CHAPTER 1

Introduction

CHAPTER OBJECTIVES

After you read, discuss, study, and apply ideas in this chapter, you will be able to:

1. Define mechatronics and appreciate its relevance to contemporary engineering design
2. Identify a mechatronic system and its primary elements
3. Define the elements of a general measurement system

1.1 MECHATRONICS

Mechanical engineering, as a widespread professional practice, experienced a surge of growth during the early 19th century because it provided a necessary foundation for the rapid and successful development of the industrial revolution. At that time, mines needed large pumps never before seen to keep their shafts dry, iron and steel mills required pressures and temperatures beyond levels used commercially until then, transportation systems needed more than real horse power to move goods; structures began to stretch across ever wider abysses and to climb to dizzying heights, manufacturing moved from the shop bench to large factories; and to support these technical feats, people began to specialize and build bodies of knowledge that formed the beginnings of the engineering disciplines.

The primary engineering disciplines of the 20th century—mechanical, electrical, civil, and chemical—retained their individual bodies of knowledge, textbooks, and professional journals because the disciplines were viewed as having mutually exclusive intellectual and professional territory. Entering students could assess their individual intellectual talents and choose one of the fields as a profession. We are now witnessing a new scientific and social revolution known as the information revolution, where engineering specialization ironically seems to be simultaneously focusing and diversifying. This contemporary revolution was spawned by the engineering development of semiconductor electronics, which has driven an information and communications explosion that is transforming human life. To practice engineering today, we must understand new ways to process information and be able to utilize semiconductor electronics within our products, no matter what label we put on ourselves as practitioners. Mechatronics is one of the new and exciting fields on the engineering landscape, subsuming parts of traditional engineering fields and requiring a broader approach to the design of systems that we can formally call mechatronic systems.

Internet Link

1.1 Definitions of "mechatronics"

Then what precisely is mechatronics? The term **mechatronics** is used to denote a rapidly developing, interdisciplinary field of engineering dealing with the design of products whose function relies on the integration of mechanical and electronic components coordinated by a control architecture. Other definitions of the term "mechatronics" can be found online at Internet Link 1.1. The word mechatronics was coined in Japan in the late 1960s, spread through Europe, and is now commonly used in the United States. The primary disciplines important in the design of mechatronic systems include mechanics, electronics, controls, and computer engineering. A mechatronic system engineer must be able to design and select analog and digital circuits, microprocessor-based components, mechanical devices, sensors and actuators, and controls so that the final product achieves a desired goal.

Mechatronic systems are sometimes referred to as smart devices. While the term smart is elusive in precise definition, in the engineering sense we mean the inclusion of elements such as logic, feedback, and computation that in a complex design may appear to simulate human thinking processes. It is not easy to compartmentalize mechatronic system design within a traditional field of engineering because such design draws from knowledge across many fields. The mechatronic system designer must be a generalist, willing to seek and apply knowledge from a broad range of sources. This may intimidate the student at first, but it offers great benefits for individuality and continued learning during one's career.

Today, practically all mechanical devices include electronic components and some type of computer monitoring or control. Therefore, the term mechatronic system encompasses a myriad of devices and systems. Increasingly, microcontrollers are embedded in electromechanical devices, creating much more flexibility and control possibilities in system design. Examples of mechatronic systems include an aircraft flight control and navigation system, automobile air bag safety system and antilock brake systems, automated manufacturing equipment such as robots and numerically controlled (NC) machine tools, smart kitchen and home appliances such as bread machines and clothes washing machines, and even toys.

Internet Link

1.2 Online mechatronics resources

Figure 1.1 illustrates all the components in a typical mechatronic system. The actuators produce motion or cause some action; the sensors detect the state of the system parameters, inputs, and outputs; digital devices control the system; conditioning and interfacing circuits provide connections between the control circuits and the input/output devices; and graphical displays provide visual feedback to users. The subsequent chapters provide an introduction to the elements listed in this block diagram and describe aspects of their analysis and design. At the beginning of each chapter, the elements presented are emphasized in a copy of Figure 1.1. This will help you maintain a perspective on the importance of each element as you gradually build your capability to design a mechatronic system. Internet Link 1.2 provides links to various vendors and sources of information for researching and purchasing different types of mechatronics components.

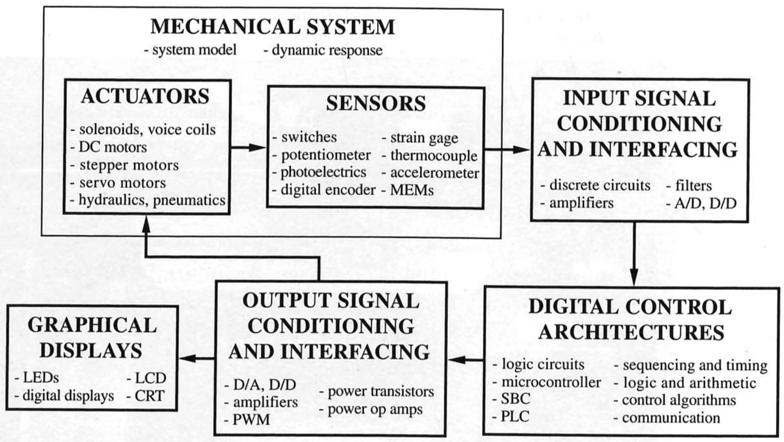


Figure 1.1 Mechatronic system components.

Example 1.1 describes a good example of a mechatronic system—an office copy machine. All of the components in Figure 1.1 can be found in this common piece of office equipment. Other mechatronic system examples can be found on the book website. See the Segway Human Transporter at Internet Link 1.3, the Adept pick-and-place industrial robot in Video Demos 1.1 and 1.2, the Honda Asimo and Sony Qrio humanoid-like robots in Video Demos 1.3 and 1.4, and the inkjet printer in Video Demo 1.5. As with the copy machine in Example 1.1, these robots and printer contain all of the mechatronic system components shown in Figure 1.1. Figure 1.2 labels the specific components mentioned in Video Demo 1.5. Video demonstrations of many more robotics-related devices can be found

Internet Link

1.3 Segway human transporter

Video Demo

1.1 Adept One robot demonstration

1.2 Adept One robot internal design and construction

1.3 Honda Asimo Raleigh, NC, demonstration

1.4 Sony "Qrio" Japanese dance demo

1.5 Inkjet printer components

Mechatronic System—Copy Machine

EXAMPLE 1.1

An office copy machine is a good example of a contemporary mechatronic system. It includes analog and digital circuits, sensors, actuators, and microprocessors. The copying process works as follows: The user places an original in a loading bin and pushes a button to start the process; the original is transported to the platen glass; and a high intensity light source scans the original and transfers the corresponding image as a charge distribution to a drum. Next, a blank piece of paper is retrieved from a loading cartridge, and the image is transferred onto the paper with an electrostatic deposition of ink toner powder that is heated to bond to the paper. A sorting mechanism then optionally delivers the copy to an appropriate bin.

Analog circuits control the lamp, heater, and other power circuits in the machine. Digital circuits control the digital displays, indicator lights, buttons, and switches forming the user interface. Other digital circuits include logic circuits and microprocessors that coordinate all of the functions in the machine. Optical sensors and microswitches detect the presence or absence of paper, its proper positioning, and whether or not doors and latches are in their correct positions. Other sensors include encoders used to track motor rotation. Actuators include servo and stepper motors that load and transport the paper, turn the drum, and index the sorter.

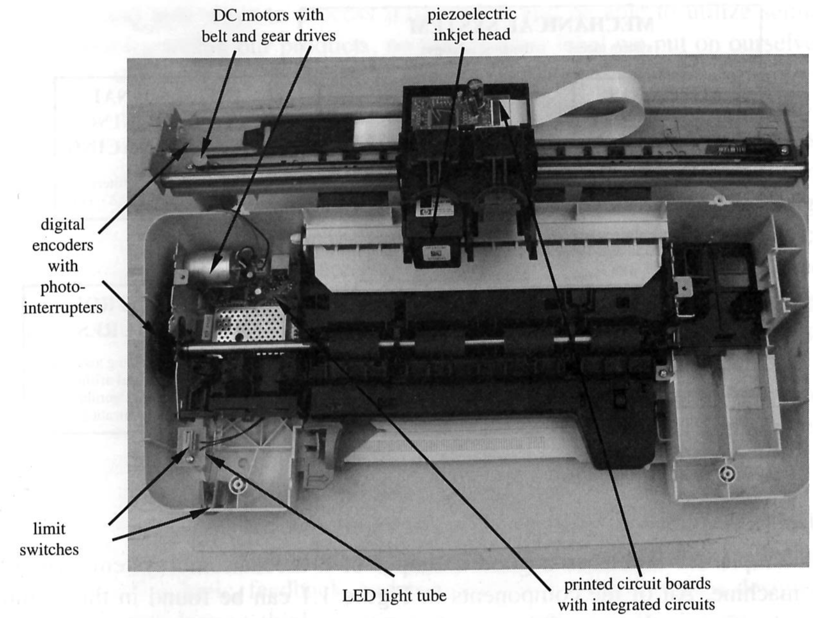


Figure 1.2 Inkjet printer components.

Internet Link

1.4 Robotics video demonstrations

1.5 Mechatronic system video demonstrations

at Internet Link 1.4, and demonstrations of other mechatronic system examples can be found at Internet Link 1.5.

■ **CLASS DISCUSSION ITEM 1.1**
Household Mechatronic Systems

What typical household items can be characterized as mechatronic systems? What components do they contain that help you identify them as mechatronic systems? If an item contains a microprocessor, describe the functions performed by the microprocessor.

1.2 MEASUREMENT SYSTEMS

A fundamental part of many mechatronic systems is a **measurement system** composed of the three basic parts illustrated in Figure 1.3. The **transducer** is a sensing device that converts a physical input into an output, usually a voltage. The **signal processor** performs filtering, amplification, or other signal conditioning on the transducer output. The term **sensor** is often used to refer to the transducer or to the combination of transducer and signal processor. Finally, the **recorder** is an instrument, a computer, a hard-copy device, or simply a display that maintains the sensor data for online monitoring or subsequent processing.

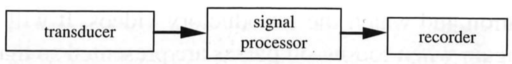
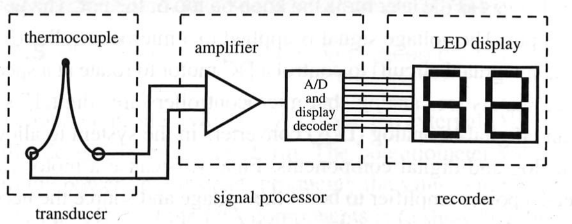


Figure 1.3 Elements of a measurement system.

These three building blocks of measurement systems come in many types with wide variations in cost and performance. It is important for designers and users of measurement systems to develop confidence in their use, to know their important characteristics and limitations, and to be able to select the best elements for the measurement task at hand. In addition to being an integral part of most mechatronic systems, a measurement system is often used as a stand-alone device to acquire data in a laboratory or field environment.

Measurement System—Digital Thermometer — EXAMPLE 1.2

The following figure shows an example of a measurement system. The thermocouple is a transducer that converts temperature to a small voltage; the amplifier increases the magnitude of the voltage; the A/D (analog-to-digital) converter is a device that changes the analog signal to a coded digital signal; and the LEDs (light emitting diodes) display the value of the temperature.



Supplemental information important to measurement systems and analysis is provided in Appendix A. Included are sections on systems of units, numerical precision, and statistics. You should review this material on an as-needed basis.

1.3 THREADED DESIGN EXAMPLES

Throughout the book, there are Examples, which show basic analysis calculations, and Design Examples, which show how to select and synthesize components and subsystems. There are also three more complicated Threaded Design Examples, which build upon new topics as they are covered, culminating in complete mechatronic systems by the end. These designs involve systems for controlling the position and speed of different types of motors in various ways. Threaded Design Examples A.1, B.1, and C.1 introduce each thread. All three designs incorporate components important in mechatronic systems: microcontrollers, input devices, output devices, sensors, actuators, and support electronics and software. Please read through the following information and watch the introductory videos. It will also be helpful to watch the videos again when follow-on pieces are presented so that you can see how everything fits in the "big picture." The list of Threaded Design Example citations at the beginning of the book, with the page numbers, can be useful for looking ahead or reflecting back as new portions are presented.

All of the components used to build the systems in all three threaded designs are listed at Internet Link 1.6, along with descriptions and price information. Most of the parts were purchased through Digikey Corporation (see Internet Link 1.7) and Jameco Electronics Corporation (see Internet Link 1.8), two of the better online suppliers of electronic parts. By entering part numbers from Internet Link 1.6 at the supplier websites, you can access technical datasheets for each product.

THREADED DESIGN EXAMPLE

A.1 *DC motor power-op-amp speed controller—Introduction*

Internet Link

1.6 Threaded design example components

1.7 Digikey electronics supplier

1.8 Jameco electronics supplier

Video Demo

1.6 DC motor power-op-amp speed controller

This design example deals with controlling the rotational speed of a direct current (DC) permanent magnet motor. Figure 1.4 illustrates the major components and interconnections in the system. The light-emitting diode (LED) provides a visual cue to the user that the microcontroller is running properly. The speed input device is a potentiometer (or pot), which is a variable resistor. The resistance changes as the user turns the knob on top of the pot. The pot can be wired to produce a voltage input. The voltage signal is applied to a microcontroller (basically a small computer on a single integrated circuit) to control a DC motor to rotate at a speed proportional to the voltage. Voltage signals are "analog" but microcontrollers are "digital," so we need analog-to-digital (A/D) and digital-to-analog (D/A) converters in the system to allow us to communicate between the analog and digital components. Finally, because a motor can require significant current, we need a power amplifier to boost the voltage and source the necessary current. Video Demo 1.6 shows a demonstration of the complete working system shown in Figure 1.5.

With all three Threaded Design Examples (A, B, and C), as you progress sequentially through the chapters in the book you will gain fuller understanding of the components in the design.

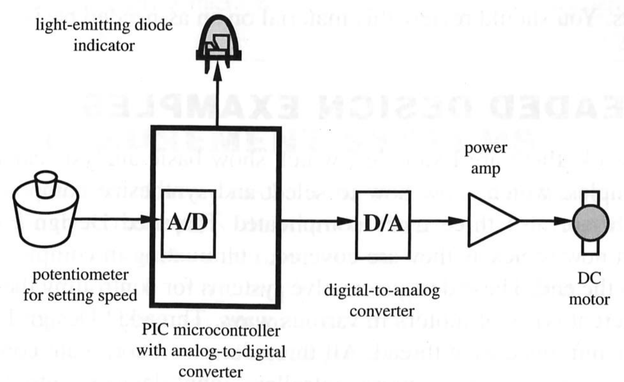


Figure 1.4 Functional diagram of the DC motor speed controller.

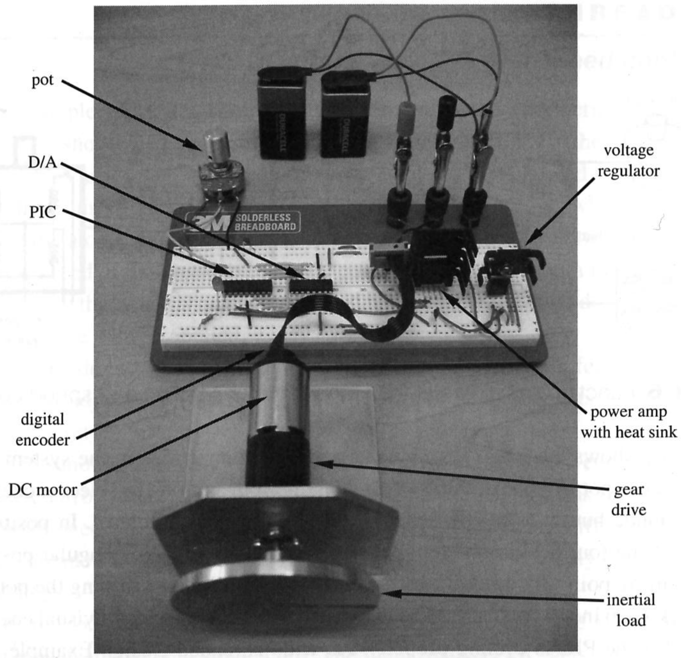


Figure 1.5 Photograph of the power-amp speed controller.

Note that the PIC microcontroller (with the A/D) and the external D/A converter are not actually required in this design, in its current form. The potentiometer voltage output could be attached directly to the power amp instead, producing the same functionality. The reason for including the PIC (with A/D) and the D/A components is to show how these components can be interfaced within an analog system (this is useful to know in many applications). Also, the design serves as a platform for further development, where the PIC can be used to implement feedback control and a user interface, in a more complex design. An example where you might need the microcontroller in the loop is in robotics or numerically controlled mills and lathes, where motors are often required to follow fairly complex motion profiles in response to inputs from sensors and user programming, or from manual inputs.

THREADED DESIGN EXAMPLE

Stepper motor position and speed controller—Introduction **B.1**

This design example deals with controlling the position and speed of a stepper motor, which can be commanded to move in discrete angular increments. Stepper motors are useful in position indexing applications, where you might need to move parts or tools to and from various fixed positions (e.g., in an automated assembly or manufacturing line). Stepper motors are also useful in accurate speed control applications (e.g., controlling the spindle speed of a computer hard-drive or DVD player), where the motor speed is directly proportional to the step rate.

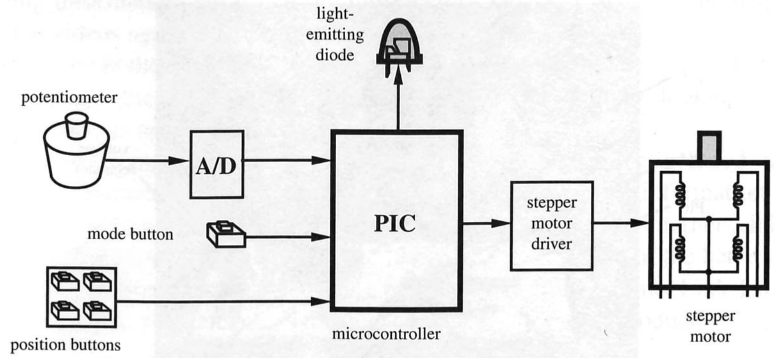


Figure 1.6 Functional diagram of the stepper motor position and speed controller.

Figure 1.6 shows the major components and interconnections in the system. The input devices include a pot to control the speed manually, four buttons to select predefined positions, and a mode button to toggle between speed and position control. In position control mode, each of the four position buttons indexes the motor to specific angular positions relative to the starting point (0°, 45°, 90°, 180°). In speed control mode, turning the pot clockwise (counterclockwise) increases (decreases) the speed. The LED provides a visual cue to the user to indicate that the PIC is cycling properly. As with Threaded Design Example A, an A/D converter is used to convert the pot's voltage to a digital value. A microcontroller uses that value to generate signals for a stepper motor driver circuit to make the motor rotate.

Video Demo

1.7 Stepper motor position and speed controller

Video Demo 1.7 shows a demonstration of the complete working system shown in Figure 1.7. As you progress through the book, you will learn about the different elements in this design.

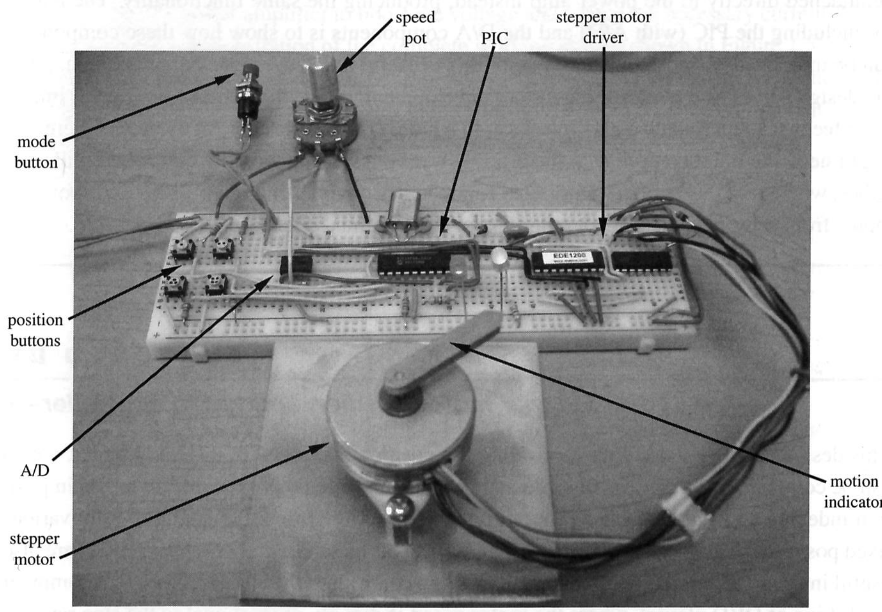


Figure 1.7 Photograph of the stepper motor position and speed controller.

THREADED DESIGN EXAMPLE

DC motor position and speed controller—Introduction C.1

This design example illustrates control of position and speed of a permanent magnet DC motor. Figure 1.8 shows the major components and interconnections in the system. A numerical keypad enables user input, and a liquid crystal display (LCD) is used to display messages and a menu-driven user interface. The motor is driven by an H-bridge, which allows the voltage applied to the motor (and therefore the direction of rotation) to be reversed. The H-bridge also allows the speed of the motor to be easily controlled by pulse-width modulation (PWM), where the power to the motor is quickly switched on and off at different duty cycles to change the average effective voltage applied.

A digital encoder attached to the motor shaft provides a position feedback signal. This signal is used to adjust the voltage signal to the motor to control its position or speed. This is called a servomotor system because we use feedback from a sensor to control the motor. Servomotors are very important in automation, robotics, consumer electronic devices, flow-control valves, and office equipment, where mechanisms or parts need to be accurately positioned or moved at certain speeds. Servomotors are different from stepper motors (see Threaded Design Example B.1) in that they move smoothly instead of in small incremental steps.

Two PIC microcontrollers are used in this design because there are a limited number of input/output pins available on a single chip. The main (master) PIC gets input from the user, drives the LCD, and sends the PWM signal to the motor. The secondary (slave) PIC monitors the digital encoder and transmits the position signal back to the master PIC upon command via a serial interface.

Video Demo 1.8 shows a demonstration of the complete working system shown in Figure 1.9. You will learn about each element of the design as you proceed sequentially through the book.

Video Demo

1.8 DC motor position and speed controller

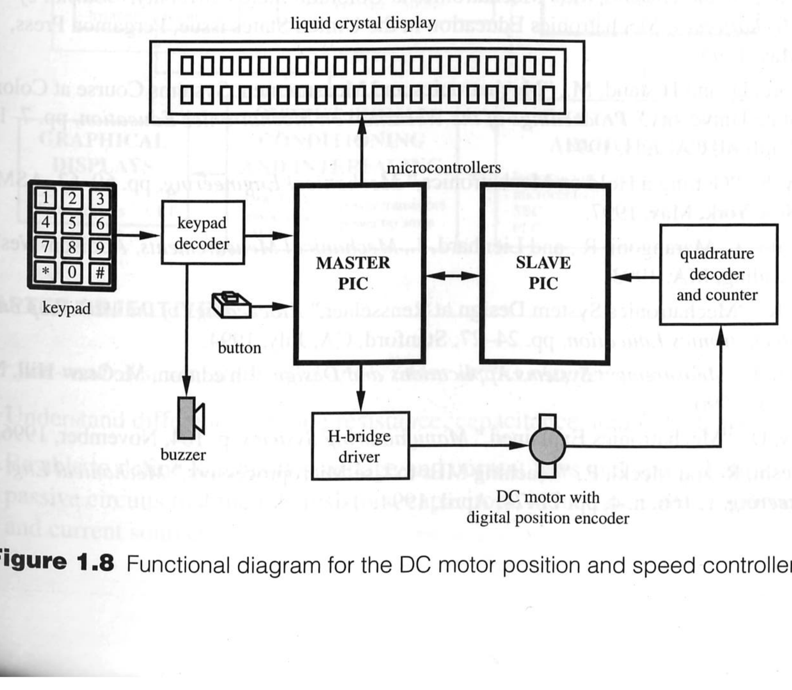


Figure 1.8 Functional diagram for the DC motor position and speed controller.

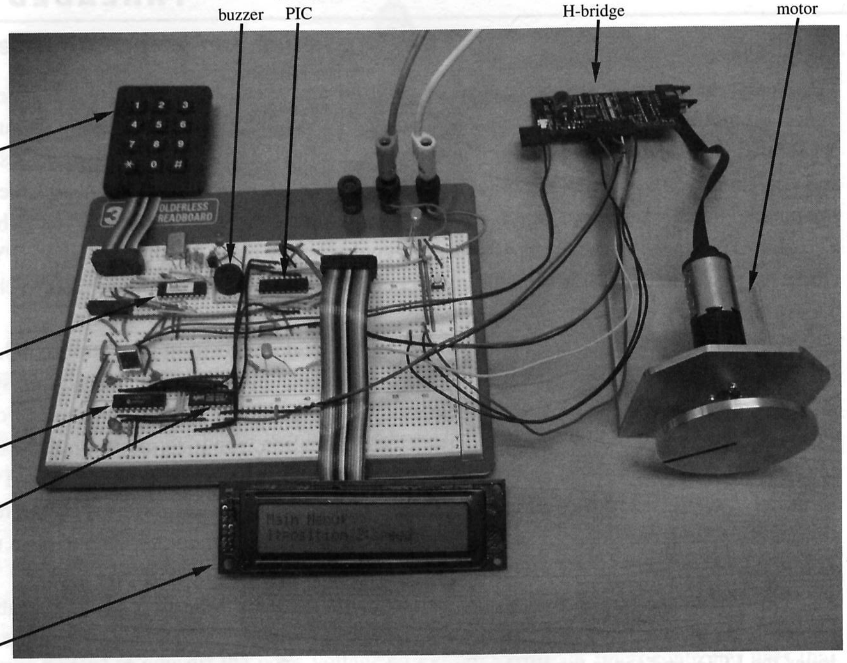


Figure 1.9 Photograph of the DC motor position and speed controller.

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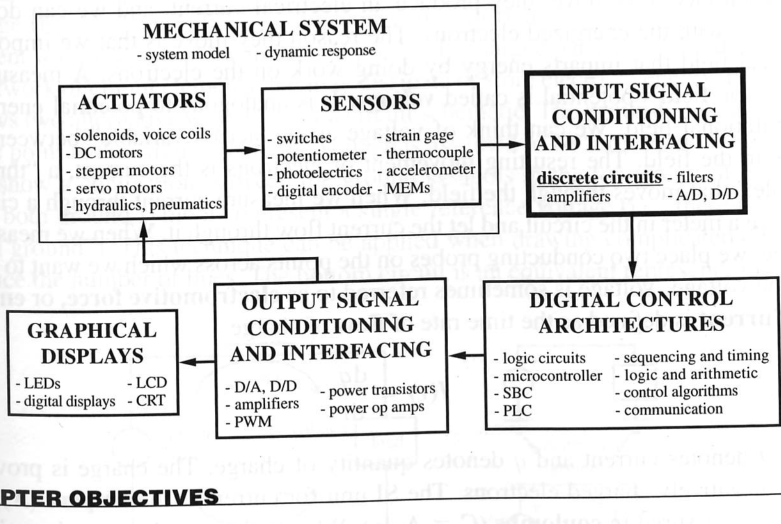
CHAPTER 2

Electric Circuits and Components

This chapter reviews the fundamentals of basic electrical components and discrete circuit analysis techniques. These topics are important in understanding and designing all elements in a mechatronic system, especially discrete circuits for signal conditioning and interfacing. ■



CHAPTER OBJECTIVES

After you read, discuss, study, and apply ideas in this chapter, you will:

1. Understand differences among resistance, capacitance, and inductance
2. Be able to define Kirchhoff's voltage and current laws and apply them to passive circuits that include resistors, capacitors, inductors, voltage sources, and current sources

3. Know how to apply models for ideal voltage and current sources
4. Be able to predict the steady-state behavior of circuits with sinusoidal inputs
5. Be able to characterize the power dissipated or generated by a circuit
6. Be able to predict the effects of mismatched impedances
7. Understand how to reduce noise and interference in electrical circuits
8. Appreciate the need to pay attention to electrical safety and to ground components properly
9. Be aware of several practical considerations that will help you assemble actual circuits and make them function properly and reliably
10. Know how to make reliable voltage and current measurements

2.1 INTRODUCTION

Practically all mechatronic and measurement systems contain electrical circuits and components. To understand how to design and analyze these systems, a firm grasp of the fundamentals of basic electrical components and circuit analysis techniques is a necessity. These topics are fundamental to understanding everything else that follows in this book.

When electrons move, they produce an electrical current, and we can do useful things with the energized electrons. The reason they move is that we impose an electrical field that imparts energy by doing work on the electrons. A measure of the electric field's potential is called **voltage.** It is analogous to potential energy in a gravitational field. We can think of voltage as an "across variable" between two points in the field. The resulting movement of electrons is the current, a "through variable," that moves through the field. When we measure current through a circuit, we place a meter in the circuit and let the current flow through it. When we measure a voltage, we place two conducting probes on the points across which we want to measure the voltage. Voltage is sometimes referred to as **electromotive force,** or **emf.**

Current is defined as the time rate of flow of charge:

$$I(t) = \frac{dq}{dt} \tag{2.1}$$

where I denotes current and q denotes quantity of charge. The charge is provided by the negatively charged electrons. The SI unit for current is the **ampere** (A), and charge is measured in **coulombs** (C = A · s). When voltage and current in a circuit are constant (i.e., independent of time), their values and the circuit are referred to as **direct current,** or DC. When the voltage and current vary with time, usually sinusoidally, we refer to their values and the circuit as **alternating current,** or AC.

An electrical circuit is a closed loop consisting of several conductors connecting electrical components. Conductors may be interrupted by components called switches. Some simple examples of valid circuits are shown in Figure 2.1.

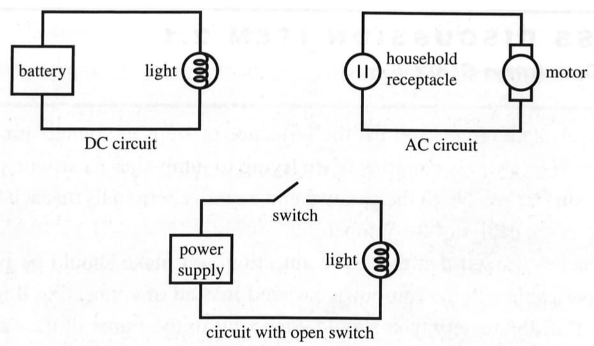


Figure 2.1 Electrical circuits.

The terminology and current flow convention used in the analysis of an electrical circuit are illustrated in Figure 2.2a. The voltage source, which provides energy to the circuit, can be a power supply, battery, or generator. The voltage source adds electrical energy to electrons, which flow from the negative terminal to the positive terminal, through the circuit. The positive side of the source attracts electrons, and the negative side releases electrons. The negative side is usually not labeled in a circuit schematic (e.g., with a minus sign) because it is implied by the positive side, which is labeled with a plus sign. Standard convention assumes that positive charge flows in a direction opposite from the electrons. **Current** describes the flow of this positive charge (not electrons). We owe this convention to Benjamin Franklin, who thought current was the result of the motion of positively charged particles. A **load** consists of a network of circuit elements that may dissipate or store electrical energy. Figure 2.2b shows two alternative ways to draw a circuit schematic. The **ground** indicates a reference point in the circuit where the voltage is assumed to be zero. Even though we do not show a connection between the ground symbols in the top circuit, it is implied that both ground symbols represent a single reference voltage (i.e., there is a "common ground"). This technique can be applied when drawing complicated circuits to reduce the number of lines. The bottom circuit is an equivalent representation.

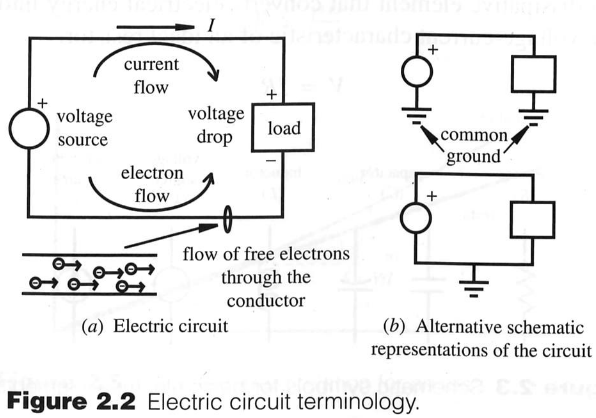


Figure 2.2 Electric circuit terminology.

■ CLASS DISCUSSION ITEM 2.1
Proper Car Jump Start

Draw an equivalent circuit and list the sequence of steps to connect jumper cables properly between two car batteries when trying to jump-start a car with a run-down battery. Be sure to label both the positive and negative terminals on each battery and the red and black cables of the jumper.

It is recommended that the last connection you make should be between the black jumper cable and the run-down car; and instead of connecting it to the negative terminal of the battery, you should connect it to the frame of the car at a point away from the battery. What is the rationale for this advice? Does it matter in what order the connections are removed when you have started the car?

Note - Hints and partial answers for many of the Class Discussion Items throughout the book (including this one) are provided on the book website at *mechatronics.colostate.edu.*

2.2 BASIC ELECTRICAL ELEMENTS

There are three basic passive electrical elements: the resistor (R) , capacitor (C), and inductor (L). Passive elements require no additional power supply, unlike active devices such as integrated circuits. The passive elements are defined by their voltage-current relationships, as summarized below, and the symbols used to represent them in circuit schematics are shown in Figure 2.3.

There are two types of ideal energy sources: a **voltage source** (V) and a **current source** (I). These ideal sources contain no internal resistance, inductance, or capacitance. Figure 2.3 also illustrates the schematic symbols for ideal sources. Figure 2.4 shows some examples of actual components that correspond to the symbols in Figure 2.3.

2.2.1 Resistor

A **resistor** is a dissipative element that converts electrical energy into heat. **Ohm's law** defines the voltage-current characteristic of an ideal resistor:

$$V = IR \tag{2.2}$$

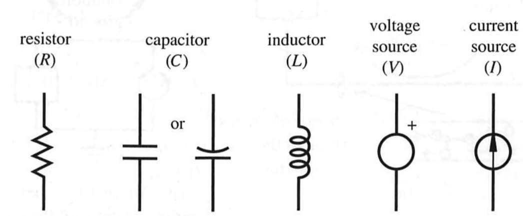


Figure 2.3 Schematic symbols for basic electrical elements.

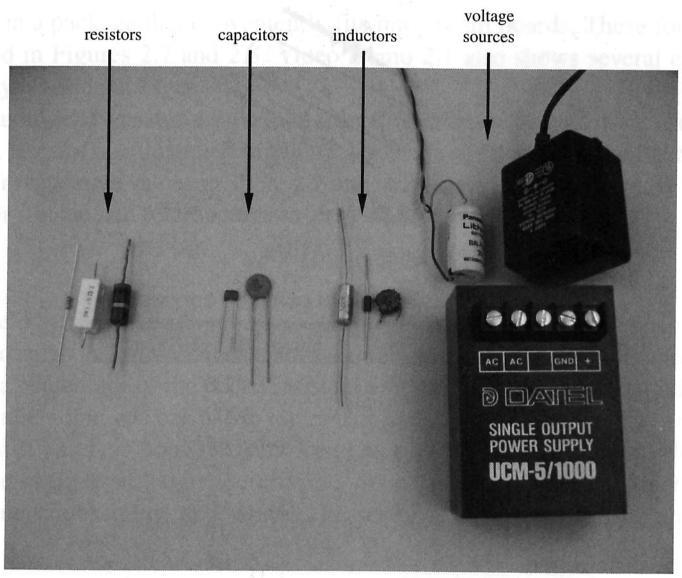


Figure 2.4 Examples of basic circuit elements.

The unit of resistance is the **ohm** (Ω). Resistance is a material property whose value is the slope of the resistor's voltage-current curve (see Figure 2.5). For an ideal resistor, the voltage-current relationship is linear, and the resistance is constant. However, real resistors are typically nonlinear due to temperature effects. As the current increases, temperature increases resulting in higher resistance. Also a real resistor has a limited power dissipation capability designated in watts, and it may fail when this limit is exceeded.

If a resistor's material is homogeneous and has a constant cross-sectional area, such as the cylindrical wire illustrated in Figure 2.6, then the resistance is given by

$$R = \frac{\rho L}{A} \tag{2.3}$$

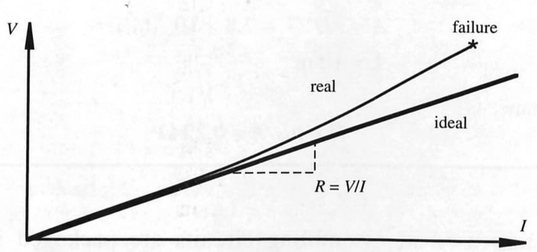


Figure 2.5 Voltage-current relation for an ideal resistor.

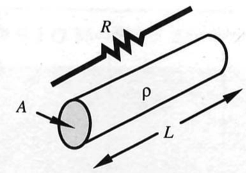


Figure 2.6 Wire resistance.

Table 2.1 Resistivities of common conductors

Material	Resistivity ($10^{-8}\Omega$m)
Aluminum	2.8
Carbon	4000
Constantan	44
Copper	1.7
Gold	2.4
Iron	10
Silver	1.6
Tungsten	5.5

Internet Link

2.1 Conductor sizes

2.2 Conductor current ratings

where ρ is the **resistivity,** or specific resistance of the material; L is the wire length; and A is the cross-sectional area. Resistivities for common conductors are given in Table 2.1. Example 2.1 demonstrates how to determine the resistance of a wire of given diameter and length. Internet Links 2.1 and 2.2 list the standard conductor diameters and current ratings.

EXAMPLE 2.1 Resistance of a Wire

As an example of the use of Equation 2.3, we will determine the resistance of a copper wire 1.0 mm in diameter and 10 m long.

From Table 2.1, the resistivity of copper is

$$\rho = 1.7 \times 10^{-8}\ \Omega\text{m}$$

Because the wire diameter, area, and length are

$$D = 0.0010\ \text{m}$$
$$A = \pi D^2/4 = 7.8 \times 10^{-7}\ \text{m}^2$$
$$L = 10\ \text{m}$$

the total wire resistance is

$$R = \rho L/A = 0.22\ \Omega$$

Actual resistors used in assembling circuits are packaged in various forms including axial-lead components, surface mount components, and the **dual in-line package (DIP)** and the **single in-line package (SIP),** which contain multiple resistors in a package that conveniently fits into circuit boards. These four types are illustrated in Figures 2.7 and 2.8. Video Demo 2.1 also shows several examples of resistor types and packages.

Video Demo

2.1 Resistors

An axial-lead resistor's value and tolerance are usually coded with four colored bands (*a, b, c, tol*) as illustrated in Figure 2.9. The colors used for the bands are listed with their respective values in Table 2.2 and at Internet Link 2.3 (for easy reference). A resistor's value and tolerance are expressed as

$$R = ab \times 10^c \pm \text{tolerance } (\%) \tag{2.4}$$

Internet Link

2.3 Resistor color codes

where the a band represents the tens digit, the b band represents the ones digit, the c band represents the power of 10, and the *tol* band represents the tolerance or uncertainty as a percentage of the coded resistance value. Here is a popular (and politically correct) mnemonic you can use to remember the resistor color codes when you don't have a table handy: "Bob BROWN Ran Over YELLOW Grass, But VIOLET Got Wet." The capitalized letters identify the colors: black, brown, red, orange, yellow, green, blue, violet, gray, and white. The set of **standard values** for the first two

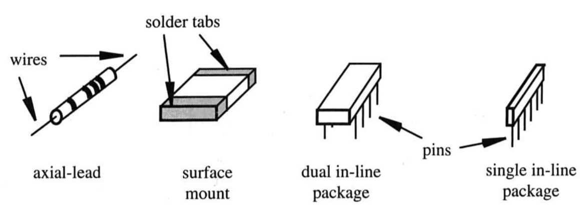


Figure 2.7 Resistor packaging.

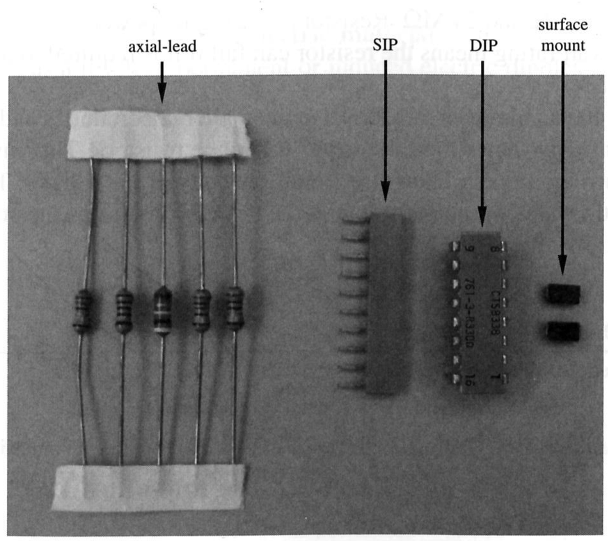


Figure 2.8 Examples of resistor packaging.

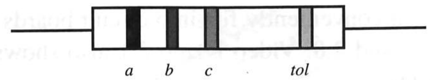


Figure 2.9 Axial-lead resistor color bands.

Table 2.2 Resistor color band codes

a, b, and *c* Bands		*tol* Band	
Color	**Value**	**Color**	**Value**
Black	0	Gold	±5%
Brown	1	Silver	±10%
Red	2	Nothing	±20%
Orange	3		
Yellow	4		
Green	5		
Blue	6		
Violet	7		
Gray	8		
White	9		

digits (*ab*) are 10, 11, 12, 13, 14, 15, 16, 18, 20, 22, 24, 27, 30, 33, 36, 39, 43, 47, 51, 56, 62, 68, 75, 82, and 91. Often, resistance values are in the kΩ range and sometimes the unit is abbreviated as k instead of kΩ. For example, 10 k next to a resistor on an electrical schematic implies 10 kΩ.

The most common resistors you will use in ordinary electronic circuitry are 1/4 watt, 5% tolerance carbon or metal-film resistors. Resistor values of this type range in value between 1 Ω and 24 MΩ. Resistors with higher power ratings are also available. The 1/4 watt rating means the resistor can fail if it is required to dissipate more power than this.

Precision metal-film resistors have 1% or smaller uncertainties and are available in a wider range of values than the lower tolerance resistors. They usually have a numerical four-digit code printed directly on the body of the resistor. The first three digits denote the value of the resistor, and the last digit indicates the power of 10 by which to multiply.

EXAMPLE 2.2

Resistance Color Codes

An axial-lead resistor has the following color bands:

$$a = \text{green},\ b = \text{brown},\ c = \text{red},\ \text{and}\ tol = \text{gold}$$

From Equation 2.4 and Table 2.2, the range of possible resistance values is

$$R = 51 \times 10^2\,\Omega \pm 5\% = 5100 \pm (0.05 \times 5100)\,\Omega$$

or

$$4800\,\Omega < R < 5300\,\Omega$$

Resistors come in a variety of shapes and sizes. As with many electrical components, the size of the device often has little to do with the characteristic value (e.g., resistance) of the device. Capacitors are one exception, where a larger device usually implies a higher capacitance value. With most devices that carry continuous current, the physical size is usually related to the maximum current or power rating, both of which are related to the power dissipation capabilities.

Video Demo 2.2 shows various types of components of various sizes to illustrate this principle. The best place to find detailed information on various components is online from vendor websites. Internet Link 2.4 points to a collection of links to the largest and most popular suppliers.

Video Demo

2.2 Electronics components of various types and sizes

Internet Link

2.4 Electronic component online resources and vendors

Variable resistors are available that provide a range of resistance values controlled by a mechanical screw, knob, or linear slide. The most common type is called a **potentiometer,** or **pot.** The various schematic symbols for a potentiometer are shown in Figure 2.10. A potentiometer that is included in a circuit to adjust or fine-tune the resistance in the circuit is called a **trim pot.** A trim pot is shown with a little symbol to denote the screw used to adjust ("trim") its value. The direction to rotate the potentiometer for increasing resistance is usually indicated on the component. Potentiometers are discussed further in Sections 4.8 and 9.2.2.

Conductance is defined as the reciprocal of resistance. It is sometimes used as an alternative to resistance to characterize a dissipative circuit element. It is a measure of how easily an element conducts current as opposed to how much it resists it. The unit of conductance is the **siemen** ($S = 1/\Omega =$ mho).

2.2.2 Capacitor

A **capacitor** is a passive element that stores energy in the form of an electric field. This field is the result of a separation of electric charge. The simplest capacitor consists of a pair of parallel conducting plates separated by a dielectric material as illustrated in Figure 2.11. The **dielectric material** is an insulator that increases the capacitance as a result of permanent or induced electric dipoles in the material.

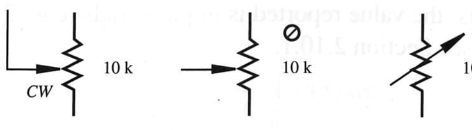


Figure 2.10 Potentiometer schematic symbols.

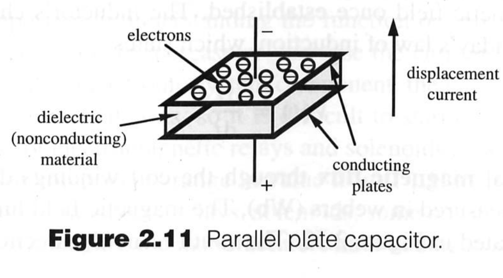


Figure 2.11 Parallel plate capacitor.

Strictly, direct current (DC) does not flow through a capacitor; rather, charges are displaced from one side of the capacitor through the conducting circuit to the other side, establishing the electric field. The displacement of charge is called a **displacement current** because current appears to flow through the device as it charges or discharges. The capacitor's voltage-current relationship is defined as

$$V(t) = \frac{1}{C}\int_0^t I(\tau)\,\mathrm{d}\tau = \frac{q(t)}{C} \tag{2.5}$$

where $q(t)$ is the amount of accumulated charge measured in coulombs and C is the capacitance measured in farads (F = coulombs/volts). By differentiating this equation, we can relate the displacement current to the rate of change of voltage:

$$I(t) = C\frac{\mathrm{d}V}{\mathrm{d}t} \tag{2.6}$$

Capacitance is a property of the dielectric material and the plate geometry and separation. Values for typical capacitors range from 1 pF to 1000 μF, but they are also available with much larger values. Because the voltage across a capacitor is the integral of the displacement current (see Equation 2.5), the voltage cannot change instantaneously. As we will see several times throughout the book, this characteristic can be used for timing purposes in electrical circuits using a simple RC circuit, which is a resistor and capacitor in series.

The primary types of commercial capacitors are electrolytic capacitors, tantalum capacitors, ceramic disk capacitors, and mylar capacitors. Electrolytic capacitors are polarized, meaning they have a positive end and a negative end. The positive lead of a polarized capacitor must be held at a higher voltage than the negative side; otherwise, the device will usually be damaged (e.g., it will short and/or explode with a popping sound). Capacitors come in many sizes and shapes (see Video Demo 2.3). Often the capacitance is printed directly on the component, typically in μF or pF, but sometimes a three-digit code is used. The first two digits are the value and the third is the power of 10 multiplied times picofarads (e.g., 102 implies 10×10^2 pF = 1 nF). If there are only two digits, the value reported is in picofarads (e.g., 22 implies 22 pF). For more information, see Section 2.10.1.

Video Demo

2.3 Capacitors

2.2.3 Inductor

An **inductor** is a passive energy storage element that stores energy in the form of a magnetic field. The simplest form of an inductor is a wire coil, which has a tendency to maintain a magnetic field once established. The inductor's characteristics are a direct result of Faraday's law of induction, which states

$$V(t) = \frac{\mathrm{d}\lambda}{\mathrm{d}t} \tag{2.7}$$

where λ is the total **magnetic flux** through the coil windings due to the current. Magnetic flux is measured in webers (Wb). The magnetic field lines surrounding an inductor are illustrated in Figure 2.12. The south-to-north direction of the magnetic

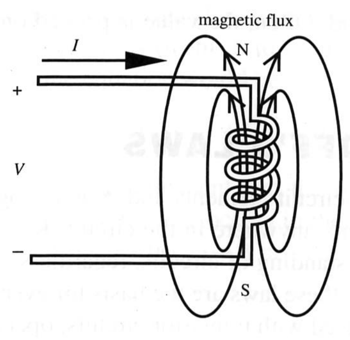


Figure 2.12 Inductor flux linkage.

field lines, shown with arrowheads in the figure, is found using the **right-hand rule** for a coil. The rule states that, if you curl the fingers of your right hand in the direction of current flow through the coil, your thumb will point in the direction of magnetic north. For an ideal coil, the flux is proportional to the current:

$$\lambda = LI \tag{2.8}$$

where L is the inductance of the coil, which is assumed to be constant. The unit of measure of inductance is the **henry** (H = Wb/A). Using Equations 2.7 and 2.8, an inductor's voltage-current relationship can be expressed as

$$V(t) = L\frac{dI}{dt} \tag{2.9}$$

The magnitude of the voltage across an inductor is proportional to the rate of change of the current through the inductor. If the current through the inductor is increasing ($dI/dt > 0$), the voltage polarity is as shown in Figure 2.12. If the current through the inductor is decreasing ($dI/dt < 0$), the voltage polarity is opposite to that shown.

Integrating Equation 2.9 results in an expression for current through an inductor given the voltage:

$$I(t) = \frac{1}{L}\int_0^t V(\tau)\,d\tau \tag{2.10}$$

where τ is a dummy variable of integration. From this we can infer that the current through an inductor cannot change instantaneously because it is the integral of the voltage. This is important in understanding the function or consequences of inductors in circuits. It takes time to increase or decrease the current flowing through an inductor. An important mechatronic system component, the electric motor, has large inductance due to its internal coils, so it is difficult to start or stop the motor very quickly. This is true of electromagnetic relays and solenoids as well.

Typical inductor components range in value from 1 μH to 100 mH. Inductance is important to consider in motors, relays, solenoids, some power supplies, and high-frequency circuits. Although some manufacturers have coding systems for inductors, there is no standard method. Often, the value is printed on the device directly, typically in μH or mH.

2.3 KIRCHHOFF'S LAWS

Now we are ready to put circuit elements and sources together in circuits and calculate voltages and currents anywhere in the circuit. Kirchhoff's laws are essential for the analysis and understanding of circuits, regardless of how simple or complex the circuit may be. In fact, these laws are the basis for even the most complex circuit analysis such as that involved with transistor circuits, operational amplifiers, or integrated circuits with hundreds of elements. **Kirchhoff's voltage law (KVL)** states that the sum of voltages around a closed loop or path is 0 (see Figure 2.13):

$$\sum_{i=1}^{N} V_i = 0 \tag{2.11}$$

Note that the loop must be closed, but the conductors themselves need not be closed (i.e., the loops can go through open circuits).

To apply KVL to a circuit, as illustrated in Figure 2.13, you first assume a current direction on each branch of the circuit. Next assign the appropriate polarity to the voltage across each passive element assuming that the voltage drops across each element in the direction of the current. Where assumed current enters a passive element, a plus is shown, and where the assumed current leaves the element, a minus is shown. The polarity of voltage across a voltage source and the direction of current through a current source must always be maintained as given. Now, starting at any point in the circuit (such as node *A* in Figure 2.13) and following either a clockwise or counterclockwise loop direction (clockwise in Figure 2.13), form the sum of the voltages across each element, assigning to each voltage the first algebraic sign encountered at each element in the loop. For Figure 2.13, the result would be

$$-V_1 - V_2 + V_3 + \cdots - V_N = 0 \tag{2.12a}$$

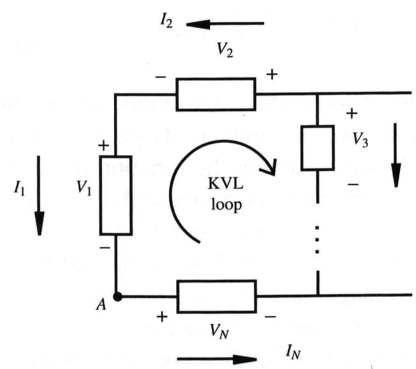


Figure 2.13 Kirchhoff's voltage law.

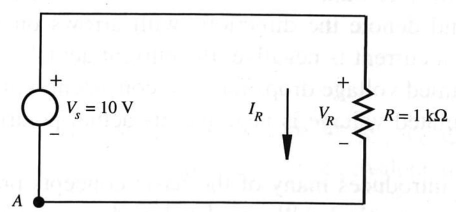
Alternatively, you can assign the signs based on whether the voltage increases (from − to +, assigning +) or drops (from + to −, assigning −) across the element. Using this convention, the equation would be:

$$V_1 + V_2 - V_3 + \cdots + V_N = 0 \quad (2.12b)$$

Equations 2.12a and 2.12b are equivalent, but the second convention is more intuitive because it represents what actually occurs in the circuit. However, the first convention is more common, probably because it involves less thought.

Kirchhoff's Voltage Law — EXAMPLE 2.3

KVL will be used to find the current I_R in the following circuit.



The first step is to assume the current direction for I_R. The chosen direction is shown in the figure. With a circuit this simple, the current direction is obvious based on the polarity of the source; but in more complex circuits, current directions might not be so obvious. Then we use the current direction through the resistor to assign the voltage-drop polarity. If the current were assumed to flow in the opposite direction instead, the voltage polarity across the resistor would also have to be reversed. The polarity for the voltage source is fixed regardless of current direction. Starting at point *A* and progressing clockwise around the loop, we assign the first voltage sign we come to on each element yielding

$$-V_s + V_R = 0$$

Applying Ohm's law,

$$-V_s + I_R R = 0$$

Therefore,

$$I_R = V_s / R = 10/1000 \text{ A} = 10 \text{ mA}$$

Kirchhoff's current law (KCL) states that the sum of the currents flowing into a closed surface or node is 0. Referring to Figure 2.14a,

$$I_1 + I_2 - I_3 = 0 \quad (2.13)$$

More generally, referring to Figure 2.14b,

$$\sum_{i=1}^{N} I_i = 0 \quad (2.14)$$

work this times example in great detail in class

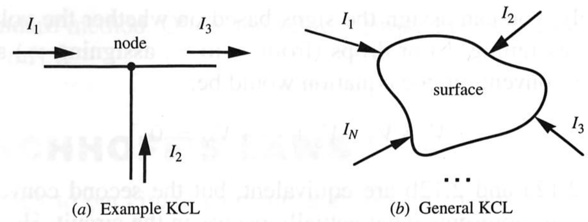


Figure 2.14 Kirchhoff's current law.

Lab Exercise

Lab 1
Introduction—Resistor codes, breadboard, and basic measurements

Video Demo

2.4 Breadboard construction

2.5 Instrumentation for powering and making measurements in circuits

Note that currents entering a node or surface are assigned a positive value, and currents leaving are assigned a negative value.

It is important to note that, when analyzing a circuit, you arbitrarily assume current directions and denote the directions with arrows on the schematic. If the calculated result for a current is negative, the current actually flows in the opposite direction. Also, assumed voltage drops must be consistent with the assumed current directions. If a calculated voltage is negative, its actual polarity is opposite to that shown.

Lab Exercise 1 introduces many of the basic concepts presented so far in this chapter. The following practical skills are developed:

- Assembling basic circuits using a breadboard (see Video Demo 2.4)
- Making voltage and current measurements (see Video Demo 2.5)
- Reading resistor and capacitor values

More information and resources dealing with all of these topics can also be found in Section 2.10.

2.3.1 Series Resistance Circuit

Applying KVL to the simple series resistor circuit illustrated in Figure 2.15 yields some useful results. Assuming a current direction *I*, starting at node *A*, and following a clockwise direction yields

$$-V_s + V_{R_1} + V_{R_2} = 0 \tag{2.15}$$

From Ohm's law,

$$V_{R_1} = IR_1 \tag{2.16}$$

and

$$V_{R_2} = IR_2 \tag{2.17}$$

Substituting these two equations into Equation 2.15 gives

$$-V_s + IR_1 + IR_2 = 0 \tag{2.18}$$

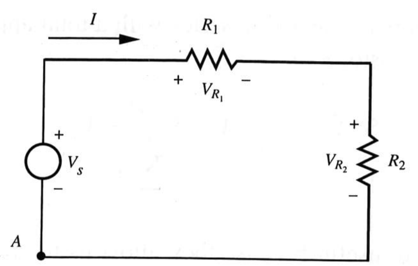


Figure 2.15 Series resistance circuit.

and solving for I yields

$$I = \frac{V_s}{(R_1 + R_2)} \tag{2.19}$$

Note that, if we had a single resistor of value $R_1 + R_2$, we would have the same result. Therefore resistors in series add, and the equivalent resistance of a series resistance circuit is

$$R_{eq} = R_1 + R_2 \tag{2.20}$$

In general, N resistors connected in series can be replaced by a single equivalent resistance given by

$$R_{eq} = \sum_{i=1}^{N} R_i \tag{2.21}$$

By applying KVL to capacitor and inductor circuits, it can be shown (Questions 2.11 and 2.13) that two capacitors in series combine as

$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2} \tag{2.22}$$

and two inductors in series add:

$$L_{eq} = L_1 + L_2 \tag{2.23}$$

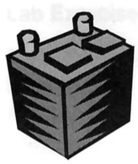
A circuit containing two resistors in series is referred to as a **voltage divider** because the source voltage V_s divides between each resistor. Expressions for the resistor voltages can be obtained by substituting Equation 2.19 into Equations 2.16 and 2.17 giving

$$V_{R_1} = \frac{R_1}{R_1 + R_2} V_s, \quad V_{R_2} = \frac{R_2}{R_1 + R_2} V_s \tag{2.24}$$

In general, for N resistors connected in series with a total applied voltage of V_s, the voltage V_{R_i} across any resistor R_i is

$$V_{R_i} = \frac{R_i}{R_{eq}} V_s = \frac{R_i}{\sum_{j=1}^{N} R_j} V_s \tag{2.25}$$

Voltage dividers are useful because they allow us to create different reference voltages in a circuit even if the circuit is energized only by a single output supply. However, care must be exercised that attached loads do not drain significant current and affect the voltage references produced with the dividers (see Class Discussion Item 2.2).



■ CLASS DISCUSSION ITEM 2.2
Improper Application of a Voltage Divider

Your car has a 12 V battery that powers some circuits in the car at lower voltage levels. Why is it inappropriate to use a simple voltage divider to create a lower voltage level for circuits that might draw variable current?

2.3.2 Parallel Resistance Circuit

Applying KCL to the simple parallel resistor circuit illustrated in Figure 2.16 also yields some useful results. Because each resistor experiences the same voltage V_s, as they are both in parallel with the source, Ohm's law gives

$$I_1 = \frac{V_s}{R_1} \tag{2.26}$$

and

$$I_2 = \frac{V_s}{R_2} \tag{2.27}$$

Applying KCL at node A gives

$$I - I_1 - I_2 = 0 \tag{2.28}$$

Substituting the currents from Equations 2.26 and 2.27 yields

$$I = \frac{V_s}{R_1} + \frac{V_s}{R_2} = V_s\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{2.29}$$

Replacing the resistance values R_1 and R_2 with their conductance equivalents $1/G_1$ and $1/G_2$ gives

$$I = V_s(G_1 + G_2) \tag{2.30}$$

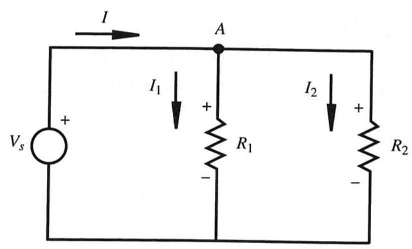


Figure 2.16 Parallel resistance circuit.

A single resistor with a conductance of value $(G_1 + G_2)$ would have given the same result; therefore, conductances in parallel add. We can write Equation 2.30 as

$$I = V_s G_{eq} = \frac{V_s}{R_{eq}} \tag{2.31}$$

where G_{eq} is the equivalent conductance and R_{eq} is the equivalent resistance. By comparing the right-hand side of this equation to Equation 2.29, we get

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} \tag{2.32}$$

or

$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2} \tag{2.33}$$

In general, N resistors connected in parallel can be replaced by a single equivalent resistance given by

$$\frac{1}{R_{eq}} = \sum_{i=1}^{N} \frac{1}{R_i} \tag{2.34}$$

or

$$R_{eq} = 1 \Big/ \sum_{i=1}^{N} \frac{1}{R_i} \tag{2.35}$$

By applying KCL to capacitor and inductor circuits, it can be shown (Questions 2.12 and 2.14) that two capacitors in parallel add:

$$C_{eq} = C_1 + C_2 \tag{2.36}$$

and two inductors in parallel combine as

$$L_{eq} = \frac{L_1 L_2}{L_1 + L_2} \tag{2.37}$$

A circuit containing two resistors connected in parallel is called a **current divider** because the source current I divides between each resistor. Expressions for the divided currents can be obtained by solving Equation 2.29 for V_s and substituting into Equation 2.26 and 2.27 giving

Video Demo

2.6 Light bulb series and parallel circuit comparison

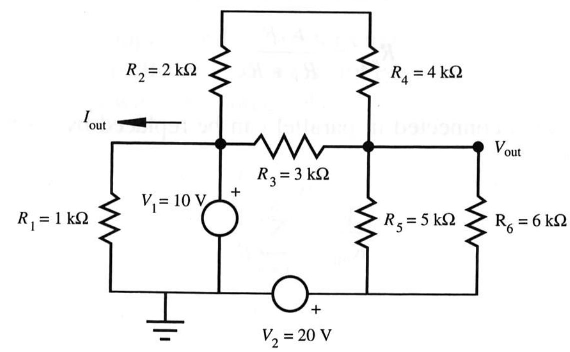
$$I_1 = \frac{R_2}{R_1 + R_2} I, \quad I_2 = \frac{R_1}{R_1 + R_2} I \tag{2.38}$$

Video Demo 2.6 illustrates the differences between parallel and series wiring of lighting. The demonstration illustrates voltage and current division and the effects on power output.

When drawing circuit schematics, by hand or with software tools, it is important to be consistent with how you show connections (or the lack thereof)

EXAMPLE 2.4 Circuit Analysis

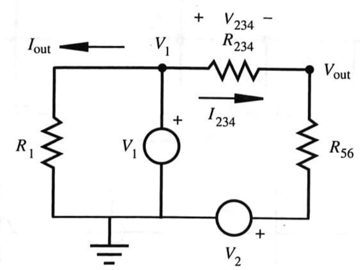
As an example of how the tools presented in the previous sections apply to a nontrivial circuit, consider the following network, where the goal is to find I_{out} and V_{out}. At any node in the circuit, such as the one labeled by V_{out}, the voltage is defined with respect to the ground reference denoted by the ground symbol ⏚. Voltage differences between any two points can be obtained by taking the difference between the ground-referenced values at the points.



The first step is to combine resistor clusters between and around the sources (V_1 and V_2) and the branches of interest (those dealing with I_{out} and V_{out}) using the series and parallel resistance formulas (Equations 2.20 and 2.33). Resistors R_2 and R_4 are in series, with an equivalent resistance of $(R_2 + R_4)$, and this is in parallel with resistor R_3. Resistors R_5 and R_6 are also in parallel. Therefore, the resultant resistances for the equivalent circuit that follows are

$$R_{234} = \frac{(R_2 + R_4)R_3}{(R_2 + R_4) + R_3} = 2.00 \text{ k}\Omega$$

$$R_{56} = \frac{R_5 R_6}{R_5 + R_6} = 2.73 \text{ k}\Omega$$



Applying KVL to the left loop gives

$$V_1 = I_{out} R_1$$

so

$$I_{out} = V_1/R_1 = 10 \text{ V}/1 \text{ k}\Omega = 10 \text{ mA}$$

Applying KVL to the right loop tells us that the total voltage across R_{234} and R_{56} in the assumed direction of I_{234} is $(V_1 - V_2)$. Voltage division (Equation 2.24) can then be used to determine the voltage drop across R_{234} in the assumed direction of I_{234}:

$$V_{234} = \frac{R_{234}}{R_{234} + R_{56}}(V_1 - V_2) = -4.23 \text{ V}$$

Because V_1 is referenced to ground, the voltage on the left side of resistor R_{234} is V_1; and because the voltage drops by V_{234} across the resistor, the desired output voltage is

$$V_{out} = V_1 - V_{234} = 14.2 \text{ V}$$

Note that because V_{234} was found to be negative, the actual flow of current through R_{234} would be in the opposite direction from that assumed in this solution.

A myriad of methods may be used to solve this problem (e.g., see Question 2.24), and the one presented here is just an example solution, not necessarily the best method.

at intersecting lines on the drawing. Figure 2.17 illustrates two conventions for doing this. The first convention (Figure 2.17a) is the most common and is what was used in Example 2.4. With this convention, a dot implies a connection, and the absence of a dot (at crossing lines only) implies no connection. Figure 2.17b shows an alternative convention where a dot is not required to indicate a connection as long as a crossing arc is used to indicate a nonconnection. Because the circuit diagrams in this chapter have been very simple, we really didn't need a convention—any crossing lines have been assumed to be connected. Even with the circuit in Example 2.4, the connection dots are not really required. People will assume there are connections at all intersecting lines in simple diagrams unless dot or arc features appear at one or more intersections. However, with more complicated circuits (e.g., those in Chapter 7 dealing with complicated microcontroller-based solutions),

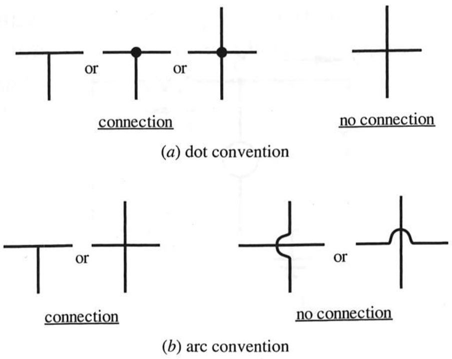


Figure 2.17 Circuit schematic connection conventions.

Lab Exercise

Lab 2 Instrument familiarization and basic electrical relations

Video Demo

2.5 Instrumentation for powering and making measurements in circuits

2.7 Connectors (BNC, banana plugs, alligator clips)

Internet Link

2.5 All about circuits - Vol. I - DC

a clear and consistent convention is very important to present and interpret the intent of the designer.

Lab Exercise 2 provides experience with using various instruments including an oscilloscope, multimeter, power supply, and function generator (see Video Demo 2.5). The Lab also covers practical application of Ohm's law, KVL, and KCL, as applied to making voltage and current measurements in circuits. Video Demo 2.7 shows the various types of cables and connectors that are used to connect instruments to each other and to circuits. Internet Link 2.5 is an excellent resource reviewing many topics related to electricity and DC circuit analysis.

2.4 VOLTAGE AND CURRENT SOURCES AND METERS

When we analyze electrical networks on paper, we usually assume that sources and meters are ideal. However, actual physical devices are not ideal, and it is sometimes necessary to account for their limitations when circuits contain these devices. The following ideal behavior is usually assumed:

- An **ideal voltage source** has zero output resistance and can supply infinite current.
- An **ideal current source** has infinite output resistance and can supply infinite voltage.
- An **ideal voltmeter** has infinite input resistance and draws no current.
- An **ideal ammeter** has zero input resistance and no voltage drop across it.

Unfortunately, real sources and meters have terminal characteristics that are somewhat different from the ideal cases. However, the terminal characteristics of the real sources and meters can be modeled using ideal sources and meters with their associated input and output resistances.

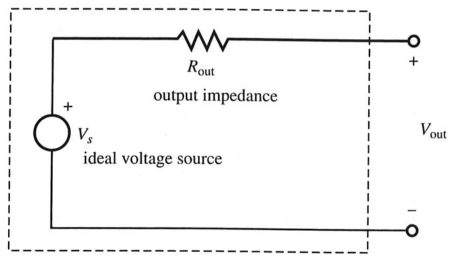


Figure 2.18 Real voltage source with output impedance.

As shown in Figure 2.18, a "real" voltage source can be modeled as an ideal voltage source in series with a resistance called the **output impedance** of the device. When a load is attached to the source and current flows, the output voltage V_{out} will be different from the ideal source voltage V_s due to voltage division. The output impedance of most commercially available voltage sources (e.g., a power supply) is very small, usually a fraction of an ohm. For most applications, this impedance is small enough to be neglected. However, the output impedance can be important when driving a circuit with small resistance because the impedance adds to the resistance of the circuit. Figure 2.19 shows examples of two commercially available voltage sources. The top unit is a triple-output power supply that can provide three different voltages relative to ground, adjustable from 0 V to 9 V, 20 V, and −20 V. The bottom unit is a programmable power supply that provides digitally controlled voltage sources.

As shown in Figure 2.20, a "real" current source can be modeled as an ideal current source in parallel with a resistance called the output impedance. When a load

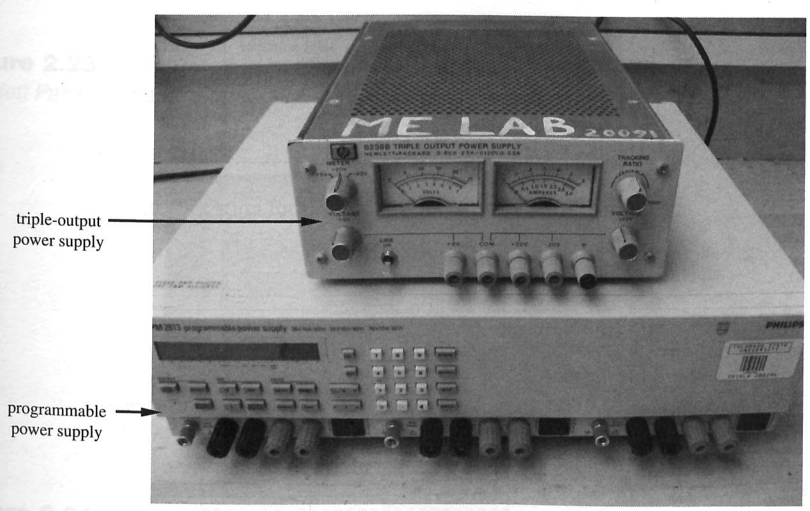


Figure 2.19 Example of commercially available voltage sources.

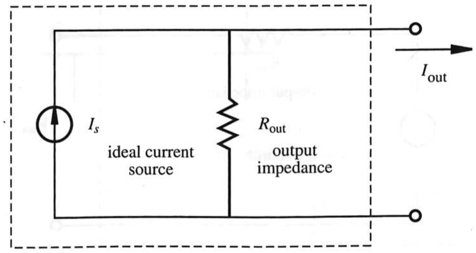


Figure 2.20 Real current source with output impedance.

is attached to the source, the source current I_s divides between the output impedance and the load. The output impedance of most commercially available current sources is very large, minimizing the current division effect. However, this impedance can be important when driving a circuit with a large resistance.

As shown in Figure 2.21, a "real" ammeter can be modeled as an ideal ammeter in series with a resistance called the **input impedance** of the device. The input impedance of most commercially available ammeters is very small, minimizing the voltage drop V_R added in the circuit. However, this resistance can be important when making a current measurement through a circuit branch with small resistance because the output impedance adds to the resistance of the branch.

As shown in Figure 2.22, a "real" voltmeter can be modeled as an ideal voltmeter in parallel with an input impedance. The input impedance of most commercially available voltmeters (e.g., an oscilloscope or multimeter) is very large, usually on the order of 1 to 10 MΩ. However, this resistance must be considered when making a voltage measurement across a circuit branch with large resistance because the

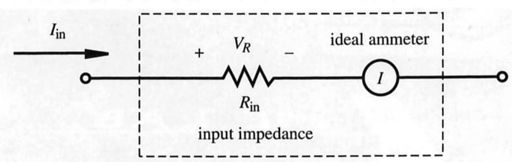


Figure 2.21 Real ammeter with input impedance.

Figure 2.22 Real voltmeter with input impedance.

parallel combination of the meter input impedance and the circuit branch would result in significant error in the measured value.

Figure 2.23 shows examples of commercially available **digital multimeters** (DMMs) that contain, among other things, ammeters and voltmeters. Figure 2.24 shows an example of a commercially available oscilloscope that contains a voltmeter capable of digitizing, displaying, and recording dynamic measurements. Internet Link 2.6 provides links to various online resources and vendors that offer an assortment of instrumentation (power supplies, function generators, multimeters, oscilloscopes, data acquisition equipment, and more).

Lab Exercise 2 provides experience with the effects of input and output impedance of various instruments. It is important to know how these instrument characteristics can affect voltage and current measurements. Section 2.10.3 has more information and resources on these topics. Lab Exercise 3 provides a complete overview of how to use an oscilloscope. Features and concepts covered include how to connect signals, grounding, coupling, and triggering. Video Demo 2.8 demonstrates how to use a typical analog oscilloscope. Many of the concepts involved with using an analog scope are also relevant with other scopes, even more sophisticated digital scopes. More information and resources dealing with how to use an oscilloscope properly can be found in Section 2.10.5.

Internet Link

2.6 Instrumentation online resources and vendors

Lab Exercise

Lab 2 Instrument familiarization and basic electrical relations

Lab 3 The oscilloscope

Video Demo

2.8 Oscilloscope demonstrations using the Tektronix 2215 analog scope

Figure 2.23 Examples of commercially available digital multimeters. *(Courtesy of Hewlett Packard, Santa Clara, CA)*

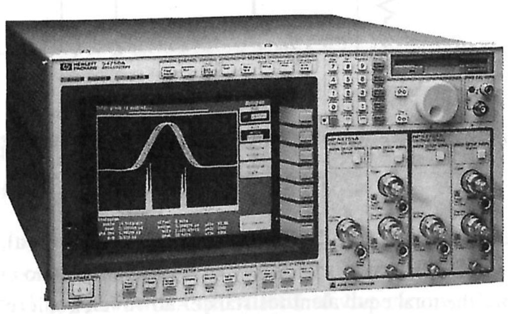
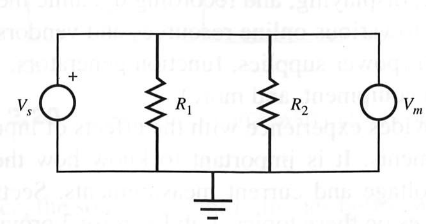


Figure 2.24 Example of a commercially available oscilloscope. *(Courtesy of Hewlett Packard, Santa Clara, CA)*

EXAMPLE 2.5 Input and Output Impedance

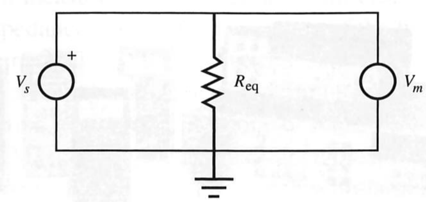
This example illustrates the effects of source and meter output and input impedance on making measurements in a circuit. Consider the following circuit with voltage source V_s and voltage meter V_m.



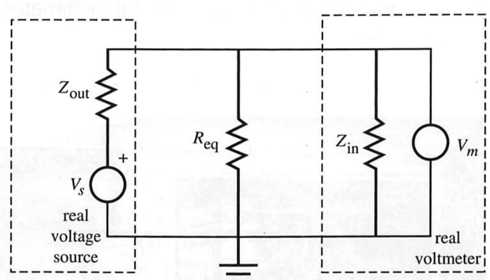
The equivalent resistance for this circuit is

$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$$

If the source and meter were both ideal, the measured voltage V_m would be equal to V_s, and the equivalent circuit would look like this:

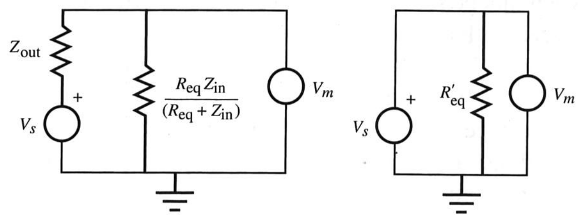


However, if the source has output impedance Z_{out} and the meter has input impedance Z_{in}, the "real" circuit actually looks like this:



The parallel combination of R_{eq} and Z_{in} yields the following circuit (a). Z_{out} and the parallel combination of R_{eq} and Z_{in} are now effectively in series because no current flows into the ideal meter V_m. Thus, the total equivalent resistance shown in circuit (b) is

$$R'_{eq} = \frac{R_{eq} Z_{in}}{R_{eq} + Z_{in}} + Z_{out}$$



(a) (b)

Note that R'_{eq} defined in the previous equation approaches R_{eq} as Z_{in} approaches infinity and as Z_{out} approaches 0. From voltage division in circuit (a), the voltage measured by the actual meter would be

$$V_m = \frac{\frac{R_{eq}Z_{in}}{(R_{eq}+Z_{in})}}{\frac{R_{eq}Z_{in}}{(R_{eq}+Z_{in})}+Z_{out}} V_s = \frac{R'_{eq} - Z_{out}}{R'_{eq}} V_s$$

The measured voltage V_m equals V_s for $Z_{in} = \infty$ and $Z_{out} = 0$, but with a real source and real meter, the measured voltage could differ appreciably from the expected ideal result. For example, if $R_1 = R_2 = 1\ \text{k}\Omega$,

$$R_{eq} = \frac{1 \cdot 1}{1+1}\ \text{k}\Omega = 0.5\ \text{k}\Omega$$

and if $Z_{in} = 1\ \text{M}\Omega$ and $Z_{out} = 50\ \Omega$,

$$R'_{eq} = \frac{0.5 \cdot 1000}{0.5 + 1000} + 0.05\ \text{k}\Omega = 0.550\ \text{k}\Omega$$

Therefore, if $V_s = 10$ V,

$$V_m = \left(\frac{0.550 - 0.05}{0.550}\right) 10\ \text{V} = 9.09\ \text{V}$$

This differs substantially from the result that would be expected (10 V) with an ideal source and meter.

2.5 THEVENIN AND NORTON EQUIVALENT CIRCUITS

Sometimes, to simplify the analysis of more complex circuits, we wish to replace voltage sources and resistor networks with an equivalent voltage source and series resistor. This is called a **Thevenin equivalent** of the circuit. Thevenin's theorem states that, given a pair of terminals in a linear network, the network may be replaced by an ideal voltage source V_{OC} in series with a resistance R_{TH}. V_{OC} is equal to the open circuit voltage across the terminals, and R_{TH} is the equivalent resistance across the terminals when independent voltage sources are shorted and independent current sources are replaced with open circuits.

We will illustrate Thevenin's theorem with the circuit shown in Figure 2.25. The part of the circuit in the dashed box will be replaced by its Thevenin equivalent. The open circuit voltage V_{OC} is found by disconnecting the rest of the circuit and determining the voltage across the terminals of the remaining open circuit. For this example, the voltage divider rule gives

$$V_{OC} = \frac{R_2}{R_1 + R_2} V_s \tag{2.39}$$

To find R_{TH}, the supply V_s is shorted (i.e., $V_s = 0$), grounding the left end of R_1. If there were current sources in the circuit, they would be replaced with open circuits. Because R_1 and R_2 are in parallel relative to the open terminals, the equivalent resistance is

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} \tag{2.40}$$

The Thevenin equivalent circuit is shown in Figure 2.26.

Another equivalent circuit representation is the **Norton equivalent,** shown in Figure 2.27. Here the linear network is replaced by an ideal current source I_{SC} and the Thevenin resistance R_{TH} in parallel with this source. I_{SC} is found by calculating

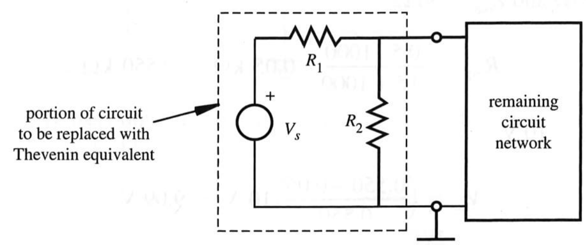


Figure 2.25 Example illustrating Thevenin's theorem.

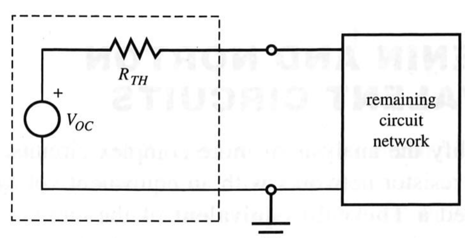


Figure 2.26 Thevenin equivalent circuit.

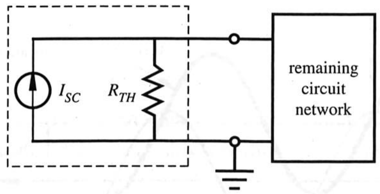


Figure 2.27 Norton equivalent circuit.

the current that would flow through the terminals if they were shorted together, having removed the remaining load circuit. It can be shown that the current I_{SC} flowing through R_{TH} produces the Thevenin voltage V_{OC} just discussed.

The Thevenin and Norton equivalents are independent of the remaining circuit network representing a load. This is useful because it is possible to make changes in the load without reanalyzing the Thevenin or Norton equivalent.

2.6 ALTERNATING CURRENT CIRCUIT ANALYSIS

When linear circuits are excited by alternating current (AC) signals of a given frequency, the current through and voltage across every element in the circuit are AC signals of the same frequency. A sinusoidal AC voltage $V(t)$ is illustrated in Figure 2.28 and can be expressed mathematically as

$$V(t) = V_m \sin(\omega t + \phi) \tag{2.41}$$

where V_m is the signal **amplitude,** ω is the **radian frequency** measured in radians per second, and ϕ is the **phase angle** relative to the reference sinusoid $V_m \sin(\omega t)$ measured in radians. The phase angle is related to the **time shift** (Δt) between the signal and reference:

$$\phi = \omega \Delta t \tag{2.42}$$

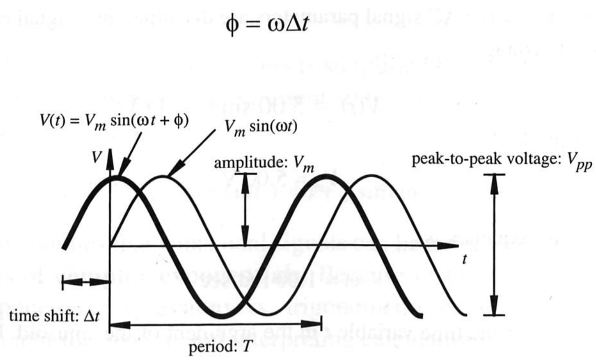


Figure 2.28 Sinusoidal waveform.

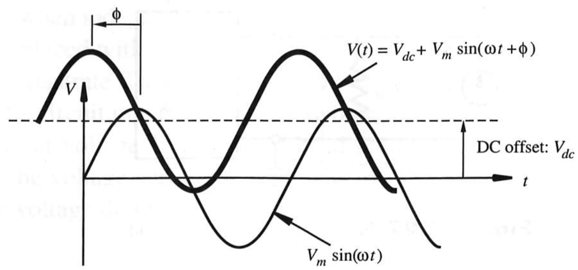


Figure 2.29 Sinusoidal signal DC offset.

A positive phase angle ϕ implies a **leading** waveform (i.e., it occurs earlier on the time axis), and a negative angle implies a **lagging** waveform (i.e., it occurs later on the time axis). The **period** T of the waveform is the time required for a full cycle. The frequency of the signal, measured in hertz (Hz = cycles/sec), is related to the period and radian frequency as

$$f = \frac{1}{T} = \frac{\omega}{2\pi} \tag{2.43}$$

Figure 2.29 illustrates another important sinusoidal waveform parameter called the **DC offset.** It represents the vertical shift of the signal from the reference sinusoid. Mathematically, the DC offset is represented by the term V_{dc} in the equation:

$$V(t) = V_{dc} + V_m \sin(\omega t + \phi) \tag{2.44}$$

Figures 2.28 and 2.29 illustrate a positive phase angle (ϕ), where the voltage signal $V(t)$ leads (i.e., occurs earlier in time relative to) the reference sine wave.

EXAMPLE 2.6 AC Signal Parameters

As an example of how the AC signal parameters are discerned in a signal equation, consider the following AC voltage:

$$V(t) = 5.00 \sin(t - 1) \text{ V}$$

The signal amplitude is

$$V_m = 5.00 \text{ V}$$

The signal radian frequency is

$$\omega = 1.00 \text{ rad/sec}$$

ω is the coefficient of the time variable t in the argument of the sinusoid. Likewise, the frequency in hertz is

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \text{ Hz} = 0.159 \text{ Hz}$$

and the phase angle is

$$\phi = -1 \text{ rad} = -57.3^\circ$$

The negative phase indicates the signal lags (i.e., occurs later in time relative to) the reference ($\sin(t)$). The arguments of the sinsusoids are always assumed to be specified in radians for computational purposes.

Alternating current power is used in many applications where direct current (DC) power is impractical or infeasible. Principal reasons for using AC power include

- AC power is more efficient to transmit over long distances because it is easily transformed to a high-voltage, low-current form, minimizing power losses (see Section 2.7) during transmission. In residential areas, it is easily transformed back to required levels. Note that the voltage drop in the transmission line is small compared to the voltage level at the source.
- AC power is easy to generate with rotating machinery (e.g., an electric generator).
- AC power is easy to use to drive rotating machinery (e.g., an AC electric motor).
- AC power provides a fixed frequency signal (60 Hz in the United States, 50 Hz in Europe) that can be used for timing purposes and synchronization.

■ CLASS DISCUSSION ITEM 2.3

Reasons for AC

Justify and fully explain the reasons AC power is used in virtually all commercial and public utility systems. Refer to the reasons just listed.

The steady state analysis of AC circuits is simplified by the use of **phasor** analysis, which uses complex numbers to represent sinusoidal signals. **Euler's formula** forms the basis for this analysis:

$$e^{j(\omega t + \phi)} = \cos(\omega t + \phi) + j\sin(\omega t + \phi) \tag{2.45}$$

where $j = \sqrt{-1}$. This implies that sinusoidal signals can be expressed as real and imaginary components of **complex exponentials.** Because of the mathematical ease of manipulating exponential expressions vs. trigonometric expressions, this form of analysis is convenient for making and interpreting calculations.

Once all transients have dissipated in an AC circuit after power is applied, the voltage across and current through each element will oscillate with the same frequency ω as the input. The amplitude of the voltage and current for each element will be constant but may differ in phase from the input. This fact lets us treat circuit variables V and I as complex exponentials with magnitudes V_m and I_m and phase ϕ for a "steady state" analysis. A phasor (e.g., voltage V) is a vector representation of the complex exponential:

$$V = V_m e^{j(\omega t + \phi)} = V_m\langle\phi\rangle = V_m[\cos(\omega t + \phi) + j\sin(\omega t + \phi)] \quad (2.46)$$

where $V_m e^{j(\omega t + \phi)}$ is the complex exponential form, $V_m\langle\phi\rangle$ is the **polar form,** and $V_m[\cos(\omega t + \phi) + j\sin(\omega t + \phi)]$ is the complex **rectangular form** of the phasor. A graphical interpretation of these quantities is shown on the complex plane in Figure 2.30. Note that the phase angle ϕ is measured from the ωt reference.

Useful mathematical relations for manipulating complex numbers and phasors include

$$r = \sqrt{x^2 + y^2} \quad (2.47)$$

$$\phi = \tan^{-1}\left(\frac{y}{x}\right) \quad (2.48)$$

$$x = r\cos(\phi) \quad (2.49)$$

$$y = r\sin(\phi) \quad (2.50)$$

$$(x_1 + y_1 j) + (x_2 + y_2 j) = (x_1 + x_2) + (y_1 + y_2)j \quad (2.51)$$

$$r_1\langle\phi_1\rangle \cdot r_2\langle\phi_2\rangle = r_1 \cdot r_2\langle\phi_1 + \phi_2\rangle \quad (2.52)$$

$$r_1\langle\phi_1\rangle / r_2\langle\phi_2\rangle = r_1/r_2\langle\phi_1 - \phi_2\rangle \quad (2.53)$$

where r is the phasor magnitude, ϕ is the phasor angle, x is the real component, and y is the imaginary component. Note that the quadrant determined by the arguments (x, y) of the arctangent function must be carefully considered when converting from rectangular to polar form. For example, if $x = y = -1$, $\phi = -135°$, not 45° that you

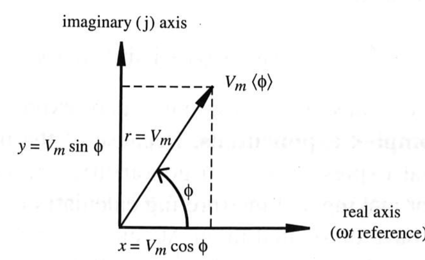


Figure 2.30 Phasor representation of a sinusoidal signal.

would get if you carelessly used a single argument $\tan^{-1}$ function on a calculator or in a computer program.

Ohm's law can be extended to the AC circuit analysis of resistor, capacitor, and inductor elements as

$$V = ZI \tag{2.54}$$

where Z is called the **impedance** of the element. This is a complex number, and you can imagine Z as a complex, frequency-dependent resistance. Impedances can be derived from the fundamental constitutive equations for the elements using complex exponentials. The unit of impedance is the ohm (Ω).

For the resistor, because $V = IR$,

$$Z_R = R \tag{2.55}$$

For the inductor, because $V = L\dfrac{dI}{dt}$, if $I = I_m e^{j(\omega t + \phi)}$, then

$$V = Lj\omega I_m e^{j(\omega t + \phi)} = (Lj\omega)I \tag{2.56}$$

Therefore, the impedance of an inductor is given by

$$Z_L = j\omega L = \omega L\langle 90°\rangle \tag{2.57}$$

which implies that the voltage will lead the current by 90°. Note that because a DC signal can be considered an AC signal with zero frequency ($\omega = 0$), the impedance of an inductor in a DC circuit is 0. Therefore, it acts as a short in a DC circuit. At very high AC frequencies ($\omega = \infty$), the inductor has infinite impedance, so it behaves as an open circuit.

For the capacitor, because $I = C\dfrac{dV}{dt}$, if $V = V_m e^{j(\omega t + \phi)}$, then

$$I = Cj\omega V_m e^{j(\omega t + \phi)} = (Cj\omega)V \tag{2.58}$$

giving

$$V = \left(\frac{1}{Cj\omega}\right)I \tag{2.59}$$

Therefore, the impedance of a capacitor is given by

$$Z_C = \frac{1}{j\omega C} = \frac{-j}{\omega C} = \frac{1}{\omega C}\langle -90°\rangle \tag{2.60}$$

which implies the voltage will lag the current by 90°. The impedance of a capacitor in a DC circuit ($\omega = 0$) is infinite, so it acts as an open circuit. At very high AC frequencies ($\omega = \infty$), the capacitor has zero impedance, so it acts as a short circuit.

As illustrated in Example 2.7, every result presented in previous sections for analyzing simple DC circuits, including Ohm's law, series and parallel resistance combinations, voltage division, and current division, applies to the AC signals and impedances just presented! Internet Link 2.7 is an excellent resource that reviews AC electricity, circuit analysis, and devices.

In circuits with multiple sources, it is important to express them all in either their sine or cosine form consistently so that the phase relationships are relative to a consistent reference. The following trigonometric identities are useful in accomplishing this:

$$\sin(\omega t + \phi) = \cos(\omega t + \phi - \pi/2) \tag{2.61}$$

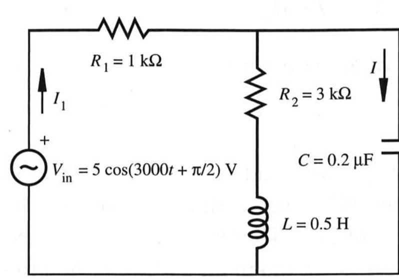
$$\cos(\omega t + \phi) = \sin(\omega t + \phi + \pi/2) \tag{2.62}$$

EXAMPLE 2.7 AC Circuit Analysis

Internet Link

2.7 All about circuits - Vol. II - AC

The following is an illustrative example of AC circuit analysis. The goal is to find the steady state current *I* through the capacitor in the following circuit:



Because the input voltage source is

$$V_{in} = 5\cos\left(3000\,t + \frac{\pi}{2}\right)\ \text{V}$$

each element in the circuit will respond at the radian frequency:

$$\omega = 3000 \text{ rad/sec}$$

Because the voltage source has a magnitude of 5 *V* and a phase of $\pi/2$, relative to $\cos(3000t)$, the phasor and complex form of the source is

$$V_{in} = 5\langle 90°\rangle\ V = (0 + 5\mathrm{j})\ V$$

The complex and phasor form of the capacitor impedance is

$$Z_C = -\mathrm{j}/\omega C = -1666.67\mathrm{j}\ \Omega = 1666.67\langle -90°\rangle\ \Omega$$

The complex and phasor form of the inductor impedance is

$$Z_L = \mathrm{j}\omega L = 1500\mathrm{j}\ \Omega = 1500\langle 90°\rangle\ \Omega$$

To find the current (I) through the capacitor, we will first find the current through the entire circuit (I_1) and then use current division. Therefore, we need the impedance of the middle branch of the circuit, along with the equivalent impedance of the entire circuit.

Resistor R_2 and inductor L are in series, so their combined impedance, in both rectangular and phasor form, using Equations 2.47 and 2.48, is:

$$R_2 + Z_L = (3000 + 1500j)\ \Omega = 3354.1\ \langle 26.57°\rangle\ \Omega$$

This impedance is in parallel with capacitor C, and the combined impedance of this parallel combination, using Equation 2.33, is:

$$\frac{(R_2 + Z_L)Z_C}{(R_2 + Z_L) + Z_C}$$

The numerator of this expression can be calculated using Equation 2.52:

$$(R_2 + Z_L)Z_C = 3354.1\ \langle 26.57°\rangle \cdot 1666.67\ \langle -90°\rangle\ \Omega = 5{,}590{,}180\ \langle -63.43°\rangle\ \Omega$$

The denominator can be found using Equation 2.51:

$$(R_2 + Z_L) + Z_C = ((3000 + 1500j) - 1666.67j)\ \Omega = (3000 - 166.67j)\ \Omega$$

Using Equations 2.47 and 2.48, the phasor form of this impedance, which is required to perform the division with the numerator, is:

$$(R_2 + Z_L) + Z_C = (3000 - 166.67j)\ \Omega = (3004.63\ \langle -3.18°\rangle\ \Omega$$

Therefore, the parallel combination of $(R_2 + Z_L)$ and Z_C, using Equation 2.53, is:

$$\frac{(R_2 + Z_L)Z_C}{(R_2 + Z_L) + Z_C} = \frac{5{,}590{,}180\langle -63.43°\rangle}{3004.63\langle -3.18°\rangle}\ \Omega = 1860.52\ \langle -60.25°\rangle\ \Omega$$

The rectangular form of this impedance, using Equations 2.49 and 2.50, is:

$$\frac{(R_2 + Z_L)Z_C}{(R_2 + Z_L) + Z_C} = 1860.52\ \langle -60.25°\rangle\ \Omega = (923.22 - 1615.30j)\ \Omega$$

This impedance is in series with resistor R_1, so the equivalent impedance of the entire circuit is:

$$Z_{eq} = R_1 + \frac{(R_2 + Z_L)Z_C}{(R_2 + Z_L) + Z_C} = 1000 + (923.22 - 1615.30j))\ \Omega = 1923.22 - 1615.30j\ \Omega$$

From Equations 2.47 and 2.48, the phasor form of this impedance is:

$$Z_{eq} = 1923.22 - 1615.30j)\ \Omega = 2511.57\ \langle -40.03°\rangle\ \Omega$$

We can now find I_1 from Ohm's law:

$$I_1 = \frac{V_{in}}{Z_{eq}} = \frac{5\langle 90°\rangle}{2511.57\langle -40.03°\rangle} = 1.991\langle 130.03°\rangle\ \text{mA}$$

Current division is used to find I

$$I = \frac{(R_2 + Z_L)}{(R_2 + Z_L) + Z_C} I_1 = \frac{3354.1\langle 26.57°\rangle}{3004.63\langle -3.18°\rangle} 1.991\langle 130.03°\rangle\ \text{mA}$$

(continued)

work this times (type in great detail) in class

(concluded)

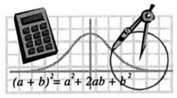
which, using Equations 2.52 and 2.53, gives

$$I = 2.22\langle 159.8°\rangle \text{ mA}$$

so the capacitor current leads the input reference by 159.8° or 2.789 rad, and the resulting current is

$$I(t) = 2.22 \cos(3000t + 2.789) \text{ mA}$$

Note that if the input voltage were $V_{in} = 5 \sin(3000t + \pi/2)$ V instead, the resulting current would be $I(t) = 2.22 \sin(3000t + 2.789)$ mA. But in this example, the reference was $\cos(3000t)$.



MathCAD Example

2.1 AC circuit analysis

MathCAD Example 2.1 executes all of the analyses above in software. Phasors can be entered or displayed in polar or rectangular form, and all calculations are performed with ease. If you are not familiar with MathCAD, you might want to watch Video Demo 2.9, which describes and demonstrates the software and its capabilities.

2.7 POWER IN ELECTRICAL CIRCUITS

All circuit elements dissipate, store, or deliver power through the physical interaction between charges and electromagnetic fields. An expression for power can be derived by first looking at the infinitesimal work (dW) done when an infinitesimal charge (dq) moves through an electric field resulting in a change in potential represented by a voltage V. This infinitesimal work is given by

Video Demo

2.9 MathCAD analysis software demo

$$dW = V dq \tag{2.63}$$

Because **power** is the rate of work done,

$$P = \frac{dW}{dt} = V\frac{dq}{dt} = VI \tag{2.64}$$

Therefore, the power consumed or generated by an element is simply the product of the voltage across and the current through the element. If the current flows in the direction of decreasing voltage as shown in Figure 2.31, P is negative, implying that the element is dissipating or storing energy. If the current flows in the direction of increasing voltage, P is positive, implying that the element is generating or releasing energy. The instantaneous power in a resistive circuit can be expressed as

$$P = VI = I^2R = V^2/R \tag{2.65}$$

For AC signals, because $V = V_m \sin(\omega t + \phi_V)$ and $I = I_m \sin(\omega t + \phi_I)$, the power changes continuously over a period of the AC waveform. Instantaneous power is not a useful quantity by itself, but if we look at the average power delivered over a period, we get a good measure of the circuit's or component's overall

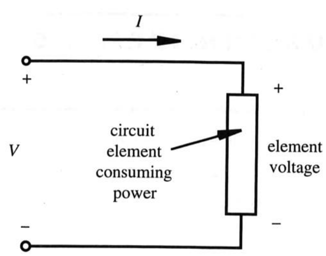


Figure 2.31 Power in a circuit element.

power characteristics. It can be shown (Question 2.42) that the average power over a period is

$$P_{avg} = \frac{V_m I_m}{2} \cos(\theta) \tag{2.66}$$

where θ is the difference between the voltage and current phase angles ($\phi_V - \phi_I$), which is the phase angle of the complex impedance $Z = V/I$.

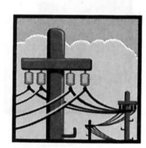
If we use the rms, or **root-mean-square** values of the voltage and current defined by

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T I^2 \, dt} = \frac{I_m}{\sqrt{2}} \quad \text{and} \quad V_{rms} = \sqrt{\frac{1}{T}\int_0^T V^2 \, dt} = \frac{V_m}{\sqrt{2}} \tag{2.67}$$

the average AC power consumed by a resistor can be expressed in the same form as with DC circuits (see Question 2.43):

$$P_{avg} = V_{rms} I_{rms} = RI_{rms}^2 = V_{rms}^2/R \tag{2.68}$$

Apparent power
$S = V_{RMS} I_{RMS}$
Reactive power
$Q = V_{RMS} I_{RMS} \sin\theta$



■ CLASS DISCUSSION ITEM 2.4
Transmission Line Losses

When power is transmitted from power plants over large distances, high-voltage lines are used. Transformers (see Section 2.8) are used to change voltage levels both before and after transmission. Because current is lower at the higher voltage, less power is lost during the transmission, based on the middle expression for power in Equation 2.65. But doesn't the last expression imply that more power is lost at a higher voltage? How do you explain this apparent discrepancy?

work this ... times
(take in great detail)
in class

■ CLASS DISCUSSION ITEM 2.5
International AC

In European countries, the household AC signal is 220 V_{rms} at 50 Hz. What effect does this have on electrical devices such as an electric razor purchased in the United States but used in these countries?

For AC networks with inductance and capacitance in addition to resistance, the average power consumed by the network can be expressed, using Equations 2.66 and 2.67, as

$$P_{avg} = I_{rms}V_{rms}\cos\theta = I_{rms}^2|Z|\cos\theta = (V_{rms}^2/|Z|)\cos\theta \tag{2.69}$$

where $|Z|$ is the magnitude of the complex impedance. Cosθ is called the **power factor,** because the average power dissipated by the network is dependent on this term.

■ CLASS DISCUSSION ITEM 2.6
AC Line Waveform

Draw a figure that represents one cycle of the AC voltage signal present at a typical household wall receptacle. What is the amplitude, frequency, period, and rms value for the voltage? Also, what is a typical rms current capacity for a household circuit?

2.8 TRANSFORMER

Video Demo

2.10 Power transformer with laminated core

A transformer is a device used to change the relative amplitudes of voltage and current in an AC circuit. As illustrated in Figure 2.32, it consists of primary and secondary windings whose magnetic fluxes are linked by a ferromagnetic core.

Video Demo 2.10 shows an example of an actual transformer, in this case a laminated core, shell-type power transformer.

Using Faraday's law of induction and neglecting magnetic losses, the voltage per turn of wire is the same for both the primary and secondary windings, because the windings experience the same alternating magnetic flux. Therefore, the primary and secondary voltages (V_P and V_S) are related by

$$\frac{V_P}{N_P} = \frac{V_S}{N_S} = -\frac{d\phi}{dt} \tag{2.70}$$

where N_P is the number of turns in the primary winding, N_S is the number of turns in the secondary winding, and ϕ is the magnetic flux linked between the two coils. Thus, the secondary voltage is related to the primary voltage by

$$V_S = \frac{N_S}{N_P}V_P \tag{2.71}$$

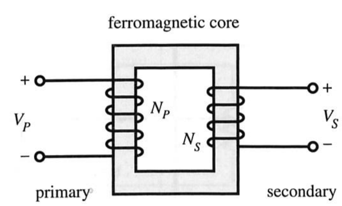


Figure 2.32 Transformer.

where N_S/N_P is the turns ratio of the transformer. If $N_S > N_P$, the transformer is called a **step-up transformer** because the voltage increases. If $N_S < N_P$, it is called a **step-down transformer** because the voltage decreases. If $N_S = N_P$, it is called an **isolation transformer,** and the output voltage is the same as the input voltage. All transformers electrically isolate the output circuit from the input circuit.

If we neglect losses in the transformer due to winding resistance and magnetic effects, the power in the primary and secondary circuits is equal:

$$I_P V_P = I_S V_S \tag{2.72}$$

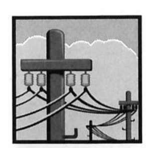
Substituting Equation 2.71 results in the following relation between the secondary and primary currents:

$$I_S = \frac{N_P}{N_S} I_P \tag{2.73}$$

Thus, a step-up transformer results in lower current in the secondary and a step-down transformer results in higher current. An isolation transformer has equal alternating currents in both the primary and secondary. Note that any DC component of voltage or current in a transformer primary will not appear in the secondary. Only alternating currents are transformed.

■ CLASS DISCUSSION ITEM 2.7
DC Transformer

Can a transformer be used to increase voltage in a DC circuit? Why or why not?



times work this example in great detail in class

2.9 IMPEDANCE MATCHING

Often we must be careful when connecting different devices and circuits together. For example, when using certain function generators to drive a circuit, proper **signal termination,** or loading, may be required as illustrated in Figure 2.33. Placing the 50 Ω termination resistance in parallel with a higher impedance network helps match the receiving network input impedance to the function generator output

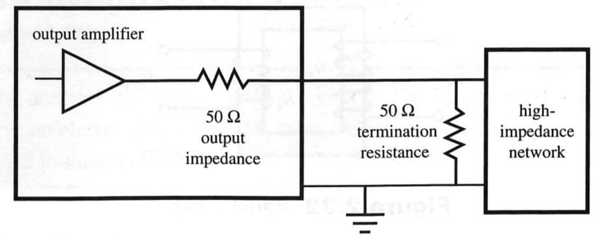


Figure 2.33 Signal termination.

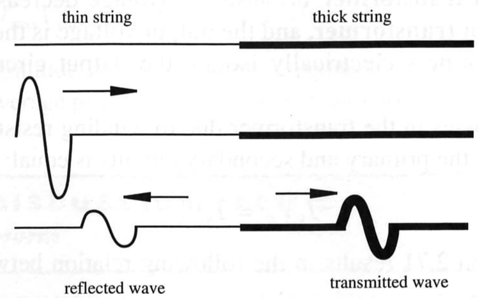


Figure 2.34 Impedance matching—string analogy.

impedance. This is called **impedance matching.** If we do not match impedances, a high-impedance network will reflect frequency components of the driving circuit (e.g., the function generator), especially the high-frequency components. A good analogy to this effect is a thin string attached to a thicker string. As illustrated in Figure 2.34, if we propagate transverse vibrations along the thin string, there will be partial transmission to the thick string and partial reflection back to the source. This is a result of the mismatch of the properties at the interface between the two strings.

In addition to signal termination concerns, impedance matching is important in applications where it is desired to transmit maximum power to a load from a source. This concept is easily illustrated with the simple resistive circuit shown in Figure 2.35 with source voltage V_s, source output impedance R_s, and load resistance R_L. The voltage across the load is given by voltage division:

$$V_L = \frac{R_L}{R_L + R_s} V_s \tag{2.74}$$

Therefore, the power transmitted to the load is

$$P_L = \frac{V_L^2}{R_L} = \frac{R_L}{(R_L + R_s)^2} V_s^2 \tag{2.75}$$

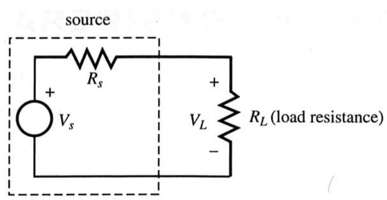


Figure 2.35 Impedance matching.

To find the load resistance that maximizes this power, we set the derivative of the power equal to 0 and solve for the load resistance:

$$\frac{dP_L}{dR_L} = V_s^2 \frac{(R_L + R_s)^2 - 2R_L(R_L + R_s)}{(R_L + R_s)^4} = 0 \qquad (2.76)$$

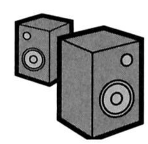
The derivative is 0 only when the numerator is 0, so

$$(R_L + R_s)^2 = 2R_L(R_L + R_s) \qquad (2.77)$$

Solving for R_L gives

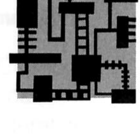
$$R_L = R_s \qquad (2.78)$$

The second derivative of power can be checked to verify that this solution results in a maximum and not a minimum. The result of this analysis is as follows: To maximize power transmission to a load, the load's impedance should match the source's impedance.



■ CLASS DISCUSSION ITEM 2.8
Audio Stereo Amplifier Impedances

Why are audio stereo amplifier output impedances important specifications when selecting speakers?



■ CLASS DISCUSSION ITEM 2.9
Common Usage of Electrical Components

Cite specific examples in your experience where and how each of the following electrical components is used:

- Battery
- Resistor
- Capacitor
- Inductor
- Voltage divider
- Transformer

work this times
example in great detail
in class

2.10 PRACTICAL CONSIDERATIONS

This chapter has presented all of the fundamentals and theory of basic electrical circuits. This final section presents various practical considerations that come up when trying to assemble actual circuits that function properly and reliably. The Laboratory Exercises book (see *mechatronics.colostate.edu/lab_book.html*) that accompanies this textbook provides some useful experiences to help you develop prototyping and measurement skills, and the sections below provide some additional supporting information.

2.10.1 Capacitor Information

As we saw in Section 2.2.1, determining resistance values from a discrete resistor component is very easy—a simple matter of looking up color values in a table. Unfortunately, capacitor labeling is not nearly as straightforward.

A capacitor is sometimes referred to as a "cap." Large caps are usually the electrolytic type that must be attached to a circuit with an indicated polarity. Because large capacitors have a large package size, the manufacturer usually prints the value clearly on the package, including the unit prefix. The only thing you need to be careful with is the capital letter M, which is often used to indicate micro, not mega. For example, an electrolytic capacitor labeled "+500MF" indicates a 500 μF capacitor.

It is very important to be careful with electrolytic-capacitor polarity. The capacitor's internal construction is not symmetrical, and you can destroy the cap if you apply the wrong polarity to the terminals: the terminal marked + must be at a higher voltage than the other terminal. Sometimes, violating this rule will result in gas formation internally that can cause the cap to explode. Improper polarity can also cause the cap to become shorted.

As the caps get smaller, determining the value becomes more difficult. Tantalum caps are silver-colored cylinders. They are polarized: a + mark and/or a metal nipple mark the positive end. An example label is +4R7m. This is fairly clear as long as you know that the "R" marks the decimal place: A +4R7m is a 4.7 mF (millifarad) cap. The same cap could also be labeled +475K, which you might think is 475 kilofarads, but you would be wrong. Here, the "K" is a tolerance indicator, not a unit prefix. "K" means $\pm 10\%$ (see more below). Capacitance values are usually quite small on the Farad scale. The values are usually in the microfarad ($\mu F = 10^{-6}$ F) to picofarad ($pF = 10^{-12}$ F) range. Labeling on tantalum caps mimics the resistor code system: 475 indicates 47 times ten to the fifth power, and the unit prefix pF is assumed. In general, if a cap's numerical value is indicated as a fraction (e.g., 0.01), the unit prefix will almost always be micro (μ); and if the value is a large integer (e.g., 47×10^5), pF will apply. The prefix nano ($n = 10^{-9}$) is usually not used for capacitance values. Returning to the example, a tantalum cap labeled "475" must be 47×10^5 pF, which is 4.7×10^6 pF, which is 4.7×10^{-6} F or 4.7 μF.

Mylar capacitors are usually yellow cylinders that are rather clearly marked. For example, ".01M" is just 0.01 μF. Mylar caps are not polarized, so you can orient them at random in your circuits. Because they are fabricated as long coils of metal foil (separated by a thin dielectric—the "mylar" that gives them their name), mylar caps betray their function at very high frequencies where the inductance of the coil become significant, blocking the very high frequencies you would expect a cap to pass. Ceramic caps, described next, are better in this respect, although they are very poor in other characteristics.

Ceramic caps have a flat, round shape (like pancakes) and are usually orange-colored. Because of their shape and construction (in contrast to the coiled mylars), they act like capacitors even at high frequencies. The trick in reading these is to ignore the markings that might accidentally be interpreted as units. For example, a ceramic cap labeled "Z5U .02M 1kV" is a 0.02 μF cap with a maximum voltage rating of 1kV. The M is a tolerance marking, in this case ± 20%.

CK05 caps have a small box shape, with their leads 0.2 inches apart so they can be easily inserted in prototyping or printed circuit boards. Therefore, they are common and useful. An example marking is 101K, which is 100 pF (10×10^1 pF), as described above.

The tolerance codes that often appear on capacitors are listed in Table 2.3. These codes apply to both capacitors and resistors with printed labels. Note that the Z tolerance code indicates a very tight tolerance if on a resistor, but a very large tolerance if on a capacitor!

Table 2.3 Capacitor and resistor tolerance codes

Code Letter	Meaning
Z	+80%, –20% for caps, ± 0.025 (precision resistors)
M	± 20%
K	± 10%
J	± 5%
G	± 2%
F	± 1%
D	± 0.5%
C	± 0.25%
B	± 0.1%
N	± 0.02%
A	± 0.005

More information dealing with practical considerations concerning capacitors can be found at Internet Link 2.8.

Internet Link

2.8 Capacitor practical considerations

2.10.2 Breadboard and Prototyping Advice

A **breadboard** is a convenient device for prototyping circuits in a form that can be easily tested and modified. Figure 2.36 illustrates a typical breadboard layout consisting of a rectangular matrix of insertion points spaced 0.1 inches apart. As

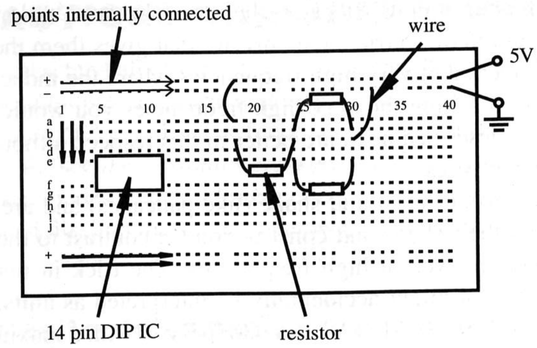


Figure 2.36 Breadboard.

shown in the figure, each column a through e, and f through j, is internally connected, as illustrated by the arrows in the diagram. The + and − rows that lie along the top and bottom edges of the breadboard are also internally connected to provide convenient DC voltage and ground busses. As illustrated in the figure, integrated circuits (ICs, or "chips") are usually inserted across the gap between columns a through e, and f through j. A 14-pin dual in-line package (DIP) IC is shown here. When the IC is placed across the gap, each pin of the IC is connected to a separate numbered column, making it easy to connect wires to and from the IC pins. The figure also shows an example of how to construct a simple resistor circuit. The schematic for this circuit is shown in Figure 2.37. The techniques for measuring voltage V_1 and current I_3 are described in Section 2.10.3. Figure 2.38 shows an example of a wired breadboard including resistors, an integrated circuit, and a push-button switch. When constructing such circuits, care should be exercised in trimming leads so the components lie on top of the breadboard in an organized geometric pattern. This will make it easier to see connections and find potential problems and errors later.

Video Demo

2.11 Breadboard construction

2.12 Breadboard advice and rules of thumb

Video Demo 2.11 shows how a breadboard is constructed, and Video Demo 2.12 provides "rules of thumb" for how to properly assemble circuits on the board. Internet Link 2.9 is an excellent resource, providing useful tips when prototyping with breadboards (solderless protoboards), perf boards (soldered protoboards), and printed circuit boards (PCBs) for when a design is finalized.

Internet Link

2.9 Prototyping tips

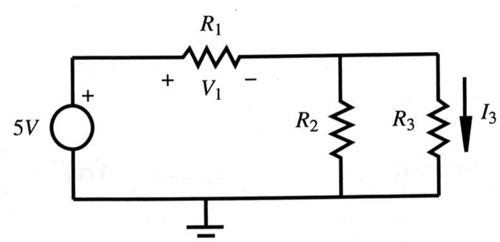


Figure 2.37 Example resistor circuit schematic.

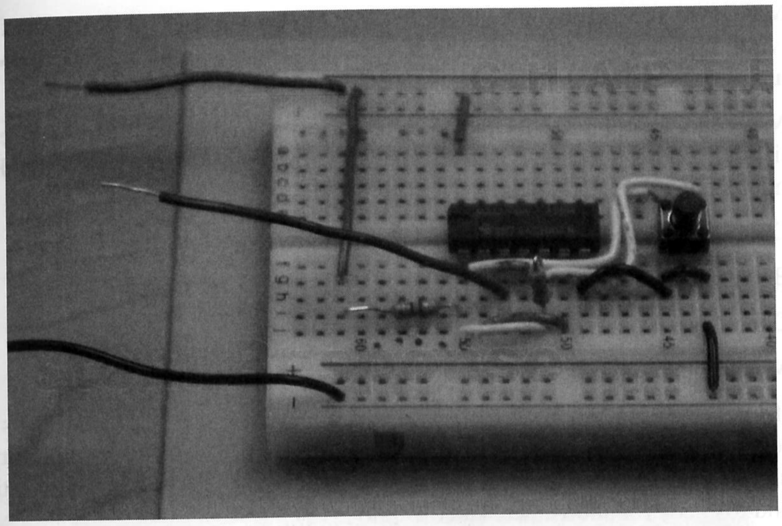


Figure 2.38 Example Breadboard Circuit.

Below is a set of basic guidelines you should follow when using breadboards to prototype circuits involving integrated circuits. Generally, if you carefully follow this protocol, you will save a lot of time and avoid a lot of frustration:

a. Start with a clearly drawn schematic illustrating all components, inputs, outputs, and connections.

b. Draw a detailed wiring diagram, using the information from datasheets regarding device pin-outs. Label and number each pin used on each IC and fully specify each component. This will be your wiring guide.

c. Double-check the functions you want to perform with each device and test them individually.

d. Insert the ICs into your breadboard.

e. Wire all connections carefully, checking off or highlighting each line on your schematic as you insert each wire. Select wire colors in a consistent and meaningful way (e.g., red for +5V, black for ground, other colors for signals), and use appropriate lengths (~ 1/4 in) for exposed wire ends. If the ends are too short, you might not establish good connections; and if too long, you might damage the breadboard or risk shorts. Also be careful to not insert component (e.g., resistor and capacitor) leads too far into the breadboard holes. This can also result in breadboard damage or shorting problems.

f. Be very gentle with the breadboards. Don't force wires into or out of the holes. If you do this, the breadboard might be damaged, and you will no longer be able to create reliable connections in the damaged holes or rows. Use a "chip puller" (small tool) to remove ICs from the breadboard to prevent bent or broken pins.

g. Make sure your wiring is very neat (i.e., not a "rat's nest"), and keep all of your wires as short as possible to minimize electrical magnetic interference (EMI) and added resistance, inductance, and capacitance.

h. Make sure all components and wires are firmly seated in the breadboard, establishing good connections. This is especially important with large ICs like PIC microcontrollers.

i. Double check the +5V and ground connections to each IC.

j. Before connecting the power supply, set the output to +5V and turn it off.

k. Connect the power supply to your breadboard and then turn it on.

l. Measure signals at inputs and outputs to verify proper functionality.

m. If your circuit is not functioning properly, go back through the above steps in reverse order checking everything carefully. If you are still having difficulty, use the beep continuity-check feature on a multimeter to verify all connections and to check for shorts (see Video Demo 2.13).

n. When prototyping with a soldered protoboard or PCB, use IC sockets to allow easy installation and removal of ICs.

Video Demo

2.13 Current measurement and checking continuity

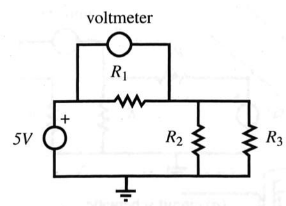
2.10.3 Voltage and Current Measurement

It is very important that you know how to measure voltage and current, especially when prototyping a circuit. Figure 2.39 illustrates how you measure voltage across an element in a circuit, in this case a resistor. To measure voltage, the leads of the voltmeter are simply placed across the element. However, as shown in Figure 2.40, when measuring current through an element, the ammeter must be connected in series with the element. This requires physically altering the circuit to insert the ammeter in series. For the example in the figure, the top lead of resistor R_3 is removed from the breadboard to make the necessary connections to the ammeter. A demonstration of these techniques can be found in Video Demo 2.13. It is also important to be aware of input impedance effects, especially when measuring voltage across a large resistance or measuring current through a circuit branch with low resistance (see Section 2.4 for more information).

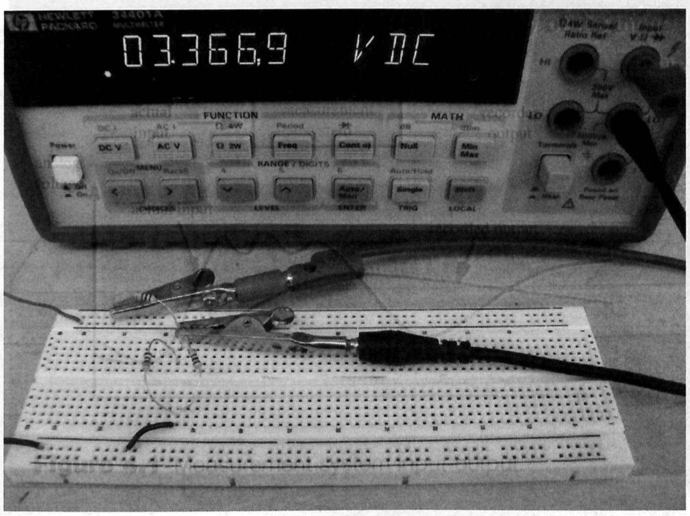
2.10.4 Soldering

Once a prototype circuit has been tested on a breadboard, a permanent prototype can be created by soldering components and connections using a **protoboard** (also called a perf board, perforated board, or vector board). These boards are manufactured with a regular square matrix of holes spaced 0.1 inch apart as with the insertion points in a breadboard. Unlike with the breadboard, there are no prewired connections between the holes. All connections must be completed with external wire and solder joints. The result is a prototype that is more robust and reliable.

For multiple versions of a prototype or production version of a circuit, a **printed circuit board (PCB)** is usually manufactured. Here, components are inserted and soldered to perforations in the board and all connections between the components



(*a*) circuit schematic



(*b*) photograph

Figure 2.39 Measuring voltage.

are "printed" on the board with a conducting medium. For more information about PCBs and how to make them, see Internet Links 2.10 and 2.11.

Solder is a metallic alloy of tin, lead, and other elements that has a low melting point (approximately 375°F). The solder usually is supplied in wire form, often with a core of flux, which facilitates melting, helps enhance wetting of the metal surfaces, and helps prevent oxidation. Solder is applied using a soldering iron consisting of a heated tip and support handle (see Figure 2.41). Some soldering irons also include a rheostat to control tip temperature. When using a soldering iron, be sure the tip is securely installed. Also, after heating, make sure the tip is clean and shiny, wiping it on a wet sponge or steel wool if necessary.

Internet Link

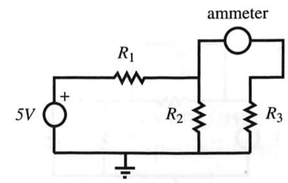
2.10 ExpressPCB free PCB layout software and inexpensive manufacturing

2.11 Printed circuit board information resource

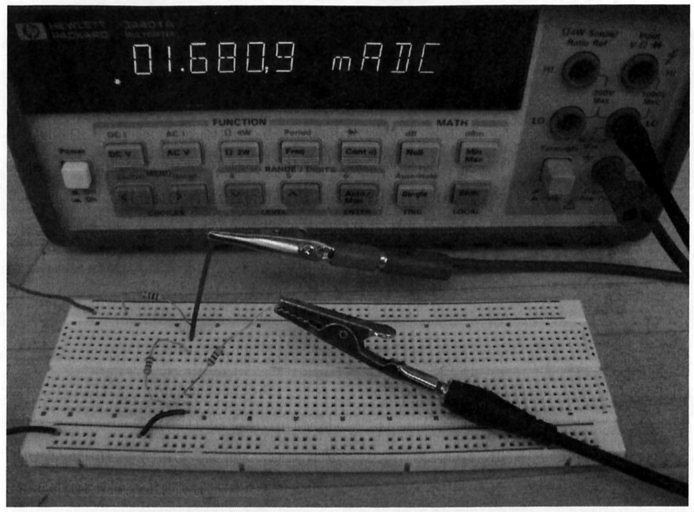
Here is a helpful list of steps you should follow to create a good solder connection:

(1) Before soldering, make sure you have everything you need: hot soldering iron, solder, components, wire, protoboard or PCB, tip-cleaning pad, and magnifying glass.

(2) Clean any surfaces that are to be joined. You can use fine emery paper, steel wool, or a metal brush to remove oxide layers and dirt so that the solder can easily wet the surface. Rosin core (flux) solder will enhance the wetting process.



(*a*) circuit schematic



(*b*) photograph

Figure 2.40 Measuring current.

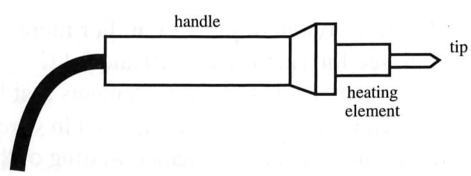
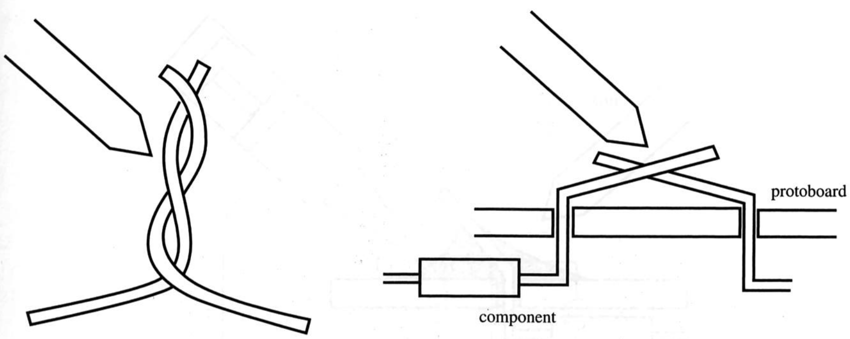


Figure 2.41 Soldering iron.

(3) Make a mechanical connection between the wires to be joined, either by bending or twisting, and ensure the components are secure so that they will not move when you apply the iron. Figure 2.42 illustrates two wires twisted together and a component inserted into a protoboard in preparation for soldering.

(4) Heating the wires and metal surfaces to be joined is necessary so that the solder properly wets the metal for a strong bond to result. When soldering electronic components, practice in heating is necessary so that the process is swift enough to not damage components. Soldering irons with sharper tips are convenient



(*a*) wires twisted together

(*b*) bent leads through protoboard holes

Figure 2.42 Preparing a soldered joint.

for joining small electronic components, because they can deliver the heat very locally.

(5) When the surfaces have been heated momentarily, apply the solder to the work (not the soldering iron) and it should flow fluidly over the surfaces. Feed enough solder to provide a robust but not blobby joint. (If the solder balls up on the work, the iron is not hot enough.) Smoothly remove the iron and allow the joint to solidify momentarily. You should see a slight change in surface texture of the solder when it solidifies. If the joint is ragged or dull, you may have a cold joint, one where the solder has not properly wetted the surfaces. Such a joint will not have adequate or reliable conductivity and must be repaired by resoldering. Figure 2.43 illustrates a successful solder joint where the solder has wet both surfaces, in this case a component lead in a metal-rim-hole perforated board.

(6) If flux solvent is available, wipe the joint clean.

(7) Inspect your work with a magnifying glass to make sure the joint looks good.

Often you may have a small component or IC that you do not want to heat excessively. To avoid excessive heat, you can use a heat sink. A heat sink is a piece of metal like an alligator clip connected to the wire between the component and the connection to help absorb some of the heat that would be conducted to the component. However, if the heat sink is too close to the connection, it will be

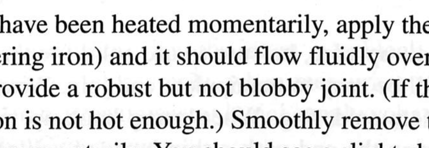


Figure 2.43 Successful solder joint.

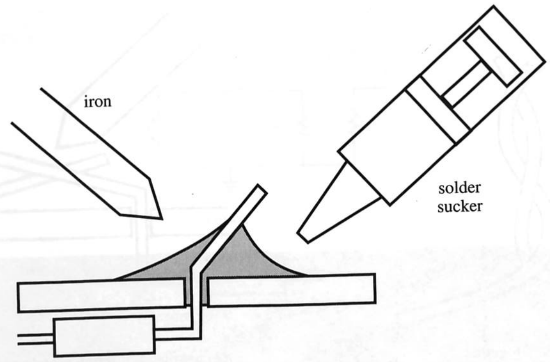


Figure 2.44 Removing a soldered joint.

Internet Link

2.12 Electronics Club "Guide to Soldering"

2.13 Curious Inventor–"How to Solder"

difficult to heat the wires. When using an IC, a socket can be soldered into the protoboard first, and then the IC inserted, thereby avoiding any thermal stress on the IC.

When using hook-up wire, be sure to use solid (nonbraided) wire on a protoboard, because it will be easy to manipulate and join. Wire must be stripped of its insulating cover before soldering. When using hook-up wire in a circuit, tinning the wire first (covering the end with a thin layer of solder) facilitates the joining process.

Video Demo

2.14 How and why to solder correctly

Often you may make mistakes in attaching components and need to remove one or more soldered joints. A solder sucker makes this a lot easier. To use a solder sucker (see Figure 2.44), cock it first, heat the joint with the soldering iron, then trigger the solder sucker to absorb the molten solder. Then the component can easily be removed, because very little solder will be left to hold it.

For more information and advice on how to solder properly, see Internet Links 2.12 and 2.13. Video Demo 2.14 is also an excellent resource.

Lab Exercise

Lab 3 The oscilloscope

2.10.5 The Oscilloscope

The oscilloscope, or o-scope for short, is probably one of the most widely used electrical instruments and is one of the most misunderstood. Lab Exercise 3 provides experiences to become familiar with the proper methods for connecting inputs, grounding, coupling, and triggering the oscilloscope. Video Demo 2.8 provides a demonstration of typical oscilloscope functionality, and this section provides information on some important oscilloscope concepts.

Video Demo

2.8 Oscilloscope demonstrations using the Tektronix 2215 analog scope

Most oscilloscopes are provided with a switch to select between AC or DC coupling of a signal to the oscilloscope input amplifier. When AC coupling is selected, the DC component of the signal is blocked by a capacitor inside the oscilloscope that is connected between the input terminal and the amplifier stage. Both AC and DC coupling configurations are illustrated in Figure 2.45. R_{in} is the input resistance (impedance) and C_{in} is the input capacitance. C_c is the coupling capacitor, which is present only when AC coupling is selected.

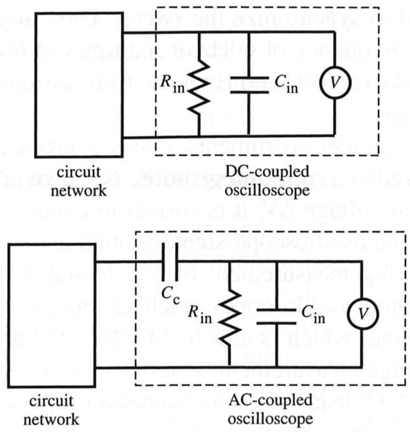


Figure 2.45 Oscilloscope coupling.

AC coupling must be selected when the intent is to block any DC component of a signal. This is important, for example, when measuring small AC spikes and transients on a 5 V TTL (transistor-transistor logic) supply voltage. However, it must be kept in mind that with AC coupling:

- One is not aware of the presence of any DC level with respect to ground.
- The lower-frequency components of a signal are attenuated.
- When the oscilloscope is switched from DC to AC coupling, it takes a little time before the display stabilizes. This is due to the time required to charge the coupling capacitor C_c to the value of the DC component (average value) of the signal.
- Sometimes the input time constant ($\tau = R_{in}C_c$) is quoted among the oscilloscope specifications. This number is useful, because after about five time constants (5τ), the displayed signal is stable.

AC coupling can be explained by considering the impedance of the coupling capacitor as a function of frequency: $Z_C = 1/(j\omega C)$. With a DC voltage ($\omega = 0$) the impedance of the capacitor is infinite, and all of the DC voltage at the input is blocked by the capacitor. For AC signals, the impedance is less than infinite, resulting in attenuation of the input signal dependent upon the frequency. As the input frequency increases, the attenuation decreases to zero.

Triggering is another important concept when attempting to display a signal on an oscilloscope. A trigger is an event that causes the signal to sweep across the display. If the signal being measured is periodic, and the trigger is consistent with each sweep, the signal will appear static on the display, which is desirable. The oscilloscope may be level triggered, where the sweep starts when the signal reaches a selectable voltage level, or slope triggered, where a certain rate of signal change triggers the sweep. Another triggering option available is line triggering, where the

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AC power input is used to synchronize the sweep. Thus, any terminal voltage synchronized with the line frequency of 60Hz or multiples of 60Hz can be triggered in this mode. This is useful to detect if 60 Hz noise from various line-related sources is superimposed on a signal.

Normally all measurement instruments, power sources, and signal sources in a circuit must be referenced to a **common ground,** as shown in Figure 2.46. However, to measure a differential voltage ΔV, it is correct to connect the scope as shown in Figure 2.47. Note that the oscilloscope signal ground and external network ground are not common, allowing measurement of a potential difference anywhere in a circuit. However, in some oscilloscopes, each channel's "−" signal reference is attached to chassis ground, which is attached to the AC line ground. Therefore, to make a differential voltage measurement, you must use a two-channel signal difference feature, using the "+" leads of each channel for the measurement. An alternative for DC circuits is to measure the voltage at each node separately, relative to ground, and then manually subtract the voltage readings.

The **input impedance** of an oscilloscope is typically in the 1 MΩ range, which is fairly large. However, as described in Section 2.4, when measuring the voltage drop across an element whose impedance is of similar or greater magnitude than the input impedance, serious errors can result. One approach to avoid this problem is to increase the input impedance of the oscilloscope using an attenuator probe, which increases the input impedance by some known factor, at the same time decreasing

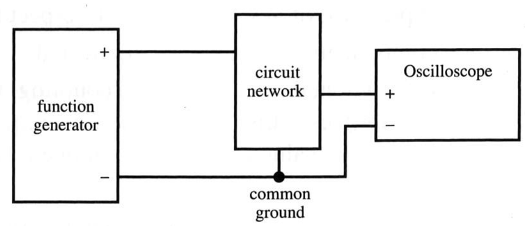


Figure 2.46 Common ground connection.

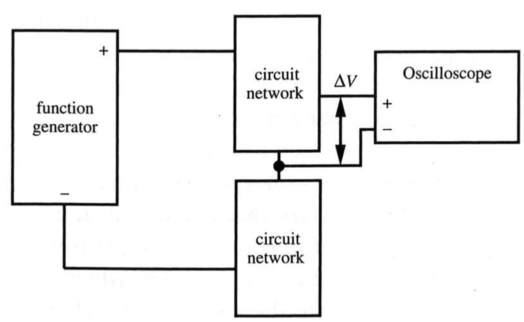


Figure 2.47 Relative ground connection.

the amplitude of the input signal by the same factor. Thus a 10X probe will increase the magnitude of the input impedance of the oscilloscope by a factor of 10, but the displayed voltage will be only 1/10 of the amplitude of the actual terminal voltage. Most oscilloscopes offer an alternative scale to be used with a 10X probe.

2.10.6 Grounding and Electrical Interference

It is important to provide a common ground defining a common voltage reference among all instruments and power sources used in a circuit or system. As illustrated in Figure 2.48, many power supplies have both a positive DC output (+ output) and a negative DC output (− output). These outputs produce both positive and negative voltages referenced to a common ground, usually labeled COM. On other instruments and circuits that may be connected to the power supply, all input and output voltages must be referenced to the same common ground. It is wise to double-check the integrity of each signal ground connection when assembling a group of devices.

It is important not to confuse the signal ground with the chassis ground. The **chassis ground** is internally connected to the ground wire on the power cord and may not be connected to the signal ground (COM). The chassis ground is attached to the metal case enclosing an instrument to provide user safety if there is an internal fault in the instrument (see Section 2.10.7).

Figure 2.49 illustrates an interference problem where high-frequency electrical **noise** can be induced in a signal by magnetic induction in the measurement leads. The area circumscribed by the leads encloses external magnetic fields from any AC magnetic sources in the environment, such as AC power lines or electric machinery. This would result in an undesirable magnetically induced AC voltage, as a result of Faraday's law of induction, given by

$$V_{noise} = A \cdot \frac{dB}{dt} \qquad (2.79)$$

where A is the area enclosed by the leads and B is the external magnetic field. The measured voltage differs from the actual value according to

$$V_{measured} = V_{actual} + V_{noise} \qquad (2.80)$$

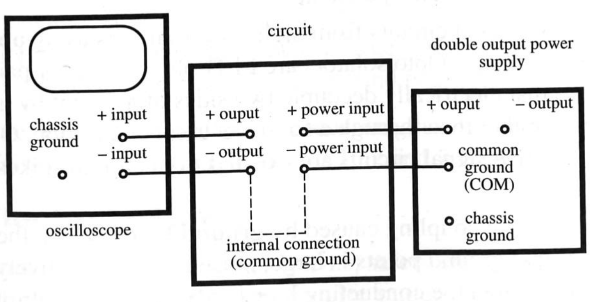


Figure 2.48 Common ground.

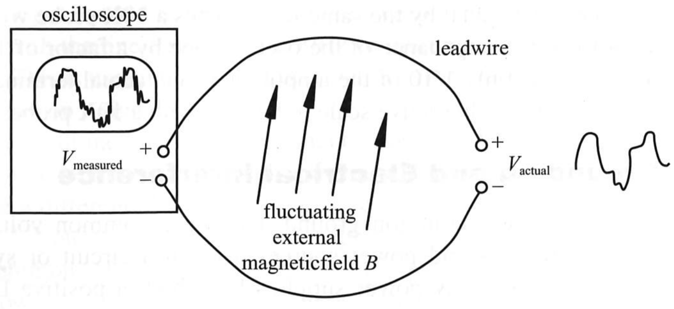


Figure 2.49 Inductive coupling.

■ **CLASS DISCUSSION ITEM 2.10**
Automotive Circuits

Often, electrical components in an automobile such as the alternator or starter motor are grounded to the frame. Explain how this results in an electrical circuit.

Many types of **electromagnetic interference** (EMI) can reduce the effectiveness and reliability of a circuit or system. Also, poorly designed connections within a circuit can cause noise and unwanted signals. These effects can be mitigated using a number of standard methods. The first approach is to eliminate or move the source of the interference, if possible. The source may be a switch, motor, or AC power line in close proximity to the circuit. It may be possible to remove, relocate, shield, or improve grounding of the interference source. However, this is not usually possible, and standard methods to reduce external EMI or internal coupling may be applied. Some standard methods are

- Eliminate potential differences caused by **multiple point grounding.** A common ground bus (large conductor, plate, or solder plane) should have a resistance small enough that voltage drops between grounding points are negligibly small. Also, make the multiple point connections close to ensure that each ground point is at approximately the same potential.
- Isolate sensitive signal circuits from high-power circuits using **optoisolators** or transformer couplings. Optoisolators are LED-phototransistor pairs (described in Chapter 3) that electrically decouple two sides of a circuit by transmitting a signal as light rather than through a solid electrical connection. One advantage is that the sensitive signal circuits are isolated from current spikes in the high-power circuit.
- Eliminate inductive coupling caused by **ground loops.** When the distance between multiple ground points is large, noise can be inductively coupled to the circuit through the conducting loops created by the multiple ground

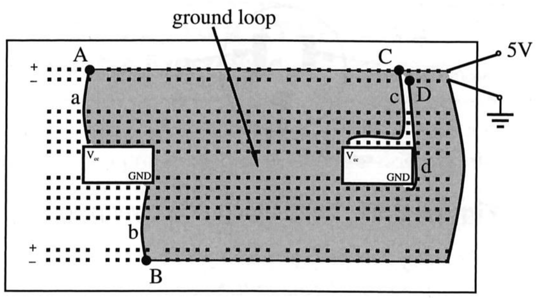


Figure 2.50 Ground loop.

points. Figure 2.50 illustrates how you should be careful to not create large ground loops when wiring a circuit on a breadboard. Both circuits shown are providing power (5V and ground) to an integrated circuit. The wiring on the left, connected at points *A* and *B* via wires *a* and *b* creates a large ground loop area which can pick up induced voltages in the presence of fluctuating magnetic fields, as described above. The wiring on the right, connected to points *C* and *D* via wires *c* and *d* creates very little area in the resulting circuit; therefore, very little induced voltage will occur even in the presence of external fields.

- Shield sensitive circuits with earth-grounded metal covers to block external electric and magnetic fields.
- Use short leads in connecting all circuits to reduce capacitive and inductive coupling between leads.
- Use "**decoupling**" or "**bypass**" **capacitors** (e.g., 0.1 μF) between the power and ground pins of integrated circuits to provide a short circuit for high-frequency noise.
- Use coaxial cable or twisted pair cable for high-frequency signal lines to minimize the effects of external magnetic fields.
- Use multiple-conductor shielded cable instead of ribbon cable for signal lines in the presence of power circuits (where large currents produce large magnetic fields) to help maintain signal integrity.
- If printed circuit boards are being designed, ensure that adequate **ground planes** are provided. A ground plane is a large surface conductor that minimizes potential differences among ground points.

Much more information and advice concerning how to prototype circuits properly and carefully can be found in Sections 2.10.2 and 7.10.4.

2.10.7 Electrical Safety

When using and designing electrical systems, safety should always be a concern. In the United States, electrical codes require outlets with three terminals: hot,

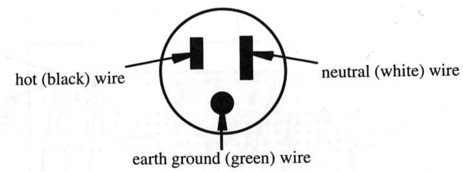
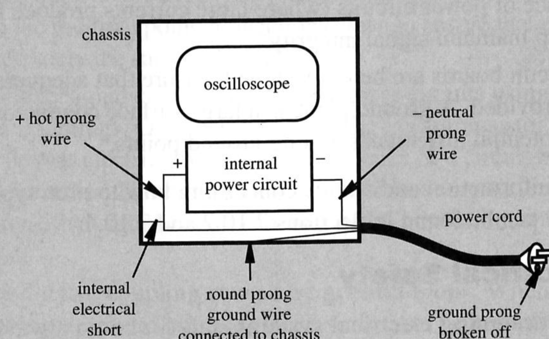


Figure 2.51 Three-prong AC power plug.

neutral, and ground. Figure 2.51 illustrates the prongs on a plug that is inserted into an outlet. The wires in the plug cable include a black wire connected to the hot prong, a white wire connected to the neutral prong, and a bare or green wire connected to the ground prong. The two flat prongs (hot and neutral) of a plug complete the active circuit, allowing alternating current to flow from the wall outlet through an electrical device. The round ground prong is connected only to the chassis of the device and not to the power circuit ground in the device. The chassis ground provides an alternative path to earth ground, reducing the danger to a person who may contact the chassis when there is a fault in the power circuit. Without a separation between chassis and power ground, a high voltage can exist on the chassis, creating a safety hazard for the user because he or she can complete a path to ground. Removing the ground prong or using a three-prong-to-two-prong adapter carelessly creates a hazard (see v Discussion Items 2.11 and 2.12).

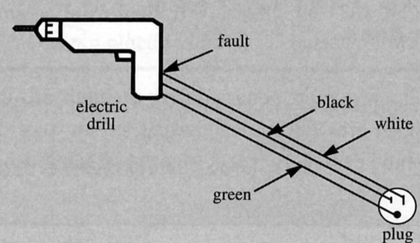
■ CLASS DISCUSSION ITEM 2.11
Safe Grounding

Consider the following oscilloscope whose power cord ground prong has been broken so that the chassis is not connected to ground. If you use this instrument, describe the possible danger you face.



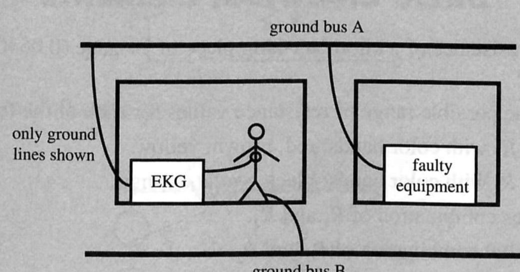
■ CLASS DISCUSSION ITEM 2.12
Electric Drill Bathtub Experience

The following electric drill runs on household power and has a metal housing. You use a three-prong-to-two-prong adapter to plug the drill into the wall socket. You are standing in a wet bathtub drilling a hole in the wall. You are unaware that the black wire's insulation has worn thin and the bare copper black wire is contacting the metal housing of the drill. How have you created a lethal situation for yourself? How could it have been prevented or mitigated?



■ CLASS DISCUSSION ITEM 2.13
Dangerous EKG

A cardiac patient is lying in his hospital bed with electrocardiograph (EKG) leads attached to his chest to monitor his cardiac rhythm. An electrical short occurs in the next room, and our patient experiences a cardiac arrest. You and the hospital facilities engineer have determined that there were multiple grounding points in the patient's room (see the illustration), and a fault in electrical equipment in the next room caused current to flow in the ground wire from the piece of the equipment. You are on the scene to determine if there could have been a lethal current through the patient. Consider the fact that ground lines have finite resistance per unit length and that a few microamps through the heart can cause ventricular fibrillation (a fatal malfunction).



■ CLASS DISCUSSION ITEM 2.14
High-Voltage Measurement Pose

When performing a high-voltage test, a creative electrical technician claims that standing on your right foot and using your right hand to hold the probe is the safest posture for making the measurement. What possible logic could support this claim?

■ CLASS DISCUSSION ITEM 2.15
Lightning Storm Pose

A park ranger at Rocky Mountain National Park recommends that if your hair rises when hiking in an open area during a lightning storm, it is imperative to crouch down low to the ground keeping your feet together. Explain why this might be life-saving advice.

Video Demo

2.15 Human circuit toy ball

2.16 Squirrel zapped by power lines

2.17 Stupid man zapped by power lines

Electricity passing through a person can cause discomfort, injury, and even death. The human body, electrically speaking, is roughly composed of a low-resistance core (on the order of 500 Ω across the abdomen) surrounded by high-resistance skin (on the order of 10 kΩ through the skin when dry). When the skin is wet, its resistance drops dramatically. Currents through the body below 1 mA are usually not perceived. Currents as low as 10 mA can cause tingling and muscle contractions. Currents through the thorax as low as 100 mA can affect normal heart rhythm. Currents above 5 A can cause tissue burning. Video Demo 2.15 shows an electronic toy that illustrates how current can flow through human skin. In this case a person's hand is being used to complete a circuit to control a blinking LED. Video Demos 2.16 and 2.17 graphically illustrate what can happen to animals and humans when they are not carefui around high-voltage lines.

QUESTIONS AND EXERCISES

Section 2.2 Basic Electrical Elements

2.1. What is the resistance of a kilometer-long piece of 14-gage (0.06408 inch diameter) copper wire?

2.2. Determine the possible range of resistance values for each of the following:

a. Resistor R_1 with color bands: red, brown, yellow.

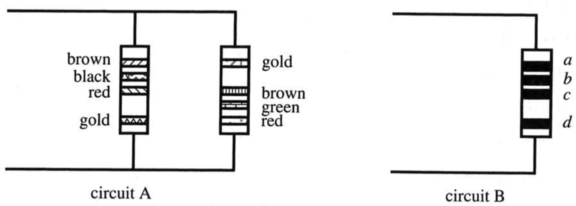
b. Resistor R_2 with color bands: black, violet, orange.

c. The series combination of R_1 and R_2.

d. The parallel combination of R_1 and R_2.

Note: the color bands are listed in order, starting with the first.

2.3. What colors should bands a, b, c, and d be for the following circuit B to have the equivalent resistance of circuit A?



2.4. When using a trim pot in a circuit, it is usually placed in series with another fixed value resistor. Why is it not placed in parallel instead? Support your conclusions with analysis.

2.5. Document a complete and thorough answer to Class Discussion Item 2.1.

Section 2.3 Kirchhoff's Laws

2.6. Does it matter in which direction you assume the current flows when applying Kirchhoff's laws to a circuit? Why?

2.7. You quickly need a 50 Ω resistor but have a store of only 100 Ω resistors. What can you do?

2.8. Using Ohm's law, KVL, and KCL, derive an expression for the equivalent resistance of three parallel resistors (R_1, R_2, and R_3).

2.9. Derive current division formulas, similar to Equation 2.38, for three resistors in parallel.

2.10. Given two resistors R_1 and R_2, where R_1 is much greater than R_2, prove that the parallel combination is approximately equal to R_2.

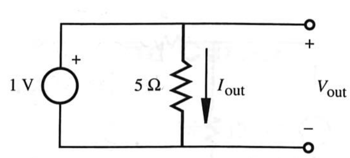
2.11. Derive an expression for the equivalent capacitance of two capacitors attached in series.

2.12. Derive an expression for the equivalent capacitance of two capacitors attached in parallel.

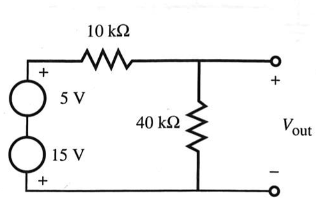
2.13. Derive an expression for the equivalent inductance of two inductors attached in series.

2.14. Derive an expression for the equivalent inductance of two inductors attached in parallel.

2.15. Find I_{out} and V_{out} in the following circuit:



2.16. Find V_{out} in the following circuit:



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2.17. For the circuit in Question 2.27, with $R_1 = 1\ \text{k}\Omega$, $R_2 = 2\ \text{k}\Omega$, $R_3 = 3\ \text{k}\Omega$, and $V_{in} = 5$ V, find

a. the current through R_1

b. the current through R_3

c. the voltage across R_2

2.18. For the circuit in Example 2.4, find

a. the current through R_4

b. the voltage across R_5

You can use results from the example to help with your calculations.

2.19. Given the following circuit with $R_1 = 1\ \text{k}\Omega$, $R_2 = 2\ \text{k}\Omega$, $R_3 = 3\ \text{k}\Omega$, $R_4 = 4\ \text{k}\Omega$, $R_5 = 1\ \text{k}\Omega$, and $V_s = 10$ V, determine

a. the total equivalent resistance seen by V_s

b. the voltage at node A

c. the current through resistor R_5

2.20. Given the following circuit with $R_1 = 2\ \text{k}\Omega$, $R_2 = 4\ \text{k}\Omega$, $R_3 = 5\ \text{k}\Omega$, $R_4 = 3\ \text{k}\Omega$, $R_5 = 1\ \text{k}\Omega$, and $V_s = 10$ V, determine

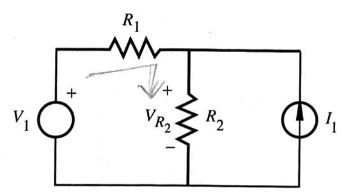
a. the total equivalent resistance seen by V_s

b. the voltage at node A

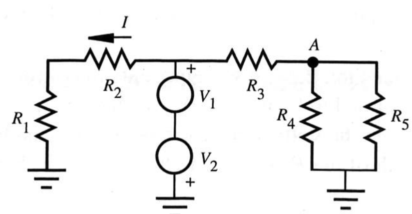
c. the current through resistor R_5

Also, how is this circuit different from the circuit in Question 2.19? If the resistance values were the same, would the circuits be identical? If not, what parts are different?

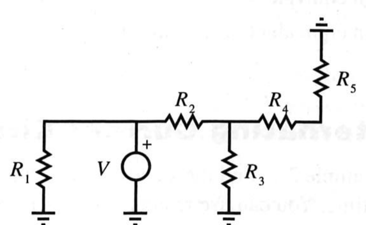
2.21. For the following circuit with $V_1 = 1$ V, $I_1 = 1$ A, $R_1 = 10\ \Omega$, and $R_2 = 100\ \Omega$, what is V_{R_2}?



2.22. For the following circuit with $R_1 = 1$ kΩ, $R_2 = 9$ kΩ, $R_3 = 10$ kΩ, $R_4 = 1$ kΩ, $R_5 = 1$ kΩ, $V_1 = 5$ V, and $V_2 = 10$ V, find I and the voltage at node A.



2.23. Find the equivalent resistance of the circuit below, as seen by voltage source V. Use the following values for the resistors: $R_1 = 1$ kΩ, $R_2 = 2$ kΩ, $R_3 = 3$ kΩ, $R_4 = 4$ kΩ, and $R_5 = 5$ kΩ.



2.24. Solve for I_{out} and V_{out} in Example 2.4 by writing and solving KVL and KCL equations for all loops and nodes in the original circuit.

Section 2.4 Voltage and Current Sources and Meters

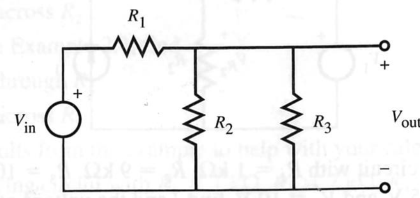
2.25. What is the output impedance of your laboratory DC power supply? What is the input impedance of your laboratory oscilloscope when DC coupled?

2.26. Explain why measuring voltages with an oscilloscope across impedances on the order of 1 MΩ may result in significant errors. Document your conclusions with analysis.

2.27. For the following circuit, what is V_{out} in terms of V_{in} for

a. $R_1 = 50\ \Omega$, $R_2 = 10\ k\Omega$, $R_3 = 1.0\ M\Omega$?

b. $R_1 = 50\ \Omega$, $R_2 = 500\ k\Omega$, $R_3 = 1.0\ M\Omega$?



If R_3 represents the input impedance associated with a device measuring the voltage across R_2, what conclusions can you make about the two voltage measurements?

2.28. For the circuit in Question 2.27, if R_1 represents the output impedance of a voltage source and R_3 is assumed to be infinite (representing an ideal voltmeter), what effect does R_1 have on the voltage measurement being made? Also, what would the effect be for each of the R_2 values in Question 2.27? Please comment on the results.

Section 2.5 Thevenin and Norton Equivalent Circuits

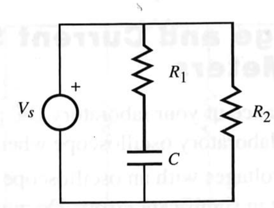
2.29. What is the Thevenin equivalent of your laboratory DC power supply?

2.30. What is the Thevenin equivalent of the circuit in Question 2.27 for the resistance values in part "a?"

Section 2.6 Alternating Current Circuit Analysis

2.31. For the circuit in Example 2.7, find the steady state voltage across the capacitor as a function of time. You can use results from the example to help with your calculations.

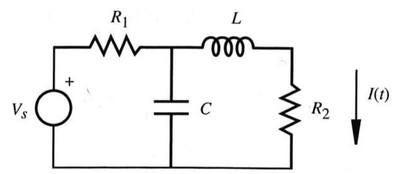
2.32. For the following circuit, what are the steady state voltages across R_1, R_2, and C, if $V_s = 10$ V DC, $R_1 = 1\ k\Omega$, $R_2 = 1\ k\Omega$, and $C = 0.01\ \mu F$?



2.33. Find the steady state current $I(t)$ in the following circuit, where $R_1 = R_2 = 100\ k\Omega$, $C = 1\ \mu F$, and $L = 20$ H for

a. $V_s = 5$ V DC

b. $V_s = 5\cos(\pi t)$ V



2.34. For each of these waveforms, what is the frequency in Hz and in rad/sec, the peak-to-peak amplitude, and the DC offset?

a. $2.0\sin(\pi t)$

b. $10.0 + \cos(2\pi t)$

c. $3.0\sin(2\pi t + \pi)$

d. $\sin(\pi) + \cos(\pi)$

Section 2.7 Power in Electrical Circuits

2.35. If 100 volts rms is applied across a 100 Ω power resistor, what is the power dissipated in watts?

2.36. If 100 volts peak-to-peak is applied across a 100 Ω power resistor, what is the power dissipated in watts?

2.37. If standard U.S. household voltage is 120 volts rms, what is the peak voltage that would be observed on an oscilloscope?

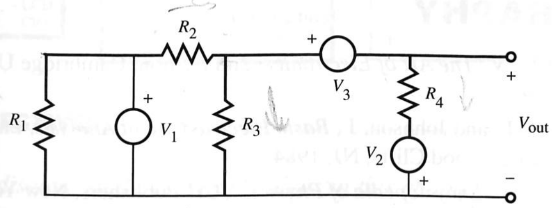
2.38. Write a function to represent a typical household voltage signal.

2.39. A circuit designer needs to choose an appropriate size resistor to be used in series with a light emitting diode (LED). The LED manufacturer claims that the LED requires 2 V to keep it on and 10 mA to generate bright light. Also, the current should not exceed 100 mA. Assuming that a 5 V source is being used to drive the LED circuit, what range of resistance values would be appropriate for the job? Also, what resistor power rating would be required?

2.40. For the following circuit with $R_1 = 1\text{ k}\Omega$, $R_2 = 2\text{ k}\Omega$, $R_3 = 3\text{ k}\Omega$, $R_4 = 4\text{ k}\Omega$, $V_1 = 10\text{ V}$, $V_2 = 5\text{ V}$, and $V_3 = 10\text{ V}$, find

a. V_{out}

b. the power produced by each voltage source



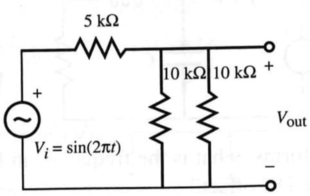
2.41. Solve the previous question with $R_3 = 2\text{ k}\Omega$ and $R_4 = 1\text{ k}\Omega$, keeping everything else the same.

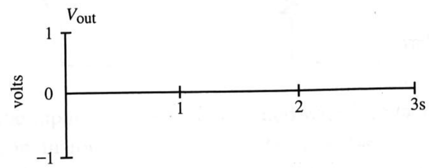
2.42. Prove Equation 2.66.

2.43. Derive the rms expressions in Equation 2.67 and show that Equation 2.68 is correct.

work this times in great detail in class

2.44. Sketch the output waveform for V_{out} in the following circuit on the axes as shown:





2.45. Document a complete and thorough answer to Class Discussion Item 2.6.

Section 2.8 Transformer

2.46. If you were to design a transformer for 24 V_{rms} low-voltage lighting in a new kitchen, what should the turns ratio of the primary to secondary windings be to provide a satisfactory voltage source?

Section 2.9 Impedance Matching

2.47. If your audio stereo amplifier has an output impedance of 8 Ω, what resistance should your speaker coils have to maximize the generated sound power?

Section 2.10 Grounding and Electrical Interference

2.48. When making high-frequency voltage measurements with an oscilloscope, why is it good practice to use BNC (coaxial) cable rather than two separate wires to the probe?

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