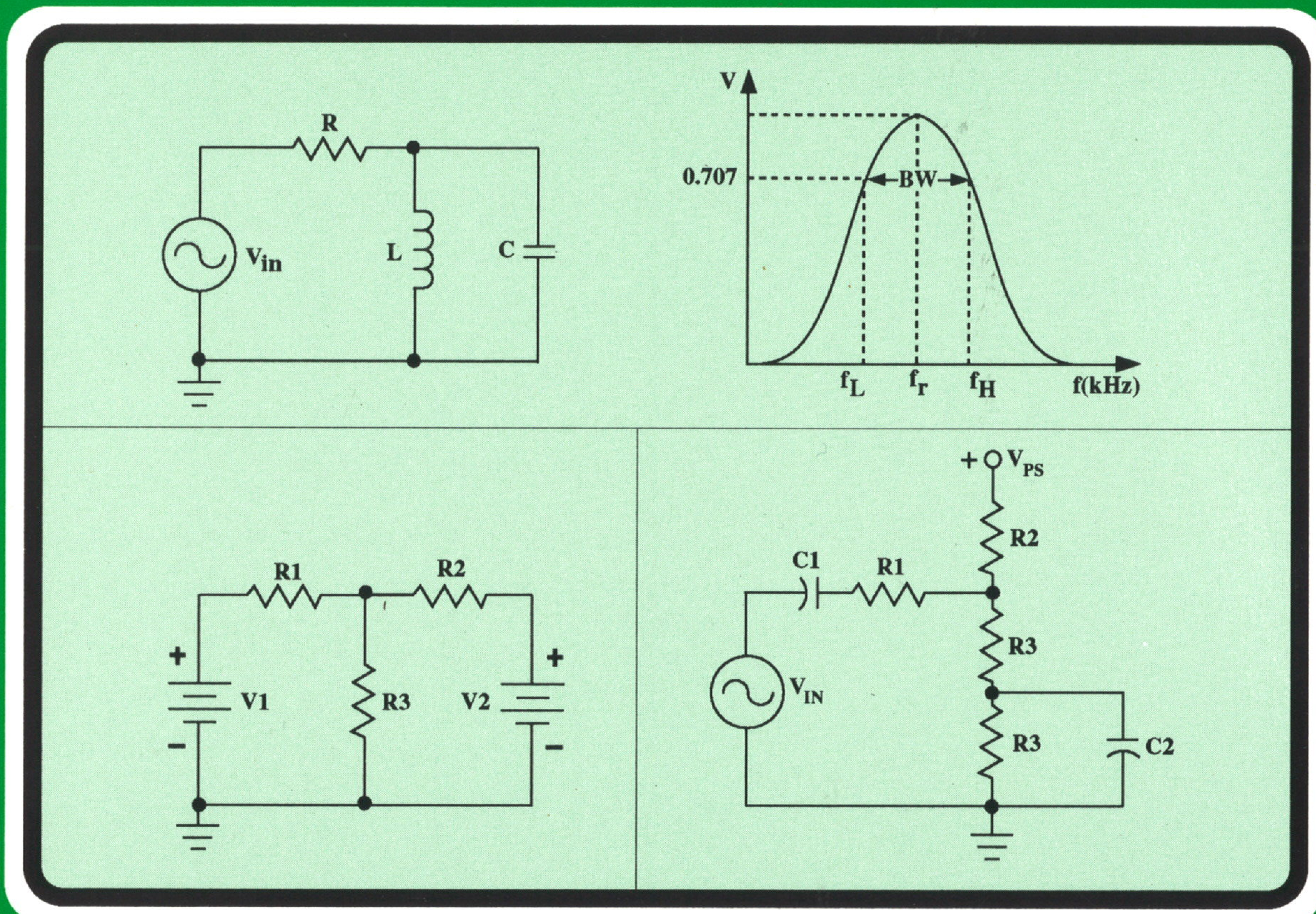
BASIC CIRCUIT ANALYSIS FOR ELECTRONICS

THROUGH EXPERIMENTATION

3rd Edition



by Lorne MacDonald

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Through Experimentation

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Preface

BASIC CIRCUIT ANALYSIS FOR ELECTRONICS Through Experimentation is a text-laboratory manual for the beginning electric circuit course in the electronics technology sequence. It provides analytical methods and laboratory exercises needed to understand basic circuits containing resistance, inductance, and capacitance. The book blends theory and laboratory work but the theory is directed toward the basic concepts necessary to do the laboratory work. So, if a student experiences problems in the laboratory, needed help is available by merely looking back to the theory section of the book.

The book is divided into two sections. The first section covers basic and advanced direct current concepts and second section covers basic and advanced alternating current concepts. The topics in each section are logically sequenced so that they range from easy to the more difficult. The concepts are explained, the formulas are derived, and circuit applications are provided and solved.

In the laboratory calculations are recorded and measurements taken, recorded, and compared. Any deviation between calculated and measured values are anticipated and explained. All circuits work. They have been logically sequenced to give students a sense of direction and to enhance self-confidence. Questions and problems are used to emphasize and summarize the major ideas of each chapter. The book can be used as a stand alone text or in conjunction with all dc-ac theory books.

Correlated with the main text is a computer simulated circuit laboratory book using the Electronic Workbench program. This book covers in detail those same laboratory exercises developed for the hardware laboratory and makes it possible to do the work without the need for regular laboratory equipment. It also serves as a check on the hardware lab exercises and helps make the concepts clearer. So, the same work can be done on the computer, in the hardware lab, or both ways. A floppy disc with pre-built circuits is available. The computer simulation program is particularly useful to students working on their own or doing distance learning course work.

Acknowledgments

A debt of gratitude is owed to the many former students, who class-tested the experiments, and to colleagues, who provided encouragement and valuable suggestions. I am especially grateful to Leon Lucchesi of Truckee Meadows Community College, John Fitzen of Idaho State University, Bud Johnson and staff at Long Beach City College, Dick Raines of Shasta College, the staff of Regency College in South Australia, the staff at British Columbia Institute of Technology, Ken Manders and Roy Brixen of the College of San Mateo, and Albert Paul Malvino. I would also like to acknowledge LeRoy Olson for his editorial advice and assistance. Lastly, I wish to thank my wife Annette, who typed the manuscript and provided encouragement.

Lorne MacDonald
1998

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by Lorne MacDonald

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"The child is father of the man"
Wordsworth

Dedicated to My Grandchildren
Jennifer
Steven
Matthew
Stephanie
Gregory
Shannon
Meghan
Brandon
Kathleen
Erin

CHAPTER 1

INTRODUCTION AND MATHEMATICS REVIEW

INTRODUCTION

The study of electronics usually begins with an electric circuit course covering direct current (dc) and alternating current (ac) circuit analysis. The basic electrical units of voltage, current, and resistance are introduced early, along with Ohm's law, the most widely used formula for the analysis of electrical and electronic circuits. The formula for Ohm's law ($I = V/R$) provides the mathematical relationship between current, voltage, and resistance in electric circuits.

Midway through the electric circuit course, capacitors and inductors are introduced. Capacitors and inductors have the characteristic of being able to store energy. Capacitors store electrostatic energy in the form of voltage and inductors store magnetic energy in the form of current. It is the study of resistors, capacitors, and inductors in various circuit combinations, using both dc and ac voltages, that provides the focus for the first course in electronics. Schematic symbols for the resistor, inductor and capacitor are shown in Figure 1-1.

(a) Resistor **(b) Inductor** **(c) Capacitor**

FIGURE 1-1: Schematic drawing symbols for the resistor, inductor, and capacitor

This chapter provides an overview of energy, voltage, current, and resistance and a discussion of conductors and insulators. A basic circuit is then described so electron current flow and conventional current flow can be compared. Following the theory review, such standard laboratory equipment as power supplies, multimeters, and solderless breadboard sockets are illustrated and described. The chapter closes with a review of powers of ten, scientific notation, and engineering notation.

ENERGY

Energy is defined as the ability to do work. The most widely used forms of energy are electrical, thermal, chemical, mechanical, nuclear, and solar. Converting energy from one form to another is common practice. One example of energy conversion is the burning of wood or coal, which transforms chemical energy to thermal (heat) energy. The combustion of gasoline in a car engine results in chemical energy being converted into mechanical energy to power the car. In addition, the fan belt in the car rotates the alternator and converts mechanical to electrical energy to recharge the car battery. The battery, in turn, delivers energy in the form of electrical current to the starter motor, head lamps, car radio, and to the remaining loads in the electrical system of the car.

VOLTAGE

Batteries are a source of potential energy in the form of dc voltage. Batteries are polarized, that is to say they have positive and negative terminals. Therefore, when batteries are connected into an electric circuit, direct current (dc) flows, but only in one direction. The dc voltage of the battery is the result of chemical energy being converted to electrical energy. The positive (+) charges on one terminal and the negative charges (–) on the other terminal are caused by the chemical separation of positive and negative charges. It is the potential difference between the positive and negatively charged terminals that has the potential to do work. Potential difference is also referred to as electromotive force (emf). The letter symbol for electromotive force is E, which is used along with V to identify voltage. In most schematics, and in circuit analysis, the term emf (E) gives way to the more general term for voltage, which is V.

Laboratory power supplies are also used to supply dc voltage, and they do so by converting the ac line voltage to dc voltage. In fact, most of the dc voltage used to power electronic systems comes from power supplies. The term used to designate power supply voltage is generally V or V_{PS}. A battery, a dc power supply, and the schematic symbol for dc voltage sources are shown in Figure 1- 2.

Courtesy of Hewlett-Packard Company

(a) Battery **(b) Power Supply** **(c) Schematic Symbol**

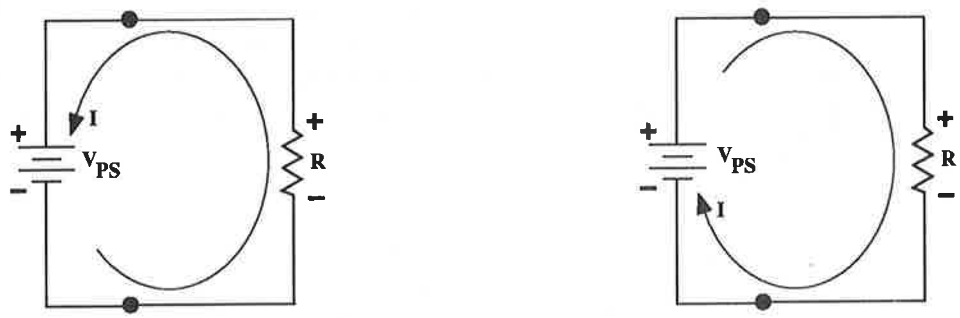
FIGURE 1-2: Commonly used voltage sources and the schematic symbol for dc voltage sources.

CURRENT FLOW

The unit of current is the ampere named after the French scientist Andre Ampere. The letter symbol for current is I (from the French *intensitē*). Electric current in metals, such as copper or silver, is the controlled flow of free electrons. All atoms, the smallest particle of any material, contains a nucleus of positively charged protons surrounded by an equal number of negatively charged electrons. Since like charges repel and unlike charges attract, a balanced atom has the negatively charged electrons, attracted to, but orbiting around the positively charged nucleus. However, under the influence of voltage or heat, an electron can be removed from an atom, especially those electrons that are far removed from nucleus. Then, as one negatively charged electron drifts away, another one is immediately attracted to fill the void. Although the drift is of a short distance and a short duration, it is the large number of free electrons being exchanged between atoms, billions at a time in a conductor, that causes current to flow. The flow of electrons in a conductor under the influence of an external voltage is from negative to positive, and the term given to the movement of these electrons is electron current flow.

However, in the analysis of dc circuits, conventional current flow is also widely used, where current is considered to flow from positive to negative. Essentially, years before the electron was discovered, the flow of current was assumed to flow from positive to negative, like the current in rivers that flows from high to low. However, even after the discovery of electron current flow, not everyone changed to the "correct" method. Those that did not, and continued to use the conventional current method, realized that using one method or the other simply indicated the direction of the current, and nothing else, since either method maintained the same polarities and practical connections of ammeters or voltmeters. Therefore, it was decided "by convention" to maintain the positive to negative conventional current flow.

So, at the atomic level, electron flow in conductors may be necessary to fully understand the basic laws. However, at the component level, both electron current flow and conventional current flow are successfully used. The two methods of current flow are shown in Figure 1-3. While beginning students find electron flow easier to understand, working technicians and engineers generally use conventional current flow. So, it is necessary to choose one method or other of current flow, and use that method consistently in the analysis of dc circuits. However, the understanding of both current flows is necessary in more advanced course work. This is especially true in the study of semiconductors, where both negative to positive (electron flow) and positive to negative (hole flow) are found.



(a) Electron Current Flow (b) Conventional Current Flow

FIGURE 1-3: Schematic drawings showing (a) electron current flow and (b) conventional current flow.

CONDUCTORS

Metals are the materials most commonly used to conduct current. Such metals as copper, silver, gold and aluminum conduct current easily because they have a huge number of free electrons and, therefore, low resistance to current flow. For example, a cubic inch of copper at room temperature has approximately 10^{23} free electrons. Only silver has more free electrons and, for this reason, is slightly more conductive than copper. However, silver is costly. Gold is also expensive, but it has relatively low resistance and doesn't corrode. For that reason gold is widely used in semiconductor devices and in specialized connectors.

INSULATORS

Insulators are nonconducting materials since they have very few free electrons. They are used to prevent the flow of electricity between conductors. For example, in ordinary lamp cords the conductors are kept separate by using rubber or plastic types of insulation. Other materials that make good insulators, because they do not conduct current, are glass, plastic, paper, mica, porcelain, ceramic, and Bakelite. Dry air is also considered an insulator.

RESISTANCE

Resistance is defined as the opposition to current flow and the higher the resistance the lower the current flow. The unit of resistance is the ohm named after the German physicist Georg Ohm. The letter symbol for resistance is R and the symbol for ohm is the Greek letter Ω (omega). Basically, one volt (1 V) of voltage applied to one ohm (1 Ω) of resistance causes one ampere (1 A) of current to flow in a circuit. The resistance of any conductive materials is based on its physical size and shape, and it is subject to temperature change. For example, with reference to Table 1-1, the materials are listed by their resistance in ohms in circular mils at 20° C. So, one foot of one mil copper wire at 20° C is 10.5 Ω. Silver is the most conductive (least resistive) followed by copper, gold, and so forth. Carbon at 4200 ohms is the substance used in the construction of carbon composition resistors. The resistivity values of insulators such as glass and rubber is much higher and they are, for all practical purposes, not conductive.

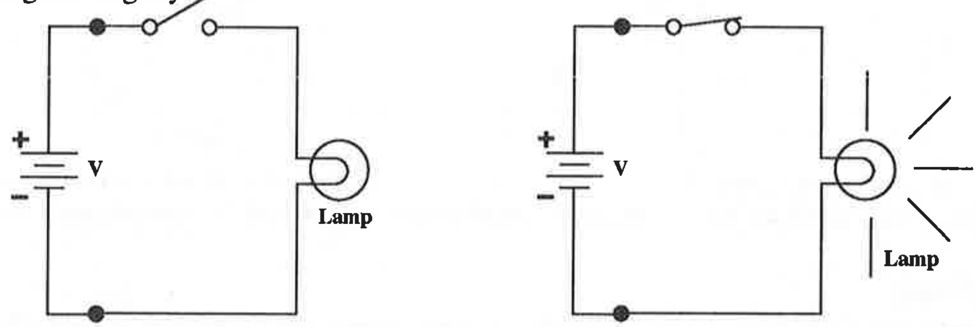
SUBSTANCE	circular mils per ft. in Ω		SUBSTANCE	circular mils per ft. in Ω	
Silver	9.9 Ω	Conductors	Carbon	4200 Ω	Semiconductors
Copper	10.5 Ω		Silicon	3.3×10^5 Ω	
Gold	15 Ω		Glass	10^{15} Ω	Insulators
Aluminum	17 Ω		Rubber	10^{20} Ω	

TABLE 1-1

THE BASIC ELECTRIC CIRCUIT

A basic electric circuit contains a power source, a load, connecting conductors, and a switch, as shown in Figure 1-4. The power source could be batteries or a laboratory power supply, the load is an incandescent lamp, and the conductors are generally copper wire.

When the switch is open, as shown in Figure 1-4(a), no voltage is applied across the lamp, no current flows, and the lamp is off. However, when the switch is closed, as shown in Figure 1-4(b), voltage is applied across the lamp, current flows through the lamp, and the combination of current and voltage (power) causes the lamp to glow. If there is enough voltage (pressure) across the lamp, the current through the lamp will be high and the lamp will glow brightly.



(a) Switch Open with No Current Flow **(b) Switch Closed with Current Flow**

FIGURE 1-4: A basic electric circuit contains a power source, a load, connecting conductors, and a switch.

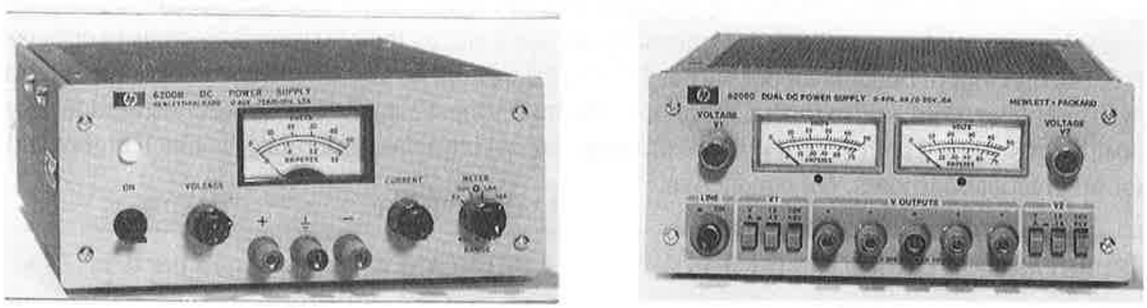
STANDARD LABORATORY EQUIPMENT

The standard laboratory equipment needed to perform most dc-ac circuit experiments includes a power supply, a multimeter, a signal generator, and an oscilloscope. A well equipped laboratory work station is equipped with a single or dual-trace oscilloscope, an analog and/or digital multimeter, a sine-wave signal generator and/or function generator (provides sine, square, and triangle waveshape outputs), and a power supply, preferably dual, capable of providing plus (+) and minus (–) dc voltages.

DIRECT CURRENT POWER SUPPLIES

Power supplies are the most widely used source for dc voltages in electronic systems. They are also standard equipment in laboratories. The power supplies in laboratories are normally variable, which means they can be varied to operate at any voltage between a given limit, such as 0-50 volts. These supplies are designed to be reliable. Despite an occasional blown fuse, power supplies should operate efficiently for many trouble-free years.

Examples of standard laboratory power supplies are shown in Figure 1-5. A single 0-50 V dc power supply is shown in Figure 1-5(a) and a dual 0-50 V plus (+) and minus (-) supply is shown in Figure 1-5(b). Plus-and-minus d-c voltages can also be obtained by connecting two single supplies together.



Courtesy of Hewlett-Packard Company *Courtesy of Hewlett-Packard Company*

(a) Single Power Supply **(b) Dual Power Supply**

FIGURE 1-5: Power supplies are the most common source of dc voltage for electronic systems.

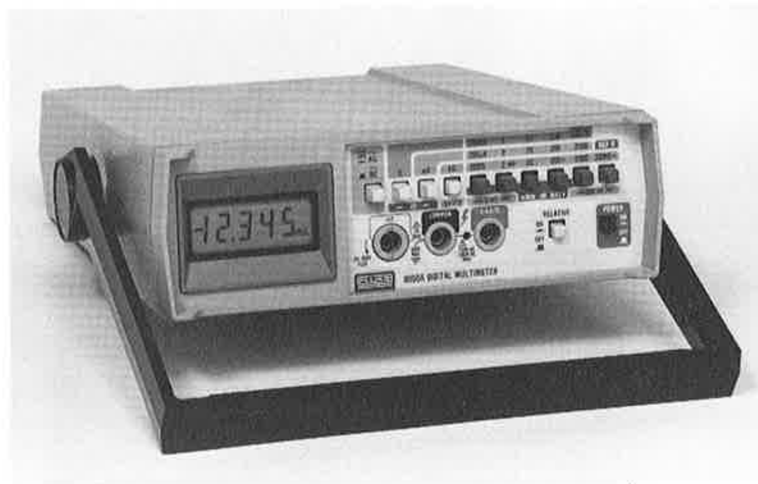
MULTIMETERS

A Multimeter is an instruments capable of measuring dc and ac volts, dc and ac current in amperes, and resistance in ohms. Multimeters are often called VOM's (volt-ohm-milliampere) and can be analog or digital.

In analog meters the volt-ohm-milliampere functions use the same meter movement, while the functions on a digital meter are all displayed on a common digital readout. Although the use of digital multimeters has increased dramatically in recent years, mainly due to their exactness and ease of use, analog meters still have certain advantages, such as monitoring exponential rises of dc voltage across a capacitor. An analog multimeter is shown in Figure 1-6(a) and a digital multimeter is shown in Figure 1-6(b).

Courtesy of Simpson Electric Company

(a) Analog Multimeter



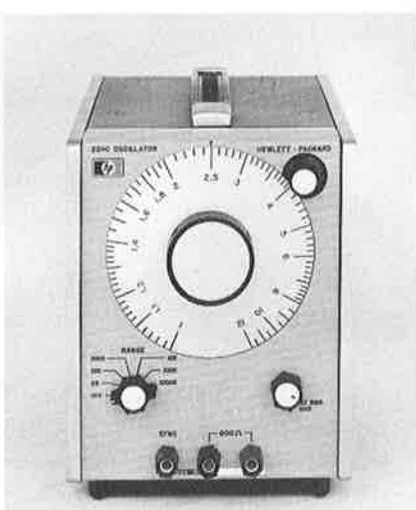
Courtesy of John Fluke Mfg. Co., Inc.

(b) Digital Multimeter

FIGURE 1-6: Multimeters measure dc and ac volts, current in amperes, and resistance in ohms.

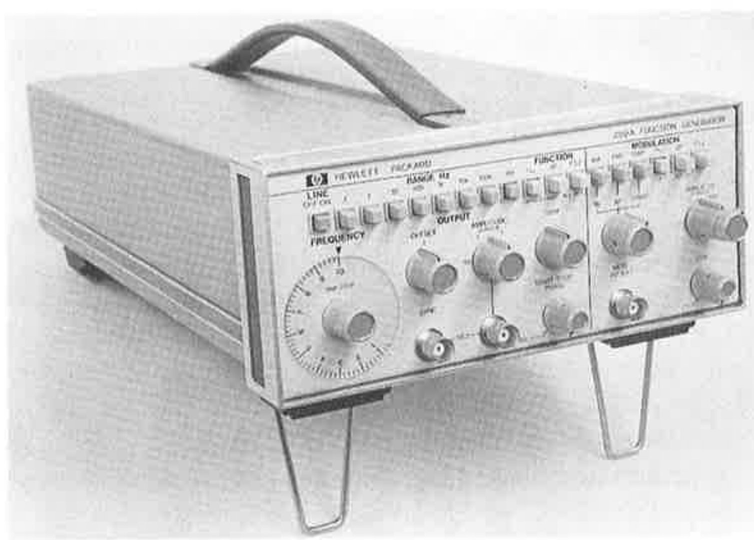
SIGNAL AND FUNCTION GENERATORS

Signal generators and function generators are used to provide sources for ac signal voltages. A signal generator, such as that shown in Figure 1-7(a), can provide sine waves with output signals in excess of 15 Vp-p with a frequency response from below 10 Hz to 1 MHz. The function generator, such as that shown in Figure 1- 7(b), will provide sine, square, and triangle waves at a nominal output signal of 10 Vp-p with frequency responses below 1 Hz to above 5 MHz.



Courtesy of Hewlett-Packard Company

(a) Signal Generator



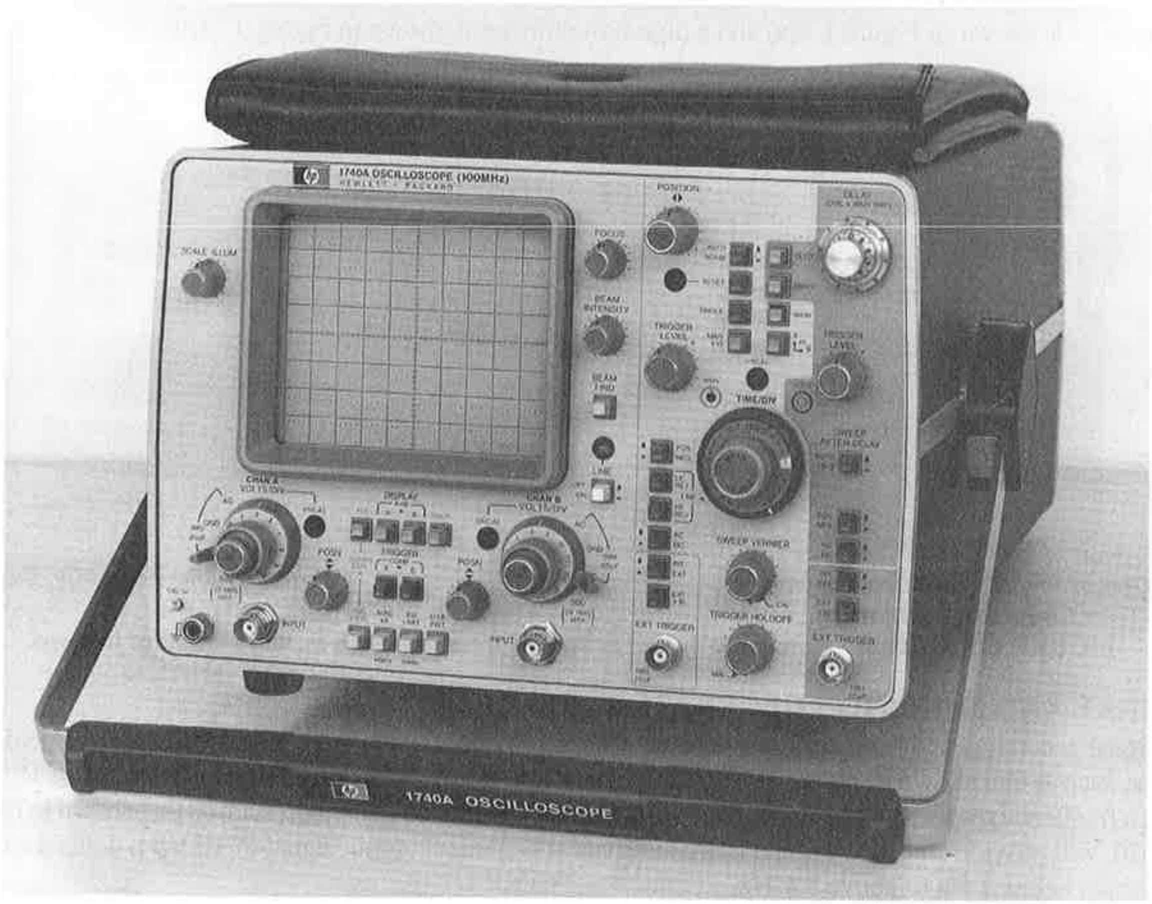
Courtesy of Hewlett-Packard Company

(b) Function Generator

FIGURE 1-7: Signal and function generators provide ac signal source voltages.

OSCILLOSCOPES

Oscilloscopes provide a visual measurement of dc voltage and ac signal voltage. Therefore, the shape and amplitude of ac signals can be fully observed. Any distortions can be readily seen. Oscilloscopes, normally referred to as "scopes", measure the ac signal in peak-to-peak voltage, while voltmeters provide the rms (rootmean-square) value of the ac wave. Scopes can also measure the frequency and time of periodic (ac) waves. Scopes can measure signal voltages that range from millivolts (mV) to more than 100 V, and they have a frequency response that extends from dc to above 100 MHz. A dual-trace oscilloscope is shown in Figure 1-8.



Courtesy of Hewlett-Packard Company

FIGURE 1-8: Oscilloscopes provide a visual measurement of dc voltage and ac signal voltage.

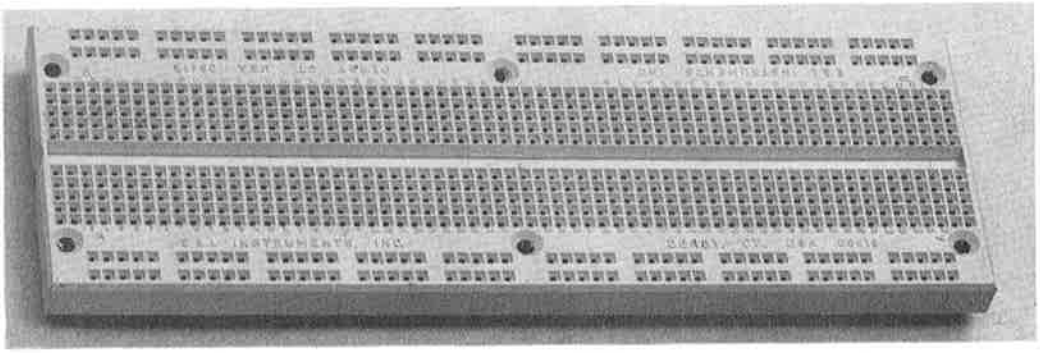
THE ART OF BREADBOARDING

Regardless of how large or how small an eventual electronic system is at completion, all systems begin at the circuit component level. Breadboarding is the "art" of connecting or building circuits at the component level and then electrically testing them. Different methods of breadboarding can be used in the laboratory depending on the eventual use of the circuit.

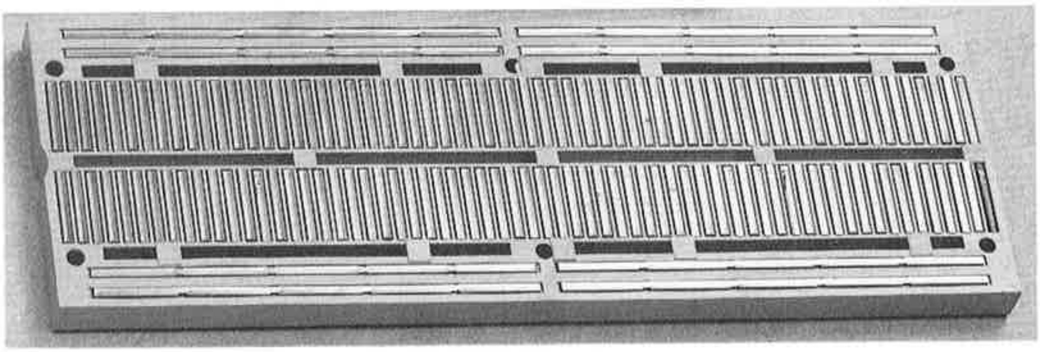
One of the most popular methods of breadboarding is the use of the solderless breadboarding socket, like that shown in Figure 1-9. The advantage of using solderless connectors is the ease of circuit assembly and circuit changes. However, solderless connectors should be limited to voltages of no higher than 50 volts and currents no greater than 10 amps. Solderless connectors are typically limited to circuits with operating frequencies no greater than 10 MHz. Also, the use of oversize wire can damage the contacts on the socket, so component leads larger than #22 should be avoided. One way to avoid damage to the pins from oversize leads is to solder #22 wire to the leads. Another technique is to trim the oversize leads by cutting them at a 45^o angle. Front and back views of the SK-10 universal breadboarding socket are shown in Figure 1-9. Notice how the holes are electrically connected both horizontally and vertically. The horizontal strips connecting the two outer rows are commonly used for the power supply connections and the vertical strips provide 5 connections at each of the 128 individual locations.

SCIENTIFIC NOTATION AND ENGINEERING NOTATION

Electric and electronic circuit analysis is applied mathematics and often involves very large and very small numbers. Therefore, scientific and engineering notation, which are forms of powers of ten notation, must be



(a) Component Side



(b) Conductor Side

Courtesy of E & L Instruments, an Interplex Electronics Co., New Haven, CT

FIGURE 1-9: The SK-10 universal solderless breadboarding socket.

mastered to help simplify the mathematical calculations. Essentially, in scientific notation all numbers are converted to numbers between 1 and 10 multiplied by a power of ten. Engineering notation is similar to scientific notation except the powers of ten exponents used are all multiples of 3 (3, 6, 9, 12, etc.). The following list shows the powers of ten numbers between 1 and 100,000 (positive exponents) and then between 0.1 to 0.00001 (negative exponents).

$1 = 1 \times 1 = 1 \times 10^0$

$10 = 1 \times 10 = 1 \times 10^1$

$100 = 1 \times 100 = 1 \times 10^2$

$1{,}000 = 1 \times 1{,}000 = 1 \times 10^3$

$10{,}000 = 1 \times 10{,}000 = 1 \times 10^4$

$100{,}000 = 1 \times 100{,}000 = 1 \times 10^5$

$0.1 = 1/10 = 1/10^1 = 1 \times 10^{-1}$

$0.01 = 1/100 = 1/10^2 = 1 \times 10^{-2}$

$0.001 = 1/1{,}000 = 1/10^3 = 1 \times 10^{-3}$

$0.0001 = 1/10{,}000 = 1/10^4 = 1 \times 10^{-4}$

$0.00001 = 1/100{,}000 = 1/10^5 = 1 \times 10^{-5}$

SCIENTIFIC NOTATION

Scientific notation is powers of ten notation. All numbers are written between 1 and 10 times a power of ten. For example, 354 in scientific notation is 3.54×10^2. The decimal was moved to the right of the first digit and the number of spaces moved is counted. Since two spaces were moved, the multiple is $100 = 10^2$. In other words, the exponent, or power to which the 10 is raised, simply indicated the multiple or number of zeros. Therefore 354 indicates 3.54 and a multiple of 100, or $3.54 \times 100 = 3.54 \times 10^2$.

Examples of numbers expressed in scientific notation:

$3{,}000{,}000 = 3 \times 1{,}000{,}000 = 3 \times 10^6$

$27{,}000 = 2.7 \times 10{,}000 = 2.7 \times 10^4$

$3{,}300 = 3.3 \times 1{,}000 = 3.3 \times 10^3$

$250 = 2.5 \times 100 = 2.5 \times 10^2$

$12 = 1.2 \times 10 = 1.2 \times 10^1$

$3 = 3 \times 1 = 3 \times 10^0$

$0.3 = 3/10 = 3/10^1 = 3 \times 10^{-1}$

$0.025 = 2.5/100 = 2.5/10^2 = 2.5 \times 10^{-2}$

$0.0063 = 6.3/1{,}000 = 6.3/10^3 = 6.3 \times 10^{-3}$

$0.0005 = 5/10{,}000 = 5/10^4 = 5 \times 10^{-4}$

$0.00004 = 4/100{,}000 = 4/10^5 = 4 \times 10^{-5}$

$0.000002 = 2/1{,}000{,}000 = 2/10^6 = 2 \times 10^{-6}$

ENGINEERING NOTATION

Engineering notation is powers of ten notation using exponents that are multiples of 3 such as; 10^3, 10^6, 10^9, 10^{-3}, 10^{-6}, and 10^{-9}.

$1{,}000{,}000 = 1 \times 10^6$	$0.1 = 1 \times 10^{-1} = 100 \times 10^{-3}$
$100{,}000 = 1 \times 10^5 = 100 \times 10^3$	$0.01 = 1 \times 10^{-2} = 10 \times 10^{-3}$
$10{,}000 = 1 \times 10^4 = 10 \times 10^3$	$0.001 = 1 \times 10^{-3} = 1 \times 10^{-3}$
$1{,}000 = 1 \times 10^3$	$0.0001 = 1 \times 10^{-4} = 100 \times 10^{-6}$
$100 = 0.1 \times 10^3$	$0.00001 = 1 \times 10^{-5} = 10 \times 10^{-6}$
$10 = 0.01 \times 10^3$	$0.000001 = 1 \times 10^{-6}$

Some of the most commonly used multiples and submultiples of numbers are provided in the following list.

10^{12}	Tera	T	10^{-3}	milli	m
10^9	Giga	G	10^{-6}	micro	μ
10^6	Mega	M	10^{-9}	nano	n
10^3	kilo	k	10^{-12}	pico	p
10^0	Basic unit	(1)	10^{-15}	femto	f

NOTE: The 10^3 multiple for 1000 is given by a lower case k because K is allocated for degrees Kelvin. The remaining multiples greater than unity (M, G, and T) are all capital letters.

Volts, amps, ohms, farads, henries, and hertz are terms widely used in electrical and electronic circuit analysis. However, when used in circuit analysis, these terms are expressed by numbers which are much larger or much smaller than the basic unit.

Examples of numbers expressed in engineering notation:

a. Examples in volts:
$10\ \mu V = 10 \times 10^{-6}$ V
1.8 kV $= 1.8 \times 10^3$ V

b. Examples in current:
$3\ \mu A = 3 \times 10^{-6}$ A
15 mA $= 15 \times 10^{-3}$ A

c. Examples in frequency:
10 kHz $= 10 \times 10^3$ Hz
1 GHz $= 1 \times 10^9$ Hz

d. Examples in resistance:
$1.2\ M\Omega = 1.2 \times 10^6\ \Omega$
$300\ k\Omega = 300 \text{ x } 10^3\ \Omega$

e. Examples in farads:
$10\ \mu F = 10 \times 10^{-6}$ F
100 pF $= 100 \times 10^{-12}$ F

f. Examples in time:
$10\ \mu S = 10 \times 10^{-6}$ s
5 mS $= 5 \times 10^{-3}$ s

OPERATION OF NUMBERS

The addition, subtraction, multiplication, and division of numbers can be simplified using powers of ten. Also, as stated previously, in electronics most answers are expressed in engineering notation.

ADDITION AND SUBTRACTION

Addition and subtraction of numbers using powers of ten notation requires that the numbers involved be initially converted to scientific notation. Then, they are converted to the same powers of ten for ease in addition or subtraction. Lastly, they are converted to engineering notation.

ADDITION

1. Add 750 and 3600.

$750 + 3600 = 7.5 \times 10^2 + 3.6 \times 10^3 = 7.5 \times 10^2 + 36 \times 10^2 = 43.50 \times 10^2 = 4.35 \times 10^3 = 4.35$ k

(If the calculations were in ohms, the answer would be $4.35\ k\Omega$.)

2. Add 900 k and 3.3 M.
   $900\text{ k} + 3.3\text{ M} = 9 \times 10^5 + 3.3 \times 10^6 = 9 \times 10^5 + 33 \times 10^5 = 42 \times 10^5 = 4.2 \times 10^6 = 4.2\text{ M}$
   (If the calculations were in ohms, the answer would be 4.2 MΩ .)

3. Add 0.003 and 0.06.
   $0.003 + 0.06 = 3 \times 10^{-3} + 60 \times 10^{-3} = 63 \times 10^{-3} = 63\text{ m}$
   (If the calculations were in amps, the answer would be 63 mA.)

SUBTRACTION

1. Subtract 750 from 3,600.
   $3{,}600 - 750 = 3.6 \times 10^3 - 7.5 \times 10^2 = 36 \times 10^2 - 7.5 \times 10^2 = 28.5 \times 10^2 = 2.85 \times 10^3 = 2.85\text{ k}$
   (If the calculations were in ohms, the answer would be 2.85 kΩ.)

2. Subtract 900 k from 3.3 M.
   $3.3\text{ M} - 900\text{ k} = 3.3 \times 10^6 - 9 \times 10^5 = 33 \times 10^5 - 9 \times 10^5 = 24 \times 10^5 = 2.4 \times 10^6 = 2.4\text{ M}$
   (If the calculations were in ohms, the answer would be 2.4 MΩ.)

3. Subtract 0.003 from 0.06.
   $0.06 - 0.003 = 6 \times 10^{-2} - 3 \times 10^{-3} = 60 \times 10^{-3} - 3 \times 10^{-3} = 57 \times 10^{-3} = 57\text{ m}$
   (If the calculations were in amps, the answer would be 57 mA.)

MULTIPLICATION AND DIVISION

To multiply, the numbers are converted to scientific notation, the base numbers are multiplied, and the exponents are added. The number is then converted to engineering notation. To divide, the numbers are converted to scientific notation, the base numbers are divided, and the exponents are subtracted. The number is then converted to engineering notation. For example:

MULTIPLICATION

1. Multiply 750 times 3,600.
   $750 \times 3{,}600 = 7.5 \times 10^2 \times 3.6 \times 10^3 = 27 \times 10^{2+3} = 27 \times 10^5 = 2.7 \times 10^6 = 2.7\text{ M}$
   (If the calculations where in ohms, the answer would be 2.7 MΩ.)

2. Multiply 900 k times 0.036.
   $900\text{ k} \times 0.036 = 9 \times 10^5 \times 3.6 \times 10^{-2} = 32.4 \times 10^{5-2} = 32.4 \times 10^3 = 32.4\text{ k}$
   (If the calculations were in ohms, the answer would be 32.4 kΩ.)

3. Multiply 0.003 times 0.06.
   $0.003 \times 0.06 = 3 \times 10^{-3} \times 6 \times 10^{-2} = 18 \times 10^{-3-2} = 18 \times 10^{-5} = 180 \times 10^{-6} = 180\ \mu$
   (If the calculations were in amps, the answer would be 180 μA.)

DIVISION

1. Divide 360 k by 750.
   $360\text{ k}/750 = 3.6 \times 10^5/7.5\text{ x }10^2 = 0.48 \times 10^{5-2} = 0.48 \times 10^3 = 4.8 \times 10^2 = 480$
   (If the calculations where in ohms, the answer would be 480 Ω.)

2. Divide 3.3 M by 900 k.
   $3.3\text{M}/900\text{ k} = 3.3 \times 10^6/9 \times 10^5 = 0.367 \times 10^{6-5} = 0.367 \times 10^1 = 3.67$
   (If the calculations where in ohms, the answer would be 3.67 Ω.)

3. Divide 0.06 by 0.003.
   $0.06/0.003 = 6 \times 10^{-2}/3 \times 10^{-3} = 2 \times 10^{-2+3} = 2 \times 10^1 = 20$
   (If the calculations where in ohms, the answer would be 20 Ω.)

POWERS

Raising a number to a power effectively multiplies the exponents.

1. Square 1,000.
   $(1{,}000)^2 = (1 \times 10^3)^2 = 1 \times 10^{3 \times 2} = 1 \times 10^6$

2. Take the square root of 100.
   $(100)^{1/2} = (1 \times 10^2)^{1/2} = 1 \times 10^{2 \times 1/2} = 1 \times 10^1 = 10$

ACCURACY AND ROUNDING

The answers to most calculations in electronics usually need to be extended only two places to the right of the decimal point to achieve reasonable accuracy. For example, 3.3 M divided by 90 k is 36.6666.... However, if only two places to the right of the decimal point are used, the number is rounded off and the answer is 36.67. In rounding the number, the number 5 is the determining factor to obtain the least significant number. For example, the 6 of 36.666 is more than 5, so the number is rounded to 36.67. Likewise, 3.543 is rounded off to 3.54 because 3 is less than 5. Also, 3.546 is rounded off to 3.55 because 6 is greater than 5.

CALCULATOR NOTATION

Calculator notation typically shows the powers of 10 by the exponent only, where 10^2 is 2, 10^3 is 3, and so on. So the scientific notation of 330 would be 3.30 and 2 to indicate the exponent. For example :

1. Multiply 750 by 3,600.
   750 × 3,600 = 7.5 Exp 2 × 3.6 Exp 3 = 27 Exp 5 = 2.7 Exp 6 = 2.7×10^6.

2. Divide 360 k by 750.
   360 k/750 = 3.6 Exp 5/7.5 Exp 2 = 0.48 Exp 3 = 4.8 Exp 2 = 480

CHAPTER QUESTIONS

1. Is silver a better conductor than copper? Explain!

2. What is one advantage and one disadvantage for using gold instead of copper in special connectors and semiconductor devices? Explain!

3. Why is one material a conductor while another material is a non-conductor?

4. Name four pieces of equipment found in most well-equipped labs.

5. What is one advantage of using solderless breadboarding sockets to construct circuits in the lab?

6. Why is engineering notation so widely used in the analysis of circuits? Explain!

CHAPTER PROBLEMS

1. Write the following numbers in scientific notation:

    a. 3369

    b. 30,000

    c. 9,605,000

    d. 0.025

    e. 0.00033

2. Write the following numbers in engineering notation:

    a. 3369 V

    b. 30,000 Ω

    c. 9,605,000 Ω

    d. 0.025 A

    e. 0.00033 V

3. Express the answers to the following problems in kΩ;

    a. Add 720 Ω and 3670 Ω

    b. Add 33 kΩ and 47 kΩ

    c. Subtract 720 Ω from 3670 Ω

    d. Subtract 33 k from 47 k

4. Express the answers to the following problems as indicated:

    a. Multiply 720 times 3670 Ω and express the answer in MΩ.

    b. Multiply 33 kΩ and 47 kΩ and express the answer in GΩ.

    c. Divide 3670 by 720 and express the result in ohms.

    d. Divide 37 k by 33 k and express the answer in ohms.

CHAPTER 2

RESISTORS AND RESISTOR MEASUREMENTS

INTRODUCTION

Resistors are the most commonly used component in electronic circuits. Circuit boards in any system (television, radio, computer, radar, etc.) contain dozens of them. The term resistor comes from the function of the device's ability to resist the flow of current in a circuit, where the higher the resistance value the lower the current flow through the resistor. However, current flow through a resistor generates heat that must be dissipated, and the larger the physical size of the resistor the more heat the resistor can safely dissipate. The unit for resistance is the ohm and its symbol is the Greek letter omega (Ω).

Resistors can be either fixed or variable and fixed resistors can be either general purpose or precision. The resistive value of most fixed resistors is identified through color coding, while the resistive value of all variable resistors and some larger sized fixed resistors are marked directly on the resistor. The most commonly used resistors are the four-band general purpose resistors, which are typically carbon composition and carbon film. General purpose fixed resistors have four-band color coding and precision resistors generally have five-band color coding. A typical five-band precision resistor is metal film. Higher power wire wound resistors normally have the resistance stamped directly on the body of the resistor. The schematic symbol of a fixed resistor is shown in Figure 2-1(a), and a variable resistor is shown in Figure 2-1(b).

(a) Fixed Resistor **(b) Variable Resistor**

FIGURE 2-1: Schematic symbols for resistors.

RESISTANCE OF COPPER WIRE

Wire that connects the resistors (and other components) in circuits is typically copper or copper clad. (Silver is the most conductive metal and copper is next, followed by gold and aluminum.) Because copper wire is inexpensive and plentiful, it is the most widely used. Copper like most metallic conductors has a positive temperature coefficient, so it increases in resistive value with increased temperature. The American Wire Gauge (AWG) indicates wire size by a number, where the higher the gauge number, the smaller the diameter of the wire, and the lower the current carrying capability of the wire. For example, at room temperature, 100 feet of 16 gauge copper wire has a resistance of about 0.4 Ω and carries a maximum allowable current of about 10 amps, 100 feet of 20 gauge copper wire is about 1 Ω and carries about 3 amps of current, and 100 feet of 24 gauge copper wire is about 2.5 Ω and carries about 1 amp of current. Obviously the smaller the wire diameter, the higher the gauge number, and the lower the current carrying capabilities of the copper wire.

RESISTOR TYPES

Carbon composition resistors have been around since the beginning of the electronic age and, while they are still used, they are being replaced as the general purpose resistor in all new designs by carbon film or metal film resistors. Carbon film resistors are not only less expensive to manufacture (due to automation) than carbon composition resistors, but they are also more stable in humid conditions. Also, for the same wattage resistor, they are usually smaller in size. Metal film are precision resistors that have tighter tolerances than carbon film resistors, but are costlier to manufacture. Wire wound resistors are generally used in higher power applications and can be precise and are flame proof. Metal oxide resistors are small in size, stable and flame proof. A brief description of the resistor types follows.

Carbon composition resistors are general purpose resistors that are made from carbon granules and insulating powder mixed together with a resin binder. The ratio of the carbon to insulating powder determines the resistance value of the resistor. Wire leads are imbedded and the resistor is hot molded to produce its cylindrical shape. The body of all resistors are then coated with an insulating material to provide electrical and structural protection. The resistance range of carbon composition resistors is generally from about 2.7 Ω to 22 MΩ and tolerances are 5% and 10%, although some older resistors can be 20%. The wattage rating of carbon composition resistors is typically in the 1/4 to 2 watt range.

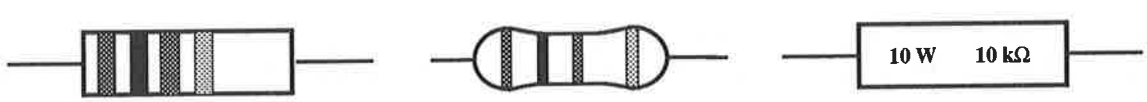
Carbon film resistors are general purpose resistors that typically replace carbon composition resistors in new circuit design, because they have tighter tolerances, are more stable (maintaining the same resistance) with temperature change, and are less costly to manufacture due to automation. Carbon film resistors are made by depositing a thin layer of carbon on the surface of a ceramic rod. The value of the resistor is obtained by removing part of the carbon material using a helix or spiral technique. Leads are attached and epoxy is used as the insulating material to provide electrical and structural protection for the body. The resistance range of carbon film resistors is generally from about 1 Ω to 22 MΩ and tolerances are typically 5%. The wattage rating of carbon film resistors is in the 1/8 to 2 watt range.

Metal film resistors are precision resistors constructed much like carbon film resistors where a thin layer of metal film is also deposited on the surface of a ceramic rod. The value of the resistor is obtained by removing part of the metal film material using the helix or spiral technique. Leads are attached and epoxy is used as the insulating material to provide electrical and structural protection for the body. The resistance range of metal film resistors is from about 1 Ω to 22 MΩ and, being precision resistors, they have tighter tolerances than either carbon film or carbon composition resistors, typically 1% and lower. The wattage rating of metal film resistors is in the 1/4 to 1/2 watt range.

Wire wound resistors are constructed by winding metal wire, such as copper-nickel or nickel-chrome, on a ceramic core. Leads are then attached and the body is electrically and structurally protected with a molded insulating material, such as enamel or silicon. Wire wound resistors can be constructed to dissipate high amounts of power, typically in excess of 1 watt to greater than 200 watts. Wire wound resistors can be made very precise, having tolerances as low as 0.1%. The main disadvantage of wire wound resistors is that they are inherently inductive and generally can not be used in high frequency applications.

Metal oxide resistors have low inductance, are flame proof, and are used when stability at high temperatures is a requirement. The ohmic value range is generally from 1 Ω to 100 kΩ and the wattage range is typically from about 1/2 to 10 watts. The percent tolerance is typically 5%.

Surface mount chip resistors (SMD), single-in-line (SIP), and dual-in-line (DIP) resistor networks can be assembled by automatic surface mount equipment, resulting in lower assembly costs. The resistance range of these resistors is from about 1 Ω to 10 MΩ, and the power rating is typically low at about 1/8 watt.



(a) Carbon Composition Resistors **(b) Film Resistors** **(c) Wire Wound Resistors**

FIGURE 2-2

RESISTOR COLOR CODE

Color codes are used to identify the value and tolerance of general purpose and precision resistors. The tolerance of general purpose resistors, like carbon composition or carbon film, is typically 5% and higher. Generally, four bands are used to indicate the resistance value and tolerance of resistors, although a fifth band can be used to indicate reliability of carbon composition resistors. The tolerance of precision resistors like metal film is 2% and lower, and five bands are used to indicate their resistance value and tolerance. The color code for four- band general purpose and five-band precision resistors is the same. The color code is shown in Table 2-1.

COLOR	DIGIT	MULTIPLIER	TOLERANCE
Black	0	$10^0 = 1$	
Brown	1	$10^1 = 10$	± 1%
Red	2	$10^2 = 100$	± 2%
Orange	3	$10^3 = 1{,}000$	
Yellow	4	$10^4 = 10{,}000$	
Green	5	$10^5 = 100{,}000$	
Blue	6	$10^6 = 1{,}000{,}000$	
Violet	7	$10^7 = 10{,}000{,}000$	
Gray	8	$10^8 = 100{,}000{,}000$	
White	9	$10^9 = 1{,}000{,}000{,}000$	
Gold		$10^{-1} = 0.1$	± 5%
Silver		$10^{-2} = 0.01$	± 10%
No Color			± 20%

RELIABILITY % per 1000 hours Color	Level
Brown	1.0%
Red	0.1%
Orange	0.01%
Yellow	0.001%

TABLE 2-1: Resistor color code.

COLOR CODING OF CARBON COMPOSITION RESISTORS

The most commonly used resistors in electronics are the four-band general purpose resistors. The first band is identified as the band closest to an end of the resistor. For the four-band carbon composition resistor of Figure 2-3, the first band indicates the first digit of the resistor value. The second band indicates the second digit and the third band is the multiplier. The multiplier effectively indicates how many zeros follow the first two digits. The exception is when the third band is gold or silver. Then, the first two numbers are multiplied by 0.1 for gold and the 0.01 for silver. The fourth color band indicates tolerance. If this band is gold, the resistor is within 5% of its nominal color-coded value. If it is silver, the resistor is within 10% of its nominal color-coded value. No band (no longer manufactured) indicates a 20 percent tolerance.

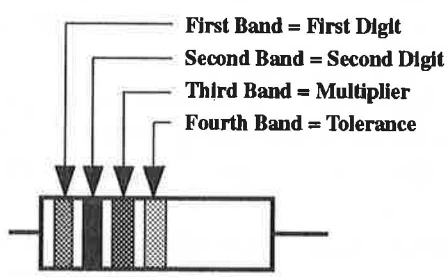


FIGURE 2-3: Standard four-band resistor color code.

If a fifth band is used for carbon composition resistors (Figure 2-4) it denotes reliability. The reliability for brown is 1% per 1,000 hours, red is 0.1%, orange is 0.01%, and yellow is 0.001%. For example, if the fifth band is red then the reliability is 0.1% per thousand hours. Stated another way, only one out of every 1,000 resistors can be out of tolerance after 1,000 hours of operation and meet specifications.

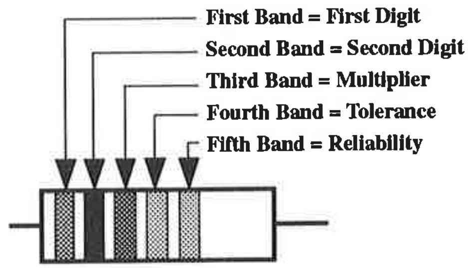


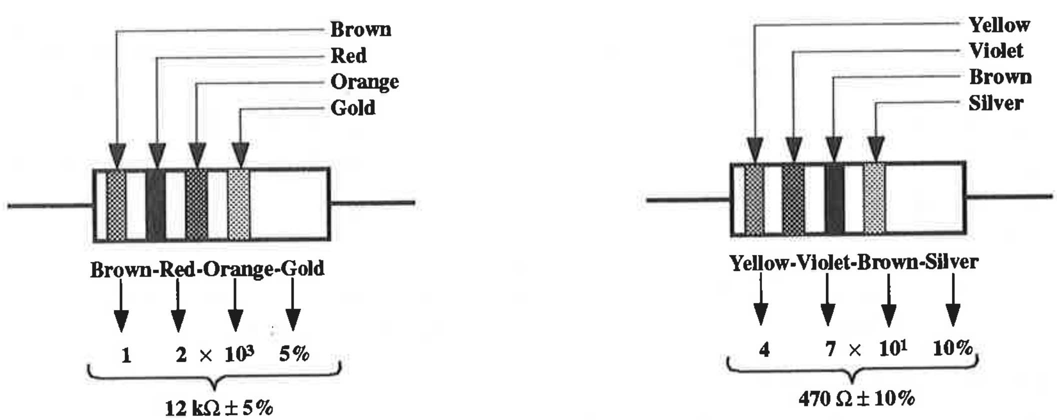
FIGURE 2-4: Color coding of five-band carbon composition resistors.

CARBON COMPOSITION COLOR CODE EXAMPLES

Examples using the color code to identify the resistance and tolerance of four-band resistors are shown in Figure 2-5. The first band is the first digit, the second band is the second digit, the third band is the multiplier, and the fourth band denotes tolerance.

In Figure 2-5(a), the resistor is coded brown-red-orange-gold. So, the first band is one (1) since the color is brown. The second band is two (2) since the color is red. The third band is the multiplier and three (3) since the color is orange. (The multiplier [10^3] effectively adds three zeros to the first two digits to provide 12,000 Ω.) Lastly, the fourth band is gold which indicates a 5 percent tolerance. Hence, the resistor value is 12 kΩ plus-or-minus 5%.

In Figure 2-5(b), the resistor is coded yellow-violet-brown-silver. So, the first band is four (4) since the color is yellow. The second band is seven (7) since the color is violet. The third band is the multiplier and one (1) since the color is brown. (The multiplier [10^1] effectively adds one zero to the first two digits to provide 470 Ω.) Lastly, the fourth band is silver which indicates a 10 percent tolerance. Hence, the resistor value is 470 Ω plus-or-minus 10%.



(a) **(b)**

FIGURE 2-5: Determining the value of carbon composition resistors using the color code.

COLOR CODING OF LOWER VALUED RESISTORS

In Figure 2-6(a), the resistor is coded green-blue-black-gold. The first band is five (5) since the color is green. The second band is six (6) since the color is blue. The third band is black (a multiplier of 1) which is 10^0 and effectively adds no zeros to the first two digits to provide 56 Ω. (Resistors that have resistances between 10 Ω and 99 Ω have multipliers of 1 [black]). Lastly, the fourth band is gold which indicates a 5 percent tolerance. So, the resistor value is 56 Ω plus-or-minus 5%.

In Figure 2-6(b), the resistor is coded orange-orange-gold-silver. The first band is three (3) since the color is orange. The second band is three (3) since the color is orange. The third band is the multiplier ($0.1 = 10^1$) since the color is gold. Thus, the first two digits are multiplied by 0.1 to provide 3.3 Ω. (Resistors that have resistance values lower than 10 Ω have multipliers of $10^{-1} = 0.1$ [gold] and $10^{-2} = 0.01$ [silver].) Lastly the fourth band is silver which indicates a 10 percent tolerance. So, the resistor value is 3.3 Ω plus-or-minus 10%.

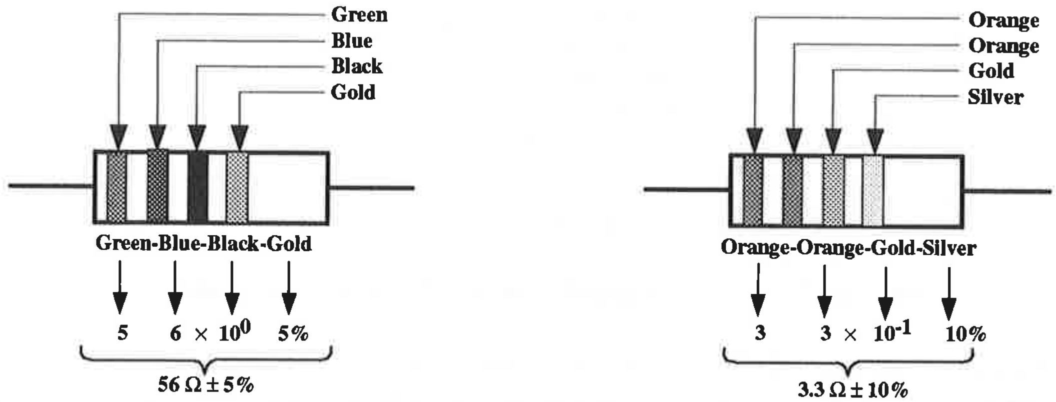
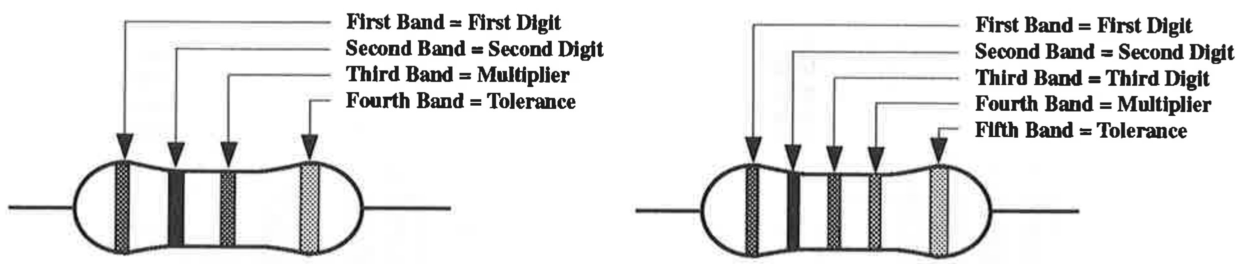


FIGURE 2-6: Color coding for lower valued resistors.

FILM RESISTOR COLOR CODE EXAMPLES

Carbon film are general purpose resistors that have four-band color coding with tolerances of 2% and 5%. Metal film precision resistors have five-band color coding with tolerances of 1%, or lower. For the four-band, color-coded, carbon-film resistor of Figure 2-7(a), the color coding is identical to that of the carbon composition resistor, except that carbon film have tighter tolerances. So the fourth band of the carbon film resistor is typically gold (5%) or red (2%). For the metal film precision five-band color-coded resistor of Figure 2-7(b), the first three bands are used as digits, the fourth band is the multiplier, and the fifth band denotes tolerance. If the fifth (tolerance) band is red the tolerance of the resistor is 2%, and if the fifth band is brown the tolerance of the resistor is 1%. Although the band closest to an end is generally the first band, another indicator is the space between the tolerance band and other bands (digits and multiplier band) is wider.



(a) Four-Band, Carbon-Film Resistor Color Coding (b) Five-Band, Metal-Film Resistor Color Coding
FIGURE 2-7: Color code for carbon film and metal film resistors.

CARBON FILM CODING

Examples using the color code to identify the resistance and tolerance of four-band, carbon-film resistors are shown in Figure 2-8. The first band is the first digit, the second band is the second digit, the third band is the multiplier, and the fourth band denotes tolerance.

In Figure 2-8(a), the resistor is coded yellow-orange-red-gold. The first band is four (4) since the color is yellow. The second band is three (3) since the color is orange. The third band is the multiplier and since the color is red (2) the multiplier effectively adds two zeros to the first two digits to denote 4,300 Ω. Lastly, the fourth band is gold which indicates a 5 percent tolerance. So the resistor value is 4.3 kΩ plus-or-minus 5%.

In Figure 2-8(b), the resistor is coded brown-gray-brown-red. The first band is one (1) since the color is brown. The second band is eight (8) since the color is gray. The third band is the multiplier and one (1) since the color is brown. and this effectively adds one zero to the first two digits to indicate 180 Ω. Lastly the fourth band is red which indicates a 2 percent tolerance. So the resistor value is 180 Ω plus-or-minus 2%.

METAL FILM CODING

Examples using the color code to identify the resistance and tolerance of five-band, metal-film resistors are shown in Figure 2-9. In the five-band code the first band is the first digit, the second band is the second digit,

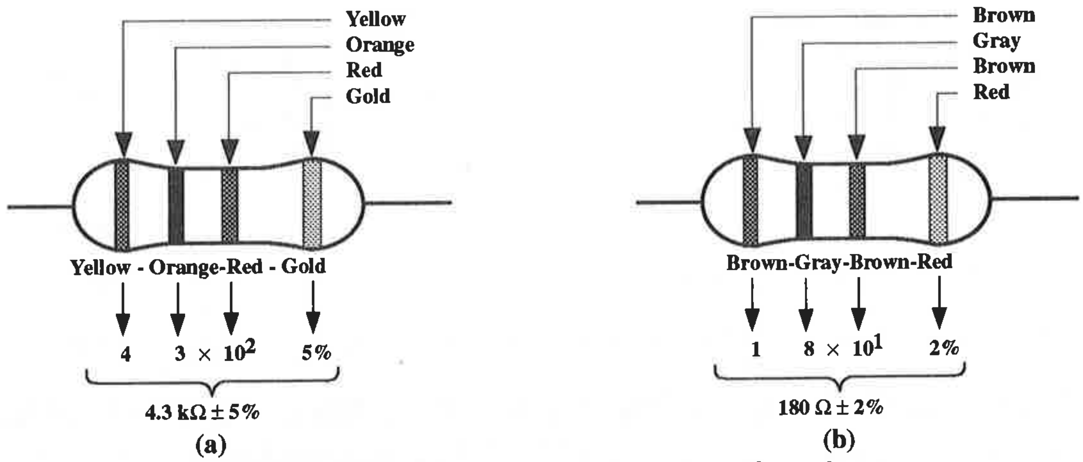


FIGURE 2-8: Four band color code for carbon film resistors.

the third band is the third digit, the fourth band is the multiplier, and the fifth band the tolerance.

In the example for Figure 2-9(a), the resistor is coded brown-green-black-brown-red. The first band is one (1) since the color is brown. The second band is five (5) since the color is green. The third band is zero (0) since the color is black. The fourth band is the multiplier and since the color is brown (1) which effectively adds one zero to the first three digits to indicate 1,500 Ω. Lastly, the fifth band is red which indicates a 2 percent tolerance. So the resistor value is 1.5 kΩ plus-or-minus 2%.

In the example for Figure 2-9(b), the resistor is coded violet-green-black-red-brown. The first band is seven (7) since the color is violet. The second band is five (5) since the color is green. The third band is zero (0) since the color is black. The fourth band is the multiplier and since the color is red (2), which effectively adds two zeros to the first three digits to provide 75,000 Ω. Lastly, the fifth band is brown which indicates a 1 percent tolerance. So the resistor value is 75 kΩ plus-or-minus 1%.

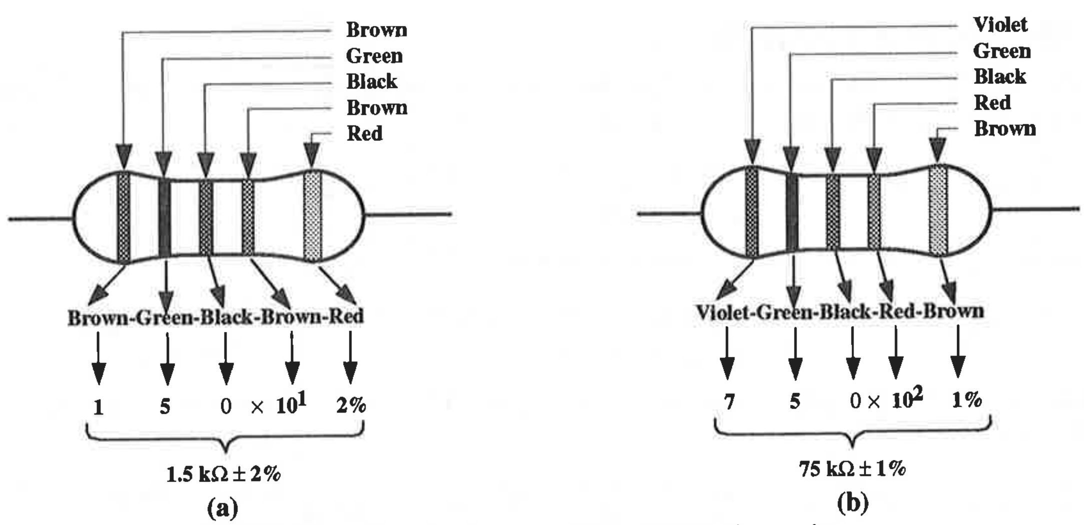


FIGURE 2-9: Five-band color code for metal film resistors.

CONVERTING RESISTANCE TO THE COLOR CODE

To convert a known four-band resistance to color code, reverse the previously discussed four-band process and select the coded colors for the resistance value. For the example of Figure 2-10(a), to convert the known 4.7 kΩ resistance with 5% tolerance to color code, select yellow (4), violet (7), and red for the multiplier of two (2). Then, gold is selected to indicate 5% fourth band tolerance.

Likewise, to convert a known five-band resistance to color code, the previously discussed five-band process is reversed and the coded colors are selected for the resistance value. For the example of Figure 2-10(b), the known 28 kΩ resistance with 1% tolerance is converted to color code by selecting red (2), gray (8), black (0), and red for the multiplier of two (2). Then, brown is selected to indicate 1% fifth band tolerance.

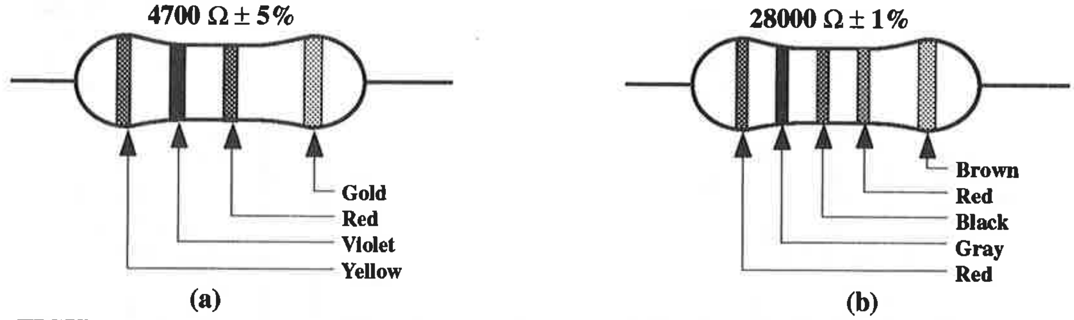


FIGURE 2-10: Conversion of four-band resistance and five-band resistance to color code.

MINIMUM AND MAXIMUM RESISTANCE VALUES OF % TOLERANCE

The actual value of a resistor color-coded to be 100 Ω and 10%, can be anywhere between 90 Ω and 110 Ω. For a 100 Ω ± 5% resistor, the actual resistance value can be anywhere between 95 Ω and 105 Ω. The variance between the actual value and the coded value is called its tolerance. The maximum and minimum values of resistor knowing the % tolerance is solved from:

Maximum ohms = Coded resistance + % Coded resistance

Minimum ohms = Coded resistance – % Coded resistance

For example for a 100 Ω ± 5% coded resistance, the maximum and minimum values resistor is solved at 105 Ω and 95 Ω from:

$$\text{Maximum ohms} = \text{Coded resistance} + \%\text{ of Coded} = 100\,\Omega + (100\,\Omega \times 5/100) = 100\,\Omega + 5\,\Omega = 105\,\Omega$$

$$\text{Minimum ohms} = \text{Coded resistance} - \%\text{ of Coded} = 100\,\Omega - (100\,\Omega \times 5/100) = 100\,\Omega - 5\,\Omega = 95\,\Omega$$

SOLVING % TOLERANCE

If the resistance of a resistor is measured and the measured value of the resistance is different from the color coded value, the % tolerance of that resistor can be solved from:

$$\%\text{ tolerance} = \frac{\text{Measured resistance} - \text{Coded resistance}}{\text{Coded Resistance}} \times 100$$

For example, if a 120 Ω color-coded resistor is measured at 123 Ω, then the percent tolerance is solved from:

$$\%\text{ tolerance} = \frac{\text{Measured resistance} - \text{Coded resistance}}{\text{Coded Resistance}} \times 100 = \frac{123\,\Omega - 120\,\Omega}{120\,\Omega} \times 100 = 2.5\%$$

However, if the 120 Ω color-coded resistor is measured at 118 Ω, then the percent tolerance is solved at – 1.67% from:

$$\%\text{ tolerance} = \frac{\text{Measured Resistance} - \text{Coded Resistance}}{\text{Coded Resistance}} \times 100 = \frac{118\,\Omega - 120\,\Omega}{120\,\Omega} \times 100 = -1.67\%$$

NOTE: Since the 123 Ω resistance is higher than the coded 120 Ω resistance value, it is represented with a % tolerance of (+) 2.5% and, since the 118 Ω resistance is lower than the coded 120 Ω resistance value, it is represented with a percent tolerance of (–)1.67%.

STANDARD FOUR BAND RESISTANCE VALUES

Fixed resistor values range from about 1Ω to greater than 20 MΩ. The availability depends on the type of resistor used, the tolerance required, and the amount of power dissipated. Standard 10% resistors ranging in value from 2.7 Ω to 22 MΩ are shown in the Table 2-2.

					2.7	3.3	3.9	4.7	5.6	6.8	8.2
10	12	15	18	22	27	33	39	47	56	68	82
100	120	150	180	220	270	330	390	470	560	680	820
1 k	1.2 k	1.5 k	1.8 k	2.2 k	2.7 k	3.3 k	3.9 k	4.7 k	5.6 k	6.8 k	8.2 k
10 k	12 k	15 k	18 k	22 k	27 k	33 k	39 k	47 k	56 k	68 k	82 k
100 k	120 k	150k	180 k	220 k	270 k	330 k	390 k	470 k	560 k	680 k	820 k
1 M	1.2 M	1.5 M	1.8 M	2.2 M	2.7 M	3.3 M	3.9 M	4.7 M	5.6 M	6.8 M	8.2 M
10 M	12 M	15 M	18 M	22 M							

TABLE 2-2: Table of values for 10% tolerance resistors.

Standard 5% resistors have twice the number of resistance choices as standard 10% resistors. Table 2-3 indicates the 5% choices. Multiples by powers of 10 provide the higher valued resistances. An example is 2.4Ω, 24 Ω, 240 Ω, 2.4 kΩ, 24 kΩ, 240 kΩ, and 2.4 MΩ.

1.0	1.2	1.5	1.8	2.2	2.7	3.3	3.9	4.7	5.6	6.8	8.2
1.1	1.3	1.6	2.0	2.4	3.0	3.6	4.3	5.1	6.2	7.5	9.1

TABLE 2-3: Table of values for 5% tolerance resistors. Multiples by powers of ten provide the higher values.

A table of standard values for 1% tolerance five-band resistors is shown in Table 2-4.

1.00	1.02	1.05	1.07	1.10	1.13	1.15	1.18	1.21	1.24	1.27	1.30
1.33	1.37	1.40	1.43	1.47	1.50	1.54	1.58	1.62	1.65	1.69	1.74
1.78	1.82	1.87	1.91	1.96	2.00	2.05	2.10	2.15	2.21	2.26	2.32
2.37	2.43	2.49	2.55	2.61	2.67	2.74	2.80	2.87	2.94	3.01	3.09
3.16	3.24	3.32	3.40	3.48	3.57	3.65	3.74	3.83	3.92	4.02	4.12
4.22	4.32	4.42	4.53	4.64	4.75	4.87	4.99	5.11	5.23	5.36	5.49
5.62	5.76	5.90	6.04	6.19	6.34	6.49	6.65	6.81	6.98	7.15	7.32
7.50	7.68	7.87	8.06	8.25	8.45	8.66	8.87	9.09	9.31	9.53	9.76

TABLE 2-4: Table of values for 1% tolerance resistors. Multiples by powers of ten provide the higher values.

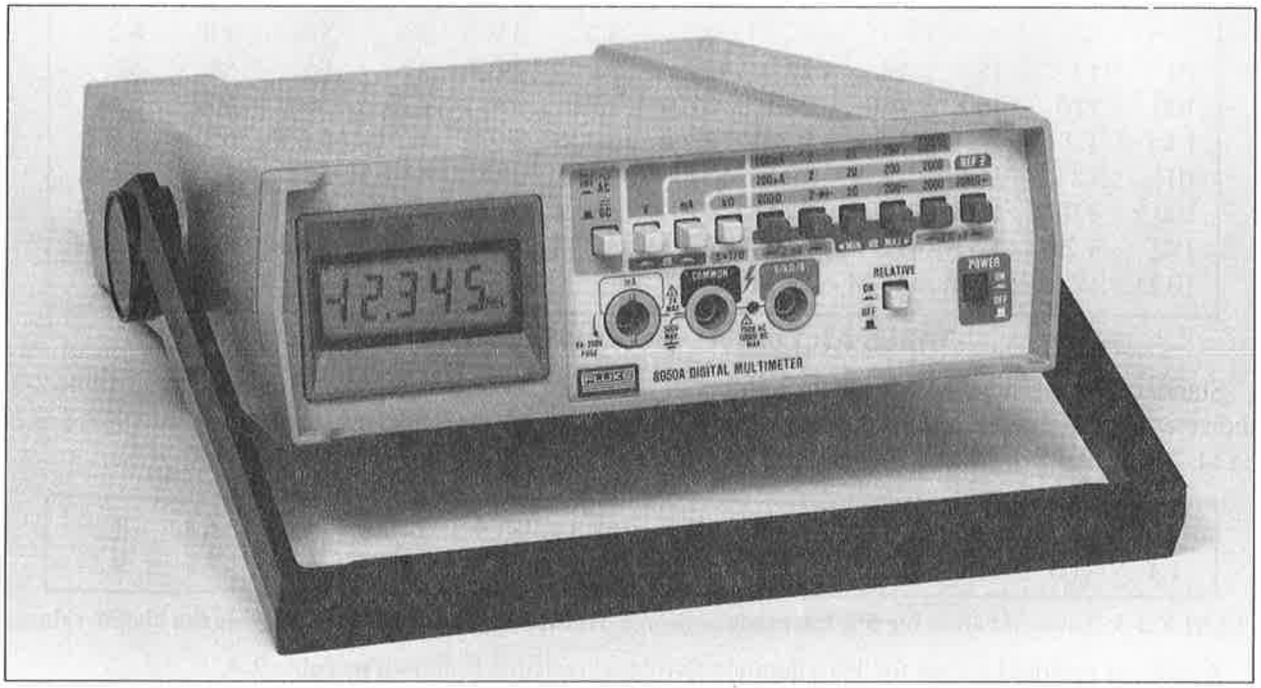
MEASURING RESISTORS

The resistance of resistors is measured in ohms using an ohmmeter. The instrument mostly used to measure ohms is the multimeter, which has the capability of measuring ohms, volts, and amps. So in order to measure ohms, the multimeter must be switched to the ohms range. Then, ohmmeter leads are connected directly across the resistor under test. The ohmmeter actually has its own internal battery and measures the current through the unknown resistance in measuring the resistance. So, it is very important not to make any resistance measurements if there is power connected to the resistor being measured. Also, in order to accurately measure resistors, no other component should be connected across the resistor being measured. So, shut the power off and isolate the resistor prior to making the resistance measurement.

DIGITAL METERS

Measuring resistance on a digital meter is straight-forward. Select the resistance mode and the upper limit of the resistor under test. For example digital multimeters, such as the Fluke multimeter shown in Figure 2-11, have upper limits based on the resistance range used. For example, a 2 kΩ limit allows a resistor with a value under 2 kΩ, such as 1.8 kΩ, to be measured. For any value over 2 kΩ, such as a 2.7 kΩ resistor, the higher than 2 kΩ readout will be indicated by (1-). In order to measure the 2.7 kΩ resistor, the next higher resistance range (20 kΩ/S) should be used.

For example, if a 15 kΩ resister is being measured, press kΩ/S and press 20 to provide a 20 kΩ limit. A 200 kΩ limit could also be used, but using the lowest value 20 kΩ limit will provide better resolution than the higher 200 kΩ limit. Also, low resistance values such as 180 Ω have better resolution on the 200 Ω limit or



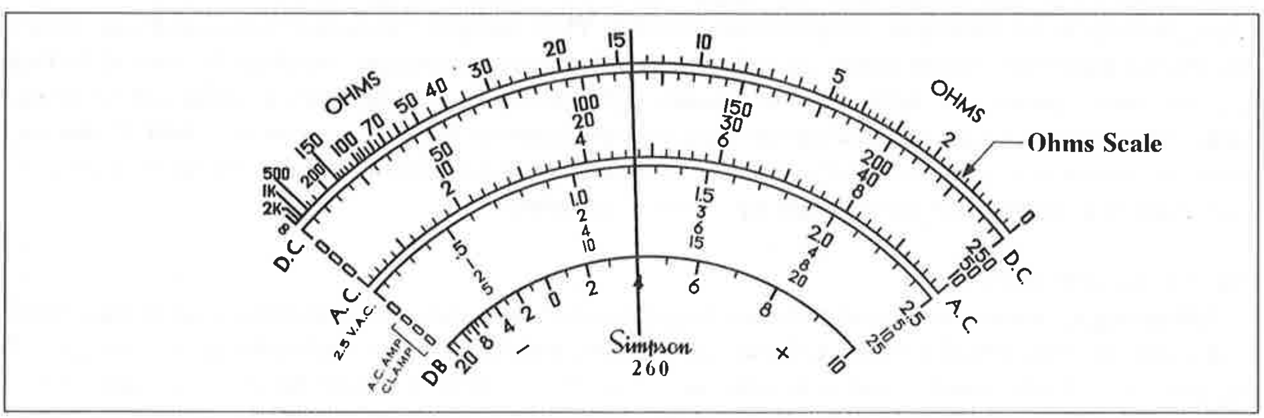
(Reproduced with permission from John Fluke Mfg. Co., Inc.)

FIGURE 2-11: The Fluke Model 8050A Digital Multimeter (DMM).

0.2 kΩ/S, so 180 Ω will read out as 0.18 kΩ. Again, opens or resistances that are higher than the resistance limits of the meter will show a readout of 1-.

ANALOG METERS:

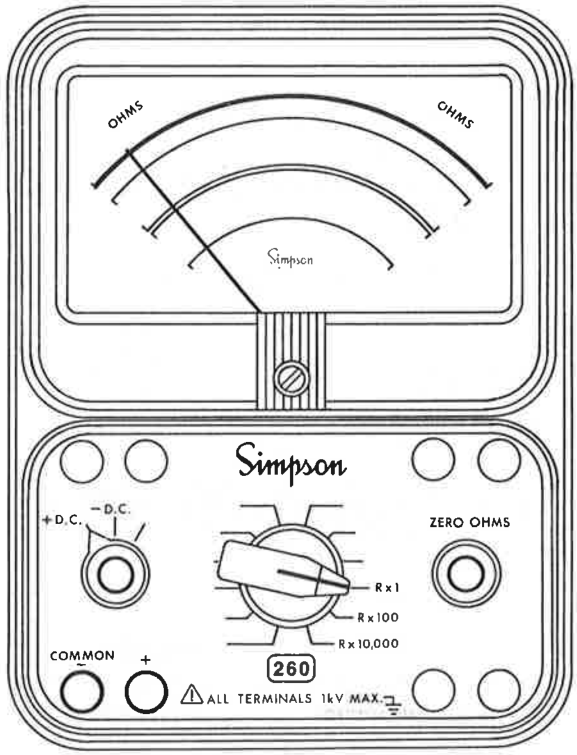
Measuring resistance on the analog meter, such as a Simpson 260® analog VOM, normally begins by selecting of the R × 1, R × 100, or R × 10,000 ranges and then calibrating the meter. Calibration means zeroing the meter for the range being used. Generally the most accurate resistance measurements are made in the low to middle portion of the scale typically between 0 and 50 on the ohms scale. Once the needle goes above 100 the meter is usually switched to the next range. The Simpson 260® has three resistance ranges. So if the indicator needle is on 14, shown in Figure 2-12, the resistance is 14 × 1 = 14 Ω on the R × 1 range, 14 × 100 = 1400 Ω on the R × 100 range, and 14 × 10 kΩ = 140 kΩ on the R × 10,000 range.



(Courtesy of Simpson Electric Company)

FIGURE 2-12: Meter face scale of the Simpson 260® volt-ohm-milliameter (VOM).

General operating procedures for the measurement of resistance using a Simpson 260® analog VOM are shown in Figure 2-13. The procedure is typical for use with most analog meters.



JACKS AND SWITCH POSITIONS FOR MEASURING RESISTANCE

Operation

RESISTANCE MEASUREMENTS

When resistance is measured, the INTERNAL batteries B1 and B2 furnish power for the circuit. Since batteries are subject to variation in voltage and internal resistance, the Instrument must be adjusted to zero before measuring a resistance, as follows:

a. Turn range switch to desired ohms range.
b. Plug the black test lead into the – COMMON jack and the red test lead into the + jack.
c. Connect ends of test leads together to short the VOM resistance circuit.
d. Rotate the ZERO OHMS control until pointer indicates zero ohms. If pointer cannot be adjusted to zero, one or both of the batteries must be replaced.
e. Disconnect shorted ends of test leads.

MEASURING RESISTANCE

a. Before measuring resistance in the circuit make sure the power is off to the circuit being tested and all capacitors are discharged. Disconnect shunted component from the circuit before measuring its resistance.
b. Set the range switch to one of the resistance range positions as follows:
   1. Use R × 1 for resistance readings from 0 to 200 ohms.
   2. Use R × 100 for resistance readings from 200 to 20,000 ohms.
   3. Use R × 10,000 for resistance readings above 20,000 ohms.
c. Set the function switch at either -DC or +DC position: Adjust ZERO OHMS control for each resistance range.
d. Observe the reading on the OHMS scale at the top of the dial. *Note: The OHMS scale reads from right to left for increasing values of resistance.*
e. To determine the actual resistance value, multiply the reading by the factor at the switch position. (K on the OHMS scale equals one thousand.)

(Courtesy of Simpson Electric Company)

FIGURE 2-13: Jacks, switch positions, and directions for measuring resistance with the Simpson 260®.

RESISTOR CONNECTIONS

In electronic circuits, resistors are connected in series, in parallel, and in series-parallel combinations. When analyzing these circuits, it is often necessary to reduce the resistor combinations (networks) to a single equivalent resistance, which is the total resistance at the terminals of the resistor combination. In later chapters these series, parallel, and series-parallel resistor combinations will be solved again, but in greater detail. They are provided now as an introduction to show how resistors in series are added and how two resistors in parallel are less than either parallel resistor value. Another reason is to show that when resistors are measured, they must be measured out of the circuit, to avoid the possibility of having another circuit resistor in parallel or of being inadvertently connected to the circuit's power supply.

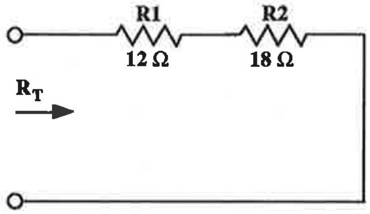
RESISTORS CONNECTED IN SERIES

Resistors in a series connection are connected end-to-end, such as the two resistors shown in Figure 2-14(a). The total resistance in a series connection is found by adding the values of the resistor in combination. Therefore, the total resistance is $R_T = R1 + R2$. The schematic diagram of the two resistors in series is shown in Figure 2-14(b).

(a) $R_T = R1 + R2$ **(b) Schematic Diagram**

FIGURE 2-14: Two resistors in series.

For example, if R1 = 12 Ω and R2 = 18 Ω, then R_T = 30 Ω, as shown solved in conjunction with the circuit of Figure 2-15.

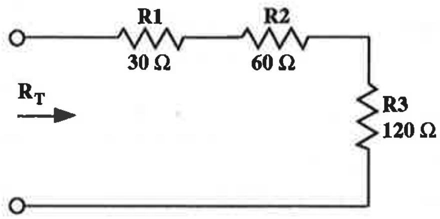


$R_T = R1 + R2$

$R_T = 12\ \Omega + 18\ \Omega = 30\ \Omega$

FIGURE 2-15: Solving the total resistance value of two resistors in series.

Three resistors connected in series are solved from $R_T = R1 + R2 + R3$. Therefore, if R1 = 30 Ω, R2 = 60 Ω, and R3 = 120 Ω, then R_T = 210 Ω, as shown solved in conjunction with the circuit of Figure 2-16.



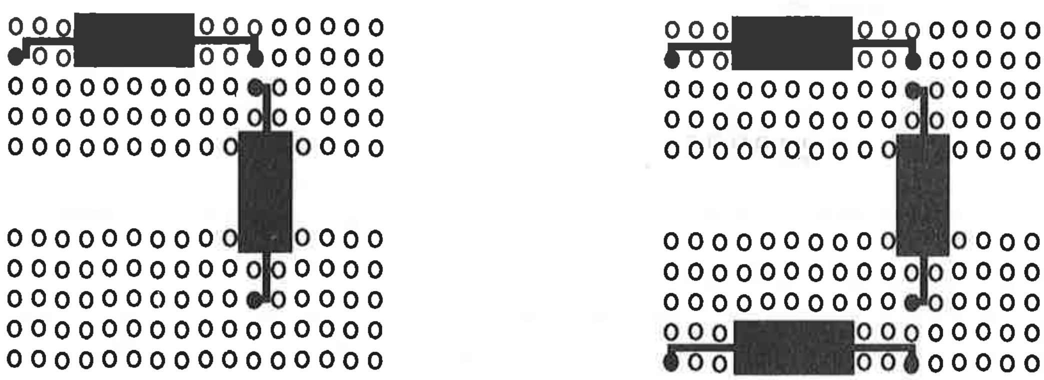
$R_T = R1 + R2 + R3$

$R_T = 30\ \Omega + 60\ \Omega + 120\ \Omega = 210\ \Omega$

FIGURE 2-16: Solving the total resistance value of three resistors in series.

SOLDERLESS BREADBOARDING OF SERIES RESISTORS

An example of two resistors connected in series on a solderless breadboard is shown in Figure 2-17(a). Each vertical strip provides five possible electrical connections and a common connection for the series resistors. An example of three resistors connected in series is shown in Figure 2-17(b).



(a) Two Resistors in Series **(b) Three Resistors in Series**

FIGURE 2-17

RESISTORS CONNECTED IN PARALLEL

The total resistance of two resistors in parallel, as shown in Figure 2-18, can be solved from either:

$$R_T = \frac{1}{1/R1 + 1/R2} \quad \text{or from} \quad R_T = \frac{R1 \times R2}{R1 + R2}$$

Therefore, if R1 = 30 Ω and R2 = 60 Ω, then R_T = 20 Ω, as shown solved by both formulas in conjunction with the illustration of Figure 2-18.

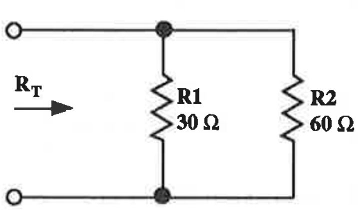


FIGURE 2-18

1. Method #1: $R_T = R1 \parallel R2 = \dfrac{1}{1/R1 + 1/R2} = \dfrac{1}{1/30\ \Omega + 1/60\ \Omega}$

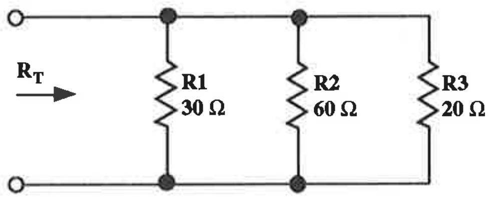
$$R_T \approx \frac{1}{0.0333 + 0.0166} = \frac{1}{0.05} = 20\ \Omega$$

2. Method #2: $R_T = R1 \parallel R2 = \dfrac{R1 \times R2}{R1 + R2}$

$$R_T = \frac{30\ \Omega \times 60\ \Omega}{30\ \Omega + 60\ \Omega} = \frac{1800\ \Omega}{90\ \Omega} = 20\ \Omega$$

NOTE: Parallel resistance values are easily solved on standard calculators using the 1/X button. For the two resistor parallel circuit enter 30 and push the 1/X button to provide 0.0333 and then push plus (+). Next, enter 60 and push the 1/X button to provide 0.0166 and push = to provide (0.05). Finally, push the 1/X button to provide 20 in ohms.

The total resistance of the three resistors in parallel shown in Figure 2-19 is solved from:



$$R_T = R1 \parallel R2 \parallel R3 = \frac{1}{1/R1 + 1/R2 + 1/R3}$$

$$R_T = \frac{1}{1/30\,\Omega + 1/60\,\Omega + 1/20\,\Omega}$$

$$R_T = \frac{1}{0.033 + 0.016 + 0.05} = \frac{1}{0.1} = 10\,\Omega$$

FIGURE 2-19: Finding the total resistance of three resistors connected in parallel.

NOTE: For the three resistor parallel circuit enter 30 and push (1/X) and (+), enter 60 and push (1/X) and (+), enter 20 and push (1/X). Then, push (=) and (1/X) to obtain 10 in ohms.

SOLDERLESS BREADBOARDING OF PARALLEL RESISTORS

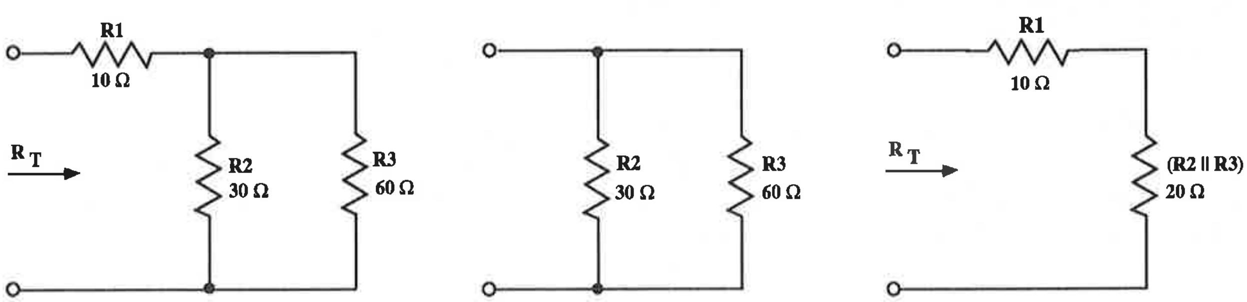
An example of two resistors connected in parallel on a solderless breadboard is shown in Figure 2-20(a). A connection of three resistors in parallel is shown in Figure 2-20(b).

(a) Two Resistors in Parallel **(b) Three Resistors in Parallel**

FIGURE 2-20

RESISTORS CONNECTED IN SERIES-PARALLEL

Resistor connections that combine series resistors with parallel resistors are called series-parallel resistor circuits. The total resistance of the series-parallel connection of Figure 2-21(a) begins by solving the resistance of the parallel combination of R2 and R3 as shown in Figure 2-21(b). Then, the parallel combination of R2 || R3 is placed in series with the R1 resistor, and the total resistance is solved, as shown in Figure 2- 21(c).



$R_T = R1 + (R2 \parallel R3)$

$$R2 \parallel R3 = \frac{R2 \times R3}{R2 + R3} = \frac{30\,\Omega \times 60\,\Omega}{30\,\Omega + 60\,\Omega} = 20\,\Omega$$

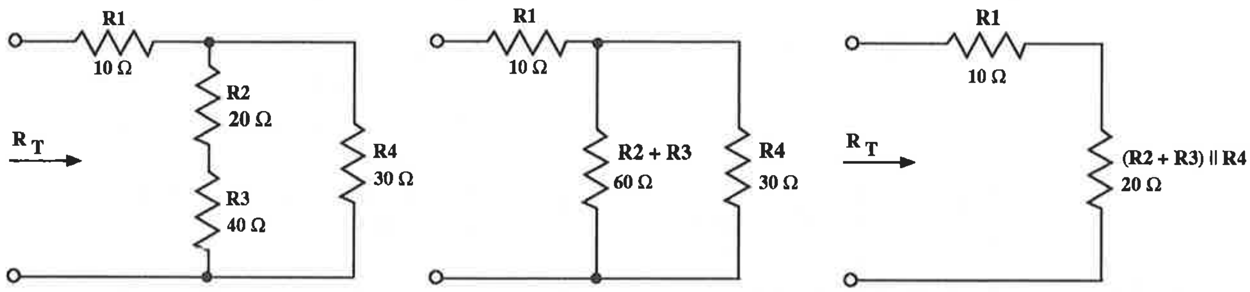
$R_T = R1 + (R2 \parallel R3)$

$= 10\,\Omega + 20\,\Omega = 30\,\Omega$

(a) **(b)** **(c)**

FIGURE 2-21

The total resistance of a slightly more complex connection is shown solved in Figure 2-22. First, the series resistance of resistors R2 and R3 is found. Then, this value is placed in parallel with the R4 resistor, as shown in Figure 2-22(b). The total resistance is then solved by placing the (R2 + R3) || R4 resistance in series with the R1 resistor as shown in Figure 2-22(c).



R_T = R1 + [(R2 + R3) || R4]

(a)

(R2 + R3) || R4

(20 Ω + 40 Ω) || 30 Ω

$$= \frac{60\ \Omega \times 30\ \Omega}{60\ \Omega + 30\ \Omega} = 20\ \Omega$$

(b)

R_T = R1 + [(R2 + R3) || R4]

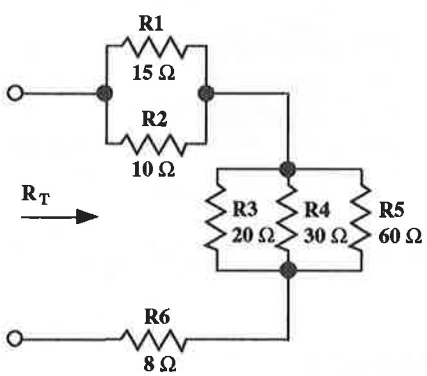
= 10 Ω + [(20 Ω + 40 Ω) || 30 Ω]

= 10 Ω + 20 Ω = 30 Ω

(c)

FIGURE 2-22

A more complex series-parallel network with six resistors is shown in Figure 2-23. Finding the total resistance of the combination begins by solving the resistance of R1 || R2 and R3 || R4 || R5. Then, the total resistance of (R1 || R2), (R3 || R4 || R5), and R6 is calculated.



$$\text{R1} \parallel \text{R2} = \frac{\text{R1} \times \text{R2}}{\text{R1} + \text{R2}} = \frac{15\ \Omega \times 10\ \Omega}{15\ \Omega + 10\ \Omega} = 6\ \Omega$$

$$\text{R3} \parallel \text{R4} \parallel \text{R5} = \frac{1}{1/\text{R3} + 1/\text{R4} + 1/\text{R5}}$$

$$= \frac{1}{1/20\ \Omega + 1/30\ \Omega + 1/60\Omega}$$

$$= \frac{1}{0.05\ \Omega + 0.033\ \Omega + 0.0166\ \Omega} = \frac{1}{0.1} = 10\ \Omega$$

= (R1 || R2) + (R3 || R4 || R5) + R6

= 6 Ω + 10 Ω + 8 Ω = 24 Ω

FIGURE 2-23: Solving the total resistance of a six-resistor, series-parallel combination.

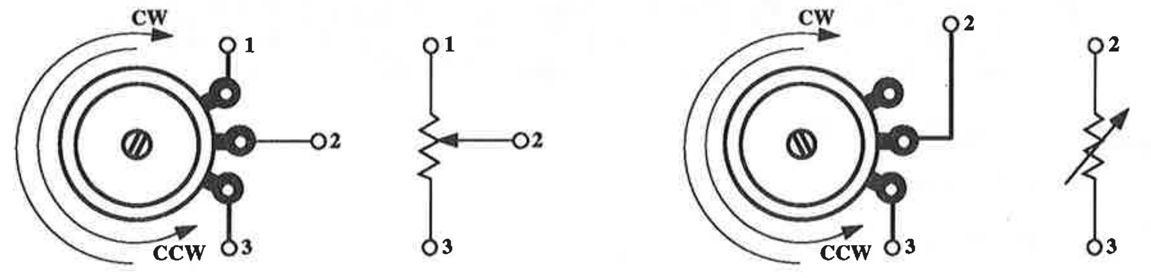
VARIABLE RESISTORS

Variable resistors are used to vary the resistance or to vary the resistance ratio of the variable resistor. Variable resistors that vary the resistance ratio are called potentiometers and are typically used to vary the voltage in circuits. One example is the volume control in the radio or television. A potentiometer is shown in Figure 2-24(a).

Variable resistors that vary the resistance, typically to provide an exact resistance in controlling the current in a circuit, are called rheostats. Rheostats require only two terminals in varying the resistance, so three terminal potentiometers can easily be converted to rheostats, simply by using the center terminal and one of the end terminals. A rheostat is shown in Figure 2-24(b).

POTENTIOMETERS

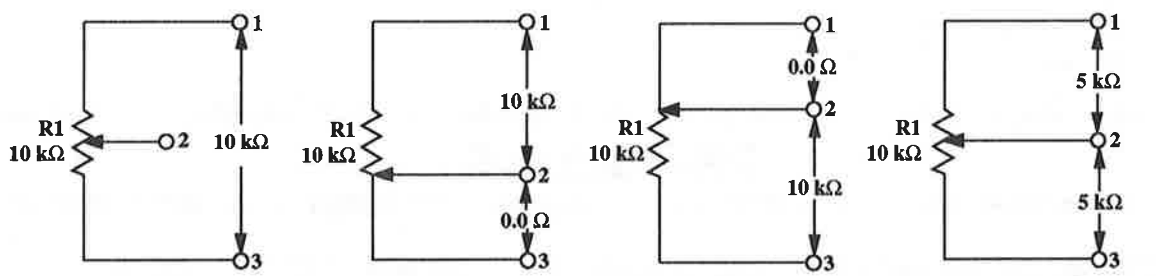
The potentiometer, shown in Figure 2-24(a), has its three terminals designated 1, 2 and 3. The resistance between terminals 1 and 3 is the resistance of the potentiometer and fixed, while the resistance between the center terminal (wiper) designated 2 and either end (1 or 3) terminal is variable. For example, in Figure 2-25(a), if the potentiometer is labeled 10 kΩ, an ohmmeter connected across the outside 1 and 3 terminals (R1,3) should measure about 10 kΩ. However at full counter-clockwise (CCW) rotation, see Figure 2-25(b), the



(a) Potentiometer **(b) Potentiometer Converted to Rheostat**

FIGURE 2-24: Variable resistors (shaft side).

resistance between the 2 and 3 terminals (R2,3) should be 0.0 Ω. Then when the shaft is rotated to full clockwise (CW) position, see Figure 2-25(c), the resistance (R2,3) increases to 10 kΩ. Measuring between terminals 1 and 2, provides just the opposite results. Essentially, the potentiometer divides the resistance into two in-series resistors. So if the 10 kΩ potentiometer is rotated to mid-rotation, Figure 2-25(d), the resistance between the 1 and 2 terminals (R1,2) is 5 kΩ, and the resistance between the 2 and 3 terminals (R2,3) is 5 kΩ.



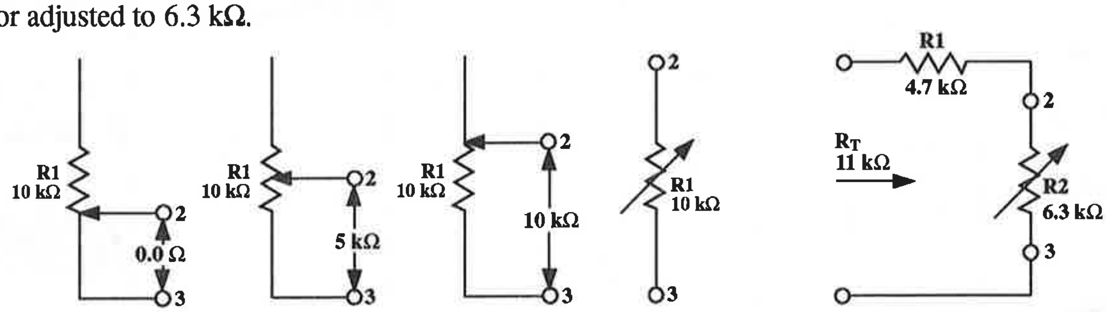
(a) (b) (c) (d)

FIGURE 2-25: The potentiometer has three terminals and provides a variable ratio of two resistances.

RHEOSTATS

In the rheostat, shown in Figure 2-26(b), only two of the three available terminals of a potentiometer are used, typically terminals 1 and 2 or terminals 2 and 3. For example, if the potentiometer is 10 kΩ, an ohmmeter connected between the 2 and 3 terminals at full counter-clockwise rotation (CCW) as shown in Figure 2-26(a), will measure a resistance of 0.0 Ω. Then, when the shaft is rotated clockwise, Figure 2-26(b), the resistance of (R2,3) increases and reaches 5 kΩ at mid-rotation. At the full clockwise rotation, Figure 2-26(c) the resistance increases to 10 kΩ. Using terminals 1 and 2 provides just the opposite resistive effect. The schematic symbol for the 10 kΩ rheostat is shown in Figure 2-26(d).

An application for a rheostat to obtain a precise resistance is shown in Figure 2-26(e). In this circuit a precise resistance of 11 kΩ is needed. The 11 kΩ value is obtained by using a standard resistor of 4.7 kΩ and a variable resistor adjusted to 6.3 kΩ.



(a) (b) (c) (d) (e)

FIGURE 2-26: Rheostat connections and a rheostat connected in series with a standard value resistor to give a precise resistance value.

LABORATORY EXERCISE

EXERCISE OBJECTIVES

To become familiar with:

- Resistor color code.
- The ohmmeter to measure resistance values.
- The equivalent resistance of resistors connected in series, parallel, and series-parallel combinations.
- Variable resistors

LIST OF MATERIALS

1. Resistors (one each): 220 Ω, 1 kΩ, 1.8 kΩ, 3.3 kΩ, 4.7 kΩ, 10 kΩ, 12 kΩ, 15 kΩ, 27 kΩ, 100 kΩ, 10 kΩ potentiometer
2. Multimeter.

PROCEDURE

SECTION I (Guided Laboratory Exercise): Resistor Color Code

PART A: Pre-laboratory Identification and Calculations

1. From the assortment of resistors listed in Table 2-5, select each successive resistor by color code. Then, based on the color code, determine the resistance value and percent tolerance of each resistor. From the percent tolerance, calculate the expected upper and lower resistance limit of each resistor. The resistance values of the BR-BK-BK-Gold resistor have been filled into the first line of Table 2-5 as an example, where the expected upper limit (maximum ohms) of the 10 Ω ± 5% resistor is 10.5 Ω and the expected lower limit (minimum ohms) is 9.5 Ω.

TABLE 2-5 RESISTIORS	IDENTIFY		CALCULATE		MEASURE		VERIFY
	Nominal Ohms	Tolerance Percent	Maximum Ohms	Minimum Ohms	Analog Meter	Digital Meter	Percent Tolerance
BR-BK-BK	10 Ω	5%	10.5 Ω	9.5Ω			
R-R-BR							
BR-BK-R							
O-O-R							
Y-V-R							
BR-BK-O							
BR-G-O							
BR-BK-Y							
BR-BK-G							

2. Resistance and percent tolerance:
   a. Use the color code to determine the value of the next resistor listed in Table 2-5. Record this value into the nominal (coded resistance) ohms column of Table 2-5.
   b. Use the tolerance band on the resistor to find the percent value of the tolerance of this resistor. Insert this value into the Tolerance Percent column of Table 2-5 .

3. Minimum and maximum resistance limits:
   a. Use the percent tolerance to find the maximum acceptable resistance limit where:
      Maximum resistance = Coded Resistance + Percent Tolerance of Coded Resistance.
   b. Use the percent tolerance to find the minimum acceptable resistance limit where:
      Minimum Resistance = Coded Resistance - Percent Tolerance of Coded Resistance.
   c. Insert the maximum and minimum acceptable resistance limit values into Table 2-5.

4. Repeat this process for all of the remaining resistor values listed in Table 2-5.

NOTE: As stated in the theory and shown in Figure 2-27, the first resistor color code band of a four band general purpose resistor indicates the first digit of the resistance value, the second band indicates the second digit, and the third band is the multiplier (used to determine the number of zeros). The fourth color band indicates tolerance, where red indicates 2%, gold indicates 5%, and silver indicates 10%.

COLOR	DIGIT	MULTIPLIER	TOLERANCE
Black (BK)	0	$10^0 = 1$	
Brown (BR)	1	$10^1 = 10$	± 1%
Red (R)	2	$10^2 = 100$	± 2%
Orange (O)	3	$10^3 = 1{,}000$	
Yellow (Y)	4	$10^4 = 10{,}000$	
Green (G)	5	$10^5 = 100{,}000$	
Blue (B)	6	$10^6 = 1{,}000{,}000$	
Violet (V)	7	$10^7 = 10{,}000{,}000$	
Gray (GR)	8	$10^8 = 100{,}000{,}000$	
White (W)	9	$10^9 = 1{,}000{,}000{,}000$	
Gold		$10^{-1} = 0.1$	± 5%
Silver		$10^{-2} = 0.01$	± 10%
No Color			± 20%

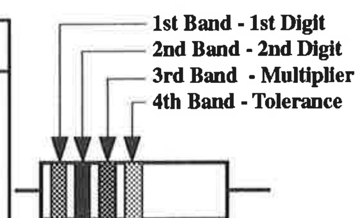


FIGURE 2-27: Standard resistor color code.

TABLE 2-6: Standard resistor color code.

PART B: Measuring Resistors

1. Measure each of the resistors listed in Table 2-5. Use either a digital or an analog ohmmeter and measure directly across the resistor as shown in Figure 2-28.

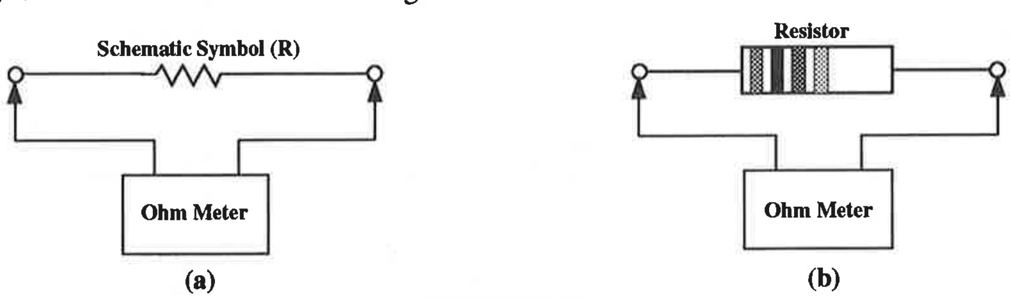


FIGURE 2-28

2. Follow these basic steps:
   a. Set the multimeter to measure ohms.
   b. Connect the test leads into the proper jacks. (Calibrate if using an analog meter.)
   c. Measure the resistance of the resistor under test. Read the measured value on the meter and incorporate the range (multiplier) setting to determine the correct resistance value.

3. Record the measured value of each resistor, as indicated, into Table 2-5.

NOTE: The resistance of resistors can be measured directly in ohms using an analog ohmmeter or a digital ohmmeter. Analog ohmmeters typically have to be calibrated (adjusted to zero) after each range change, while digital ohmmeters have an upper limit that is indicated by a single digit (1) when the limit is exceeded. For example, an 18 kΩ resistor can be measured on the (typical) 20 k scale of a digital meter, but a 22 kΩ resistor will exceed the limit and have to be measured on the 200 k scale. Refer to the text for other examples. Also do not hold the resistor in your hands while making measurements. This can provide a resistance path through your body, which because it is in parallel with the measured resistance, can produce erroneous measurements, especially with high resistance values. If the instructions for using the ohmmeter are not clear to you, consult the text material, the meter instruction manual, or ask your instructor/professor.

4. Finding the percent tolerance of measured resistors:
   a. Find the percent tolerance of four (4) of the resistors listed in Table 2-5. Start with R-R-BR resistor. If both analog and digital measurements are made, use the digital resistance measurements in the percent tolerance calculations. If the resistance value is higher than the coded value it does not require a sign,but if the measured resistance is lower than the coded resistance indicates, use a minus sign (–). The percent tolerance, knowing the measured and the coded resistance, is determined from:

$$\% \text{ tolerance} = \frac{\text{Measured Resistance} - \text{Coded Resistance}}{\text{Coded Resistance}} \times 100$$

   b. Insert the derived percent tolerance value for each of the resistors indicated into Table 2-5.

SECTION II: Resistors Connected in Series

PART A: Two Resistors in Series

1. Connect the two series resistors series of Figure 2-29, where R1 is O-O-R and R2 is Y-V-R. The schematic is shown in Figure 2-29(a) and the component diagram is shown in Figure 2-29(b).

FIGURE 2-29

2. Guided Laboratory exercise:
   a. Find each R1 and R2 resistor value. Then find the total series resistance, where $R_T = R1 + R2$.
   b. Measure the individual R1 and R2 resistors shown in Figure 2-30(a). Then, measure the total series resistance as shown in Figure 2-30(b).

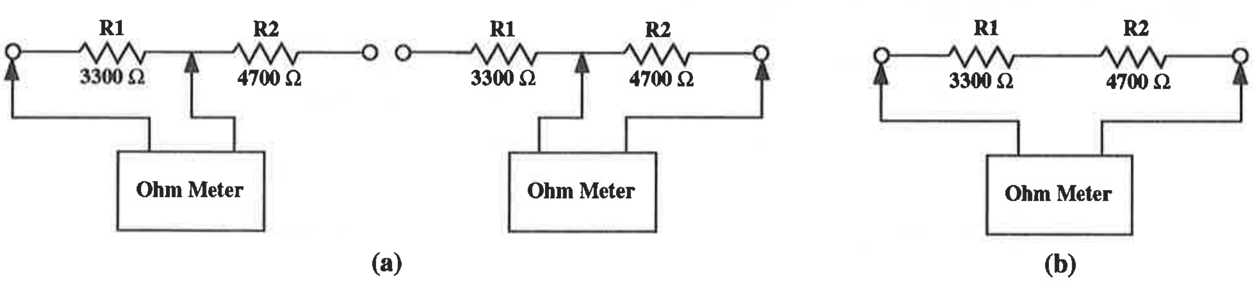


FIGURE 2-30

3. Insert the calculated and measured series resistances, as indicated, into Table 2-7.

PART B: Three Resistors in Series

1. Connect the three series resistors of Figure 2-31, where R1 is O-O-R, R2 is Y-V-R, and R3 is BR-BK-O. The schematic is shown in Figure 2-31(a) and component diagram is shown in Figure 2-31(b).

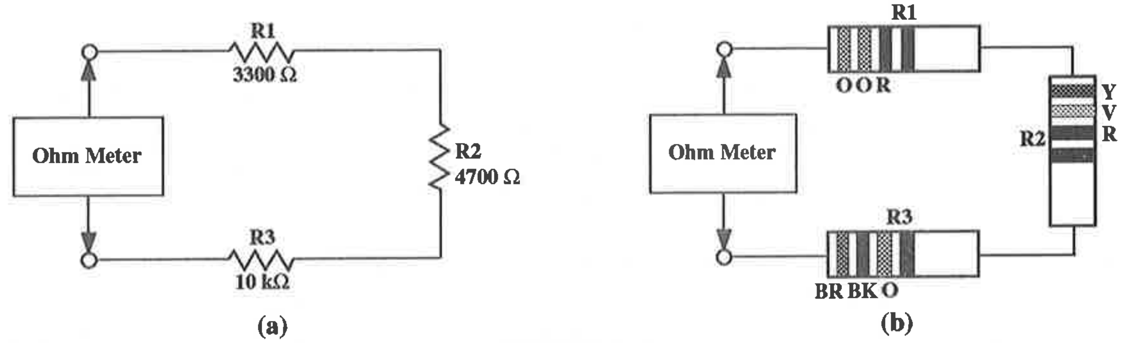


FIGURE 2-31

2. Unguided laboratory exercise:
   a. Find the total series resistance of the R1, R2, and R3 resistors of Figure 2-31.
   b. Measure the R3 resistance and then measure the total series resistance of R1, R2, and R3.

3. Insert the indicated calculated and measured resistances into Table 2-7.

TABLE 2-7	FIGURES 2-30			FIGURE 2-31	
	R1	R2	$R_T = R1 + R2$	R3	$R_T = R1 + R2 + R3$
CALCULATED	3300 Ω	4700 Ω		10 kΩ	
MEASURED					

SECTION III: Resistors Connected in Parallel

PART A: Two Resistors in Parallel

1. Connect the parallel resistors of Figure 2-32, where R1 is O-O-R and R2 is Y-V-R. The schematic is shown in Figure 2-32(a) and component diagram is shown in Figure 2-32(b).

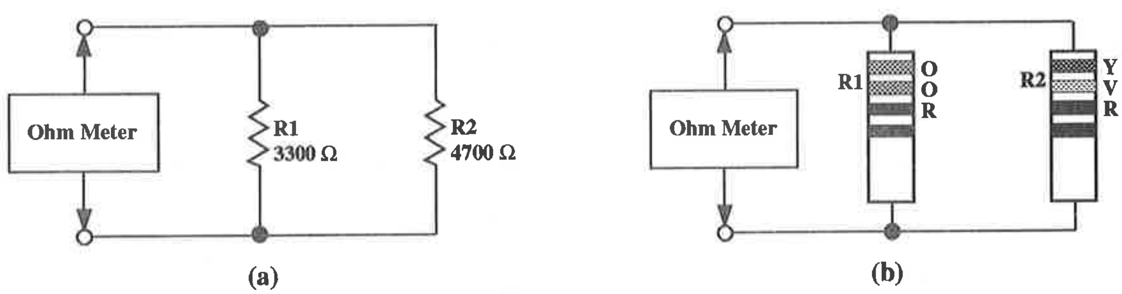


FIGURE 2-32

2. Guided laboratory exercise:
   a. Calculate the equivalent resistance of R1 and R2, where: $R_T = R1 \parallel R2 = \dfrac{1}{\dfrac{1}{R1} + \dfrac{1}{R2}}$.
   b. Measure the resistance of the parallel R1 and R2 resistor circuit.

NOTE: Two resistors in parallel can also be solved from: $R_T = \dfrac{R1 \times R2}{R1 + R2}$.

3. Insert the calculated and measured values, as indicated, into Table 2-8.

PART B: Three Resistors in Parallel

1. Connect the three parallel resistors of Figure 2-33, where R1 is O-O-R, R2 is Y-V-R, and R3 is BR-BK-O. The schematic is shown in Figure 2-33(a) and component diagram is shown in Figure 2-33(b).

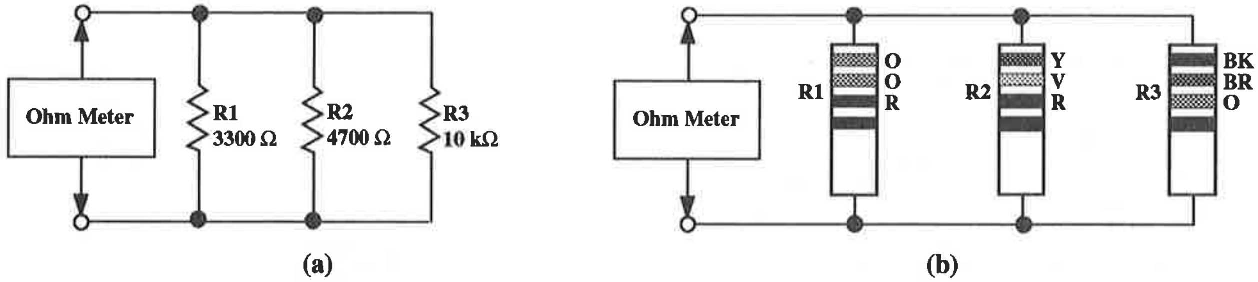


FIGURE 2-33

2. Unguided laboratory exercise:
   a. Calculate the resistance of the parallel R1, R2 and R3 resistors of Figure 2-33.
   b. Measure the resistance of the parallel R1, R2 and R3 resistors of Figure 2-33.

3. Insert the calculated and measured values, as indicated, into Table 2-8.

TABLE 2-8	FIGURE 2-32	FIGURE 2-33
	R_T = R1 ‖ R2	R_T = R1 ‖ R2 ‖ R3
CALCULATED		
MEASURED		

SECTION IV: Resistors Connected in Series-Parallel

PART A: Three Resistors in Series-Parallel

1. Connect the series-parallel resistors of Figure 2-34. The schematic is shown in Figure 2-34(a) and the component diagram is shown in Figure 2-34(b).

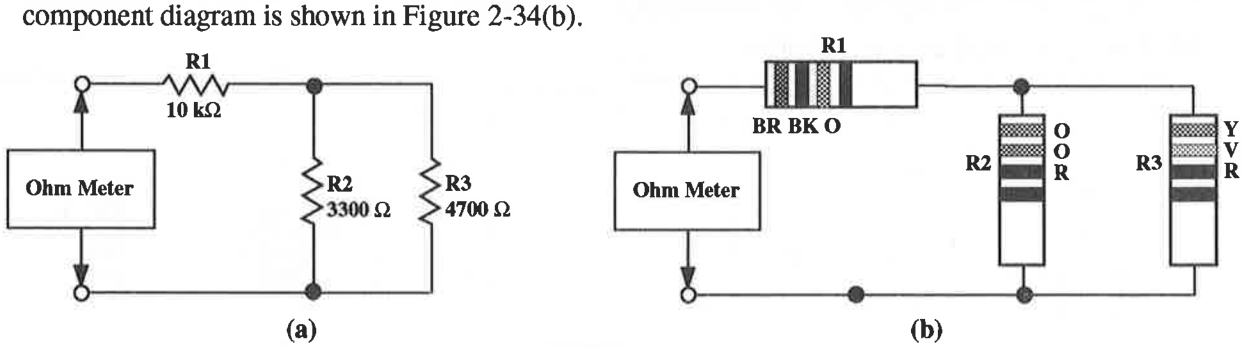


FIGURE 2-34

2. Guided laboratory exercise:
   a. Calculate the equivalent resistance of R1 in series with the parallel combination of R2 and R3, where:
      R_T = R1 + (R2 ‖ R3)
   b. Measure the resistance of the three resistor series-parallel resistors of Figure 2-34.

3. Insert the calculated and measured values, as indicated, into Table 2-9.

PART B: Four Series-Parallel Resistors

1. Connect the series-parallel resistors of Figure 2-35. The schematic is shown in Figure 2-35(a) and the component diagram is shown in Figure 2-35(b).

2. Unguided laboratory exercise:
   a. Calculate the equivalent resistance of the four series-parallel resistors of Figure 2-35.
   b. Measure the resistance of the four resistor series-parallel resistors.

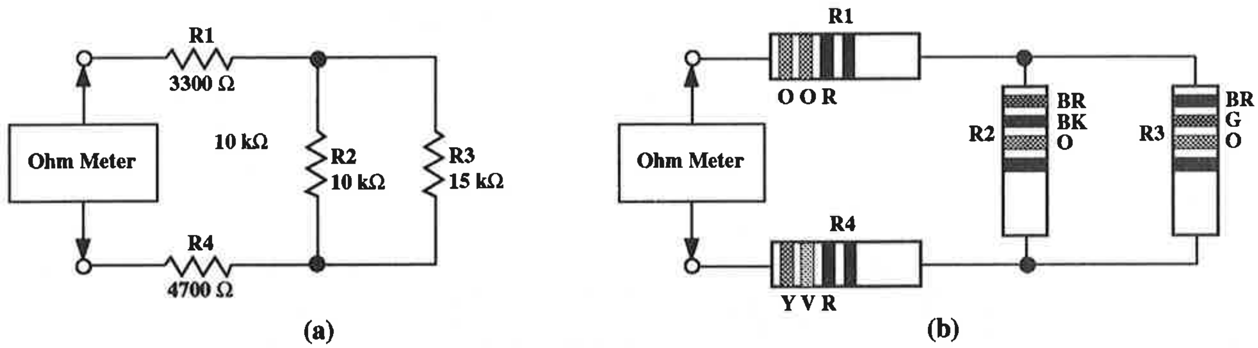


FIGURE 2-35

3. Insert the calculated and measured values, as indicated, into Table 2-9.

TABLE 2-9	FIGURE 2-34 R_T = R1 + (R2 ‖ R3)	FIGURE 2-35 R_T = R1 + (R2 ‖ R3) + R4
CALCULATED		
MEASURED		

SECTION V (Optional Lab Exercise): Variable Resistor Measurements

PART A (Guided Laboratory Exercise): Counter Clockwise (CCW) and Clockwise (CW) Rotation of a Variable Resistor

1. With reference to variable resistor terminals 1 and 3 of a 10 kΩ potentiometer:
   a. Connect the Ohmmeter across the 1 and 3 terminals of the variable resistor, as shown in Figure 2-36.
   b. Measure the resistance between terminals 1 and 3. Rotate the shaft both in a counter clockwise (CCW) and then a clockwise (CW) direction. Note any resistance change. Insert measurements into Table 2-10.

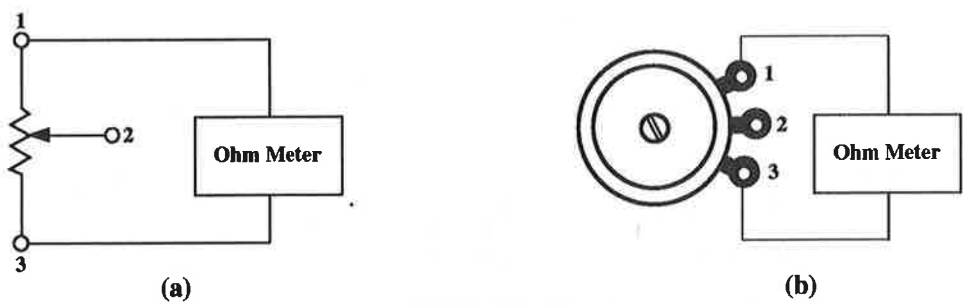


FIGURE 2-36

2. With reference to variable resistor terminals 2 and 3 of the 10 kΩ potentiometer:
   a. Measure (R2,3), the resistance between terminals 2 and 3, as shown in Figure 2-37(a).
   b. First at full counter clockwise (CCW) rotation, and then at full clockwise (CW) rotation. Insert measurements into Table 2-10.

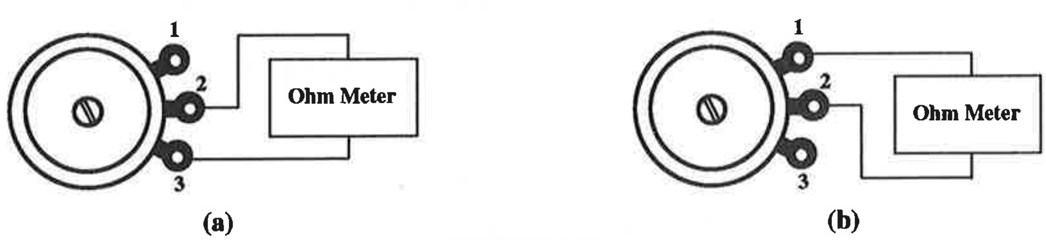


FIGURE 2-37

3. With reference to variable resistor terminals 1 and 2 of the 10 kΩ potentiometer:
   a. Measure R1,2, the resistance between terminals 1 and 2, as shown in Figure 2-37(b).
   b. First measure at full counter clockwise (CCW) rotation, and then at full clockwise (CW) rotation. Insert measurements into Table 2-10.

TABLE 2-10	Terminal 1,3		Terminal 2,3		Terminal 1,2		Mid-Rotation	
	CCW	CW	CCW	CW	CCW	CW	R2,3	R1,2
CALCULATED								
MEASURED								

PART B (Guided Laboratory Exercise): Mid-Rotation of a VariableResistor

1. Calculate R2,3, the resistance between terminals 2 and 3, at the mid-rotation of Figure 2-38. Use the measured R1,3 resistance in the calculations, where at mid-rotation R2,3 = R1,3/2.

2. Rotate the variable resistor, until the R2,3 resistance is about one-half the total R1,3 resistance.

3. Measure the R2,3 resistance between terminals 2 and 3 (Figure 2-38[a]). Then measure the R1,2 resistance between terminals 1 and 2 (Figure 2-38[b]).

4. Insert the calculated and measured resistance, as indicated, into table 2-10.

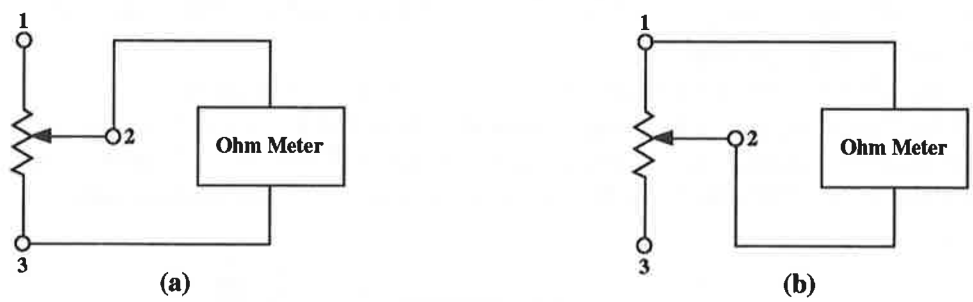


FIGURE 2-38

CHAPTER QUESTIONS

1. Does connecting a resistor in series with another resistor increase or decrease the total resistance? Explain.

2. Does connecting a resistor in parallel with another resistor increase or decrease the total resistance? Explain.

3. In what part of the scale is an analog ohmmeter typically the most accurate and why?

4. Are digital ohmmeters generally more accurate than analog ohmmeters? Explain.

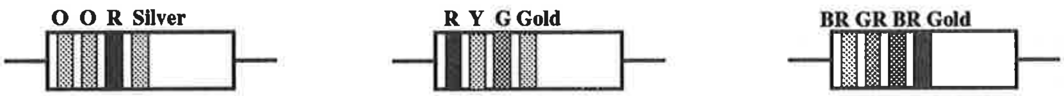
5. Did the resistance between terminals 1 and 2 of the variable resistor increase or decrease as the shaft was rotated clockwise (CW)? Explain.

6. Did the resistance between terminals 1 and 3 of the variable resistor increase or decrease as the shaft was rotated? Explain.

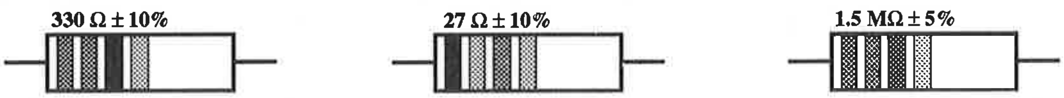
CHAPTER PROBLEMS

1. Solve the resistance and percent tolerance of the following color-coded resistors.

2. Solve for the resistance and the minimum and maximum resistance values of the following color-coded resistors.



3. Solve the color code from the resistance value and percent tolerance given for the following resistors.



4. Solve the percent tolerance of:

   a. A coded 2200 Ω resistor measuring 2050 Ω.

   b. A coded 120 kΩ resistor measuring 125 kΩ.

5. Solve the total resistance R_T value:

   a. For the two resistors in series, shown in Figure 2- 39(a).

   b. For the three resistors in series, shown in Figure 2-39(b).

   c. For the two resistors in parallel, shown in Figure 2-39(c).

   d. For the three resistors in parallel, shown in Figure 2-39(d).

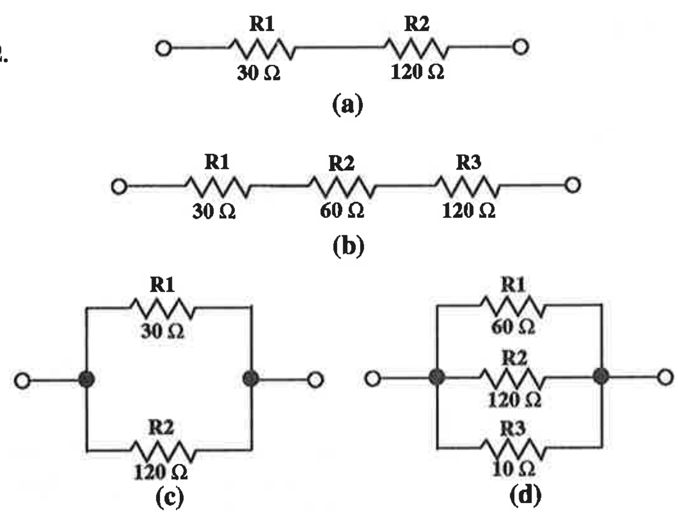


FIGURE 2-39: Schematics for Problem 4.

6. Solve the total resistance R_T for the series-parallel resistor networks, shown in Figure 2-40.

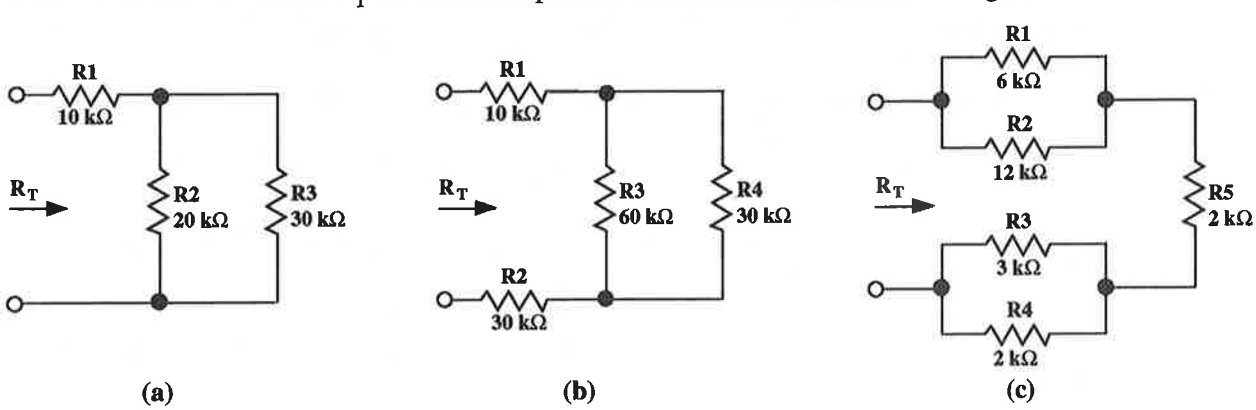


FIGURE 2-40: Schematics for Problem.

7. Solve the total resistance R_T for the series-parallel resistor network shown in Figure 2-41.

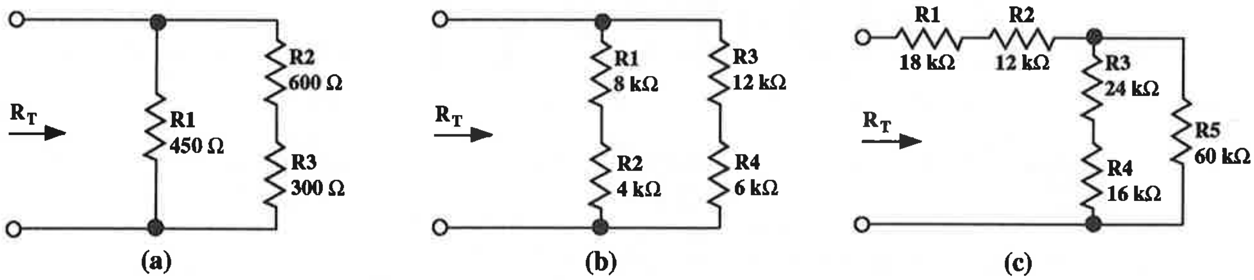


FIGURE 2-41: Schematics for Problem.

8. Determine the resistance in ohms when the pointer indication is as shown in Figure 2-42 and the R times multiplier is on the:

   a. R time 100 scale.

   b. R times 10 k scale.

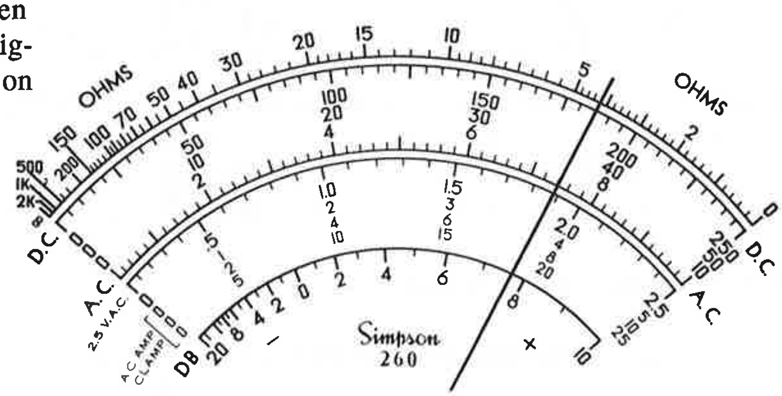


FIGURE 2-42

9. Determine the resistance in ohms when the pointer indication is as shown in Figure 2-43 and the R times multiplier is on the:

   a. R time 1 scale.

   b. R times 100 scale.

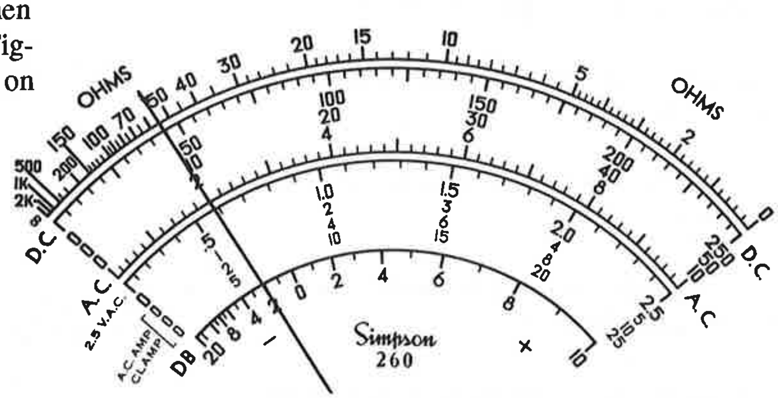


FIGURE 2-43

10. Determine the resistance in ohms when the pointer indication is as shown in Figure 2-44 and the R times multiplier is on the:

    a. R times 100 scale

    b. R time 10 kΩ scale.

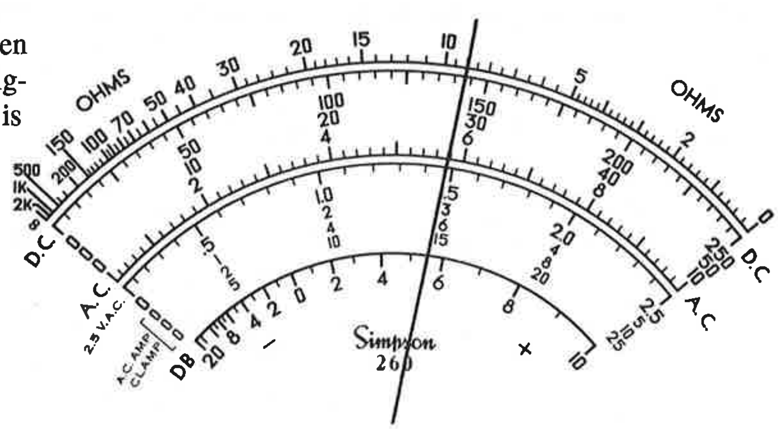


FIGURE 2-44

CHAPTER 3

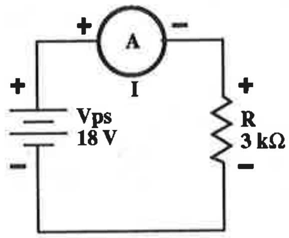
OHM'S LAW

INTRODUCTION

The discovery of the mathematical relationship between current, voltage, and resistance in an electric circuit by Georg Ohm, in the early 1800's, marks the beginning of the practical use of electricity. What Ohm discovered was that the current in an electric circuit is directly proportional to the applied voltage and inversely proportional to the resistance. In other words, Ohm's law states that in an electric circuit the current in amperes is equal to the voltage in volts divided by the resistance in Ohms ($I = V/R$). However solving for I is only one form of Ohms law. The other two forms are: solving for voltage knowing the current and resistance ($V = I \times R$), and solving for resistance knowing the voltage and current ($R = V/I$). The design and analysis of every circuit in electronics involves the use of Ohm's law.

SOLVING CURRENT (I) KNOWING V AND R

In the closed circuit of Figure 3-1, the voltage is the force that causes the current to flow through the circuit resistance, and the amount of current is determined by the Ohms law formula $I = V/R$. Essentially, the circuit current is directly proportional to the applied voltage and inversely proportional to the resistance, where I is the current in amperes, V is the voltage in volts and R is the resistance in ohms. For example, if the power supply voltage is 18 V and the resistor value is 3 kΩ, the current flow through the resistor is 6 mA. The current is solved in conjunction with the circuit of Figure 3-1.

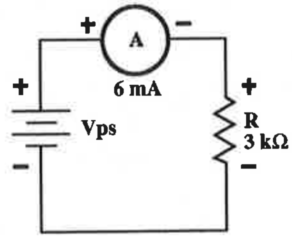


$$I = \frac{V}{R} = \frac{18\text{ V}}{3\text{ k}\Omega} = \frac{18\text{ V}}{3 \times 10^3} = 6 \times 10^{-3} = 6\text{ mA}$$

FIGURE 3-1

SOLVING VOLTAGE (V) KNOWING I AND R

The voltage across a known resistor can be solved, when the current through the resistor is known. For example, if the current of 6 mA flows through a 3 kΩ resistor, the voltage developed across the resistor is 18 V. The voltage is solved in conjunction with the circuit of Figure 3-2.



$$V = IR = 6\text{ mA} \times 3\text{ k}\Omega = 6 \times 10^{-3} \times 3 \times 10^3 = 18\text{ V}$$

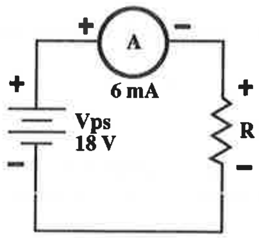
FIGURE 3-2

NOTE: Multiplying both sides of the equation by R, converts the $I = V/R$ formula to $V = IR$.

$$I = \frac{V}{R}, \Rightarrow I(R) = \frac{V(R)}{R}, \Rightarrow IR = V, \text{ or in formula form } V = IR$$

SOLVING RESISTANCE (R) KNOWING V AND I

The value in ohms of an unknown resistor can be solved, when the voltage across the resistor and the current through the resistor are known. For example, if a voltage dropped across a resistor is 18 V and the current that flows through the resistor is 6 mA, the resistor value is 3 kΩ. The resistance is solved in conjunction with the circuit of Figure 3-3.



$$R = \frac{V}{I} = \frac{18\ V}{6\ mA} = \frac{18\ V}{6 \times 10^{-3}} = 3 \times 10^3 = 3\ k\Omega$$

FIGURE 3-3

NOTE: Dividing both sides of the equation by I, converts the V = IR to R = V/I.

$$V = IR, \Rightarrow \frac{V}{(I)} = \frac{IR}{(I)} \Rightarrow \frac{V}{I} = R, \text{ or in formula form } R = \frac{V}{I}$$

POWER DISSIPATION OF RESISTORS

The moment voltage is applied and current flows through a resistor, electrons colliding with atoms cause the temperature to rise and power in the resistor to be dissipated in the form of heat. If the applied voltage is increased or the resistance of the resistor lowered, the current through the resistor increases and the power dissipated by the resistor increases. Power dissipation is caused by both the voltage across and current through the resistor. The basic power dissipation formula is P = VI. Other forms of power dissipation are $P = V^2/R$ and $P = I^2R$. Each are algebraically derived from P = VI formula. Power dissipation units are given in watts (W).

1. $P = VI$ — basic formula
2. $P = V(I) = V \times \frac{V}{R} = \frac{V^2}{R}$ — substituting I = V/R
3. $P = (V)I = (IR)I = I^2R$ — substituting V = IR

For example in the circuit of Figure 3-4, the power supply is 12 V and the resistor value is 300 Ω. In the analysis, I is solved first, prior to using all three forms of the power formula to calculate power.

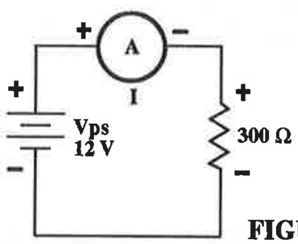


FIGURE 3-4

$I = V/R = 12\ V/300\ \Omega = 40\ mA$

$P = VI = 12\ V \times 40\ mA = 480\ mW$

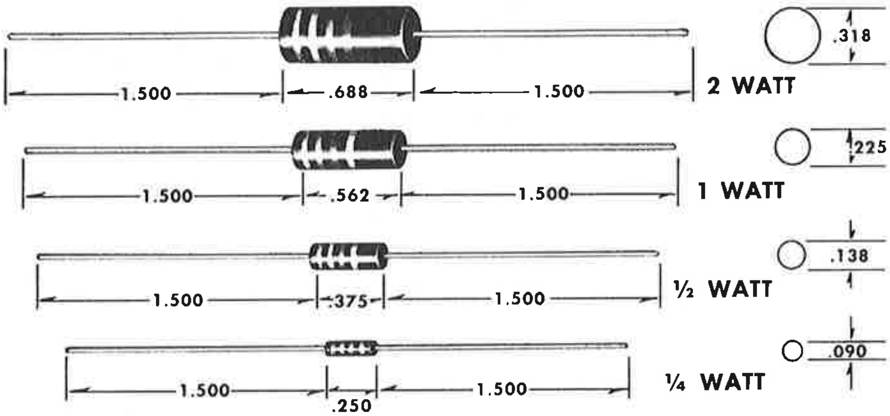
$P = V^2/R = 12\ V^2/300\ \Omega = 480\ mW$

$P = I^2 \times R = (40\ mA)^2 \times 300\ \Omega = 480\ mW$

POWER LIMITATION OF RESISTORS

All resistors have power ratings and manufacturing processes determine how much power a resistor can safely dissipate. Wire wound resistors can be constructed to dissipate 50 W, while most general purpose resistors typically dissipate 2 W or less. If the power dissipated by a resistor is larger than the rated power of the resistor, excessive heat can cause the resistor to be destroyed. To avoid the possibility, a general rule of thumb is to use a factor of 2 in selecting the wattage rating of the resistor. For example, if a resistor in a circuit dissipates 250 milliwatts (1/4 watt) of power, a 1/2 watt resistor should be used.

Knowing the power dissipation limits of a circuit resistor is another important consideration when selecting a resistor. Essentially, the larger the physical size of the resistor the more power the resistor can dissipate. In other words, power is dissipated in the form of heat, and the larger the resistor's surface area the easier it is for heat to escape to the surrounding air. A comparison of the physical sizes of carbon composition resistors ranging from 1/4 watt to 2 watts, is shown in Figure 3-5.

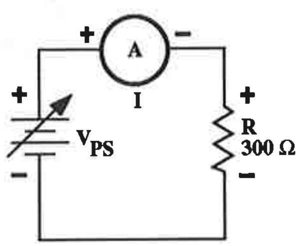


(Courtesy of Stackpole Carbon Company)

FIGURE 3-5: The physical size indicates wattage ratings of carbon composition resistors.

PLOTTING GRAPHS

When the voltage across a resistor is increased the current through the resistor increases linearly. For example in the circuit of Figure 3-6(a), if the voltage is increased from 3 V to 6 V and then to 12 V, the current changes, but in proportion to the applied voltage. When plotted on the graph of Figure 3-6(b), the current versus voltage graph results in a straight line.

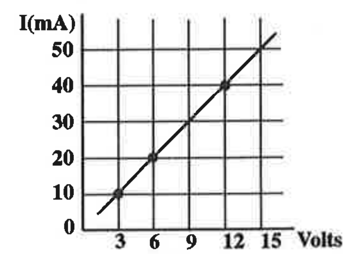


(a)

$I = V/R = 3\ V/300\ \Omega = 10\ mA$

$I = V/R = 6\ V/300\ \Omega = 20\ mA$

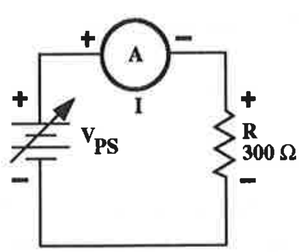
$I = V/R = 12\ V/300\ \Omega = 40\ mA$



(b)

FIGURE 3-6

However, when the increase in voltage versus the increase in watts is solved, the plotted graph is non-linear. Essentially, when the voltage is doubled, the current in the circuit doubles and the power dissipated by the resistor increases by a factor of four. The power dissipation across the resistor, as the voltage is increased from 3 V to 6 V and then to 12 V, is shown in conjunction with Figure 3-7(a). Graphic results of the voltage versus power increase is show in Figure 3-7(b).

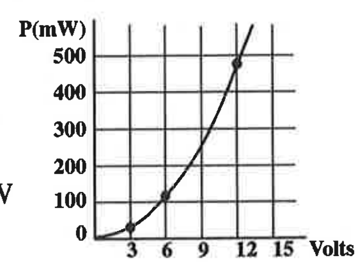


(a)

$P = V^2/R = 3\ V^2/300\ \Omega = 30\ mW$

$P = V^2/R = 6\ V^2/300\ \Omega = 120\ mW$

$P = V^2/R = 12\ V^2/300\ \Omega = 480\ mW$

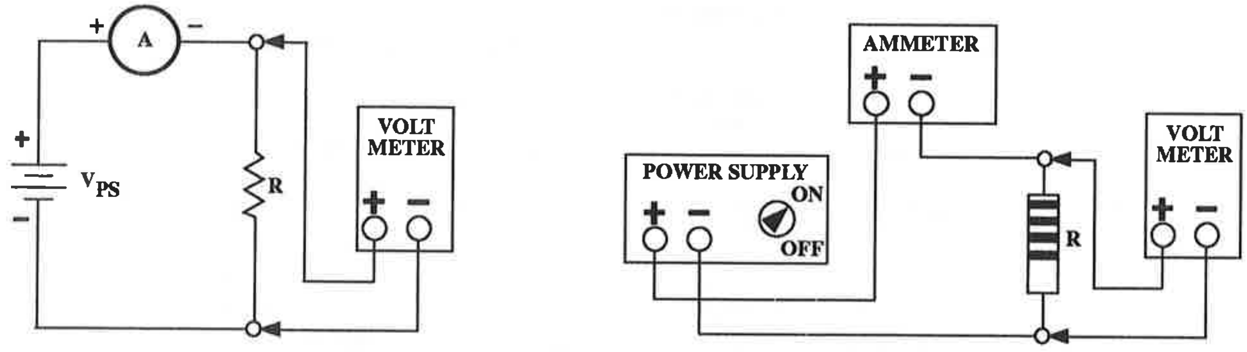


(b)

FIGURE 3-7

MEASURING VOLTAGE AND CURRENT

Multimeters can be analog or digital, and typically can be used to measure voltage, resistance, and current. Voltmeters are connected in parallel with the resistor to read the voltage, while ammeters are connected in series with the resistor to measure the current through the resistor. The schematic diagram of the connection is shown in Figure 3-8(a). The hookup diagram of Figure 3-8(b) shows the proper connections, where the polarity of the test equipment must be observed. An incorrect polarity connection of analog meters can cause the indicating needle to be deflected downscale and possibly damaged. On digital meters a negative sign (–) is displayed on the readout.



(a) (b)

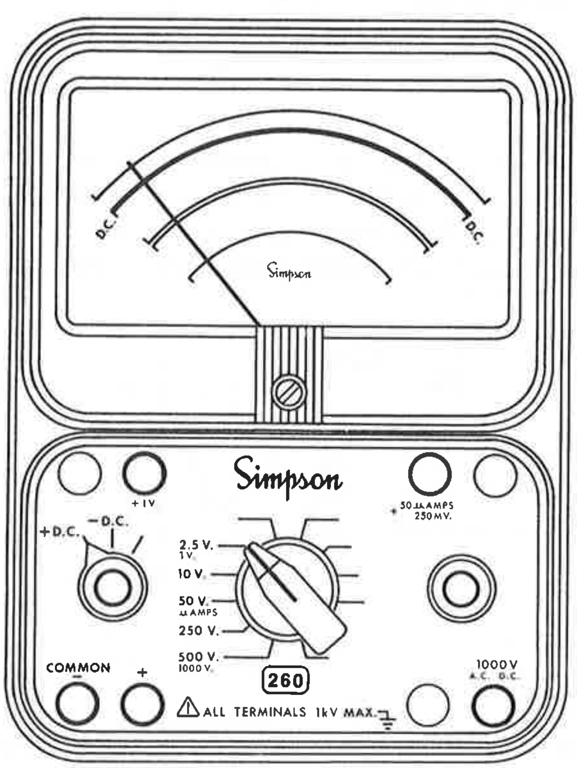
FIGURE 3-8: Voltmeters are connected in parallel across the resistor to measure voltage, and ammeters are connected in series with the resistor to measure the current through the resistor.

ANALOG VOLTMETERS

Analog multimeters are multiscale and the range switch indicates full-scale deflection. On the Simpson 260® there are five voltage ranges. However, do not attempt to measure voltage on any range scale other than the voltage scale. Measuring the voltage on either the resistance or ammeter scale can cause protective fuses to be blown and damage to the meter.

The directions for using the 0-2.5 V through the 0-500 V ranges of the Simpson 260® volt-ohm-miliammeter (VOM) are given in conjunction with the illustration of Figure 3-9. These are representative directions that can be used for any analog voltmeter.

Measuring voltage on analog meter scales is determined by both the voltage range and the scale reading.



Operation

DC VOLTAGE MEASUREMENT 0-2.5 THROUGH 0-500V RANGE

a. Set the function switch at +DC

b. Plug the black test lead into the – COMMON jack and the red test lead into the + jack.

c. Set the range switch at one of the five voltage range positions marked 2.5V, 10V, 50V, 250V or 500V.

NOTE: When in doubt as to the voltage present, always use the highest voltage range as a protection to the Instrument. If the voltage is within a lower range, the switch may be set for the lower range to obtain a more accurate reading. Be sure power is off in the circuit being measured and all capacitors discharged.

d. Connect the black test lead to the negative side of the circuit being measured and the red test lead to the positive side of the circuit.

e. Turn on the power in the circuit being measured.

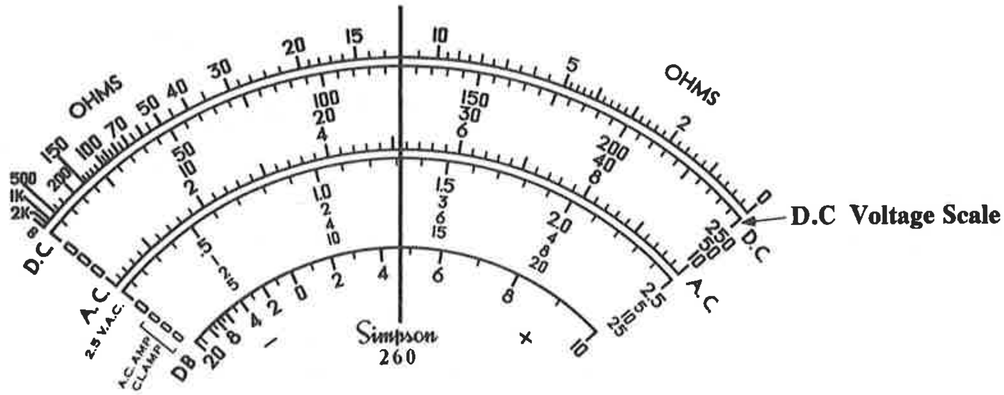
f. Read the voltage on the black scale marked DC. For the 2.5V range, use the 0-250 figures and divide by 100. For the 10V, 50V, and 250V ranges, read the figures directly. For the 500V range, use the 0-50 figures and multiply by 10.

NOTE: Turn off power to the circuit and wait until the meter indicates zero before disconnecting the test leads.

(Courtesy of Simpson Electric Company)

FIGURE 3-9: Jacks, switch positions, and directions for measuring dc voltage with a Simpson 260® meter.

For example, as shown in Figure 3-10, the needle indicates 125 V on the 250 V scale, 25 V on the 50 V scale, and 5 V on the 10 V scale. Since the tolerance for the linear scale of an analog meter is rated as a percent of full scale needle deflection, the most accurate voltage reading is measured in the top 50% of the scale.



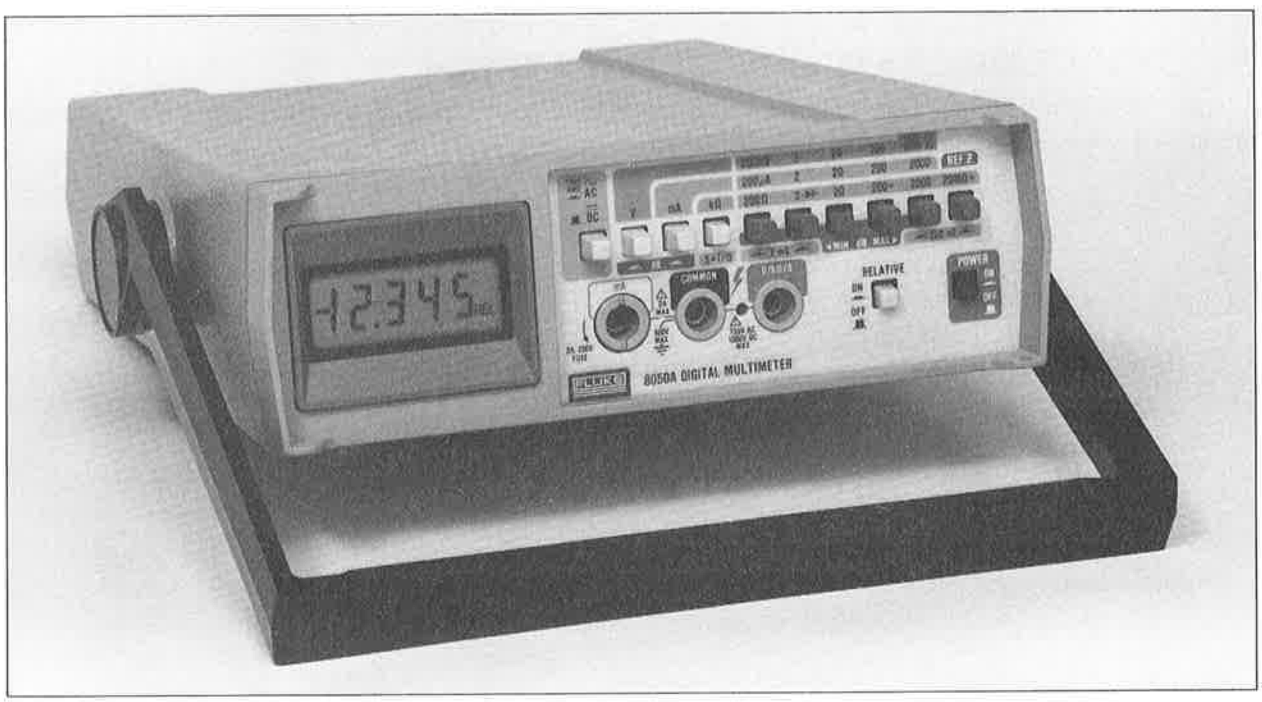
(Courtesy of Simpson Electric Company)

FIGURE 3-10: The Simpson 260® meter scale with centered indicator needle..

DIGITAL VOLTMETERS

The digital meter, like the analog meter, measures current, voltage, and resistance, and has range and function switches. However, digital meters are generally easier to use than analog meters because, rather than having to interpret a needle position on the scale, the voltage value measured is read directly off a numerical readout . Therefore, on the digital meter, it is only necessary to turn on the meter, push the function switch, select the range switch, and take the measurement directly off the numerical readout. If the leads of the voltmeter are reversed, it will be indicated with a (–). If the range is too low for the voltage being measured, it will be indicated by a 1. Increasing to a higher scale should then provide the measured voltage.

Like analog meters, digital meters have better resolution on the lowest possible scale that provides a reading. The Fluke digital meter 8050, shown in Figure 3-11, has voltage upper limits depending on the scale of 2 V, 20 V, 200 V, and 2000 V. Therefore 12.34 V, as an example, has the best accuracy at an upper limit of 20 V.



(Reproduced with permission from John Fluke Mfg. Co., Inc.)

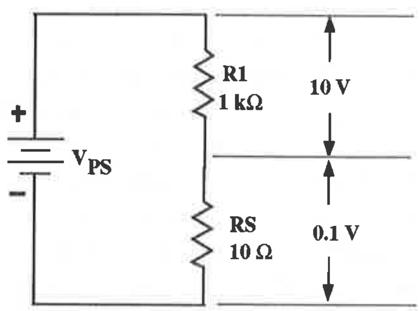
FIGURE 3-11: The Fluke Model 8050A Digital Multimeter.

AMMETERS

Ammeters are typically placed in series with circuit resistors. They have very low internal resistances so they don't contribute any additional series resistance to the circuit under test. Since ammeters have such a low resistance, however, connecting the ammeter inadvertently across a voltage source will produce a very large current. On the analog meter, it could blow fuses, peg the indicating needle, or totally ruin the meter. On a digital meter, it will generally blow a fuse. However, the inputs for measuring current on the digital meter, aside from the common ground, are different than they are for measurement of voltage and resistance. So even if the fuse is blown on the ammeter circuit of the Fluke 8050, for example, the separate circuits and inputs still make it possible to continue to take voltage and resistance measurements on the meter.

PRACTICAL OHM'S LAW APPLICATIONS

In practice, connecting an ammeter in series with a resistor is generally impractical, since it would require unsoldering the resistor to make the measurement. A better and more practical method of measuring current is to measure the current indirectly. This involves using a known voltage across a known resistance and solving the current from I = V/R. However, in breadboard construction and measurements using a small known 10 Ω resistor in series with the resistor under test is an acceptable method. If the value of the test resistor is 1 kΩ or greater, adding the 10 Ω current sampling resistor still provides a total series resistance that is within that of a 1% tolerance resistor. For example in Figure 3-12, if 0.1 V is measured across the 10 Ω current sampling resistor, then V_{R1} = 10 V since the current through both the in-series R1 and RS resistors is 10 mA.



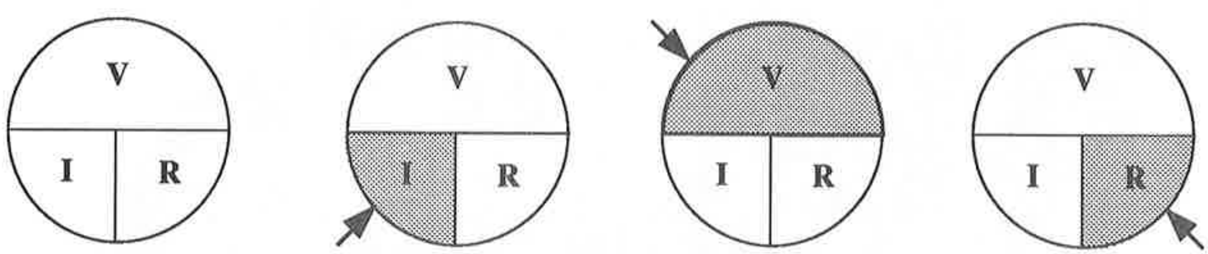
$I = V/RS = 0.1\ V/10\ \Omega = 10\ mA.$

$V_{R1} = IR_1 = 10\ mA \times 1\ k\Omega = 10\ V$

FIGURE 3-12

REFERENCE DIAGRAM AND FORMULA TABLE

Ohm's law is easily remembered using the diagrams of Figure 3-13. Essentially, where the arrow is pointing provides the formula.



I = V/R   V = IR   R = V/1

FIGURE 3-13

Further formula derivations include:

In terms of voltage: P = VI and V = P/I.

In terms of current: P = VI and I = P/V. Also, $P = I^2R$, so $I^2 = P/R$ and $I = \sqrt{P/R}$.

In terms of resistance: $P = V^2/R$ and $R = V^2/P$. Also, $P = I^2R$, so $R = P/I^2$.

The three Ohm's law formulas and nine power formulas are given for handy reference use in Table 3-1.

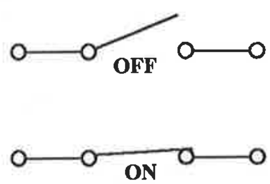
P (Power)	VI	I^2R	V^2/R
V (Voltage)	IR	P/I	$\sqrt{PR}$
I (Current)	V/R	P/V	$\sqrt{P/R}$
R (Resistance)	V/I	V^2/P	P/I^2

TABLE 3-1

SWITCHES AND FUSES

All circuits in a system are powered by dc voltage that is generally turned on and turned off by an on/off switch. When the switch is on current flows in the circuit, and when the switch is off the circuit is open and no current flows. The schematic symbol of a single pole, single throw switch (SPST) is shown in Figure 3-14(a).

Fuses are used as a protection against excessive current that can cause damage to the circuit. Since the metal used in fuses has a low melting point, once the current limit of the fuse is exceeded, the fuse, which is generally in series in the circuit, will open or "blow" causing the current in the circuit to cease. Short circuits caused by faulty components, or even poor measuring techniques, like accidentally connecting an ammeter across a voltage source, can cause excessive current and blown fuses. The schematic symbol of a fuse is shown in Figure 3-14(b).



(a) SPST Switch

(b) Fuse Schematic Symbol

FIGURE 3-14

SAFETY PRECAUTIONS

Volt-ohm-milliameters (VOM's) such as the Simpson 260® are designated for use with low power circuitry found in radio and television receivers, household appliances, and most general laboratory work. These meters should not be used in high-voltage, high-power applications. When it is necessary to take voltage measurements over 300 volts use leads with clips on them. Do not hold the leads in your hands when measuring the circuit. Also, work with only one hand, keeping the other hand behind your back or in your pocket. Make sure another person is present as a safety observer. High voltage is dangerous. Electric shocks can cause serious injury or death.

LABORATORY EXERCISE

EXERCISE OBJECTIVES

To become familiar with:

- Basic voltage and current measurements using voltmeters and ammeters.
- Verifying Ohm's law using voltage and current measurements.
- Resistor power dissipation

LIST OF MATERIALS

1. Resistors (one each): 1.5 kΩ and 1/2 W, 1.5 kΩ and 1/4 W or 1/8 W
2 Variable dc Power Supply
3. Analog or Digital Voltmeter

PROCEDURE

SECTION I (Guided Laboratory Exercise): Using the Voltmeter

PART A: Measuring the Power Supply Voltage Limits

1. Connect the circuit as shown in Figure 3-15, where a wire (typically red) is connected from the positive terminal of the power supply to the positive terminal of the voltmeter and a wire (typically black) is connected from the negative terminal to the negative terminal of the voltmeter. Do not turn on the power supply until the polarity of the leads are verified. Analog meters require that proper polarities are observed, since a negative deflection can damage the meter. Digital meters will simply indicate a negative (–) sign when the leads are reversed (incorrectly connected).

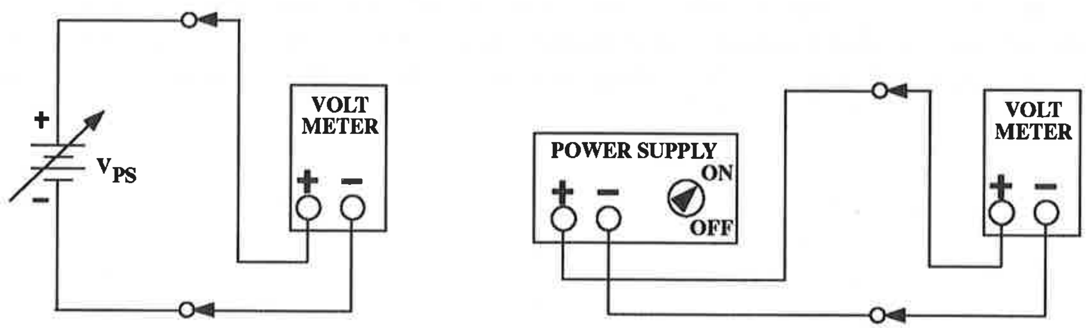


FIGURE 3-15: Voltmeter connected to measure the votage of the power supply.

2. Maximum power supply voltage measurement.
   a. Set the voltmeter to measure volts and dc and set the voltage range switch to greater than (+)100 volts. Next turn on the power supply and increase the power supply voltage (clockwise direction) to the maximum voltage limit.
   b. Measure the maximum voltage on the voltmeter. Use either an analog or digital voltmeter and record both the measured voltage and the voltage range setting of the meter.

NOTE: If the analog voltmeter needle deflection is negative the leads are reversed. If no deflection occurs, then the power supply is not turned on, the variable voltage knob is set at zero volts and needs to be increased, or one (or both) of the leads (from the meter to the power supply) is open.

3. Minimum power supply voltage measurement:
   a. Decrease the power supply voltage to the minimum voltage limit (counter-clockwise direction). Then set the range switch to the lowest range setting that obtains the most accurate voltage reading.
   b. Measure the minimum voltage on the voltmeter. Use either an analog or digital voltmeter and record the voltage and the voltage range setting of the meter.

4. Insert the minimum and maximum measured dc voltage values, as indicated, into Table 3-2 (Part A).

PART B: Achieving the best Accuracy.

Voltmeters can measure the same voltage on more than one range scale and with varying degrees of accuracy. Therefore, for the purpose of voltmeter familiarity, measure voltages of 6 V, 12 V and 18 V on a minimum of two voltage ranges. The measurements shown in Figure 3-15 can be made on a digital or analog voltmeter.

1. Measuring 18 volts on two scales of the voltmeter:
   a. Initially switch the voltmeter range switch to 100 V or greater. Then vary the power supply voltage so that the voltmeter reads 18 V. Record the voltage range setting of the meter.
   b. Then switch the range switch on the voltmeter to the next lowest range and again measure the voltage. Record both the voltage and the voltage range setting of the meter.

2. Measuring 12 volts on two scales of the voltmeter:
   a. Initially switch the voltmeter range switch to 100 V or greater. Then vary the power supply voltage so that the voltmeter reads 12 V. Record the voltage range setting of the meter.
   b. Then switch the range switch on the voltmeter to the next lowest range and again measure the voltage. Record both the voltage and the voltage range setting of the meter.

3. Measuring 6 volts on two scales of the voltmeter:
   a. Initially switch the voltmeter range switch to 100 V or greater. Then vary the power supply voltage so that the voltmeter reads 6 V. Record the voltage range setting of the meter.
   b. Then switch the range switch of the voltmeter to the next lowest range and again measure the voltage. Record both the voltage and the voltage range setting of the meter.

NOTE: Digital voltmeters provide the best accuracy when the voltage range is set to the lowest possible measurable range. Analog meters provide the best voltage accuracy when the reading is taken from the top 50% of the scale.

4. Insert the 18 V, 12 V and 6 V dc voltage values and their associated voltage ranges at each setting into Table 3-2 (Part B).

TABLE 3-2	Part A		Part B					
	Vmax	Vmin	Volts	Lower Range	Volts	Lower Range	Volts	Lower Range
Voltage			18 V		12 V		6 V	
Voltage Range								

SECTION II (Guided Laboratory Exercise): Measuring Current

PART A: Pre-Laboratory Calculations

1. In the circuit of Figure 3-16, a 1.5 kΩ, 1/2 watt resistor is added to the circuit and the power supply is varied, initially to 6 V, then to 12 V, and lastly to 18 V. At each voltage variation, solve the current through the 1.5 kΩ resistor and the power developed by the resistor.