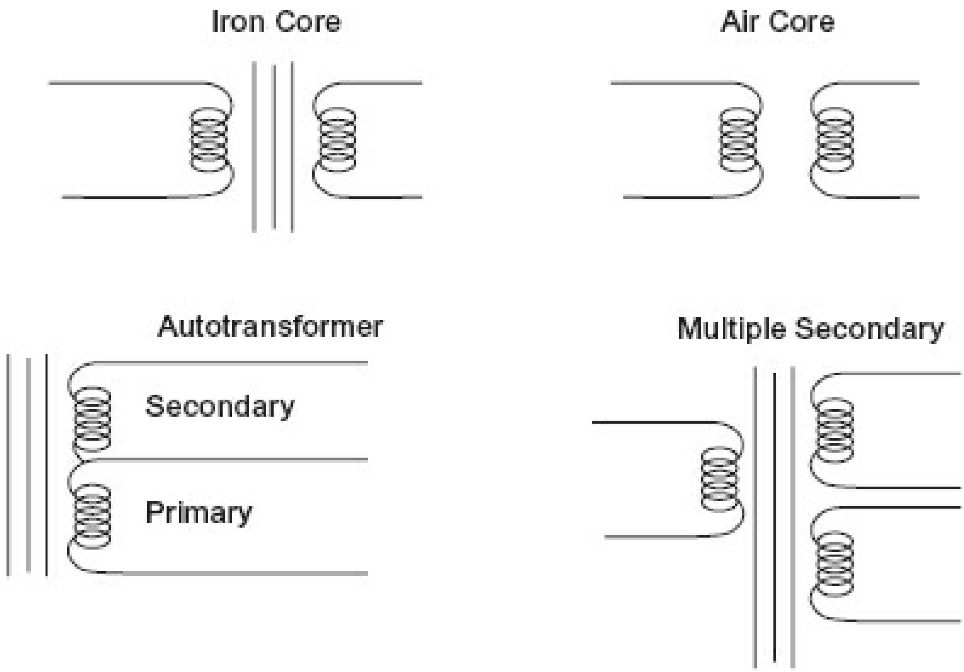

Figure 2-35. Transformer schematics.

Keep in mind that what has been discussed previously for inductors is true of transformers because they are nothing more than inductors in the same magnetic field.

Primary and Secondary Windings

Transformers transfer power from the primary to the secondary windings. This is done totally by magnetic coupling, without direct connection of any type. Because the primary and secondary are insulated (electrically) from each other (except in the autotransformer, whose primary and secondary are the same winding), a transformer isolates the primary circuit from the secondary circuit.

The designation *primary* is given to the transformer coil that is driven by the power source. *Secondary* is the designation for the winding that drives the load. Generally, a transformer will have one primary and one or more secondary windings.

Coefficient of Coupling

How tightly coupled the primary and secondary windings are—that is, how many of the lines of magnetic flux the primary and secondary have in common—is referred to as the *coefficient of coupling*. Power transformers and those with ferrous (iron-like) materials for cores generally have high coefficients of coupling. If 100% of the lines of force (flux) are common to both the primary and secondary, they have a coefficient of coupling of 100%. Air core transformers have a much lower coefficient of coupling.

Turns Ratio

A transformer can step a voltage up or step a voltage down, that is, it can change voltage levels from the primary to the secondary. This is determined by the *turns ratio* of the transformer. Assuming 100% for the coefficient of coupling, the turns ratio will tell you exactly what secondary voltage you will have with any primary voltage. The following ratios express that relationship, as shown in Figure 2-36.

$$\frac{\text{turns primary}}{\text{turns secondary}} = \frac{\text{voltage primary}}{\text{voltage secondary}}$$

$$\frac{\text{turns primary}}{\text{voltage primary}} = \frac{\text{turns secondary}}{\text{voltage secondary}}$$

Figure 2-36. Turns ratios.

So, if the transformer had a 10:1 (the primary is always given first) turns ratio and 120 V rms input to the primary, then 120 is to 10 as 12 is to 1, so 12 V would be the secondary voltage. Caution: This is only true for a coefficient of coupling near 100%.

Conversely, if the turns ratio was 1:10 and 12 V rms was applied to the primary, the secondary would be 120 V rms. Before you think that this is an ideal way to a free lunch, remember power. The secondary cannot create power. The power supplied by the secondary must come from the primary source. Figure 2-37 illustrates a transformer circuit.

Example

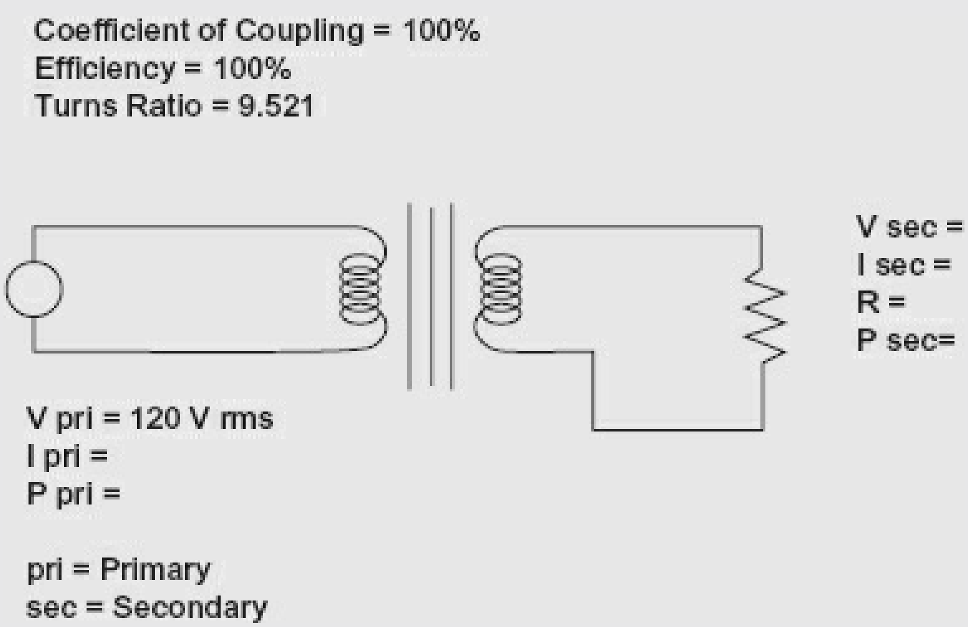

Figure 2-37. Transformer circuit.

If R = 10 Ω, what is the secondary voltage, secondary current, secondary power, primary current, and primary power?

The turns ratio is 9.52:1. For 120 V rms, the secondary voltage will be 12.6 V rms; 12.6 V (effective) across 10 Ω will have a current of 1.26 A. The power will be (P = E • I) = 15.8 W. Assuming 100% coupling and efficiency, the same power will be drawn in the primary. The primary current will be 132 mA (15.8 W = 120 V • 132 mA). You could solve the power formula algebraically (I = P / E), or you could simply divide the secondary current by the turns ratio. For 100% coupling and 100% efficiency, the relationship in Figure 2-38 holds true.

$$\frac{I\ sec}{I\ pri} = \frac{V\ pri}{V\ sec}$$

Figure 2-38. Power ratio.

As you can see, there is an inverse relationship between the current in the secondary and the turns ratio. The efficiency of the transformer is never going to be 100%. This is due to losses in the transformer core and the resistance of the windings. So, the power consumed in the primary is always going to be more than that used in the secondary. The point being that any power consumed in the secondary is drawn from (reflected to) the primary. Efficiency of a transformer is expressed (Figure 2-39) as:

$$Eff = \frac{P\ sec}{P\ pri} \cdot 100$$

Figure 2-39. Transformer efficiency.

Although it is always true that the primary will draw as much or more power than the secondary, the turns ratio will not predict the secondary voltage as neatly when the coefficient of coupling is less than 100%.

Application

Conductor size determines the *ampacity* of a conductor. The larger the cross section of the conductor, the greater the amount of current or ampacity of that conductor. When distributing power, a utility company must be concerned about ampacity. If your residence draws 100 A, then a certain size wire will be required. Multiply that by the number of residences in a given distribution area, and the wire would have to carry, for example, nearly 100 kA. It would require a big wire, and it would cost a great deal. Instead, the utility company will step up the voltage of the generated electricity using a transformer; Figure 2-40 illustrates a typical distribution.

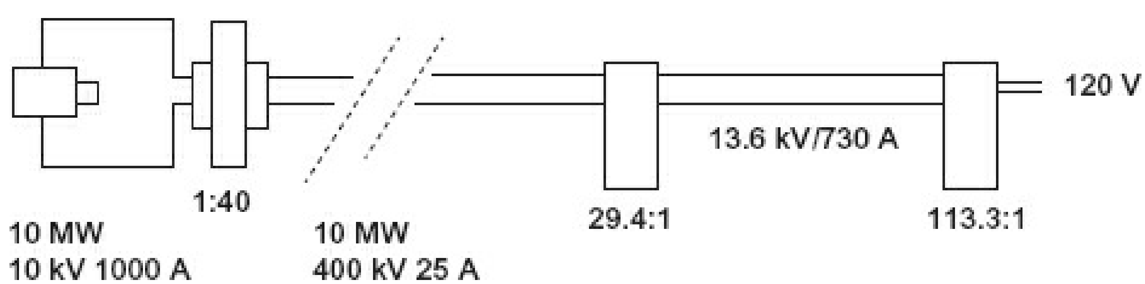

Figure 2-40. Electrical distribution.

As you can see, the long-distance transmission at 400 kV enables the use of smaller conductors. There are many intermediate voltages; this is only an example. A simple look at this should demonstrate that when the 120 V end user uses 10 A (1200 W), this is a draw of about 0.88 A, which is about 0.003 A on the 400 kV line and about a 0.12 A draw on the 10 kV generator.

Suppose there is no load on the secondary. What does the primary do? It becomes an inductor with a large amount of reactance at the frequency of operation. With no load and only the resistance of the winding and losses in the core, the primary winding without secondary load approaches 90° voltage leading current. Little power is consumed. As the secondary load increases, this phase angle becomes smaller and smaller. The efficiency of a transformer increases as the load increases (up to the specification current).

Example

If your house has a doorbell, then it has a doorbell transformer. The doorbell transformer is usually mounted in the attic or an out-of-the-way place. Figure 2-41 illustrates a doorbell circuit.

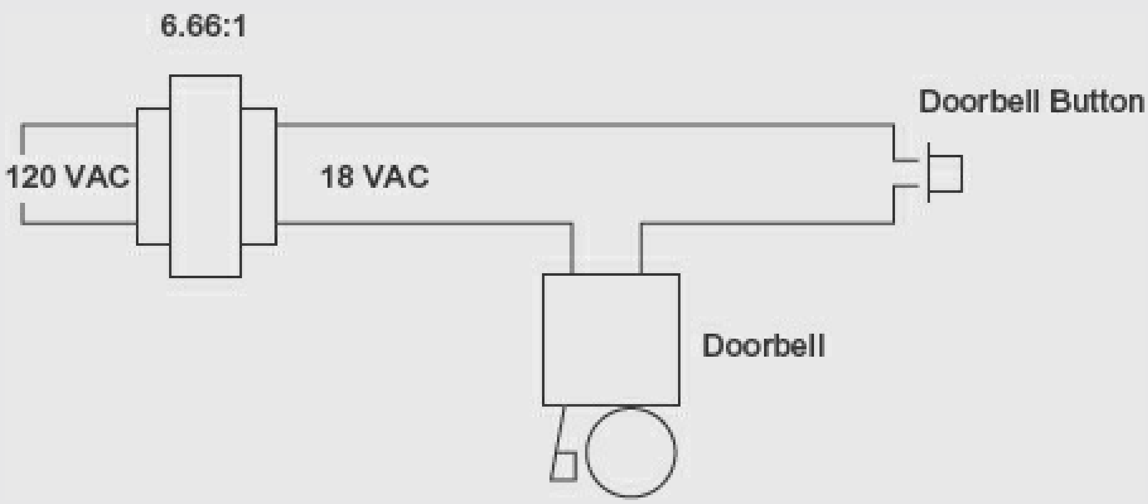

Figure 2-41. Doorbell circuit.

Notice that the 120 VAC is not brought to the doorbell button; that would be hazardous. The doorbell transformer is always across the line. It does not draw power until the door button is depressed. The transformer is not designed to supply a steady current to the door bell and in fact is overloaded when activating the doorbell. This has two advantages. First, the doorbell transformer can be made cheaper and smaller, Second, it can be designed to be quite efficient when not supplying power, generating little heat, and having low core losses.

Impedance Matching

Prior to a discussion on how transformers match impedances, we should discuss why you would want to match impedances. It is a fact that for maximum power transfer, impedances must be matched. Impedance has been previously defined, so let us see what this really means.

Matching impedances means that the source impedance matches the load impedance. Using only resistive values (and at 0° phase angle, loads are resistive in inductive circuits), Figure 2-42 illustrates power transfer.

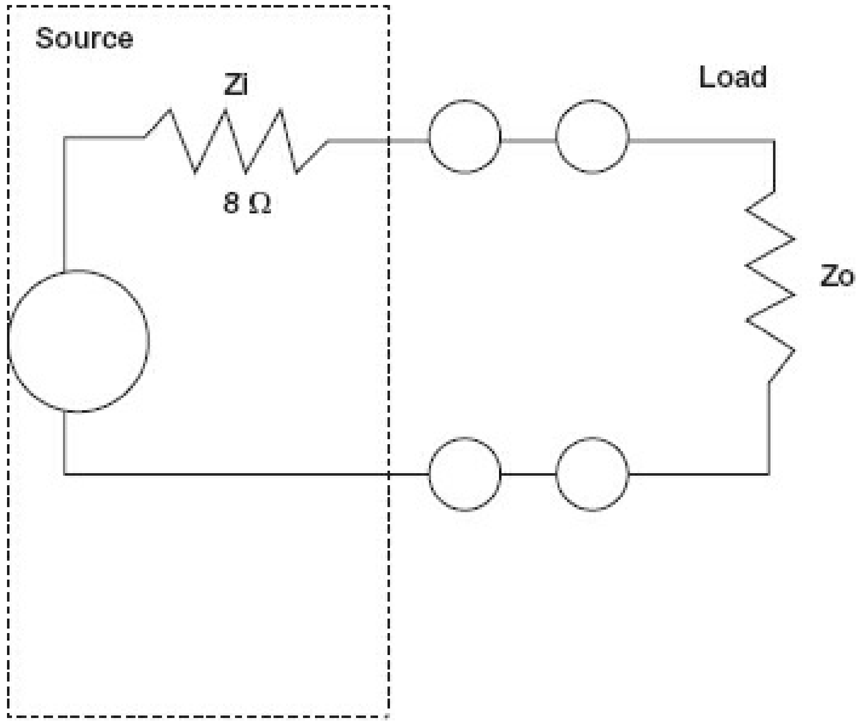

Figure 2-42. Power transfer.

Assume the supply provides 8 V. Table 2-6 shows the various values of power for differing values of Z_i in Figure 2-42.

Notice that the maximum power for the load was transferred when Z_o equaled the Z_i of 8 Ω. Transformers can match impedances because the secondary load is reflected in the primary.

Table 2-6. Power transfer example.

Z_o	R_t	I_t	VZ_o	PZ_o(W)
0	8	8	0	0
2	10	0.80	1.6	1.28
4	12	0.67	2.7	1.81
6	14	0.57	3.4	1.94
8	16	0.50	4.0	2.00
10	18	0.44	4.4	1.94
12	20	0.40	4.8	1.92
14	22	0.36	5.1	1.84

There is a direct relationship between the turns ratio (number of turns—N) and the impedance (Z) transformation. The relationships are shown in Figure 2-43.

$$\frac{Z\ pri}{Z\ sec} = \left[\frac{N\ pri}{N\ sec}\right]^2$$

or

$$\text{turns ratio}\ \frac{N\ pri}{N\ sec} = \sqrt{\frac{Z\ pri}{Z\ sec}}$$

Figure 2-43. Impedance ratios.

The turns ratio squared is the impedance ratio.

For example, if:

Z primary = 7200 Ω

Z secondary = 8 Ω

What turns ratio is required to match these impedances?

$$\frac{Z\ \text{primary}\ 7200}{Z\ \text{secondary}\ 8} = 900$$

$$\text{Turns ratio} = \sqrt{900}$$

$$\text{Turns ratio} = 30$$

The transformer must have a 30:1 turns ratio.

Isolation

Because transformers couple energy by a magnetic field and not by direct connection, they are isolating the primary from the secondary circuits. This will break up ground loops (unintentional currents flowing in the grounding system due to variances in ground potentials geographically) and diminish noise.

Transformers specifically designed for isolation are called *isolation transformers* and should be in every measurement facility. They have an equal number of primary and secondary windings. Their purpose is not to step up or step down, but to electrically isolate the secondary equipment from any other grounds, paths, and so on. In many instances, the signal ground is tied to the chassis ground, which is tied to the third-wire ground. To break this connection when using measurement devices, isolation transformers or battery-powered devices should be used on all measurements to prevent leakage and fault currents from disturbing the measurements.

Module 2G: Summary

- Transformers separate the primary and secondary windings electrically by co energy through magnetic lines of flux.
- An isolation transformer should be used with all line-powered test equipment used to measure other line-powered equipment.
- Maximum power is transferred from a source to a load when the source and impedances are matched (equal).
- A transformer can match impedances by using the relationship:

$$\text{turn ratio } \frac{N_{pri}}{N_{sec}} = \sqrt{\frac{Z_{pri}}{Z_{sec}}}$$

Module 2G: Review

See Appendix B for the answers.

1. A transformer has a 1:25 turns ratio. Is it a step-up or step-down transformer?

   ____

2. A transformer with a 9.52:1 turns ratio has 220 VAC applied to the primary. Wha secondary voltage?

   ____

3. If a transformer primary has 1.5 A at 120 VAC and the secondary supplies 12 and draws 10 A, what is the efficiency of the transformer at this level of sec power?

   ____

4. If the source impedance is 16 Ω and the secondary requires 3.6 kΩ, what turns ra satisfy the requirement?

   ____

5. Turns ratio = 25:1. If the source impedance equals 10 kΩ, what is the sec impedance?

   ____

Conclusion

You have reached the end of Module 2. Please reread the module objectives (in the "Objectives" section). If you have met these objectives, continue to the next module. If you are having difficulty, please reread the text. If the difficulty persists, locate a peer, mentor, supervisor, or someone who has technical knowledge of AC and ask them to assist you.

Further Information

For additional information on the topics in this module, search for the following topics at your public or company library, or on the Internet.

- Alternating current
- Electromagnetic radiation
- Radio waves
- Alternating current basics
- Alternating current theory
- Electromagnetic radiation
- Electrostatic fields

3
Electrical Measurement Tools

Accuracy was discussed in Module 1B, and the concepts we covered will be helpful in this module where we discuss measurement tools, primarily the multimeter and oscilloscope. Here we begin the tools discussion with a more in-depth treatment of accuracy as applied to instruments.

Previously, accuracy was stated in terms of the difference between the true value and the measured value. This difference is called *error*. This module discusses methods for anticipating and correcting the error in measurement, which include applying statistical techniques and using computer-generated calibration curves, which are either manually or automatically applied. You should be familiar with the concepts found in this module, so you can make measurements with a degree of confidence that the required accuracy will be achieved. *Remember: All measurements have some error*.

Module 3: Objectives

- Describe the characteristics of various analog meter types.
- Describe the characteristics of digital meters.
- Describe the characteristics and features of other measuring devices, such a oscilloscope and time domain reflectometers.
- Determine the type and magnitude of measurement error.
- Define standard deviation, Gaussian curve, mean, and median.
- Discuss the effects of calibration, calibration standards, and calibration error.

Module 3A: Measuring Devices

Analog Meters

Although digital meters have become the norm in the technological arena, it is beneficial to review some of the analog meter technology as the digital meter was developed to overcome analog meter shortcomings.

There are many analog meter constructions. For DC measurements, there are three basic types of meter movements and many modifications of these basic movement types. The basic types are:

- D'Arsonval (a.k.a. moving coil)
- Core magnet
- Taught band

All these movements are similar, differing primarily in the shape and placement of the permanent magnet and method of springing the movement. Because most are obsolete given the digital revolution, only the most common type—D'Arsonval—will be presented here. Basically, movement construction presents a magnetic field to a coil (bobbin). The coil is energized by the measurement current, which creates a magnetic field. The permanent magnet's field and the coil's field interact producing a torque. Because the bobbin is free to move, it will rotate depending on the measurement current's strength and polarity. The coil is mounted with springs that produce a torque that holds the coil and its attached pointer at the zero-measurement point on the scale. The springs will return the pointer to zero when the measurement current is removed.

D'Arsonval Movement

Figure 3-1 illustrates the basic structure of the D'Arsonval meter movement. The moving coil is pivoted at both ends, usually in jeweled bearings, and wound around a metallic core.

The entire bobbin assembly is precision mounted and statically balanced. Balance is provided by pointer counterbalances, which also provide a degree of damping to the pointer movement due to their inertia. The springs (known as *control springs*) carry the current to the coil bobbin and determine the meter movement's linearity. The control springs oppose the torque developed by the current through the coil bobbin and are calibrated for the required deflection current.

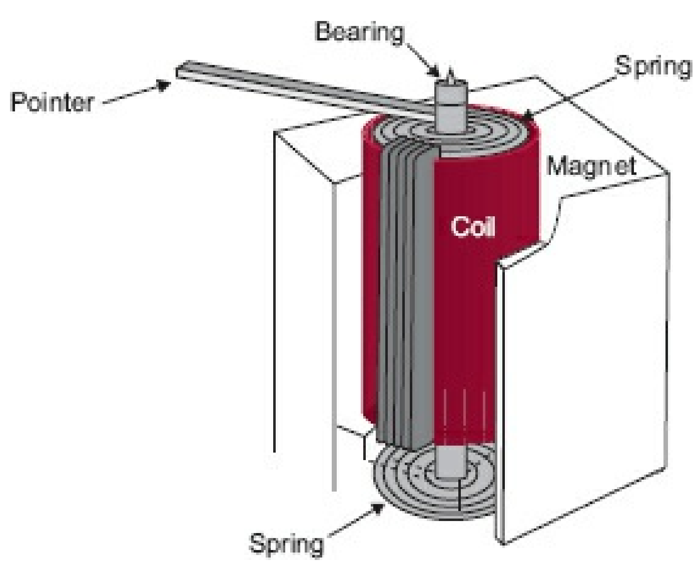

Figure 3-1. D'Arsonval meter movement.

Most meter movements provide for a mechanical zero, usually accessible from the front of the meter case as a screwdriver adjustment. This adjustment is used to align the meter point with zero prior to applying current to the meter.

⚠ CAUTION
Be careful when making this adjustment as unrestricted rotation of the external adjustment may damage the movement.

Full-Scale Deflection Current

The amount of current necessary to cause the complete rotation permitted (usually 180° to 270°) by the movement is called *full-scale deflection* (FSD) current. Meter movements come in a variety of FSD currents ranging from as little as 1.0 µA (1/1,000,000 A) to values in amperes.

The basic meter movement is that of an ammeter, a current measuring device. While it is adapted to measure voltage or resistance with the help of additional components, remember that to make a measurement, a certain amount of current will have to flow through the meter circuit.

Meter Accuracy

Analog meters are specified with a guaranteed accuracy at FSD. This will be the best accuracy obtainable as accuracy decreases for any other portion of the scale.

We will use a D'Arsonval meter as an example. If a D'Arsonval meter movement has a 10 VDC scale, it has a guaranteed accuracy of ±2%. If the meter reads exactly 10.0 V, the actual voltage measured can be anywhere from 9.8 V to 10.2 V. Using the formula for accuracy:

$$\frac{\text{true voltage} - \text{measured voltage}}{\text{true voltage}} \bullet 100 = \%\ \text{accuracy}$$

The formula for accuracy can be converted to give the range of error at FSD.

$$\frac{\pm\ \%\ \text{accuracy}}{100} \bullet \text{FSD voltage} = \pm\ \text{range true voltage}$$

For the above example:

$$\frac{0.2\ VDC}{100} = \pm 2\%$$

The range of ±0.2 V is established at full scale. This range of uncertainty remains the same for any measurement taken on this scale.

Using the meter in the previous example, and on the 10 VDC scale the meter indicates exactly 5.0 V, in what range will the true voltage be found, and what is the accuracy of reading at this point?

The range of uncertainty is the same for 5.0 V as it is for 10.0 V, that is, ±0.2 V. So, the real voltage will be between 4.8 and 5.2 V.

$$\frac{\pm 0.2\ \text{V}}{5.0\ \text{V}} \bullet 100 = \pm 4\%$$

Table 3-1 provides the percentage of accuracy for the example meter for various measurements.

Table 3-1. Tabulation of the example meter's accuracy variance in percent.

Scale Voltage	± % Accuracy
10	2.0
9	2.2
8	2.5
7	2.8
6	3.3
5	4.0
4	5.0
3	6.6
2	10.0
1	20.0

This example emphasizes the importance of taking meter readings as close to full scale as possible when measuring voltage or current using an analog meter. An old rule of thumb was to always take the readings in the upper third of the scale.

Ohms Scale

When using analog meters, there is one exception to taking the readings in the upper third of the scale. The exception is when resistance measurements are being made. The ohms scale on analog meters is a logarithmic, not linear, scale. Because of the crowding of the scale at the upper end, readings there are generally just guesses. At the lower end, the readings are quite spread out, but because this is still an analog current meter, the lowest end is where the meter movement is least accurate. Readings are best taken at mid-scale. Due to the proliferation of digital meters, their superior method of measuring small currents, and the clarity of their presentation, use of an analog meter for resistance measurements is best reserved for historical presentations.

Analog Meter Characteristics

Using Ohm's law, it becomes apparent that an analog meter movement has a resistance. It has an FSD current that will require some value of FSD voltage to force the FSD current through the coil windings. Because analog meters are generally sold based on FSD current and accuracy as their specifications, replacing a meter requires knowledge of the meter's internal resistance.

Module 3A: Summary

- One of the important characteristics of an analog meter is its full-scale deflection current.

- Another important characteristic is the internal meter resistance.

Module 3B: Digital Meters

Analog versus Digital Voltmeter

Analog voltmeters have some advantages:

- D'Arsonval meters can read true root-mean-square (rms), regardless of the wave: Electronic meters typically read peak value and divide that by 1.4142 to obtain th This "conversion" factor only works for sine waves.

- For different waveshapes, rather large error readings are possible. Dollars mig wasted and equipment damaged because of wrong calibration due to measurement errors. Of course, there are many "true rms" digital meters, bu specifications should be perused to ensure compatibility with the application.

Analog voltmeters have several significant disadvantages when compared to contemporary digital meters:

- Inaccuracy of movement

- Poor mechanical reliability

- Parallax problem

- Meter sensitivity

- Costs

In this section, we will discuss how the digital meter overcomes the analog meter disadvantages, and discuss digital meter disadvantages, if any.

Accuracy of Movement

- **Accuracy of movement** – The analog meter relies on its physical construction to g accuracy. Bearing friction, nonlinearities in the tension spring, and even ph deformities in the magnet construction all limit analog accuracy to about 0.5% best. Because a digital meter does not use a physical movement, these disadvantag overcome. Digital meters use analog-to-digital conversion circuitry and an elec reference, which gives them their basic accuracy. Even inexpensive digital r approach 0.25% accuracy, which is better than the most expensive analog vol meters (VOMs).

- **Mechanical reliability** – A digital meter is primarily an electronic device. On switch and the display itself have any contribution to lack of reliability fr mechanical viewpoint. Probes do give problems, but they are analog or digital. LCDs do not perform well in very cold weather; however, as electronic instrumer digital meters are considerably more rugged than analog meters.

- **Parallax** – This is where you may obtain different readings on an analog depending on your viewing angle. More expensive analog meters have a mi scale. The purpose is to line up the pointer with its image in the mirror, and then will be no parallax. Digital meters do not have a parallax problem.

- **Meter sensitivity** – Most modern digital voltmeters have an input resistance of 2 in total, not per volt, regardless of scale. Because a digital meter only requires current to operate (in the picoampere range), and the analog meter requires subs (comparatively speaking) current to operate, the digital meter will have a much h sensitivity.

Considering all the advantages of digital meters, and their low cost for performance, are there any analog instruments left? This is a good question, one that can be answered.

When trying to view a trend, or when trying to null (zero) a reading, in many instances an analog meter, because of the way it responds, makes it easier to visualize the quantity that is changing. If you have ever tried to record on digital media and had to set the record level, you will understand this concept. It is easier to obtain the intuitive average and separate it from the peaks with an analog meter than to do the same with a digital meter. To compensate, many digital meters also display a digital bar (like a thermometer) that is more than adequate for trend observations. In conclusion, there is no advantage to the analog meter (other than the fact that analog VOMs do not require batteries for volt and amp measurements).

Other than specialized instances, analog voltmeters have been relegated to the past as newer and smarter digital meters take their place. At this point, the only discussion relative to digital voltmeters is how many digits (accuracy) the meter provides, what type of display it has, and how many tricks (functions) the meter can perform.

With the advent of large-scale integration of semiconductor circuits, many functions were encapsulated in one small piece of silicon. Test equipment has advanced, as have other areas of electronics application. About 60 years ago, digital meters were large, expensive, bulky devices that were hard to use, calibrate, read, and understand. Today, however, digital technology has rendered the analog meter obsolete.

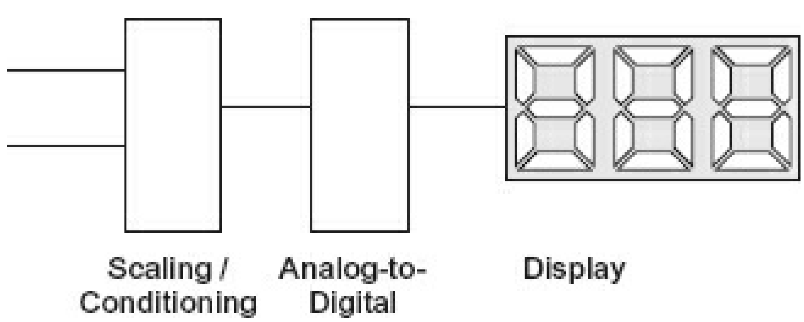

Figure 3-2. Simplified block diagram of a digital meter.

Figure 3-2 illustrates the block diagram of a digital meter. The actual analog-to-digital conversion will be covered later and is not relevant at this point; however, it is instructive to notice that the display (in digits) removes the possibility of parallax. A modern digital meter has an input resistance of above 10 MΩ, so determining the internal meter resistance will not be necessary. The meter movement has been replaced with a display, and although the display (whether LCD, LED, or EL, which are explained in the following sections) is not an object to receive a continuing large amount of shock, neither is it as fragile as the analog meter movement. The main decisions when purchasing a digital meter are whether it will display 3½, 4½, or a greater number of digits and its input power requirements.

LED Displays

Light-emitting diode (LED) displays come in various colors but for meter displays are normally red or red-orange. LEDs require considerable current for activation, on the order of 10 to 20 mA. The display is usually packaged with its driver electronics, although much older meters may have separate driver chips to convert the voltages for metal-oxide-semiconductors (MOSs) used in the chip to the currents necessary to drive the LED. Typically, the LED has a matrix as shown in Figure 3-3. One of the disadvantages of an (older or less expensive) LED display is its tendency to wash out under bright ambient light, making the display hard to read. However, today many bright LED displays are available that are easily read even in strong daylight. LED displays are easy to discern in low light levels, requiring no backlighting.

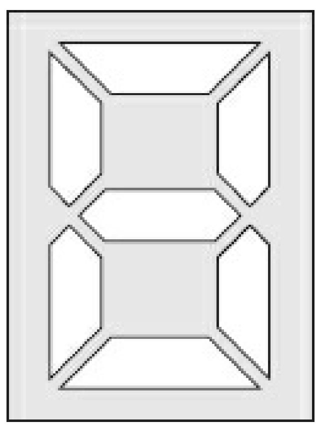

Figure 3-3. LED matrix.

Liquid Crystal Displays

The liquid crystal display (LCD) obtains its image by the cross polarization of the liquid crystal elements that make up the display. An AC voltage is applied to both the background and the element of the LCD. When an element is to present an image, an out of phase voltage of the same frequency is applied only to the element. As a result, the element will reflect light. The LCD produces no light of its own but works by reflected light. This means it is easy to read under high ambient light. Under low-light conditions, back lighting must be supplied to read the display. LCD displays are nearly as rugged as LED types but do not display as well in colder temperatures.

EL Displays

Electroluminescent (EL) displays use a gas discharge (much like neon) in the image element to provide a bright display even in the presence of high ambient light. These were the forerunners to plasma televisions. The major drawback to EL displays is that they require high voltages to ionize the gases. Once a significant problem, this has been resolved by using switching power supplies (DC-to-DC) integrated into the display matrix chip. EL displays need comparatively more power than the LED and LCD types but do not require backlighting in low light, nor will they wash out in bright light.

Overload Protection

One way to protect the measuring device, either analog or digital, from overloads and wrong scale selection is to use fast-acting fuses or circuit breakers. This is the method employed in most high-quality, general-purpose analog VOMs known as *multimeters*. It is also the principal method of protection for digital meters when used prior to the meters' scaling circuits.

Diode protection is a form of protection from overloads for measuring device input circuits where the input may exceed allowable thresholds. A diode is a two-element electrical component that acts as a check valve for electrical current, that is, it causes current to flow in one direction only. An example of a check valve is the valve in your automobile tire. If the air pressure inside the tire is equal to or greater than the pressure outside the valve, it remains closed, trapping the air in the tire. When you add air to the tire, the pressure from the pump has to be greater, and in the right direction (into the tire) for the check valve to open. The actual pressure from the pump has to be a bit more than the pressure in the tire as the pump pressure must also overcome the spring that holds the valve closed. A diode behaves the same way, only instead of air pressure, it is using electrical pressure. Current may flow in only one direction through a diode, the forward direction. Current cannot flow in the other direction, the reverse direction. Germanium and silicon diodes have a forward voltage drop (the amount of voltage in the right direction needed to overcome the diode's internal spring) of between 0.2 V and 0.8 V depending on the diode construction and type. This can be used to form a protective circuit that protects the meter movement against gross overload and the resulting meter damage.

Let's look at the diode protection in a circuit in which the meter movement has an FSD voltage of less than 0.20 V. If the voltage (in either direction) does not exceed the forward voltage of the diodes, the meter will be the only path of current flow. When the forward voltage of the diode is exceeded, it will conduct, shunting the excess current around the meter. Figure 3-4 illustrates this type of protection.

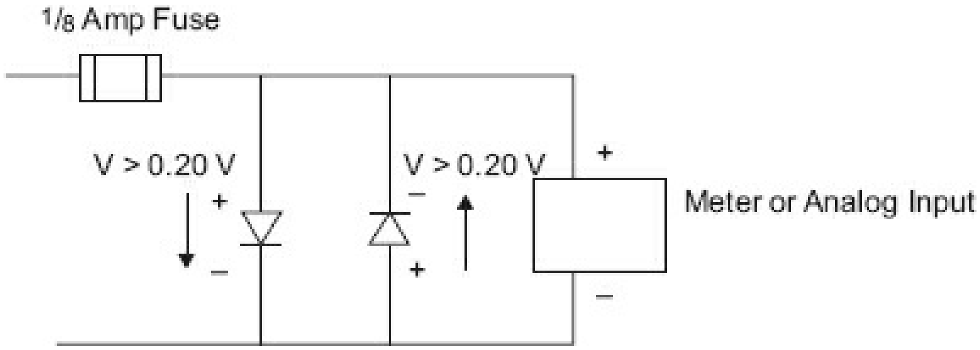

Figure 3-4. Diode protection.

Another form of protection (again depending on the measuring device and its intended application) may be photo isolation, where the internal circuitry is protected by using photo-isolators.

Measurement Common Practices

When using measurement devices in lab or field settings, some common practices should be followed:

- One should always learn, review, and follow the procedures for the facility you a Whether you are in a lab, in a maintenance shop, or out in the field, documented procedures and measurement practices should exist. If they don't, take a step bac have a discussion with those around you, including peers and safety profession the measurement can't be made safely, it should not be made.

- Ensure that you know what measurement you want to take and the range of value you expect. You should not take a measurement if you don't know what you exp see. This is not a time to guess. It should be known. Damage to equipment, proc and people can occur if you make the wrong move. Bottom line, know what yo doing or have an experienced person watching you.

- Use the right tool for the job. Be sure your measurement device is appropriate f measurement you are making.

- Regardless of the expected measurement, always start at the highest range and r the range until it gets to a readable point.

- Never come into contact with the circuit or measurement point. For example, d measure a loose resistor by holding it between your fingers so the probes make a connection. You will affect the measurement, and you will get hurt if the circuit is

- Be aware of the bare parts of the meter leads and do not allow your body to bec conductor, regardless of the voltage you think may or may not be present.

- When taking direct current measurements, ensure that the leads are of the c polarity. (While not a requirement for some digital multimeters, an analog mete be damaged by applying the wrong polarity.)

- Never go past full scale (commonly called "pegging") on an analog meter or ma an overscale connection on a digital meter.

This is in no way intended to be a comprehensive list of practices for all situations. It is critical that you understand the situation you are in, the environment around you, the measurement you are expecting, and the energy potential in case something should go wrong. A lot of work has been done in recent years around the phenomenon known as *arc flash*. Severe damage can occur to you and your surroundings simply by a bad measurement establishing an arc under the right conditions. When in doubt, bug out.Move away and assess the situation in a safe location with a qualified resource. Keep access covers and panel doors closed at all times when access is not needed. Wear the proper personal protective equipment (PPE) for the arc flash rating you are working with.

Always treat electricity with respect. Any amount of voltage can be dangerous. Never become complacent when working with electricity.

Module 3B: Summary

- LED displays require significant power and are good in low light. Newer model not wash out in bright light.
- LCDs require little power for the display but may consume significant pow backlighting in low-light situations. In high-light situations, LCDs offer an exc image requiring little power.
- EL displays require more input power than the LED and LCD types, but do not re backlighting and are resistant to washing out in bright light.
- Digital meters have a high-input resistance because they are voltage-activated than current activated (as is the analog meter movement).
- Digital meters are commonplace because of their advantages over analog types.
- Digital meters have greater than 10 MΩ input impedance.
- Analog meters have an input resistance that is dependent on the meter move which requires actual current to actuate.
- Digital meters eliminate parallax.
- Digital meters are considerably more rugged than analog meters.
- Digital meters are more accurate than analog meters (as a rule).

Module 3B: Review

See Appendix B for the answers.

1. List the three precautions that must be taken when making measurements.

   ____

   ____

   ____

2. Match the digital meter display with its significant characteristic (some charact may apply to more than one type of meter).

A. LCD ______________ Requires backlighting for dim light conditions

______________ Older versions wash out under high light conditions

B. LED ______________ Has good contrast under high light conditions

______________ Has a good image in low light conditions

C. EL ______________ Requires the least power of all types listed

______________ Requires the most power of all types listed

Module 3C: Other Electrical Measuring Devices

Oscilloscopes

An oscilloscope is a voltage measuring device that provides a picture of the changing voltage. Most sophisticated oscilloscopes use a clip-on or clamp-on current probe to measure and see current waveshapes. Current clamp-ons are usually either basic transformers or more sophisticated Hall effect types.

Several years ago, the oscilloscope was the go-to device for troubleshooting; today it is used to provide analytical information concerning an occurrence or for noise analysis. Oscilloscopes used to be expensive and quite heavy; the higher performing ones were the heaviest. Current models are typically portable, if not handheld, and provide performance only the best of the older models could provide. They include features the older devices did not, such as color, and imprinting the waveshape with current voltage and frequency.

Figure 3-5 illustrates a rather high-end oscilloscope. The operation and details of such a device are not within the scope of this text, other than to say it provides a visual method of measuring voltages.

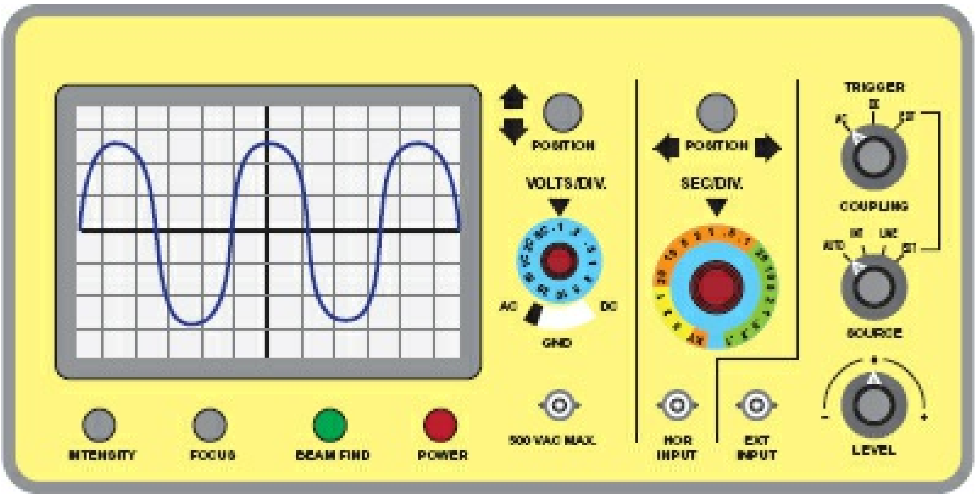

Figure 3-5. Typical oscilloscope.

Source: By Brian S. Elliott at English Wikipedia - Transferred from en.wikipedia to Commons., CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=24802292. Modified by ISA.

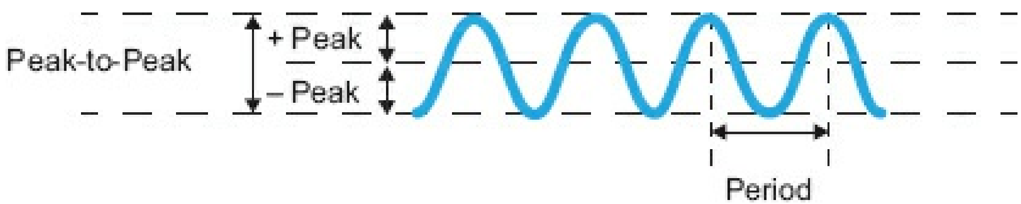

Figure 3-6. Determining waveshape values.

It is important to understand the pictures displayed on the oscilloscope. For example, when an AC waveform is shown (see Figure 3-6), one must be able to determine the actual voltage of that waveform. The complete waveshape amplitude is called the *peak-to-peak voltage*. Notice that this value cannot occur in an individual cycle; that is, although the positive alternation and the negative alternation have a peak-to-peak value, that value does not directly translate into current flow in one direction (direct current). However, half that value, the peak voltage, does. The peak voltage only exists at one instant in time. The question then becomes this: What average value (rms) of AC will heat a resistor to the same temperature as one heated by DC voltage? The effective or rms value is 0.707 of the peak value (for a sine wave). This means the peak value is 1.414 times the rms value (1.414 is the reciprocal of 0.707). Most values of AC are given as rms (effective) values. The 120 V outlet in your house has a peak value of 169.7 V and a peak-to-peak value of 339.4 V. Because the effective value is the one causing work, it is the one given.

The period (the difference between two peaks—one complete cycle) is measured in time. For example, the 120 V outlet is at 60 Hz (US). Hz means cycles per second and is never stated as Hz per second unless one is talking about the rate of frequency change. The period would be 1/60 (frequency) or 0.016667 s (166.67 ms).

One can determine frequency from the oscilloscope display by counting the horizontal divisions for one cycle and then multiplying the total by the scale multiplier (set by the time control on the oscilloscope). In the previous example of 60 Hz, if the multiplier was set on 1 ms, the complete cycle would occupy 1.37 divisions.

Vertical Deflection

A block diagram of a typical vertical deflection circuit is shown in Figure 3-7.

The input selection switch chooses between the following:

- A direct connection for observing DC levels.
- A grounded input to adjust the trace to the desired vertical position and pe balance/gain adjustments.
- A series capacitor to remove the DC component of a signal. This is necessary if changes must be observed and if these changes are riding (superimposed) on a lar value (in comparison to the magnitude of the signal's change).

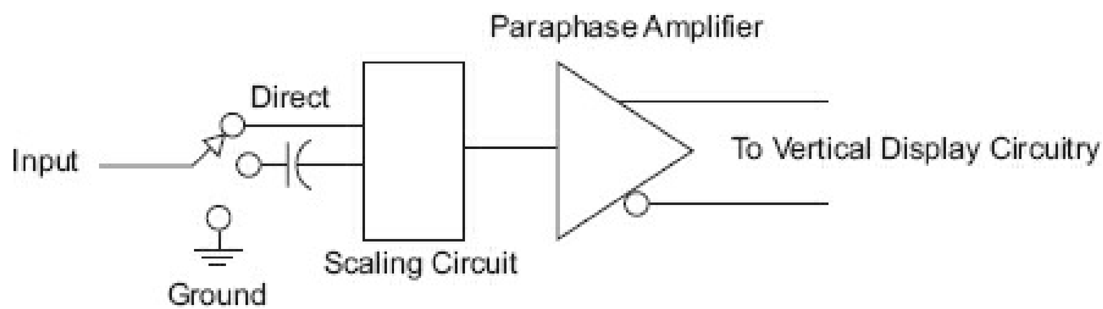

Figure 3-7. Typical vertical deflection circuitry.

The scaling circuit is used to restrict the percentage of the input signal that reaches the paraphase (DC) amplifiers. Because the oscilloscope is a voltage-measuring device, the input to the scaling circuitry is designed much like the multiplier resistors in a voltmeter. Most oscilloscope vertical inputs (which are calibrated) have several elements to maintain constant impedance to the input and to the DC amplifiers. Input voltage is reduced in steps (as in a multi-range voltmeter) while the DC amplifier operates at a constant gain.

The amplifier has one or more gain adjustments for calibration and compensation for component aging. These are not user operated or normally accessible but intended for use by calibration personnel. The paraphase amplifier must be capable of producing two opposite-phase, equal-amplitude voltages to drive the vertical display circuits.

Horizontal Deflection

A block diagram of a horizontal deflection circuit for a time-base oscilloscope is shown in Figure 3-8.

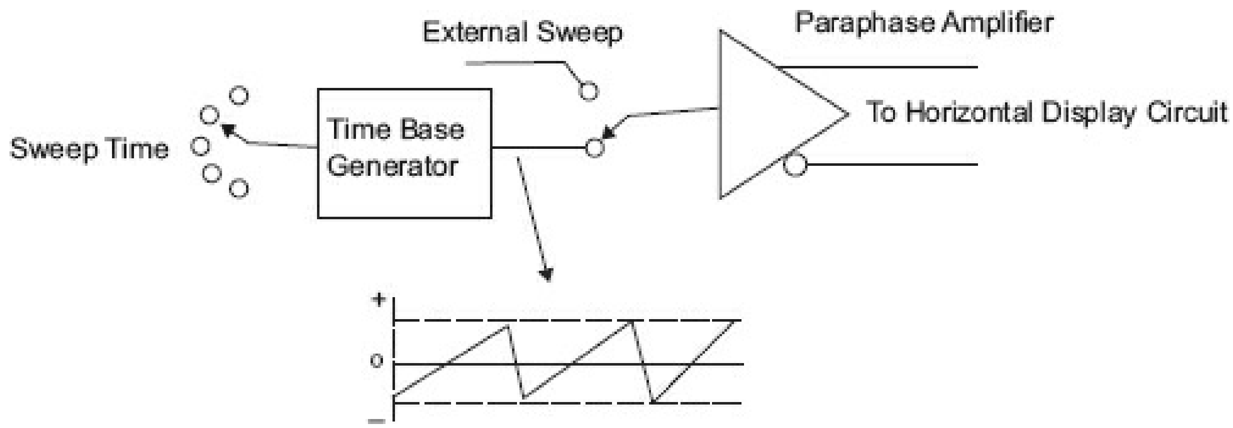

Figure 3-8. Horizontal deflection circuitry.

A choice of inputs between the external or internal sweep is selected by the internal/external sweep switch. The time-base generator develops a linear-rising (sawtooth) voltage that rises in a straight slope from a negative to a positive voltage of the same magnitude. This slope is normally called a *ramp*. The return of the ramp from its most positive voltage to its most negative is the retrace (flyback) portion.

Notice that the retrace time, though finite, is a small part of the overall sweep time. The amount of time the ramp takes to go from negative to positive is the sweep time, and the gain of the horizontal amplifier is calibrated so this line takes a certain length, usually the length of the horizontal divisions of the graticule across the display face. The faster the sweep rate, the smaller interval of time the sweep occupies. What starts the sweep? It could be free running, but then you would have no control over when it started in relation to a signal you wished to observe. To obtain this relationship, called *synchronization*, a triggering circuit is used. The block diagram of the triggering circuit is shown in Figure 3-9.

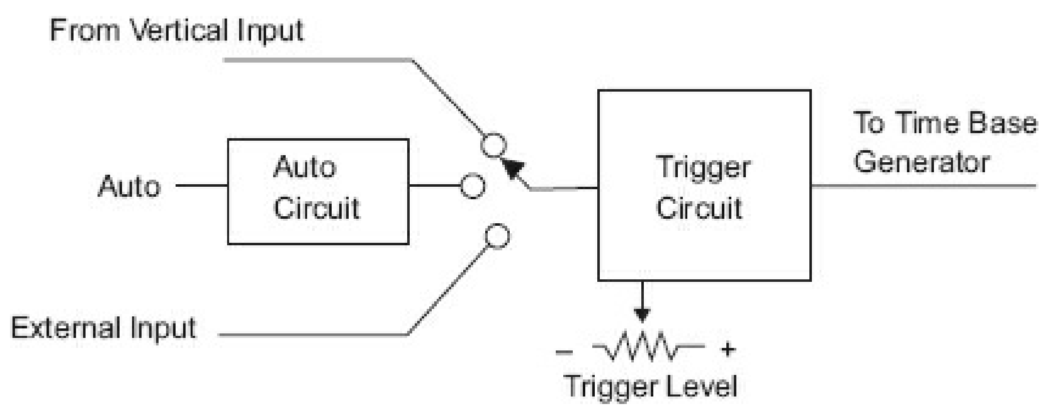

Figure 3-9. Typical trigger circuitry.

The trigger circuit decides where on the input waveform the trace (therefore, the observed waveshape) should be started. Normally, there is a preset auto trigger that will produce a trace even in the absence of an input signal. A manual trigger adjustment is provided so you may set the trigger point exactly at any location on the input waveform. On some models, a delay circuit is provided if the trace will be started at some time after the trigger point occurs.

Dual-Trace Oscilloscope

The oscilloscope typically used in industrial applications is a dual-trace (or even a higher number of traces, known as *multitrace*; however, here we will confine ourselves to the dual-trace design). This design usually features a delayed, triggered sweep, DC to 20 MHz (or higher) model. Several circuits are added to achieve dual-trace operation (using just one scan or sweep). There are two complete vertical amplifier sections. Many dual-trace oscilloscopes give you a choice of how the vertical signals are to be multiplexed (e.g., alternate, chopped, or added).

The most commonly used methods for multiplexing the vertical signals are the alternate and chopped modes. In the alternate mode, a complete sweep for channel A is made, and then a complete sweep for channel B is made. This is useful if short intervals of time (signals of high frequency) are to be observed. However, at slow sweep times this alternate switching becomes hard to observe, and comparisons of simultaneous or near simultaneous signals on channel A and channel B cannot be done. For this case, the chopped mode is used. In the chopped mode, the electronic switch free runs above 10 kHz or higher, sampling each channel 10,000 times or more per second.

Other Oscilloscope Features

Oscilloscopes may have additional circuitry such as:

- Provision for algebraically adding the signals of the two channels. This c concurrent portions of the two signals that are in phase to be of greater amplitud out-of-phase portions.

- Z-axis input for intensity modulation. Portions of the input signal that a concurrence with the signal on the z-axis will be brightened. This means that wh z-axis is positive, the trace will be brightened for only the time the z-axis is po This is used to show timing concurrence, particularly with digital circuitry.

- The A trace is delayed by the B trace. This circuitry triggers the A trace when the s trace, B, occurs.

- Calibration point, which is usually a 1 kHz square wave with a peak-to-peak volt 1 V for calibrating attenuator probes.

- X5 or X10 trace stretching. This feature takes 1/10 of the displayed wavefor graticule division) and displays it over 5 (X5) or 10 (X10) graticule divisions, cur called *ZOOM* in other display technologies.

Oscilloscope Controls and Applications

This section of the module reviews the use of typical oscilloscope controls, voltage calibration, frequency determination, and Lissajous patterns. Knowledge of oscilloscope usage and applications will greatly enhance a technician's ability to perform and interpret many electric/electronic measurements.

Oscilloscope Controls

A DC amplifier oscilloscope can be used to display a multitude of different waveforms. It can measure and/or compare signals with a versatility that no other type of test equipment possesses. Correct use of the controls is the key to proper use of the oscilloscope in making measurements.

Although each model of oscilloscope has a different control layout, there are many similarities. Among these controls are:

- Vertical channel controls
- Sweep controls
- Sync controls
- Trace characteristics controls

Vertical Channel Control Group

There are two controls in this group, both of which relate to vertical y-axis deflection.

1. **Scale** – The scaling switch control normally consists of a range switch (coarse and a variable-gain adjustment (fine-calibrate). The fine adjust/calibrate sw normally kept in the calibrate position if voltage measurements are to be take coarse adjust or range switch determines the amount of deflection (in volts per gr division) a signal will cause (provided, of course, that the fine adjust switch is calibrate position).

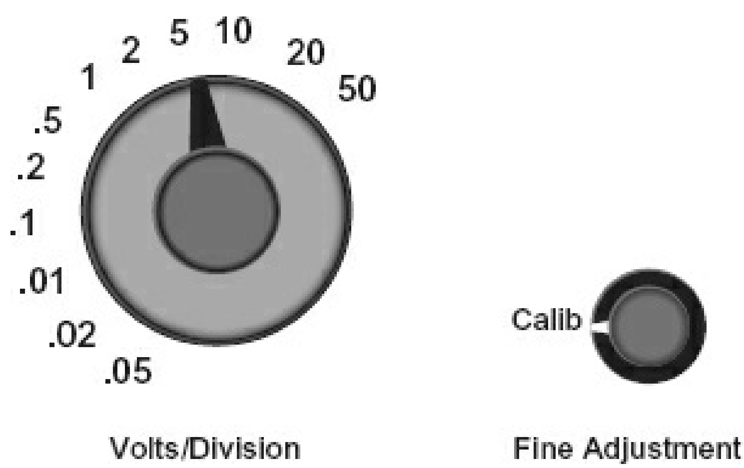

Figure 3-10. Vertical scale settings and display.

Typically, the scale in Figure 3-10 is stepped off in a 1-2-5 sequence. All modern oscilloscopes have controls scaled in this manner. Note that handheld, dual-trace portable scopes with LCDs and most modern oscilloscopes have the majority of these controls under software control, and the control functions and positions depend on the particular device. There are several devices (whose features vary with price) that convert a personal computer (PC) or smartphone to an oscilloscope; however, the same functions will be accomplished.

2. **Vertical position** – The vertical position control determines the location of the vertical reference line vertically on the screen.

Horizontal Control Group

There are several different controls in this group; all affect the horizontal (x-axis) sweep. Two are discussed below.

1. **Time/Division (Time/Div) switch or sweep control** – A typical Time/Div (Time/Cm on some models) is illustrated in Figure 3-11.

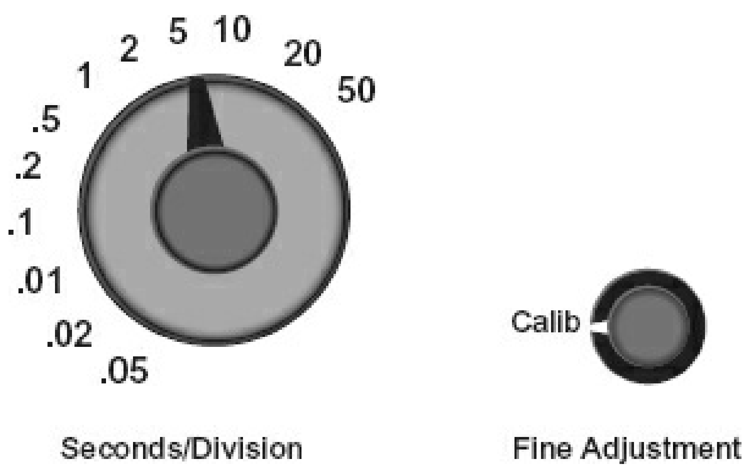

Figure 3-11. Horizontal time-base control.

2. **Horizontal position** – The horizontal position control determines the l horizontally on the screen, from the beginning of the sweep.

The variable control provides a vernier adjustment of sweep time based on the range selector position; that is, it provides a variable time between the preceding lower range to the maximum Time/Div setting of the range switch. As stated for the vertical controls, PC converters and handheld dual-trace portable scopes with LCD displays have the majority of these controls under software control, and the control functions and positions depend on the particular device; however, the same functions will be accomplished.

Example

The sweep switch is set at 2 ms/div (milliseconds per division); the center variable control will adjust the time between 1 ms/div to 2 ms/div. The variable control is normally kept in the CALIB position, which means the range switch reading is the trace Time/Div. The range switch determines the time it takes the trace to traverse one graticule division. The complete horizontal trace takes 10 times the Time/Div (or Time/Cm) setting.

If the setting is for 5 ms/div and the waveform fills the screen, starting at t0 and finishing at t10 (10 divisions), the period of the waveform is 50 ms. For the same setting with four complete waveforms filling the 10 divisions, the period would be 50/4 or 12.5 ms. Most modern oscilloscopes read out the period and frequency in text for the major waveform being displayed.

If the vertical deflection per division was set at 2 V/div and the waveform fills 3 divisions vertically, that would mean the waveform had a peak-to-peak value of 6 V (3 div • 2 V per div). If it was a sinusoidal waveform, you could then say that peak was 3 V and effective (rms) was about 2.121 V.

If it is not a sinusoidal waveform, you must have a true rms meter (generally built into modern oscilloscopes) to determine the actual voltage. The advantage of modern microprocessor-based scopes is that they can determine all this and display it simultaneously with the waveform.

Sync Control Group

Triggered oscilloscopes have controls that determine when the trace will start.

- **Sync selection** – A typical sync selection switch is shown in Figure 3-12. This s determines the type of synchronization to be used:
    - **LINE** – A 60 Hz line frequency signal is used for the trigger.
    - **INT** – This means the trigger is obtained from the vertical channel.
    - **EXT** – This means the trigger is obtained from an external source.
    - **AUTO** – When the control is in the auto position, a trace will be displayed, ev input signal is not present.

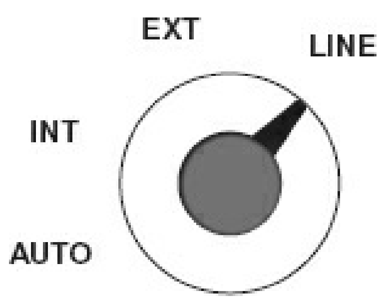

Figure 3-12. Sync selection.

In a dual-trace oscilloscope, typically a selection switch determines which channel will provide the trigger. Some oscilloscopes use an external adjustment to preset a voltage at which the auto sweep will trigger on. The AUTO position will attempt to synchronize an input signal. However, the manual sync level control must be used many times for stable display. This determines at what level of the signal and at what polarity the trace will start.

Z-Axis

Intensity enhancement is often helpful in identifying concurrent events. The Z-axis enhancement normally intensifies the beam (becomes brighter) when a positive voltage is applied to this input. This means that the parts of the input signal that occur at the same time the Z-axis input is positive will appear much brighter on the screen. Not all oscilloscopes offer this option; some have different methods of achieving the same results.

Frequency Determination by Lissajous Patterns

When determining frequency directly from the graticule of an oscilloscope, there are two opportunities for error:

1. If the oscilloscope time base is not correctly calibrated
2. If the trace does not fill exactly 10 divisions when the time base is calibrated

If a frequency standard is available, an alternate method is available to determine the frequency of a signal. Most modern oscilloscopes display the frequency or repetition rate along with the input signal display, so the following method is nothing more than a curiosity. (It was used prior to digital oscilloscopes and appears in many Class B science fiction movies.)

The Lissajous pattern method requires the unknown signal to be input to the vertical channel and the standard signal to be input to the horizontal channel. This means the horizontal sweep control should be switched to EXT HORIZ or in some dual trace oscilloscopes to x-y, where one vertical amp is the y-axis and the other vertical amp is the x-axis (horizontal). The equipment setup is shown in Figure 3-13.

Assume the standard signal and the unknown signal as shown in Figure 3-13 have the inputs shown in Figure 3-14.

Using the Lissajous setup, the display will appear as shown in Figure 3-15.

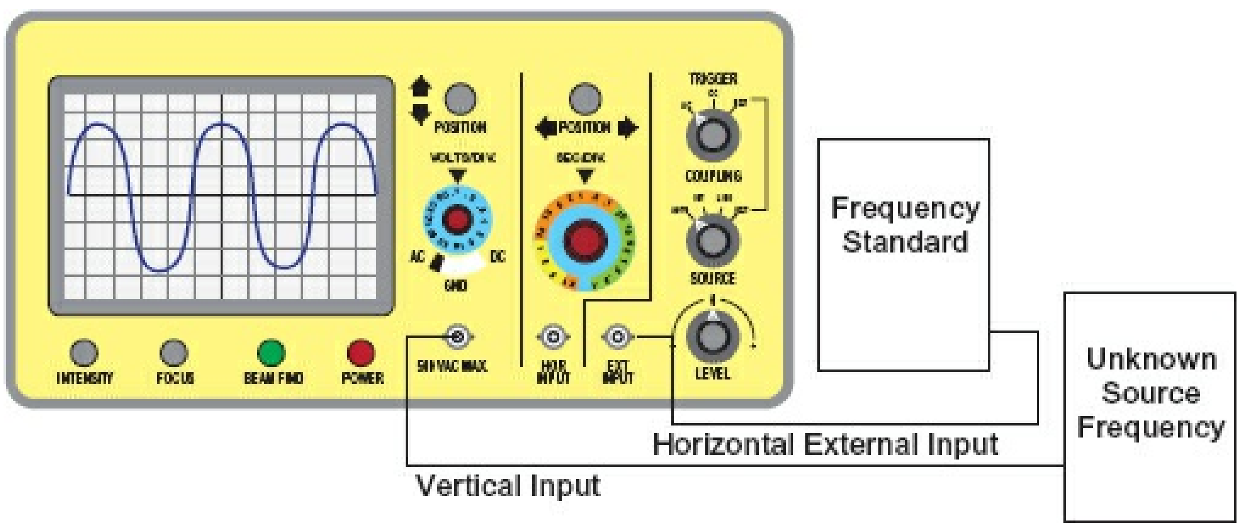

Figure 3-13. Setup for Lissajous patterns.

Source: By Brian S. Elliott at English Wikipedia - Transferred from en.wikipedia to Commons., CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=24802292. Modified by ISA.

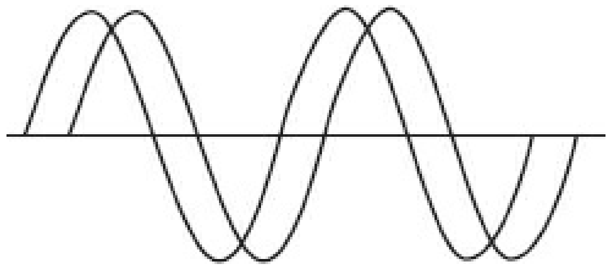

Figure 3-14. Dual-trace comparison of inputs to Figure 3-13.

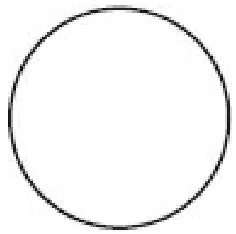

Figure 3-15. Lissajous pattern, 90° out of phase.

Two signals that have exactly the same frequency but differ by 90° will form a circle on the oscilloscope screen. If the two signals differ in amplitude, an ellipse will result.

For signals of the same frequency that are more or less than 90° (or 270°), an elongated ellipse results. If both signals are of the same frequency, amplitude, and phase, the result is a straight line left to right and from the lower to the upper portion of the display.

If the signals were 180° out of phase, the result would be a line in the opposite direction. These patterns are useful in determining when an unknown frequency is the same as the standard. What if signals are submultiples or multiples of the standard? They produce varied patterns, known as *Lissajous patterns*. A pattern where the unknown frequency is lower than the standard frequency is shown in Figure 3-16.

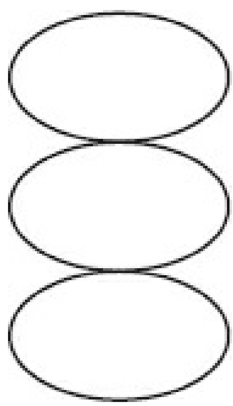

Figure 3-16. Frequency lower than standard.

To determine the fraction of frequency, count the number of loops in a vertical pattern. This number is used as the denominator, whereas the number of loops in a horizontal pattern is the numerator. This determines the fraction of the standard frequency.

To determine the unknown frequency when the frequency is higher than the standard (shown in Figure 3-17), first count the loops in a horizontal pattern.

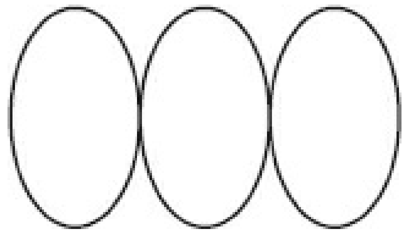

Figure 3-17. Frequency higher than standard.

This is the multiplier (or numerator). Divide this figure by the number of loops in a vertical pattern; the resultant fraction determines the multiple of the standard.

To use Lissajous patterns to determine frequency, normally the standard and its output frequency are adjusted until the desired pattern is obtained. To adjust an unknown frequency to a standard, set the standard at the desired frequency and adjust the unknown until the desired pattern is obtained.

Review of Lissajous Patterns

- Lissajous patterns do not use the oscilloscope time base to determine frequency.
- Lissajous patterns can determine multiples and submultiples of a standard frequer
- The standards are normally input to the x-axis (horizontal) for Lissajous patterns.
- The patterns are not a part of normal contemporary operations as frequency coı are generally included in modern oscilloscopes, displaying the frequency of the waveform simultaneously with the waveform.

Time-Domain Reflectometers

A time-domain reflectometer (TDR) is an electronic instrument that may use an oscilloscope for output display. However, the more contemporary types use a computer display with overwritten text, and they use time-domain reflectometry to characterize and locate faults in metallic cables (e.g., twisted pair wire or coaxial cable). A TDR may be considered an oscilloscope of sorts as it usually has one (or more) waveform displays.

A TDR performs reflectometry by sending a controlled pulse (at the frequency of interest) down the metallic cable and waiting for a reflection of the energy to return. Impedance differences, such as couplers, connections (good or bad), and any discontinuity, will reflect energy to the source. By measuring the time from the pulse to the return, the physical distance can be determined.

TDRs can also be used to locate discontinuities in a selected electrical path. The equivalent device for optical fiber is an optical TDR. Figure 3-18 illustrates a typical TDR.

Figure 3-18. Typical time-domain reflectometer (TDR).

Module 3C: Summary

You will encounter many types of electronic measuring devices in your work. For example, in process industries the standard measuring devices are temperature, flow, pressure, and level, and they usually produce a standard 4–20 mA signal as the lower and upper range values. Other measuring devices such as analyzers and specialty transmitters may produce digital signals or even a data communication protocol such as EtherNet IP or Modbus. All these devices will require various instruments to calibrate them. It is beyond the scope of this text to cover all these devices; simply be aware that they all measure and that the accuracy and repeatability requirements apply to them as well.

- Module 3C covered the oscilloscope and briefly discussed the TDR.
- Oscilloscopes must have the following features:
  - Input impedance above 10 MΩ
  - Sensitivity (what is necessary for the measurements to be made)
  - Accuracy (better than 0.05% measurement)
  - Time-base generator (to cover the application signal time base)

Module 3C: Review

See Appendix B for the answers.

1. Given the signals on the graticules in Figures R3-1, R3-2, and R3-3, determine a the approximate voltages and frequencies displayed.

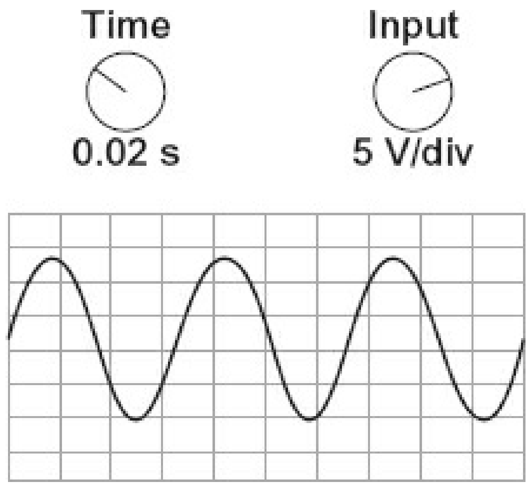

Figure R3-1.

A. Peak-to-peak voltage ____________
B. Peak voltage ____________
C. Frequency ____________

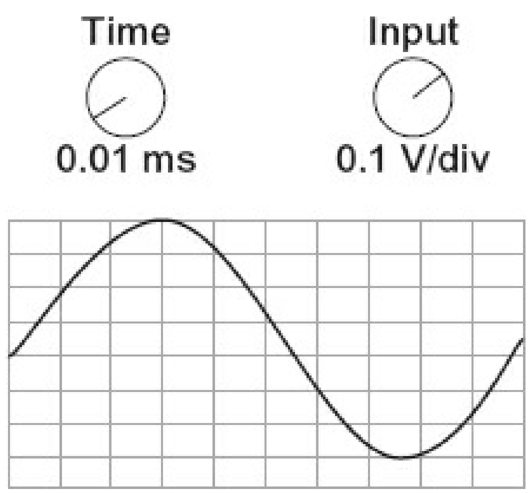

Figure R3-2.

A. Peak-to-peak voltage ____________
B. Peak voltage ____________
C. Frequency ____________

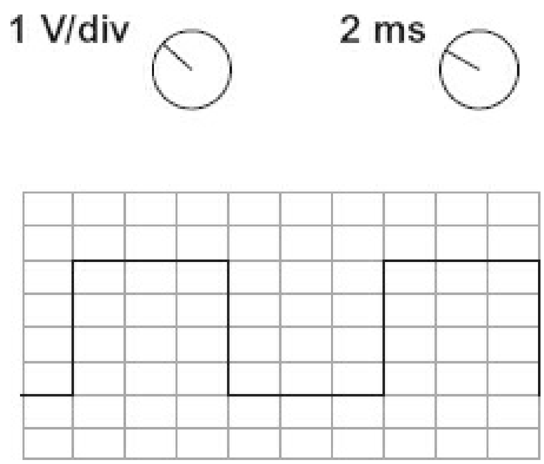

Figure R3-3.

A. Peak-to-peak voltage ________________
B. Frequency (repetition rate) ________________

2. The standard frequency is 5 kHz. Using Figure R3-4, what is the unknown freque

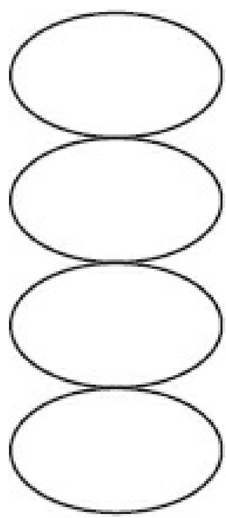

Figure R3-4.

Each oscilloscope has controls arranged differently, only typical controls have been presented. A thorough reading of the operator's manual is required for each type of oscilloscope you will operate. You must be familiar with each control on the oscilloscope; if not, improper measurements or perhaps damage to the oscilloscope will result.

Module 3D: Error

Error Types

There are three major categories of error: gross, systematic, and random.

Gross errors are errors made by people. Sources of people error are as numerous as there are people, but some of the major sources are:

- Gross
  - Wrong meter for the application.
  - Wrong scale for the measurement.
  - Wrong interpolation of the reading. Interpolation is when a number is estim derived between two known points. For example, the actual meter reading is the scale of meter is in 0.25 increments forcing the user to determine a value l 1.25 and 1.5.
- Zero error
  - Example: Failure to accurately align the zero point of the ruler with the beginn point (same as not correctly aligning the zero for any measurement)
- Parallax error (an analog meter error)
  - Error caused by reading the marks at any angle other than directly overhead
- Misread
  - Misinterpretation of numeral values

Systematic error is equipment error. This is where equipment accuracy, precision, repeatability, calibration, and tolerances come into play. For a ruler, this could mean:

- Physical deformation of the ruler
- Pencil and rule mark of different widths
- Rule mark inaccuracy
- Environmental deformities, such as absorption of moisture that would affe physical spacing of rule marks
- The accuracy of manufacture of the ruler
- The accuracy of the standard used to develop this scale

After gross error is eliminated, two types of errors can affect measurement: systematic and random. Systematic error was just explained as an equipment error. Random error is nonpredictable, and it generally affects one or a single series of measurements.

Random errors follow the laws of probability and therefore can be identified by a rigorous statistical application. Reducing random error can only be accomplished with repetitive measurements and the application of statistical techniques to establish the measurement uncertainty of the values being measured. These statistics are explained in this module. Typically, random errors result from several independent, small errors when performing repetitive measurements. The results vary in an irregular and nonpredictable pattern.

More Definitions

- **Error** – Any deviation from the true (actual, real) value.
- **Deviation** – As used in this module, the difference between the averages (arith mean) of a set of measurements.
- **Mean** – The average of a set of measurements.
- **Tolerance** – The deviation from a standard (nominal, stated) value. It is gen applied to components such as resistors and mechanical parts.
- **Accuracy** – The span of error for a measurement, or the maximum amo measurement may vary from the true (real or actual) value.
- **Range** – As used in measurement, the lowest range value to the highest range Always stated as from X_{low} to X_{high}. In reference to error, range is the lowest to h values bounding the span of error of a measurement.

Mean

Table 3-2. List of meter readings.

Measurement Number	Voltage Measured
1	9.8
2	10.3
3	10.0
4	9.7
5	10.2
6	10.0
7	9.9
8	10.1
9	9.9
10	10.1

The measuring device used to gather the measurements in Table 3-2 has a guaranteed accuracy of 5%. The scale is 0 VDC to 10 VDC. What assumptions regarding the true value could be made from scanning these measurements?

A quick scan of the numbers seems to indicate that the true value is near 10.0 V. Assuming that the only errors in the measurements are random and those of precision, it looks like the average reading will be near 10.0. Experience has taught that when given a list of measurements, the real value should be near the average for all the readings. Although the statistical proofs are beyond the scope of this text, the average value has the highest probability of being the real value (with no systematic error).

To calculate the arithmetic mean (or average), the readings are summed and divided by the number of readings. The equation denoting this process is:

$$\frac{m_1 + m_2 + m_3 + m_4 + \ldots m_n = m}{n}$$

where *m* is the numbered measurement value and *n* is the number of measurements.

Calculate the arithmetic mean for the list in Table 3-3.

Table 3-3. Calculating the mean.

Measurement Number	Voltage Measured
1	9.8
2	10.3
3	10.0
4	9.7
5	10.2
6	10.0
7	9.9
8	10.1
9	9.9
10	10.1
Total number of measurements (n) = 10	
Sum of measurement values (∑) = 100	
Arithmetic mean (average) = 100/10 = 10	

Deviation

The next logical step in analyzing the set of measurements is to determine each measurement's deviation from the mean. This is done by identifying the difference between the actual measurement and the mean. Table 3-4 is a listing of the measurements and their deviations.

Table 3-4. List of measurements and deviations.

Measurement Number	Voltage Measured	Deviation
1	9.8	–0.2
2	10.3	+0.3
3	10.0	0.0
4	9.7	–0.3
5	10.2	+0.2
6	10.0	0.0
7	9.9	–0.1
8	10.1	+0.1
9	9.9	–0.1
10	10.1	+0.1
Mean	10.0	0.14

It is now appropriate to determine the average deviation. Why? Because the lower the average deviation, the higher the precision of the measurement or the measuring device. The average deviation is determined using the same process as calculating the arithmetic mean, with one major exception. The deviations are signed numbers and if summed may come out to 0 (as in this case). It is difficult to divide zero by any number other than 0. Therefore, only the unsigned or absolute values are summed. For the figures given in Figure 3-7, the sum of the deviations is 1.4. Dividing the sum by the number of measurements (10) results in the average deviation of 0.14. This means that on average, meter readings differed from the arithmetic average, or mean, by 0.14. If another set of readings was taken with a different meter and the average deviation was 0.09, then the second meter is more precise than the one that resulted in an average deviation of 0.14.

Taking a series of measurements rather than just one reading greatly reduces the probability of random and gross errors. Random effects tend to cancel over a large number of readings. This effort will most likely not diminish the effects of systematic error because much systematic error is of the constant bias type, meaning it is consistently high or low rather than having an equal chance of being above or below the true reading. Therefore, the mean will be skewed high or low over the set of readings due to systematic error.

Error Review

- All measurements have errors.
- An error is a deviation from the true value.
- Deviation is the difference between the measured value and the arithmetic mean v
- An arithmetic mean is the average of a set of measurements.
- The average deviation is the average of the deviations for a set of measurements.
- The lower the average deviation, the more precise the set of measurements.
- Using a series of measurements will tend to average out the random error and, in cases, gross error.

Standard Deviation

Standard deviation is widely used in error analysis (or in any other statistical analysis, such as statistical process control or in some cases your grade on a test) because its units are the same as the measurement units. It is obtained by following these steps:

1. Calculating the arithmetic mean for several measurements.
2. Determining the difference between the mean and the measurement—calcul deviation.

3. Squaring each deviation (multiplying the deviation by itself).

4. Summing all the squared deviations.

5. Dividing the sum of the deviations by the number of measurements less 1.

6. Determining the square root of the result in step 5.

This is represented as:

$$\sigma = \pm\sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + d_4^2 + \dots\ d_n^2}{n-1}}$$

or mathematically as:

$$\sigma = \pm\sqrt{\frac{\sum d^2}{n-1}}$$

The deviations will be positive because they are squared. Standard deviation has its value (pun intended) because it may be referenced to the normal (or Gaussian) curve. You are probably acquainted with the Gaussian curve as it is the *normal* distribution curve and typically is used to determine deviation from the norm. A Gaussian distribution curve is one that represents truly random occurrences. Measurements, accidents, births, or any measurement that has a random component should exhibit a standard curve if enough measurements are taken. The Gaussian curve is a "probability" chart; Figure 3-19 is an example.

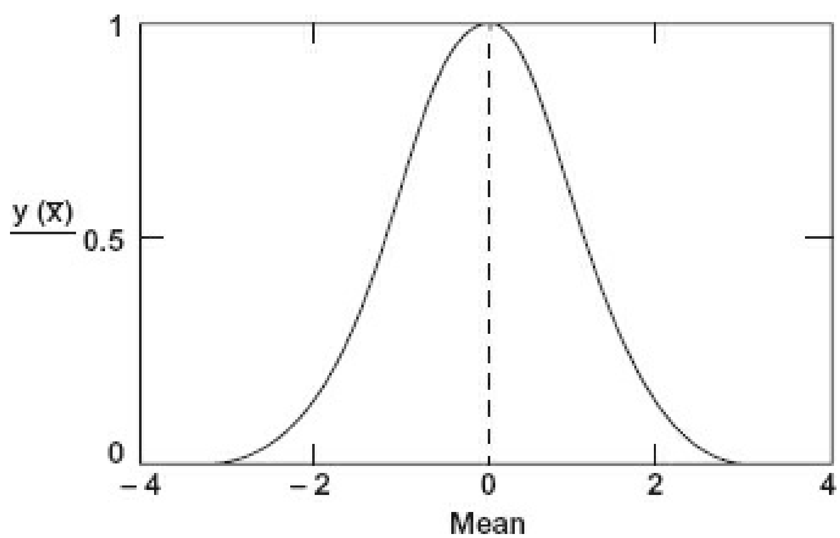

Figure 3-19. Gaussian curve.

Notice that most values fall in the area about the mean. In fact, 68% of the values are within one standard deviation (plus or minus) of the mean and 95% of the values are within plus or minus two standard deviations of the mean. If a set of readings has only random error, 97.5% of all probable readings will be within plus or minus three standard deviations.

Comparison Calibration

One method for correcting the systematic error of an instrument is calibration against a standard. This is known as *comparison* calibration. Comparison calibration is where a quantity (voltage, current, temperature, etc.) is measured both against a standard and by the instrument to be calibrated.

Typically, the instrument has internal adjustments that can be used to align it with the standard. *Note:* When an instrument is calibrated by the comparison method, it assumes the accuracy of the standard within the instrument's own tolerance. Therefore, if a meter with a stated accuracy of 1% is calibrated with a 0.05% standard, the meter is still only accurate to 1%. Although individual tolerances vary, an instrument is only guaranteed to be accurate within its specifications. The calibrated instrument cannot assume it now has 0.05% accuracy because that was the accuracy of the standard, only that it is now accurate to 1%. This indicates that the standard used needs to only be as accurate as the instrument to be measured. Although that may be true for a particular instrument, standards are expensive. When a standard is acquired, the one most accurate for the money available will be procured as it may be used for a host of other instruments as well as future instrument requirements. Additionally, modern (current good manufacturing practice—CGMP) quality standards require the calibrating instrument to be three to four times more accurate than the device under test. While this calibration standard was appropriate several years ago, the number of measurement devices with microprocessors and their own precise standard has greatly increased. Maintaining the 4:1 ratio has become cost prohibitive, and many companies outsource their calibrations.

Calibration Curves

Calibration curves appropriately derived from a large set of measurements are still used, but not as commonly as before because they are now ascribed into a computer's memory and therefore transparent to the user. Three components of error are illustrated by calibration curves: *zero*, *span*, and *linearity*. These are common to all measuring instruments regardless of whether they are analog, digital, or another type. Although they may be reduced (within the instrument specifications), they are never eliminated, just removed from significance.

Zero Error

Zero error results when the instrument zero is not set at exactly the reference zero. Remember, for many instruments the zero value is the lower range value of some measurement scale increment. An example is when measuring the temperature from 100°C to 500°C. The lower range value is 100°C. This is where the instrument zero would be set. The span will be 400°C (span equals the upper range value minus the lower range value). If the instrument zero was set at 101°C and there is no other significant instrument error, then throughout the measured range, the instrument will be off by 1°C. Zero error curves are shown in Figure 3-20.

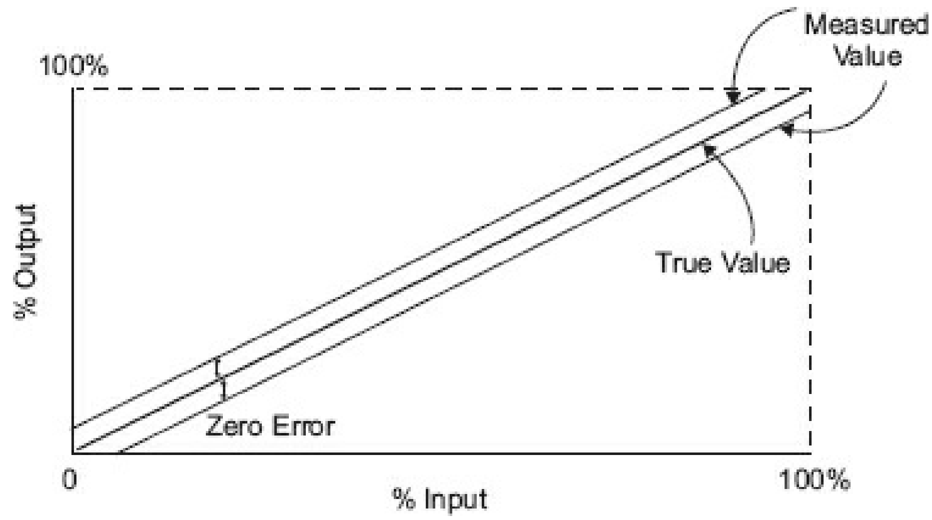

Figure 3-20. Examples of zero errors.

Span Error

Span error results when the instrument does not indicate full scale correctly even if the zero is correct. This is generally considered to be a linear error that increases as the value measured increases from zero. Span errors are shown in Figure 3-21.

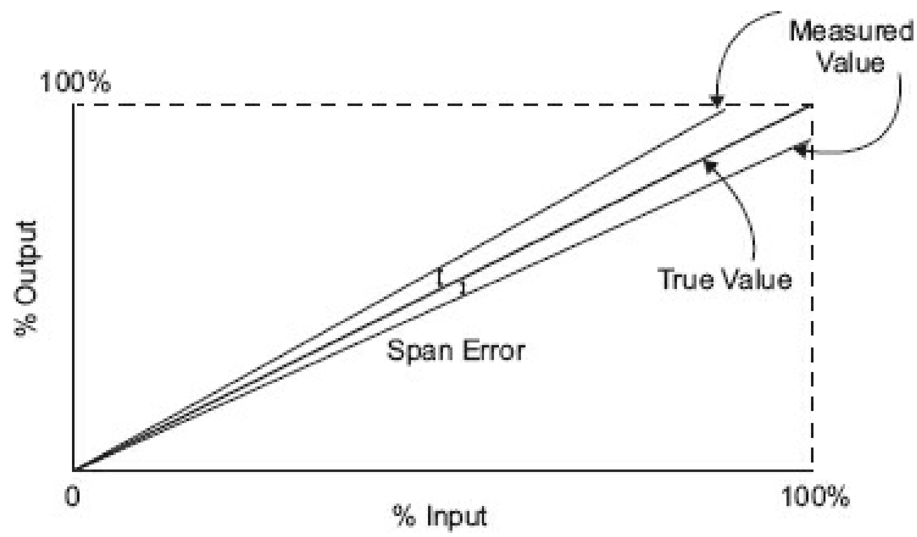

Figure 3-21. Examples of span errors.

Generally, both types of errors exist in preliminary calibrations. Figure 3-22 illustrates the combination of span and zero error.

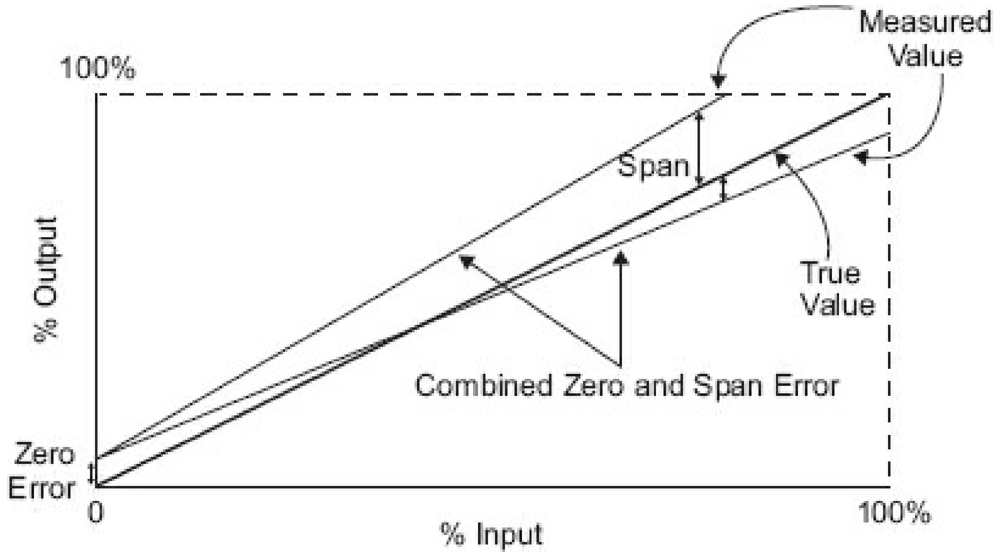

Figure 3-22. Examples of zero and span error.

Linearity Error

In real life, linear errors (those of span and zero) are reduced to an acceptable level with relative ease. Linearity implies that for a change in measurement value, the change in measurement error will be equal. This is, of course, not true. All instruments have a degree of nonlinear error. It will cause problems if it is significant for the measurements taken. Nonlinear error is extremely difficult to remove or even compensate for. Many electronic measurement instruments have compensating circuitry to remove nonlinearity by containing internal references. Prior to digital electronics, this was accomplished by using a calibration curve. Calibration curves can be drawn by several methods. Figure 3-23 illustrates the complete span of measurement drawn as actual measurement value versus indicated value. A method that more visually illustrates nonlinear error is where the error is normalized (0 error is the horizontal scale) and the deviation is shown on the vertical axis. Figure 3-24 illustrates a typical calibration curve that is normalized. These curves would not be drawn on one set of measurements but as a result of many sets of measurements, and each point would be the mean of all sets of measurements at that point.

Given the curve in Figure 3-24, is this all nonlinear error?

The answer is "no, there is a span component involved." Note that at full scale, the instrument is about 0.3% from the correct reading. And at zero, there is an almost 2% zero error. If you have a curve like this, it would be best to replace the instrument, unless the errors are within the acceptable range.

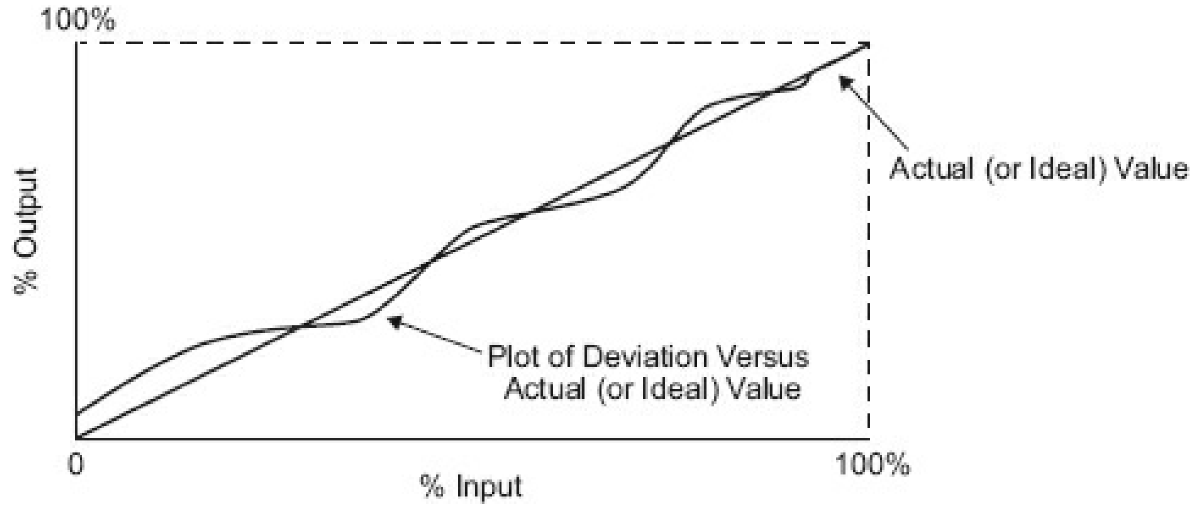

Figure 3-23. Typical calibration curve.

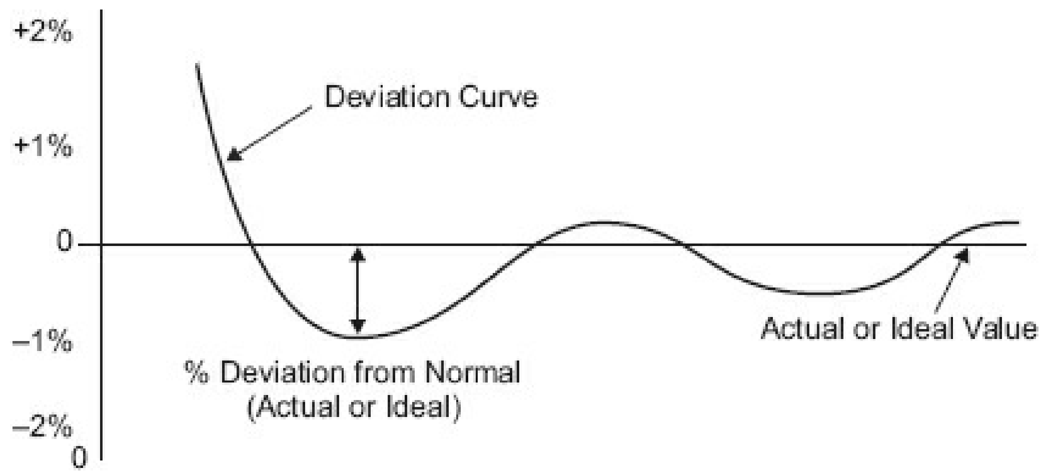

Figure 3-24. Normalized deviation curve.

Again, most modern instruments perform linearity corrections with either hardware or software, and the typical user of electronic measurement instrumentation outside of a calibration shop will probably never run across linearity problems in their normal procedures as long as the instruments are in working order.

Measurement Uncertainty

Measurement uncertainty is a term used to describe how good a measurement will be or, in more technical terms, the reliability of the measurement. It depends heavily on the use of statistical and probability mathematics. To determine measurement uncertainty with any degree of success, more than a single set of measurements is required. There is a law in statistics that states that if you average the means of several measurements (usually more than 10) the central tendency theorem will come into play. This theorem is central to all probability. Simply put, it states that the average of the means of several measurements tend to be grouped "normally"; that is, to follow the Gaussian curve. As discussed previously, the standard deviation is a measurement of how closely measurements cluster around the median or mean. The range of this clustering is called *dispersion*. The standard deviation is computed by squaring each deviation, summing all the deviations squared, dividing by the number of samples minus one, and taking the square root of the result.

$$\sigma = \pm\sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + d_4^2 + \dots d_n^2}{n-1}}$$

Median and Mean

We have previously discussed the mean and how to determine the standard deviation. The median, however, is different. While the mean (the arithmetic average) is considered the best representation of a series of measurements, extreme values may cause the mean to be offset or skewed from the point it would be if these "outriders" (extreme values) were not considered. The median is determined by taking the limits of the range of measurements and geometrically determining the center. In a true normal (random) or Gaussian curve, the mean and the median are equal in value.

When determining the average deviation (also called the *average absolute deviation*), the determined deviations must all be absolute (unsigned) values. To calculate the average deviation, the absolute deviation values are summed and then divided by the number of measurements.

$$\overline{D} = |d_1| = |d_2| = |d_3| = |d_n|$$

$$\text{Average Deviation} = \overline{D} = \frac{d_1 + d_2 + d_3 + \dots d_n}{n}$$

Uncertainty

It is understood that the greater the number of measurements, the more representative the statistics are of the actual values and associated error. However, this is not necessarily true. Determining the correct number of measurements (or sample size) is a function of the distribution of error and the judgment of the person conducting the measurements. It seems probable that if experience has dictated the dispersion for a measurement is not significant, then one measurement will do. If, on the other hand, there is a wide span of values around some central value, more observations will have to be used.

Measurement uncertainty tries to separate the systematic and random components of measurement, particularly for an entire measurement system as opposed to just one component of the system. The random component will be compensated for by statistical methods and the systematic component by calibration. An in-depth discussion of measurement uncertainty is beyond the scope of this text; however, the methods of statistically treating random errors and eliminating system errors have been described to reduce uncertainty. These include using more than one set of measurements and selecting and calibrating the correct measuring devices for an application. In industry, there is an emphasis on product quality. Documenting systematic error (by listing the test equipment used for measurement and the calibration dates), training in methods to reduce error, and using statistical methodology on measurements are standard practice in industry.

Module 3D: Summary

In this module, we discussed the treatment of error, definitions of the types of errors, some of the arithmetic used to better interpret data, and the use of a calibration curve. Whether these methods of error treatment are performed manually or by a computer device, they must still be accomplished if the data is to be accurate. Remember, all measurements will have some error; therefore, some thought must be given to the methods and equipment in order to establish measurement certainty and confidence in our measurements.

Module 3D: Review

See Appendix B for the answers.

1. For the listed measurements, calculate the mean, average deviation, deviatio absolute deviation.

Mean _______________ Average deviation _______________

Measurement	Value	Deviation	Absolute Deviation
1	10.13		
2	9.97		
3	9.99		
4	10.02		
5	10.08		
6	10.16		
7	9.86		
8	9.88		
9	10.12		
10	10.18		

2. What is one method to use to consistently reduce random error in measurements?

____

3. Given the following table of values, calculate the standard deviation and the de squared.

Measurement	Value	Deviation	Deviation Squared
1	10.13		
2	9.97		

3	9.99
4	10.02
5	10.08
6	10.16
7	9.86
8	9.88
9	10.12
10	10.18
11	9.94
12	9.91
13	9.97
14	10.15
15	10.13
16	9.95

Module 3E: Calibration, Terminologies, and Standards

There are several methods for calibrating a measuring device, and they are much the same whether the device is analog or digital. The primary method of device calibration is comparison calibration. The equipment is set up as in Figure 3-25.

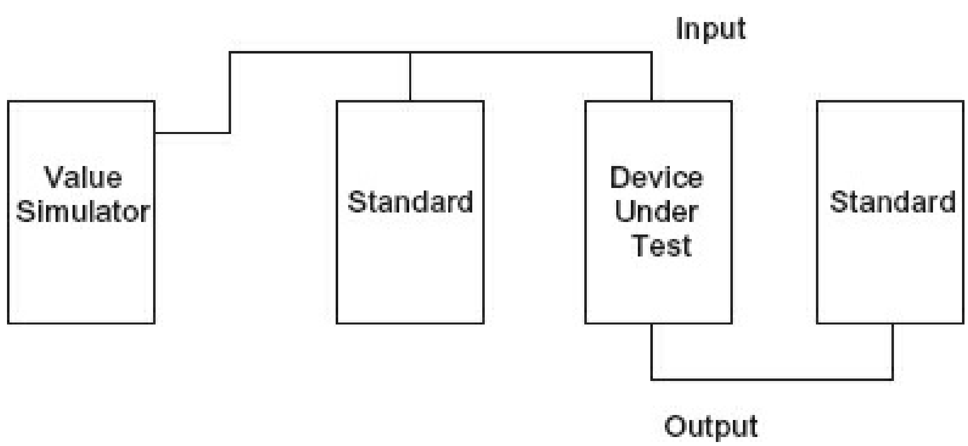

Figure 3-25. Measuring device comparison calibration.

The measurement source is in increments (or discrete steps at a time) at the scale divisions on the device under test. The true value as measured by the standard is noted, and the deviation by the device under test is documented.

To use measurement equipment correctly and accurately, it must be calibrated. We have stated that we use comparison calibration, but what is the standard our measurement device is calibrated against?

Standards

Instruments used as calibration standards are called *test instruments*.

- **Primary (US) standard** – This is the test instrument against which the accuracy others are compared (kept at the National Institute of Standards and Technol NIST).

- **Secondary (US) standard** – Accuracy is directly traceable to primary (US) standarc

- **Shop standard** – Accuracy is traceable to secondary standards.

All test instruments should be periodically certified.

The following is a short summary of the current state of calibration actions for CGMP.

There is a recognized hierarchy of US standards, as shown in Figure 3-26. Primary (US) standards are kept by NIST for the United States. Other countries have their own laboratories and storage locations, all of which are linked to l'Organisation internationale de normalization (ISO—also known as the International Organization for Standardization) in Geneva, Switzerland.

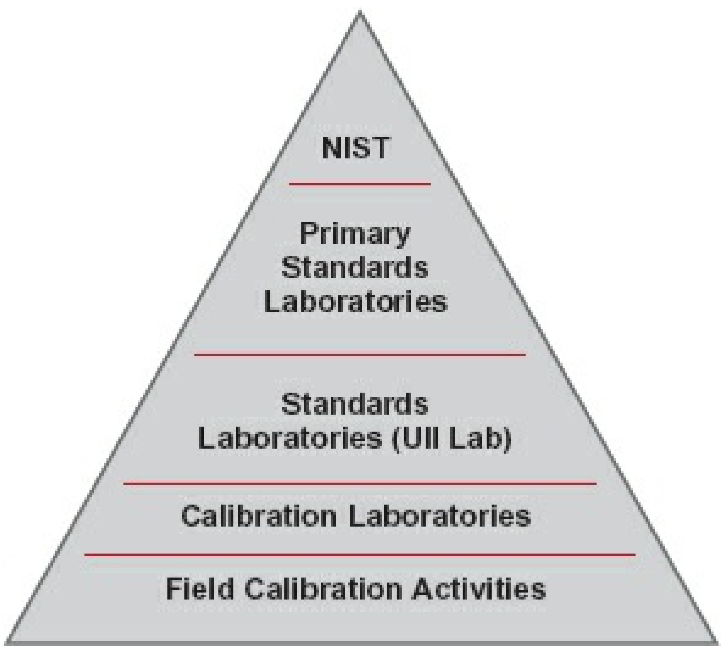

Figure 3-26. Hierarchy of US standards.

The general rule is that there is a definite line connecting the working standard back to the primary standard. This is called the *chain of custody*, and although the procedures are standardized, it is required by many quality standards and particularly in industries that have validated or critical measurements. The US chain of custody is illustrated in Figure 3-27.

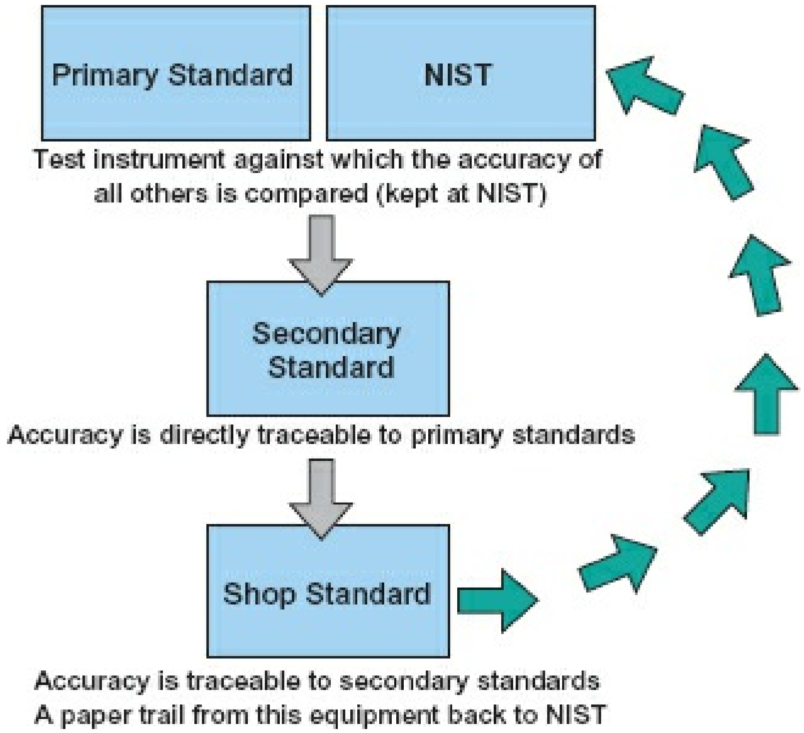

Figure 3-27. US custody chain for calibration.

Note that the calibration device configuration is measured against the primary (for a price per point), and if that configuration does not change (through the model or models run), there is no requirement for recalibration. A shop or working standard is periodically calibrated against the secondary standard.

When is it calibration and when is it verification? Verification is when a series of measurements are taken on a nonadjustable device to determine whether it is performing as accurately (error-free) as necessary to meet the device specifications. Such devices include:

- Thermocouples
- Resistance temperature detectors
- Nonadjustable gauges and indicators

Error Terminologies Used in Calibration

Total probable error (TPE) incorporates all the individual product differences with the specifics of a given application to provide the relevant error calculation. TPE can be calculated as the root-sum-square of the errors (U).

$$\text{Linear Summing: } U_{TOTAL} = U_1 + U_2 \ldots + U_n$$

$$\text{Root-Sum-Square: } U_{TOTAL} = \sqrt{U_1^2 + U_2^2 \ldots + U_n^2}$$

As early as the 1930s, the "Gauge Maker's Rule of Ten" was understood to be a good measurement practice. According to this rule, the device used to make a measurement should be 10 times as accurate as the object being calibrated. This rule was standardized in the 1960 version of military standard MIL-C-45662 but missing in the 1962 version. Under the ISO-9000 series, three to four times more accurate is acceptable without further testing.

In the world of metrology, the three-letter acronyms TAR, TUR, and CMC are routinely used.

- **TAR** – Test accuracy ratio; the ratio of the accuracy of the standard used to calibra device and the stated accuracy of the device. Metrology labs would like to h minimum 4:1 TAR.
- **TUR** – Test uncertainty ratio; the ratio of the combined uncertainties of a measur system to the tolerance of the measurement that is being made.
- **CMC** - Calibration measurement capability; a calibration and measurement capa available to customers under normal conditions.

Any further discussion of calibration, standards, and measurement uncertainty is beyond the scope of this text, although excellent references on these topics are available.

Module 3E: Summary

- Comparison calibration is the most common method of calibration.
- There is a hierarchy of standards with the primary standard at the top.
- Secondary standards are occasionally calibrated against the primary.
- All other devices that are not primary or secondary standards are calibrated agair shop standard.
- There is a chain of custody for calibrated (and validated) devices that must r broken to ensure the accuracy stated is the accuracy of the measurement.
- Calibration has an adjustment to meet the standard.
- Verification has no adjustment but verifies the device to the specification.
- Total probable error (TPE) is the square root of the sum of individual errors square

Module 3E: Review

See Appendix B for the answers.

1. If you have a working standard calibrator last calibrated at 4:35 p.m. on June 3(

and you discover on September 24, 2018, that it is out of range (compared to a working standard):

A. When would you consider any calibrations by this machine not valid?

____

B. What would be necessary to maintain the chain of custody?

____

____

____

2. You have five devices whose uncertainties are as follows:

$U_1 = 0.05$

$U_2 = 0.21$

$U_3 = 0.09$

$U_4 = 0.01$

$U_5 = 0.04$

Use both the linear and root-sum-square method to determine the TPE.

Linear sum = ____________

Sum of errors squared = ____________

Linear = 0.04, square root of sum of errors squared = ____________

TPE = ____________

3. Define TAR.

____

____

____

Conclusion

You have reached the end of Module 3. Please reread the module objectives. If you have met these objectives, continue to the next module. If you are having difficulty, please reread the text. If the difficulty persists, locate a peer, mentor, supervisor, or someone who has technical knowledge of oscilloscopes and ask them to assist you. It would be of considerable benefit to you to locate an oscilloscope (one used in your shop, one you may otherwise have access to, or one of the inexpensive conversions for a PC or smartphone) and familiarize yourself with the controls and measurement of differing input signals.

Further Information

For additional information on the topics in this module, search for the following topics at your public or company library or on the Internet.

- Oscilloscope principles
- Cathode ray tubes
- DC amplifiers
- Lissajous patterns
- Oscilloscope manufacturers
- Waveform analysis
- Measurement
- Measurement uncertainty
- Mean
- Average
- Median
- Bell curve
- Calibration
- Total probable error
- Gross error of measurement
- Systematic error of measurement
- Random error in measurement
- Comparison calibration
- Chain of custody (calibration)

4 Bridges

Bridges are an integral part of measurement and measurement devices. Of the many DC bridges in existence, the Wheatstone bridge is used the most often because of its ability to measure unknown resistance values. Sections 4A and 4B of this module explain the operation of Wheatstone and AC bridges. You must have a thorough understanding of bridge operation because bridges are fundamental to many measurements, devices, and techniques. As a plus, they will exercise your understanding of Ohm's law and its applications.

Module 4: Objectives

- Determine the operation and component values of the Wheatstone bridge.
- Review common operations between the DC Wheatstone bridge and AC bridge ci
- Determine the operation of the most common AC bridge.

Module 4A: DC Bridges

Wheatstone Bridge

A bridge is essentially a two-branch balancing network that is in balance when there is no difference in potential between a point on one branch and the same point on the other branch. The advantage lies in the fact that when balance is indicated, the indicator draws no current, a condition called NULL.

A Wheatstone bridge, which is used to measure resistance, is illustrated in Figure 4-1. R_a and R_b are called the *ratio arms*. R_s is a variable *standard* resistance; it has a calibrated scale, so as you vary the resistance, the scale indicates the resistance within the accuracy of the scale. R_x is the unknown resistance. Bridges, like the Wheatstone, are used extensively in measurement because they provide a comparison measurement, that is, you are comparing an unknown value to a known value, much like comparison calibration.

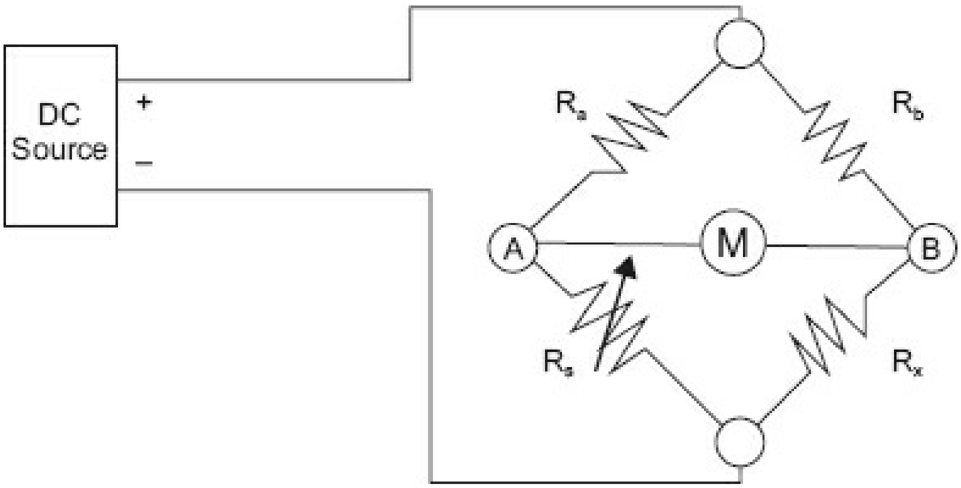

Figure 4-1. Wheatstone bridge.

The accuracy of this device primarily depends on the tolerance of R_a, R_b, and R_s. The meter is a null meter. It has a center zero and reads to the left for a negative voltage and to the right for a positive voltage. Some electronic multimeters (volt-ohm meters—VOMs) and almost all digital meters (as they read ±0 V) have a center zero scale and may be used as null meters. The scale itself is unimportant because the meter's only purpose is to determine when there is *no* potential between points A and B, not the magnitude of the potential voltage. To explain the operation of the Wheatstone bridge, values have been assigned in Figure 4-2.

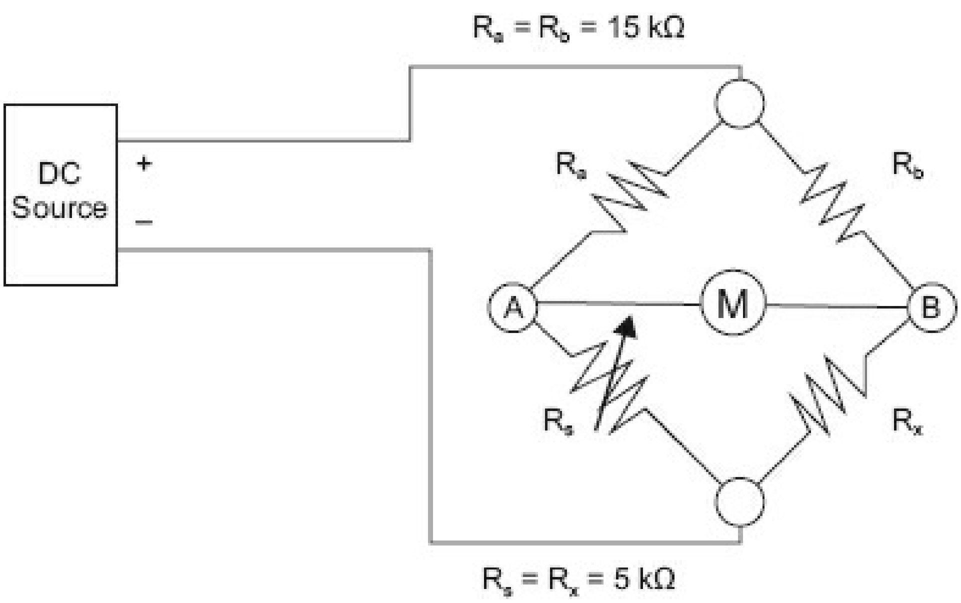

Figure 4-2. A balanced Wheatstone bridge.

If $R_s = R_x$, then the bridge will be "balanced" for the values of R_a and R_b in Figure 4-2. This is illustrated by redrawing Figure 4-2 as shown in Figure 4-3.

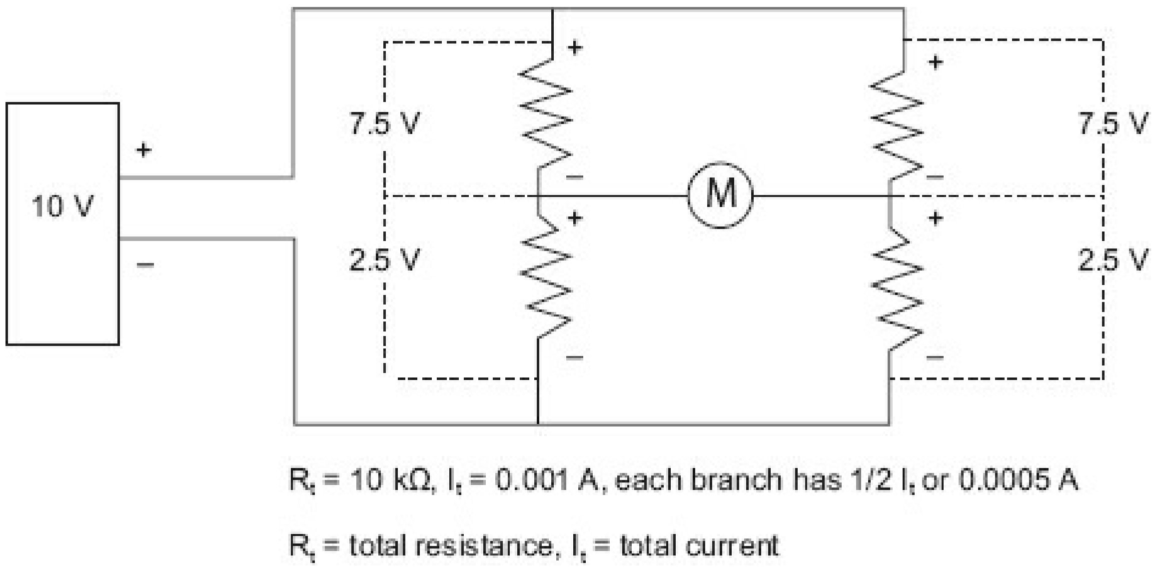

Figure 4-3. Current in a balanced bridge.

Because $R_a = R_b = 15\ k\Omega$ and $R_s = R_x$, current in each branch will be equal. Therefore, the voltage drop across the meter will be 0 V.

Assume that R_x is not 5 kΩ but 10 kΩ and that all other values remain the same. The resulting circuit appears in Figure 4-4.

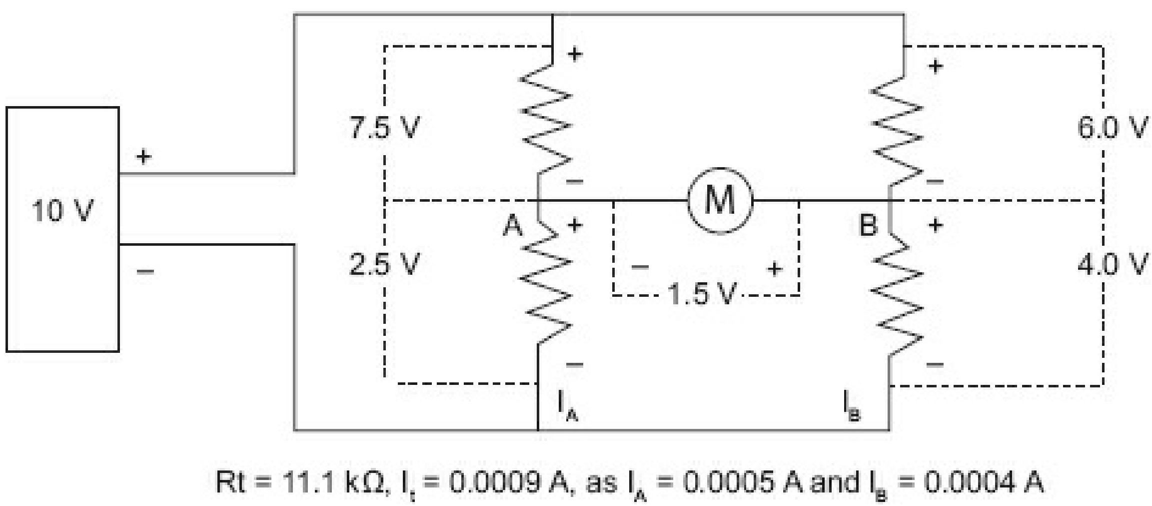

Figure 4-4. Current in an unbalanced bridge.

Point A (2.5 V positive) and point B (4.0 V positive) differ by 1.5 V. A current will flow from B to A if a path (e.g., the voltmeter) is connected.

If you knew the sensitivity of the meter and considered it in the circuit, the current values and voltage drops would be different because the resistance would also affect the overall current, but only slightly if a sensitive meter is used. Originally, a galvanometer was used in place of the meter. A galvanometer is an extremely sensitive current meter that requires very little current for deflection. To determine the actual currents with a meter connected would involve network theory. Fortunately, when using a bridge for resistance measurement, you do not care (other than for bridge sensitivity) how much current flows through the meter resistance because you adjust the bridge by varying R_s for a NO CURRENT FLOW or NULL condition. For this condition, the value of R_x will equal R_s (assuming $R_a = R_b$), and the resistance may be read from the standard potentiometer dial. That is how the bridge was and is used to determine an unknown resistance.

Bridge Sensitivity

A manufactured bridge normally has a galvanometer for a meter movement. The more sensitive the meter movement (less current for scale deflection), the smaller the difference between R_s and R_x that can be resolved. With the values given in Figure 4-3, the meter would have to have sensitivity in the microamp range to detect small differences in resistance.

The reason you are not concerned (to any large degree) with meter sensitivity is that if you are using a manufactured bridge, the company has determined the sensitivity for the ranges involved. If you build a bridge for resistance measurement, you will use a digital meter or commercial null meter whose sensitivity is predetermined.

Meter sensitivity determines the amount of measurement resolution or the smallest change of resistance the bridge can detect. Note that meter sensitivity can be of any reasonable value when measuring resistance because the value of the applied voltage and the values of the ratio arm resistors R_a and R_b can be chosen for the degree of resolution required.

Resistance Determination

How do you determine the resistance after a NULL has been obtained? You could measure the resistance of R_s. If you have the ability to measure R_s to the accuracy desired, why not just measure R_x? Commercial bridges have the R_s scale calibrated in ohms, so you can take the reading directly from this scale.

Bridge Mathematics

Although an understanding of bridge mathematics is not required to complete this course successfully, if you have the ability to perform ratios, this section will help you understand bridge operations.

For the bridge in Figure 4-5 to be balanced (no potential difference between A and B), the following conditions must be met:

1. $I_a R_a = I_b R_b$ (voltage drop across R_a = voltage drop across R_b). Ohm's law:

$$(I \bullet R = E)$$

2. $I_a = I_s = \dfrac{E}{R_a + R_s}$

(This means that if condition 1 is true, the current through R_a is the same as the current through R_s. When the current through R_a is the same as the current through R_s, no current flows through the NULL circuit. And, according to Ohm's law, I = E / R.)

3. $I_b = I_x = \frac{E}{R_b + R_x}$

(The current through R_b is the same as the current through R_x. No current flows through the NULL circuit. According to Ohm's law, I = E / R.)

4. The simplest expression of a bridge is:

$$\frac{R_a}{R_s} = \frac{R_b}{R_x}$$

Therefore, for the bridge in Figure 4-5:

$$\frac{R_x \bullet R_a}{R_s} = R_b \Rightarrow R_x \bullet R_a = R_b \bullet R_s \Rightarrow R_x = \frac{R_b}{R_s} \bullet R_s$$

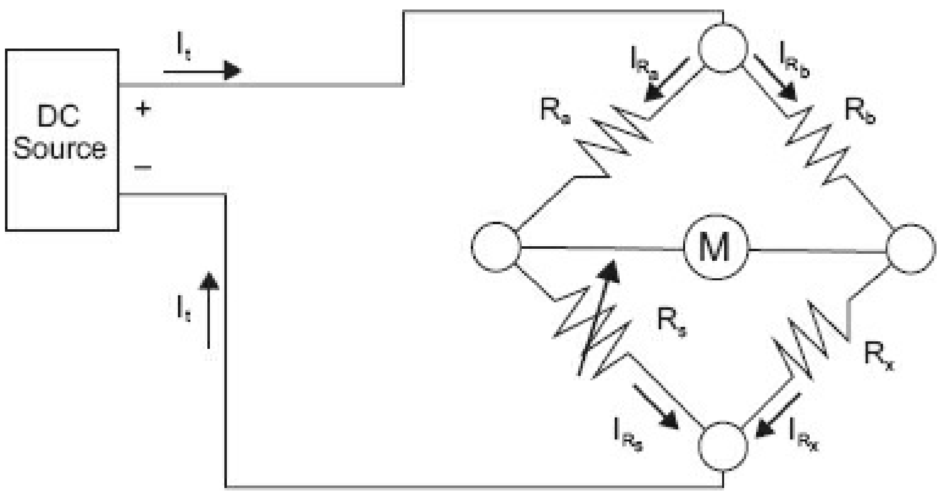

Figure 4-5. Current for bridge mathematics.

This is the standard expression of balance for the Wheatstone bridge. If you have three of the values (R_a, R_b, and R_s), R_x may be determined by solving the expression for R_x.

You can now see why R_a and R_b are called the ratio arms. When $R_a = R_b$, the ratio is 1, so $R_x = R_s$ when the bridge is balanced.

Module 4A: Summary

- Bridges provide a method of measurement whose accuracy depends on the compc rather than the meter movement.

- Bridges are used so a NULL condition equals balance.

- The formula for a Wheatstone bridge (as drawn in Figure 4-5) is $R_x = R_b / R_a \bullet R_s$.

- The bridge is balanced if current through one branch equals current through the or if $R_a / R_s = R_b / R_x$.

Module 4B: Multiplier Resistors

Ratio Arms

To expand the range of a bridge, particularly to the higher ranges, yet maintain the resolution of R_x used on the lower scales, a multiplier resistor is used in one of the ratio arms. In Figure 4-6, R_b has been changed to 100 kΩ, and R_s is set to 5 kΩ. When will the balance occur?

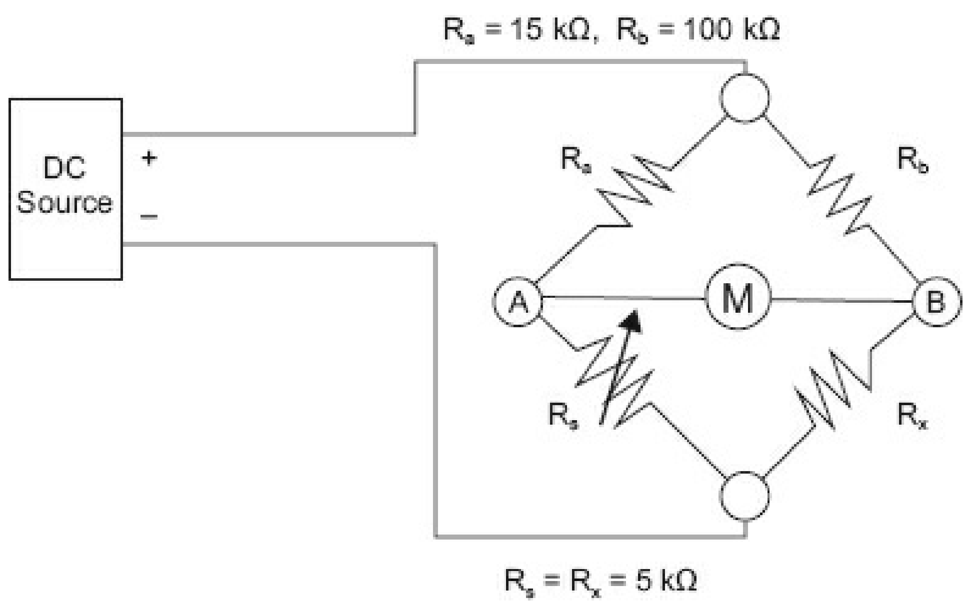

Figure 4-6. Multiplier ratio arm.

If you use the known side R_a and R_s, the current (for balance—no current through A to B) is

$$\frac{10 \text{ V}}{15 \text{ k}\Omega} = 0.67 \text{ mA}$$

which gives a voltage drop across R_a of 6.7 V and across R_s of 3.3 V.

For the bridge to balance, the drop across R_b must equal the drop across R_a. To have a 6.7 V drop across R_b (100 kΩ), a current of 6.7 V / 100 kΩ = 0.067 mA must flow. This same 0.067 mA must flow through R_x for a balanced condition, and must drop 3.3 V, so:

$$R_x = \frac{3.3}{0.000067 \text{A}} = 50 \text{ K}\Omega$$

Note that R_x is now 10 times R_s. A much faster method of determining the resistance is to use the bridge formula:

$$R_x = \frac{R_b}{R_a} \bullet R_s$$

As illustrated, R_b / R_a forms a ratio of 10. This same process works for fractional ratios. If R_b = 1 kΩ, and R_s is set to 5 kΩ for balance, thereby the formula is:

$$R_x = \frac{1\ K\Omega}{10\ K\Omega} \bullet 5\ K\Omega$$

R_x would equal 500 Ω because the R_b/R_a ratio was 1/10.

Note: Neither the applied voltage nor the meter sensitivity enters into these equations. In fact, any voltage may be used, provided the resistor's wattage rating is not exceeded. Heat generated by too much current will cause the resistors to change in value, destroying the accuracy of the bridge. The lower the individual resistance of the ratio arms, the more overall current will flow.

Question: If R_b is 100 Ω, R_a is 10 kΩ (this ratio will measure resistors in the 5 Ω range), and 10 V is applied, what power must the bridge resistors dissipate?

Answer: 10 W. Because Power (P) = E (volts) • I (amps), and with 5 Ω or less for R_x, most of E will be dropped across R_a and $I_a \approx 1$ A so 10 • 1 = 10 W.

The majority of resistors used in bridges are 1/8 to 1/4 W rating. If 10 W is dissipated, smoke and damage to the bridge are the results. A good policy to follow is to use only the voltage necessary to produce the meter deflection desired. In most cases, the voltage is supplied as part of the bridge circuitry and packaging. Only lead connections, meter resolution, and meter sensitivity set the limits for the Wheatstone bridge in resistance measurement.

The lower limit is set by the resistance of the connecting leads and the contact resistance of the *binding posts*. Binding posts are the physical connectors used to connect the wires to R_x. Compensation for connecting leads is easily achieved, but the contact resistance of the binding posts is difficult, if not impossible, to measure, and compensating for that resistance is just as difficult.

The upper limit is set by the bridge's sensitivity to unbalance. As the resistances involved become higher, the current available for the null meter decreases until the current is too small to deflect the null meter. A more sensitive null meter and higher applied voltages (along with higher power dissipation resistors) are required to measure increasingly higher resistances.

Lead Resistance

To use a bridge to measure less than 1 Ω resistances, some method of compensation for meter lead resistance must be employed. The bridge circuit in Figure 4-7 illustrates the problem of trying to measure less than 1 Ω resistors with a Wheatstone bridge.

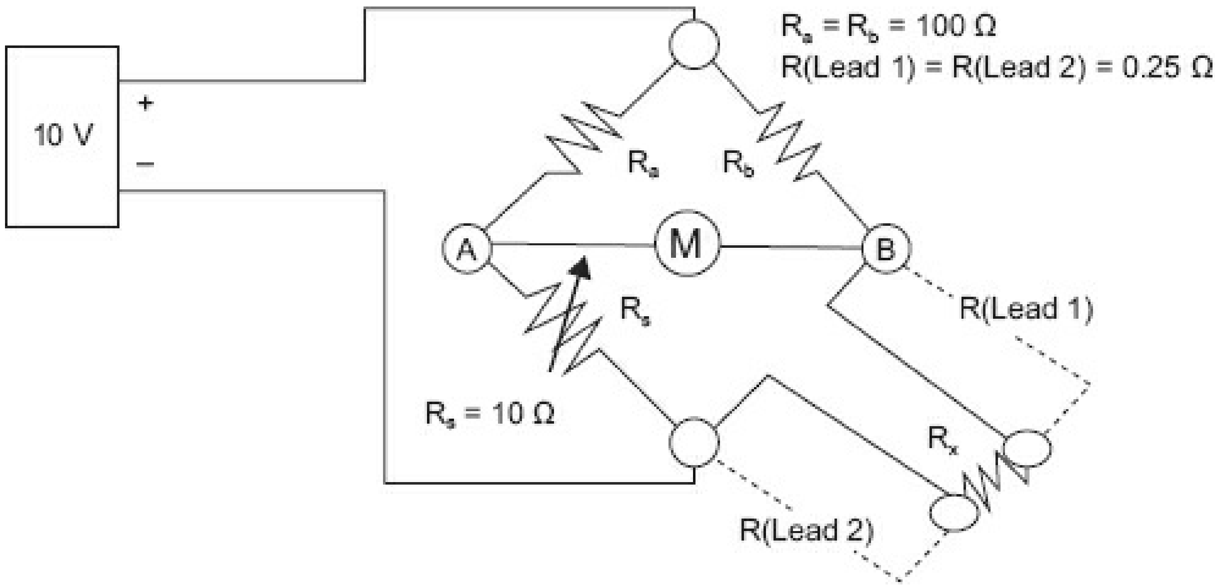

Figure 4-7. Lead resistance problem.

The figure shows that the lead resistance will contribute 0.5 Ω uncertainty to the determination of R_x. Worse, the lead resistance is not necessarily fixed, depending on temperature and other environmental influences. To reduce the effect of lead resistance, a simple change is necessary. Another lead is added to the bridge connection to R_x. Figure 4-8 illustrates this technique.

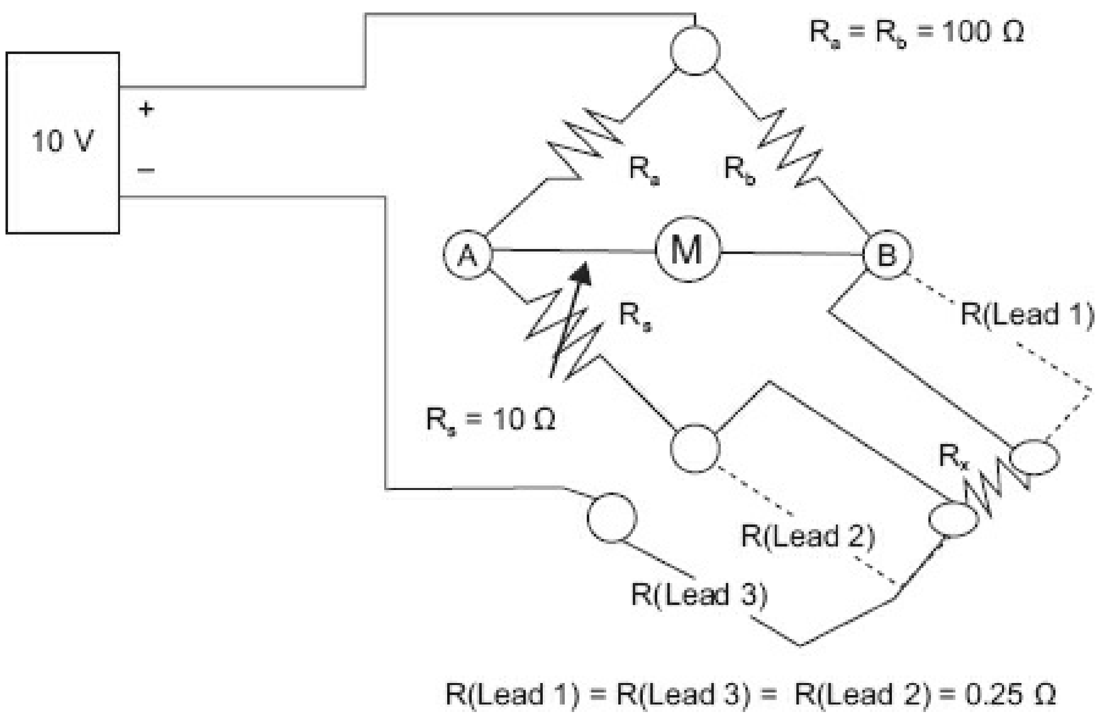

Figure 4-8. Adaptation of Wheatstone bridge.

Note that the third lead, R (Lead 3), now ties the bridge to the power supply return. This places the resistance of R(Lead 2) on the R_s side of the bridge. Any voltage dropped across R(Lead 1) will be offset by the drop across R(Lead 2). R(Lead 3) does not enter into the bridge equations as current from both branches must pass through it. This makes the bridge equation:

$$R_x + R(Lead\ 1) = \frac{R_b}{R_a} \bullet R_s + R(Lead\ 2)$$

Because R(Lead 1) = R(Lead 2), you may subtract this equal quantity from both sides of the equation, and you again have the bridge equation without lead resistance.

Other types of bridges are available, such as the Kelvin bridge, which is a bridge within a bridge to compensate for binding post (connector) resistances.

Module 4B: Summary

- A multiplier resistor may be used with the Wheatstone bridge to expand its range.
- Lower resistance measurements require considering applied voltage and resistor p dissipation.
- A Wheatstone bridge has an application in measuring resistances from near 1 Ω MΩ.
- Meter lead and contact resistance limit the lower resistance measurement Wheatstone bridge.
- Sufficient current for null meter deflection limits the upper resistance measureme a Wheatstone bridge.

Application

One of the tools used to measure temperature is a resistance thermometer detector (RTD). It operates on the principle that a conductor's resistance will change with temperature. Several materials lend themselves to linear change in resistance over large spans of temperature. Platinum is one of the materials. A standard industrial RTD typically has a resistance of 100 Ω at 0°C. It will change about 0.00385 Ω per degree. Therefore, to measure an RTD within 1°, you must use a method that can resolve less than 1 Ω.

Without going into the actual circuitry of an RTD transmitter, the operation can be modeled using a Wheatstone bridge for a two-wire RTD. This is the case when the bridge and the RTD are physically very close to each other. If the conditions are such that the RTD is not coupled directly to the bridge (as when the location where the RTD is mounted is too hot for the bridge to accurately measure), connecting leads will be used. The problem is that these leads have resistance, and worse yet, they are subject to the ambient temperature (temperature of the surroundings), which is always varying.

This means the lead resistances may change. Because both leads are the same length and are generally twisted together (although insulated from each other), they will have the same resistance.

Question: How would you compensate for this problem?

Answer: Use a three-wire RTD. Three-wire RTDs are manufactured for this purpose, and, generally, all RTD measurement devices allow for three-wire connection. The resulting simplified circuit appears in Figure 4-9.

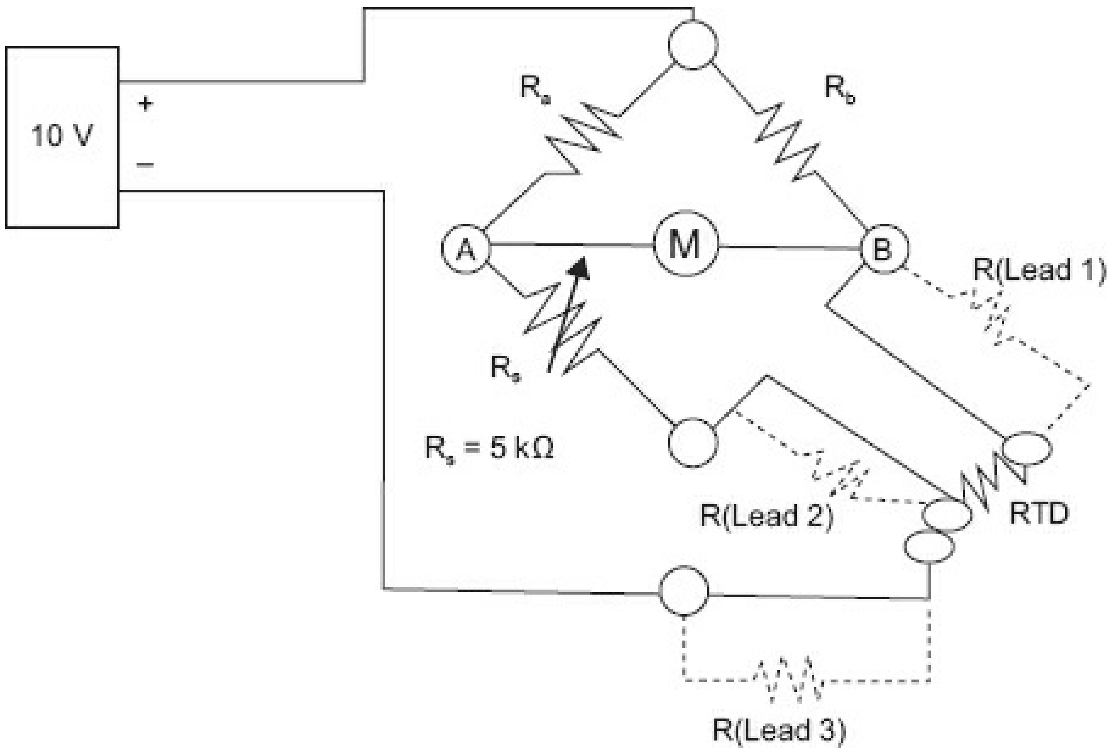

Figure 4-9. Three-wire RTD connections.

Connect a third lead, R(Lead 3), which has the same resistance as the other two, to the power supply rather than to the negative side of R_S. Current from both branches flows through R(Lead 3) and therefore does not enter into any but the total resistance calculations. This places R(Lead 2) in series with R_S. Because R(Lead 1) is in series with the RTD, the resistances of the leads (which are identical) will cancel each other's effect. This is how a three-wire RTD compensates for lead resistance.

Module 4B: Review

See Appendix B for the answers.

1. Using Figure R4-1, fill in the blanks for questions A, B, and C.

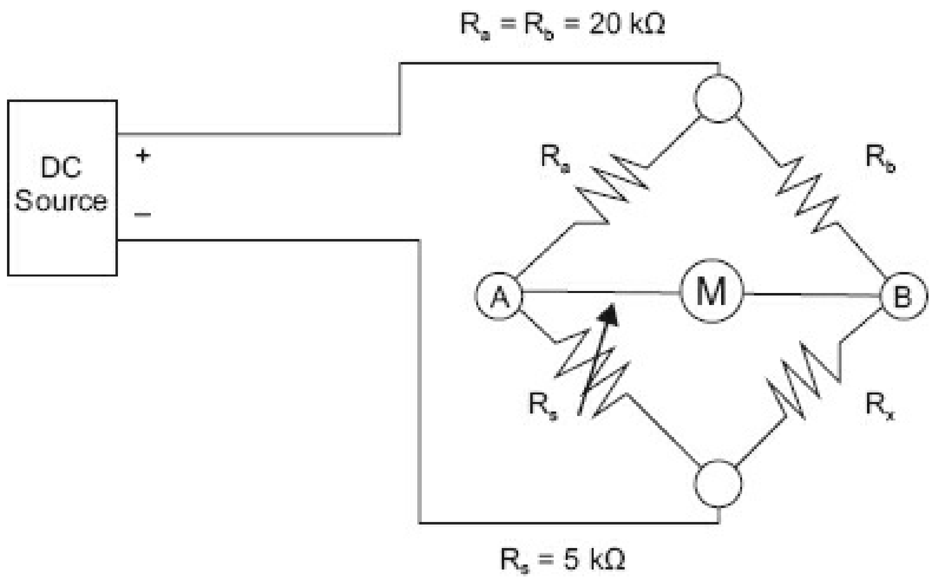

Figure R4-1.

A. If R_s is set to 3.850 kΩ for a balanced condition, what is the value of R_x?

____________________ Ω

B. If the DC source = 10 V at balance, what current flows in the:

(1) R_a-R_s branch	____________________	mA
(2) R_b-R_x branch	____________________	mA
(3) A-B branch	____________________	mA

C. What is the range (in ohms) that can be measured with this bridge?

____________________ Ω to ____________________ Ω

2. Using Figure R4-2, determine the value of the multiplier resistor to measure res in the range of:

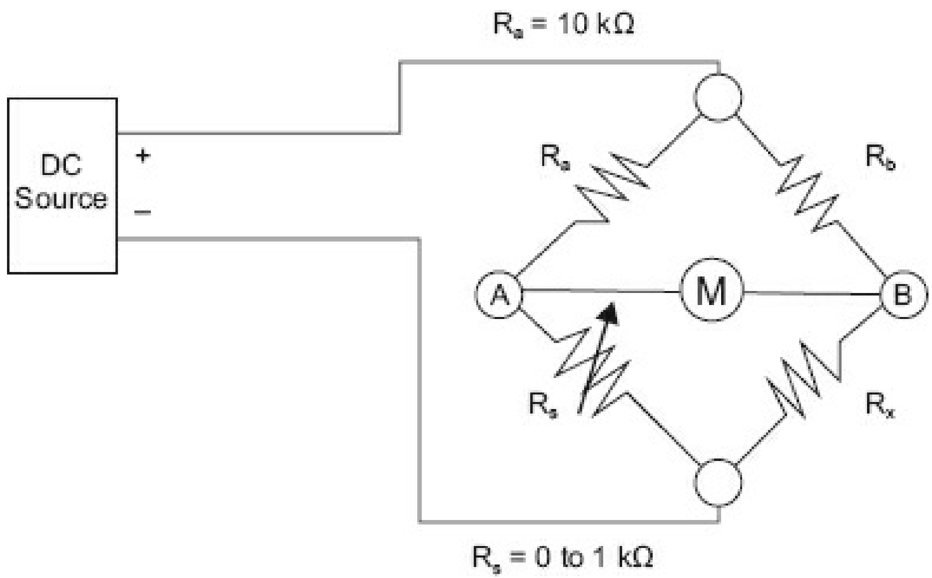

Figure R4-2.

A. 10 Ω to 1 kΩ ________________ Ω

B. 5 kΩ to 10 kΩ ________________ Ω

C. 0.1 MΩ to 1 MΩ ________________ Ω

D. 50 kΩ to 100 kΩ ________________ Ω

E. 1Ω to 100 Ω ________________ Ω

Module 4C: AC Bridge

In industry, AC bridges are

- used for precise measurements of resistance, reactive components, imped temperature, pressure, strain, and other physical quantities (measured or sensec transducers);
- present in many expensive real-time monitoring devices that utilize transduc measure and sense physical quantities; and
- present in many expensive component-measuring devices, such as inductive-capa meters and high-end ohmmeters.

AC Bridge Operation

AC bridge circuits work on the same basic principle as DC bridge circuits: a balanced ratio of impedances (rather than resistances) will result in a "balanced" condition as indicated by the NULL-detector device. A simplified schematic of an impedance bridge is shown in Figure 4-10.

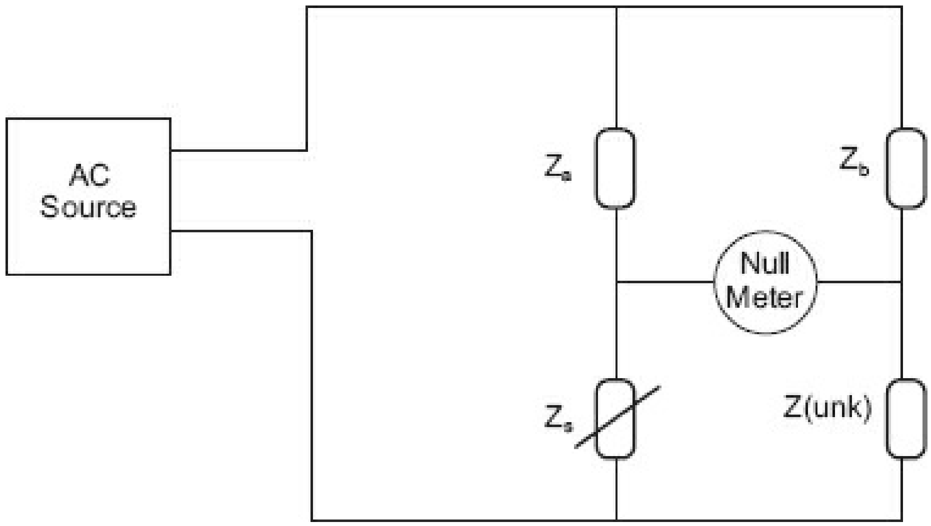

Figure 4-10. A simplified form impedance bridge.

If Z_a is equal to Z_b and the circuit is NULL, then Z(unk) = Z_s.

If Z_a does not equal Z_b, then at NULL, Z(unk) = Z_b / Z_a • Z_s.

NULL detectors for AC bridges may be sensitive to AC meter movements or any other device capable of detecting small AC voltage levels.

Like DC NULL detectors, the only required point of calibration accuracy is at NULL.

AC bridge circuits can be symmetrical, where an unknown impedance is balanced by a known impedance of the same type (capacitive or inductive) located on the same side (top or bottom) of the bridge.

AC bridge circuits also can be nonsymmetrical, using parallel impedances to balance series impedances or using capacitances to balance out inductances (at certain frequencies).

As opposed to DC bridges, AC bridge circuits often have more than one adjustment because both the magnitude of impedance and the phase angle must be the same to obtain balance. Because some impedance bridge circuits are frequency-sensitive, they can also be used as frequency measurement devices.

To summarize, the main differences between a DC and an AC Wheatstone bridge are that the AC Wheatstone bridge has a common AC source; and the resistances R_a, R_b, R_s, and R(unk) may be replaced by impedances. For these reasons, the AC Wheatstone bridge is often called an *impedance bridge*.

General Impedance Bridge

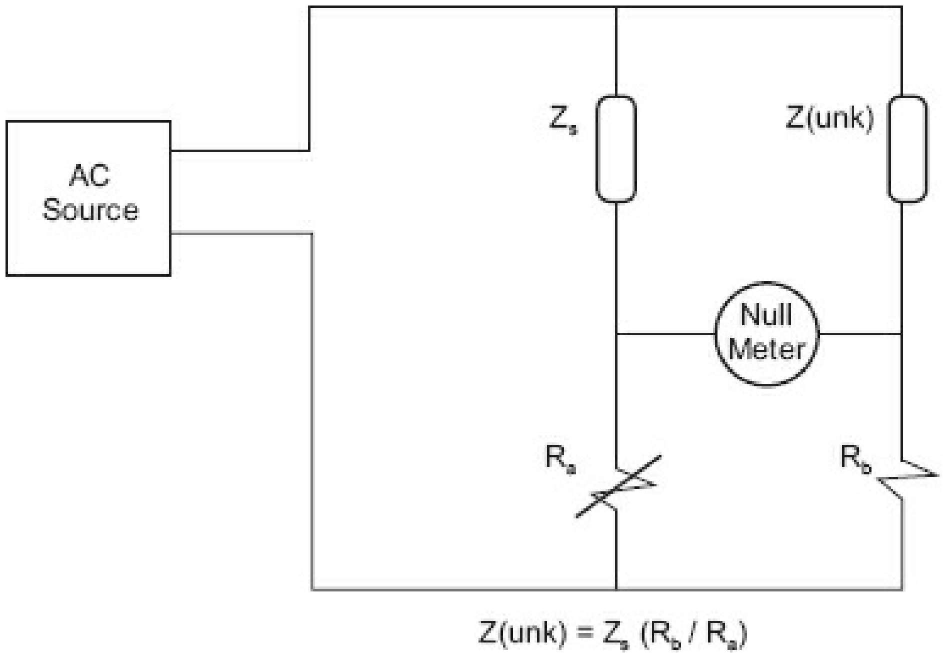

Figure 4-11. General impedance bridge.

This is the general model of an impedance bridge (Figure 4-11). Notice that it closely follows the DC Wheatstone bridge. Actual impedance bridges are discussed next.

In the simple capacitive bridge (Figure 4-12), when the current through (no current actually flows through the capacitor, but the charge/discharge cycle is fast enough that it appears to be drawing current) each capacitive arm is made equal, the unknown capacitance equals the standard capacitor.

The bridge formulas shown are only correct when the instrument is nulled, that is, at zero. The simple capacitive bridge is not frequency dependent (meaning that within a range of frequencies, the NULL condition will remain the same. The reactance in each opposite branch will also change the same amount with the change in frequency).

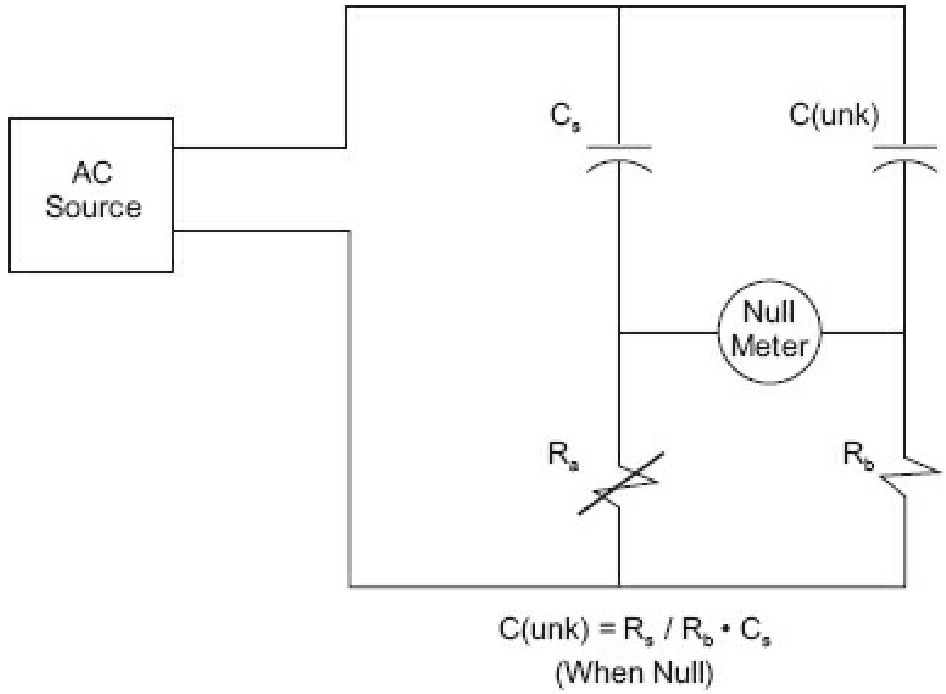

Figure 4-12. Simple capacitive bridge.

The use of series resistors (Figure 4-13) makes balance much easier to obtain and measures the internal resistance component of the capacitor. This bridge (like the simple capacitive bridge) is not frequency dependent.

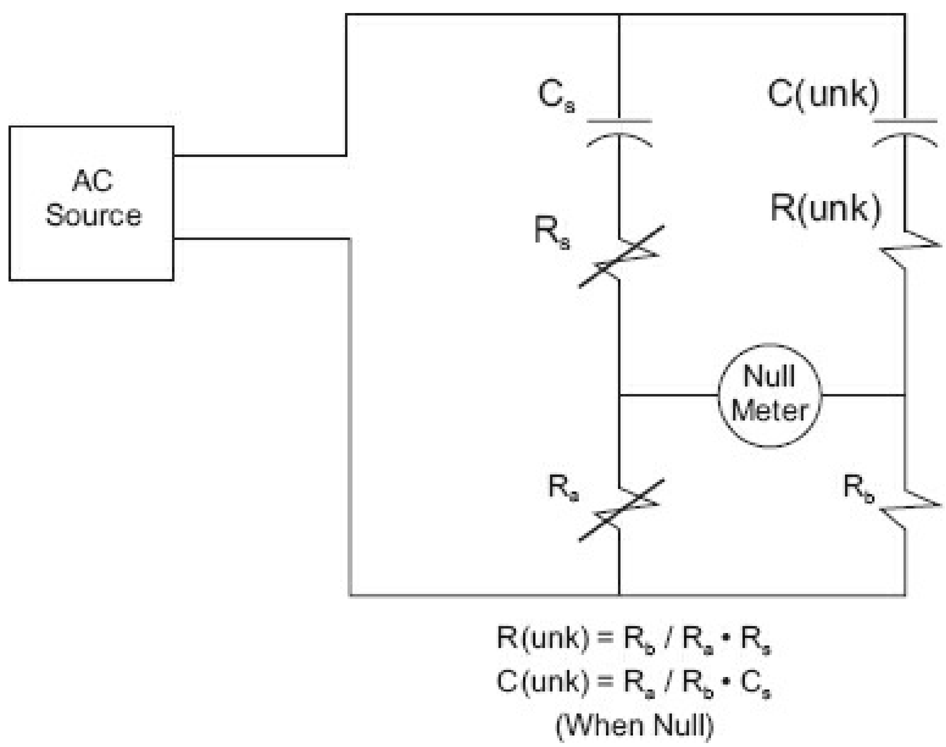

Figure 4-13. Series resistor-capacitance bridge.

Maxwell Bridge

The Maxwell bridge (Figure 4-14) measures inductances in the same way the capacitive bridge measures capacitance. When at NULL, the unknown inductor is equal to the known or standard inductor. As with the series capacitance bridge, using series resistors makes identifying the balanced condition easier and measures the inductor's internal resistance.

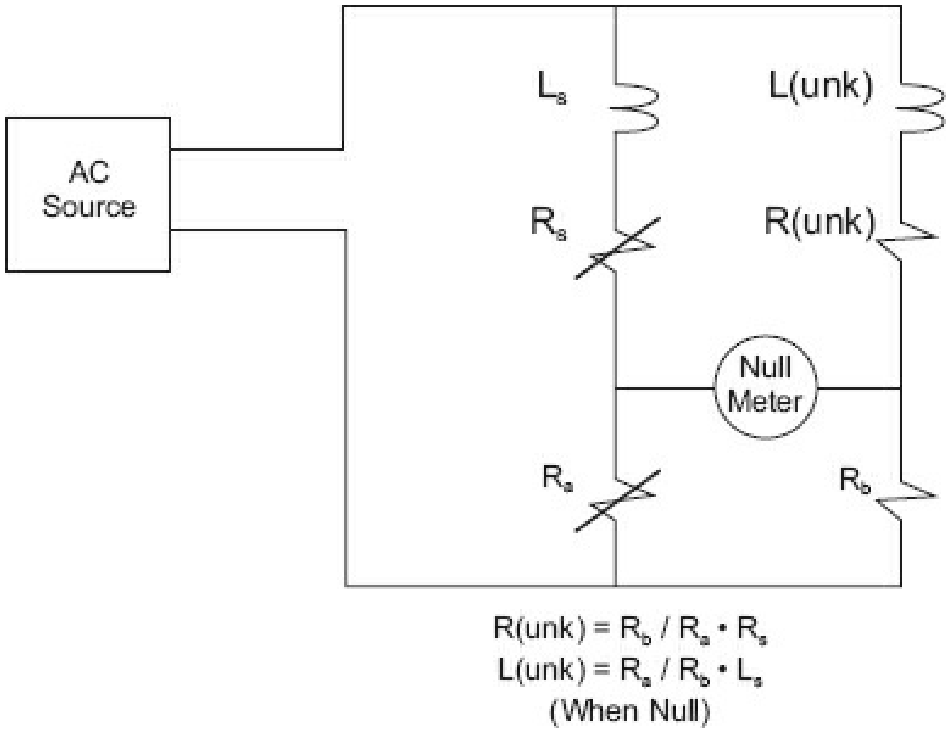

Figure 4-14. Maxwell bridge.

Capacitive Wien Bridge

Figure 4-15 illustrates a capacitive Wien bridge. This bridge will only be NULL at one frequency, and when that frequency is reached, the unknown capacitance will equal the known or standard capacitance. Tuning and adjusting for balance will vary somewhat by manufacturer; but in the end, NULL is achieved at one frequency only, and any desired component can be determined by algebraic dexterity.

Maxwell-Wien Bridge

A Maxwell-Wien bridge (Figure 4-16) measures inductances but is not frequency dependent.

Module 4C: Summary

AC bridges are not discussed in great detail in this text because most control technicians will have little use for or practice with them. They are mostly incorporated into equipment and, other than some calibrations, are no longer relevant to typical control system maintenance.

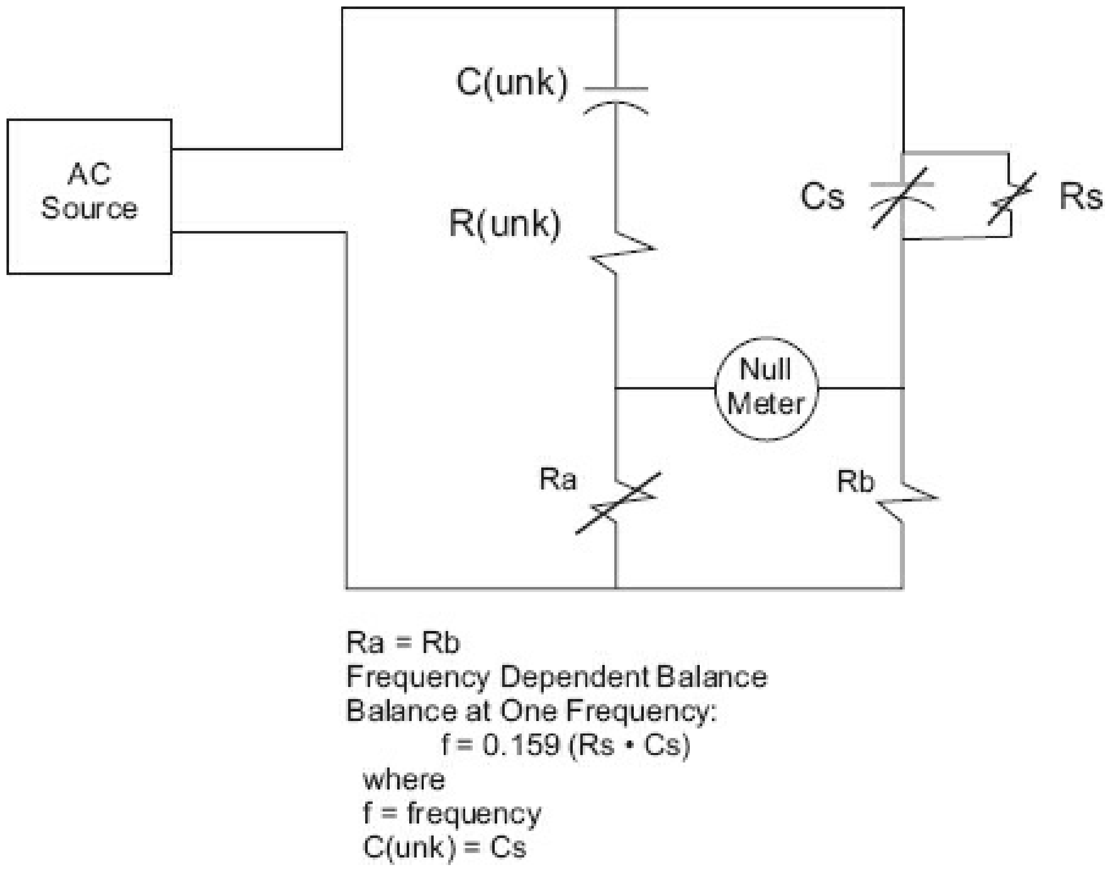

Figure 4-15. Capacitive Wien bridge.

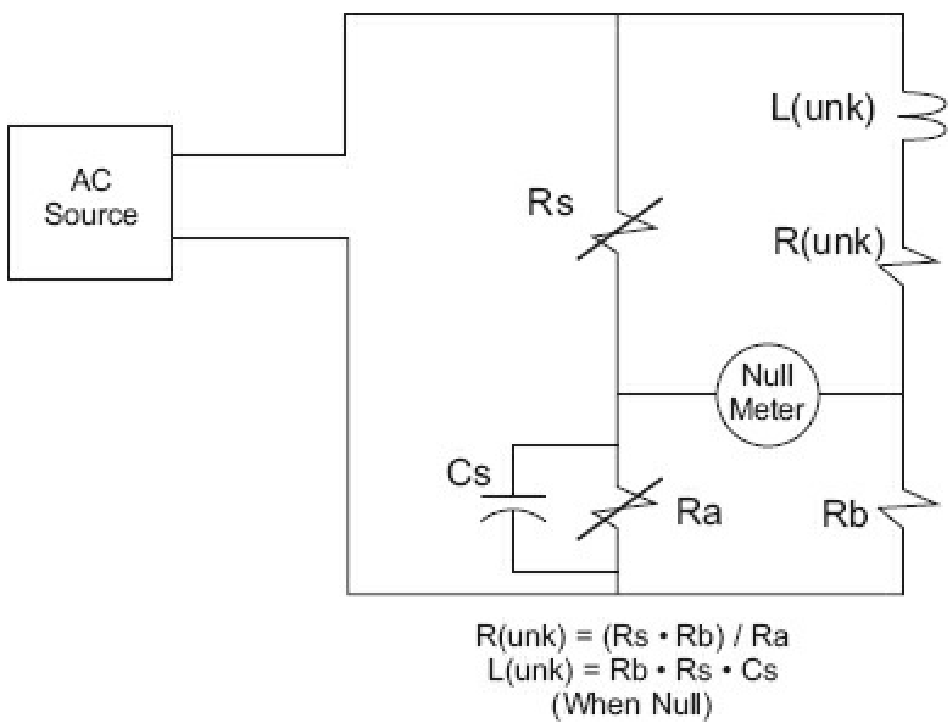

Figure 4-16. Maxwell-Wien bridge.

The AC bridges discussed so far are sometimes referred to as *differential-ended AC bridges* because the output of the bridges is floating (not referenced to ground). These types of bridges are quite sensitive to bridge component changes and are susceptible to external noise depending on the circuitry and circuit environments.

Module 4C: Review

See Appendix B for the answers.

1. For the values given, determine the frequency at NULL ___________________:

   R_a = 5 k, R_b = 5 k, R_s = 5 k, C_s = C_x = 1 µF

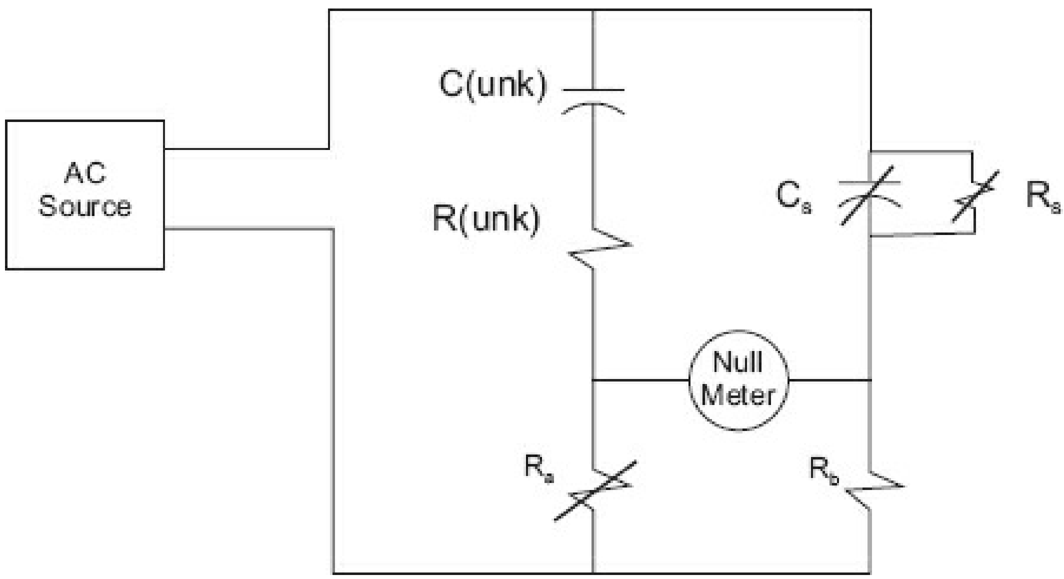

Figure R4-3.

2. For the values given, determine the unknown capacitance, C(unk) __________ unknown resistor, R(unk) ___________.

   R_a = 5 k, R_b = 10 k, R_s = 3 k, C_s = 0.001 µF

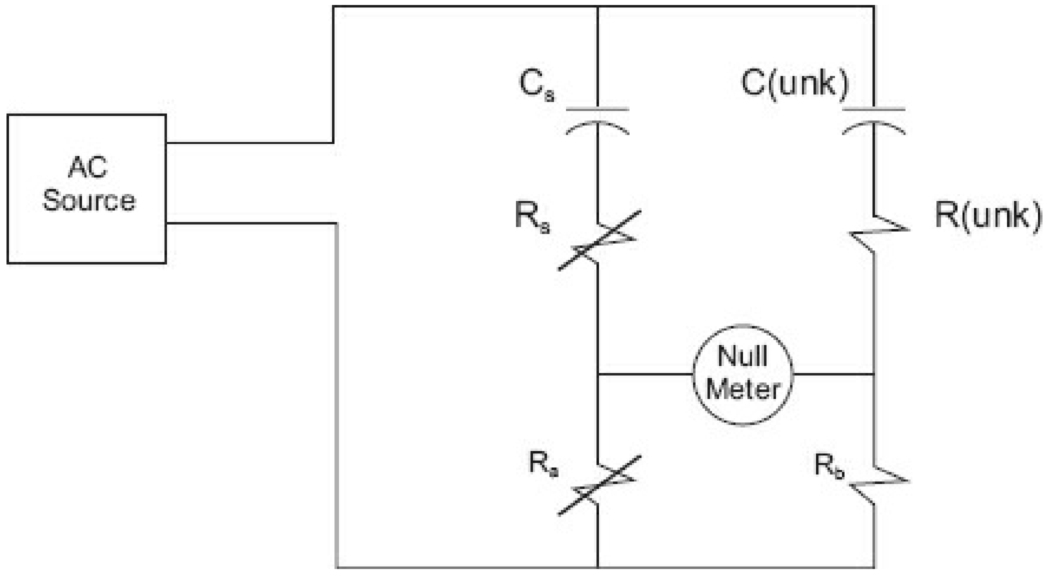

Figure R4-4.

Conclusion

You have reached the end of Module 4. Please reread the module objectives. If you have met these objectives, continue to the next module. If you are having difficulty, please reread the text. If the difficulty persists, locate a peer, mentor, supervisor, or someone who has technical knowledge of bridges and ask them to assist you.

Further Information

For additional information on the topics in this module, search for the following topics at your public or company library, or on the Internet.

- Wheatstone bridge
- Kelvin bridge
- Maxwell bridge
- Wien bridge
- Hay bridge
- Owen bridge
- Schering bridge

5
AC Measurement

This unit explains alternating current (AC) measurement using rectification to convert the AC to direct current (DC) for measurement and rectifying instruments. Knowledge of the circuit principles behind how these devices operate will assist you in properly using and in making correct AC measurements. In Module 4, we explained the AC bridges used to measure reactive components (capacitors and inductors) but not the actual measurement of AC values.

One of the most common and economical methods of measuring AC is to rectify these currents and read the resultant DC on an analog or digital volt-ohm meter (VOM) scaled in AC values. Many factors must be considered when rectification is used, including what type of rectification is used, what scale conversion will be required, and the sensitivity of the meter employed.

Module 5: Objectives

After successfully completing this module, you will be able to:

- Describe both half-wave and full-wave rectification.
- Determine the operating characteristics of analog AC meters.
- Determine the operating characteristics of digital AC meters.
- Describe the operation of, and determine the operating values for, current transfc

Module 5A: Rectification

AC periodically changes direction, which is why it is called alternating current. DC, on the other hand, maintains one direction, or polarity, of current. Rectification is the process of changing an AC into a DC. Whether we use one direction (half-cycle or half-wave), or both directions (full-cycle or full-wave) is determined by the circuitry.

The Diode

A diode operates exactly like a check valve for electrical current. Current may flow in only one direction through a diode. The diode obtains its name from *di-*, meaning “two,” and *ode*, for “electrode.” The electrodes are named the *anode* (positive electrode) and *cathode* (negative electrode). There are many types of diodes based on their chemical makeup. We will restrict ourselves here to just two solid-state types, germanium and silicon. There are some significant differences between the two types:

- Voltage necessary to maintain current flow in the positive direction
  - Germanium: approximately 0.01 to 0.3 V
  - Silicon: approximately 0.5 to 0.9 V
- Peak inverse voltage rating (explained later in this module)
- Power handling capability (Silicon is far more capable in part because of its higher maximum operating temperature.)

Figure 5-1 represents a diode schematically. Current flow is shown as electronic, or from an electron perspective, meaning that the electron will flow from the negative to the positive following the laws discussed in Module 1.

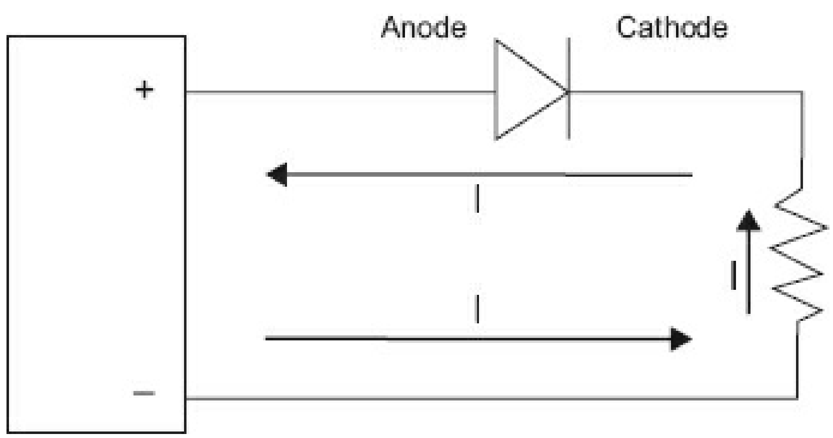

Figure 5-1. Schematic of a diode in a circuit.

The cathode is the bar, and the arrowhead is the anode. This schematic diagram came about because the original solid-state diode was as shown in Figure 5-2.

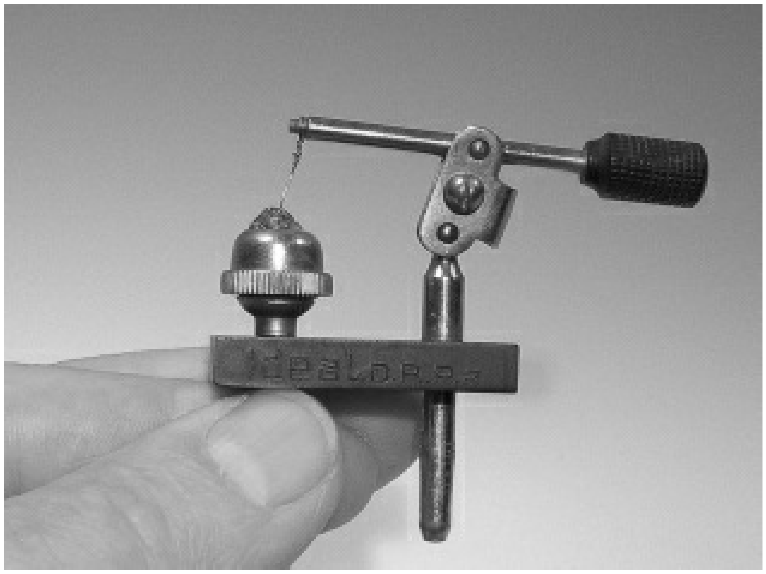

Figure 5-2. Cat whisker and crystal.

Source: Holger.Ellgaard [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)].[1]

This was the original diode used in a crystal radio. The operator would scratch on the galena crystal until a rectifying junction was found. Then, along with the tuning circuit, usually an inductor capacitor (LC) parallel set, the operator would tune in a sufficiently strong AM radio station and would hear the audio in his headphones, no battery required. Note the similarity between the physical cat whisker device and the schematic of a diode.

Germanium diodes will forward conduct (again, electron flow from negative to positive) from almost 0 V, and the forward voltage drop varies with the current. In comparison, a silicon diode has a sharp “knee,” around 0.7 V, so a diode with 0.6 V applied will practically be an “open circuit” equivalent, whereas a 0.7 V drop will be sustained to a high level of current. (See Figure 5-3.)

Forward Voltage Drop

Forward voltage drop is the amount of voltage required to maintain current through the diode. Just as in a mechanical check valve, where the fluid in the correct direction must have a pressure high enough to overcome the pressure on the reverse side of the check valve, and a bit more to overcome the spring of the check valve, a diode must have more than just equal voltages to conduct. The voltage needed ranges from 0.05 V to 0.9 V for germanium diodes and from 0.6 V to 0.9 V for silicon diodes.

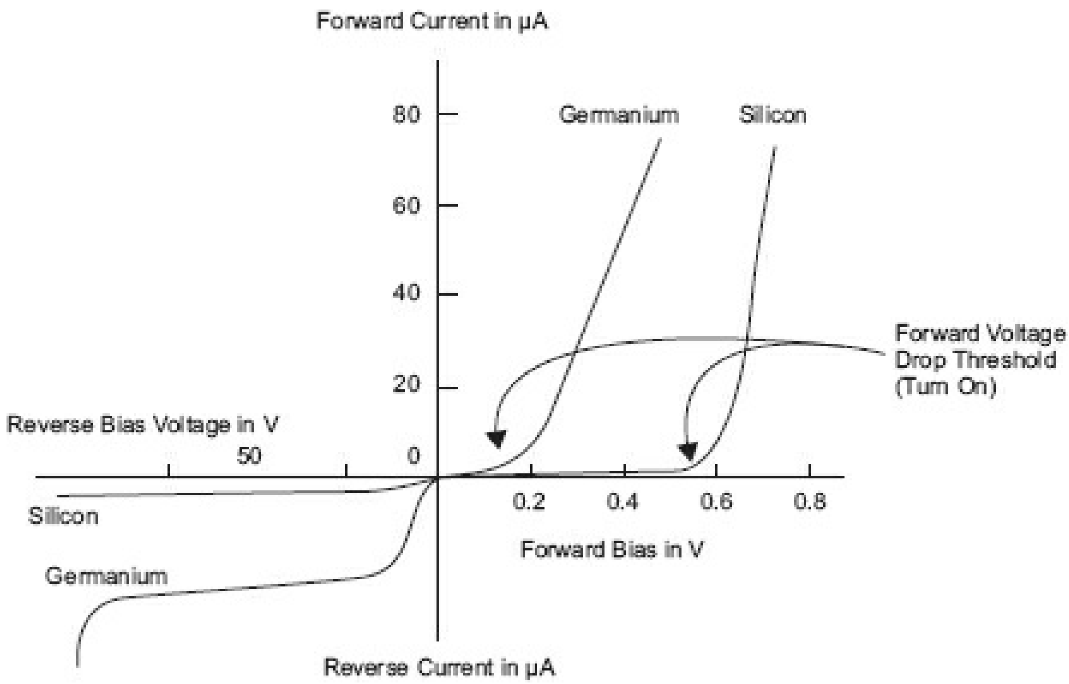

Figure 5-3. Germanium versus silicon voltage/current.

Forward Current

An important characteristic of a diode is that it will pass current in the forward direction when the forward voltage drop threshold is met. The nominal current the diode can safely pass is called forward current. The maximum current the diode can pass—only for a very short time (one or two cycles)—is called peak forward current. Exceeding either of these parameters for a relatively long period of time will damage or destroy the diode.

Peak Inverse Voltage

With the mechanical check valve, if pressure on the reverse side becomes high enough (in relation to the forward side), the valve will be destroyed. There is always a limit. Because voltage is pressure, this limit applies to rectifying diodes as well. (Rectifying diodes are standard diodes, as opposed to Zener and avalanche devices that exploit the peak inverse voltage, PIV, avalanche effect.) The specifications always provide the amount of voltage that the diode can withstand in the nonconducting direction. This is the reverse potential across the diode. If it is exceeded, a standard diode will be destroyed.

Rectification

The process of converting AC to DC will require one or more standard diodes. There are several rectifying circuits, each with its own advantages and disadvantages.

Half-Wave Rectifier

Figure 5-4 illustrates a half-wave rectifying circuit.

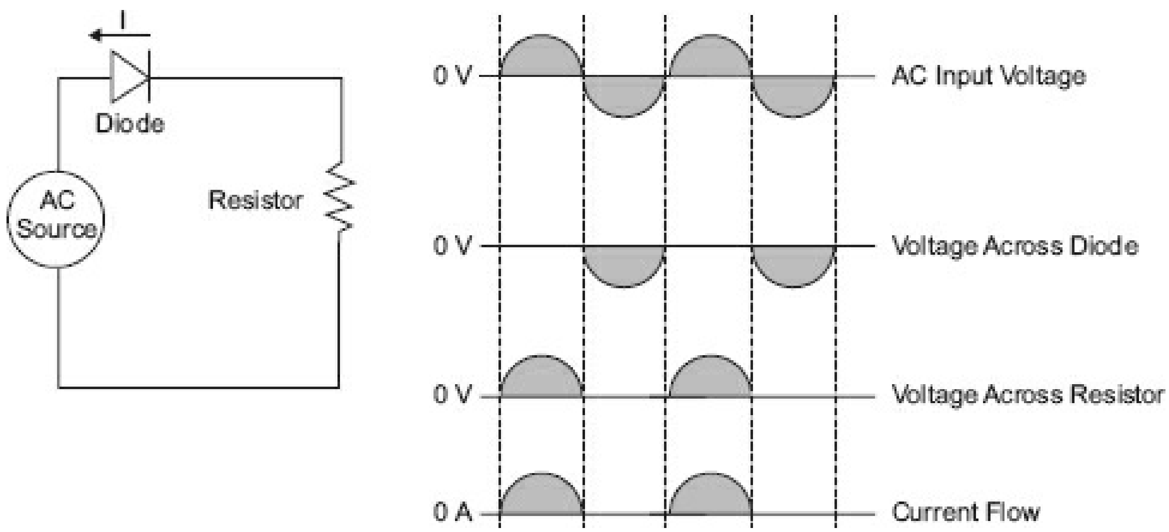

Figure 5-4. Half-wave rectification.

Of importance is the magnitude of these voltages. As shown in Figure 5-4, the current through the load (and through the diode) is for only half of the waveshape (which explains the name *half-wave rectifier*). The voltage across the resistor when the diode is conducting will range from just above 0 to the peak voltage input.

Example

If the AC source is 12.6 V rms, what is the voltage across the resistor? The diode?

Because the input is in effective (rms), multiply the effective by 1.414 to obtain the peak.

12.6 • 1.414 = 17.8 V (peak)

This will be exhibited as a positive peak across the resistor (due to the direction of current flow), and when the diode is off, there will be a potential of 17.8 V peak across the diode and 0 V across the resistor because no current is flowing. Because the sum of all the voltage drops must equal the applied voltage, and 0 V is across the resistor, the applied voltage must appear across the diode.

Ripple Frequency

Previously, frequency has been discussed in regard to a sinusoidal waveform. However, the output across the resistor in the half-wave rectifier can be defined in terms of frequency because it is continuously changing in amplitude and occurs at a periodic rate. There will be one output waveform for each cycle of input waveform. The input frequency is the “ripple” frequency for the output of a half-wave rectifier.

Example

If the source voltage is at a 60 Hz rate, what is the ripple frequency for a half-wave rectifier?

Answer: 60 Hz. For half-wave circuits, the ripple frequency is the same as the input frequency.

Full-Wave Rectifier

A full-wave rectifier uses both alternations of the input waveshape to develop power across a load. There are two common circuits for producing full-wave rectification, the center tapped transformer and the bridge. The discussion here will be limited to the bridge circuit because today it is by far the most commonly used circuit for full-wave rectification. Figure 5-5 illustrates a bridge rectifier circuit.

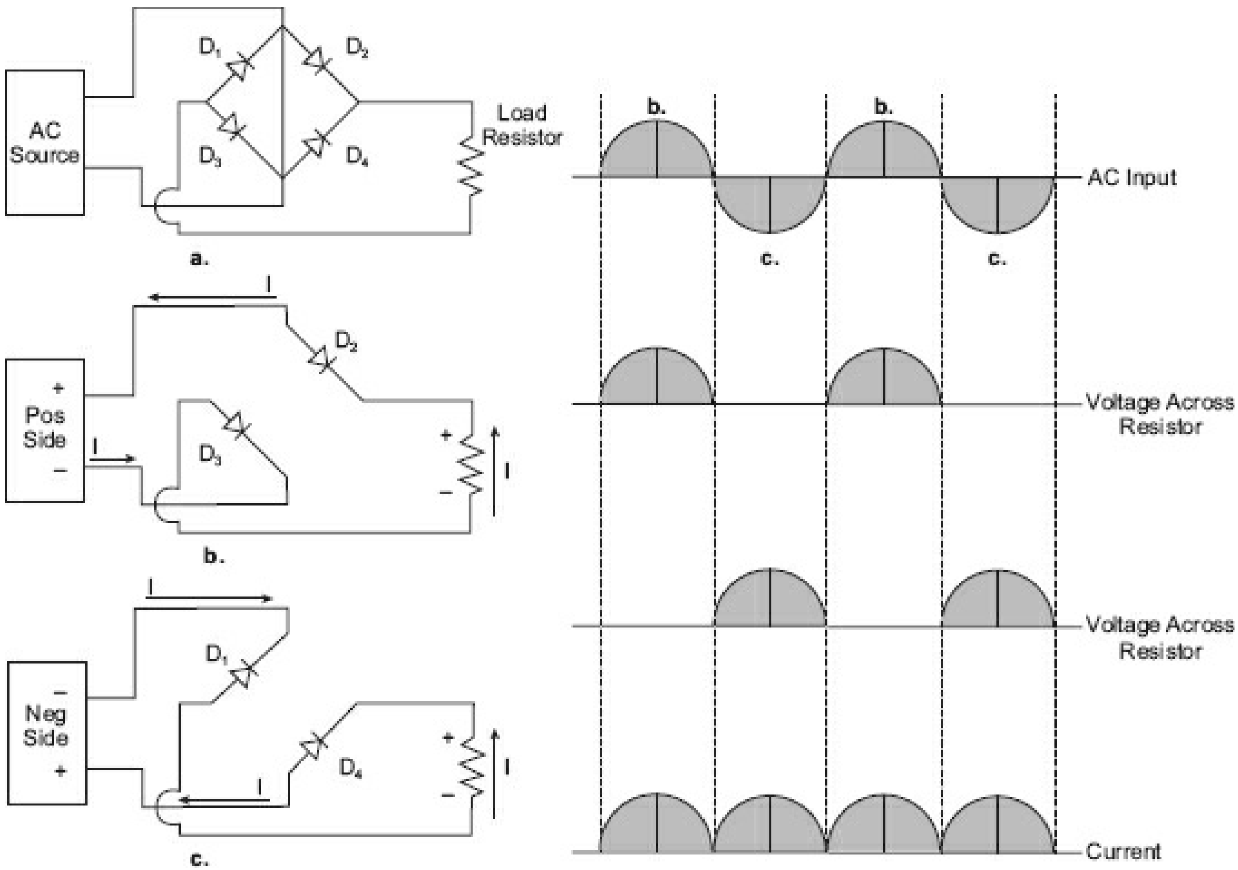

Figure 5-5. Full-wave rectifier.

Figure 5-5a is the complete circuit. Figure 5-5b is the current path when the upper source terminal is positive in respect to the lower source terminal. Figure 5-5c is the current path when the lower source terminal is positive in respect to the upper source terminal. Notice that both alternations of the input waveform are used. What is the ripple frequency for a full-wave rectifier?

Example

Determine the ripple frequency for the full- wave rectifier if the input frequency is 60 Hz.

Answer: The output now has two alternations, or occurrences, per input cycle. Therefore, the ripple frequency is two times the input frequency for a full- wave rectifier, and in this example, the ripple frequency would be: 2 • 60 = 120 Hz.

It should be obvious that the full-wave circuit will supply more power per input cycle than the half-wave circuit. Table 5-1 gives the conversion factors necessary to determine the effective and average values for half-wave and full-wave rectification.

Table 5-1. Conversion factors.

	Half-Wave	Full-Wave
Average	0.45 • rms	0.90 • rms
rms	1.11 • Average	2.22 • Average

The average current is measured by most meters (other than the true rms types).

Module 5A: Summary

- For half-wave rectifiers, only one polarity of the input sine wave is passed throug
- The ripple frequency for half-wave rectifiers is the same as the input line frequen
- Full-wave rectifiers pass both portions of the sine wave input but with th polarity.
- The ripple frequency for a full-wave rectifier is twice the input line frequency.
- Whatever portion of the input voltage that is not dropped across the load resis be dropped across the diode(s).

Module 5B: AC Meters

This section discusses full-wave and half-wave meters. We begin with analog full-wave meters for voltage measurement.

Full-Wave Meters

An analog AC meter is basically a DC meter behind an input rectifier. The meter deflection current is first rectified by the full-wave bridge whose rectified current activates the meter. However, this current is not true DC, but a pulsating DC. This will require correction both in the meter scale and in determining the multiplier resistance. The current that activates the meter is the average value of the input signal. Although some other meter types use the effective (rms) voltage, a typical rectifying meter uses the average current because there is no filtering of the pulsating DC, and the inertia of the meter movement limits the amount of travel the meter movement can make in trying to follow each pulsation. For very low frequency AC voltages, the meter movement may approach the rms value.

However, at 60 Hz, one of the more common AC frequencies, only the average value will be measured. As most measurements of AC are in rms, the *meter scale* is converted from average to rms. This means the DC scales cannot be used because the average voltage using full-wave rectification is 0.9 of the rms value for a sinusoidal waveform. *Sinusoidal waveforms are* the only ones included in the discussion of full-wave and half-wave rectifying meters. To determine the multiplier resistance, the average versus the rms scale must be considered.

Examples

Suppose you want to measure 10 V rms at full scale. The meter movement is a 1 mA FSD with 100 Ω resistance. What is the multiplier resistor value?

Determine the average voltage for the value of rms at full scale. At 10 V rms (full scale), the average (for full-wave rectification) is 0.9 • rms, then 10 V • 0.9 = 9 V. Therefore, when 10 V rms is to be measured, you want 9 V to give FSD. This means the multiplier must be figured for 9 V, not 10 V.

The total resistance required to drop 9 V at 1.0 mA is 9000 Ω. The meter has 100 Ω, so the multiplier resistor will be 8900 Ω.

Even though the meter had a DC sensitivity of 1000 Ω/V, the AC sensitivity using full-wave rectification is 900 Ω/V. This is due to measuring the average voltage and converting the scale to rms.

The diode resistance must be considered when determining the multiplier resistor values.

Examples

Any circuit path through the bridge must go through two diodes. Therefore, if the diode resistances of D through D_4 were 54 Ω (a realistic value), the total diode resistance for the diodes in this example is 108 Ω.

$$Rm + D + d + R = 9000\ \Omega$$

$$100 + 54 + 54 + R = 9000\ \Omega$$

$$R = 9000 - 208\ \Omega$$

$$R = 8792\ \Omega$$

where
R = multiplier resistance
R_m = meter resistance
D_x = one diode resistance in bridge
D_y = companion diode resistance in bridge

The diode resistances for a multirange meter are included in the computation of the first meter range only.

A factor that must be considered is the forward voltage drop of the diodes. The voltage drop across the diode obeys Ohm's law in the linear portion of the diode characteristic, as shown in Figure 5-6a and Figure 5-6b.

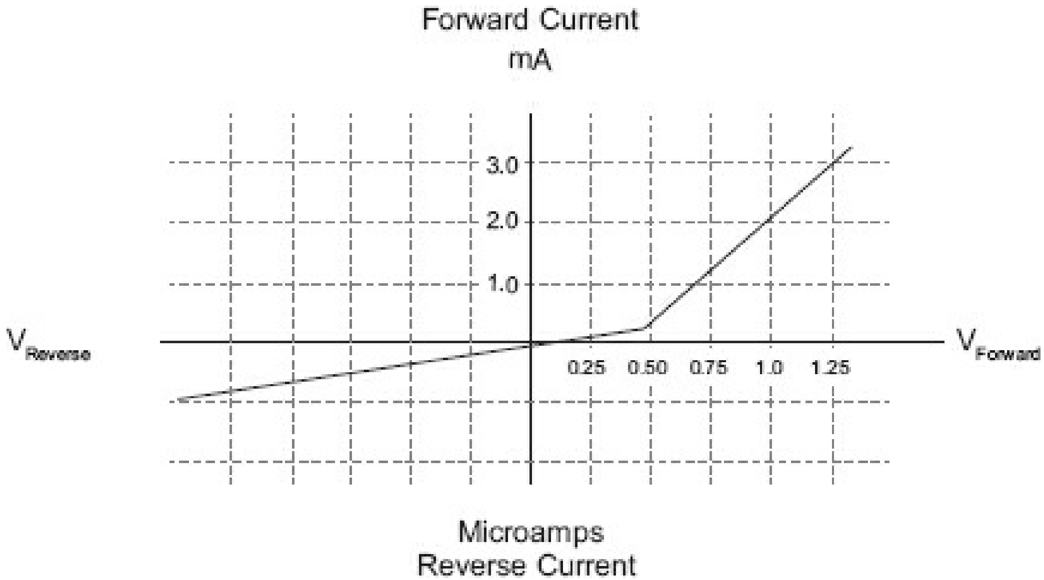

Figure 5-6a. Typical germanium diode curve.

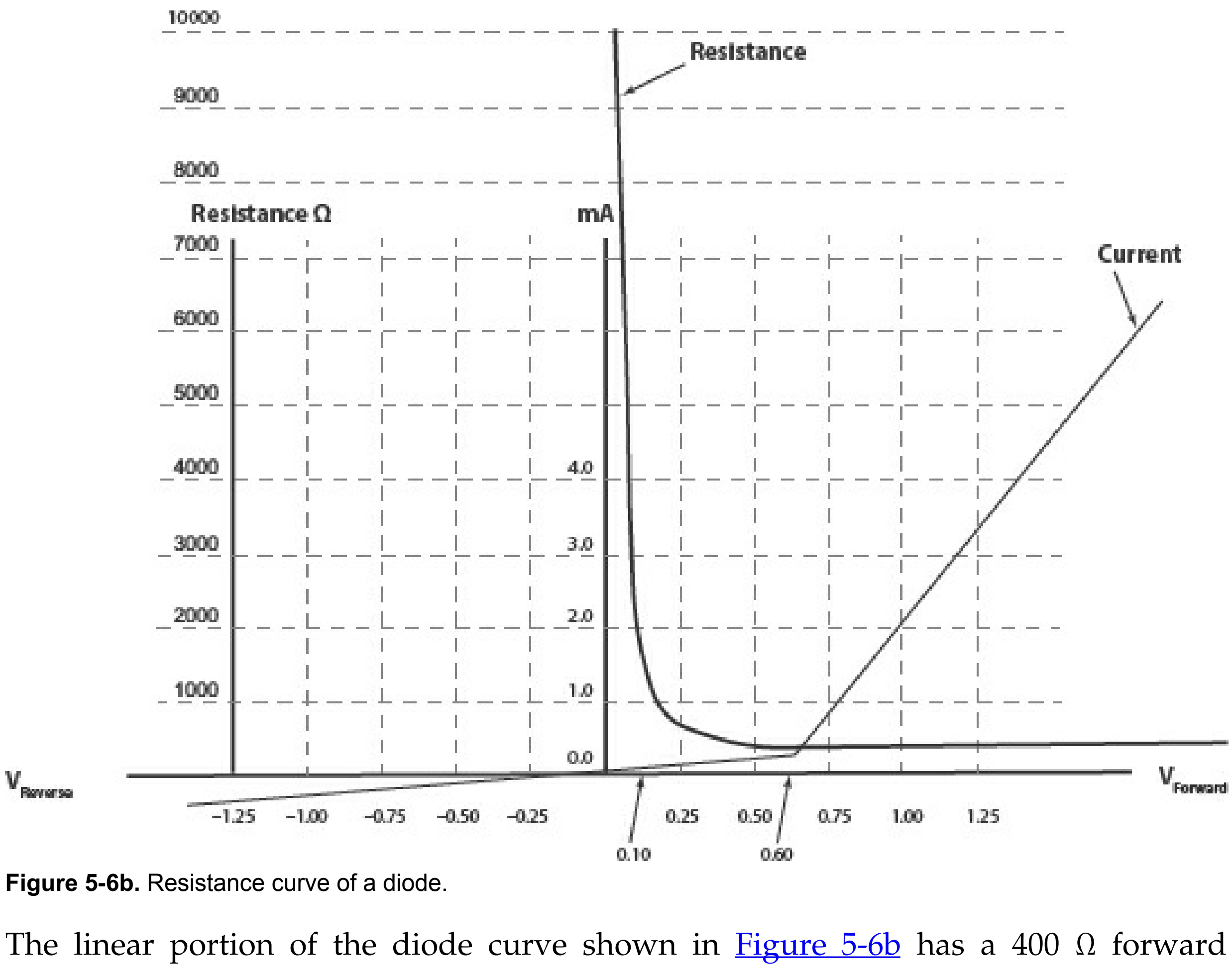

Figure 5-6b. Resistance curve of a diode.

The linear portion of the diode curve shown in Figure 5-6b has a 400 Ω forward resistance. Below the linear portion (approximately 0.6 V), the resistance rapidly increases. At 0.5 V, it is 1000 Ω and rises rapidly; at 0.1 V, it is approaching 10 kΩ.

The diode is a *current activated device*, the forward voltage drop across the diode being the result of the amount of forward current. A current more than 1.0 mA (requiring approximately 0.6 V) for the diode curve shown will cause the diode to operate in the linear portion of its characteristic curve.

For a bridge circuit, these voltage drops, as well as the diode forward resistance, must be added.

Examples

In the circuit shown in Figure�5-5, if the diodes had a forward drop of 0.6 V (to operate in the linear portion of their curve), the combined drop would be 1.2 V. This drop has the effect of crowding the low end of the AC scale (in this case, any voltage below 1.2 V), requiring other techniques to be used to measure very small AC voltages.

Half-Wave Meters

To overcome some of the disadvantages of the bridge-type AC rectifier, the half-wave circuit shown in Figure 5-7 is used in most general-purpose analog multimeters.

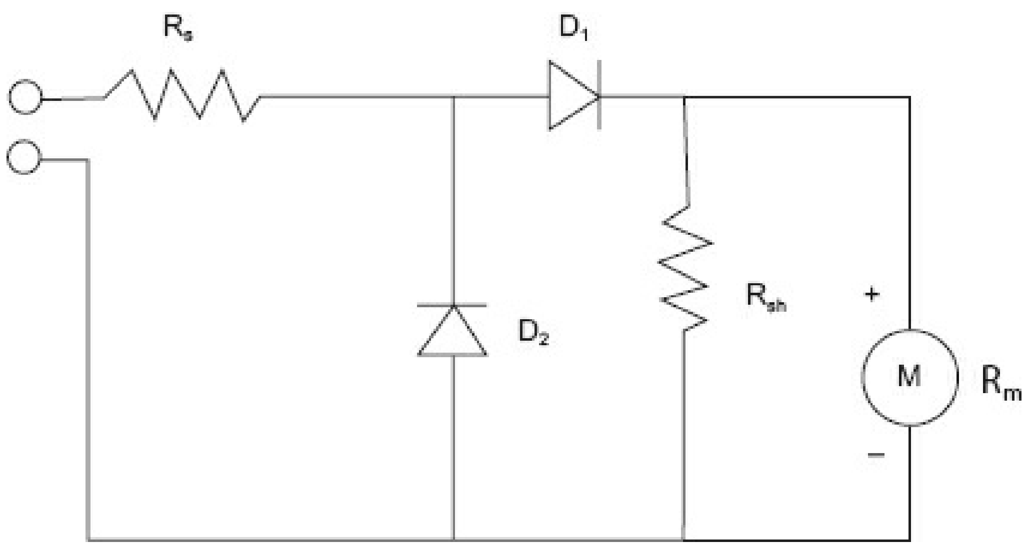

Figure 5-7. Half-wave meter.

D_2 is used to pass the negative alternation to ground, preventing a high peak inverse voltage across D_1 and the resultant leakage currents. R_{sh} is a shunt resistor, usually the same value as R_m but may be less. For $R_{sh} = R_m$, twice the current will flow for a given voltage. This will cause the diode to operate on the linear portion of its characteristic curve for lower applied voltages, reducing the sensitivity by half.

To determine the multiplier resistor value, the combined (total) current value must be used. Note that when using a half-wave circuit (and a sine wave input), the average current will be 0.45 of rms. This entails some vigorous meter scaling, particularly when using the shunt resistor.

Module 5B: Analog Meter Review

- An analog meter movement using rectifiers will measure average voltage.
- The average voltage (for full-wave rectifications of a sinusoid) is 0.9 times t voltage.
- Scales are calibrated to read in rms while measuring average.
- A full-wave rectifier circuit reduces accuracy on the lower scales because o voltage drops.
- The sensitivity of the meter is reduced because the meter measures average curr is scaled to rms values.
- To convert rms to average for a half-wave circuit, the factor 0.45 is used for sin waveforms.
- The half-wave rectifier meter uses a shunt resistor to measure lower voltages acc
- The half-wave circuit with a shunt resistor reduces the sensitivity of the circuit.
- Both half-wave and full-wave rectifying instruments require a sinusoidal wavefo have an upper frequency limit for measurement accuracy.
- The diode forward voltage drop is less in a half-wave meter circuit, thereby inc the accuracy of the lower scale.

Digital AC Meters

The primary difference between digital and analog meters is that the analog types depend on the FSD current of the meter for their sensitivity, and to filter the pulsations. As we've learned previously, this is work (P = E • R) and why the meters read average voltage (although scaled to rms).

Digital meters have the advantage in that they are powered, usually by batteries or an AC line adapter, whereas analog meters are powered by the measured circuit voltage and current. However, with modern electronics, it takes very little power to perform many complex operations. Figure 5-8 is a block diagram of the AC measuring circuitry of a typical digital voltmeter (DVM).

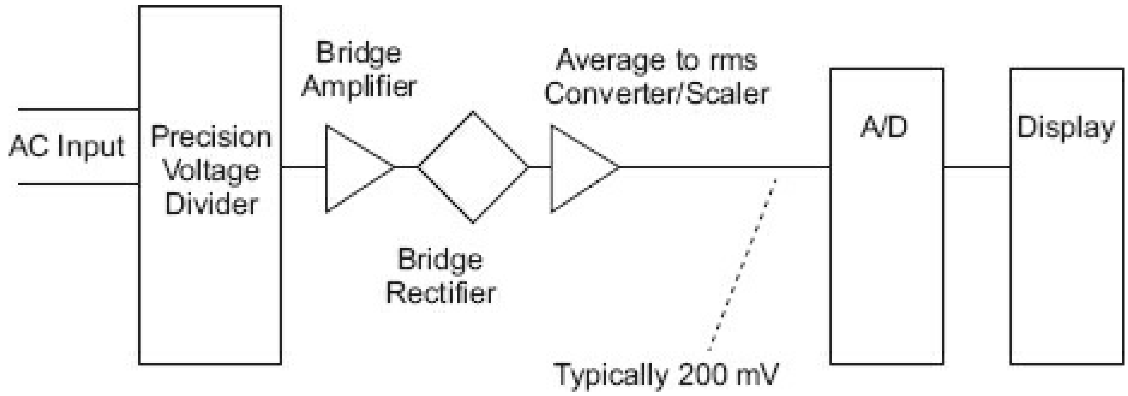

Figure 5-8. Typical AC portion of a DVM.

The precision divider generally divides in units of 10. The signal presented to the bridge amplifier/bridge rectifier is in the 0 to 200 mV range. The amplifier is used to bring the signals to an amplitude that will force the rectifiers (small signal germanium) to operate in the linear portion of their range (among other things). After rectification, the signal is filtered and applied to the converter/scaler, which outputs a DC signal proportional to the input on the 0 to 200 mV span input to the A/D, which is normally a dual slope converter. The measured signal, because it is rectified, is an average, but the scaler outputs the voltage as an rms value.

There are several calibration points on the digital multimeters, but calibration is normally performed in a calibration shop by experienced and qualified personnel.

Considerations When Using AC Meters

There are two main considerations when using AC meters.

1. Frequency of input signal
2. Waveform of input signal

Input Signal Frequency

The frequency of input signal affects both digital and analog meters, but it affects the analog meters more. As frequency continues upward, there are inductive and capacitive effects that tend to reduce the amount of AC available to operate the meter. As the frequency continues upward, the actual indicator response will drop off, so even if the source is at 10 V rms, the meter may not read 1 V rms or even less. This drop-off starts at a fairly low frequency for analog meters, generally anywhere above 500 Hz. Because of the way digital meters are constructed, the effects are not noticeable until (in many cases) 10 kHz or much higher. Remember, though, these devices generally use a slow integrating AC to DC converter, and at some frequency the sampling rate will not permit accurate measurement.

Input Signal Waveform

This affects both analog and digital meters that use rectification equally. All the conversions between peak and average, peak and rms, and so forth, discussed to date require a sinusoidal waveform. Many AC waveforms are not sinusoidal and are not measured well with a rectifying type of AC meter.

Examples

Use Figure�5-9 to determine the average power and peak voltage.

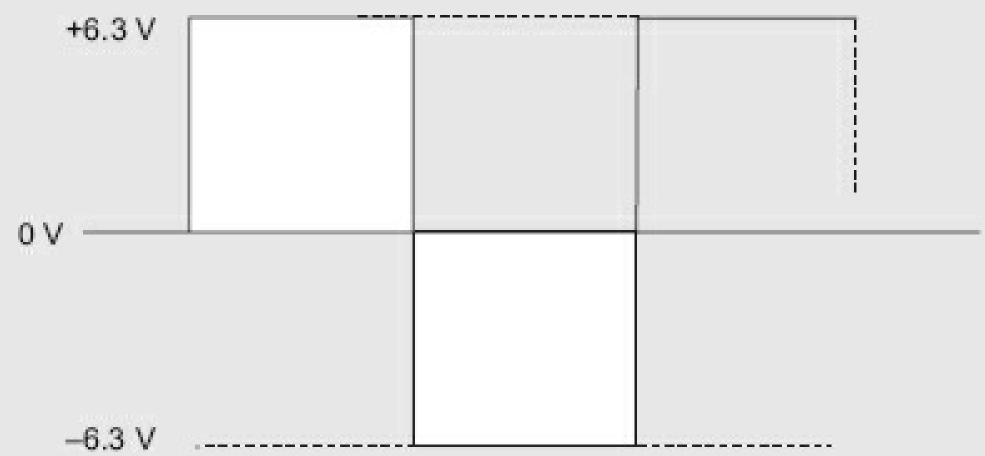

Figure 5-9. Square wave.

If a half-wave rectifier meter is used with this signal input, the output would have one or the other alternation. In either case, the average voltage would equal half the peak (conversion factor of 0.5). In full-wave rectification, the average voltage would equal the peak voltage (conversion factor of 1.0). Obviously, if the meter is using the average voltage and scaling it to rms, this waveshape will not display correctly.

Few measurements of AC involve pure sine waves. Even the 60 Hz power line has harmonic (multiples of the frequency) information. This is why the oscilloscope was necessary historically and is still necessary to view nonsinusoidal waveforms.

Module 5B: Summary

- The frequency of the input signal has an effect on the measurement by re meters.
- The waveshape of the input signal affects the measurement taken by rectifying m

Module 5B: Review

1. Using Figure R5-1, draw the waveforms that will be present across the resistor diode. Label each waveform with the voltage level.

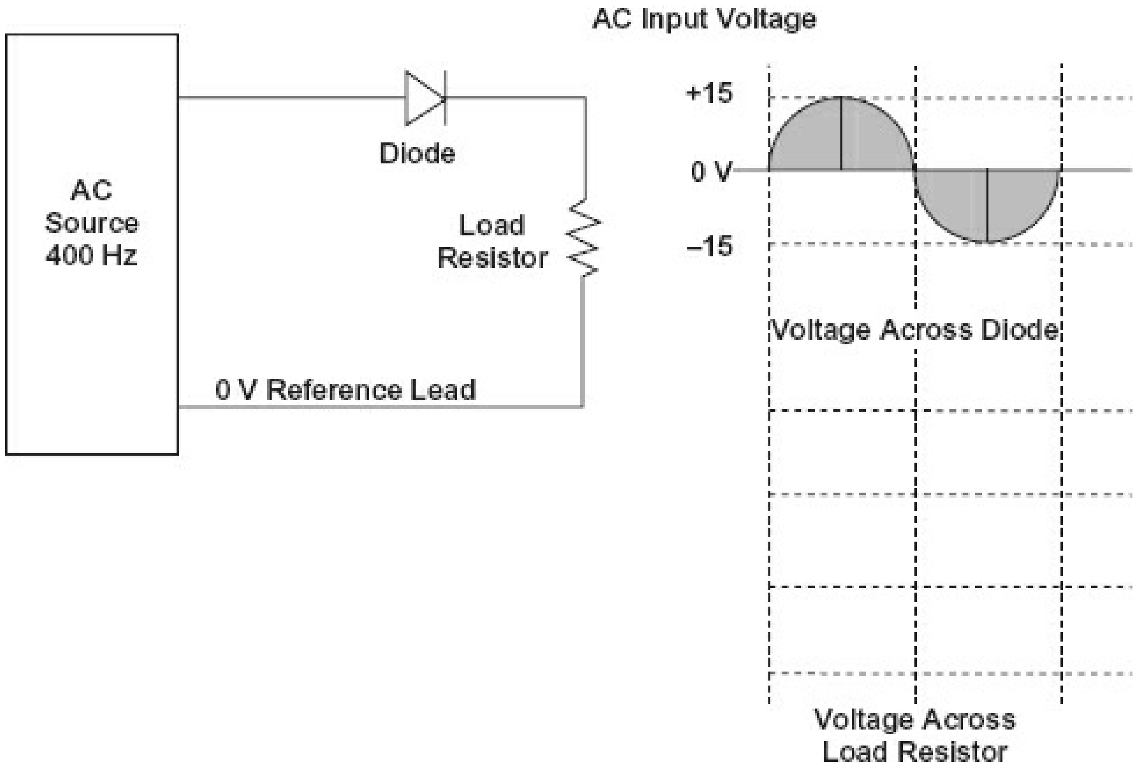

Figure R5-1.

2. Draw the output waveform for a full-wave rectifier (without a filter), assuming a frequency of 400 Hz at 100 V rms.

3. In the waveform you just drew, what is the average voltage? What is the peak vo

Average voltage _______________

Peak voltage _______________

Module 5C: Current Transformers

A current transformer (CT) produces an output in proportion to the current flowing through the primary winding. The CT is an instrument transformer designed to generate an AC in its secondary winding that is proportional to the current flowing in its primary winding. CTs reduce high-voltage currents to a much lower value and provide a method of safely monitoring the actual high-potential electrical current flowing in an AC load using a standard ammeter. A typical CT is illustrated in Figure 5-10.

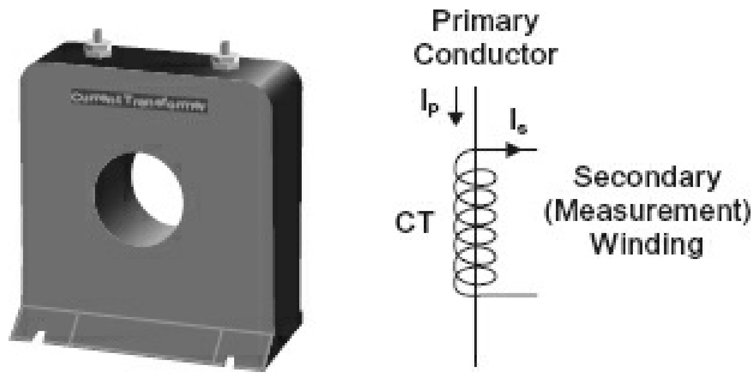

Figure 5-10. Typical CT.

The principle of operation of a basic CT is slightly different from that of an ordinary voltage transformer. The difference between previously described transformers and the CT is that the CT primary winding consists of only one or very few turns. This primary winding can be a coil of wire wrapped around the core or just a conductor or bus bar placed through a central hole in the CT as shown in Figure 5-10.

The secondary winding has many coil turns wound on a laminated core of low-loss magnetic material. Due to the core's large cross-sectional area, the magnetic flux density is low, and by using a much smaller gauge wire, the secondary current is independent of the secondary connected load (within reason).

The secondary winding supplies current into either a short circuit (an ammeter) or a resistive load. This current will increase until the current induced in the secondary saturates the core or the core fails because of an excessive voltage breakdown.

The primary current of a CT does not depend on the secondary load current but on the external load. Typically, the secondary current is rated at a 1 A (or 5 A for larger primary current ratings).

CTs are generally constructed in one of three ways:

- **Wound current transformer** – The primary winding is physically connected i with the load conductor. The secondary current depends on the turns ratio transformer.
- **Bar-type current transformer** – This type uses the actual cable or bus bar of th circuit as the primary winding (equivalent to a single turn).
- **Toroidal current transformer** – There is no primary winding. The line that car load current is placed through the center hole in the toroidal transformer. Ty CTs have a split core that can be opened, installed, and closed without discon the load circuit.

CTs can step down currents from thousands of amperes to a secondary output of 1 A (or 5 A for high currents). Because of this reduction, standard instrumentation may be used with CTs as they are isolated from any high-voltage power.

Typically, CTs and ammeters are produced as a connected set; the design provides a maximum secondary current that corresponds to the full-scale deflection of the ammeter. For this reason, a CT is generally calibrated for a specific type of ammeter.

CTs have a standard secondary rating of 1 A or 5 A, with the primary and secondary currents being a ratio such as 100:1 or 100:5. A ratio of 100:1 means the primary current in the secondary circuit is 100 times greater than the secondary current. A 100:5 ratio means there is 20 times greater current in the primary than in the secondary circuit. In either case, when 100 A is flowing in the primary conductor, it will result in either 1 A (100:1) or 5 A (100:5) in the secondary. A CT of 300:5 will produce 5 A in the secondary for 300 A in the primary conductor.

Note that by increasing the number of secondary windings, the secondary current will be smaller. This increases the ratio, so the secondary current will decrease for a specific primary current. The number of primary turns and the primary current and the number of secondary windings is in an inverse proportion.

A CT must conform to the amp-turn equation more commonly known as the turns ratio. As discussed in Module 2G on transformers, the turns ratio for voltage transformers is equal to:

$$\text{Turns Ratio} = n = \frac{Np}{Ns} = \frac{Is}{Ip} \tag{5-1}$$

With a little algebraic dexterity,

$$\text{Secondary Current} = Is = Ip\,\frac{Np}{Ns} \tag{5-2}$$

The primary typically consists of one or two turns, whereas the secondary may have up to several hundred turns.

Examples

With a primary winding current rating of 200 A, the secondary has the standard rating of 5 A, which means that when the primary has a 200 A current, the secondary will output 5 A. The ratio between the primary and the secondary currents is 40:1.

If the secondary is not shorted (connected to an ammeter) when not in use, high voltages can appear at the terminals. Remember that we are doing current ratios; the actual windings might be 1 on the primary and up to 200 on the secondary. In this case, an *unsafe* condition may result. Always short the secondary windings until they are connected to the actual instrumentation (and ensure that a terminating resistance is connected). If the ammeter (or load) is to be removed, a short circuit should be placed across the secondary terminals prior to removal to eliminate the risk of shock.

Clamp-on Ammeters

Many specialized types of current transformers are available. One type, which can be used to measure circuit loading without disconnecting the load circuits, is called a *clamp-on ammeter*. Typical clamp-on ammeters are illustrated in Figure 5-11.

Clamp-on ammeters open and close the ferrous core around a current-carrying conductor and measure its current by determining the magnetic field around it. This provides a quick measurement reading (usually on a digital display) without disconnecting or opening the circuit.

Clamp-on ammeters are available for measuring currents from 0.004 to 5000 A, with square window sizes from 1 to over 12 in (from 25 to 300 mm). There are also multirange meters that can measure from 10 to 5000 A in full range.

Figure 5-11. Typical clamp-on ammeters.

DC Clamp-on Ammeters

DC clamp-on ammeters look similar to, and operate similarly to, the AC types; in fact, most DC types offer AC measurements as well. Because this type of ammeter uses a clamp-on ferrous detector, there is no need to break the circuit. In addition, because a DC clamp-on ammeter is contactless, it is much safer than using an ammeter that is inserted in-line. Using a clamp-on ammeter to measure control circuits is less disturbing to the circuit and much more convenient, and the process is not bumped. Current probes for oscilloscopes use the Hall effect rather than an inductive pickup.

To measure DC, the ammeter uses a Hall effect device to measure the axial magnetic field generated in the primary wire by the current flowing through it. The clamp surrounds the wire (which is creating a magnetic field around it, according to Ampere's law). The magnetic field is concentrated by a ferrous core contained in the clamp. This magnetic field is sensed at an air gap that contains a semiconductor Hall effect detector. Current flowing through the Hall effect chip is deflected by the magnetic field, creating a voltage perpendicular to the direction of electron flow. This voltage is detected, amplified, and converted to amperes by internal circuitry and then displayed.

The polarity of the magnetic field depends on the direction of current flow in the wire and is indicated by the plus and minus readings. Indicators on the clamp ring specify which direction the primary flow must be for a positive reading.

Module 5C: Summary

- The current transformer (CT) is an instrument transformer that uses a magnetic convert a primary current into a secondary current. The secondary winding pro greatly reduced current (relative to the primary current) that can be used to det display primary current conditions.

- A CT's primary coil is always connected in series with the load conductor, whi then be referred to as a *series transformer*. The nominal secondary current is ratec or 5 A for ease of measurement. Construction can be one single primary tur toroidal or bar types, or a few wound primary turns, usually for low current ratic

- CTs are intended to be used as current, not voltage, devices. A CT's secondary w should never be operated in an open circuit.

- The high voltages that result from open circuiting the secondary circuit of an en CT are hazardous to both equipment and personnel, so their terminals must be circuited if the ammeter is to be removed or when a CT is not in use *before* powe the system.

Module 5C: Review

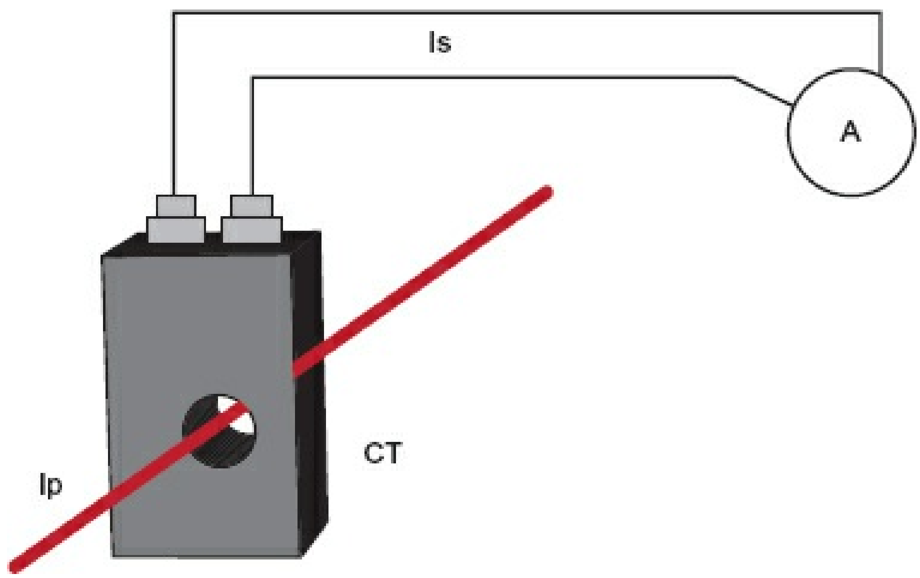

Figure R5-2.

For the circuit shown in Figure R5-2, the CT has a 250:5 ratio.

1. If 125 A flows in the primary, what will the Is value be?

___

2. At 125 A in the primary, what should the meter read if the meter is scaled 0 to 2!

___

Conclusion

You have reached the end of Module 5. Please reread the module objectives (in the "Objectives" section). If you have met these objectives, continue to the next module. If you are having difficulty, please reread the text. If the difficulty persists, locate a peer, mentor, supervisor, or someone who has technical knowledge of AC measurement and ask them to assist you.

Further Information

For additional information on the topics in this module, search for the following topics at your public or company library, or on the Internet.

- AC meters
- AC voltage measurement
- Waveform effects on AC measurements
- Digital AC multimeters
- Analog-to-digital conversions

- Current transformer operations
- Clamp-on ammeters
- 4–20 mA clamp-on ammeters

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1 Holger.Ellgaard, “Galena cat whisker detector from a 1920s’ crystal radio,” Wikipedia, last modified January 1, 2008, accessed October 25, 2022, https://en.wikipedia.org/wiki/Crystal_detector#/media/File:Kristallradio_(3).jpg.

6
Solid-State Components

This module approaches the topic of solid-state devices a bit differently than traditional texts. In most modern industrial equipment, there are few solid-state devices other than large-scale integrated circuits. Occasionally, operational amplifiers, transistors, and silicon-controlled rectifiers (in discrete power handling devices) are used. Rather than devote a lot of space to how a bipolar transistor is manufactured and designed, this module focuses on solid-state behavior and operation in circuitry.

Module 6: Objectives

After successfully completing this module, you will be able to determine the operation of:

- Bipolar devices
  - NPN (emitter is negative, base is positive, collector is negative)
  - PNP (emitter is positive, base is negative, collector is positive)
- Unipolar devices
  - Junction field-effect transistors (JFETs)
  - Insulated-gate field-effect transistors (IGFETs)
- Zener diodes
- Silicon-controlled rectifiers (SCRs) and silicon-controlled switches (SCSs)
- Triode alternating current switches (TRIACs) and diode alternating current sw (DIACs)

Module 6A: Positive Material/Negative Material Junction Devices

A discussion of modern semiconductor operation begins with the operation of a single junction. A positive material/negative material (PN) junction starts out as a crystal of extremely pure semiconductor material. It is so pure that it is an excellent insulator. The PN junction has no internal carriers for current flow, which means that its constituent atoms are in a lower energy state, requiring larger amounts of energy for energy transfer (called *current flow*) than when the material is less pure. It is a *monolithic* crystal structure, meaning that the atoms have arranged themselves in a geometric pattern. (Because we cannot see atoms, we mathematically model them in a crystalline structure.) To arrange themselves this way, they must enter a lower energy state. Using contemporary imagery, all the outer shell (valence) electrons are shared with other atoms to satisfy a requirement that the outer shell be filled, and in doing so they enter a state of less energy, which requires more external energy to move the electrons—that is, give them the energy to overcome their state.

> *Note:* There are many explanations of how a semiconductor junction works; some are based on the Bohr model of the atom, others on the quantum theory model (which has had great success in predicting behavior and, as of this writing, has not yet been proven wrong), and some are based on other simplified models. The correct theory of its formation and operation is of little concern to a person using a junction device (as opposed to the person designing the device). The behavior of the device in the circuit is the important focus; therefore, the way you picture transistor operation at the atomic/subatomic level is important to you, but important only in that it provides a basis for visualizing operation. Whatever picture works for you, keep it.

If the semiconductor material remained in its pure state only, it would be of little use as a device because there are less expensive insulators. However, by "doping," or adding impurity atoms that raise the energy level (contribute either positive or negative charges to the material), we change it into either N type (contains negative charges) or P type (contains positive charges). This simply means that the material added either leaves the outer ring unfilled (a higher energy state) or leaves an extra negatively charged electron after the outer ring is filled (a higher energy state). These charges are local in that they remain (and are electrically chained) around the impurity atom. External energy applied to these materials can force the charges to move. Because they are at a higher energy level than the atoms in the crystal structure, smaller amounts of energy are required to put them in motion. A charge in motion constitutes an electric current.

Semiconductor material is doped as it is grown. There is no mechanical method of creating a junction of materials; rather, the material is alternately doped. This will create a PN junction. When the junction of two materials is formed (*and only at that time*), there will be a combination of N-type carriers (electrons) and P-type carriers (holes). This leaves an area (depletion region) devoid of current carriers with ionized atoms along the boundary due to the P-type material accepting an electron, making it a negative charge state, or the N-type material giving up an electron, making that atom a positive charge state. An ion is a charged atom. Normal atoms are essentially neutral, having a balanced number of positive and negative charges. When an atom is forced to accept an electron (has a net negative charge) or when an electron is stripped from an atom (has a net positive charge), it has a local charge. Refer to Figure 6-1 and note that this *ionic charge* is opposite to the type of material.

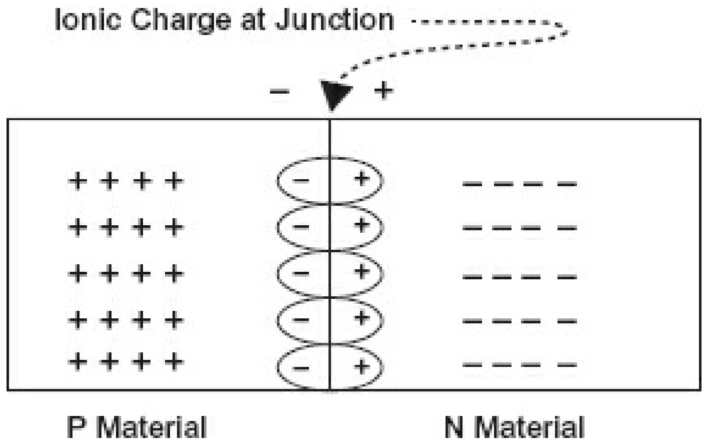


Figure 6-1. The ionic charge.

This ionic charge must be overcome if current (movement of charge) is to cross the depletion region.

If a conductor is connected from the N side to the P side, no current will flow. Kirchhoff's first law states that no more current can arrive at any one point than leaves that point. That is true whether one is speaking of an electrical current in a conductor or a semiconductor. If a potential source (e.g., a battery) is connected so the negative (battery cathode) is connected to P material and the positive side (battery anode) is connected to N material, the only effect will be to attract the current carriers toward the connections (none will leave because that would constitute current flow) and effectively widen the depletion region (see Figure 6-2a).

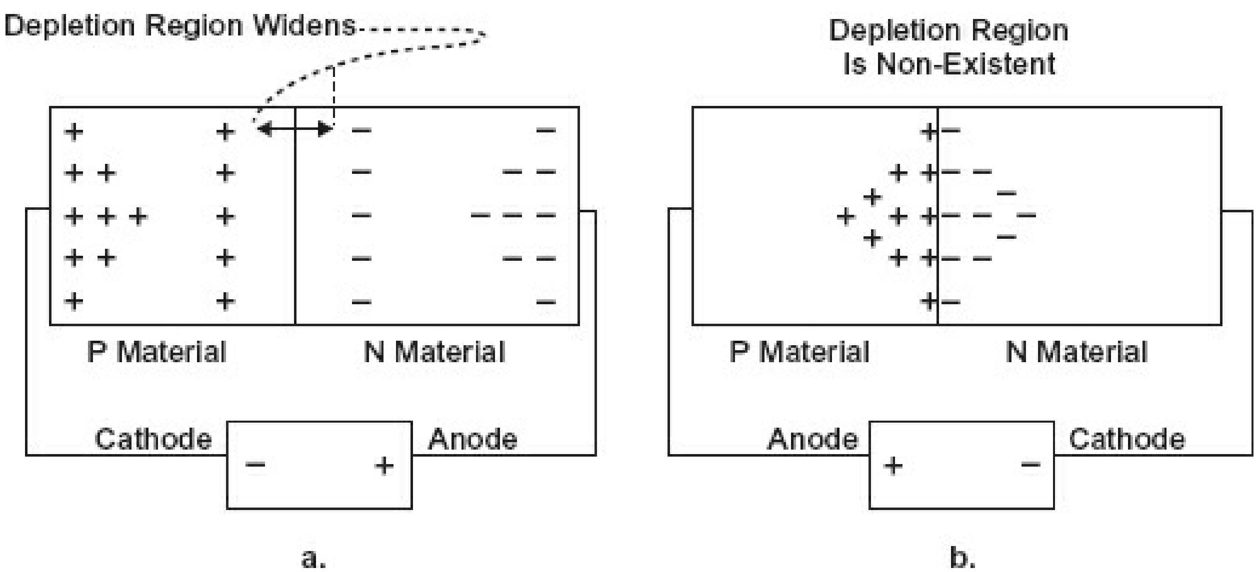


Figure 6-2. Junction bias.

If the negative source is connected to the N-type material and the positive source connected to the P-type material, the following will happen. If the source potential is less than the amount necessary to overcome the ionic charge, conditions will remain as before. When the potential is greater than the amount needed to overcome the ionic charge (0.2 V to 0.4 V in germanium, 0.6 V to 0.9 V in silicon), the negative carriers are forced to combine with the positive carriers (see Figure 6-2b).

As each pair combines, a vacancy of charge is created in each of the materials (and this is strictly prohibited by Kirchhoff). A negative carrier (electron) must then be injected into the N material while an electron must be extracted (creating a positive charge or hole) from the P material. This, of course, happens at near the speed of light; what is observed in the external circuit is that a current is flowing.

The conclusion to be reached is that *if* any of the following apply, then *no current* will flow in the external (or internal) circuit.

- No battery applied
- A battery applied with negative to P and positive to N
- A battery applied with negative to N and positive to P (with battery potential less that necessary to overcome the ionic charge at the depletion region)

If the battery is connected negative to N and positive to P and the battery voltage is enough to overcome the depletion region ionic charge, current will flow in the external (and internal) circuit.

The connections where the battery anode (+) is connected to the N material and the battery cathode (–) is connected to the P material are called *reverse bias*.

The polarity of connection causing current flow (battery of sufficient voltage, battery anode (+) connected to the P material and battery cathode (–) connected to the N material) is called *forward bias*.

Because there are two active electrodes (the N and P materials), this device is called a *diode*. The principal function of a diode is to conduct current in one direction only. Diode operation was covered in Module 5, "AC Measurement."

Bipolar Transistor

It is possible to create two PN junctions by growing PNP or NPN crystals. If the middle material is made sufficiently thin, a "transfer resistor" (transistor) is formed (see Figure 6-3).

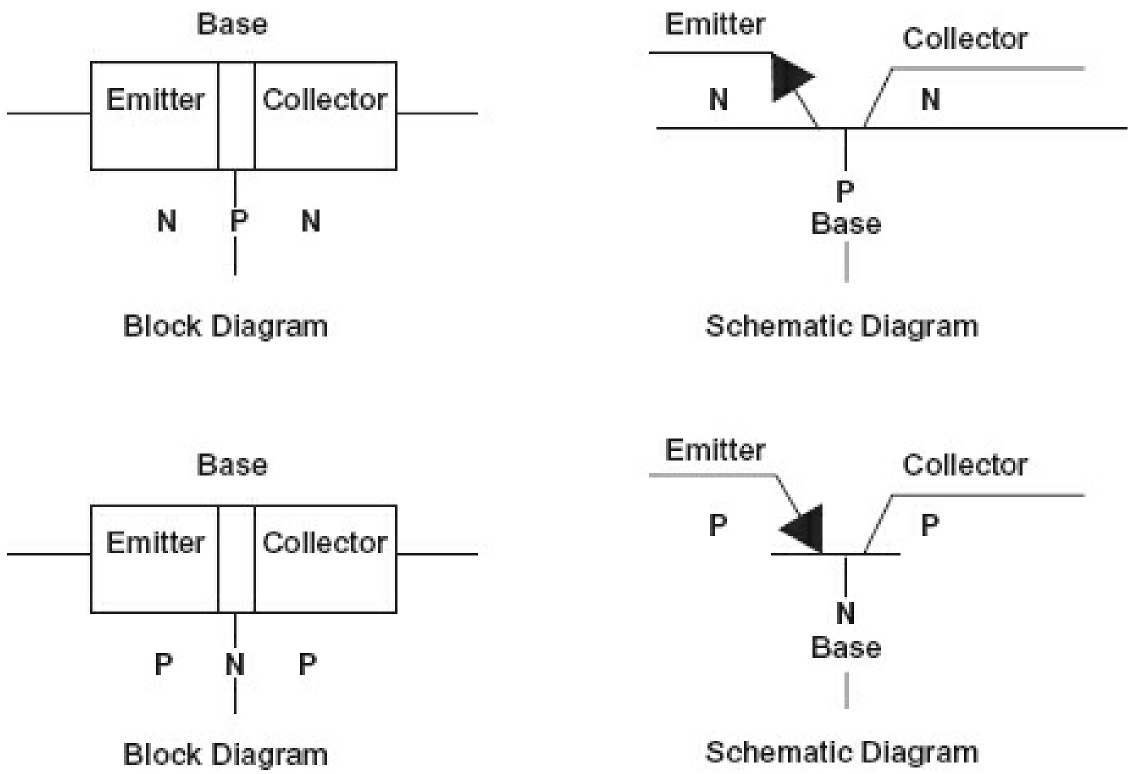


Figure 6-3. Bipolar transistors.

For linear and most switched operations, the material designated *collector* is reverse biased (+ to N, – to P). As this example uses an NPN transistor, the collector has a positive charge relative to the thin material designated *base* (the base is P-type). See Figure 6-4. This means that no current flows between the collector and the base. Note, however, that if an N-type carrier ever got into the base region, it would proceed with great haste to the large positive charge on the collector. This is only possible if the positive carriers in the base are occupied or otherwise not readily available. Having an N-type carrier in the base is not possible under the conditions so far described. The large attractive force (in this case positive) on the collector is supplied by a power source or battery typically called the *voltage common collector*, or Vcc. In series with the Vcc and the collector is a resistor, one whose value is large compared to all the other resistances in the circuit shown in Figure 6-4. The value used here is 1000 Ω.

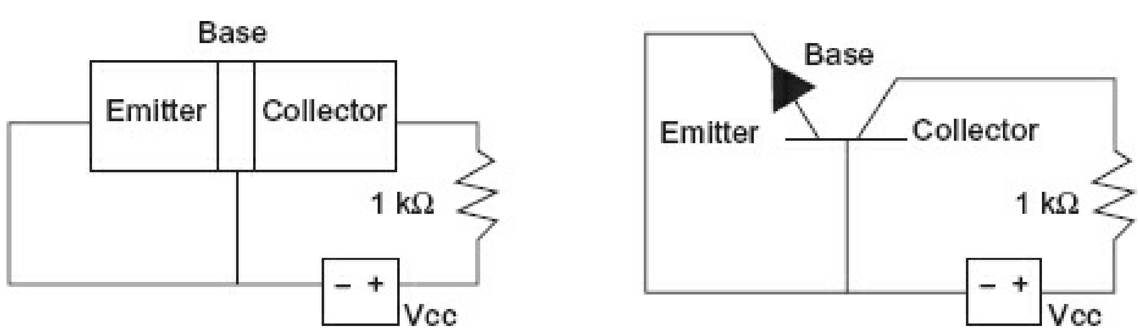


Figure 6-4. Correct biasing for an NPN collector base.

As long as the *emitter* circuit (the other N side) has no battery applied or has reverse bias applied, or if it is forward biased and the applied voltage does not exceed the ionic charge (approximately 0.7 V for silicon), nothing in the circuits will change and no current will flow. When the emitter-base junction is forward biased, current will flow in the emitter base circuit. However, the base is physically very small and has few carriers (compared to the emitter and collector). Observe Figure 6-5.

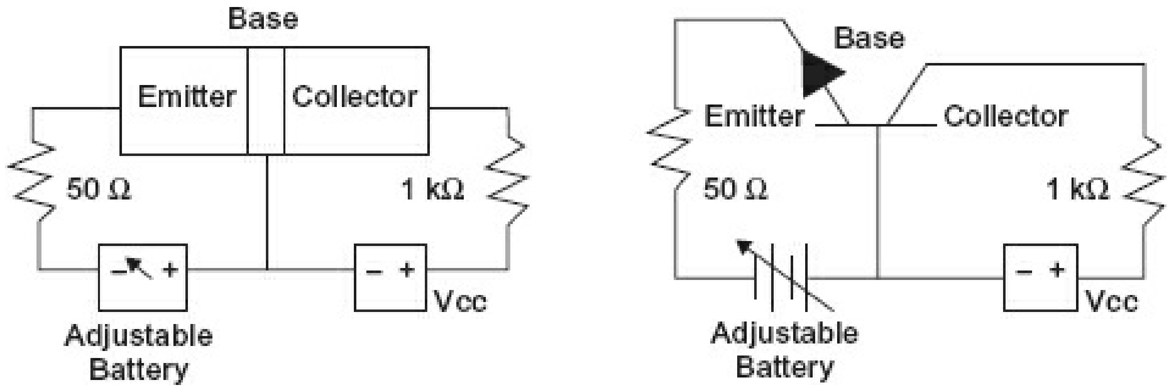


Figure 6-5. Forward-biased NPN transistor.

When the adjustable battery is set above the ionic voltage (approximately 0.4 V for germanium and 0.7 V for silicon), current flows in the emitter base circuit. Many of the emitter's N-type carriers can cross into the base region but will find no P-type carrier with which to combine. As stated before, if an N-type carrier found itself in the base without meeting a P-type carrier, it would be attracted to the large positive on the collector. This is precisely the condition brought about by current flowing in the emitter base circuit. The larger the emitter base current, the larger the number of N-type carriers introduced into the base without partners. This emitter base current is the primary factor in determining the number of carriers that leave the emitter and go to the collector. If a carrier leaves the emitter, then one must be injected from the external circuit. And, as a carrier from the emitter arrives at the collector, one must be ejected into the collector's external circuit. This is current flow. Generally, less than 2% of the total emitter current will be found in the base circuit, which means that 98% of the emitter current will arrive at the collector. You might wonder, of course, where the gain is if only 98% of the current is available at the collector.

The gain is a power gain. The emitter circuit has approximately 10 to 50 Ω of forward resistance, a forward-biased junction having a very low impedance. The collector circuit, being reverse biased, has an extremely high resistance, but current is not flowing from the collector to the base. It is flowing in the external collector circuit, which has 1000 Ω. The formula for power is P = I • I • R. Using P equals I squared times R, the input circuit power is 1 (100%) • 1 • 50 = 50, and the output power is 0.98 • 0.98 • 1000 = 960.4. Using Gain = Output / Input, then 960 / 50 > 19, so there is a power gain in excess of 19. Because the device transfers current from a low-resistance circuit to one of higher resistance, it is a *transfer resistor*. While understanding the operation is nice, one must remember two essential points about a bipolar device as it is a current-activated device.

1. The primary control of the collector current is the emitter forward bias current. reason, the collector voltage may change significantly with little effect on the co current (provided it is enough to overcome all resistances in the collector circuit).

2. The emitter forward bias voltage will be the ionic voltage (0.62 V to 0.82 V for s regardless of the emitter forward current until either the emitter base curren saturation (> 100%) or there is not enough voltage to cause forward current (0%).

Lead Identification

Identifying the leads on transistors can be time-consuming. Generally, if you replace a transistor, it is good policy to replace it with one of the same type from the same manufacturer, which of course should have the same lead arrangement. This is not always possible.

Transistors come in a variety of packages, too numerous to illustrate here. In each of these packages, the three leads may be arranged in any manner. Figure 6-6 illustrates a TO-92 package (not real size) and shows the two most common lead arrangements.

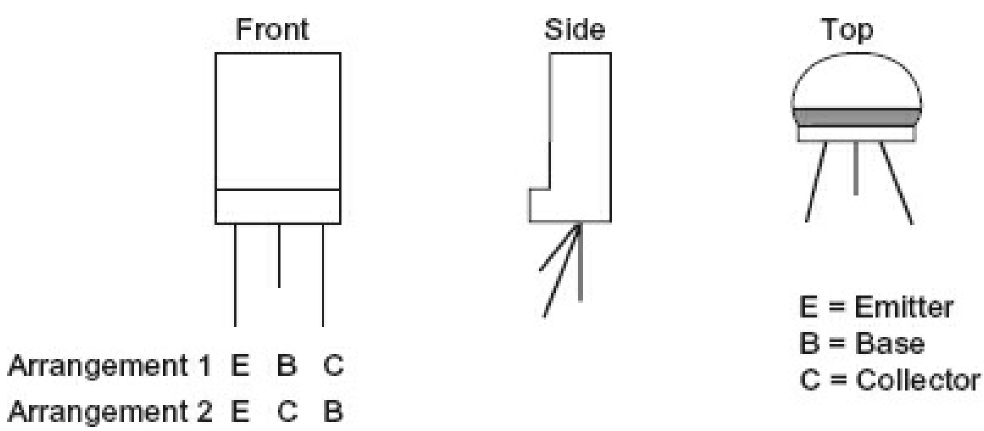


Figure 6-6. Lead arrangement.

Historically, several methods were taught to identify transistor leads using an analog voltmeter. However, given the generally low price of transistors, if you don't know the transistor's leads, why are you using it to replace another? Only new transistors should ever be used as replacements. To identify the lead placement of a transistor in a circuit, check the circuit components (the maintenance manual is a good place to start). On some circuit boards, the leads are identified. From a measurement perspective, it will be hard to take measurements without some documentation—not impossible, just time-consuming.

Measuring the operating voltages (it is hard to see currents directly with a voltmeter or an oscilloscope) can assist in locating defective stages. After all, if there are about 0.7 V across the junction of a silicon transistor, you can be assured it is biased correctly and at least the emitter base junction is OK. Taking resistance readings can be misleading. Analog voltmeters use a large enough battery to turn on PN junctions. Digital volt-ohm-meters (VOMs) do not. Most digital voltmeters (DVMs) have a special scale and battery to test the drop across a PN junction. This is a good test, except when the two junctions you are checking are shunted by a low impedance (such as a transformer winding). Still, the collector voltage is the higher (positive for NPN, negative for PNP) voltage, and a working emitter base has the ionic voltage across the emitter base.

The key to understanding a bipolar transistor is to know that you are using a small current (the emitter base current) to control a larger one (the emitter collector current). The transistor cannot amplify by itself; it must be placed in a circuit with the appropriate voltages and resistances.

Module 6A: Summary

1. A PN junction will pass current in one direction (forward) and not in the (reverse).
2. A bipolar transistor consists of two similar materials with a thin region of the opp charged material sandwiched between.
3. Bipolar transistors can be PNP or NPN.
4. The function of a bipolar transistor is to enable a small current to control a large o
5. The three elements of a bipolar transistor are the emitter, base, and collector.
6. Normally, the collector base junction is reverse biased.
7. The emitter base junction controls the emitter collector current.
8. The collector voltage has little effect on collector current (assuming correct po and voltages).
9. Transistor lead identification is best done with a technical manual.
10. An operating transistor will have 0.2 V to 0.4 V (germanium) or 0.5 V to 0.8 V (si across the emitter base junction.
11. Bipolar transistors are normally off and require external voltages to put them in t condition.

Module 6A: Review

See Appendix B for the answers.

1. Describe the condition of forward bias as it relates to a PN junction.

____

____

2. What are the three elements of a bipolar transistor?

____

3. Are bipolar transistors normally on or normally off devices?

____

Module 6B: Amplifiers

The transistor alone will not do anything; it must be connected in a circuit to perform a function. There are three basic configurations of amplifiers. They are classified by which of three leads is common to both the input and the output signals. The most common configuration is the common emitter (CE) illustrated in Figure 6-7.

Note that in this configuration the *input signal supplies only the emitter base current*. Using the previous example of 2% for the emitter base current, this 2% controls the 98% for a current gain of 49%. The important consideration is that by causing changes in the emitter base current, the emitter collector current is changed. Generally, a very small change in emitter base current causes a rather large change in the collector current. These are current-activated devices and as such have relatively low input impedances and only moderate output impedances.

Other configurations of amplifiers are the common base (the configuration shown in Figure 6-5 and discussed in Section 6A), common emitter (illustrated in Figure 6-7), and common collector. A common collector (illustrated in Figure 6-8) has the collector common to the input and output signals. (The battery is considered to be a short as far as the signal currents are concerned.)

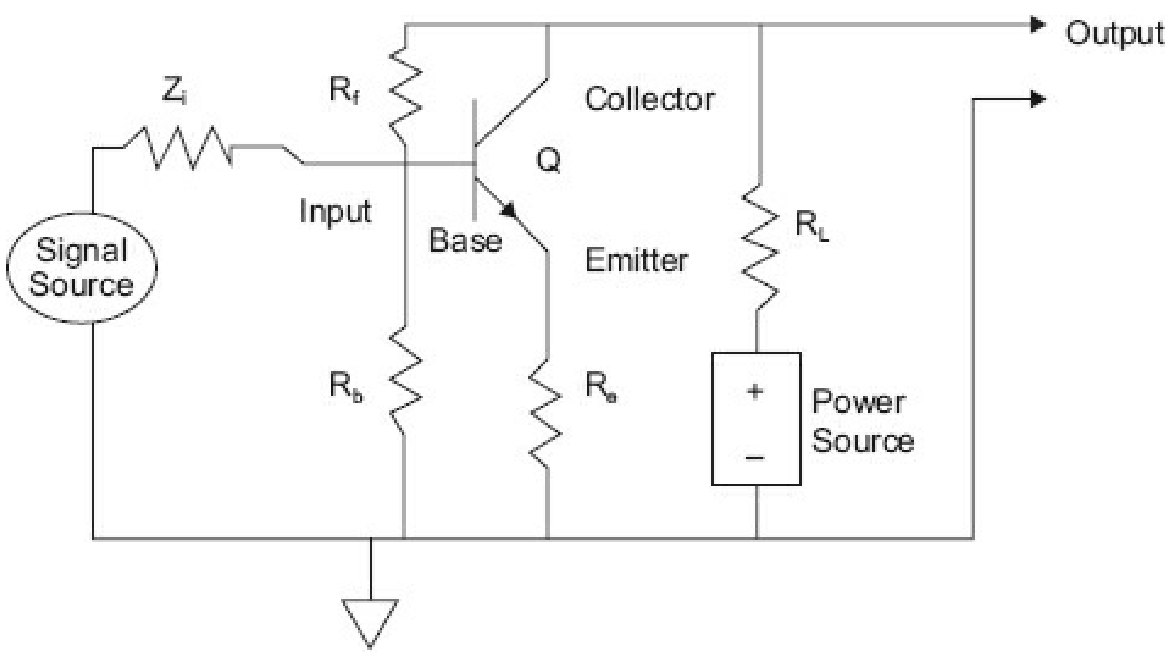


Figure 6-7. NPN common emitter configuration.

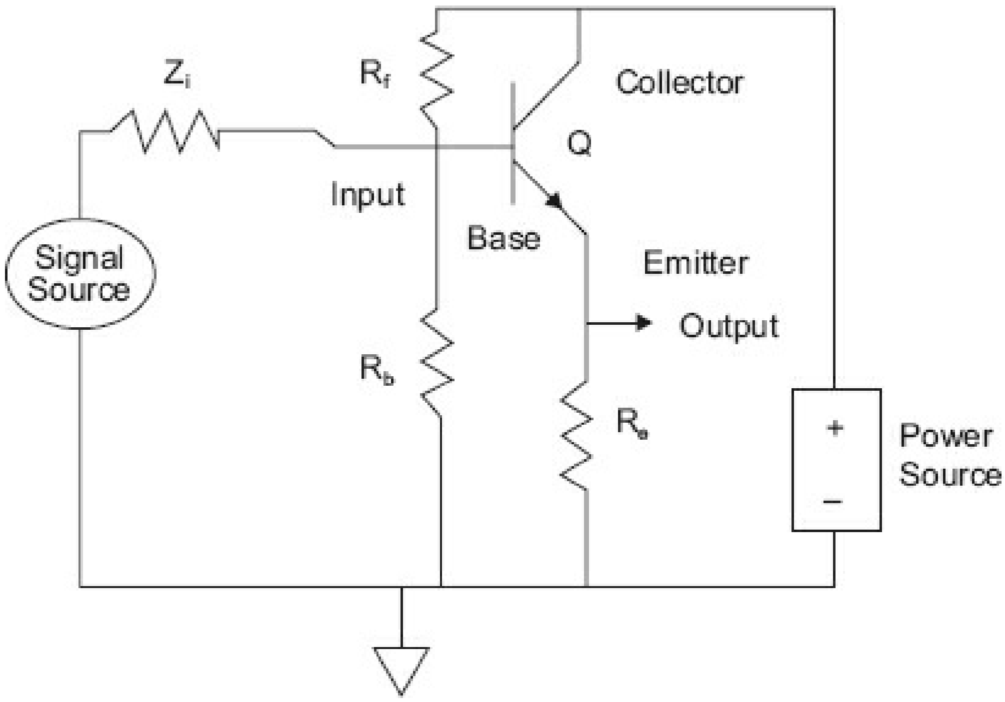


Figure 6-8. Common collector (emitter follower).

Table 6-1. Transistor amplifier characteristics.

Type	Z_{in}	Z_{out}	V_{gain}	I_{gain}	P_{gain}
Common ase (CB)	Low	High	High	<1	Moderate
Common emitter (CE)	Moderate	Moderate	Moderate	Moderate	High
Common collector (CC)	High	Low	< 1	High	Moderate

This configuration, also known as an *emitter follower*, has a very high input resistance, a very low output resistance, and a voltage gain less than 1. It is used for isolation and impedance matching.

Table 6-1 contains information on each amplifier type. Although the table refers to transistor amplifiers, most electronic amplifiers fall into these general classifications.

Amplifier Operation

This is a brief discussion on the operation of the CE amplifier. The amplifier is schematically shown in Figure 6-9.

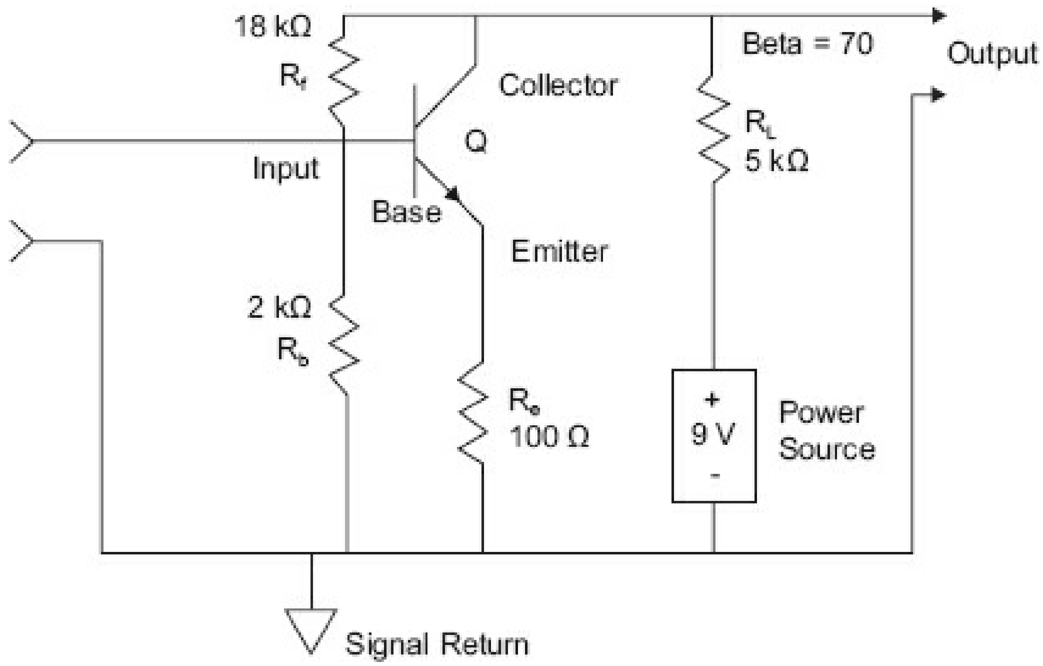


Figure 6-9. Typical CE amplifier.

Notice R_f and R_b. They are used to bias the emitter base junction forward. Because the bipolar transistor is a normally off device, it must be turned on during the entire input cycle of the input signal to operate. Generally, amplifiers used in linear operation are biased to output about half the power source potential with no input signal. In our case, this would be 4.5 V. The transistor gain, beta B, beta of a bipolar transistor is a ratio of input current change to output current change. Figure 6-9 indicates that every 1 unit input to the emitter base will produce 70 units in the emitter collector circuit. To drop 4.5 V, our 5 kΩ resistor must have 0.0009 A flowing through it.

The emitter base current necessary to cause that drop is 1/70 of 0.001 A or 12.8 µA. The voltage across the emitter base is near 0.7 V (for a silicon transistor). The combination of R_f and R_e (20 kΩ) is 0.45 mA (at 9 V). The necessary current for operation is less than 2% of the current flowing in the series combination. The voltage at the emitter in respect to ground is near 1.0 V. The voltage across the transistor is 3.5 V. The output is 4.5 V (3.5 + 1.0). And with a ±12.8 µA input signal, the amplifier will swing ±4.5 V.

Amplifier Troubleshooting

Rather than make a design exercise out of every amplifier circuit, let's consider what should be examined to understand if the amplifier is working correctly.

1. Look at the collector voltage in reference to ground.

   a. If it is at the source (Vcc), it may be that the transistor is not conducting.
   b. If it is 0 V, the transistor is full on or the source is not applied.

      i. If the source voltage is not at the amplifier circuit, there could be a bad powe broken connection, an open lead, or a dropping resistor between the amplif power source.

ii. If the transistor is full on (and is not supposed to be), it could have an collector short (typical) or input signal problems.

c. If the output is somewhere between 0 V and Vcc, then the DC portion of tl operation is probably working.
d. If none of these issues exist, a signal (oscilloscope time) may be deformed or r correct amplitude. Continue to step 2.

2. Look at the input.

a. Is the signal as it should be? Refer to the maintenance documentation if it is a otherwise, the decision will have to be based on experience.
b. If there is no signal, go to the previous amplification stage.
c. If the input signal is deformed, either the previous stage has a problem or the t is faulty.

Transistors may be used as amplifiers (linear operation) or as switches (switched operation). In switched operation, the transistor is either full on or full off, never in between. In either the switched or linear operation, you are *still using a small current to control a large current*.

Application

A transistor in the linear mode with a 30 Vcc and 0.5 A maximum collector current will have to dissipate up to 5 W (because of varying voltage for collector current, Ic, it does not equal 15 W). Because of the different combinations of voltage and current a transistor experiences in linear mode, a good deal of power is lost through heat dissipation and the transistor (along with its heat sink, if there is one) must lose the heat or suffer catastrophic failure. In the switching mode, with the same values (500 mA collector current, a 30 V Vcc), the transistor can have a much smaller dissipation rate depending on the duty cycle (ratio of on to off time). The reason is this:

- When the transistor is off, there is 30 V at the collector, but no current is flowing, power use is 0.

- When the transistor is full on, there is nearly 0 V across the transistor and 0.5 flowing, but the power (E • I) used is almost insignificant.

Factors that determine when a switching transistor begins to heat include:

- How long it takes to switch. Any time spent between full on and full off draws cu and dissipates heat.

- How many times it is switched on and off (the frequency of switching). Becau transistor cannot switch instantly between on and off, energy is dissipated. frequent switching means more energy dissipated.

Module 6B: Summary

- A transistor must be in an amplifier circuit to amplify.
- There are three configurations of amplifiers:

1. Common emitter
2. Common collector
3. Common base

Module 6B: Review

See Appendix B for the answers.

1. When a good power gain is desired, what is the most commonly used an configuration?

   ____

2. Why would one use a common collector configuration?

   ____

Module 6C: Field-Effect Transistors

Field-effect transistors (FETs), also called *unipolar transistors* because the current channel is made of one type of material, come in five distinct varieties. These are:

1. Junction field-effect
2. Insulated-gate
3. Depletion mode insulated gate
4. Enhanced mode insulated gate
5. Insulated-gate bipolar transistors

Most of these transistors are also called *metal-oxide-semiconductor field-effect transistors* (MOSFETs), and most modern circuitry, discrete or integrated, is of this variety. As with bipolar transistors, these transistors come in N and P variations for each of the three main groups.

Junction Field-Effect Transistors

Figure 6-10 is a simplified drawing of junction field-effect transistor (JFET) operation.

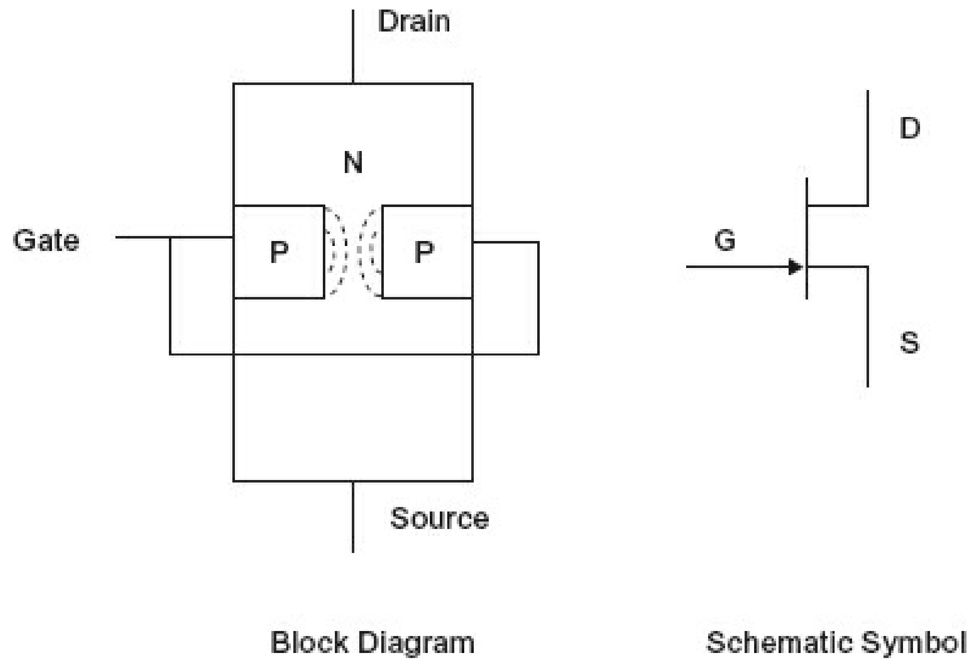


Figure 6-10. JFET operation.

This is an N-channel JFET. The N-type material is the current channel. The gate is a PN junction in the channel that is reverse biased. This means no current flows in the PN junction circuit, and it has a very high impedance (between 10 and 30 MΩ). By varying the amount of reverse bias, the strength of the electrostatic field between the reverse-biased junction and the N channel is varied. This is a normally on device, that is, if the reverse bias is not present, current will flow from the source to the drain. The greater the reverse bias, the more the field constricts the channel, causing fewer and fewer charges to pass through until the bias is great enough to stop the current flow altogether. This point is called the *pinch-off* point. All the incoming signal has to do is affect the junction *voltage*, *not the current,* to control the drain current. Here we have a case (as it is with all the unipolar devices) of using *a small voltage to control a large current*. As voltage-activated devices, the unipolar devices have extremely high input impedances. This means they are vulnerable to static damage. *Never handle a board populated with these devices without taking the proper static precautions*. The P-type JFET operates the same way as the N channel, except all the polarities are reversed. The same amplifier configurations (albeit with slightly different circuitry and certainly different values) provide the same features as their bipolar cousins.

Insulated-Gate FETs

Rather than having to use a reverse-biased diode as the gate, semiconductor techniques have advanced to the point where a very small amount of material insulated by a thin layer of oxide can be used, in effect as a very small capacitor. This is the predominate technology of integrated circuitry: NMOS (N-channel insulated gate MOSFETs), PMOS (P-channel insulated gate MOSFETs), and CMOS (complementary—both P-channel and N-channel MOSFET devices on same substrate). By using an extremely small area, the electrostatic field is concentrated in a small region of the channel enabling control of the larger current channel. With the advent of metallic oxide semiconductor (MOS) technology came two types of devices: *enhancement* and *depletion*.

Depletion Mode

Depletion mode devices operate much the same as the JFET. Increasing amounts of reverse (to the current channel) bias will choke off current in the channel. Schematic symbols for the N-channel and P-channel depletion devices are shown in Figure 6-11.

Again, these are normally on devices and require bias to turn them off.

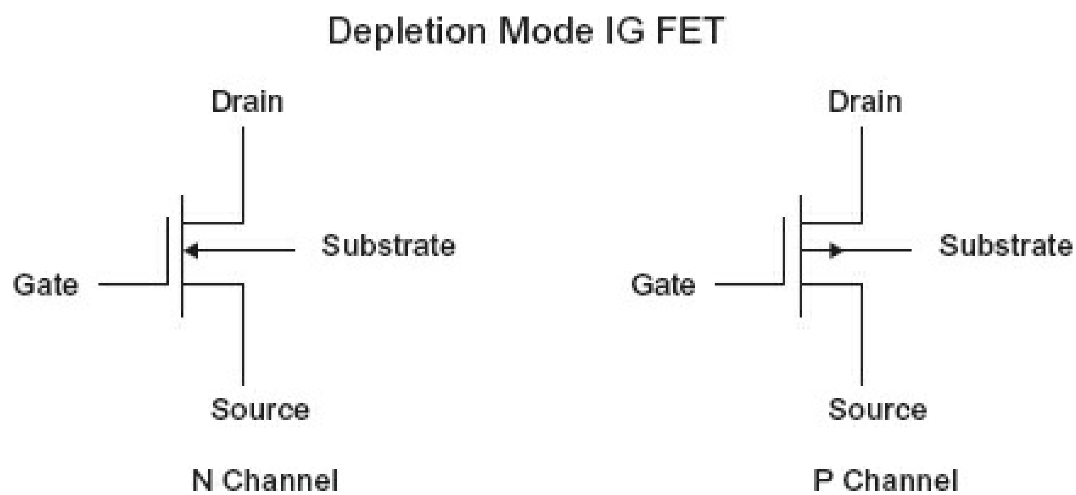


Figure 6-11. Depletion mode MOSFETs.

Enhancement Mode

Another construction of insulated gate field-effect transistor is the enhancement mode type. This device is normally off, and bias must be applied to turn it on. Figure 6-12 illustrates the schematic diagrams for the enhancement types.

Figure 6-12. Enhancement type MOSFETs.

Other than the JFETs (either channel), most of the insulated gate MOSFET devices are found in integrated circuits rather than as discrete transistors. JFETs predominate as discrete devices because they typically have lower noise in practical circuits.

Because of the extremely high gate impedance and the thinness of the oxide coating, relatively small voltages (around 30 V) can penetrate the oxide and render the device useless. It takes little induced current to create a 30 V drop in this large impedance, so these devices are extremely static sensitive. They should never be handled out of a circuit without the device leads being shorted together and the handler exercising static precautions, including grounding with a wrist strip and conductive mats on the bench top. Production facilities may wish to use an air ionizer or other methods to insure low probabilities of creating static electricity.

Insulated-Gate Bipolar Transistors

An insulated-gate bipolar transistor (IGBT, Figure 6-13) is generally a hybrid transistor combination of an FET input coupled to a bipolar output, resulting in a very high input impedance (voltage-controlled input) and a low output impedance with relatively high current output.

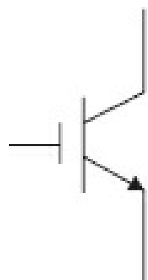


Figure 6-13. IGBT.

Features

- Switching is controlled by gate voltage.
- IGBTs have medium power capability.
- High-frequency switching is possible.
- IGBTs provide simple connection to microprocessor devices.

IGBTs are primarily used in variable frequency drives and uninterruptible power supplies.

Module 6C: Summary

- There are two basic types of field-effect transistors: junction (JFET) and insulate (MOSFET).
- JFETs come in N-channel and P-channel types and are normally on devices.
- JFETs require a reverse-biased gate.
- Enough reverse bias to cut off the current is called the pinch-off point.

- Insulated gate MOSFETs are available in two distinct operating modes: enhanc
  and depletion.
- Depletion insulated gate MOSFETs are normally on, whereas enhancement insu
  gate MOSFETs are normally off.
- Both the depletion type and the enhancement type are available in N- and P-ch
  varieties.
- All FETs require static precautions when handling.

Module 6C: Review

See Appendix B for the answers.

1. What does MOSFET mean?

   ____

2. A JFET requires what bias on its gate to channel?

   ____

3. A P-channel depletion type requires what polarity voltage on the gate in respect
   channel to conduct?

   ____

4. An N-channel enhancement type requires what polarity voltage on the gate in res
   the channel to conduct?

   ____

5. What are the normal storage and handling requirements for FETs?

   ____

Module 6D: Zener Diodes and Silicon-Controlled Devices

Although Zener diodes might sound different than SCRs, they are both found where voltages must be controlled or regulated. This module outlines the operation of Zener diodes and their typical applications, as well as the behaviors and typical applications of SCR and TRIAC diodes. This information is important because these devices are found everywhere in modern electronic circuitry dealing with power and power applications.

Zener Diodes

A Zener diode is intended to be operated in a reverse-bias condition. Usually, when you exceed a diode's peak inverse voltage (PIV) rating, the diode is ruined. However, by doping the junction in a particular manner, a diode is developed that, although it will operate in its forward bias mode, is intended to operate in a reverse-bias condition at its designer PIV or Zener voltage.

What is the result? The diode will conduct any amount of current (within its dissipation rating) while maintaining the same voltage drop across the reverse-biased junction as long as a specified minimum current is maintained. The diode in a forward direction requires about a 0.7 V (silicon) drop to conduct and will maintain that drop until saturated (no further increase in emitter current for an increase in voltage across the emitter base junction).

The Zener will maintain the Zener voltage until the current conducted becomes so great that the heat generated destroys the diode.

This diode is ideal for use as a voltage reference or a voltage regulator. Figure 6-14 illustrates a Zener diode (schematic symbol) in a voltage regulating circuit.

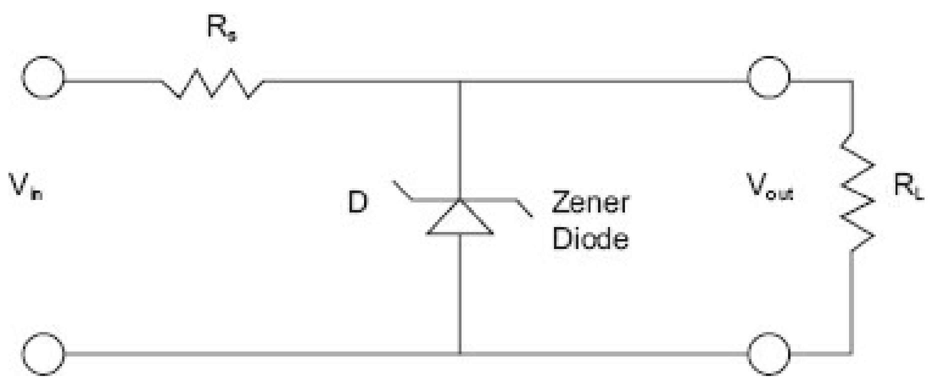


Figure 6-14. Zener diode circuit.

Examples

Assume V_{in} = 30 V. V_{out} is desired to be 12 V. So, a 12 V Zener diode is chosen.

The load is nominally 48 Ω. To determine R_S, the current through the load must be known.

Using Ohm's law: 12 V / 48 Ω = 0.250 A

The drop necessary across R_S will have to be:

30 V – 12 V = 18 V

For the Zener to be able to control as large of range as possible, set the Zener current to equal the nominal load current, in this case 0.250 A. The total current through R_S will be 0.500 A. Its value will then be:

18 V / 0.500 A = 36 Ω.

Now if the load current should drop to 200 mA, the Zener will conduct harder, lowering its resistance to make up the difference, and will conduct 300 mA. The net through the resistor R_S is still 500 mA. If the load should then draw more current, say up to 300 mA, the Zener will increase its resistance and draw less current, 200 mA. The net current through R_S is still 500 mA. Regardless (within reason) of the current excursions by the load, the Zener will conduct more or less to maintain the 12 V across its junction. If the load was disconnected, or just did not draw any current, the Zener must be capable of drawing 500 mA. On the other hand, there is a minimum amount of current that the Zener must maintain to drop 12 V across its junction. While it differs for various Zener ratings and dissipations, typically it is in the 10 to 20 mA range.

This circuit can maintain 12 V for a current draw of 0 mA to 480/490 mA. What dissipation rating must this diode have? Maximum current comes at the no-load current point, and to maintain 12 V by dropping 18 across R_s, the diode must pass 500 mA. Using the power formula P = E • I:

$$P = 12 \bullet 0.5\ A$$

$$P = 6\ W$$

Therefore, a 10 W Zener would be required as diodes normally come in ¼, ½, 1, 5, and 10 W varieties.

Voltage Regulation

In a real-world application, there are two factors to consider when discussing regulation: regulation of output voltage due to load change, and regulation of output voltage due to input voltage changes. Care should be taken to design a circuit that can regulate both of these changes, such as minimum input voltage with maximum load to maximum input voltage with minimum load.

Typically, when talking about a particular supply or regulator and the term *regulation* comes up, it refers to what is known as *load regulation*, which is the change in output voltage for a change in load current. A more common term is a value called *percent regulation*:

$$\frac{\text{no load voltage} - \text{full load voltage}}{\text{no load voltage}} \bullet 100 = \%\ \text{regulation}$$

Examples

A power supply has a no-load voltage of 5.2 VDC. When fully loaded, the output is 4.9 VDC. What percent regulation does this supply have?

$$\%\ \text{regulation} = \frac{5.2\ V - 4.9\ V}{5.2\ V} \bullet 100$$

$$\%\ \text{regulation} = 0.0577 \bullet 100$$

$$\%\ \text{regulation} = 5.77\%$$

Series Pass Regulator

Because the requirements for a typical Zener circuit have the Zener current 5 to 10 times the nominal load current, and Zener diodes larger than 1 W are quite expensive, a better design is to combine the Zener with a bipolar transistor. The bipolar transistor will take the place of R_s, and the Zener as a reference to the base of the transistor, using the current gain (hfe) of the transistor to amplify the Zener effect. Figure 6-15 is a series pass regulator circuit.

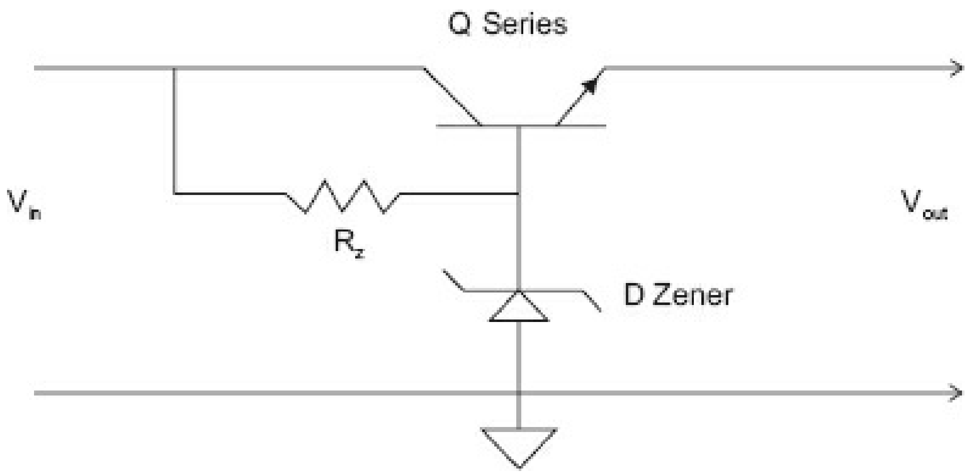


Figure 6-15. Series pass regulator.

If the Zener chosen has a 6.8 V Zener voltage, the output will be at 6.1 V.

Circuit operation is summed up as follows:

- If the load is constant, the output will be the Zener voltage—the emitter base volta
- If the load increases, the output voltage will tend to decrease. Doing so will decrea emitter-base voltage.
- The Zener, which maintains a constant voltage, will then decrease its condu causing the total current to remain constant through R_z. This increases the emitte current, causing Q to conduct harder (lowering its series resistance), and the c voltage is maintained.
- If the load decreases, the output voltage will tend to increase. Doing so will increa emitter-base voltage.
- The Zener, which maintains a constant voltage, will then increase its condu causing the total current to remain constant through R_z. This decreases the emitte current, causing Q to conduct less (raising its series resistance), and the output v is maintained.
- Connecting the Zener diode with the wrong polarity would make it work as a n silicon diode with about a 0.7 V drop.
- Some Zener diodes for higher voltage applications are made with series-conn Zeners within the same case. To determine how many diodes are connected, direct polarity to them and measure the direct voltage drops: a reading of indicates a single Zener, a 1.4 V reading indicates two Zeners connected in series V reading indicates three Zeners, and so on.

Regulator Review

- Zener diodes are manufactured for a specific Zener voltage.
- Zener diodes are used as voltage references and regulators.
- Selection is based on the Zener voltage and dissipation rating.
- Zener diodes are operated with reverse bias for the Zener effect.
- Percent regulation is:

$$\frac{\text{no load voltage} - \text{full load voltage}}{\text{no load voltage}} \bullet 100 = \%\ \text{regulation}$$

- A series pass transistor is often used to multiply the Zener current so a Zener v lesser dissipation may be used.

Silicon-Controlled Devices

This section discusses a special class of semiconductor devices primarily used for phase control and regulation. There are four-layer devices—silicon-controlled rectifiers (SCRs), also known as *thyristors*; five-layer devices—diode AC switches (DIACs); four-quadrant devices—triode alternating current switches (TRIACs); and other thyristor-type devices, namely silicon-controlled switches (SCSs).

SCRs

The schematic symbol for an SCR is illustrated in Figure 6-16.

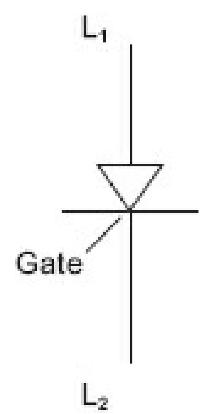


Figure 6-16. SCR schematic symbol.

There are many ways to explain the operation of the SCR, but the simplest is merely to state what it does. If there is no gate current, regardless of the polarity across the diode, it will not conduct. Assuming the gate current is of the appropriate magnitude, and if the diode is forward biased (the line current is in the correct polarity, positive to anode and negative to cathode), then and only then will the SCR conduct. And once it conducts, it will not stop regardless of what the gate current does until the forward polarity is removed from the diode's terminals. Figure 6-17 illustrates SCR operation.

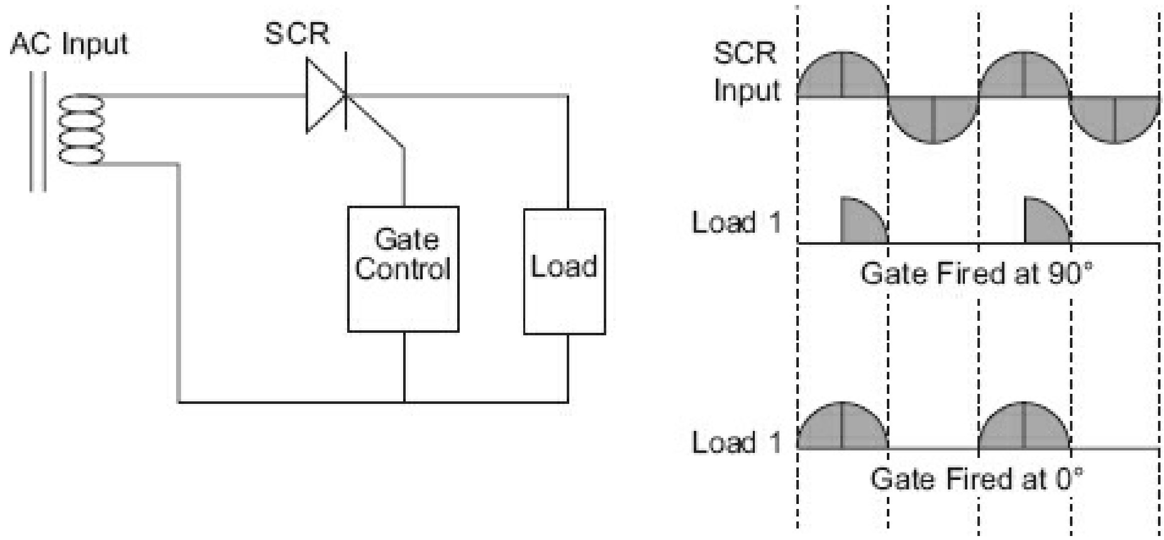


Figure 6-17. SCR operation.

Once the gate has put the SCR into conduction, it remains in conduction until the forward voltage is removed. When using AC, this is accomplished every alternation. Figure 6-17 illustrates two different gate firings. In the lower output diagram, the gate was fired (appropriate current pulse) when the input voltage started its positive climb from 0 V. In the upper output diagram, the gate was fired when the input voltage awas at its peak. Note that once fired, the SCR will conduct until the voltage across it reaches 0 V.

An SCR may also be used as a "crowbar" (creates a short across the power supply to open the fuse) for overvoltage conditions, and in numerous motor control circuits. This is because SCRs can handle large amperage (up to 10,000 A in some models).

DIACs

A DIAC is a member of the thyristor family that is usually employed to trigger TRIACs. A DIAC is a two-electrode, bidirectional avalanche diode that can be switched from the off state to the on state for either polarity of the applied voltage. It operates like a TRIAC without the gate terminal (Figure 6-18).

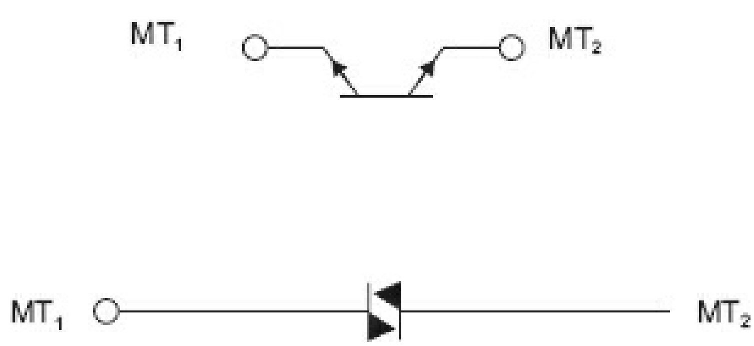


Figure 6-18. DIAC.

As shown in Figure 6-18, in an AC circuit, for whichever alteration, one diode will conduct and the other must have the drop exceed the Zener voltage in order for any current to pass. If the Zener voltage for both was 2.6 V and you applied a 6.3 VAC signal across the DIAC, then the diode would conduct from +2.6 to +6.3 V and –2.6 to –6.3 V, leaving a band between ±2.6 V that current would flow through the diodes. Why is this device necessary? A DIAC is typically used with a TRIAC (coming up next) to prevent false triggering.

TRIACs

A TRIAC is used for lower voltage AC work. It is essentially two SCRs facing in opposite directions so it may be gated on for both of the AC alternations. Figure 6-19 is the schematic representation of a TRIAC. Note that the trigger circuit has a DIAC.

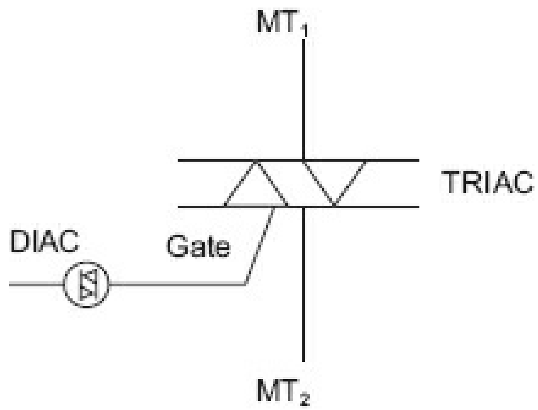


Figure 6-19. TRIAC with DIAC.

The DIAC is used to suppress false triggering. As explained previously, a DIAC is essentially a silicon switch (like an SCR or thyristor) that ensures the trigger pulse must be above a minimal voltage range (in either polarity) before the TRIAC may be fired.

False triggering occurs many times in poorly designed SCR and TRIAC circuits. If an inductive load is being switched, the transient voltages are many and some are of a large magnitude. The problem is that with the gating shown so far, the SCR or TRIAC is gated on during a portion of its conducting alternation. Rather than do this, which is inexpensive and simple, using slightly more circuitry, a *zero-crossing* gate circuit can be derived. In this case, if you wished to have half power (for example) from a TRIAC, rather than gating it on at 90°, you would gate it on at 0° every *other* alternation. Over time, the net power is the same without having to switch the TRIAC (or SCR) in the middle of an alternation.

Although TRIACs are prevalent in commercial circuitry for low voltage (230 VAC or lower), higher powers (above 12 A and anything above 230 VAC) or industrial use dictates the need for SCR circuits as the TRIAC is somewhat leaky (tends to latch on and causes some current to flow even in the off state).

SCSs

The SCS is a four-layer device that can be turned on or off by gate pulses. The SCS never achieved the popularity of its SCR counterpart; however, one may still stumble upon one of these in power circuits developed in the 70s and 80s. An SCS can be triggered on and off by a positive pulse to the appropriate gate. Figure 6-20 illustrates both an application and the schematic of the SCS.

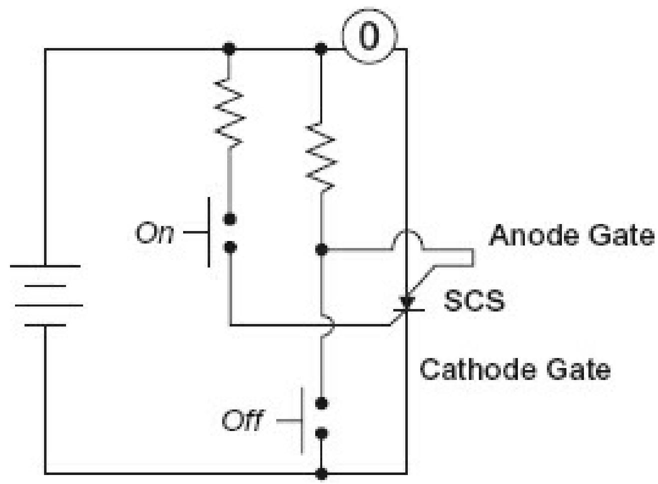


Figure 6-20. SCS.

> ⚠ **WARNING**
>
> If you work on, build, experiment, or otherwise come into contact with the TRIAC and SCR circuits shown, or are building your own, you are dealing with voltages that can be lethal. Please observe all safety precautions when working around energized equipment, particularly when engaged in troubleshooting the circuit.

Troubleshooting

To properly troubleshoot these devices, one should have an appropriate tester (to test under load), although the majority of these testers will require the device be removed from the circuit. Some simple troubleshooting can be performed using a digital multimeter with a diode test feature.

It is assumed you have determined that you have the appropriate circuit voltages when the power is on. If the device is shorted, there will be blown fuses, and checking for appropriate voltages must be done on the hot side of the fuse or breaker. Usually, you must determine the gate drive with an oscilloscope if the power supply side is normal.

1. Ensure power is removed from the circuitry.
2. Disconnect either the anode or cathode lead (MT_1 or MT_2 for TRIACs).
3. Use the diode check to ascertain if the device is shorted (the normal failure mode)
4. If the device is not shorted, check the gate-to-anode resistance. One polarity connection should indicate a diode connection; if not, the gate connection may be
5. Determine that the load circuit is correct and not drawing excessive current, resul the device failure.
6. Replace the device with a good one and re-power the unit. If it is still not worki problem is most likely not the device in question.

Module 6D: Summary

- An SCR is a unidirectional device that may be triggered on anywhere duri alternation that is of the correct polarity.
- Once on, the SCR will not turn off until the correct polarity voltage is removed.
- A TRIAC is a bidirectional device for use in AC circuits as it may be fired in alternation of a cycle.
- A TRIAC is usually used with a DIAC to prevent false triggering.
- Zero-crossing gating makes for a quieter and longer-lived switching circuit.

Module 6D: Review

See Appendix B for the answers.

1. If the no-load voltage is 12.7 V and the full load voltage is 12.5 V, what is the perc of regulation?

   ____

2. Draw the output waveform of an SCR triggered on at the peak of its applied p alternation.

3. Draw the output waveform of a TRIAC triggered on at the peak of its a alternations.

4. Draw the output waveform of an SCR circuit using zero crossing that is fired third alternation.

Conclusion

You have reached the end of Module 6. Please reread the module objectives. If you have met these objectives, continue to the next module. If you are having difficulty, please reread the text. If the difficulty persists, locate a peer, mentor, supervisor, or someone who has technical knowledge of Zener, SCR, and TRIAC devices and ask them to assist you.

Further Information

For additional information on the topics in this module, search for the following topics at your public or company library, or on the Internet.

- Zener diode
- Silicon-controlled rectifier
- Silicon-controlled switch
- DIAC
- TRIAC
- Zero-crossing SCR circuits

7 Operational Amplifiers

Operational amplifiers, *op-amps* for short, are utilized in many areas of electronics, such as filters, amplifiers, analog-to-digital and digital-to-analog converters, and in any circuit (below ultra high frequencies) that requires gain and/or isolation. Op-amps have been the basic building block of control circuits, and even though they are embedded in application-specific integrated circuits (ASICs) or in stand-alone form on rare occasion, they play an important role in automation and instrumentation.

Module 7: Objectives

After successfully completing this module, you will be able to:

- Identify various op-amp configurations and how the configuration determine output.
- Determine the circuit gains for various op-amp configurations.
- Determine the output characteristics for various op-amp configurations.

Module 7A: Basic Op-Amp

An op-amp is basically a direct current (DC) coupled, multistage, linear amplifier. It is not necessary to understand the operation of the internals of an op-amp, but it is necessary to understand two general rules pertaining to them: Assumption #1 and Assumption #2. Before we discuss the rules, the following must be understood:

- An op-amp is a DC amplifier. In other words, when a DC level is placed on the an amplified proportional change will be obtained in the output.
- Op-amps have extremely high gain—above 100,000 when in the "open" loo negative feedback) mode. If you put a 1 µV (microvolt) change on the input, a cha 0.1 V will appear in the output.
- Op-amps use differential input. They measure the difference in voltage between th inputs, not any voltage that is common to both inputs.

It will be instructive to look at a discrete version of an op-amp. This is not a very good op-amp, but it does illustrate basic op-amp operation.

The Discrete Op-Amp Circuit

Figure 7-1 illustrates the basic op-amp circuit.

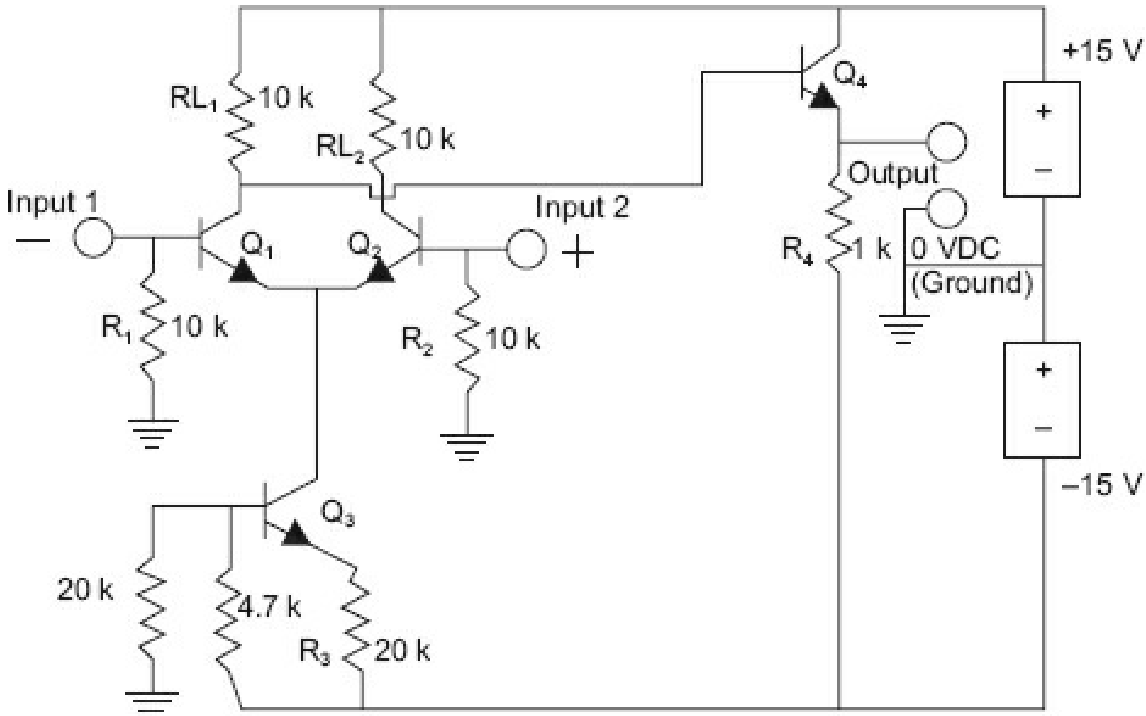


Figure 7-1. Discrete op-amp.

RL_1 and RL_2 are load resistors, Q_1 and Q_2 form a differential amplifier pair, and Q_3 is a constant current generator. A bipolar transistor with fixed bias will enable a current determined by the gain of the transistor and the base current determined by resistors R_3 and R_4. The voltage at collector Q_3 has little effect on the current provided. It is some value more positive than the base, which in turn must be a diode drop more positive than the emitter. In large part, the effectiveness of this circuit determines the operating characteristics of the input amplifier. Input 1 is an inverting input. That is, if a signal goes positive on Input 1 in relation to Input 2, the output will go negative. If the signal on Input 1 goes negative in relation to Input 2, the output will go positive. It is marked with the negative sign (–) to show it is the inverting input. The noninverting input is marked with a (+) sign. A signal on the noninverting input in relation to Input 1 will cause the output to go in the same direction.

Figure 7-2 replaces the amplifier in Figure 7-1 with a triangle, the standard symbol for an amplifier, and adds two resistors.

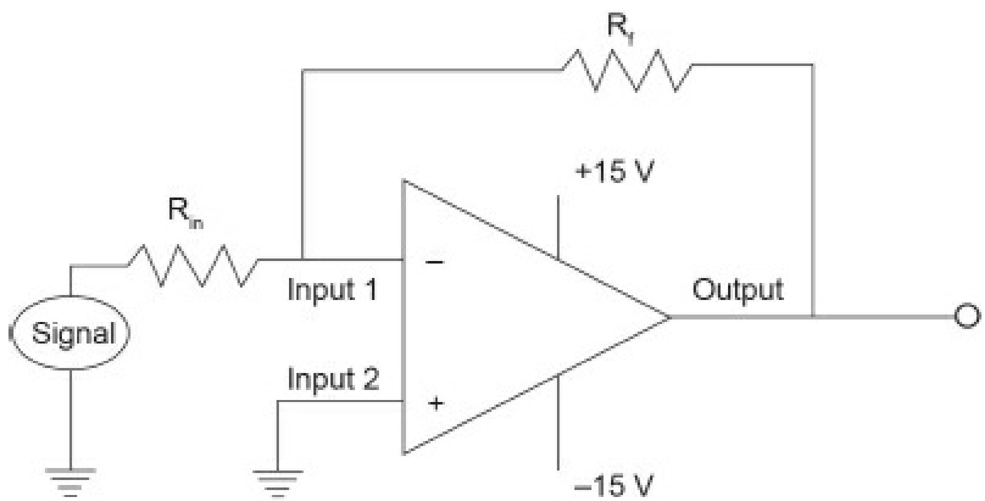


Figure 7-2. Op-amp circuit.

Figure 7-1 is the circuit of a typical early op-amp, and all that circuitry (with the exception of the power sources) is contained in the triangle in Figure 7-2. This is appropriate as you cannot physically see these components or measure any of the internal voltages—the circuit is for all intents and purposes a black box (triangle), which gives the output specified for the inputs specified with no care as to how the internal circuit is configured. Figure 7-2 is an op-amp circuit complete with resistors R_f and R_{in}. Note that these resistors divide the output and feed a portion of the output into the input circuit, the inverting input to be specific. This is called *negative* feedback because it is 180° out of phase with the input signal. That is, if the input on the inverting side goes positive, the output goes negative. The portion fed back to the input is always in the opposite direction to the input.

Positive and negative supplies are used with these op-amps so that if 0 V is input, 0 V will be the output. This is a normal condition for industrial measurements because most signals vary above and below ground. An op-amp can be used on a single supply; however, the reference will usually be made at half the supply voltage.

An op-amp by itself will not do anything. It must be in a circuit. Op-amps normally have an extremely high “open-loop” gain. For most contemporary op-amps with the power source connected to the op-amp, if an extremely small signal were input to the amplifier and the output measured, the gain would be in the 100s of thousands. Obviously, with a gain of 100 dB (see the definition of decibel in the next section), it would take only a very small voltage to drive the output to one or the other of the supply voltages. Because this would accomplish little, most op-amps (in linear circuits) are in circuits with large amounts of negative feedback. This allows for good linearity, while component aging, variances in component tolerances, distortion, temperature, and other physical changes have little effect on the amplifier circuit. This is the typical case.

This module deals only with operational voltage amplifier (OVA) op-amps. There is another class of op-amps, the operational transconductance amplifiers (OTAs). The

OVA transfer characteristic is described in terms of input voltage to output voltage, whereas the OTA transfer characteristic is described as input voltage to output current. With the appropriate components, an OTA op-amp can be made to act as an OVA, but the reverse is not true. OTAs are generally used in gyrators (simulated inductances) and are not discussed in this book.

Decibel

The *decibel* (dB) is a logarithmic unit used to express the ratio of two values of a physical quantity, most often power or intensity. One value is a standard reference value, and the decibel is used to express the magnitude of the other value to this reference.

In contemporary use, the unit is used for a wide variety of measurements in science and engineering, prominently in electronics. In electronics, the gains of amplifiers, attenuation of signals, and signal-to-noise ratios are usually expressed in decibels. The term *decibel* is used when discussing operational amplifiers, filters, and other electronic applications.

Using the decibel has advantages, such as the ability to conveniently represent very large or small numbers and the ability to carry out the multiplication of ratios by simple addition and subtraction.

A change in power by a factor of 10 corresponds to a 10 dB change in level. At the half power point, a filter or an antenna exhibits an attenuation of 3 dB. A change in voltage by a factor of 10 results in a change in power by a factor of 100, which corresponds to a 20 dB change in level.

A change in the voltage ratio by a factor of 2 (equivalently a factor of 4 in power change) is approximately a 6.02 dB change in level.

The decibel symbol with a suffix indicates the reference quantity that has been used or some other property of the quantity being measured. For example, dBm indicates a reference power of 1 milliwatt.

Table 7-1 includes a range of dB values in both power and amplitude (usually voltage).

Table 7-1. Decibel ratios.

dB	Power Ratio	Amplitude Ratio
100	10,000,000,000	100,000
90	1,000,000,000	31,623
80	100,000,000	10,000
70	10,000,000	3162
60	1,000,000	1000
50	100,000	316.2
40	10,000	100
30	1000	31.62
20	100	10
10	10	3.162
6	3.981	1.995 (~2)
3	1.995 (~2)	1.413

1	1.259	1.122
0	1	1
−1	0.794	0.891
−3	0.501 (~½)	0.708
−6	0.251	0.501 (~½)
−10	0	0.3162
−20	0.01	0.1
−30	0.001	0
−40	0.0001	0.01
−50	0.00001	0.003162
−60	0.000001	0.001
−70	0.0000001	0.0003162
−80	0.00000001	0.0001
−90	0.000000001	0.00003162
−100	0.0000000001	0.00001

Assumptions

Two rules (assumptions) about the operation of op-amps will make the op-amp circuit's operation easier to understand and are necessary to diagnose and determine op-amp operation in any circuit.

Assumption #1

No current flows into or out of either op-amp input.

R_f and R_{in} provide a path for the input current to the output transistor and ground. While very small bias currents do flow into (or out of) either input, it will be *assumed* that no currents flow into (or out of) either input.

Assumption #2

There is no voltage difference between the two inputs.

This is not strictly true either. If the circuit is saturated, the voltage across one or the other inputs may vary considerably from the other. In most cases, however, the voltage difference between the two leads will be less than several dozen millivolts. The entire input voltage appears to drop across resistor R_f or R_{in}.

In Figure 7-3, the noninverting input, the input marked as positive or Input 2, is tied to ground (as shown); there is a "virtual ground" at the inverting input. This is why Assumption #2 is important.

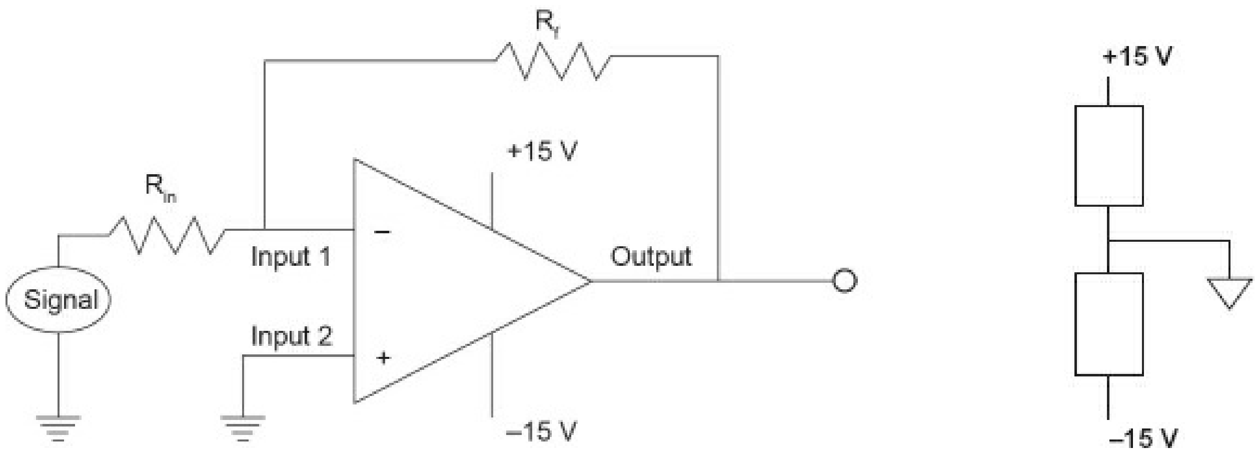


Figure 7-3. Inverting amplifier circuit.

Op-Amp Operation

To explain the operation, use a value of 1 kΩ for R_{in} and 10 kΩ for R_f. If the signal at Input 1 is 0 V, then the output will be at 0 V. If the signal at Input 1 goes from 0 to −1 V, then the output will tend toward a positive output. How far positive? Because R_{in} is 1 kΩ and the change was −1 V, there will be a current inward of −1 mA. This is contrary to Assumption #1. The output will therefore rise (go positive) to whatever value it takes to force +1 mA into the junction of R_f and R_{in}. This current will effectively cancel the input current. The term used is *summed*.

Summed refers to an algebraic sum. In Figure 7-3, R_f is 10 kΩ, so it will take 10 V (positive) to force 1 mA into the summing junction (1 mA through 10 kΩ). Because there was a change of 1 V in for a change of 10 V out, the gain of the circuit is 10 (actually, −10 because it is inverted). Note that the gain of the op-amp circuit is set by the external resistors. Because the open-loop gain (without the negative feedback) is 100,000 or more, the closed gain can be any value below that (generally held to less than 100 per stage). The formula for an inverting op-amp gain is:

$$V_{gain} = -\frac{R_f}{R_{in}}$$

If the sum of the currents at the summing junction equals zero, the op-amp is being operated in its linear range.

Terminology

There are, of course, some specific op-amp terms.

- **Bandwidth** – This is normally the frequency limit at which the output voltage f 0.707 of the voltage present at the center frequency. It is measured in hertz Because an op-amp is usually a DC amplifier, bandwidth is from 0 Hz to some frequency, which is known as the *half power point*.

- **Common mode rejection ratio** – This is a ratio of the change in output caused

common mode voltage (a simultaneous change on both inputs) divided into the c
in output by an input signal (differential gain). This ratio is converted into a d
value and is known as *common mode rejection*. For modern op-amps, this value is fr
to 120 dB.

- **Input bias current** – This is the average of the two input bias currents.

- **Input common mode voltage range** – This is the range of common mode voltag
the inputs) the amplifier can withstand without being destroyed.

- **Input offset current** – Using dual supplies, with the output at 0 V, it is the diffe
between the two input currents. Ideally, these currents are equal, but there are
differences that show up as an output offset. With 0 V on both inputs, the output v
offset from 0 V by the difference in input currents.

- **Input resistance** – With one input grounded, it is the ratio of change in the
voltage to the change in input current in the nongrounded lead.

- **Output impedance** – With the source and load resistance specified, it is the ra
output voltage to output current.

- **Settling time** – With a step function input (large instantaneous change from one le
another), it is the time it takes the output to arrive at a steady-state value based
new input level.

- **Slew rate** – This is the fastest rate of change the amplifier is capable of. It is u
measured from one output peak to the opposite output peak. It depends on the s
voltage, input voltage overdrive, amount of loading, and device design constraints

- **Unity gain bandwidth** – This is the frequency range from 0 Hz to the upper freq
at which the amplifier's open-loop gain becomes 1.

Module 7A: Summary

- An op-amp is a high-gain, direct-coupled amplifier.

- Op-amps use a differential input stage (or one that acts differentially).

- Op-amps have open-loop gains in excess of 100,000.

- Op-amps have inverting and noninverting input.

- The schematic representation of an op-amp is a triangle.

- There are two assumptions regarding op-amp operation that will explain most op
circuits:

- Assumption #1
  No current flows into or out of either op-amp input.
- Assumption #2
  There is no voltage difference between the two inputs.

- Op-amp amplifiers use external components to determine amplifier parameters.
- The junction at the inverting input between the input resistor and the feedback re is known as a *virtual ground*. With a signal on the inverting input, the output op will drive in the opposite direction until the current through the feedback re equals the input current.

Module 7B: Linear Op-Amp Circuits

As with any amplifier, there are a few basic circuits that the majority of applications use as a foundation. The three basic linear circuits are:

1. Inverting amplifier
2. Noninverting amplifier
3. Voltage follower

Inverting Amplifier

Figure 7-4 illustrates an op-amp connected as an inverting amplifier.

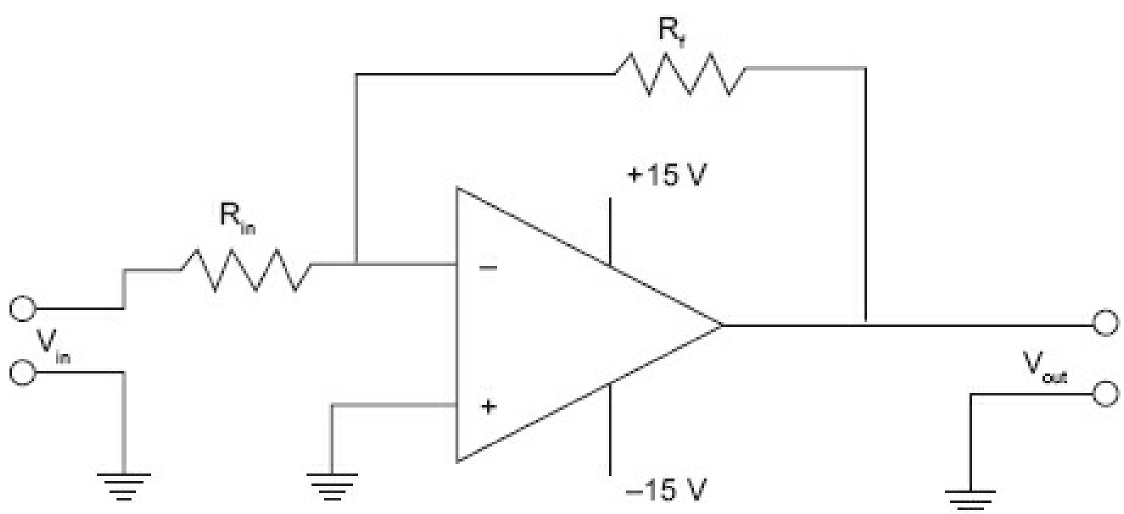


Figure 7-4. Inverting amplifier.

The formula for the output voltage is:

$$V_{out} = \frac{R_f}{R_{in}} \bullet V_{in}$$

The input impedance of this amplifier is approximately the value of R_{in}.

Noninverting Amplifier

Figure 7-5 illustrates the basic noninverting amplifier.

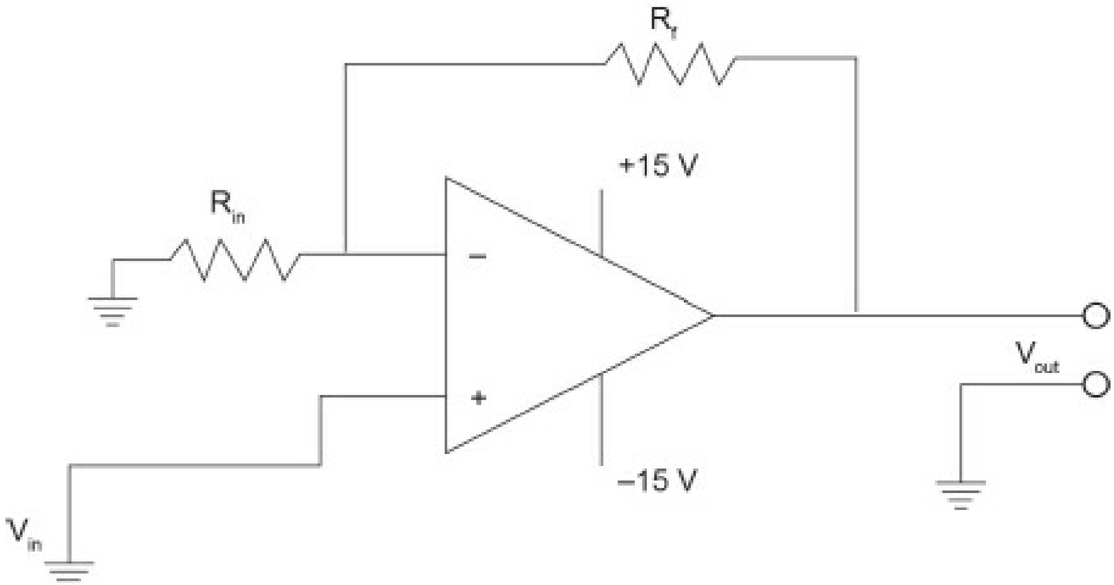


Figure 7-5. Noninverting amplifier.

The input signal appears on the noninverting input. Unlike the inverting amplifier, the noninverting amplifier will always have a gain greater than 1. This is due to the way the input is biased. The gain is:

$$V_{out} + \left(1 + \frac{R_f}{R_{in}}\right) \bullet V_{in}$$

At 0 V input, there will be 0 V on both inputs so the output will be 0 V. If the inverting input changes in a positive manner that will place some positive voltage on the input, our assumption says there will be no voltage difference. The output will go positive, as positive as necessary to place the same voltage at the junction of R_f and R_{in} as is on the noninverting input.

Example: Noninverting Op-Amp

Using the circuit shown in Figure 7-5, give R_{in} the value of 1 kΩ and R_f the value of 5 kΩ. A change from 0 V to +1 V occurs at the noninverting input. The output goes positive and will continue to go positive until the voltage drop across R_{in} equals +1 V. R_{in} is a 1 kΩ resistor, so it will require 1 mA of current to drop 1 V. 1 mA through 5 kΩ requires 5 V. Add the 1 V across R_{in} and the 5 V across R_f, and that equals 6 V. So, for a 1 V change in, there is a 6 V change out—a gain of 6. The noninverting op-amp cannot have a gain less than 1 because the voltage appearing at the noninverting input must be dropped across R_{in} to meet Assumption #2.

Voltage Follower

The voltage follower, sometimes called a *source follower*, is illustrated in Figure 7-6.

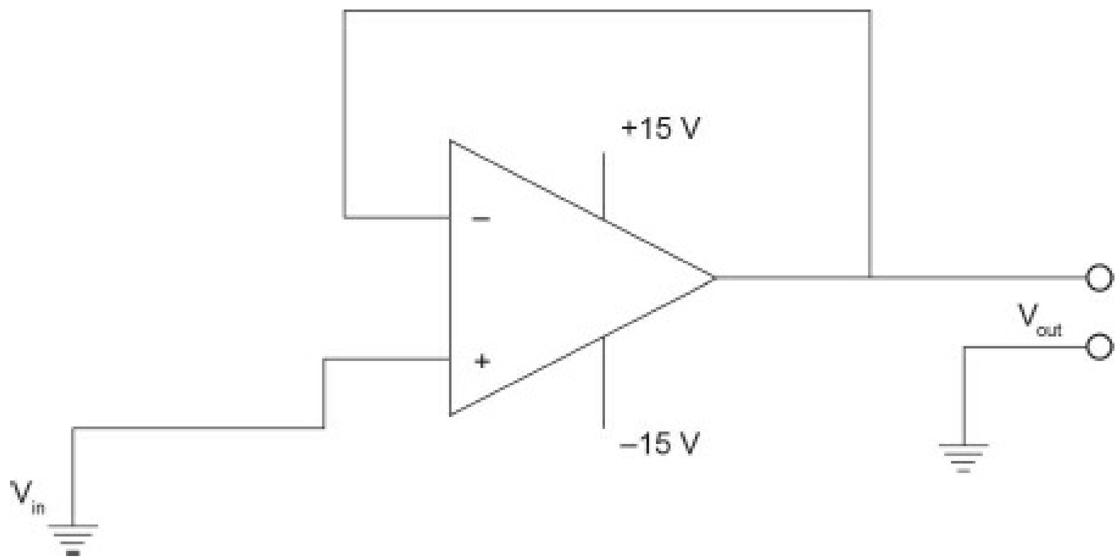


Figure 7-6. Voltage follower.

The voltage follower is a unity gain noninverting amplifier. As with the noninverting amplifier described previously, the source follower has an extremely high input resistance whereas the output resistance is very low. As with the transistor emitter follower, this circuit is used primarily for isolation, buffering, and impedance matching.

Using the assumption that there is no voltage difference between the two inputs, we will demonstrate how this circuit works. If 0 V is on the input, then 0 V will be on the output and the inverting input. If a −1 V change is made on the input lead, then to maintain equal voltage across the two inputs, the output goes to −1 V, which is also the inverting input lead. Whatever signal appears on the input lead (within the operating range of the amplifier), the output will follow that signal, placing the same voltage on the inverting input to maintain no difference.

Output Offset Voltages

An ideal op-amp will output 0 V when 0 V is the input. One of the main reasons for using a split power supply (± V) is to be able to operate with input signals that vary above and below ground by small amounts. An ideal op-amp should output 0 V with 0 V_{input}; *a real-world op-amp will not exactly do this*. Practical op-amps have some offset; that is, with 0 V_{input}, the output will be some voltage above or below 0 V. It is the result of three input offsets:

1. Input bias current
2. Input offset current
3. Input offset voltage

To understand input bias current offset, assume both inputs are grounded.

Although we have made the assumption that no current flows into either lead, this is not strictly true. There are small bias currents that are the forward currents of the input transistors, and there are unequal paths for the input bias current to travel. One method of compensating for the unequal paths is to include an equivalent resistor in the noninverting path. Because the $R_f||R_{in}$ (parallel combination of R_f and R_{in}) pair causes the unequal path, the equivalent resistor must be equal to that value. This method will certainly reduce the output offset, but it presents its own problems. The value of bias current given in the specification is the average of the two input bias currents; it does not mean they are equal. Because there will be some small difference in these currents when multiplied by the gain of the op-amp, there will be an offset even with the compensatory resistor. Other methods can be used, mostly involving external components to compensate for whatever offset is left if it is necessary for correct circuit operation.

Example: One-Supply Operation

If you require linear operation and you are going to operate from a single supply (e.g., 12 V), you must bias the op-amp so the output will be at ½ V_{SS} (in our example, this will be 6 V) to ensure maximum output swing without distortion. Using our assumption of no voltage difference between the two inputs, if you bias the noninverting input at 6 V (using a resistive divider between V_{SS} and ground), then the output will operate around 6 V and the noninverting input will also add algebraically around 6 V.

Module 7B: Summary

- The inverting op-amp circuit offers a gain based on the ratio between the feedbac input resistor.
- The noninverting op-amp circuit always has a gain of 1 or greater.
- The voltage (source) follower has a gain of 1.

Module 7C: Comparators

Previously, we discussed using an op-amp in its linear mode as an amplifier. The op-amp may also be used for other nonlinear functions. Due to the op-amp's high open-loop gain, it may be used as a switching circuit. One type of circuit that uses an op-amp as a switch is the comparator circuit. This circuit compares the voltage on one lead (input voltage) with the voltage on the other lead (reference voltage). Any significant difference multiplied by the open-loop gain results in the output being driven to either the most positive or most negative supply. Figure 7-7 illustrates the basic comparator circuit.

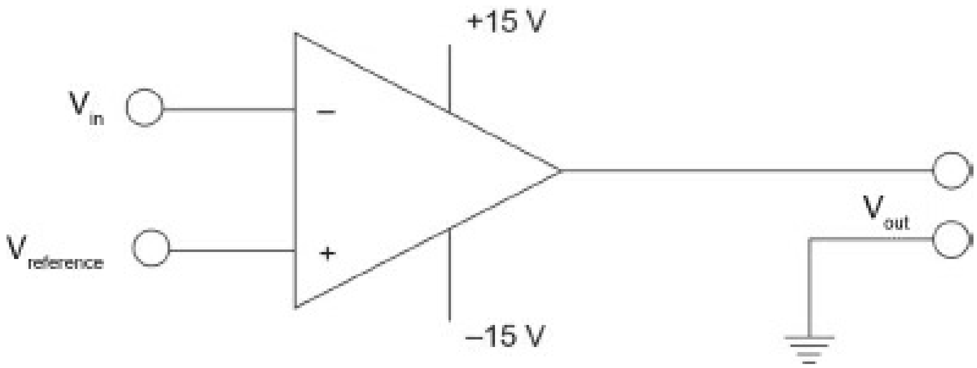


Figure 7-7. Comparator.

If a device is a general-purpose op-amp being used as a comparator, the one chosen should have as high a slew rate as possible. Because external compensation tends to slow the slew rate, compensation would not be used. As used here, slew rate is the rate of change in the output voltage resulting from a step change on the input voltage. It is measured as a voltage change over a time frame (V/μs or V/ms).

Comparator Operation

Figure 7-8 illustrates the two different output states of the basic noninverting comparator; Figure 7-9 illustrates the basic inverting comparator.

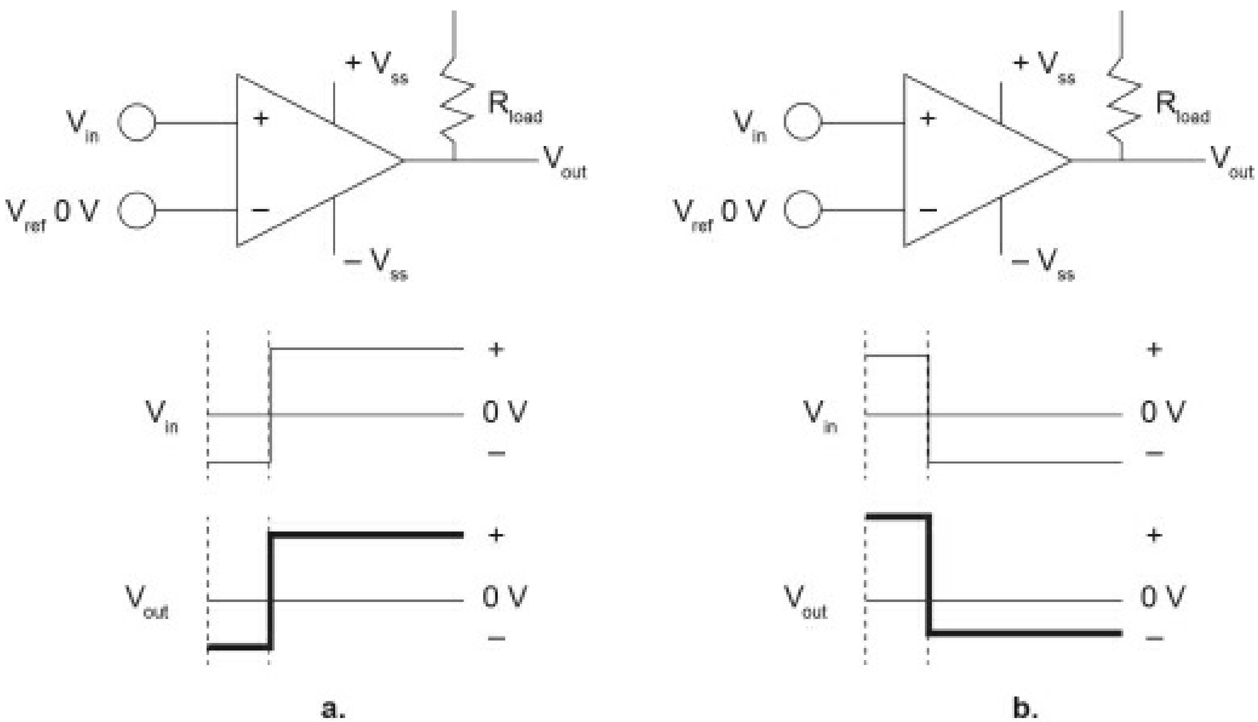


Figure 7-8. Comparator operation, noninverting.

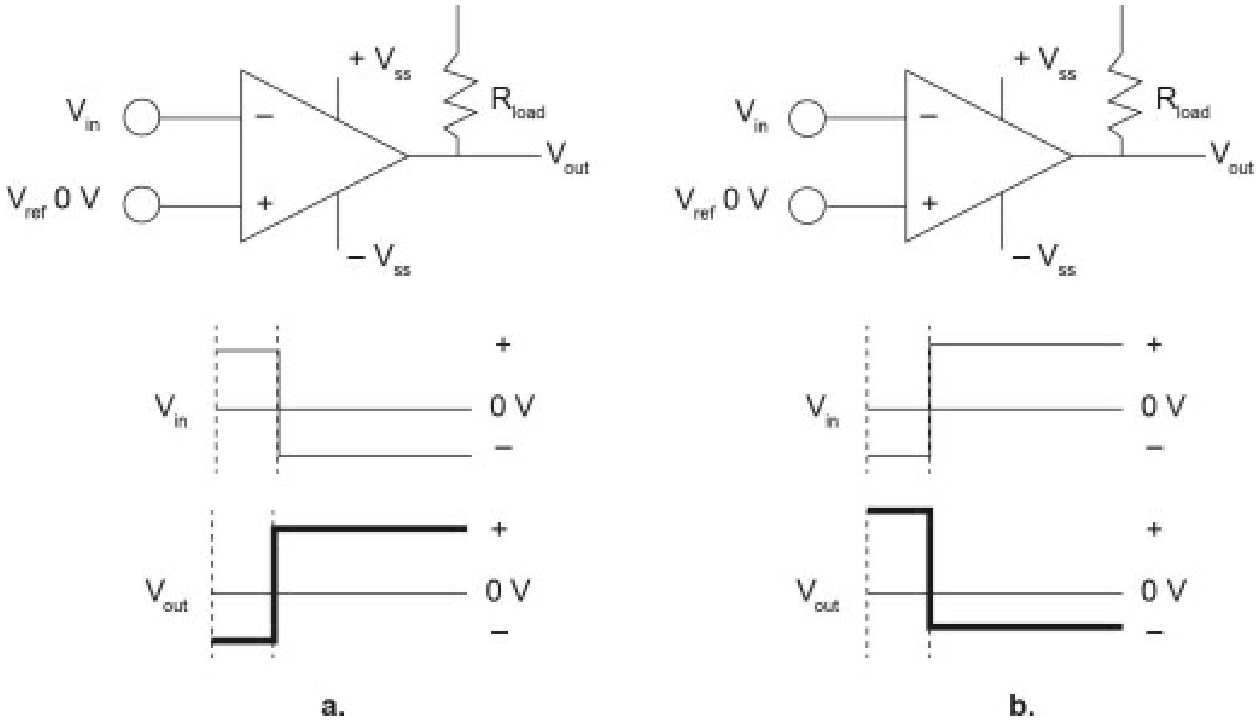


Figure 7-9. Comparator operation, inverting.

Most comparators are high-gain devices that may easily oscillate with less than optimum lead placement. These oscillations tend to show up during output transitions when the comparator is changing states. A technique for reducing the chance of oscillations is to add hysteresis to the circuit. This is done by inserting a small amount of positive feedback. Figure 7-10 illustrates the basic comparator with hysteresis.

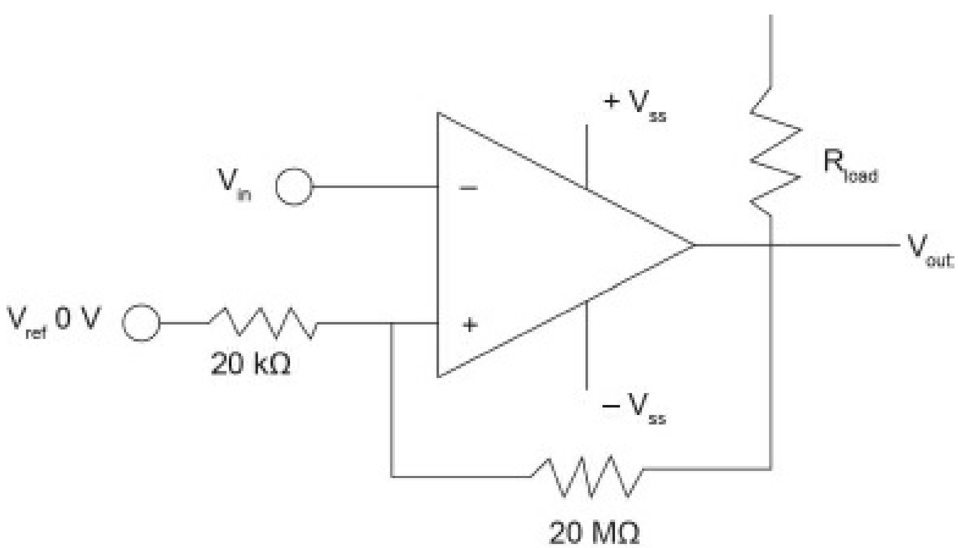


Figure 7-10. Adding hysteresis.

Hysteresis is generally unnecessary if the signal is a pulse with sharp rise and fall times; it is most often required when dealing with signals that have a slow rise and fall (e.g., those found in process control).

Module 7C: Summary

- Comparators are used to determine when a signal exceeds a reference voltage.
- Comparators are designed with a high slew rate.
- Comparators can be connected as inverting or noninverting comparators.
- A slight positive feedback will add hysteresis to the comparator circuit.

Module 7D: Functional Circuits

Integrator

Figure 7-11 illustrates an op-amp used as an integrator.

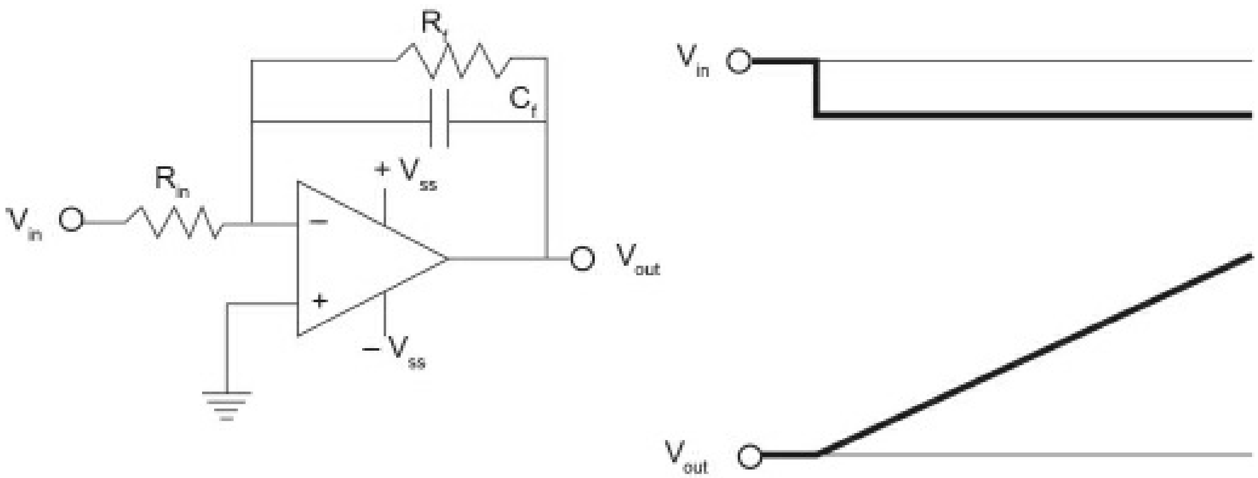


Figure 7-11. Op-amp integrator.

In this circuit, the integrating action is caused by the feedback circuit, which consists of the capacitor (Cf) and a parallel resistor (R_f). The resistor serves to limit the DC (static gain). The capacitor and the input resistor (R_{in}) provide the integration. When there is a step change on the input as shown, the capacitor will immediately feed back a large current, with the current falling off by the RC time constant rate (1 TC = R • C, where R is in ohms, C is in farads, and T is in seconds). The current will have decayed 63% from its maximum amount in one time constant. Therefore, to keep the voltage difference between the two inputs at 0 V, the output must keep changing toward the supply voltage, in this case the positive supply. This results in a linear slope (until the supply limit is reached). The greater the magnitude of the input change, the steeper the slope of the output waveform.

To perform integration, as we use the word in this text, means to average over time. The output of the integrator rises toward its limit (also set by R_f) of the supply voltage. For a small change, it might take a large amount of time because the output only has to change slowly to maintain the summing current. If the input changes are quite large, the output will have to rise faster to meet the demands of the summing current.

If a series of alternate step changes (a square wave) are input at the correct frequency, the output of the integrator will be a triangular waveshape. If sinusoidal changes are input rather than step functions, this circuit is a low-pass filter (you cannot integrate or differentiate a sine wave, only change its amplitude and phase) providing maximum attenuation to higher frequencies where the reactance of the capacitor is low and the feedback current is high. Where the rate of change (frequency) is low, the capacitor offers a large amount of reactance, thereby limiting the amount of feedback current. The transfer function for nonsinusoidal waveforms can be modeled as an integral of the input signal over time, which explains the name *integrator*.

Differentiator

Figure 7-12 is an op-amp connected as a differentiator.

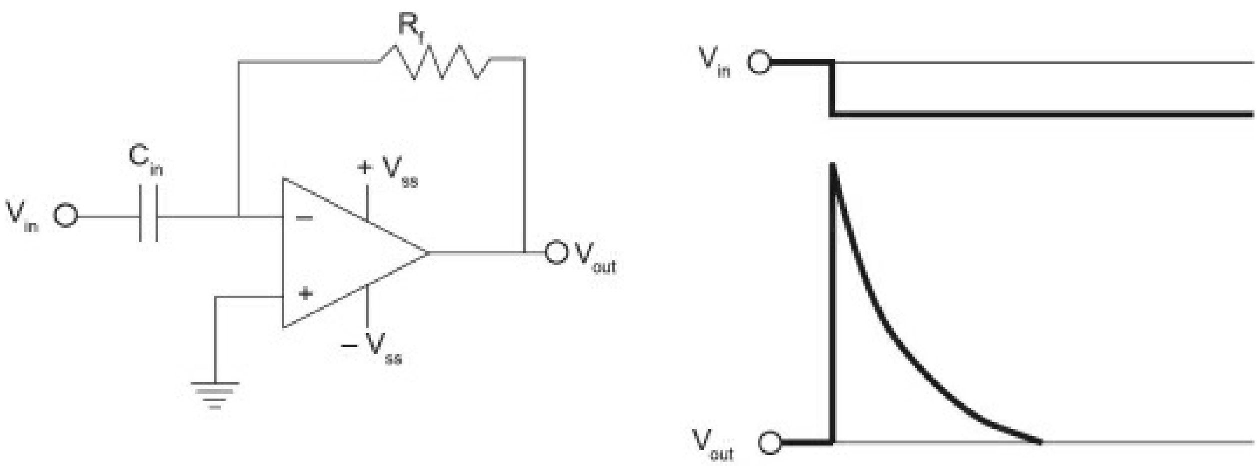


Figure 7-12. Op-amp differentiator.

Note that in this case (as opposed to the integrator), the op-amp has a capacitor in the input lead (C_{in}) and a resistor as a feedback path (R_f). For a step function change, the rise time will be coupled through the capacitor, and the input current will fall off by the RC time constant of $R_f \bullet C_{in}$. Therefore, the output will also fall off as it tries to maintain a 0 V difference between the two inputs. The faster (higher frequency) signal components appear to the feedback resistor as having a very low input resistance, whereas the slower changing components appear to have higher input resistances. Because gain is determined by the ratio of R_f:XC_{in}, the faster changing components will have the most amplification. If sinusoidal signals are input, this circuit will act as a high-pass filter; that is, it will pass high-frequency signals and attenuate lower frequency signals based on the values of R_f and C_{in}. The faster the step change, the greater the output swing. The differentiator is a rate of change detector in that slow signals (relative to $R_f \bullet C_{in}$) will have little output, while quick (and large) input changes will cause a large output.

Summer

Figure 7-13 illustrates a basic inverting summer.

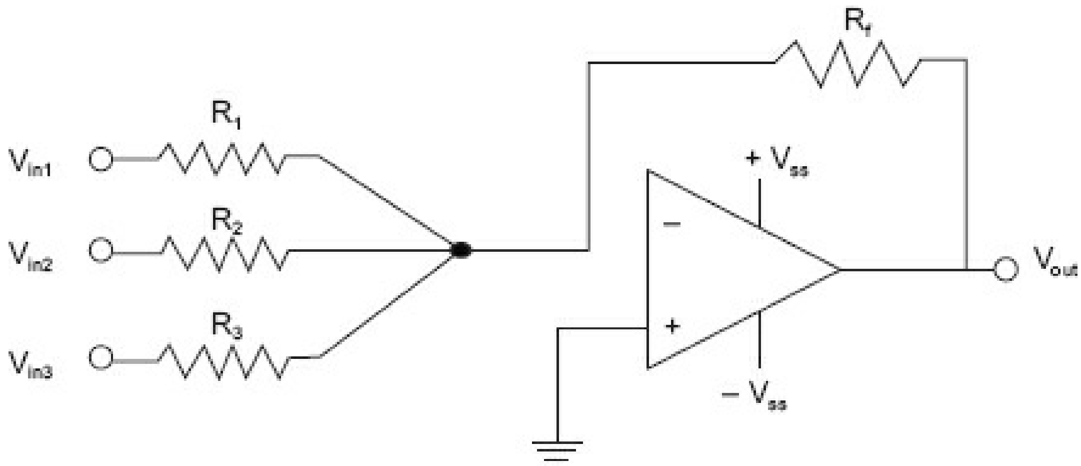


Figure 7-13. Op-amp summing amplifier.

The algebraic sum of the currents at the summing junction must be balanced by the current through R_f and so is proportional to the sum of the inputs.

Example: Summer

$R_f = R_1 = R_2 = R_3 = 10\ k\Omega$

$V_{in1} = +2$ V

$V_{in2} = -1$ V

$V_{in3} = -3$ V

Determine the output.

1. Using Ohm's law:

   $I_{R1} = +2/10{,}000 = +0.2$ mA

   $I_{R2} = -1/10{,}000 = -0.1$ mA

   $I_{R3} = -3/10{,}000 = -0.3$ mA

2. Sum the currents.

   +0.2 mA − 0.1 mA − 0.3 mA = −0.2 mA

3. What voltage must the output be in order to push −0.2 mA through 10 kΩ?

   −0.2 • 10,000 = −2; this is an inverting amp, and +2 V is the output. If you sum the voltages, you will get −2 V; invert, and the output is +2 V.

Differential Amplifier

This is a circuit that only amplifies the difference between the voltages on the input leads. A differential amplifier is shown in Figure 7-14.

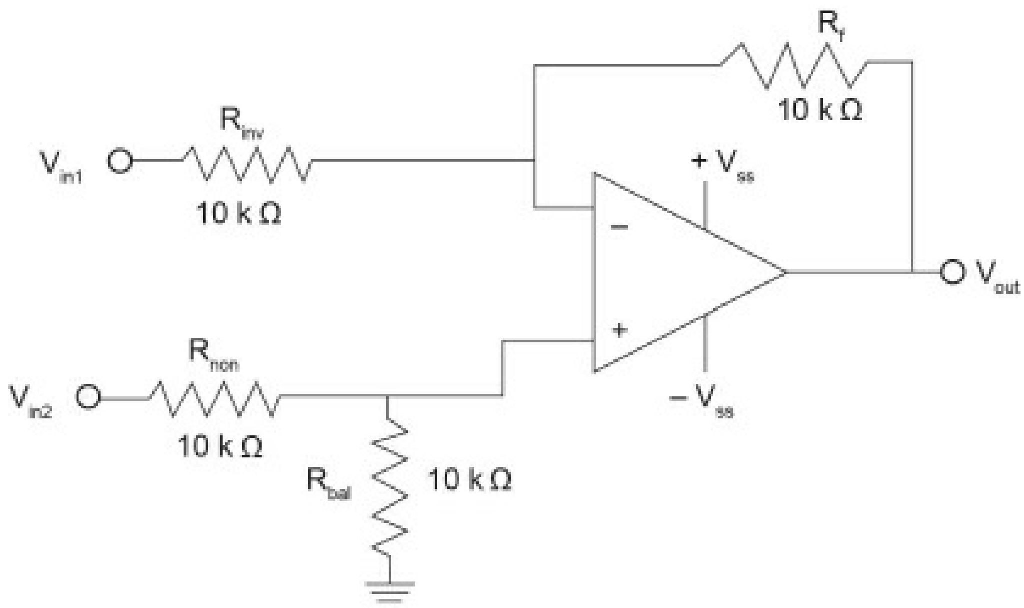


Figure 7-14. Differential amplifier.

Using the assumptions will make this explanation much easier than trudging out some formulas.

Examples: Differential Amplifier

1. Input: 0 V on the inverting input, 0 V on the noninverting input. Output will be 0 V.
2. Input: 0 V on the inverting input, +1 V on the noninverting input. Because the input voltage on the noninvert will be divided by R_{non} and R_{bal}, the actual difference between the two leads is +0.5 V. To match that, the will have to rise to +1 V (0.5 across R_f and 0.5 across R_{inv}).
3. Input: +1 V on inverting input, +1 V on noninverting input. Again, +1 V on the noninverting side puts +0.5 V input. The output must match that by going to 0 V, so the 1 V input will be divided between R_f and R_{inv} with across each.
4. Input: +2 V on the inverting side, +1 V on the noninverting side. The summing junction must be at +0.5 V. T output must cause R_f and R_{inv} to divide +1 V. By going negative 1 V (+2 V – 1 V = +1 V), this condition will reached.

Other solutions are left to the reader.

Module 7D: Summary

- Op-amp integrators produce a linear rising (or falling) slope depending o magnitude of input change over time.
- Differentiators output a peaked signal corresponding to the rate of change of the signal.
- An integrator with sinusoidal waveform inputs is a low-pass filter, attenuatir high-frequency signals.

- A differentiator with sinusoidal waveform inputs is a high-pass filter, attenuatin frequency signals.
- A summer algebraically adds the input signals.
- A differential amplifier outputs the algebraic difference between two signals.

Module 7D: Review

See Appendix B for the answers.

1. Given an inverting op-amp circuit, R_{in} = 2.2 kΩ and R_f = 6.8 kΩ, what is the gain circuit?

 ____

2. With the circuit in question 1, a −100 mV input change will cause what output change?

 ____

3. Given an inverting op-amp circuit, R_{in} = 10 kΩ and R_f = 4.7 kΩ, what is the gain circuit?

 ____

4. If a voltage follower with a ±15 V supply has +2 V applied to the input, what output be?

 ____

5. For the circuit in question 4, if the input was +16 V, what would the output be?

 ____

6. When using a comparator, when is hysteresis necessary?

 ____

7. How does the comparator differ from previous op-amp circuits?

 ____

8. If you input a square wave to an integrator (of the appropriate frequency) waveform will the output have?

 ____

9. If you input a square wave to a differentiator (of the appropriate frequency) waveform will the output have?

 ____

10. An inverting summer has four inputs. Input 1 has −2.5 V, input 2 has +1 V, input +1.5 V, and input 4 has +0.5 V. If the summer has a gain of 1, what will the o voltage be?

____

11. A noninverting amplifier has R_f = 5 kΩ and R_{in} = 10 kΩ. With V_{in} equal to 6 V, wha the output be?

____

12. A source follower has an input impedance of 100 kΩ and an output impedance of 1 With +4 V on the input, what voltage will be on the output?

____

13. Using an integrating circuit, a signal with a band of frequencies from 100 Hz to 15 is the input. Which end of the frequency band will be attenuated most?

____

14. Using a differentiating circuit, a signal with a band of frequencies from 100 Hz kHz is the input. Which end of the frequency band will be attenuated most?

____

Conclusion

You have reached the end of Module 7. Please reread the module objectives (in the "Objectives" section). If you have met these objectives, continue to the next module. If you are having difficulty, please reread the text. If the difficulty persists, locate a peer, mentor, supervisor, or someone who has technical knowledge of operational amplifiers and ask them to assist you.

Further Information

For additional information on the topics in this module, search for the following topics at your public or company library, or on the Internet.

- Operational voltage amplifier (OVA)
- Operational transconductance amplifier (OTA)
- Op-amp integrating circuit
- Op-amp differentiating circuit
- Op-amp comparator circuit
- Op-amp summing circuit

8
Analog and Digital Conversion

Modern electronic industrial devices are generally digital as features through software can make a more efficient and scalable networked device useful in many different environments.

While the majority of systems communicate in digital format, the measurements that must be made in industry operate in a continuous or analog world. For the digital device to communicate and control, analog-to-digital (A/D) and digital-to-analog (D/A) conversions are required. There are different methods for performing either type of conversion; this module will outline some of the more prevalent techniques.

Module 8 Objectives

After successfully completing this module, you will be able to:

- Convert between binary, octal, digital, and hexadecimal values.
- Define and demonstrate natural binary, offset binary, and two's compl representations.
- Describe the operation of digital-to-analog converters including the weighted re and R-2R ladder types.
- Describe the operation of analog-to-digital converter types including:
  - Integrating
  - Successive approximation
  - Flash

Before we can perform conversions of any type, we must have some way to represent values as binary numbers. These representations are called *binary codes*. The first section of this module is concerned with number systems, primarily the binary number system. Although binary numbers were discussed earlier in this book, this discussion will aim toward conversion symbols and values rather than binary logic.

Module 8A: Number Systems

All number systems follow the same rules. You are familiar with the decimal system. *Decimal* means that the number system has a radix or base of 10; it is based on 10 digits.

- The decimal system's base (radix) is 10.
- The only numbers allowed in the decimal system are 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9.
- All the numbers that we can use to describe numerical quantities in decimal are up of those 10 numbers and no others.

Figure 8-1 illustrates the powers of 10. Notice that the number 4302.63 is really 4000 + 300 + 2 + 0.6 + 0.03 or, more correctly, 4 • 1000 (10 to the third power) + 3 • 100 (10 to the second power) + 0 • 10 (10 to the first power) + 2 • 1 (10 to the 0 power, or 1) + 6 • 1 • 1/10 (10 to the negative first power) + 3 • 1 • 1/100 (10 to the negative second power).

1 • 1000	1 • 100	1 • 10	1 • 1	Decimal Point	1 • –1/10	1 • 1/100
4	3	0	2	.	6	3

Figure 8-1. Powers of 10 example.

All other number systems are constructed the same way, except rather than being based on 10, they are based on a different number. For example, the base used will be 2, if binary, or 16, if hexadecimal.

For this discussion of number systems, the emphasis is on the use of the number system as a means of pattern recognition. The number systems chosen here are the ones presently used in data communications. Binary is the number system used by computers, decimal is used to represent binary values so they make sense to humans, and hexadecimal is used to reduce binary streams to recognizable patterns. Computers presently work only with binary patterns, and humans only understand decimal.

The Binary System

The pattern to recognize in the binary system is the value of each digit in the binary number --the column decimal value. Each digit from right to left has a value twice that of the previous digit: 1, 2, 4, 8, 16, 32, 64, and so on. Figure 8-2 illustrates the binary values for 0 through 15 decimal. As an example, let's determine the decimal number for hexadecimal E. The binary number is 1110. To determine the decimal number, add the column values for each 1 in the binary number. Working from right to left, the first 1 is in the second column so the value is 2. The third digit is a 1 with a value of 4, and the fourth digit is a 1 with a value of 8: 2 + 4 + 8 = 14.

	Binary	Octal	Decimal	Hexadecimal
	0000	0	0	0
	0001	1	1	1
	0010	2	2	2
	0011	3	3	3
	0100	4	4	4
	0101	5	5	5
	0110	6	6	6
	0111	7	7	7
	1000		8	8
	1001		9	9
	1010			A
	1011			B
	1100			C
	1101			D
	1110			E
	1111			F
Column Decimal Value	8421			

Figure 8-2. Binary numbers 0 through 15.

Binary Coded Decimal

Figure 8-3 illustrates the binary patterns for decimal values 0 through 9, which are called *binary coded decimals* (BCDs). This means that the decimal numbers (0 through 9) are each represented by four binary digits, 0000 through 1001.

1	3	0	2	Decimal
0001	0011	0000	0010	BCD

Figure 8-3. BCD coding.

This coding (BCD) was done so humans could see familiar-looking numbers rather than strings of ones and zeros. BCD coding is used to represent decimal values in a binary format.

Octal Coding

Early computers used a 12-bit *word*; breaking the word into four 3-bit patterns enabled representation of each of the 3 bits by its BCD value. Four-bit patterns were not desirable because using a leading 1 (BCD digits 8 and 9) wastes six patterns (10 through 15) as each pattern must be represented by a unique single digit. Because the BCD coding for 0 through 7 only uses 3 bits, has eight unique patterns, and is based on the number 8, it is called *octal* (see Figure 8-4).

1	3	0	2	Decimal
001	011	000	010	OCTAL

Figure 8-4. Octal coding.

Conversion from binary is performed by separating the binary number into groups of three, starting at the right. Assign the octal value for the 3-bit group, and you have performed the conversion.

Example: Convert from binary to octal: 111010100010.

Part A:

Separate the binary pattern *starting from the right digit* (the least significant bit—LSB) next to the octal point, into 3-bit groups. Assign the octal representation to each group

Break into groups of three	111	010	100	001
Assign BCD value	7	2	4	1

Take the octal value and, starting with the LSB, assign the binary representation in groups of three. Then combine them into a single binary number.

Part B:

Convert from octal to binary: 5,731.

Assign the binary value: 101 111 011 001.

Combine the digits: 101111011001.

The Hexadecimal System

The hexadecimal system is based on the number 16, with numbering from 0 to F (see Figure 8-5). Each hexadecimal number is 4 bits. As communications were 8 bits, this made representing the binary values simpler.

Binary	Decimal	Hexadecimal
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	8
1001	9	9
1010		A
1011		B
1100		C
1101		D
1110		E
1111		F

Figure 8-5. Decimal and hexadecimal.

Note that this is the same arrangement used to illustrate BCD, except that patterns that were illegal in BCD (10 through 15) are assigned unique single character representation for hexadecimal. Therefore, the six patterns that were wasted can now be used. This allows us to represent 16 unique 4-bit binary patterns. Modern computers perform all operations on 4-bit or some multiple of 4-bit patterns; therefore, hexadecimal representation is most often used.

Example: Convert binary to hex: 1101001110100001.

Separate the binary pattern into 4-bit groups, *starting from the least significant bit*. (Hexadecimal numbers are generally written as 0hexnumberH, leading 0, following H.)

Part A:

Break the number into 4-bit patterns: 1101 0011 1010 0001.

Assign the hex value: D 3 A 1.

Part B:

Convert hex to binary: 0EF87H.

Assign 4-bit

values: 1110 1111 1000 0111.

Combine the digits: 1110111110000111.

Decimal-to-Hexadecimal Conversion

Converting decimal numbers is a two-step process: (1) Convert the decimal number to binary, and (2) convert the binary number to hexadecimal. Octal is not included as it is usually not used in contemporary digital machines and only a knowledge that it exists is necessary at this point.

To accomplish decimal-to-hex conversions, some patterns should be memorized, both decimal and hex, because they are among the most common patterns encountered. These patterns are 0 through 15 (0 through F in hex) listed in Figure 8-6.

Binary Pattern	Decimal	Hex
1 0000	16	10
10 0000	32	20
100 0000	64	40
1000 0000	128	80
1111 1111	255	FF
1 0000 0000	256	100
10 0000 0000	512	200
100 0000 0000	1024	400
1000 0000 0000	2048	800
1 0000 0000 0000	4096	1000
10 0000 0000 0000	8192	2000
100 0000 0000 0000	16384	4000
1000 0000 0000 0000	32768	8000
1111 1111 1111 1111	65535	FFFF

Figure 8-6. Popular conversion numbers.

To convert a binary number to decimal (and then to hex), you would use the powers chart in Figure 8-7. In this example, we will convert the binary number 10101010010.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Power of 2
32768	16384	8192	4096	2048	1024	512	256	128	64	32	16	8	4	2	1	Decimal Value
0	0	0	0	0	1	0	1	0	1	0	1	0	0	1	0	Sample Number

Figure 8-7. Binary/decimal conversions.

Simply add up the columns that contain a 1:

1024 + 256 + 64 + 16 = 1362 The decimal equivalent of 10101010010

To convert a decimal number to binary, you perform a procedure much like long division. In this example, we will convert 953 to binary

1. Using the powers of two chart, locate the largest power of two that will go into 9 answer is 512, place a 1 in the 512 column; using a 12-bit binary number mea digits for the bits above 512 will be 0s.

11	10	9	8	7	6	5	4	3	2	1	0	Power of 2
2048	1024	512	256	128	64	32	16	8	4	2	1	Decimal Value
0	0	1										Binary Value

2. Determine the remaining digits.

11	10	9	8	7	6	5	4	3	2	1	0	Power of 2
2048	1024	512	256	128	64	32	16	8	4	2	1	Decimal Value
0	0	1	1	1	0	1	1	1	0	0	1	Binary Value

a. Subtract decimal value 512 from 953. Find the next lowest decimal value that exceed the result. In this case, 953 – 512 = 441 which is greater than 256; there include that decimal value by putting a 1 in the 256 column.
b. Subtract decimal value 256 from 441. The result is 185 which is greater than 1 include decimal value 128 by putting a 1 in that column.
c. Subtract decimal value 128 from 185. The result is 57, which is less than 64 decimal value), but greater than 32 (the value below 64). Therefore, we enter the 64 column and a 1 in the 32 column.
d. Subtract decimal value 32 from 57. The result is 25 which is more than 16; so, w that decimal value by putting a 1 in the 16 column.
e. Subtract decimal value 16 from 25. The result is 9, which is greater than 8, so w that decimal value by putting a 1 in the 8 column.
f. Subtract decimal value 8 from 9. The result is 1, which is less than 4 and less t equal to 1. Therefore, we enter zeros in the columns for 4 and 2 and place a 1 column.

g. 512 + 256 + 128 + 64 + 2 + 1 = 953.

The resulting binary pattern is 0011 1011 1001.

In hex form it is: 3B3.

You should rarely have to perform these procedures, but if you do, an inexpensive calculator will be of great assistance as most can perform these conversions. However, understanding how to do the conversion helps when attempting to understand A/D conversions, using diagnostics, and performing software programming. This skill also comes in handy when deciphering network addresses.

Converting between hex and binary requires knowledge (or memorization) of 16 patterns, two of which are the same (0 and 1).

Module 8A: Summary

Although this section does not present an extensive review of number systems; it should provide a sufficient base from which to manipulate the most commonly used number systems and aid in understanding of analog/digital conversions.

- BCD (binary coded decimal)
- Binary (base 2)
- Octal (base 8)
- Decimal (base 10)
- Hexadecimal (base 16)

Module 8B: A/D Codes

We previously discussed the binary number system, along with binary, BCD, octal, and hex representations. A/D conversions involve coding. Different converters output (A/D) and input (D/A) different codes. To properly understand A/D conversions, one must understand the coding.

The binary number system can be used in its natural format. If the binary number system uses binary 0 to represent the least positive voltage and binary 1 to represent the most positive voltage, then the coding system is called *natural binary*.

Natural Binary

Natural binary is also called *unipolar* because it is used to represent voltages (currents, etc.) of only one polarity (e.g., 0 to +5 V). The binary number system previously discussed (values 0 through 15 represented by 0 through F hex) would be natural binary if they were used to represent 0 to some positive value. Binary numbers are used in their fractional form in many industrial settings. Table 8-1 illustrates a 4-bit fractional code.

Table 8-1. Fractional values.

MSB (most significant bit)	B2B3	LSB (least significant bit)	Decimal
1	1 1	1	0.9375 15/16
1	1 1	0	0.8750 14/16 (7/8)
1	1 0	1	0.8125 13/16
1	1 0	0	0.7500 12/16 (3/4)
1	0 1	1	0.6875 11/16
1	0 1	0	0.6250 10/16 (5/8)
1	0 0	1	0.5625 9/16
1	0 0	0	0.5000 8/16 (1/2)
0	1 1	1	0.4375 7/16
0	1 1	0	0.3750 6/16 (3/8)
0	1 0	1	0.3125 5/16
0	1 0	0	0.2500 4/16 (1/4)
0	0 1	1	0.1875 3/16
0	0 1	0	0.1250 2/16 (1/8)
0	0 0	1	0.0625 1/16
0	0 0	0	0.0000 0/16 (0/4)

Note that if a 4-bit number is used to represent 0 to 1 V, or 0% to 100% of full scale, there is an *error inherent* in the representation. This is 1/16 or 0.0625. There is always one least significant bit (LSB) error in the binary representation of a range if 0 is chosen to be the binary zero value and the scale corresponds to the binary fractions. At any part of the input range of the A/D conversion process, there is a constant value between digital codes (in this case, ±0.0625 V). This is the least amount of error (with the number of bits used) for the system. In real systems, this error can be determined as:

$$Q = \frac{\text{full scale}}{\text{number of bits}}$$

where Q = quantization error or quantization noise, which is the uncertainty of the measurement due to the conversion process. The only way to reduce this error is by increasing the number of bits used. The typical bit counts used in industrial control systems are in Table 8-2.

Table 8-2. Common conversion word sizes.

Bits in Conversion Word	± (Error)
8	0.00391
10	0.00097
12	0.00024
14	0.00006
16	0.000015

Generally, full scale is standardized at either 0 to +5 V or 0 to +10 V for unipolar converters.

Bipolar Codes

To represent ± values, bipolar coding is used. The standard bipolar values are ±2.5, ±5.0, and ±10.0 V. To represent these values, straight or natural binary can be used by having the "all zeros" state represent the most negative value and the "all ones" state to represent the most positive value. Table 8-3 illustrates a 4-bit natural binary bipolar coding.

Table 8-3. Bipolar coding using natural binary.

Natural Binary	Decimal
1111	+7/8
1110	+6/8
1101	+5/8
1100	+4/8
1011	+3/8
1010	+2/8
1001	+1/8
1000	+0/8
0111	−1/8
0110	−2/8
0101	−3/8
0100	−4/8
0011	−5/8
0010	−6/8
0001	−7/8
0000	−8/8

When natural binary is used to represent bipolar values, the halfway value, 1000, is used to represent the value 0. So, 1000 (binary) is the "offset" from binary 0000. This is why natural binary is called *offset binary* when it is used to represent bipolar values.

Although there are many other codes to represent bipolar values, the two's complement is the most common in computer-driven systems. Two's complement coding is illustrated in Table 8-4.

Table 8-4. Two's complement.

Natural Binary	Two's Binary	Decimal
1111	0111	+7/8
1110	0110	+6/8
1101	0101	+5/8
1100	0100	+4/8
1011	0011	+3/8
1010	0010	+2/8
1001	0001	+1/8
1000	0000	0/8
0111	1111	–1/8
0110	1110	–2/8

0101	1101	–3/8
0100	1100	–4/8
0011	1011	–5/8
0010	1010	–6/8
0001	1001	–7/8
0000	1000	–8/8

Several items concerning two's complements coding should be noted. Zero value is represented by 0 binary. If you add a positive number and the same negative number (e.g., +2/8 added to –2/8), the result is 0 with a carry. Two's complement is the offset (natural) binary system with the most significant bit inverted (complemented). Most binary computers perform arithmetic operations using two's complement, so its use in these systems is understandable. Throughout this module, natural binary representing 0 to 10 V will be used to explain conversion operations.

Module 8B: Summary

- Natural binary proceeds from all zeros to the highest number value and is gen used with unipolar values (i.e., only positive numbers).

- Offset binary is natural binary with the center (1 00…) representing the zero between a negative and a positive endpoint. It is generally used with bipolar v (i.e., positive and negative. For example, –10 to +10). For example, with a 3-bit nu the most significant bit (MSB) is used to determine the polarity so only the firs digits are the number. In this case, our values are:

111 = 3

110 = 2

101 = 1

100 = 0

011 = -1

010 = -2

001 = -3

000 = -4.

- By inverting the offset binary MSB, you obtain two's complement values where value is 0 and the binary numbers proceed from negative to positive with incre values. If the MSB is a 0, it is a positive number. If the MSB is a 1, it is a ne number in two's complement representation (i.e., positive and negative; for exam 10 to +10). For example, with a 3-bit number, the MSB is used to determine the po so only the first two digits are the number. In this case, our values are:

011 = 3

010 = 2

001 = 1

000 = 0

111 = -1

110 = -2

101 = -3

100 = -4.

Module 8C: D/A Conversion

D/A conversions are discussed first for several reasons, the primary one being that most successive approximation A/D converters use a D/A converter (either internally or externally) as a reference.

Many different techniques are used to convert digital values to either voltage or current values. Almost all contemporary converters are of the parallel (originally called *flash*) type, meaning that they convert the entire number of bits simultaneously to the voltage or current value.

Weighted Resistor Networks

One of the more popular methods used by discrete circuitry or hybrid integrated circuit converters is the weighted resistor network. This is illustrated in Figure 8-8.

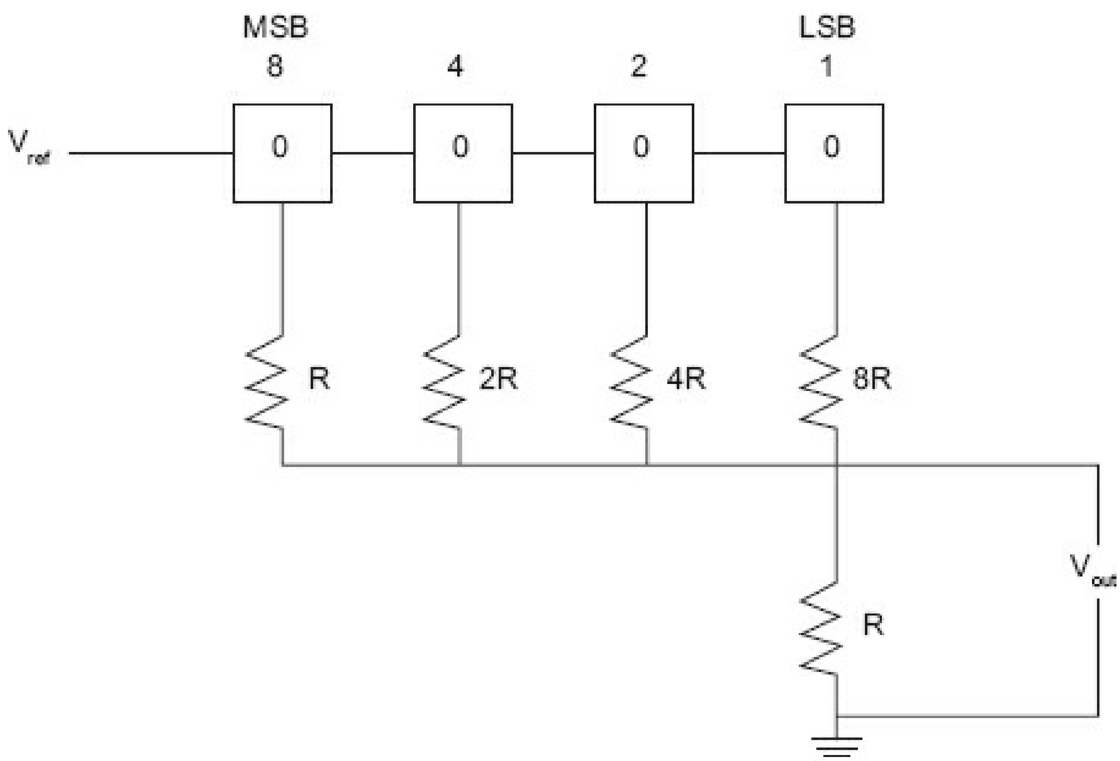


Figure 8-8. Weighted resistor network.

In the figure, the boxes represent switches that are either on or off, and the current-limiting resistors have a binary weight. Note that this is a simplified diagram. R is set at 50 Ω. The switches are put in the on state by a positive voltage (representing the 1 state), and in the off state by 0 V (representing the 0 state). If the binary number 1000 with 1 as the MSB is applied to this circuit, the switch with R will be on; the others are off. The output voltage will be V_{ref} / 2 because R is equal to R. This means that the voltage at the output will be what you would expect with a 4-bit system using natural binary coding as binary "1000" equals half of full scale.

Note that each bit has a resistor that is twice the value of the preceding resistor. If the output voltage with the current through R is 5.0 V, then half of that current (which is the current value if 2R is on only) will give an output of 2.5 V. If 4R is on only, the output will be 1.25 V; if 8R is on only, the output will be 0.625 V. Because the currents are summed, if more than one resistor is on, one has only to add the current values to obtain the output. *Note:* this is a simplified diagram assuming that half of the current will go through 2R, one-fourth of the current through 4R, and one-eighth of the current through 8R.

If R had a realistic value, it would be closer to 10,000 Ω. This means that 8R would be 80,000 Ω. While these values are not unreasonable, the requirements of an 8-bit D/A converter, 128R would be 1.28 MΩ. This large range of resistance values required is generally not feasible on integrated circuits.

R-2R Networks

One of the more common methods of D/A conversion uses a resistive network composed of only two values. It is called the *R-2R ladder method*. It is used primarily with the successive approximation type of A/D converters and is quite suitable for integrated circuit construction because only two resistance values are required.

Figure 8-9a illustrates an R-2R ladder (only a 3-bit ladder is shown to ease explanation of its operation). If we assume the binary value for half of the full-scale range (100), the equivalent circuit is developed through a series of steps illustrated in Figure 8-9a, b, c, d, e, and f. The development of other combinations is left to the reader. This is an exercise in Ohm's law. Previously, you learned that if two resistors of the same value are in parallel, the equivalent resistance is half the value. In this case, if you have 2R and 2R in parallel then the equivalent is R.

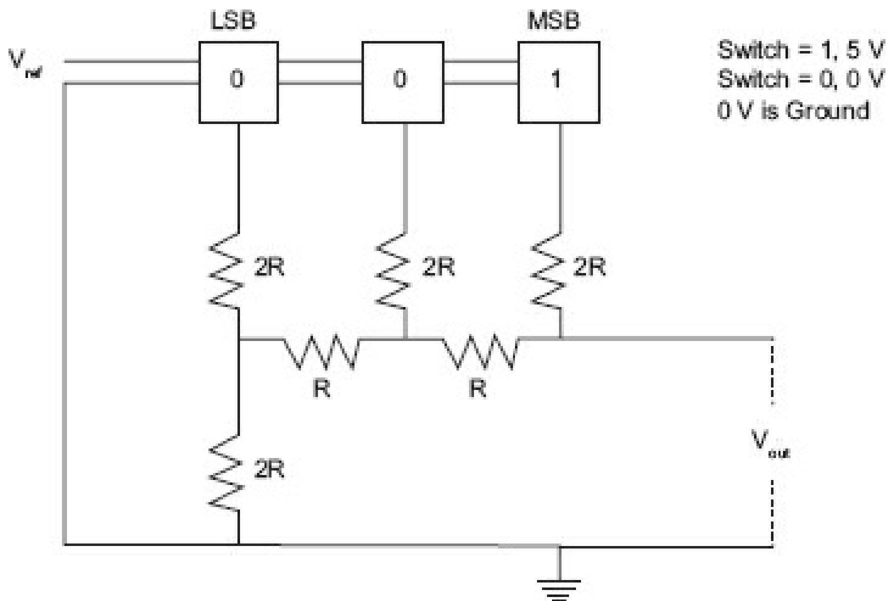


Figure 8-9a. R-2R ladder circuit with switch in position 100.

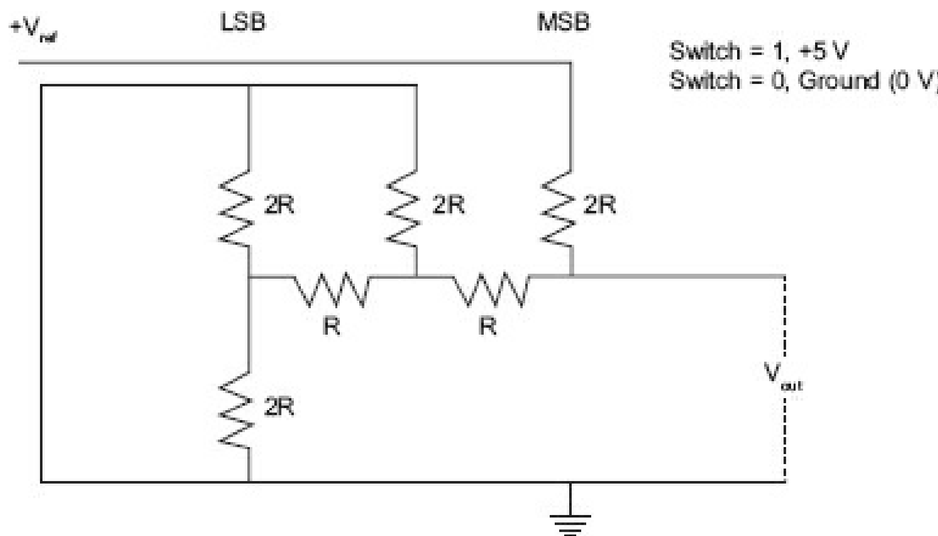


Figure 8-9b. Circuit representation of switch position 100.

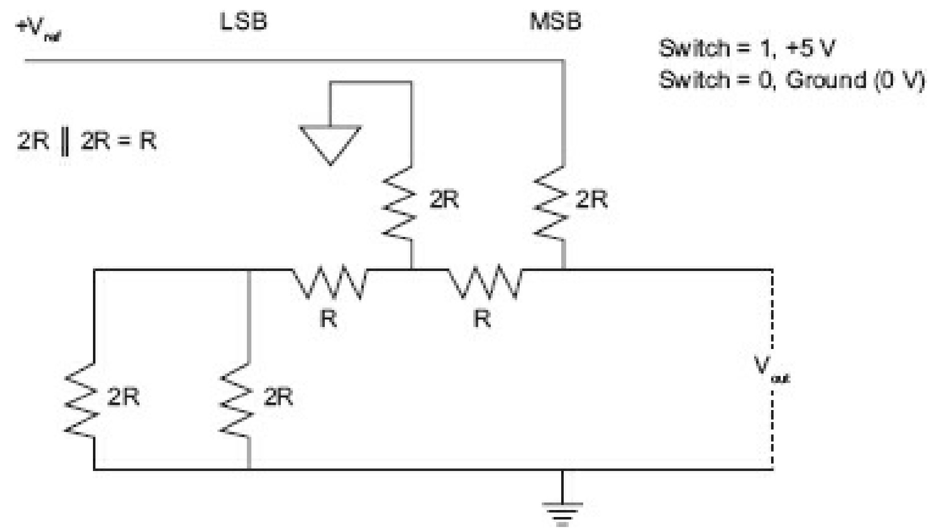


Figure 8-9c. Configuring the circuit to illustrate the principle more clearly.

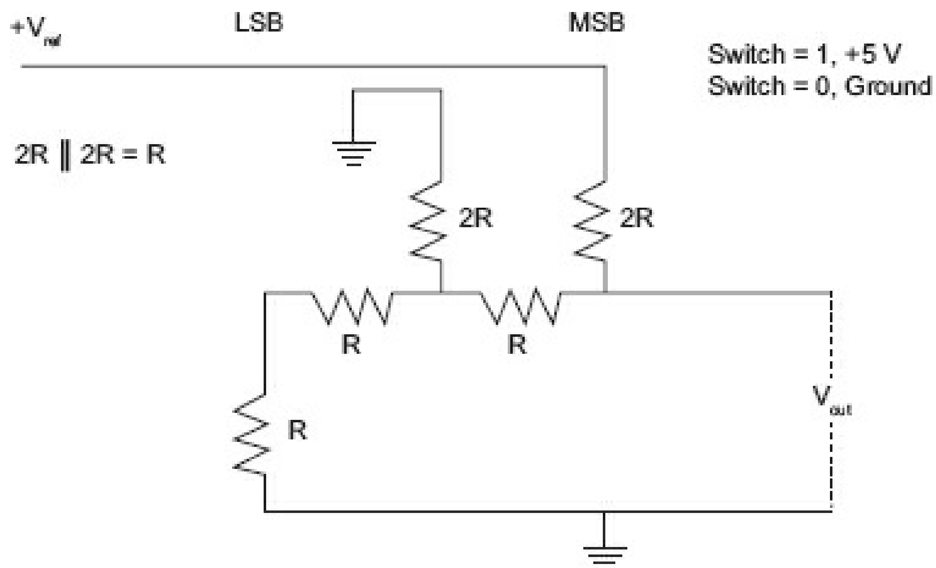


Figure 8-9d. Combining the values of 2R in parallel with 2R.

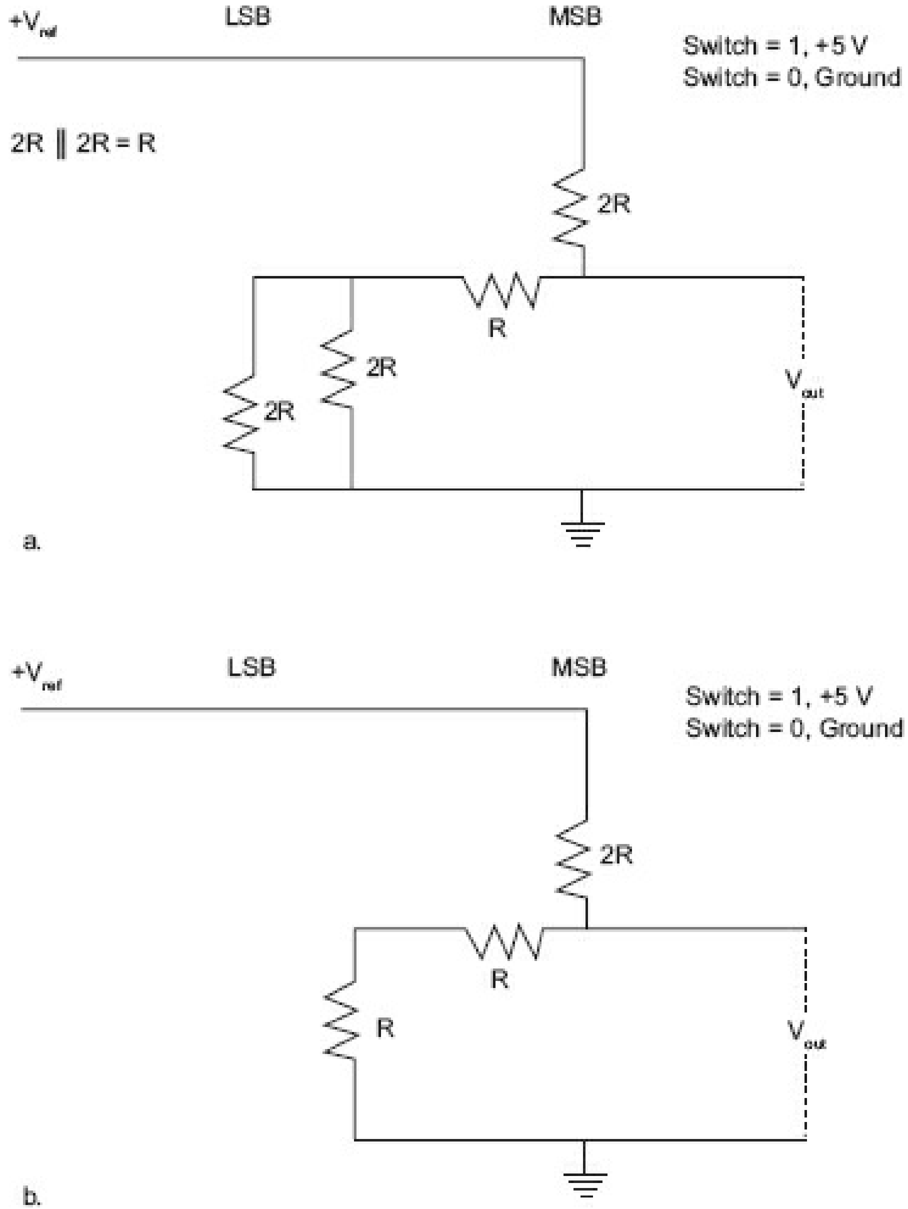


Figure 8-9e. Combining the two series resistors (R and R) to get 2R again.

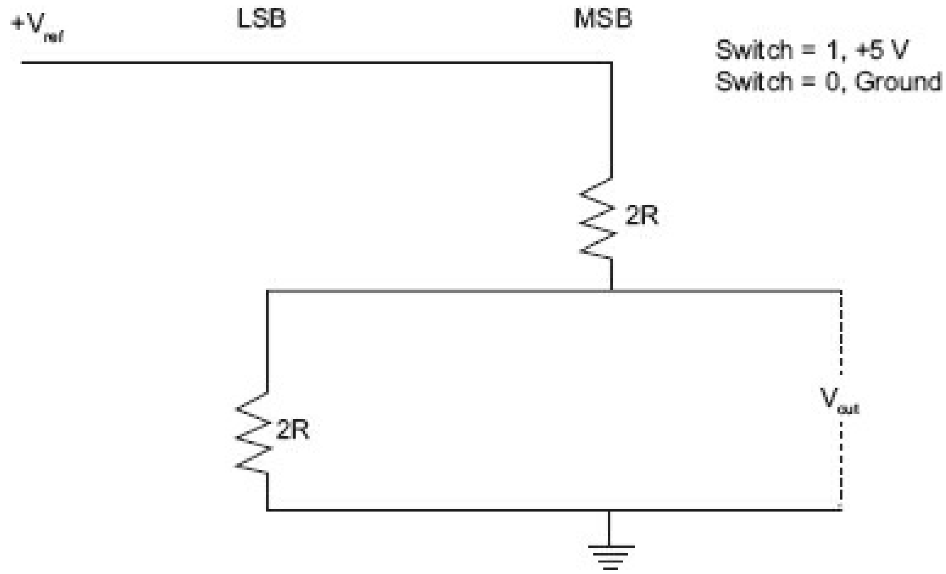


Figure 8-9f. Repeating steps above, we again end up with 2R.

Other Considerations

Regardless of which method is used, the output will not be continuous but rather a series of levels, switching each time a new binary value is placed into the D/A unit. A typical waveshape is illustrated in Figure 8-10. To smooth out the switching transients, the output signal is averaged over time (integrated). This may be accomplished by using a low-pass filter or an integrating device. While the integrated output is an approximation of the output, the more bits used, the closer the approximation to the binary representation. The lower the rate of change from one level to another, in other words, the lower the frequency of the signal, the more accurately the output represents the binary value.

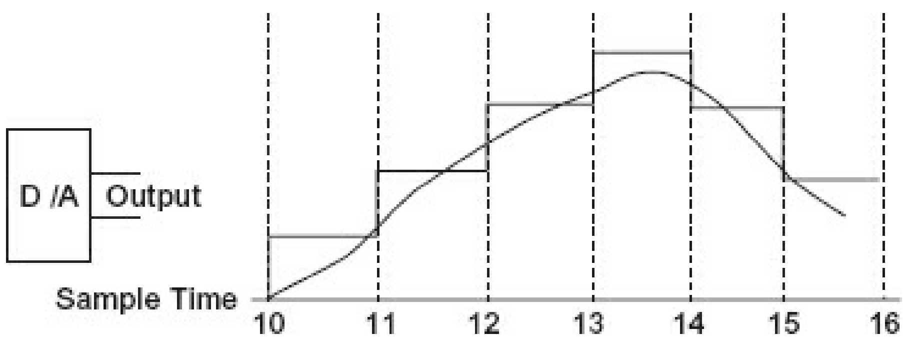


Figure 8-10. D/A output waveshape.

Module 8C: Summary

- Weighted resistors were originally used with discrete components; however, a number of bits increased, the value of the resistors required became too hi reproduce in integrated form.
- The R-2R method is a resistive network of just two values and can be extended fo number of bits required.

Module 8D: A/D Conversion

The three types of conversions discussed in this section are: (1) integrating, (2) successive approximation, and (3) flash (parallel).

Integrating

One common method for converting low-frequency signals (including most industrial process variables) is the integrating type. Currently, two techniques are used:

1. Dual slope

2. Voltage-to-frequency

Dual Slope

Figure 8-11 is a simplified block diagram of a dual-slope A/D converter. The operation has two distinct phases. The capacitor (C) is connected to the unknown input voltage for a fixed time (or number of counts). The capacitor and the resistor (R) form a time constant. The capacitor will charge through the resistor to an amount that is proportional to the input voltage.

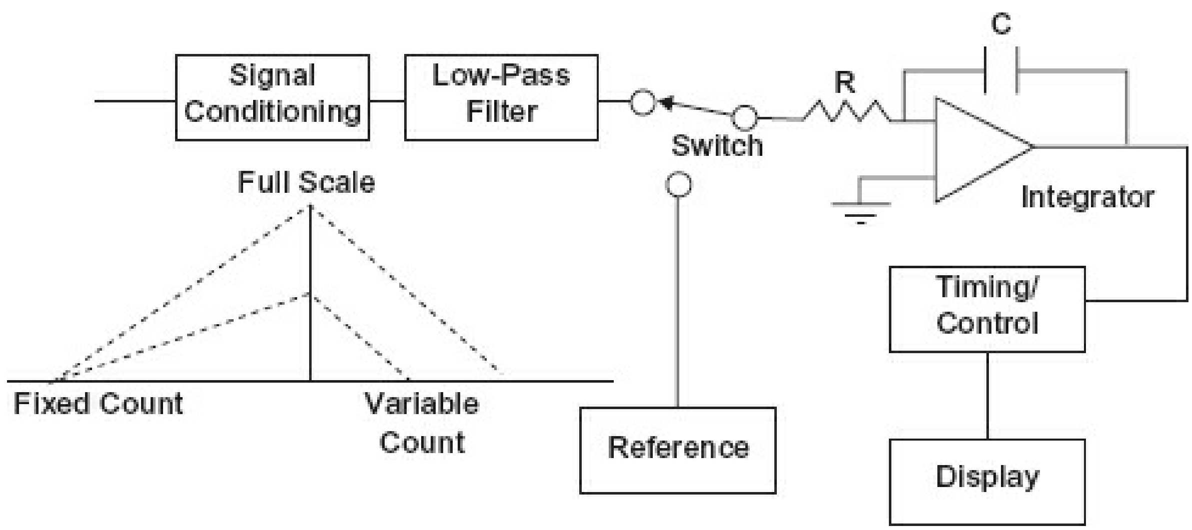


Figure 8-11. Dual-slope operation.

That charge is an integral of the input voltage because it is done over a fixed period of time. When the count is finished, the capacitor is connected through the switch to the reference voltage, which is the opposite polarity of the input voltage. The counter starts again and counts until the voltage across the capacitor is zero. This count is then displayed as the voltage.

Although it would seem easier to just count the time to charge, this would make the conversion accuracy depend on the time constant values (C and R) and the frequency of the clock. This method uses the same time constant to charge the capacitor and to discharge the capacitor. It uses the same clock frequency to count the charge period as it does to count the discharge period. Therefore, the only limitation on accuracy (theoretically) is the reference voltage. Figure 8-11 illustrates the integrator output versus the charge/discharge times. Note that the charge time is a fixed number of counts, and at the end of the fixed period, the integrator output value depends on the input voltage.

The time to discharge then depends on the integrator output (which depends on the input voltage). For a small voltage input, the time to discharge is short, and for a full-scale input voltage, the time to discharge is proportionately longer.

Because this is an integrating circuit, noise with a time constant less than the fixed count (higher frequencies) will be integrated, or averaged out. This type of converter is relatively inexpensive, will not miss any code combinations, and offers excellent linearity. The features that are advantages also cause the converter's primary disadvantage, conversion speed. It is slow. Because of this limitation, this type of converter is used mostly for digital voltmeters and panel meters.

Voltage-to-Frequency

This method is currently used in many industrial process controllers as well as many A/D conversion modules for use with personal computers. Figure 8-12 illustrates a simplified block diagram of a charge-balancing converter (voltage-to-frequency).

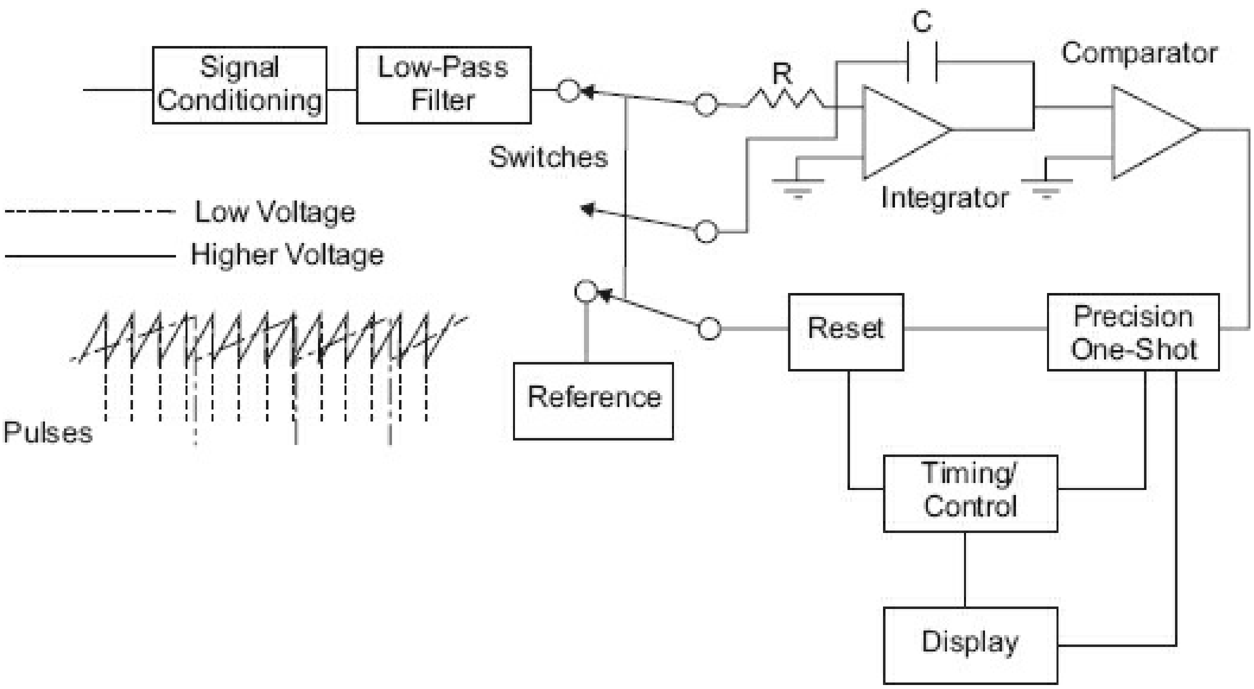


Figure 8-12. Voltage-to-frequency conversion.

These converters generate a pulse train (a series of pulses) with a frequency that is proportional to the input voltage, and then counts the pulses over some period of time. Assume a positive input at the integrator input. This will drive the integrator output in the opposite direction. When the integrator output crosses zero, the output of the comparator will change. This will trigger a precision one-shot (flip-flop), whose output is a pulse of precise width. This causes the electronic switch to connect C to the reference. As a result, the output of the integrator changes rather quickly, the comparator changes, and the switch goes back to normal. Note, however, that a pulse was generated each time the integrator output reached a certain value. Each time the comparator changes, a pulse is generated (which operates the switch, which discharges the integrator capacitor); therefore, the number of pulses generated depends on the magnitude of the input voltage. The larger the voltage, the greater the number of pulses produced, because the integrator must ramp up and down faster. The timer circuit will have a fixed period (usually 1 s) that gives a direct correlation to the input voltage and the number of pulses counted.

Application

When used in an industrial single-loop process controller, the voltage-to-frequency converter is set to give 10,000 Hz per volt over the 1 to 5 V range. The output, therefore, will be in the area of 10,000 to 50,000 Hz. The output of such a converter has a resolution on the order of 12 to 14 bits: 12 bits provide a resolution of 1 in 4096, 13 bits provide a resolution of 1 in 8192, and 14 bits provide a resolution of 1 in 16,384.

Although the conversion speeds are slow, these converters offer excellent linearity; it is inherent in their design. Most do not sample more than 3 to 10 readings per second, so the voltage-to-frequency converter was used in many A/D converters destined for industrial process control. Other technologies have replaced this method in recent times.

Successive Approximation A/D Conversion

At one time, successive approximation was one of the most widely used techniques for A/D conversion. Compared to the integrating methods, it is quite complex and has the disadvantage of losing some code combinations if the design is not carefully considered. But it is quite fast. Modern integrated circuit designs can approach 500,000 conversions per second in a relatively inexpensive package. The basic block diagram is illustrated in Figure 8-13. Note that there is a D/A that is used as a reference. The successive approximation converter uses the principle of binary division to make the least number of decisions necessary to locate a random number in its range.

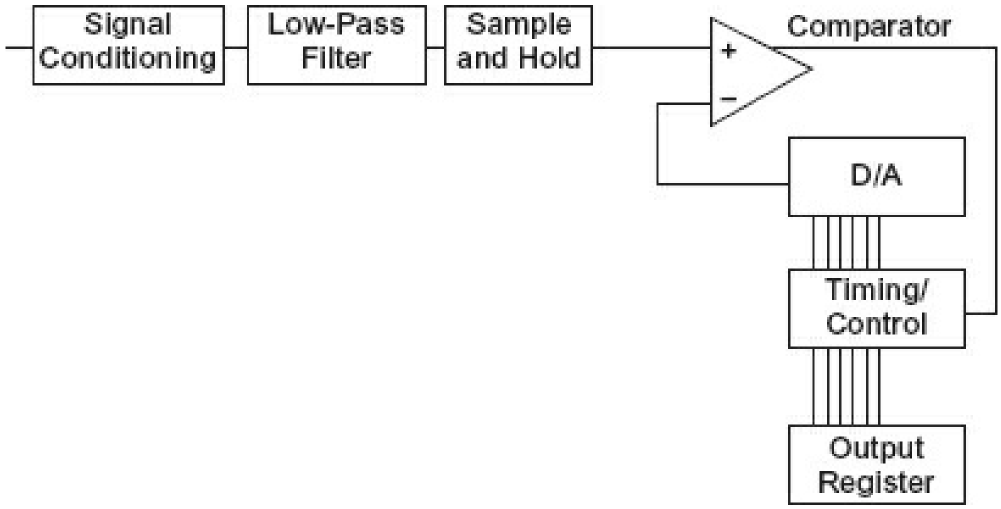


Figure 8-13. Successive approximation block diagram.

The operation is as follows:

1. The signal is input through conditioning circuits, some form of attenuator, a amplitude limiter. There is also a low-pass filter that limits the upper frequency input signal. This is crucial to the proper operation of the converter.

2. The signal is then gated through to one leg of a comparator; the other leg comparator is connected to the D/A.

3. At the start of the conversion, the D/A is fed by a timing and control register w binary (half of full scale; 100 000 binary for 6 conversion bits) placed in it by the circuit. Therefore, if the input voltage is above the reference voltage (above half scale), the comparator output will be a 1 state. If the input voltage is belo reference, the output of the comparator will be a 0 state. If the output is a 1, then t the control register will remain there. If the output is a 0, then the control regis will be set to a 0.

4. In either event, the next bit will be set to a 1 (in the case the previous decision wa 1, the D/A register would now contain 110 000).

5. The input signal is tested again against this new value, with the same operatio control bit remains a 1 if the comparator output is a 1 and is set to a 0 if the comp output is a 0.

6. Each succeeding bit is treated the same way.

Note the logic involved. It is first determined which half (upper or lower) the input voltage is closest to, then the remaining half is divided into two, and it is determined which quarter the input signal is closest to. The quarter is divided in half (one-eighth), the half closest to the input voltage is chosen, and so on for the number of bits used. This way, successive tests approximate the input signal level closer and closer to its true value.

The input signal must remain unchanging while the conversion process is underway. For this reason, a sample-and-hold circuit is used to hold the input at one value while the binary signal is developed. A sample-and-hold circuit generally contains a field-effect transistor (FET) switch and a high-quality capacitor, among other components. When the FET switch is closed (sample time), the capacitor is charged to the input voltage. The length of time the switch is closed is the *acquisition time*. The switch is then opened and the conversion begins. The capacitor must retain the input voltage during this conversion time. The sample-and-hold circuit helps avoid jitter (jumping back and forth of the least significant bit[s]).

The sample clock (the frequency at which the sample-and-hold circuit is switched) must be at least twice the highest frequency expected. It could be many times more, but it must be twice at the very least. This is to ensure at least two samples per waveform. If the sample clock is 8000 samples per second, the sample period is 125 µs (microseconds, 1/8000). During this period, a number of bit decisions must be made. For a 3-bit converter, that means each bit must be no more than 41.667 µs or one-third of 1/8000 of a second (125 µs/3), so the bit clock must run at approximately 24 Kbps (kilobits per second). You may correctly conclude from this example that the bit rate is the number of bits times the sample rate.

If a 12-bit converter (typical of industrial instrumentation) is used, then for our 8000 sample rate, the bit rate must be 96 Kbps. This requires an excellent A/D converter. Most signals used in the process and manufacturing industry seldom have more than a 100 Hz change rate, so the sample rate can be relatively slow (300 to 600 samples per second) per channel. In this case, several channels can be multiplexed (more than one signal placed on the same wire or channel) and one high-speed A/D unit can convert each, one at a time. Figure 8-14 illustrates the simplified block diagram of an analog multiplex system. It is an analog system because each of the channels is analog through the multiplex and then a single A/D unit converts the signals in turn to a digital format. At the receive end, a computer de-multiplexes the signal, using the digital representations for further processing.

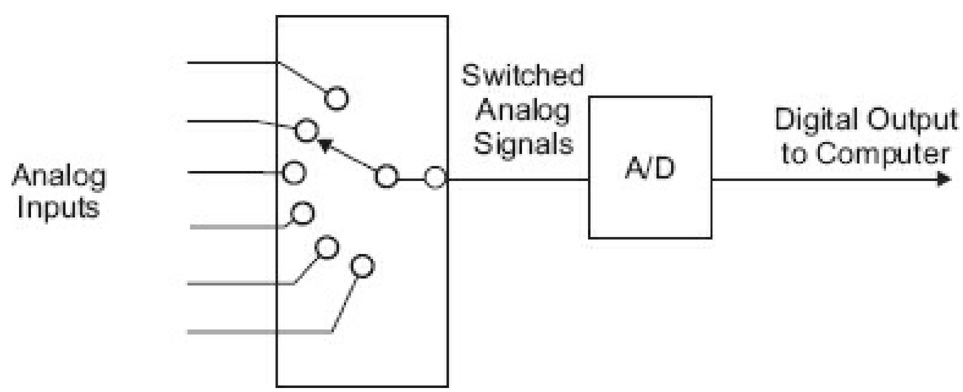


Figure 8-14. Analog multiplexing.

Since the advent of inexpensive A/D chips, a form of digital multiplexing can be used; a block diagram is shown in Figure 8-15. In this case, each of the signals is converted first to a digital signal and then each digital output is multiplexed into a digital stream. The receiving end will see the same signal as in the analog multiplex method.

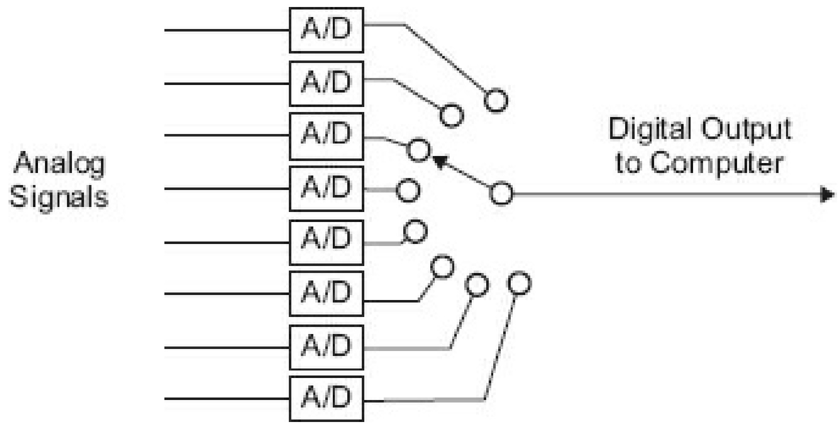


Figure 8-15. Digital multiplexing.

Flash (Parallel) Conversion

Figure 8-16 illustrates parallel conversion, also known as *flash conversion*. This is the fastest method of A/D conversion. The speed is limited only by the settling time of the comparators and the gate propagation time of the decoder logic. A precision reference is divided between each of the comparators. The number of comparators required is the power of 2 for the number of bits, less 1. That is, a bit flash converter will require 255 comparators. Because this is a large number of comparators, methods of combining two 4-bit converters (each requiring 15 comparators) are used at the penalty of slightly slower operation. Technology has reduced the price of flash converters; they are now priced competitively against successive approximation types, and they still have the high speed of conversion necessary for applications, such as video and television.

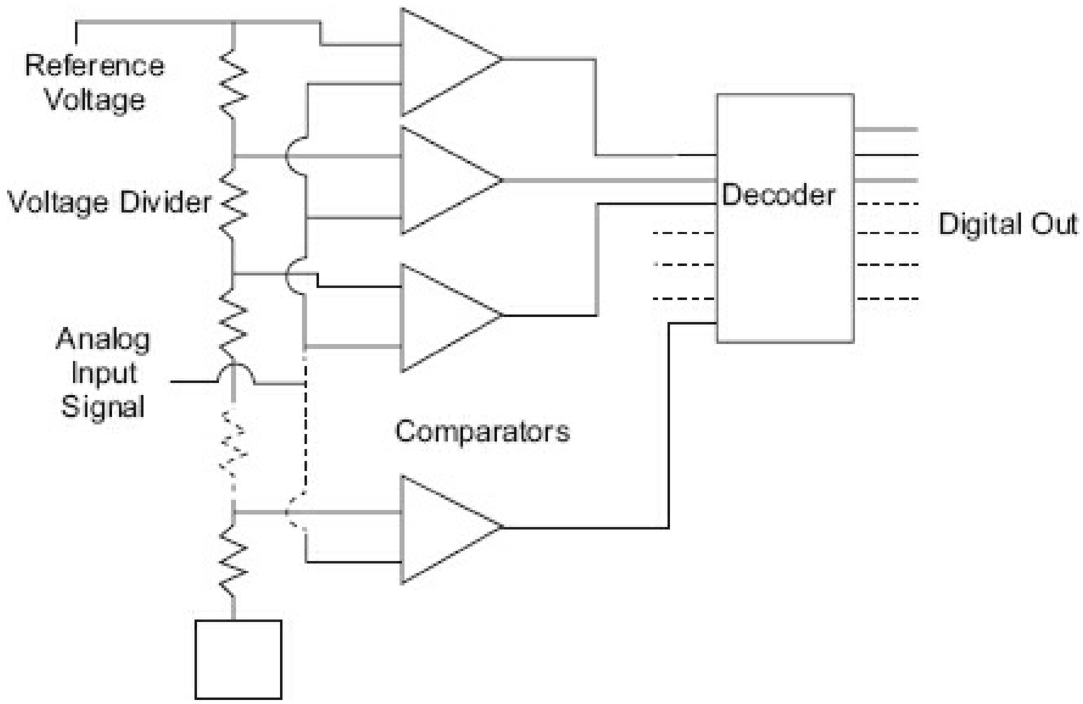


Figure 8-16. Flash A/D conversion.

Module 8D: Summary

Table 8-5 lists the different types of converters and their characteristics for easy comparison.

Table 8-5. Comparison of A/D methods.

Type	Relative Speed	Applications
Dual-slope	Slow, typically 3 to 6 conversions/second	Digital voltmeters, panel meters
Voltage-to-frequency	Slow, typically 3 to 6 conversions/second	Process instruments
Successive approximation	Medium to fast	General-purpose process devices
Flash (parallel)	Fast to really fast	Graphics, video, some instruments

Module 8: Overall Summary

Various A/D and D/A techniques have been discussed in this module. Although only a brief overview of the subject is provided, it is sufficient to understand the methods used by most data acquisition systems. The design considerations necessary for the correct selection of a converter for use in instrumentation are beyond the scope of this text. Numerous texts are available that supply the information and techniques necessary for that purpose. The majority of maintenance operations will be locating a malfunctioning unit. Most modern converters have few alignment requirements, other than an occasional zero and span when major maintenance has been performed. Linearity and other adjustments are no longer available in most cases.

Module 8: Review

See Appendix B for the answers.

1. Using a 12-bit successive approximation converter, if the input voltage range is 0 and 2.5 V is the input, what should the output be (in 1s and 0s)?

   A. Offset binary ________________________
   B. Two's complement ________________________

2. If the digital signal in question 1 is presented to an R-2R D/A (with a 10 V supply D/A), what will the output be? ________________________ V

3. If +0.0025 V is presented to a 12-bit A/D, the output code will be:

   A. In natural binary (0 to 10 V range) ________________________
   B. In offset binary (±5 V range) ________________________
   C. In two's complement (±5 V range) ________________________

Hint: 12 bits means 4096 divisions, so 10 V / 4096 = 0.00244 V for the LSB; 0.0025 V is greater than 1 LSB but less than 2 LSBs.

Conclusion

You have reached the end of Module 8. Please reread the module objectives (in the "Objectives" section). If you have met these objectives, continue to the next module. If you are having difficulty, please reread the text. If the difficulty persists, locate a peer, mentor, supervisor, or someone who has technical knowledge of analog and digital conversion and ask them to assist you.

Further Information

For additional information on the topics in this module, search for the following topics at your public or company library, or on the Internet.

- Analog-to-digital conversions
- Digital-to-analog conversions
- Weighted resistor D/A converters
- Successive approximation A/D converters
- Integrating A/D converters
- Flash A/D converters

9 Digital Logic

Digital logic is the building block of the digital revolution. From simple gates to highly complex, application-specific integrated circuits (ASICs), digital logic is found everywhere. While this chapter is not a comprehensive review of all current digital logic (that would take several volumes), it will introduce the reader to logic and various logic families and functions.

Module 9 Objectives

After successfully completing this module, you will be able to:

- Define the logic maps and the Boolean statements for the following gates:
  - AND
  - OR
  - XOR
  - NEGATE or NOT
  - NOR
  - NAND
- List the different methods and/or technologies for storing digital data.
- Determine the outcomes for various computational logic, such as:
  - ADD
  - SUBTRACT
  - MULTIPLY
  - DIVIDE

Module 9A: Functions

All digital circuitry consists of combinations of ANDs, ORs, NANDs, NORs, XORs, counters, registers, and memory. In the beginning, logics were manufactured of discrete components. This gave way to small-scale integration (SSI) and soon after to large-scale integration (LSI). Today, a central processing unit (CPU, microprocessor) is made up of millions of gates, registers, and counters.

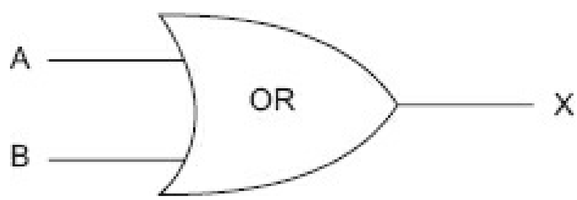
To understand digital logic, a good place to start is with gate circuits.

Gates

There are basic gate structures used in Boolean logic. Complex logic is built of various combinations of these gates. They are quite simple to understand. Although all the gates demonstrated have just two inputs, gates may have more than two inputs; the logic is the same.

OR Gate (+)

The rule for the OR gate is also shown in logic structure as +. A TRUE on any input will result in a TRUE on the output. Referring to a two-input OR gate, the rule is: A TRUE on input A OR a TRUE on input B will cause the output to be TRUE. A TRUE on both input A and input B will cause a TRUE output. Figure 9-1 illustrates the OR symbol, and Figure 9-2 illustrates a map of the logic.



A +	B =	X
0	0	0
0	1	1
1	0	1
1	1	1

Figure 9-1. An OR gate.

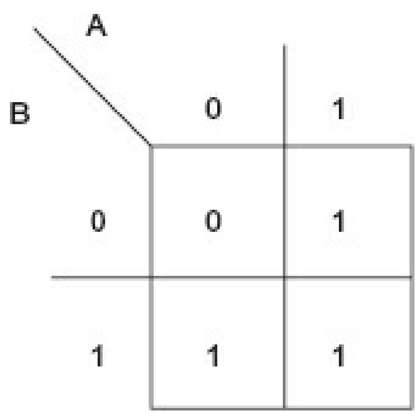
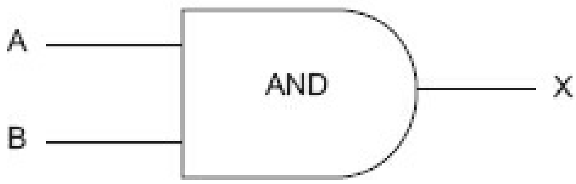


Figure 9-2. Logic map for an OR gate.

To read the logic map, the inputs are on the outside, for example, A = 1 and B = 0. If you start at the A = 1 row (top) and move down into the block 1 row, that is the B = 0 row. The value in that intersecting block is the output, in this case a 1. Note that if either A or B is a 1, the output is a 1.

AND Gate (•)

The AND gate rules are also simple. All inputs must be TRUE (have a 1) for the output to be a 1. For the two-input AND, the rule is this: It takes a 1 on input A AND a 1 on input B to have a 1 on the output. Figure 9-3 is the symbol for an AND gate, and Figure 9-4 is the logic map for an AND gate.



A	•	B	=	X
0		0		0
0		1		1
1		0		1
1		1		1

Figure 9-3. AND gate.

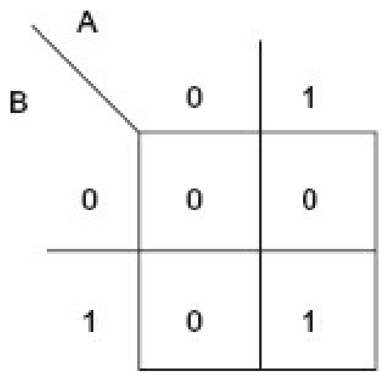
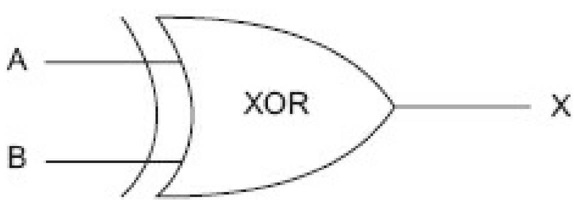


Figure 9-4. Logic map for an AND gate.

XOR Gate (⊕)

An exclusive OR (XOR) has a rather simple rule: If both inputs are at the same state, the output is a 0. If the inputs are at a different state, the output is a 1. Simply put, even inputs (both inputs are at the same state: either a 1 and a 1, or a 0 and a 0) result in a 0, and odd inputs result in a 1. Figure 9-5 is the figure for an XOR gate; Figure 9-6 is the logic map for an XOR gate.

The XOR circuit goes by many names. It is also known as a *binary half adder*; that is, it is a binary adder without a carry (the half part). Evens result in a 0 output and odds result in a 1 output.



A	⊕	B	=	X
0		0		0
0		1		1
1		0		1
1		1		0

Figure 9-5. XOR gate.

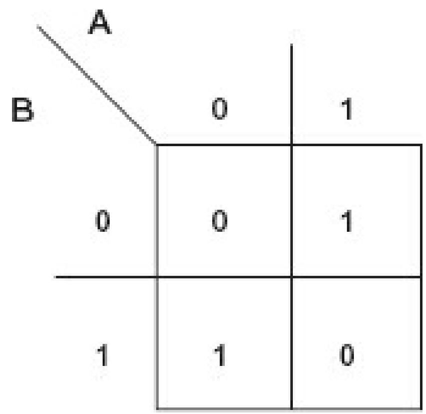


Figure 9-6. Logic map for an XOR gate.

NEGATE (Inverter) $\overline{A}$

The NEGATE function is not really a gate but an inverter. Its logic is quite simple: A 1 on the input results in a 0 output; a 0 on the input results in a 1 output. The NEGATE function is normally indicated by a small circle or bubble on the affected path, usually an output. Figure 9-7 illustrates a NEGATE circuit.

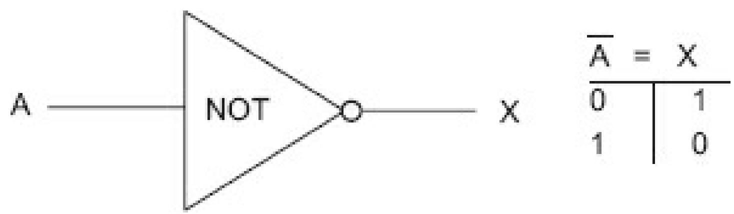


Figure 9-7. NEGATE or NOT gate circuit.

NOR Gate ($\overline{\text{A OR B}}$)

A NOR circuit is an OR circuit with an inverter on the output. Figure 9-8 illustrates a NOR gate and its logic map.

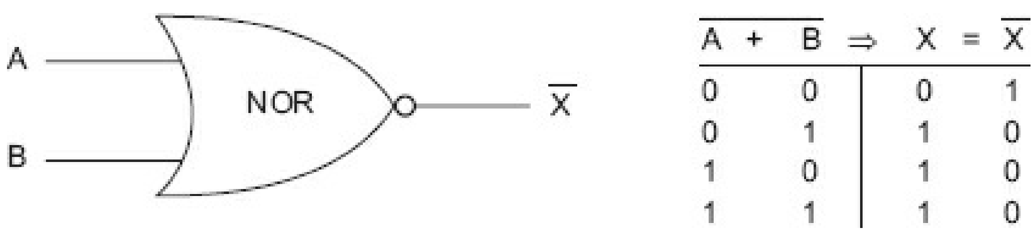


Figure 9-8. NOR gate and logic map.

NAND

A NAND gate is an AND gate with an inverter on the output. Figure 9-9 illustrates a NAND gate and its logic map.

$\overline{A \cdot B} \Rightarrow X = \overline{X}$

0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

Figure 9-9. NAND gate and logic map.

Combinational Logic

Figure 9-10 illustrates a common quandary. Which door do you go in?

It should be obvious that you go in the NOT OUT door and go out the NOT IN door. This is how you have to approach combinational logic. Although there is Boolean algebra to mathematically determine logic, most outcomes can be determined by a little thought.

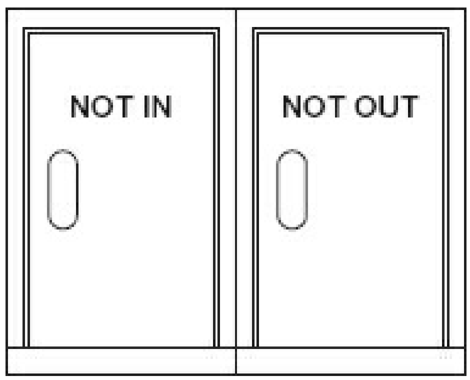


Figure 9-10. Door quandary.

With the inputs given in Figure 9-11, what is the output of this combinational circuit?

The easiest way to solve a complex logic problem, such as the one illustrated in Figure 9-11a, is to break it down in to small segments.

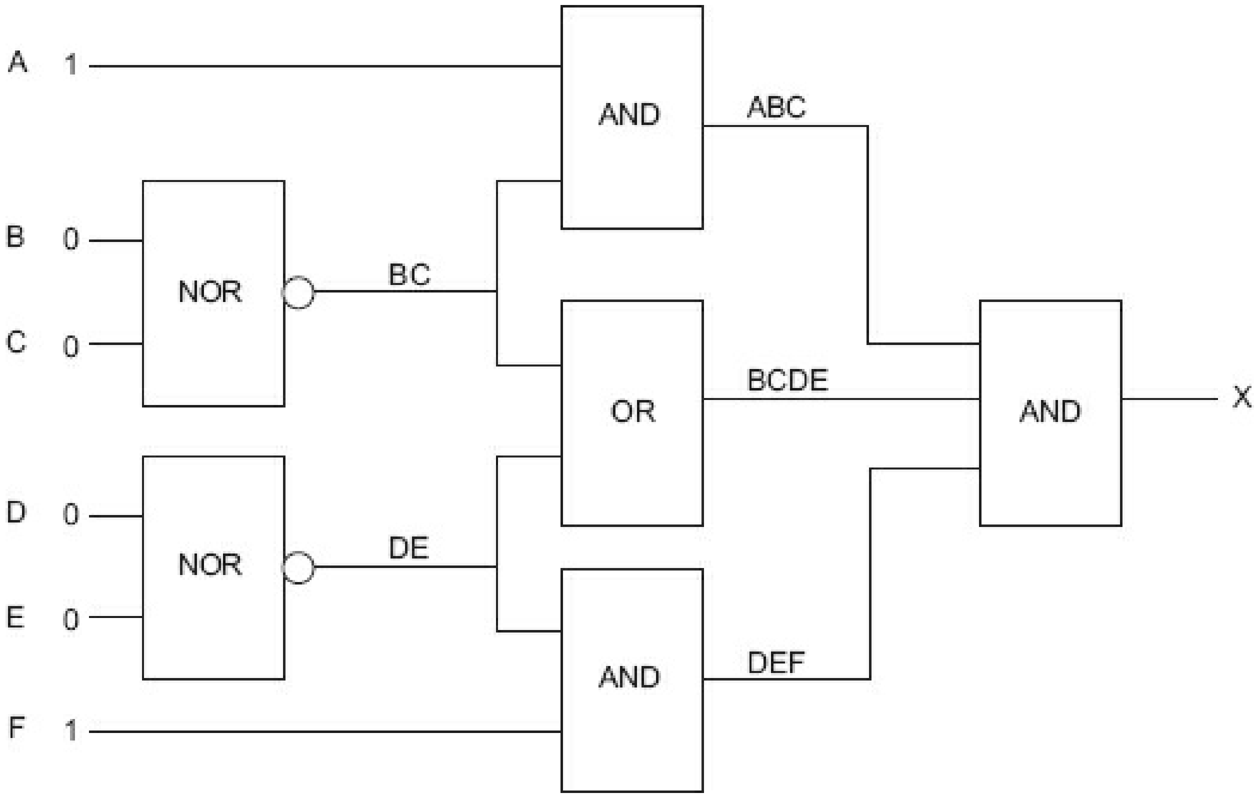


Figure 9-11a. Breaking a logic problem into segments.

First, let's assign a designator to each input and output that can be used to develop a series of equations. Beginning from the result (the right side of the diagram), we will work backward to get to the inputs.

$$ABC \bullet BCDE \bullet DEF = X$$

The next step is to start developing the equations for each variable as follows. We need to define X as an equation of the input values.

$$A \bullet BC = ABC$$

$$BC + DE = BCDE$$

$$DE \bullet F = DEF$$

Next, breaking down the next set of variables,

$$BC = (\overline{B + C})$$

$$DE = (\overline{D + E})$$

Then substitute these into the equation above gives us

$$ABC = A \bullet (\overline{B + C})$$

$$BCDE = (\overline{B + C) + (D + E})$$

$$DEF = (\overline{D + E}) \bullet F$$

Substitute these elements into the original equation for X and we are left with

$$[A \bullet (\overline{B + C})] \bullet [(\overline{B + C}) + (\overline{D + E})] \bullet [(\overline{D + E}) \bullet F] = X$$

With the final output X now in the form of an equation using the inputs (A, B, C, D, E, F), we can develop a truth table to solve the equation for all possibilities.

A	B	C	D	E	F	X
0	0	0	0	0	0	0
0	0	0	0	0	1	0
0	0	0	0	1	0	0
0	0	0	0	1	1	0
0	0	0	1	0	0	0
0	0	0	1	0	1	0
0	0	0	1	1	0	0
0	0	0	1	1	1	0
0	0	1	0	0	0	0
0	0	1	0	0	1	0
0	0	1	0	1	0	0
0	0	1	0	1	1	0
0	0	1	1	0	0	0
0	0	1	1	0	1	0
0	0	1	1	1	0	0
0	0	1	1	1	1	0
0	0	0	0	0	0	0
0	0	0	0	0	1	0
0	0	0	0	1	0	0
0	0	0	0	1	1	0
0	0	0	1	0	0	0
0	0	0	1	0	1	0
0	0	0	1	1	0	0
0	0	0	1	1	1	0
0	0	1	0	0	0	0
0	0	1	0	0	1	0
0	0	1	0	1	0	0

A	B	C	D	E	F	X
0	0	1	0	1	1	0
0	0	1	1	0	0	0
0	0	1	1	0	1	0
0	0	1	1	1	0	0
0	0	1	1	1	1	0
0	1	0	0	0	0	0
0	1	0	0	0	1	0
0	1	0	0	1	0	0
0	1	0	0	1	1	0
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0	1	0	1	1	1	0
0	1	1	0	0	0	0
0	1	1	0	0	1	0
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0	1	1	1	0	1	0
0	1	1	1	1	0	0
0	1	1	1	1	1	0
0	1	0	0	0	0	0
0	1	0	0	0	1	0
0	1	0	0	1	0	0
0	1	0	0	1	1	0
0	1	0	1	0	0	0
0	1	0	1	0	1	0

A	B	C	D	E	F	X
0	1	0	1	1	0	0
0	1	0	1	1	1	0
0	1	1	0	0	0	0
0	1	1	0	0	1	0
0	1	1	0	1	0	0
0	1	1	0	1	1	0
0	1	1	1	0	0	0
0	1	1	1	0	1	0
0	1	1	1	1	0	0
0	1	1	1	1	1	0
1	0	0	0	0	0	0
1	0	0	0	0	1	1
1	0	0	0	1	0	0
1	0	0	0	1	1	0
1	0	0	1	0	0	0
1	0	0	1	0	1	0
1	0	0	1	1	0	0
1	0	0	1	1	1	0
1	0	1	0	0	0	0
1	0	1	0	0	1	0
1	0	1	0	1	0	0
1	0	1	0	1	1	0
1	0	1	1	0	0	0
1	0	1	1	0	1	0
1	0	1	1	1	0	0
1	0	1	1	1	1	0
1	0	0	0	0	0	0
1	0	0	0	0	1	1
1	0	0	0	1	0	0
1	0	0	0	1	1	0
1	0	0	1	0	0	0
1	0	0	1	0	1	0
1	0	0	1	1	0	0
1	0	0	1	1	1	0
1	0	1	0	0	0	0
1	0	1	0	0	1	0
1	0	1	0	1	0	0

A	B	C	D	E	F	X
1	0	1	0	1	1	0
1	0	1	1	0	0	0
1	0	1	1	0	1	0
1	0	1	1	1	0	0
1	0	1	1	1	1	0
1	1	0	0	0	0	0
1	1	0	0	0	1	0
1	1	0	0	1	0	0
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1	1	0	1	0	0	0
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1	1	0	1	1	0	0
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1	1	1	0	0	0	0
1	1	1	0	0	1	0
1	1	1	0	1	0	0
1	1	1	0	1	1	0
1	1	1	1	0	0	0
1	1	1	1	0	1	0
1	1	1	1	1	0	0
1	1	1	1	1	1	0
1	1	0	0	0	0	0
1	1	0	0	0	1	0
1	1	0	0	1	0	0
1	1	0	0	1	1	0
1	1	0	1	0	0	0
1	1	0	1	0	1	0
1	1	0	1	1	0	0
1	1	0	1	1	1	0
1	1	1	0	0	0	0
1	1	1	0	0	1	0
1	1	1	0	1	0	0
1	1	1	0	1	1	0
1	1	1	1	0	0	0
1	1	1	1	0	1	0
1	1	1	1	1	0	0
1	1	1	1	1	1	0

Figure 9-11b. Truth Table.

If you just want to solve for one specific set of inputs, then simply replace the variables with the values.

For example, where A = F = 1 and B = C = D = E = 0

$$[1 \bullet (\overline{0 + 0})] \bullet [(\overline{0 + 0}) + (\overline{0 + 0})] \bullet [(\overline{0 + 0}) \bullet 1] = X$$

$$[1 \bullet (\overline{0})] \bullet [(\overline{0}) + (\overline{0})] \bullet [(\overline{0}) \bullet 1] = X$$

$$[1 \bullet 1] \bullet [1 + 1] \bullet [1 \bullet 1] = X$$

$$[1] \bullet [1] \bullet [1] = X$$

$$1 = X$$

By using combinational logic, we can derive highly complex scenarios. However, the logic itself is not enough; we need storage (counters, flip-flops, registers, etc.), and we need computational circuits to completely make up our digital logic.

Module 9A: Summary

- Digital gates consist of AND, OR, and XOR.
- Negation (NEGATE) is an inverter.
- Inverting an AND results in a NAND, and inverting an OR results in a NOR.
- AND rule: It takes all 1s in the input for the output to be a 1. NAND rule: It takes in the input for the output to be 0.
- OR rule: Any 1 in the inputs will cause the output to be 1. NOR rule: Any 1 in the i will cause the output to be 0.
- XOR rules: Even inputs result in a 0 output; odd inputs result in a 1 output.

Module 9B: Storage

There is a definite need to store the results of a logic decision to compare them to past or future results, for historical reasons, for trending, to count events, or to determine a past state in order to adjust the next state. The basic storage unit in the early days was the multivibrator, a bistable multivibrator to be exact. This was named a *flip-flop,* and it stored 1 bit, requiring decisions about when to change the bit and under what conditions. By tying flip-flops together based on a common clock or data line, a register came into being.

Registers

A register is simply a designated place of storage. It can be anywhere from a nibble (4 bits) to dual 256 bits (512) or even greater. A register differs from memory in that it has a specified length and typically is used repeatedly as temporary storage of addresses and results of computations. Figure 9-12 illustrates the logical diagram of a shift register.

The job of this register is to accept 8 bits of data from a parallel bus and then clock them out one at a time, converting the parallel data into serial data. Most registers are shift registers in that they can rotate data in one direction or, for many registers, in both directions with commands called *shift right* or *shift left* (shifting data to the left is multiplying it by 2 and shifting it to the right is dividing it by 2).

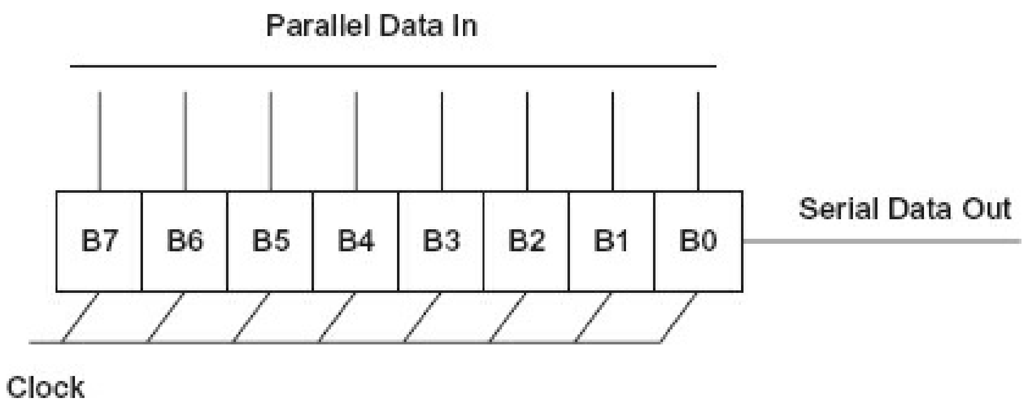


Figure 9-12. A parallel-to-serial register.

Counters

Sometimes it is necessary to count an event. A shift register is converted into a counter by simply adding one binary count to the contents of the register for each event (or, in some cases, taking one binary count away from the register for each event).

Memory

Memory is an addressed storage space. You could consider counters and registers as memory (and in many cases, that is exactly what they are), but generally when you think of the function of memory, it is to store information. There are many types of memory, including rotating memories (disk drives, CDs, DVDs, etc.), solid-state memories (RAM, ROM, EAPROM, EEPROM), and the different varieties and technologies of each of those (DDR, SRAM, etc.). In most digital technology, memory is addressed so you know how to identify each location. Memory stores whatever it is you need stored if it consists of 1s and 0s. The addressing of memory, the selection of memory type, and how memory stores a state, although quite interesting, is beyond the scope of this text. However, there are many good technical books, papers, and guides to assist you if you care to study these topics.

Module 9B: Summary

- Storage is in the form of registers, counters, and memory.
- Memory is addressed storage.

Module 9C: Computations

Before we start discussing binary computations, we must know how to represent a string of 1s and 0s, that is, how they are organized and what they mean. Some definitions first:

- **Bit** – A contraction of *binary digit*, the smallest possible piece of information. It is ei or 0, *true* or *false*.
- **Byte** – By convention, in current use, it means 8 bits.
- **Octet** – 8 bits.
- **Word** – 16 bits or 2 bytes.
- **Nibble** – A small byte, 4 bits.
- **Binary** – Only two states, 1 and 0.

Add

How do we add binary numbers? Just like we add numbers in the decimal system, only the base is different. Figure 9-13 illustrates binary addition.

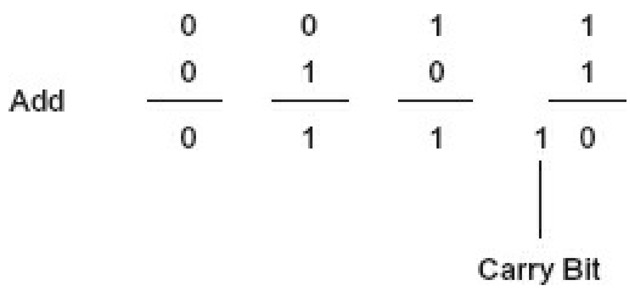


Figure 9-13. Binary addition.

It should be apparent that decimal/binary 0 = 0, and decimal/binary 1 = 1.However, the rules are the same for all number systems. If you add two numbers (in decimal, think 9 and 1) and they exceed the number of states available, you have a carry. In decimal, we add 1 to the next column over. In the case of 9 and 1 when added: 9 + 1 = 0, carry 1 or 10. To add 19 + 1, add up the units column, place a zero in the column, and add your carry to the tens column to give you 20. In binary, we only have two states, not 10, so when you add binary 1 and binary 1, you have a 0 and a carry of 1 to give you binary 2, which is represented as 10 in binary.

Representing Binary Patterns

In this text, and in most of the real world, there are three ways to represent binary numbers: (1) the binary pattern; (2) the decimal equivalent of the binary value of the pattern; and (3) the hexadecimal equivalent, used only for determining the binary pattern (see Figure 9-14, reprinted from Module 8).

Example

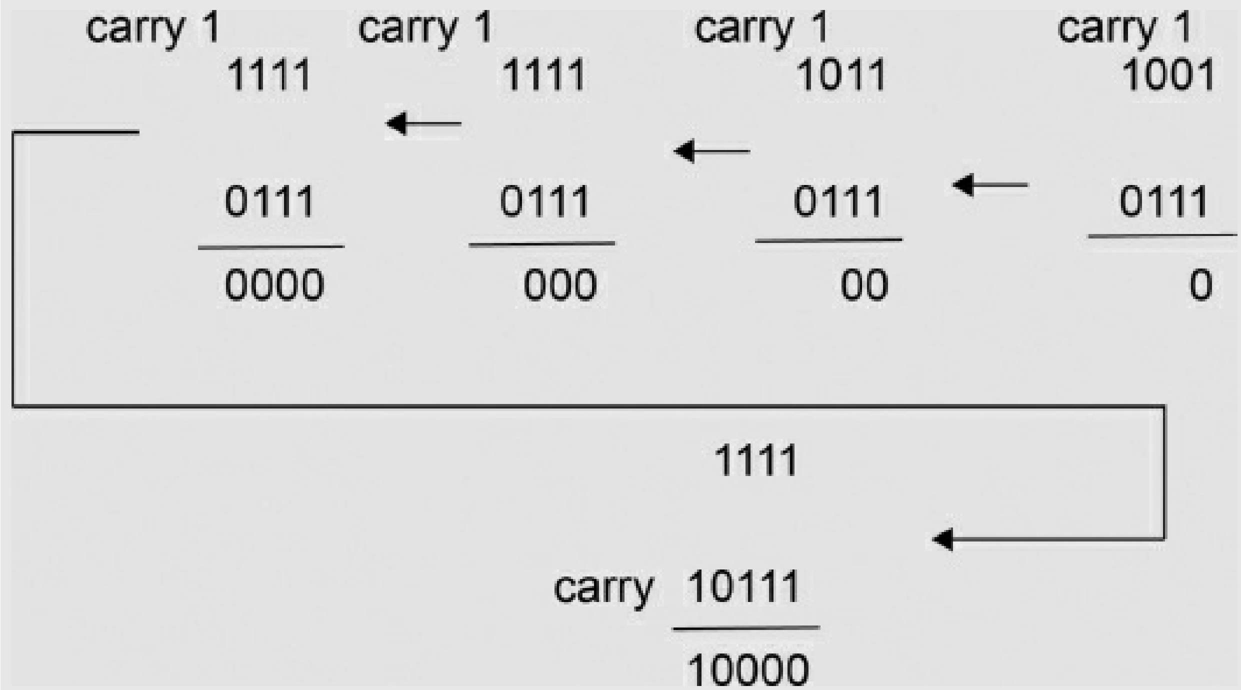
Add the binary equivalent of 9 and 7 (which, of course, you know to be 16).

decimal 9 = binary 1001

decimal 7 = binary 0111

decimal 16 = binary 10000

Added together:



Binary	Decimal	Hexadecimal
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	8
1001	9	9
1010		A
1011		B
1100		C
1101		D
1110		E
1111		F

Figure 9-14. Binary equivalents.

For example, the binary pattern represented by 10 hex is 0001 0000, which has a decimal value of 16. Now, let us look at how 8 bits can represent the decimal values 0 through 255.

Assign the value (of the power of 2) to every column with a 1.

Hint: Add the power of 2 values: 128 + 64 + 32 + 16 + 8 + 4 + 2 + 1 = 255

Example

What is the decimal value of hex C6?

1. Make the number binary. 1100 0110

128	64	32	16	8	4	2	1
1	1	0	0	0	1	1	0

2.
```
128
 64
  4
  2
___
198 is the answer.
```

Subtract

Subtraction as taught in elementary school is a mechanical process for calculating the difference. It is not how the number system works, nor is borrowing a method that will work for mechanical or electronic computations. To subtract means to add the complement of a number. A complement is the difference between the numbers you have and the other end of the number system. We will do it in decimal first before we try it in binary.

There are 10 numbers in the decimal number system, 0 through 9. The complement of 0 is 9, 1 is 8, 2 is 7, and so on; that is how far it is to 9 from the number you have. If you have the number 4, you achieved that number by counting 0, 1, 2, 3, 4. So how far is it to the other end of the number system (9)? It is 5. In decimal, 5 is the complement of 4.

Now, let us calculate the difference between 5 1 3 7 and 4 3 6 8.

How were you taught to do this? You cannot take 8 from 7, so you borrowed 10 from the next column; now you have 17 and can subtract 8 from it. However, neither mechanical nor electronic adding machines can be designed to add and subtract by borrowing. These machines calculate the difference by adding the complement of the lower number to the higher number.

First we will determine the complement of the lower number—4 3 6 8. To do this, will use the process we just discussed: determine how far it is from the number in question to the number 9.

How far is it from 4 to 9? 5

How far is it from 3 to 9? 6

How far is it from 6 to 9? 3

How far is it from 8 to 9? 1

The complement of the lower number (4 3 6 8) is 5 6 3 1. Now add 5 6 3 1 to the larger number (5 1 3 7). The total is 1 0 7 6 8. Because you know that the result (the difference between the two numbers) must be less than the two original numbers, what do you do with the 1 at the beginning of the result? The 1 at the beginning is a carry, which means it is a positive number. You must compensate for 0 being not in the middle but a positive number. Remember from Module 8 that offset binary uses 100,000 as the 0 value when using bipolar (directed number) sets. That is a positive number (or why the positive side always has one less number than the negative side). So, add the 1 to your result, which will give you: 0 7 6 9.

This is the principle that all mechanical adding machines used. The same is done in binary. This method is called *ten's complement* (because if you have a carry, it is a positive number and you add the 1 to the number). In binary, we use a method called *two's complement*. It is easier to complement because to do so you just invert (change all the 1s to 0s and vice versa).

Remember: If you have a carry, it is a positive number. What is a negative number like? It will be in complement form. If you want to see a positive number with a negative sign in front, you will have to re-complement.

Example

Calculate the difference between Hex 10 and Hex 07

	1 0000	(Decimal 16)
	0 0111	(Decimal 7)
Complement	1 0000	
	1 1000	
Add	10 1000 (You had a carry, so add the 1)	
Result	1001 (Hex 9 and Decimal Value 9)	

Multiply

To multiply in binary means to multiply by 2. This is done simply by shifting a register to the left.

The value in the register now:

00001000 (decimal 8)

To multiply by 2, shift all digits to the left one position.

00010000 (decimal 16)

Let's look at another example.

The value in the register now:

00010101 (decimal 21)

To multiply by 4, shift all numbers two places to the left.

01010100 (decimal 84)

To multiply by an odd value (e.g., 5), determine how many times 2 will go into the multiplier evenly (2 will go into 5 two times). Shift all the digits over two places to the left and the add the original value. Essentially that is 4 + 1 times that the number is added together.

Divide

To perform division by 2, shift the register to the right one position. To divide by 3, shift the register to the right two positions (dividing by 4) and add the original value.

Module 9C: Summary

- Binary addition and subtraction are performed using two's complement.
- A complement is the distance from a number to the other end of the number syste
- Multiplication is a shift-left process; division is a shift-right process.

Module 9: Review

See Appendix B for the answers.

1. See Figure R9-1. In Circuit 1, inputs A = 1, B = 0, and C = 1. What is the output?

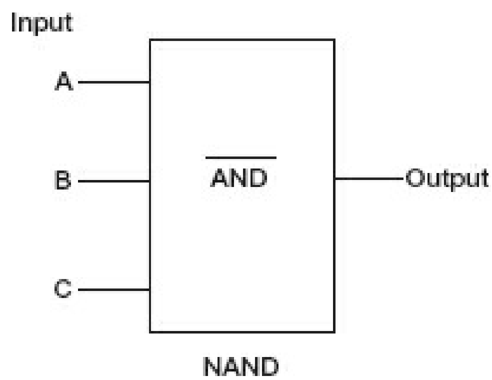


Figure R9-1. Circuit 1.

2. If Circuit 1 was a NOR with the same inputs, what would the output be?

3. If Circuit 1 was an AND, and inputs A = 1, B = 1, and C = 1, what would the outp

4. If a shift-left register had the original value of 00110010 and it is shifted twice, w

the decimal values of the original value and the resultant value?

___

5. XOR these two patterns:

   110001011011
   011000010111

___

6. Convert hex F7 to a decimal value. (*Hint:* Convert hex to the binary pattern first.)

___

7. Convert decimal 57 to hex. (*Hint:* Determine the binary value of 57 first.)

___

8. See Figure R9-2. In Circuit 2, A = 0, B = 1, C = 1, D = 0, and F = 0. What is the outp

___

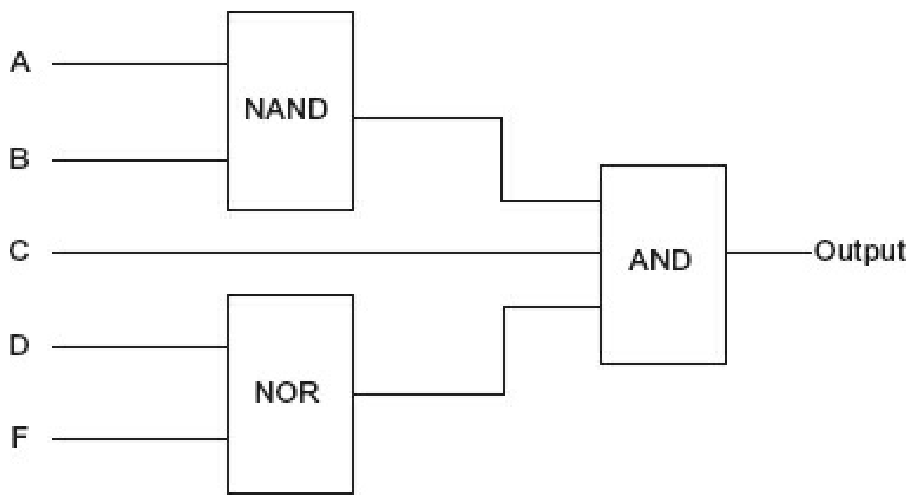


Figure R9-2. Circuit 2.

Conclusion

You have reached the end of Module 9. Please reread the module objectives (in the "Objectives" section). If you have met these objectives, continue to the next module. If you are having difficulty, please reread the text. If the difficulty persists, locate a peer, mentor, supervisor, or someone who has technical knowledge of digital logic and ask them to assist you.

Further Information

For additional information on the topics in this module, search for the following topics at your public or company library, or on the Internet.

- Digital logic
- Digital gates
- Digital logic counters and timers
- Boolean algebra

10
Industrial Applications

In this module, we will build on the facts learned in the preceding modules and observe how they apply to industrial applications. After all, the purpose of this book is to bring you to a level where you can understand the underlying operation of the industrial control equipment we use every day.

Note that this module contains a limited set of examples. Because the field is application dependent, there are an infinite number of applications and environments that contain electric/electronic equipment.

Module 10: Objectives

After successfully completing this module, you will be able to:

- Describe the actions of a two-wire loop.
- Provide alternative methods for directly measuring current in a two-wire loop.
- Determine the differences between an alternating current (AC) and direct curre solenoid.
- Describe a three-wire 365 start-stop circuit.
- Define an unbalanced-to-ground circuit.
- Define a balanced-to-ground circuit.
- Describe the advantages/disadvantages of balanced- and unbalanced-to- circuits.
- Describe the basic programmable logic controller (PLC) architecture and operatic
- Identify and determine if an input or output PLC circuit is sinking or sourcing.
- Determine PLC logics for Examine If Closed (XIC), Examine If Open (XIO), a outputs.
- List three of the five standard (IEC 61131) PLC programming languages.

Module 10A: Two-Wire Loop

One of the most common circuits found in contemporary process control is the two-wire loop. It is called this because it uses two wires (one pair) and supplies both the power and the signal on the same lines. A measurement and control loop is illustrated in Figure 10-1. It has two loops, a measurement loop and an output or control loop.

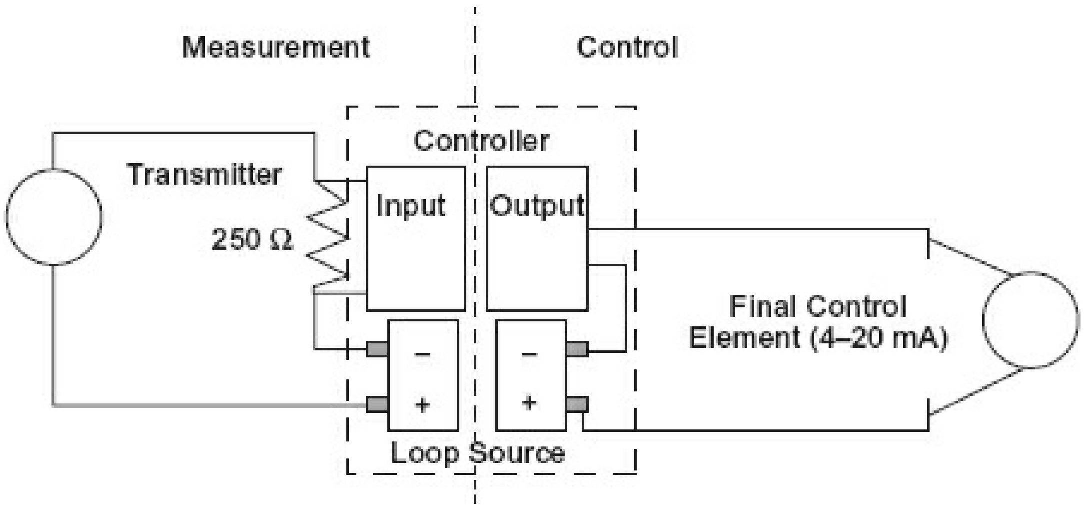


Figure 10-1. Two-wire loop.

The transmitter is a constant current device, which is a device that outputs a current determined by external factors (in this case, the process variable) and does not vary with the voltage across the device (within limits). The process variables here could be pressure, level, flow, temperature, or whatever variable you are trying to measure.

The loop source supplies 24 VDC (typically), and the transmitter is scaled so the output at 0% (whatever value that is, e.g., 100°C, 0 psig, or 20 gpm) will output 4 mA. The maximum value, 100% (e.g., 500°C, 50 psi, or 200 gpm), will output 20 mA.

At the input of the controller is a 250 Ω resistor. Using Ohm's law to determine the voltage across the resistor at 4 and 20 mA will give a result of 1 V for 4 mA and 5 V for 20 mA. This is the input to the controller, and it operates in the 0% to 100% area or with inputs of 1 to 5 V. That means (less the line resistive losses) there is 19 to 23 V across the transmitter, 23 V when it is outputting 4 mA, and 19 V when it is outputting 20 mA. Most older transmitters require a minimum of 11 V to operate. Newer devices require less voltage, sometimes as little as 3.3 V. For example, you could have several 250 Ω resistors in series for a chart recorder and a visual display. If you run three resistors in series, the current will remain the same (current in a series circuit is the same throughout), but the voltage across the transmitter will change. At 4 mA, the resistors combine to give a 3 V drop; at 20 mA, they combine to give a 15 V drop. The voltage across the transmitter will now vary from 9 to 21 V, and it is wise to check the minimum operating voltage of the transmitter before attempting this circuit. The entire effort of using a series loop with voltage inputs (through conversion by the 250 Ω resistor) is that the input impedance of the voltage devices is so high (compared to 250 Ω) that loading is negligible. Three devices with 10 MΩ inputs will not substantially change 250 Ω (think 3 MΩ in parallel with 250 Ω, which gives a total impedance of 249.979168 Ω or a deviation of 0.0083%).

Checking Current

In a circuit of this nature, the 4 to 20 mA must be periodically checked and recalibrated. How is that done? You could break one of the lines and insert a current meter. However, this has the undesirable result of "bumping" the process—that is, when you disconnect the line, it goes below the 0% input and therefore the process will have to be in manual. You could be ohm smart and measure the 1 to 5 V across the resistor instead. Or, you could use a diode (many manufacturers have installed diodes in their instruments). Figure 10-2 illustrates this method.

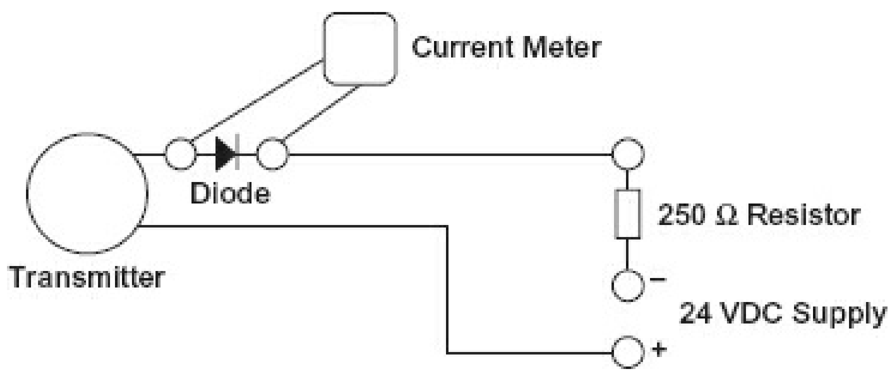


Figure 10-2. Diode for current check.

Recall that a silicon diode requires about 0.7 V across the diode in the forward direction to conduct. Without the meter in the circuit, the diode adds a 0.7 V drop to the line loss, generally an inconsequential amount. When the current meter is placed across the diode, it typically has a voltage drop of less than 0.1 V. (It is trying to measure current without interfering with the circuit under test.) As the meter is in parallel with the diode and drops 0.1 V, the diode is opened and all the current then flows through the meter. Remove the meter, and current flow is again totally in the loop.

Module 10A: Summary

- The two-wire loop is used in industry as a single pair of wires that can supply p the remote device and carry the process variable signal.
- The signal of a two-wire loop can be measured using the voltage across the res the current around a diode.
- Inserting a diode in the circuit will provide a bumpless way to measure current.

Module 10B: Solenoids

Basically, an electrical solenoid is an insulating core, coil winding, and a ferrous armature that can connect to other mechanical linkages. Figure 10-3 illustrates an electromechanical solenoid in the powered and unpowered state. When the solenoid is de-energized (unpowered), a form of mechanical or electrical force is used to bring the armature part of the way out of the coil. When energized, the immersed part of the coil has many lines of force compared to the area of the core where the armature is vacant. This imbalance causes the armature to move inward with considerable force (depending on the number of turns, diameter, materials, and amount of current passing through the coil) until it is balanced between the coil ends. The action of a solenoid can be harnessed by connecting the plunger to a mechanical device. It can be used to open or close valves, dampers, or in many cases, a set of contacts. When operating a set of contacts, the solenoid contact arrangement is referred to as a *contactor*.

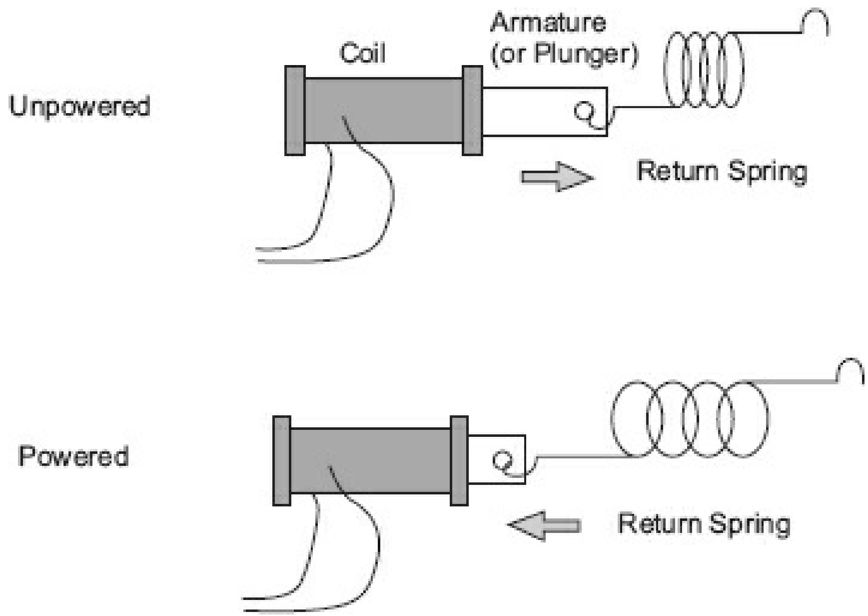


Figure 10-3. Solenoid representation.

The physical construction of the solenoid differs depending on the type of coil activation current. An AC solenoid generally has fewer turns than a DC solenoid and a core designed to prevent chattering. Chattering is caused when the AC current goes through 0 during the power-on cycle(s). It will generally cause the coil to slightly release the armature and then abruptly pull it back, resulting in a "chattering" effect.

AC solenoids require fewer turns because they expect the inductive reactance (X_L) to limit current. Because the reactance when the armature is out of the coil is much less than when the armature is fully engaged, if an AC solenoid is held open, it will quickly burn out.

Typically, DC solenoids have many turns of wire to limit the amount of current required to pull in the armature and maintain it in the closed position. (There will be no inductive reactance to limit current except on power-up and power-down.) The armature is typically a solid core. DC solenoids can be made more sensitive than AC varieties (which require smaller current to engage). As much wire as is necessary can be wound on the core because there is no reactance other than at power-up and power-down.

As mentioned earlier, when the solenoid armature is attached to switching contacts, the assembly is called a *contactor.* In physically smaller devices, they are called a *control relay*. There is a myriad of control relays and contactors, ranging from DC-operated control relays for control circuits to AC-operated, three-phase motor control contactors. Figure 10-4 illustrates a typical three-phase motor control circuit.

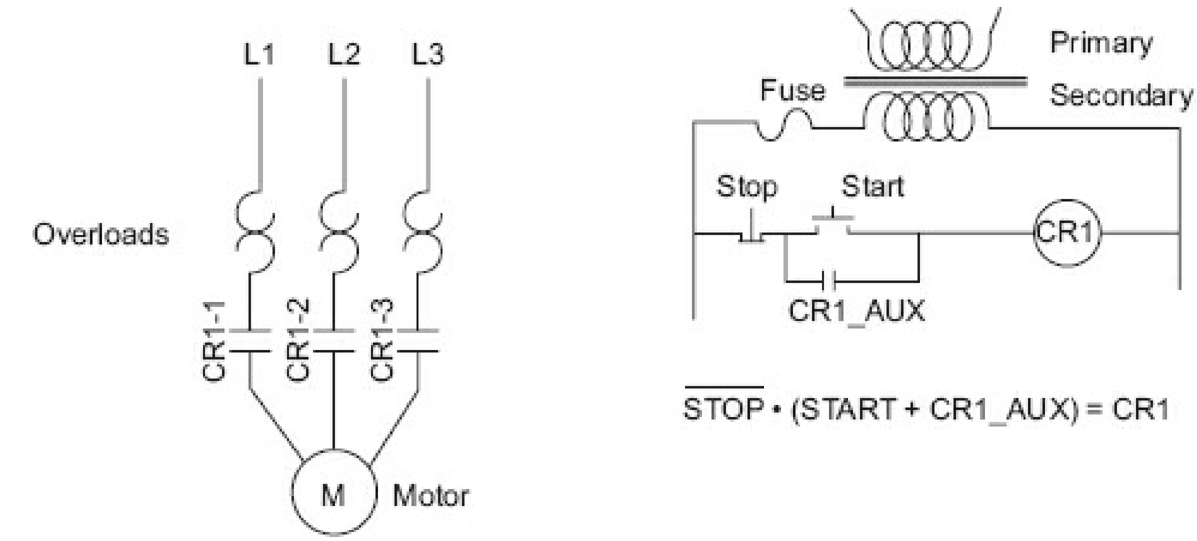


Figure 10-4. Typical motor control circuit.

The contactor solenoid is CR1. Besides its main three contacts (CR1-1, CR1-2, CR1-3), there is typically a set of normally open auxiliary contacts to be used as a sealing circuit (CR1-AUX). Assuming control power, if the start switch is depressed, the solenoid will pull in, closing the contacts. The CR1-AUX contacts will then seal in the start switch, and it may be allowed to return to the open state. Depressing the stop switch removes current from the solenoid and opens the contacts, stopping the motor. The weird hook-like devices are symbols for thermal overloads, which may be in the contactor or located externally. Using what we learned about Boolean logic, we can illustrate this circuit in a Boolean equation.

Module 10B: Summary

- Solenoids, relays, and contactors are electromechanical switches.
- In any type of solenoid, a magnetic field will move an armature to open an contacts.
- An AC solenoid requires fewer turns of wire than its DC counterpart because constrains the closed (on) condition current.
- A DC solenoid has more windings and can be made more sensitive than the AC t

- A three-wire sealing circuit known as a *start–stop circuit* is common to industry an auxiliary set of contacts is used to seal (or lock in) the on condition.

Module 10C: Balanced- and Unbalanced-to-Ground Circuits

Unbalanced-to-Ground Circuits

Unbalanced to ground simply means that the power/signal line and the return line (remember, a complete circuit is required for current to flow) have different impedances to a common 0 V reference, sometimes called *signal ground*. Figure 10-5 illustrates this nicely.

It should be obvious that even if DC resistance is measured from the output line to the common (signal ground) and from the signal return line to common, there will be a considerable difference. In the case illustrated, this difference develops the output signal. Every measurement taken in this circuit will be taken using the signal common as the 0 V reference.

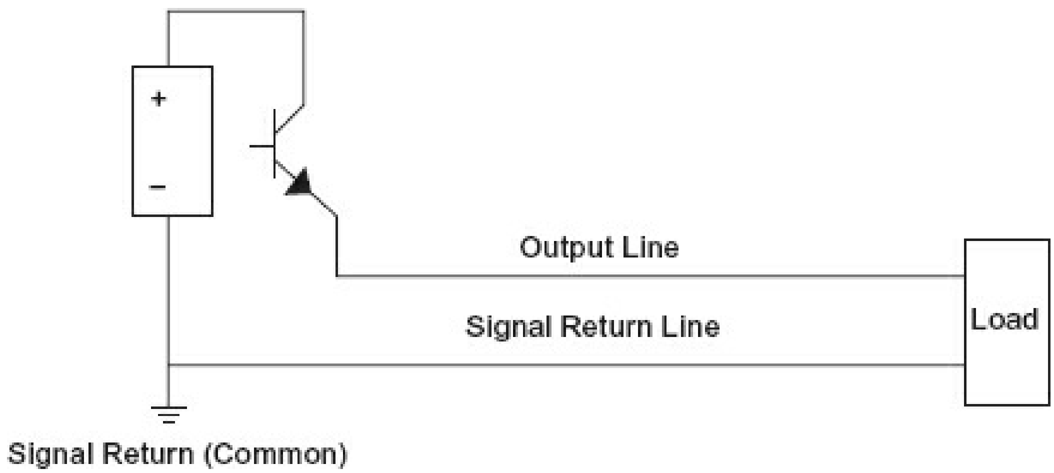


Figure 10-5. Unbalanced-to-ground circuit.

Because this is the manner in which almost all previous circuitry was explained (except for the differential amplifier), you might wonder what the downside to this arrangement is, as having just one signal return line for many signals will certainly save cable. Yet there are considerable drawbacks to this arrangement. One is that noise is also measured using the signal common as the 0 V reference. If a noise pulse (such as a transit) or a capacitively coupled noise or, in industrial arenas, a magnetically coupled noise cuts across the signal conductors, the signal return line will hold the noise (within limits) to near 0 V because it is at 0 V potential. The induced noise on the signal line will, in reference to the signal common line, be the full noise voltage and will be across the load (in this case). This is often called *common mode noise* or *longitudinal noise*.

Using a signal common effectively limits the speed at which you can change information on the line. Using binary signaling (0 to 5 V or –10 to +10 V) will influence how fast you can change signals as will the length of the cable and the environment that the cable is in. In an unbalanced-to-ground circuit, the noise and the charge/discharge characteristics of the media determine the allowable speed.

Balanced-to-Ground Circuits

To get around the disadvantages of the unbalanced-to-ground system, a balanced-to-ground system is used. Balanced to ground requires a pair of wires for every signal (no common ground), and the signal is measured relative to the other wire. We could say if Line A is positive relative to Line B, this is a 1, and if Line A is negative relative to Line B, it is a 0. Both lines have the same impedance to common (signal ground). Figure 10-6 illustrates a balanced-to-ground circuit.

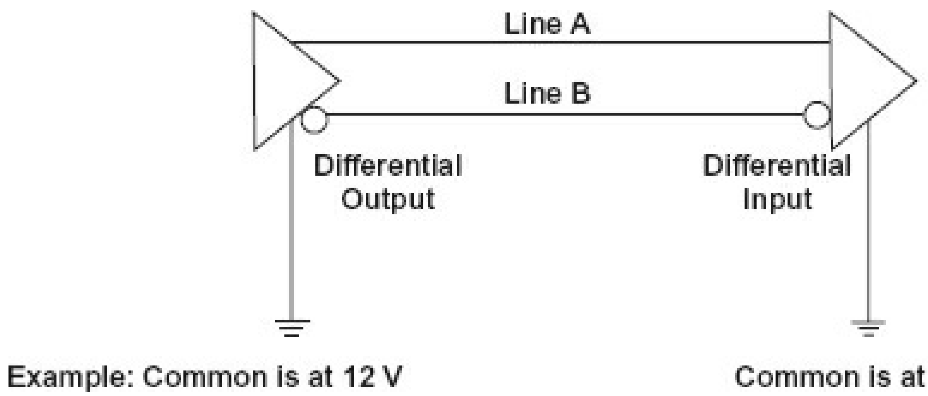


Figure 10-6. Balanced-to-ground circuit.

If the difference between Lines A and B (the desired signal) is 3 V peak-to-peak, with A as the direct side and B as the inverted side, the difference between the commons (or grounds) is 11 V. This would be added to the A side and the B side because they have equal impedance to common (ground), giving a voltage at the transmitter output and receiver input of 11 V, ±3 V. The difference in voltage between A and B will be all the input is looking at, and the difference between the two wires will be ±3 V.

This arrangement removes the noise as a speed limiting factor and it ensures that the impedance matching of the lines is correct. Using this principle, a line that looks like a telephone wire (which can support 300 to 3300 kHz as an unbalanced line) but has twists in tight conformance can pass 100 Mbps of information (Cat 5 or 6 line, which is in a balanced-to-ground arrangement).

The main difference between balanced and unbalanced lines (other than the number of twists per inch and the conformance of the twists) is that the unbalanced arrangement has a signal return common (ground), whereas in the balanced-to-ground arrangement, each wire in the pair has equal impedance to ground (requiring differential inputs and outputs).

Module 10C: Summary

- Transmission lines may be balanced or unbalanced to ground.
- *Unbalanced to ground* means that there is a common signal return, usually groun

earth at the single entry point eventually). Unbalanced-to-ground signal circui both the speed and distance allowed, enabling common mode noise to signi affect small signals.

- Power supplies also can be grounded or *floating*, meaning balanced to ground.
- Balanced-to-ground power distribution is more robust in two wires (or instru that are short-circuited to ground. Typically, one short circuit to the ground in a distribution circuit that is balanced to ground (floating) in any loop will turn balanced-to-ground circuits to unbalanced-to-ground, but all loops may cont operate. A second short circuit in any loop could cause trouble and be hard to (and eliminate), especially without disconnecting (shutting down) multiple which may lead to shutting down the entire plant area.
- Unbalanced to ground (for power sources) has the advantage (or disadvantag any short circuit to ground could blow a fuse and render inoperative one loop o one where a ground fault occurred. This makes it easier to troubleshoot and fix b a single short will render only one loop inoperative. If the systems are properl no collective shutdowns would occur, regardless of where the ground faults are l
- Balanced-to-ground signal circuits typically require differential inputs and c meaning one pair per signal. However, this allows for higher speeds and distance, greatly reducing the effects of common mode noise.

Module 10D: Programmable Logic Controller

The programmable logic controller (PLC) is a device that has significantly changed how manufacturing is accomplished. It is beyond the scope of this text to provide a thorough explanation of the PLC and how it operates. The purpose of this module is to help you apply what you have learned to PLCs. Figure 10-7 is a block diagram of an early PLC (which does not have an analog input/output—I/O).

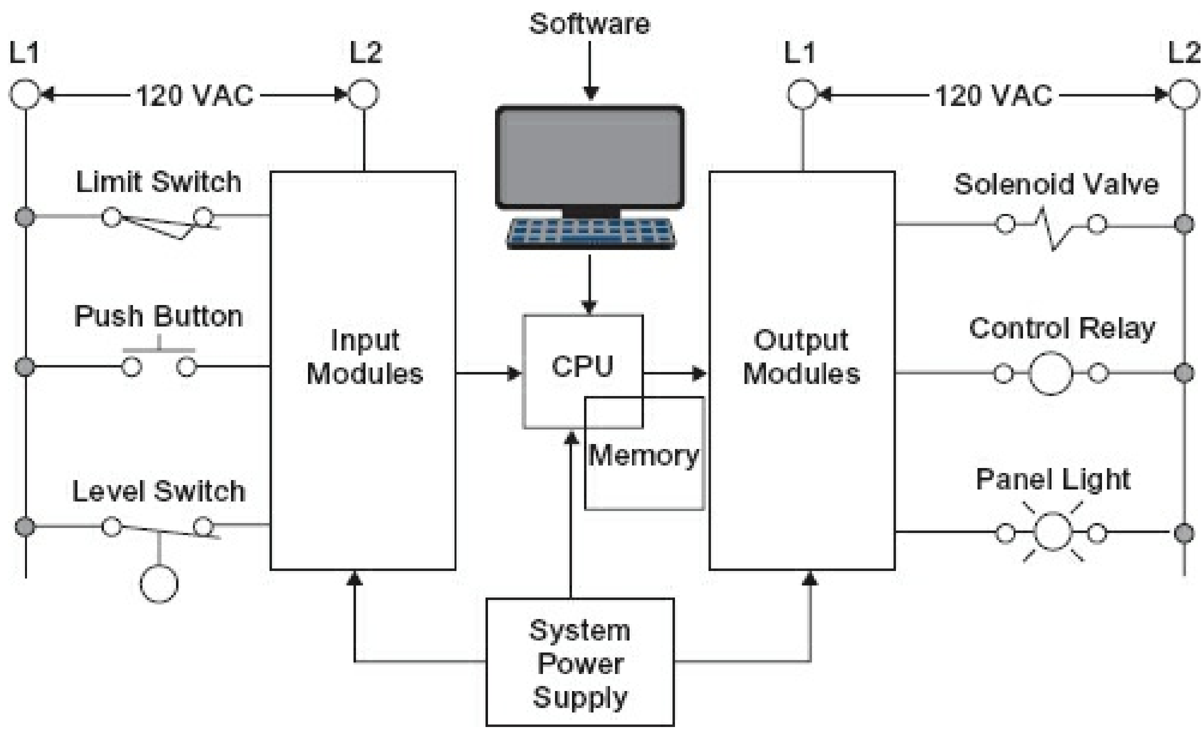


Figure 10-7. Block diagram of a PLC.

The CPU scans the input modules and updates the memory registers. It then processes the logic as written and updates the output registers. Lastly, it scans those output registers and transfers the status to the output modules to activate physical devices.

Programming PLCs and dealing with the CPU configuration are out of the scope of this text. However, the I/O, the inputs, and the outputs are within the scope. The early model PLC shown in Figure 10-7 has a switched I/O; that is, determining if an input is open or closed means detecting that a current flows when the input circuit is closed and does not flow when the input is open. The outputs are energized by switched AC (or DC), which is switched on or off by the output module. Not shown is that output module circuits are generally fused (and so may be the inputs) for their protection. Most inputs use optical isolation to protect the motherboard.

Not all PLCs use AC for the I/O modules. Often they offer DC I/Os. Most PLCs allow for a mix of AC and DC I/O modules.

A troubleshooting technique to use on an output module with no output is, of course, to check the fuse. Inputs are generally a broken wire or maladjusted switch. By looking at the block diagram, you could use what you have learned in this book to determine if either the input or the output needed maintenance.

PLCs now have an array of I/O, including digital and analog I/O. Many of the topics in this book are necessary to understand the operation and the wiring to and from the PLC I/O.

Sourcing/Sinking Inputs/Outputs

PLCs (and most electronic I/O devices) are arranged as either sinking or sourcing, and it is important that the wiring matches the configuration.

- In the input circuits, the switch is external, and if the hot wire is switched, it is the current.
- If the input voltage source is switched to the common wire, it is sourcing the curr
- In the output circuits, sinking or sourcing is determined by how the current to ar the load is handled.
- If the load is tied to common, the PLC output switch is sourcing the current.
- If the load is already sourced (attached to the current source) and it is swit common, this is sinking the current.

Note that in this sinking example (Figure 10-8), the voltage source is external and the positive lead is switched. The current is going from the source through the switch to the positive input, so it is sinking.

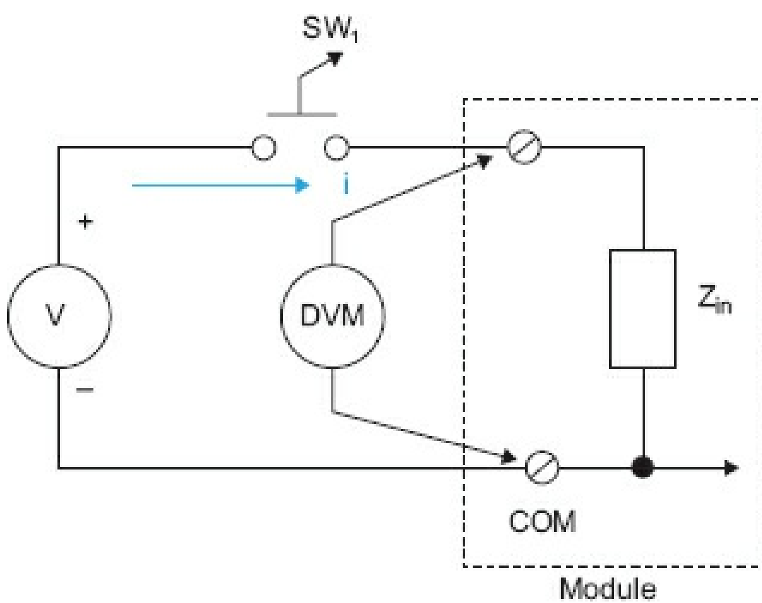


Figure 10-8. Sinking input module.

In the sourcing input (Figure 10-9), the external voltage negative lead is switched and current is being sourced (electron current: negative to positive).

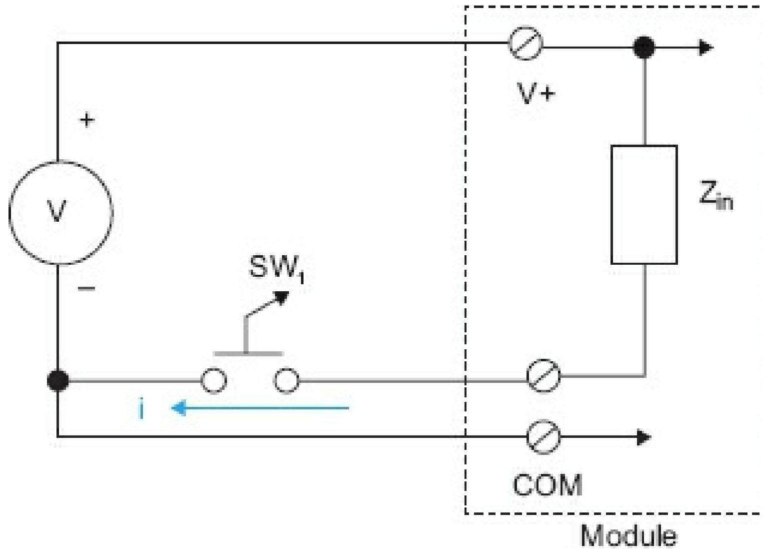


Figure 10-9. Sourcing input module.

In the sinking output (Figure 10-10), the load is in the positive source lead and the negative lead is switched so that the switch is sinking the current.

In the sourcing output (Figure 10-11), the positive lead to the load is in the negative lead, and the positive lead to the load is switched so current is being sourced.

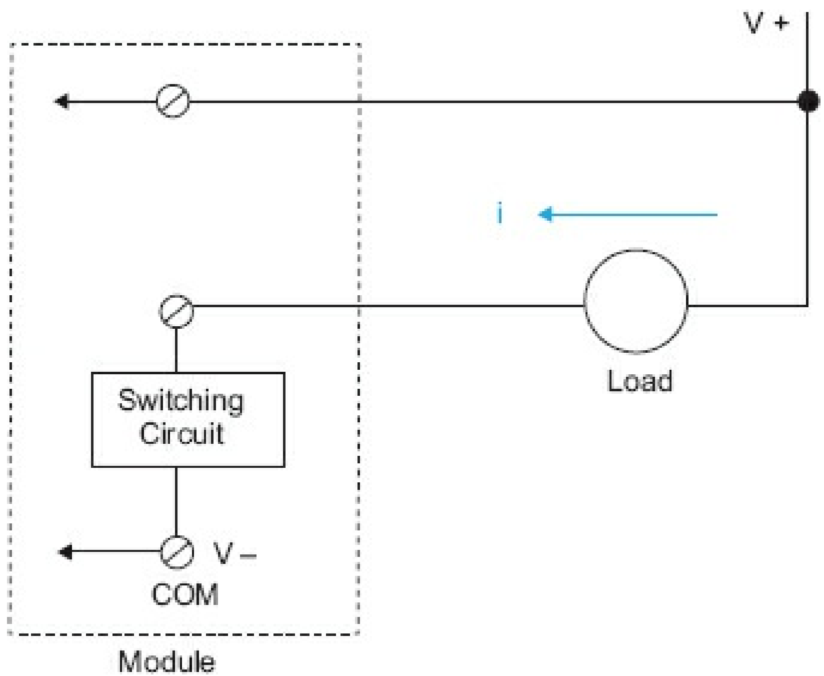


Figure 10-10. Sinking output module.

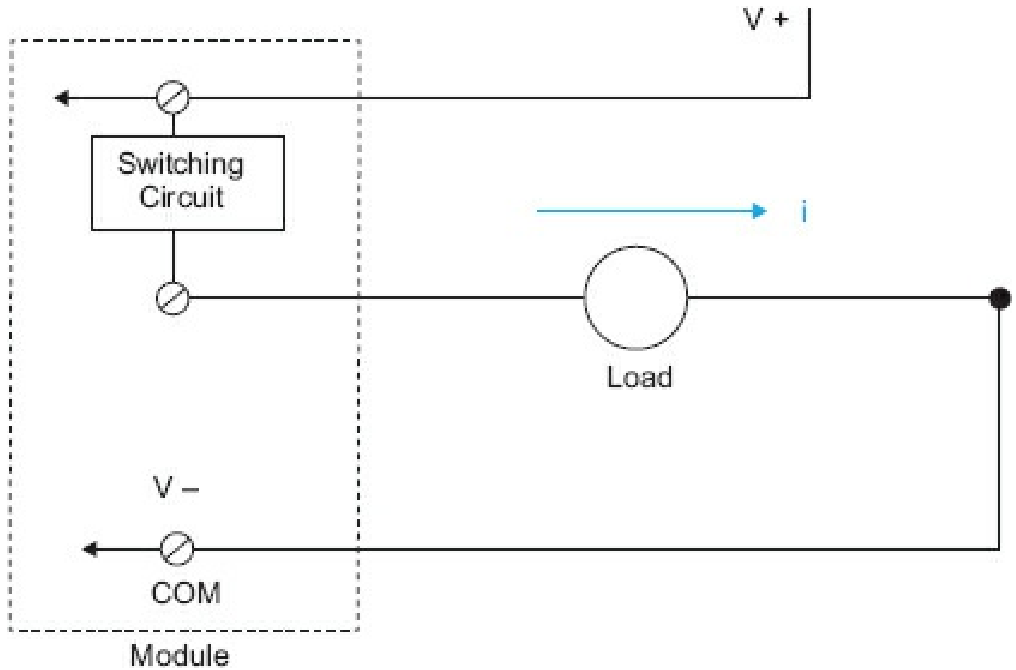


Figure 10-11. Sourcing output.

PLC Logic

This module cannot begin to do justice to the complexities of PLC coding. Here we present just the basics and note that there are many (free) sources of good information on both basic and advanced PLC coding.

PLC logic is founded on hardware relay logic (on which Ladder Diagram, also called Ladder Logic, programming is based). In hardware relay logic, current flow is followed. In the PLC, logic flow is followed.

What appears to be an open symbol has a different meaning in PLC logic. What appears to be a normally open set of contacts is actually an *Examine If Closed* (XIC) symbol. That means it is true (and only true) if it is closed (the activated state for a control relay, where it would be closed). The normally closed contacts are named *Examine If Open* (XIO), which is true and only true when it is open (Figure 10-12).

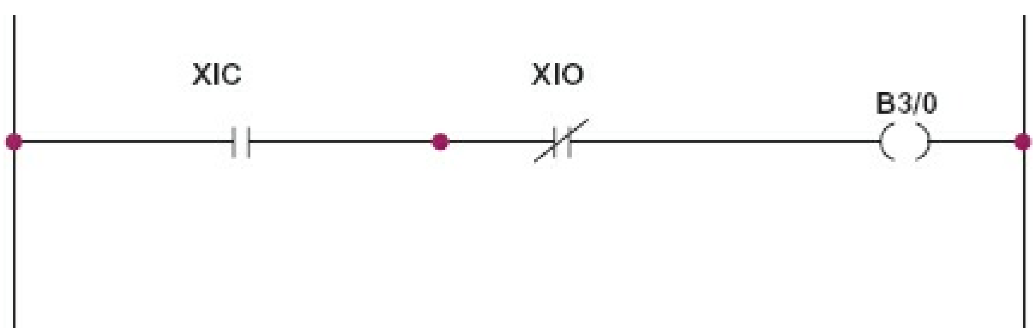


Figure 10-12. PLC logic.

Rails are the positive and negative (DC) supply leads, or the hot and common (AC) supply leads. Note that inputs are on the left-hand side between the rails and outputs on the right-hand side between the rails. The outputs are generally represented by a right and left ellipse (trying to make a circle back in the days of character-based screens) or a rectangle. Some of the common relay types are shown in Figure 10-13.

SYMBOL	MNEMONIC	INSTRUCTION
][	XIC	EXAMINE IF CLOSED
]/[	XIO	EXAMINE IF OPEN
( )	OTE	OUTPUT ENERGIZE
(L)	OTL	OUTPUT LATCH
(U)	OTU	OUTPUT UNLATCH

Figure 10-13. Relay type instructions.

To illustrate PLC logic, the simple three-wire, start–stop control is used as an example.

Let us follow this logic using Figure 10-14. Starting at the left, we look at I:1/1 (a PLC address for an input basically saying it is an Input, in Slot 1, Input 1). It is an XIC. If it is not being pushed, it is open, so it will be logic *false*. Continuing on the rung, we come to I:1/0 (Input, Slot 1, Input 0) and examine it. It is a normally closed switch (hardware), but we are looking for logic. We find it closed, so according to XIC it is *true*. B:3/0 is also XIC. This represents the auxiliary contact that closes when B:3/0 is activated (turned on) in relay logic. In this diagram, it is both an input and an output. It is open, so *false* (neither input nor output is *true*).

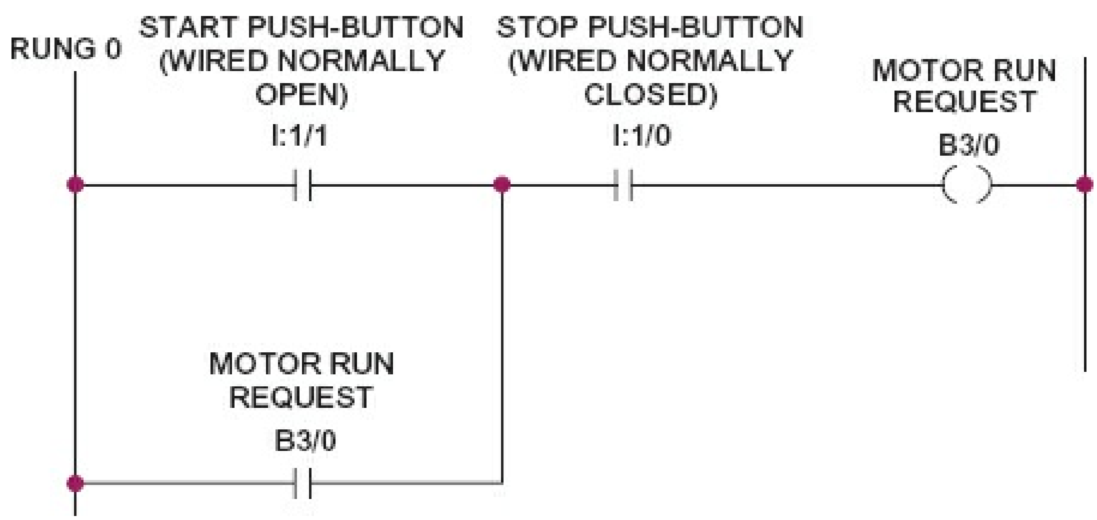


Figure 10-14. Start-stop logic.

To start the circuit, depress the start button (I:1/1). It becomes *true*, and because I:1/0 (stop switch) is already *true*, that makes B:3/0 *true*. When B:3/0 is *true*, then contacts B:3/0 is *true*, meaning you may let go of the start switch. The circuit will remain activated until the stop switch (I:1/0) is depressed and goes *false*, interrupting the logic flow and causing the circuit to revert to its initial condition.

There is an OR circuit consisting of I:1/1 and B:3/0, and their output is ANDed with

I:1/0 with the output being B:3/0.

There are many more detailed circuits (in other presentations), but this is (or should be) enough to whet your appetite for PLC logic.

Ladder Logic programming is only one of the many ways PLCs are programmed. The IEC 61131-3[1] standard states that the following PLC programming languages are approved for international use: Instruction List (IL), machine language; Structured Text (ST), assembly language; Ladder Logic (LD); Function Block Diagram (FBD); and Sequential Function Chart (SFC). The reader is encouraged to research these languages to learn more about them.

Module 10D: Summary

- PLCs are very common in control circuits.
- Basically, a PLC is a dedicated computer that is industrially hardened and ca inputs and manipulate outputs.
- The inputs and outputs are either sourcing or sinking (generally, the card in th one way or the other).
- PLC logic is based on the much older relay logic but has a significant difference it is logic flow, not current flow, that matters in the interpretation.
- There are different languages and ways to program PLCs.

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1 IEC 61131-3:2013, *Programmable Controllers – Part 3: Programming Languages* (Geneva 20 – Switzerland: IEC [International Electrotechnical Commission]).

Appendix A: Resistors

Resistor Types

All circuits (other than superconducting varieties) have resistance, either a small amount or a large amount. Often the resistance is there by design, in which case we normally use a *resistor*. A resistor is a conductor with a specified resistance. It performs its task, which is dropping a specified amount of voltage by turning the energy of the current into heat. There are different types of resistors depending on their application, and they come in a variety of sizes, shapes, and materials. Determining the resistance of a resistor is covered in the next section, but note that the amount of resistance has nothing to do with the physical size of the resistor. Because resistors function by turning electrical energy into heat, they vary in size, which is determined by the amount of power they must dissipate. Resistors are rated on the amount of heat they may dissipate before they fry themselves out of existence. The larger the size, the more heat the resistor can dissipate.

Generally, physically small resistors are used in electronic circuitry. In modern electronic circuitry, most resistors are of the surface mount variety and are extremely small, so small that they cannot be seen without a magnifier.

When a larger amount of power dissipation is required, a *power resistor* is used. Power resistors are generally wire-wound and may be extremely large. Resistors may also be adjustable; that is, their resistance can vary. Whenever you adjust the volume control on a pre-2000 car radio, you are turning a variable resistor. If the resistor is meant to reduce current, it is called a *rheostat* and has only two connections. If it is to be used as a variable voltage divider, a device that ratios two resistances across a source to obtain some voltage between minimum and maximum, it will have three connections and is called a *potentiometer*. Generally, rheostats are power devices and are rather large; on the other hand, potentiometers can be almost any size depending on the application. Figure A-1 illustrates some rheostats and potentiometers.

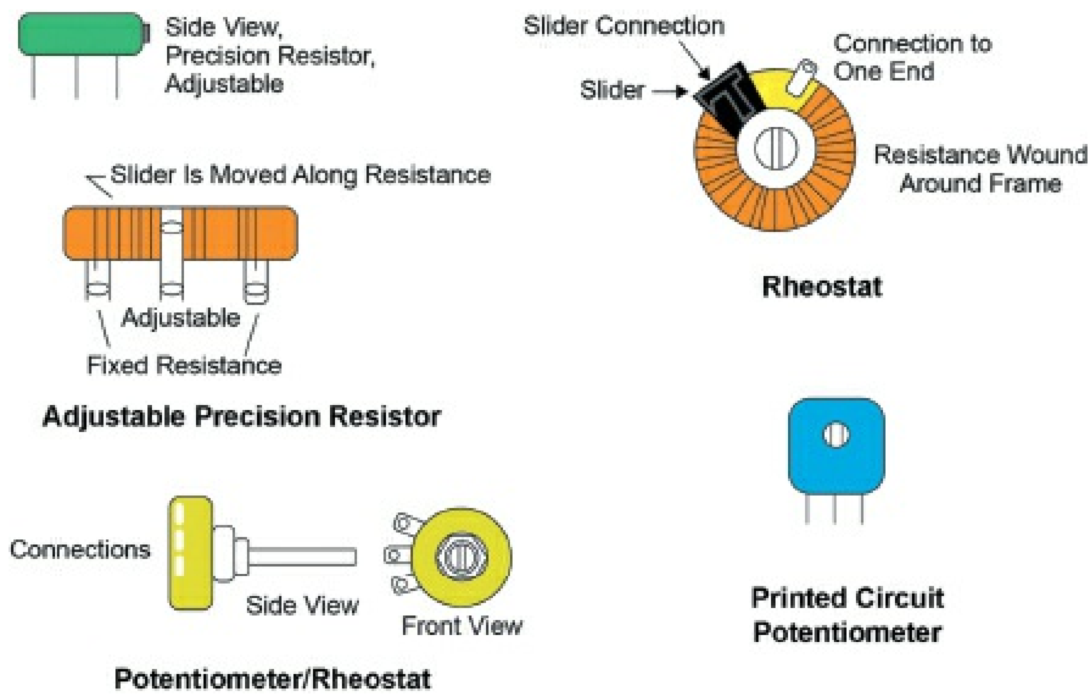


Figure A-1. Representations of various resistors.

Resistor Values

Even in the early days of electronics and resistor manufacture, it became apparent that some method was necessary to mark their value. Resistors could vary from a few hundred (at that time) to several million ohms, and it would be extremely inconvenient to have to measure a resistor every time one had to be selected. Although resistors were quite large in those days, the technology for marking them with the actual resistance was not available. A color code was devised to mark the resistors; each color stood for a decimal digit (0 to 9). A system was devised at that time (body-end-dot) but was superseded by the present system after World War II. Originally, this system used three bands of color. Other colors were added as the tolerances became tighter, but the basic system remains today. Figure A-2 represents a typical resistor with color-coded values.

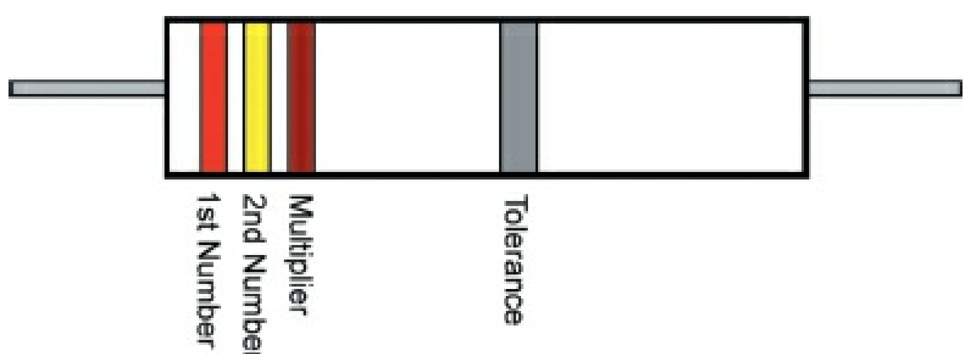


Figure A-2. Resistor color code.

The colors were assigned by the spectrum and are known as the *resistor color code* (Table A-1).

Table A-1. Color code for resistors.

Number	Color	Number	Color
0	Black	5	Green
1	Brown	6	Blue
2	Red	7	Violet
3	Orange	8	Gray
4	Yellow	9	White

There are many mnemonics to help you remember the order of the colors, or you can devise your own. Any will do if the colors are kept in order.

The first two bands are read as just significant numbers, the third band, the multiplier, is the number of zeros that follow the numbers bands. Several examples follow.

Color Code Examples

The resistor is marked: red-yellow-brown-silver

First number (red) = 2

Second number (yellow) = 4

Number of zeros (brown) = 0; therefore, the resistor is nominally a 240 Ω resistor whose tolerance (silver) is 10%. This means this resistor can measure anywhere from 216 to 264 Ω and still be in specification.

For example, a resistor is marked: blue-green-yellow-silver

First number (blue) = 6

Second number (green) = 5

Number of zeros (yellow) = 0000; therefore, this resistor is nominally 650,000 Ω

Because prefixes are used so there will not be more than three significant figures, this is properly known as a 650 kΩ resistor. The tolerance is 10% (silver). What value does this resistor have?

Hint: 10% of 650,000 = 65,000; therefore, the resistor will measure anywhere from 650 kΩ plus 65,000 Ω to 650 kΩ minus 65,000 Ω or 585,000 (585 kΩ) to 715,000 (750 kΩ) and still be in tolerance.

If the multiplier (number of zeros) band is green or above, the resistor will be in the millions of ohms, an example being brown-green-green or 1,500,000 Ω or, more properly, 1.5 MΩ. Megohms are used for those large numbers.

Tolerance

The resistance marked on a resistor is its *nominal* resistance—its desired value. The actual resistance may vary from this value. The amount it can vary is called the *tolerance* and is expressed as a percentage. A 100 Ω resistor with 10% tolerance may have any value between 90 and 110 Ω and be within specification. Because different applications call for differing amounts of tolerances, resistors come in different tolerances. The closer the tolerance, the higher the cost of the resistor. Table A-2 shows the value ranges for 1000 Ω resistors with various tolerances.

Table A-2. Standard color code.

Marked Value	Tolerance	Range of Actual Value	
Ohms	%	Low	High
1000	20	800	1200
1000	10	900	1100

1000	5	950	1050
1000	2	980	1020
1000	1	990	1010

In the three-band marking system, there is no tolerance band, and the tolerance is assumed to be ±20%; these resistors are not likely to be found in any commercial or industrial equipment. In the four-band system of marking resistors, the fourth band is the tolerance band, and it is supposed to be twice as wide as the value bands and offset from them, although looking at some of the smaller resistors, this is hard to discern. Silver represents 10%, gold represents 5%, red 2%, and brown 1%. There are no four-band resistors with a 1% or 2% tolerance. This will be clear in a moment.

This was all there was to it until transistors came into wide use in about 1956. The bipolar devices developed were current activated rather than voltage activated like the vacuum tube. Current-activated circuits generally use lower resistance than voltage-activated vacuum tube circuits. The problem comes with the color code. The lowest possible resistance that can be marked is brown-black-black, or 1–0 (and no zeros), a 10 Ω resistor. Unfortunately, smaller values were required. The color code was modified. The tolerance colors gold and silver were to be used in the number of zeros band. A silver band means you move the decimal point one place to the left (divide by 10); gold means you move the decimal point two places to the left.

Example: green-blue-silver-gold

First number (green) = 5

Second number (blue) = 6

Number of zeros (silver) = 1/10

Therefore, this is a 5.6 Ω resistor with a 5% tolerance.

Another example: brown-black-gold-gold

First number (brown) = 1

Second number (black) = 0

Number of zeros (gold) = 1/100

Therefore, this is a 0.1 Ω resistor with a 5% tolerance.

Color Code Exercises

This is a learning exercise, *not* a quiz. If you are experiencing problems:

1. Write the color code on a piece of paper so you can readily refer to it.
2. Do the exercises you find easiest first. The answers are at the end of this resource.
3. You may find it easiest to write the color code value and the number of zeros

right of the color. (Remember: black in the number of zeros column means no brown is for 1 zero).

4. After you determine the value, convert it to the appropriate prefix (meg, kilo).

5. If you are still having problems, locate a knowledgeable person who understar color code and ask for assistance.

Problem	Band 1	Band 2	Band 3	Band 4	Value
1	Brown	Green	Red	Gold	
2	Brown	Red	Black	Gold	
3	Red	Red	Yellow	Silver	
4	White	Brown	Brown	Silver	
5	Orange	White	Gold	Gold	
6	Violet	Green	Green	Silver	
7	Yellow	Violet	Brown	Gold	
8	Blue	Gray	Silver	Gold	
9	Orange	Orange	Blue	Silver	
10	Brown	Brown	Orange	Silver	
11	Brown	Black	Gold	Gold	
12	Green	Blue	Red	Silver	
13	Orange	Blue	Black	Gold	
14	Brown	Orange	Yellow	Silver	
15	Red	Black	Black	Gold	

Standard Values

Resistor values are not just random numbers. There is a set pattern of available resistors depending on tolerance. Standard values are those values that are generally available. Table A-3 shows the standard values available with 10% tolerance resistors.

Table A-3. 10% standard values.

10	12	15	18
22	27	33	39
47	56	68	82

To use this chart, place however many zeros you wish after the standard value; that is, you may expect to find as standard values: 18, 180, 1800, 18 kΩ, 180 kΩ, 1.8 MΩ, and 18 MΩ. The reason is simple. Use the 180 Ω resistor as an example. The 10% tolerance says you may expect to find its resistance between 162 and 198 Ω. The 150 Ω resistor has a high tolerance of 165 Ω, and the 220 Ω resistor has a low tolerance of 198 Ω. Therefore, with a 10% tolerance, these are all the values you can use, and there would be no sense in having a 200 Ω resistor as its tolerance would allow it to wander over the 180 or the 220 Ω resistor's range.

Obviously, if we cut the tolerance in half (5%), we should double the number of standard values. Table A-4 is the list of standard values for 5% resistors.

Table A-4. Standard values for 5% resistors.

10	11	12	13	15

16	18	20	22	24
27	30	33	36	39
43	47	51	56	62
68	75	82	91	

If you could reduce the tolerance to 1% or 2%, there would be a larger number of standard values. The need for precision resistors in modern electronics is no mystery. Manufacturing, control, and communications all require much tighter tolerances in many areas of circuitry, as these circuits must be repeatable (more precise). Table A-5 is the table of standard values for 1% and 2% resistors.

Table A-5. Standard values for 1% and 2% resistors.

100	102	105	107	110	113	115	118	121	124
127	130	133	137	140	143	147	150	154	158
162	165	169	174	178	182	187	191	196	200
205	210	215	221	226	232	237	243	249	255
261	267	274	280	287	294	301	309	316	324
332	340	348	357	365	374	383	392	402	412
422	432	442	453	464	475	487	499	511	523
536	549	562	576	590	604	619	634	649	665
681	698	715	732	750	768	787	806	825	845
866	887	909	931	953	976				

Five-Band Resistors

The 1% and 2% resistors require a new way of marking resistors. The old four-band method with its two numbers for values and one for the number of zeros will not allow us to identify the precision types. Therefore, another band for numbers was added. Figure A-3 illustrates a five-band resistor.

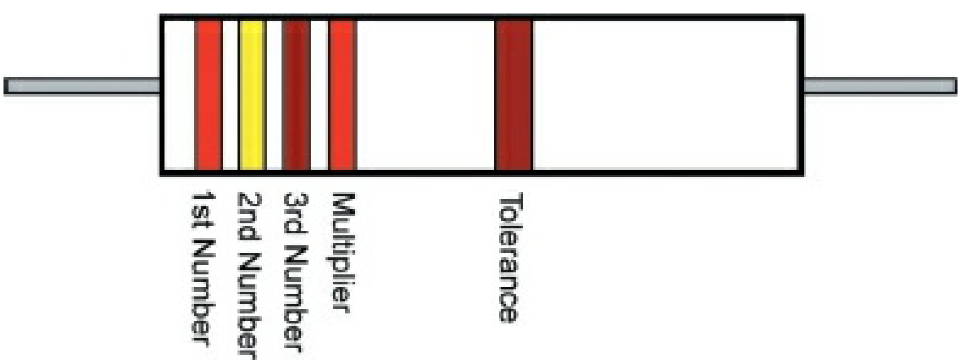


Figure A-3. Five-band resistor marking.

Although the five-band resistor is a modification of the standard color code for resistors, there will probably be no more modifications. Because of manufacturing techniques such as surface mount, the extremely small components cannot be read by the unaided eye.

Non–Color Code Marking

Some devices (particularly military resistors and many variable resistors) are marked with numbers rather than with color bands. They are always marked with two numbers and a value for the number of zeros. Tolerance will be marked elsewhere. Example: You have a variable resistor marked 123. This is a 12 kΩ resistor. The first two numbers are the values, and the third number is the number of zeros just like the color code without the colors.

Answers to Exercises on Color Codes

1	1500	1.5 kΩ	5%
2	12		5%
3	220,000	220 kΩ	10%
4	910		10%
5	0.39		5%
6	7,500,000	7.5 MΩ	10%
7	470		5%
8	6.8		5%
9	33,000,000	33 MΩ	10%
10	11,000	11 kΩ	10%
11	0.10		5%
12	5600	5.6 kΩ	10%
13	36		5%
14	130,000	130 kΩ	10%
15	20		5%

Summary

In this additional resource on resistors, type and value determination were discussed. Marking science has evolved so that even the smallest devices can be marked with the actual value, rendering the color code less useful than before. However, because there are still electric and electronic items built with color-coded resistors, technicians may need to reference the resistor color code.

Appendix B: Module Review Answers

Module 1

Module 1A: Review 1

1. Who has the ultimate responsibility for *your* safety?

   Answer: You

2. If you are given a voltmeter, can you assume this meter can safely measure any potentials in your area?

   Answer: No

3. Disrespect for electricity will eventually result in (an) injury.

Volts Conversions

Convert each listed voltage to the units that are not listed:

	kV	V	mV	μV
1	0.010	**10.0**	10.000	10,000,000
2	**0.025**	25.0	25,000	25,000,000
3	0.00078	0.780	**780**	780,000
4	0.0000000001	0.0000001	0.0001	**100**
5	**1.0**	1000	1,000,000	1,000,000,000
6	0.00506	**5.06**	5060	5,060,000
7	0.000357	0.357	3570	3,570,000
8	0.000000065	0.000065	0.065	**65,000**
9	0.0136	**13.6**	13600	13,600,000
10	0.000551	0.551	**551**	551,000

Amp Conversions

Convert each listed amperage to the units that are not listed:

	A	mA	μA
1	**20.0**	20,000	20,000,000
2	0.380	**380**	380,000
3	0.00000004	0.000040	**40**
4	**5.18**	5180	5,180,000

5	7.570	**7570**	7,570,000
6	0.00043	0.43	**43,000**
7	0.0126	**12.6**	12,600
8	0.000000951	0.000951	**951**

Ohm Conversions

Convert each listed resistance to units that are not listed:

	MΩ	kΩ	Ω
1	**2.0**	2000	2,000,000
2	0.000280	**280**	280,000
3	0.000040	0.040	**40**
4	**0.520**	520	520,000
5	3.530	3530	3,530,000
6	0.000043	43	**43,000**
7	0.0000106	**10.6**	10,600
8	0.000951	0.951	**951**

Module 1A: Review 2

1. Electromotive force is another name for electrical pressure (potential).

2. For electrical current to flow in a circuit, two things are necessary. Select t essential components from the list below.

   A. Source potential
   B. Load
   C. Complete path
   D. High resistance

   Answer: A and C

3. An insulator will conduct (*more* or *less*) current than a conductor.

   Answer: Less

4. A zero reference is necessary to determine how much potential exists bet charged object and the reference.

5. Which performs the work, electromotive force or current?

   Answer: Current

6. If you have a 10 V source and a 5 Ω load, with a complete circuit, how much curr flow in a complete circuit?

   Answer: 2 A

7. If you change the load to 10 Ω, will more or less current flow?

   Answer: Less

8. If you again change the load to 2 Ω, will more or less current flow than in questio

   Answer: More

9. Given a 230 V source and a 70 A load, what is the power being used?

   Answer: 230 • 70 = 16,100 W (or volt-amps)

10. If an incandescent lamp is rated at 100 W for 120 V, what is the current requi operate the lamp (disregard inefficiency)?

    Answer: 100/120 = 0.83 = 83%

Module 1B: Review

1. Define each of the following as concisely and accurately as possible:

   Answers:

   A. **Accuracy** – Accuracy is how closely you approximate the true value.
   B. **Precision** – Particularly in instrumentation, this means repeatability.
   C. **Measurement uncertainty** – This is the range of deviation a measurement stated tolerance; that is, the range a given reading is accurate to.
   D. **Resolution** – This is the smallest change the measurement scale/display can ac
   E. **Least count** – The determination of least count is tied directly to resolution, the interval that can be scaled/measured.
   F. **Primary standard** – Independently derived using the same methodol technology as the international standard.
   G. **Secondary standard** – Standards that are occasionally compared to the standards and are in all cases traceable to the primary standard.
   H. **Shop standard** – This is a standard device that requires periodic calibra secondary standard. Also called a *working standard*.

Module 1D: Review

1. For the circuit shown in Figure R1-1, identify the points you should use to meas voltage of:

   A. R_1 *Answer:* A to B
   B. R_2 *Answer:* B to C
   C. The applied voltage *Answer:* A to C

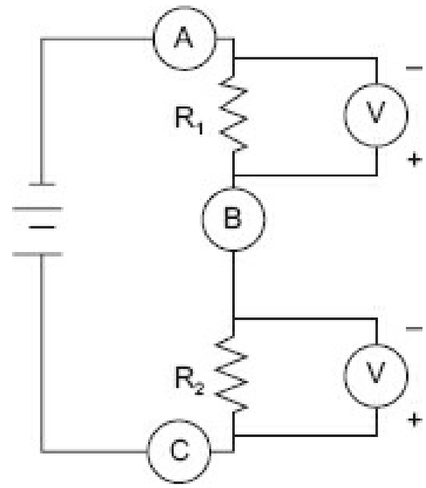


Figure R1-1.

2. In Figure R1-1, if you were to measure current, where would you insert your met

   Answer: In series, usually between the cathode (–) of the battery and A, or the anode of the battery (+) and C

3. If you have a 12.0 V source and two 1200 resistors in series, what will be the:

   A. Total current flow?

   Answer: 0.5 A, 12 (V applied) / 2,400 (Rt) = 0.5 A

   B. Total resistance?

   Answer: 2400 Ω, 1200 + 1200 Ω = 2400 Ω Rt

4. If you measure 10 mA (10/1000 A or 0.01 A) and it passes through an 1800 Ω r what is the voltage across the resistor?

   Answer: 18 V, 0.01 mA • 1800 Ω = 18 V

5. If you have a 100 V source and the total current measured is 2 A, what is tl resistance?

   Answer: 50 Ω, 100 V / 2 A = 50 Ω

6. If you wish to see a 5 V drop across a resistor for 20 mA current flow, what valu that resistor have?

   Answer: 250 Ω, 5 V / 0.02 A = 250 Ω

7. For safe measurement, voltage is always measured across the potential appropriate personal protective equipment (PPE) and safety-rated measu devices.

8. For safe measurement, current is measured in series. However, a safer way woul measure voltage across a resistor and use Ohm's law to determine current.

9. The primary safety consideration for measuring resistance is to ensure that the p
the component under test is removed.

10. Determine the requested values in problems A through C based on Figure R1-2.

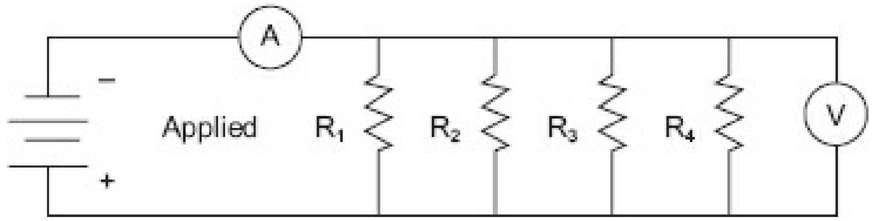


Figure R1-2.

A. Determine total current (It) when:

Applied = 100 V, R_1 = 100, R_2 = 250, R_3 = 50, and R_4 = 500

Answers:

R_1 = 100 V / 100 Ω = 1.0 A

R_2 = 100 V / 250 Ω = 0.4 A

R_3 = 100 V / 50 Ω = 2.0 A

R_4 = 100 V / 500 Ω = 0.2 A

I_t = 1.0 + 0.4 + 2.0 + 0.2 = 3.6 A

B. Determine the total resistance for problem A.

Answer: Total Resistance = 100 V / 3.6 A = 27.8 Ω

C. What is the voltage drop across R_1, R_2, R_3, and R_4 when Applied = 50 V?

R_1: 50 V R_2: 50 V

R_3: 50 V R_4: 50 V

Module 2

Module 2B: Review

1. *Answer* questions A through E based on Figure R2-1.

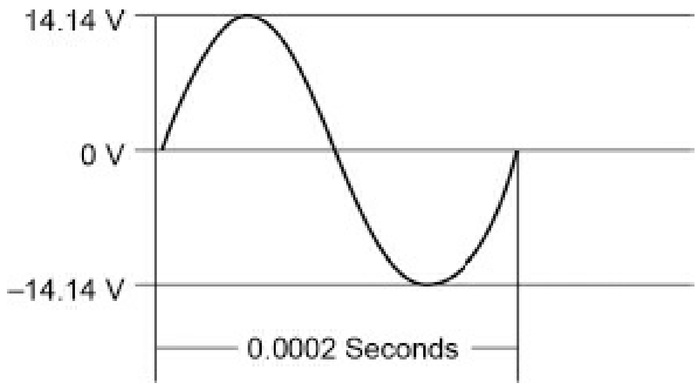


Figure R2-1.

A. What is the peak-to-peak amplitude of this signal?

Answer: 28.28 V

B. What is the peak amplitude of this signal?

Answer: 14.14 V

C. What is the rms value of this signal?

Answer: 10.0 V

D. What is the period (in seconds) of this signal?

Answer: 0.0002 s

E. What is the frequency of this signal?

Answer: 5000 Hz

2. An AC signal has an effective value of 12.6 V and a period of 16.67 ms (0.01667 s)

A. What is the peak voltage?

Answer: 17.8 V

B. What is the frequency?

Answer: 60 Hz

3. A sinusoidal AC signal has a peak-to-peak voltage of 35.6 V and a frequency o (1000 Hz).

A. What is the peak voltage?

Answer: 17.8 V

B. What is the effective voltage?

Answer: 12.58 V

C. What is the period of one cycle?

Answer: 0.01667 s

4. What is the peak instantaneous power dissipated by a 10 Ω resistor if 15 W is dis by the effective value?

   Answer: for I rms = √P / R = √15 / 10 = 1.2 A (rms)

   V (rms) = 15 / 1.2 = 12.5 V (rms)

   V (peak) = 12.5 • 1.414 = 17.7 V (peak)

   I (peak) = 17.7 V (peak) / 10 = 1.77 A (peak)

   W (peak) = 17.7 • 1.77 = 31.2 W (peak)

5. Voltage and current are ____ phase in a resistive circuit.

   A. in
   B. out of
   C. neither of the above

   Answer: A.

6. You have observed a 100 V peak-to-peak signal with a period of 0.000025 s in circuit with a 47 Ω resistor. What are the:

   A. Effective voltage — *Answer:* 35.35 V (rms)
   B. Frequency — *Answer:* 40 kHz
   C. Effective power dissipated — *Answer:* 26.6 W (rms)
   D. Peak power dissipated — *Answer:* 53.2 W (peak)

Module 2C: Review

1. A capacitor has a value of 0.047 µF. What is its value in picofarads?

   Answer: 47,000 pF

2. A capacitor has a value of 27,000 pF. What is its value in microfarads?

   Answer: 0.027 µF

3. A capacitor has a value of 0.01 µF. What is its value in picofarads?

   Answer: 1000 pF

4. A capacitor has a value of 680 pF. What is its value in microfarads?

   Answer: 0.00068 µF

5. A capacitor has a value of 0.15 µF. What is its value in picofarads?

   Answer: 15,000 pF

6. A capacitor has a value of 1000 pF. What is its value in microfarads?

Answer: 0.001 μF

7. A capacitor has a value of 10 μF. What is its value in picofarads?

   Answer: 210,000 pF

8. A capacitor has a value of 5600 pF. What is its value in microfarads?

   Answer: 0.0056 μF

9. Determine the time constant (TC) for the following values:

   A. 47 kΩ, 15 μF *Answer:* 0.705 s
   B. 1.2 MΩ, 0.001 μF *Answer:* 0.0012 s
   C. 1200 Ω, 150 μF *Answer:* 0.18 s
   D. 2.2 MΩ, 2200 μF *Answer:* 0.00484 s
   E. 390 kΩ, 2200 pF *Answer:* 0.000858 s

10. If a circuit has 450 kΩ resistance and 0.015 μF capacitance, how long will it take tc charge this circuit from a 100 VDC source? To fully discharge it?

    Answer: 0.0375 s (*Hint:* 5 TC to fully charge/discharge)

Module 2D: Review

1. Determine the capacitive reactance (X_C) of the following capacitors at the frequency.

   A. 100 kHz, 0.015 μF *Answer:* 0.11 Ω
   B. 60 Hz, 2200 μF *Answer:* 1.21 Ω
   C. 1 MHz, 680 pF *Answer:* 234 Ω
   D. 25 kHz, 1.5 μF *Answer:* 4.2 Ω
   E. 300 kHz, 0.002 μF *Answer:* 1590 Ω

Module 2E: Review

1. Determine the TC for the following resistor-inductor (RL) circuits:

   A. 12 H, 1.2 kΩ *Answer:* 0.01 s
   B. 1.5 H, 10 Ω *Answer:* 0.155 s
   C. 7 H, 25 Ω *Answer:* 0.28 s
   D. 450 mH (millihenry), 4.7 kΩ *Answer:* 0.000957 s
   E. 180 mH,120 Ω *Answer:* 0.0015 s

Module 2F: Review

1. Determine the resonant frequency for a 1 μF capacitor, 0.10 H inductor.

   Answer: (approximately) 503 Hz

2. Determine the impedance of the following circuits at the frequency given.

A. 1 kHz, 1 H, 2 kΩ — *Answer:* 1906 Ω
B. 12 kHz, 0.15 µF, 3.3 kΩ — *Answer:* 3300 Ω
C. 330 kHz, 360 pF, 1 mH, 5 kΩ — *Answer:* 5.09 kΩ

Module 2G: Review

1. A transformer has a 1:25 turns ratio. Is it a step-up or step-down transformer?

   Answer: step-up

2. A transformer with a 9.52:1 turns ratio has 220 VAC applied to the primary. Wha secondary voltage?

   Answer: 23.1 VAC

3. If a transformer primary has 1.5 A at 120 VAC and the secondary supplies 12 and draws 10 A, what is the efficiency of the transformer at this level of sec power?

   Answer: 70%

4. If the source impedance is 16 Ω and the secondary requires 3.6 kΩ, what turns ra satisfy the requirement?

   Answer: 1/15

5. Turns ratio = 25:1. If the source impedance equals 10 kΩ, what is the sec impedance?

   Answer: 16 Ω; the turns ratio squared is the impedance ratio.

Module 3

Module 3B: Review

1. List the three precautions that must be taken when making measurements.

   Answers:

   A. **Always** follow facility procedures for taking measurements.
   B. **Know** what measurement you are trying to take.
   C. **Have** the right range equipment.
   D. **Always** start on the highest range.
   E. **Never** come into contact with the circuit, bare parts of the meter leads, or allow your body to become a conductor, regardless of the voltage you thinl present or not present.
   F. **Ensure** that (in direct current measurements) the leads are of the correct polarit not a requirement for most digital multimeters, an analog meter may be dar

applying the wrong polarity.)

G. **Never** peg (go past full scale) an analog meter or keep a digital meter in an position.

2. Match the digital meter display with its significant characteristic (some charac may apply to more than one type of meter).

A. LCD	_A_	Requires backlighting for dim light conditions
	_B_	Older versions wash out under high light conditions
B. LED	_A_	Has good contrast under high light conditions
	_B_	Has a good image in low light conditions
C. EL	_C_	Requires the most power of all types listed
	_B_	Requires the least power of all types listed

Module 3C: Review

1. Given the signals on the graticules illustrated in Figures R3-1, R3-2, and R3-3, de and list the approximate voltages and frequencies displayed.

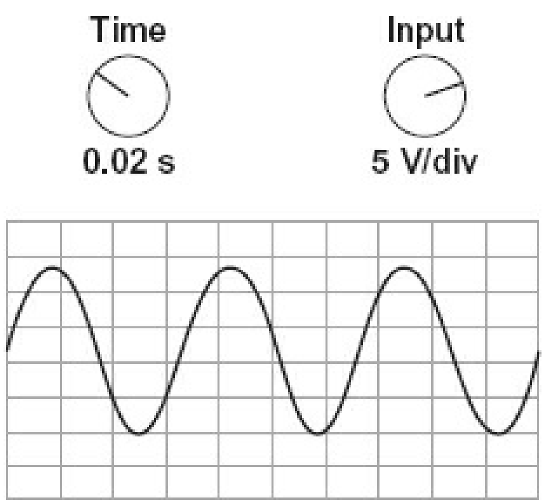


Figure R3-1.

A. Peak-to-peak voltage — *Answer:* approximately 23 V (4.6 divisions)

B. Peak voltage — *Answer:* approximately 23 V (4.6 divisions)

C. Frequency — *Answer:* 14.7 Hz (approximately 3.7 divisions •

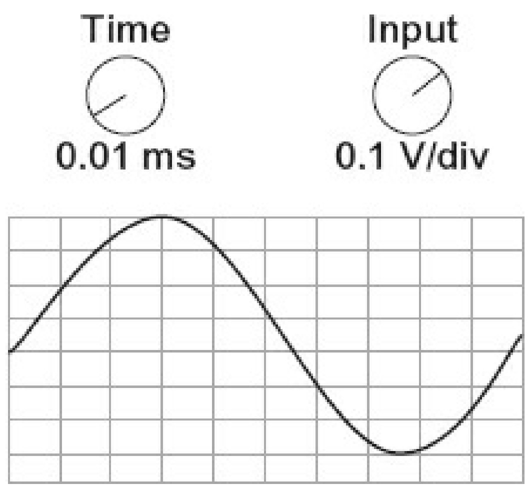


Figure R3-2.

A. Peak-to-peak voltage *Answer:* 0.7 V
B. Peak voltage *Answer:* 0.35 V
C. Frequency *Answer:* 10 kHz

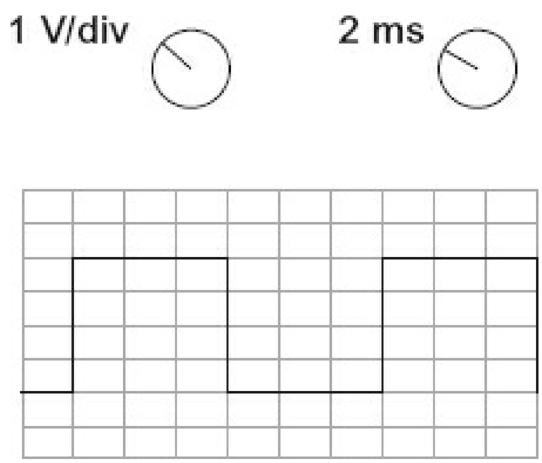


Figure R3-3.

A. Peak-to-peak voltage *Answer:* 4.0 V
B. Frequency (repetition rate) *Answer:* 166.67 Hz

2. The standard frequency is 5 kHz. Using Figure R3-4, what is the unknown freque

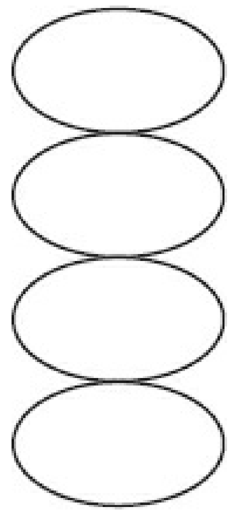


Figure R3-4.

Answer: 1250 Hz (1/4 of 5 kHz)

Module 3D: Review

1. For the listed measurements, calculate the mean, average deviation, deviation, absolute deviation.

Answers:

Mean = 10.039

Average deviation = 0.095 (add the absolute deviations and divide by 10)

Measurement	Value	Deviation	Absolute Deviation
1	10.13	**0.091**	**0.091**
2	9.97	**–0.069**	**0.069**
3	9.99	**–0.049**	**0.049**
4	10.02	**–0.019**	**0.019**
5	10.08	**0.041**	**0.041**
6	10.16	**0.121**	**0.121**
7	9.86	**–0.179**	**0.179**
8	9.88	**–0.159**	**0.159**
9	10.12	**0.081**	**0.081**
10	10.18	**0.141**	**0.141**

2. What is one method to use to consistently reduce random error in measurements?

Answer: Ensure a large number of measurement points.

3. Given the following table of values, calculate the standard deviation and the devia squared.

Answers:

To determine the standard deviation, sum the deviation squared values, divide them by 15 (n = 16, n −1 = 15), and then take the square root of that value (0.011567) = 0.107548

Measurement	Value	Deviation	Deviation Squared
1	10.13	0.1025	0.010506
2	9.97	−0.0575	0.003306
3	9.99	−0.0375	0.001406
4	10.02	−0.0075	0.000562
5	10.08	0.0525	0.002756
6	10.16	0.1325	0.017556
7	9.86	−0.1675	0.028056
8	9.88	−0.1475	0.021756
9	10.12	0.0925	0.008556
10	10.18	0.1525	0.023256
11	9.94	−0.0875	0.007656
12	9.91	−0.1175	0.013806
13	9.97	−0.0575	0.003306
14	10.15	0.1225	0.015006
15	10.13	0.1025	0.010506
16	9.95	−0.0775	0.006006

Module 3E: Review

1. If you have a working standard calibrator last calibrated at 4:35 p.m. on June 3 and you discover on September 24, 2018, that it is out of range (compared to a working standard):

   A. When would you consider any calibrations by this machine not valid?

   Answer: Any made after 4:35 p.m. on June 30, 2018

   B. What would be necessary to maintain the chain of custody?

   Answer: Recalibrate all affected devices (those calibrated after 4:35 p.m. on June 30, 2018) and investigate to see if there were product variations due to this lost calibration period.

2. You have five devices whose uncertainties are as follows:

   $U_1 = 0.05$

   $U_2 = 0.21$

$U_3 = 0.09$

$U_4 = 0.01$

$U_5 = 0.04$

Use both the linear and root-sum-square to determine the total probable error (TPE).

Answers:

Linear sum = 0.4

Sum of errors squared = 0.05

Linear = 0.04, square root of sum of errors squared = 0.24

TPE = 0.24

3. Define TAR.

Answer: TAR stands for *test accuracy ratio*, which is the ratio of the accuracy of the standard used to calibrate the device and the stated accuracy of the device.

Module 4

Module 4B: Review

1. Using Figure R4-1, fill in the blanks for A, B, and C.

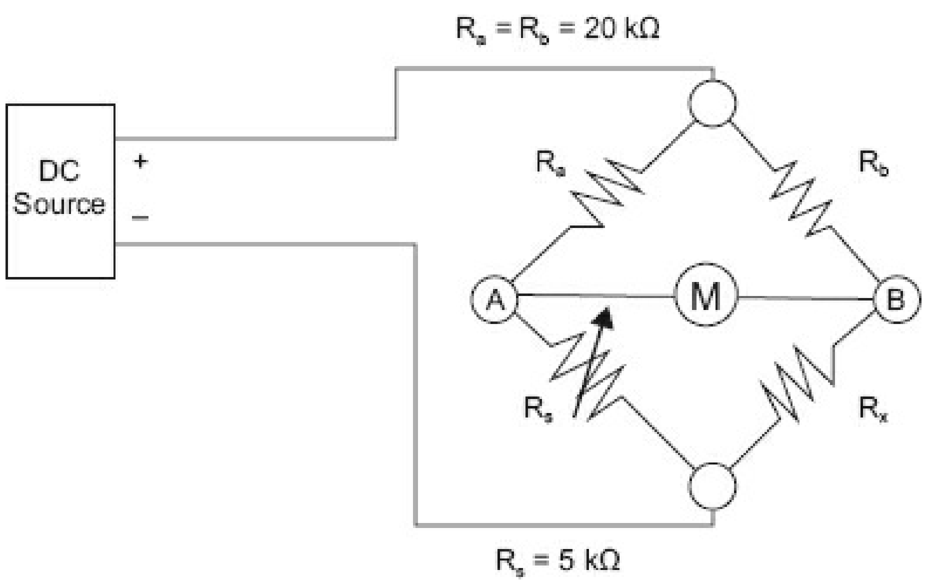


Figure R4-1.

A. If R_s is set to 3.850 kΩ for a balanced condition, what is the value of R_x?

Answer: 3.850 kΩB

B. If the DC source = 10 V at balance, what current flows in the:

(1) R_a-R_s branch *Answer:* 0.42 mA

(2) R_b-R_x branch *Answer:* 0.42 mA

(3) A-B branch *Answer:* 0.0 mA

C. What is the range (in ohms) that can be measured with this bridge?

Answer: 1 to 5000 Ω

2. Using Figure R4-2, determine the value of the multiplier resistor to measure res in the range of:

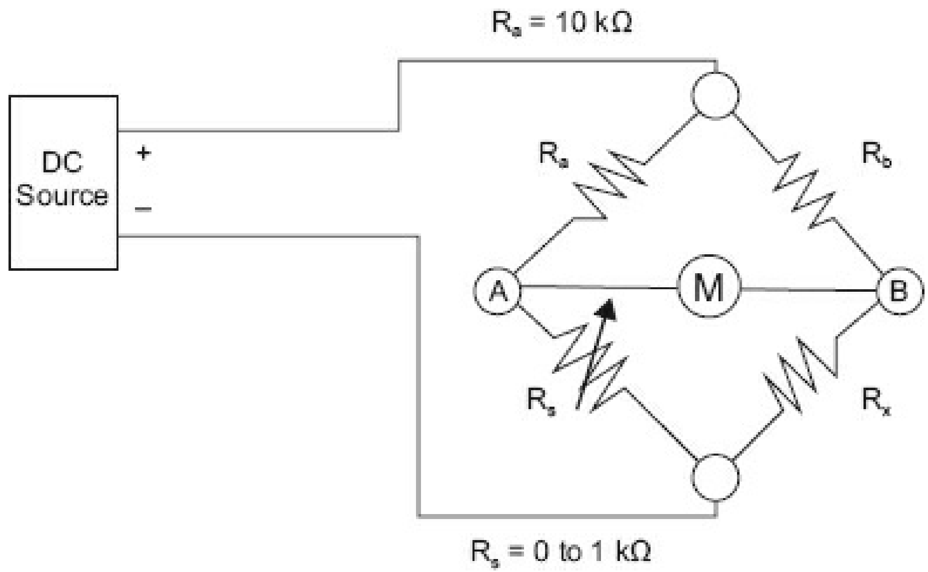


Figure R4-2.

A. 10 Ω to 1 kΩ *Answer:* 10 kΩ
B. 5 kΩ to 10 kΩ *Answer:* 100 kΩ
C. 0.1 MΩ to 1 MΩ *Answer:* 10 MΩ
D. 50 kΩ to 100 kΩ *Answer:* 1 MΩ
E. 1Ω to 100 Ω *Answer:* 1 kΩ

Module 4C: Review

1. For the values given, determine the frequency at NULL _________:

$R_a = 5$ K, $R_b = 5$ K, $R_s = 5$ K, $C_s = C_x = 1$ μF

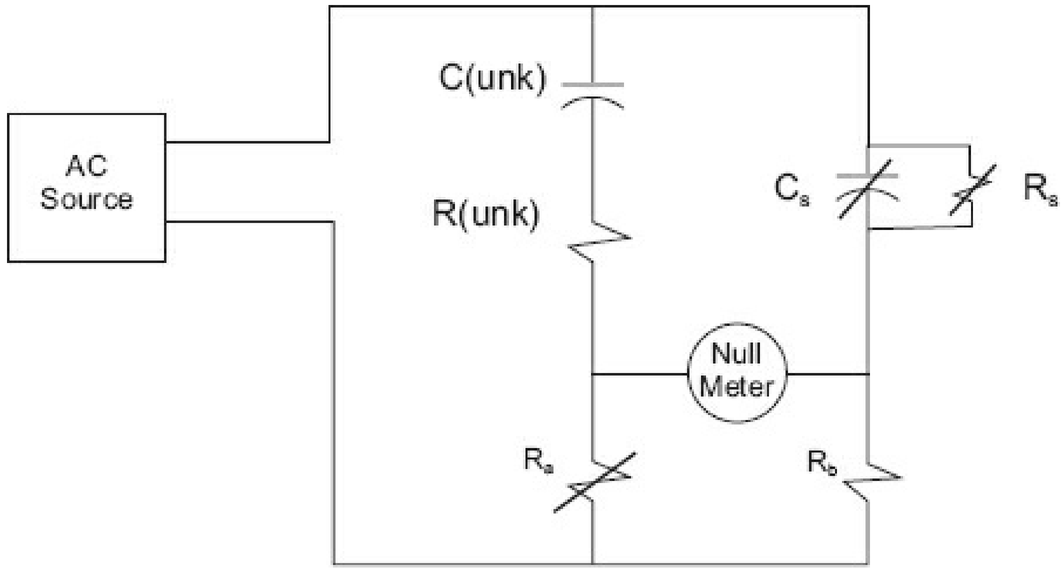


Figure R4-3.

Answer: 31.8 Hz

2. For the values given, determine the unknown capacitance, C(unk) _____ unknown resistor, R(unk) ________.

R_a = 5 K, R_b = 10 K, R_s = 3 K, C_s = 0.001 µF

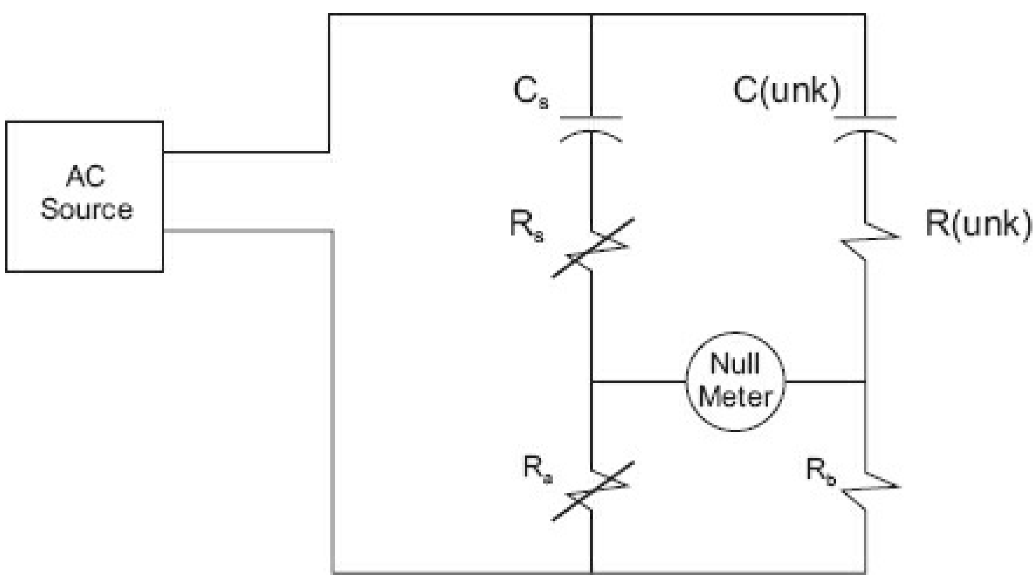


Figure R4-4.

Answers:

C(unk) = 0.0005 micro F

R(unk) = 6 kohms

Module 5

Module 5B: Review

1. Using Figure R5-1, draw the waveforms that will be present across the resistor a diode. Label each waveform with the voltage level.

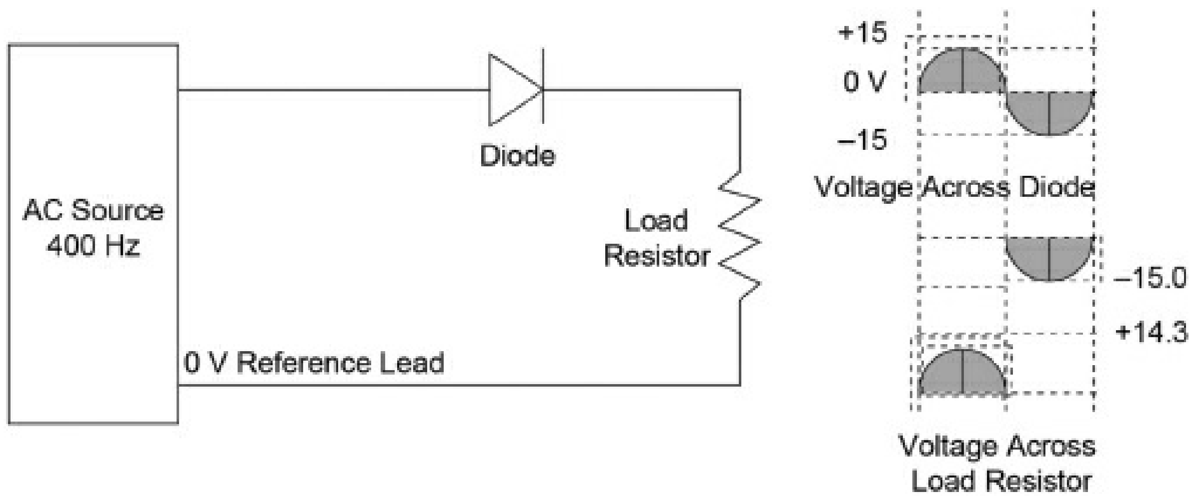


Figure R5-1.

2. Draw the output waveform for a full-wave rectifier (without a filter), assuming a frequency of 400 Hz at 100 V rms.

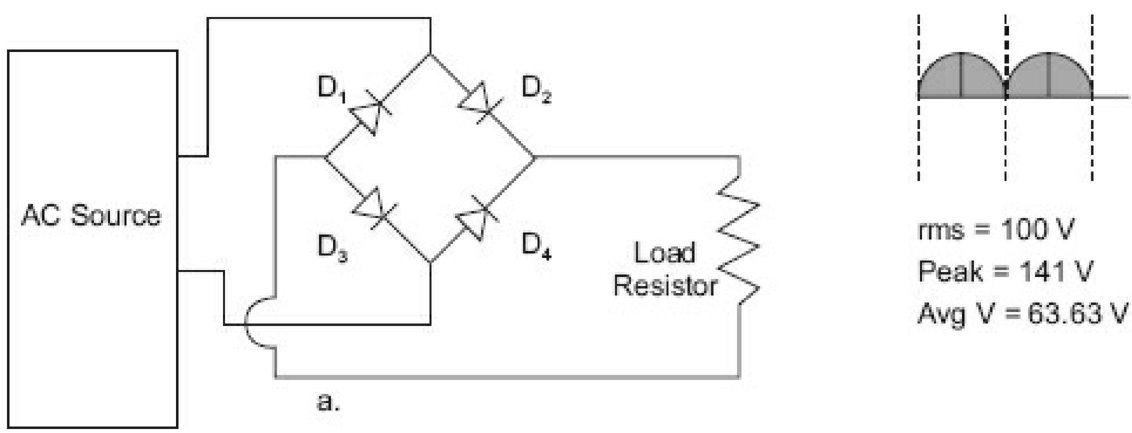


Figure R5-1.

3. In the waveform you just drew, what is the average voltage? What is the peak vo

Answers:

Average voltage = <u>63.63 V</u>

Peak voltage = <u>141 V</u>

Module 5C: Review

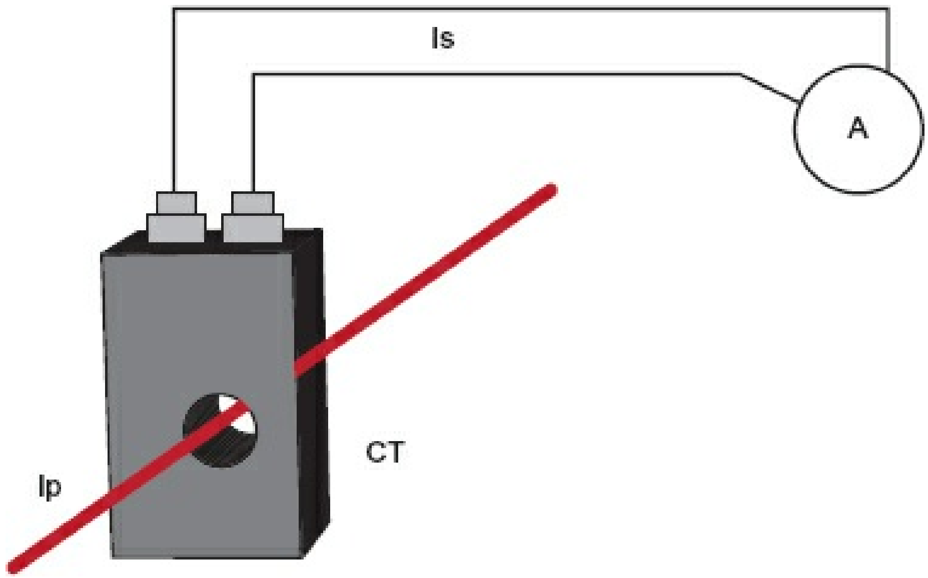


Figure R5-2.

For the circuit shown in Figure R5-2, the CT has a 250:5 ratio.

1. If 125 A flows in the primary, what will the Is value be?

   Answer: 2.5 A

2. At 125 A in the primary, what should the meter read if the meter is scaled 0 to 250 A

   Answer: 50%

Module 6

Module 6A: Review

1. Describe the condition of forward bias as it relates to a PN junction.

   Answer: If the voltage exceeds the barrier voltage (about 6.7 V in silicon), current flows.

2. What are the three elements of a bipolar transistor?

   Answer: Emitter, base, collector

3. Are bipolar transistors normally on or normally off devices?

   Answer: Normally off

Module 6B: Review

1. When a good power gain is desired, what is the most commonly used ar configuration?

   Answer: CE, common emitter

2. Why would one use a common collector configuration?

   Answer: For impedance matching

Module 6C: Review

1. What does MOSFET mean?

   Answer: Metal-oxide-semiconductor field-effect transistor

2. A JFET requires what bias on its gate to channel?

   Answer: Reverse

3. A P-channel depletion type requires what polarity voltage on the gate in respec channel to conduct?

   Answer: Reverse

4. An N-channel enhancement type requires what polarity voltage on the gate in re the channel to conduct?

   Answer: Forward

5. What are the normal storage and handling requirements for FETs?

   Answer: A conductive container, leads tied together prior to installation, and a deionizer

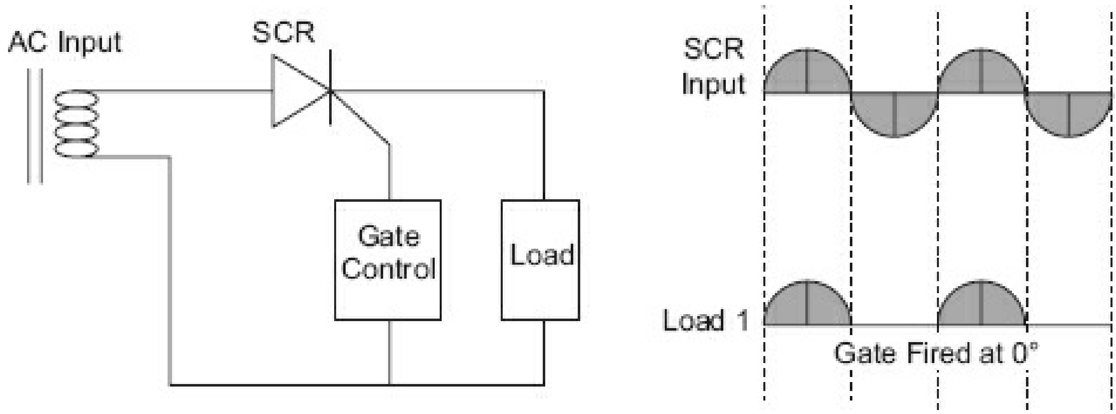
Module 6D: Review

1. If the no load voltage is 12.7 V and the full load voltage is 12.5 V, what is the per of regulation?

   Answer: 1.6%

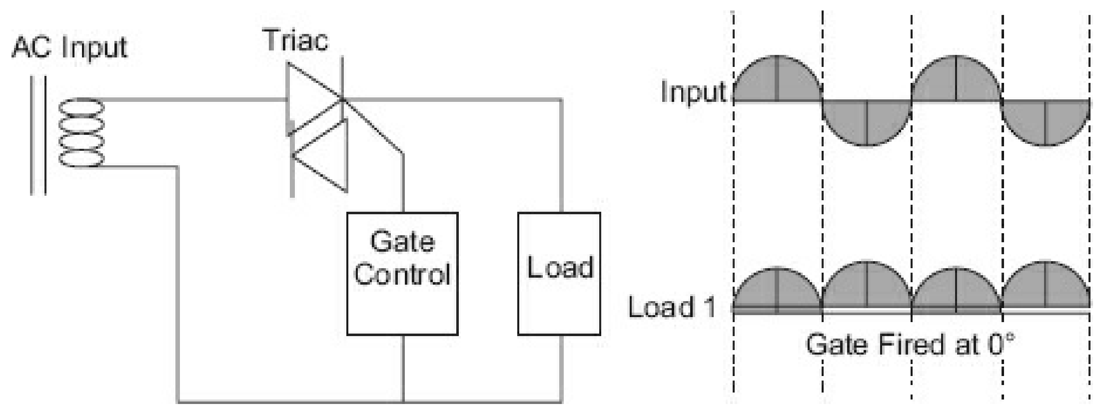
2. Draw the output waveform of an SCR triggered on at the peak of its applied alternation.

   Answer:



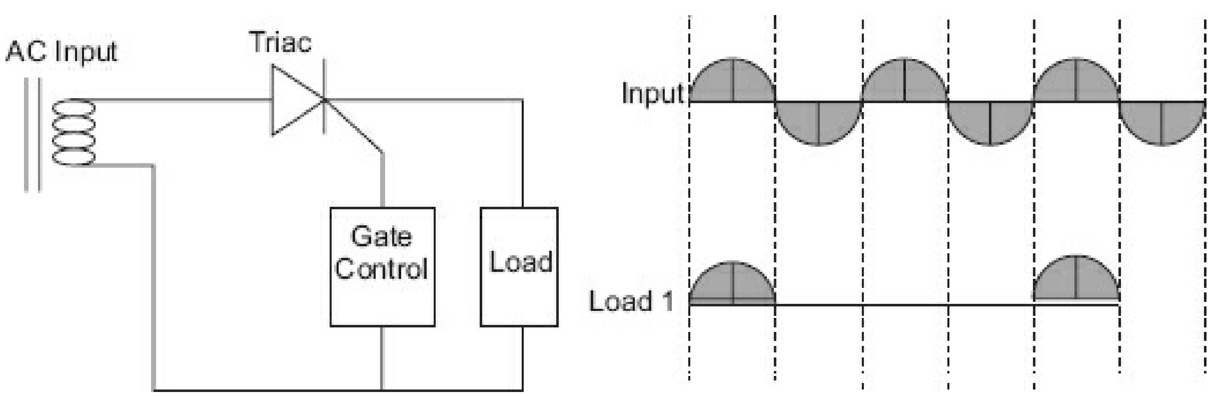
3. Draw the output waveform of a TRIAC triggered on at the peak of its
alternations.

Answer:



4. Draw the output waveform of an SCR circuit using zero crossing that is fire
third alternation.

Answer:



Module 7

Module 7D: Review

1. Given an inverting op-amp circuit, R_{in} = 2.2 kΩ and R_f = 6.8 kΩ, what is the gair circuit?

   Answer: −3.1

2. With the circuit in problem 1, a −100 mV input change will cause what output change?

   Answer: −330 mV

3. Given an inverting op-amp circuit, R_{in} = 10 kΩ and R_f = 4.7 kΩ, what is the gair circuit?

   Answer: −0.47

4. If a voltage follower with a ±15 V supply has +2 V applied to the input what output be?

   Answer: ±2 V

5. For the circuit in problem 4, if the input was +16 V, what would the output be?

   Answer: +14.3 V

6. When using a comparator, when is hysteresis necessary?

   Answer: Slow moving signals

7. How does the comparator differ from previous op-amp circuits?

   Answer: It has a binary output.

8. If you input a square wave to an integrator (of the appropriate frequency waveform will the output have?

   Answer: Triangular

9. If you input a square wave to a differentiator (of the appropriate frequency waveform will the output have?

   Answer: Peaked wave

10. An inverting summer has four inputs. Input 1 has −2.5 V, input 2 has +1 V, input +1.5 V, and input 4 has +0.5 V. If the summer has a gain of 1, what will the c voltage be?

    Answer: +0.5 V

11. A noninverting amplifier has R_f = 5 kΩ and R_{in} = 10 kΩ. With V_{in} equal to 6 V, wha the output be?

    Answer: +4 V

12. A source follower has an input impedance of 100 kΩ and an output impedance of With +4 V on the input, what voltage will be on the output?

    Answer: +4.0 V

13. Using an integrating circuit, a signal with a band of frequencies from 100 Hz to 1 is the input. Which end of the frequency band will be attenuated most?

    Answer: High end

14. Using a differentiating circuit, a signal with a band of frequencies from 100 Hz kHz is the input. Which end of the frequency band will be attenuated most?

    Answer: Low end

Module 8

1. Using a 12-bit successive approximation converter, if the input voltage range is 0 and 2.5 V is the input, what should the output be (in 1s and 0s)?

   A. Offset binary *Answer:* 100000000000
   B. Two's complement *Answer:* 000000000000

2. If the digital signal in question 1 is presented to an R-2R D/A (with a 10 V suppl D/A), what will the output be?

   Answer: 5 V

3. If +0.0025 V is presented to a 12-bit A/D, the output code will be:

   A. In natural binary (0 to 10 V range) *Answer:* 100000000001
   B. In offset binary (±5 V range) *Answer:* 100000000001
   C. In two's complement (±5 V range) *Answer:* 000000000001

   Hint: 12 bits means 4096 divisions, so 10 V/4096 = 0.00244 V for the LSB; 0.0025 V is greater than 1 LSB but less than 2 LSBs.

Module 9

1. See Figure R9-1. In Circuit 1, inputs A = 1, B = 0, and C = 1. What is the output?

   Answer: 1

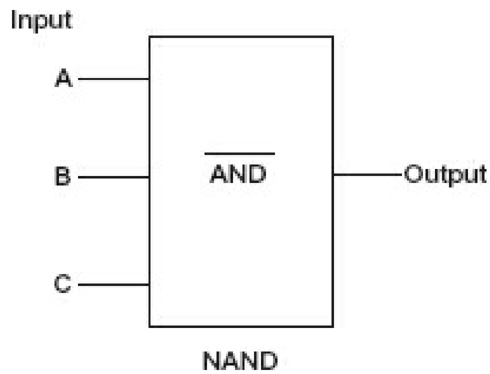


Figure R9-1. Circuit 1.

2. If Circuit 1 was a NOR with the same inputs, what would the output be?

   Answer: 0

3. If Circuit 1 was an AND, and inputs A = 1, B = 1, and C = 1, what would the outp

   Answer: 1

4. If a shift-left register had the original value of 00110010 and it is shifted twice, w the decimal values of the original value and the resultant value?

   Answer: 40, 200

5. XOR these two patterns:

   110001011011
   011000010111

   Answer: 100001011100

6. Convert hex F7 to a decimal value. (*Hint:* Convert hex to the binary pattern first.)

   Answer: 247

7. Convert decimal 57 to hex. (*Hint:* Determine the binary value of 57 first.)

   Answer: 00011100

8. See Figure R9-2. In Circuit 2, A = 0, B = 1, C = 1, D = 0, and F = 0. What is the outp

   Answer: 1

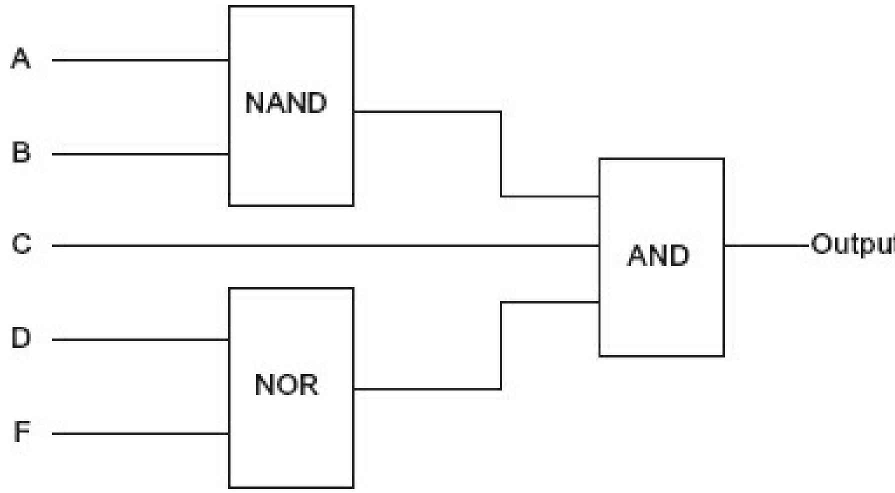


Figure R9-2. Circuit 2.

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C

Basic Electricity and Electronics for Control: Fundamentals and Applications Fourth Edition

Lawrence M. Thompson and Dean Ford, CAP, PE

As technology continues to advance, the natural laws of physics and electricity stay the same. To be an excellent automation professional, one must understand how the instrumentation measures the process and generates a signal, not just the value it delivers. You must know math and the application of math to know that the number on your calculator is correct. Without this knowledge, you may make many incorrect assumptions about the application of various instruments and the troubleshooting of those instruments.

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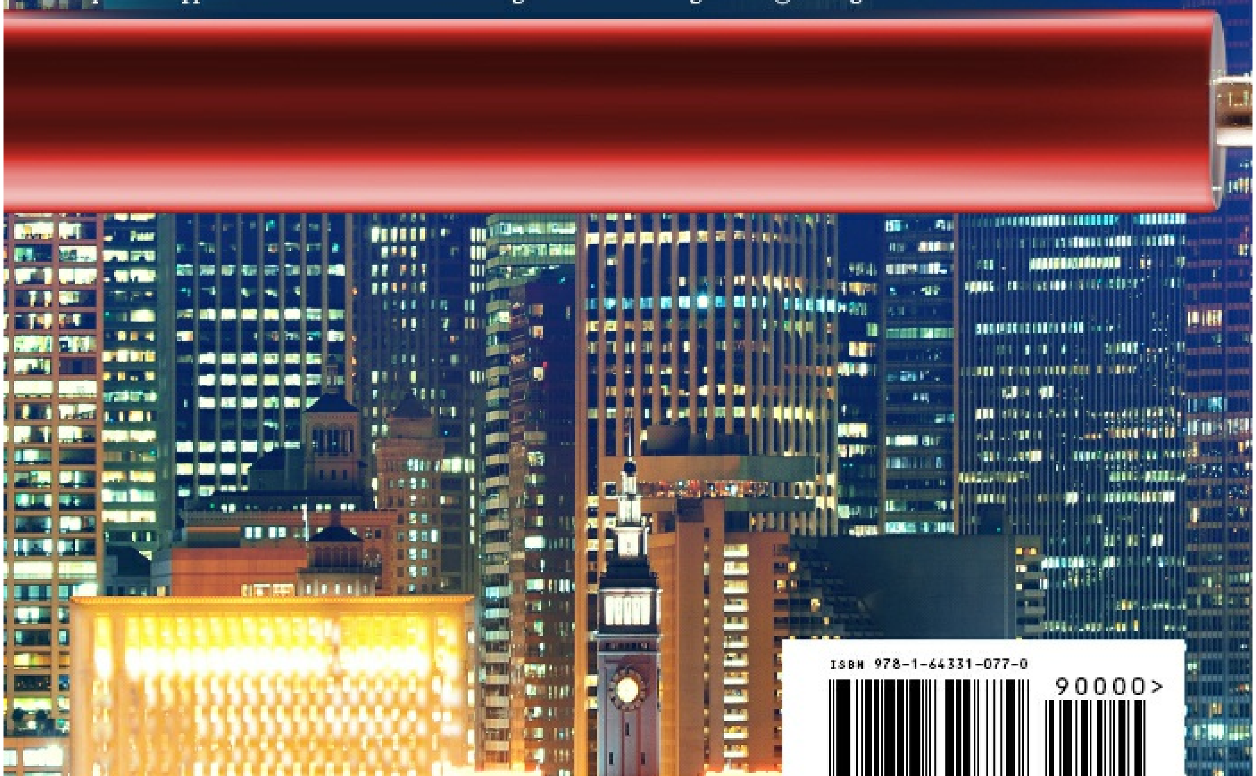

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