1 Resistors, Capacitors, and Voltage

Objectives

In this chapter you will learn:

• two definitions of electronics (and how to tell which one is intended)
• how to study electronics using the Learning Circuits
• the equipment you will need for the Learning Circuits
• the characteristics of two basic components used in most electronic equipment—the resistor and the capacitor

What Is Electronics?

The word electronics has two different, though closely related, meanings. This can be confusing, but you will find you can quite easily tell which meaning is intended. In the first definition, electronics is “the study of voltage and current waveforms that vary in time.” When this meaning is intended, the word electronics is singular, and in a sentence it is used with a singular verb. For example, one would say, “Electronics is the study of voltage and current waveforms.”
2 PRACTICAL ELECTRONICS

Electronics can also refer to electrical devices created to perform specific tasks, such as amplifying an electrical signal, sending or receiving radiation, or any one of hundreds of different functions. If this is the sense intended, the word electronics is plural and is followed by a plural verb. One would say something like, “The electronics onboard an airplane are very sophisticated.”

You will be able to tell whether electronics refers to the study or to the devices by observing the way the word is used in a sentence and the context in which it is used. In ordinary conversation, the second sense of the word is used most often. If you walk into almost any large department store, you will find a section of the store called electronics. It’s the section where you can buy DVDs, CD players, and so on. Clearly, the word refers to electronic devices. In this book, on the other hand, the word electronics refers most of the time to the study of voltage and current waveforms. That is why this section is called “What Is Electronics?” and not “What Are Electronics”!

The Learning Circuits

Throughout this book you will find experiments in electronics you can do yourself. They are called Learning Circuits, and they have been designed to give you a hands-on sense of the way electronic circuits work. A circuit is a group of interconnected electronic components. They perform such tasks as amplification, waveform generation, filtering, signal sensing, signal switching, logic, radiation, and electromagnetic field detection.

Don’t worry if you don’t know what these functions are. By the time you finish this book you will be familiar with all of them. They are the functions that make up radios, VCRs, stereo amplifiers, telephones, and all the other electronic devices we use. You will not be able to design these electronic products when you finish this book (that requires more advanced study), but you will have a much better appreciation of how they work, and you will be well prepared to take the next step toward learning to design them yourself.

In this chapter there are 8 Learning Circuits. These first experiments will show you different ways of connecting two basic electrical components: resistors and capacitors. Before you create your first cir-
cuit, however, you need some equipment and some understanding of how to use it.

First, you need some means of measuring and observing changing waveforms. The Learning Circuits include pictures of changing voltage waveforms you can expect to see, and equations describing them. Pictures and equations are helpful, of course, but there is no substitute for seeing the voltages in real time, and for this you need some equipment. The two main tools used in electronics to make observations are the waveform generator (also called a function generator or signal generator) and the oscilloscope.

So, should you dive in and immediately purchase these two pieces of equipment? That will be your decision, but be sure to read appendix I, “Preparing to Use the Learning Circuits,” first. As you’ll see, the equipment is costly. Before making the purchases, you might want to go through at least a chapter or two of this book, studying the Learning Circuits and the drawings that accompany them. You can certainly learn a great deal this way. Then, if you find you are still excited about electronics, you can look for some used equipment and start making your own observations.

For the first few Learning Circuits, you can use another piece of equipment called a multimeter. As the name implies, this is a multiuse measuring device that can function as a voltmeter, ohmmeter, or ammeter. Multimeters are not very expensive, and they can measure ac and dc volts, dc current, and resistance. What they cannot do is show waveforms—for that an oscilloscope is needed.

Circuits also need a source of power, but using utility power from a wall plug poses a safety hazard. To resolve this difficulty, all of the ac sources in the book make use of an ac adapter. An adapter is an Underwriter’s approved transformer that supplies a source of low-voltage ac power. (Underwriter’s Laboratory is a testing organization that approves electrical hardware for use by consumers.)

Connecting circuit components together requires some tinned bus wire, some insulated wire, some solder, and a soldering iron. Simple circuits can be connected using clip leads or test leads. A test lead is an insulated wire that has mechanical clips (alligator clips) on each end. In some circuits you can make a connection simply by twisting leads together. You can also purchase a circuit board that has a grid of holes so that tie pins can be pressed into the holes, and you can solder components to these pins. (Just be sure not to cut the leads short until you
are certain they are resting in their final location.) But when circuits become more complicated, soldering works best. You will find a step-by-step description of soldering in appendix 1.

You will also need some basic tools, which you may already own: a pair of needle-nosed pliers and wire cutters.

Finally, you will need a workstation to do the Learning Circuits, which does not need to be more than a few feet of counter space near a wall outlet. Ideally this should be a place where you can leave your equipment out and available while you experiment with the various Learning Circuits.

The Waveform Generator

A waveform (function) generator is a piece of electronic test equipment used to generate a repetitive changing voltage, or a voltage waveform that repeats itself over and over. The voltage waveforms that can be selected are sine, square, or triangle. The lowest settable frequency is often around 0.1 Hz (see chapter 8). The highest sine wave frequency is often 10 MHz. The voltage amplitude is often limited to 10 V peak or 20 V peak-to-peak.

Each of these waveforms has its own particular use. Sine waves are used to test the response of circuits. A sine wave is sinusoidal in character. A sine wave is often referred to as a sinusoid. See Figure 1.1. This waveform is used because the currents and voltages in a linear circuit are all sine waves. Square waves are valuable because they provide information about circuit behavior not easily seen with sine waves. A square wave voltage can transition symmetrically around 0 volts or transition from 0 to a peak voltage level once per cycle. The transition time or rise time should be short compared to the time of one cycle. This makes it difficult to generate a 2-MHz square wave, as the transition times should be around 5.0 ns. Shorter transition times raise the cost. Triangular waves are useful because the voltage slopes are constant. However, triangular waves are not generally used in testing. These three waveforms are shown in Figure 1.1. For more on these concepts, see chapter 8.

An output cable is usually supplied with the waveform generator (which can also be called a signal generator or a function generator). The cable can have alligator clips on the end so that it can be connected to various points in a circuit. The outer conductor of the cable is called the
zero reference conductor of the signal. It is also called a shield, a ground, or the common conductor. (The word ground is often used to mean “earth” but this is not always the intended meaning.) It connects to the ground or common of the circuit you are testing. In some generators this shield is connected to the safety or green wire of the power conductor. For most testing, you should remove this connection link or strap. The circuit you are testing may already be connected to ground. If this is the case, then two connections to ground can be troublesome. This can be checked by measuring a low resistance from the common output lead to the third pin on the power cord.

The Oscilloscope

An oscilloscope is a piece of electronic test equipment used to observe circuit behavior in real time. The oscilloscope generates a picture of the
changing signal patterns. All of the waveforms shown in the figures in this book can be observed in real life by applying a signal generator to a circuit and then observing the waveforms with an oscilloscope. The vertical scale on an oscilloscope displays voltage, and the horizontal axis displays time.

The operation of a basic oscilloscope is simple. A dot moves (transitions) linearly across a viewing screen from left to right. When it reaches the right edge of the screen it immediately returns to the left side. A single crossing is called a “sweep.” If the sweep frequency is set to 1 kHz, the dot moves across the screen in 1 millisecond (ms). In the first sweep, the time goes from 0 to 1 ms. The dot returns to the start and traces the same path for the second millisecond, and so on.

If the voltage probe is connected to a 1-kHz sine wave voltage, a single sine wave will be displayed on the screen. If the sine wave frequency is 2 kHz, then two full sine waves will be displayed. When the dot makes many sweeps per second, the screen pattern appears stationary.

You can observe the oscilloscope display in slow motion by observing a 1-Hz sine wave from a function generator, with the sweep frequency on the oscilloscope set to 1 Hz. At this slow rate you will be able to see the dot move across the screen, writing a sine wave pattern over and over. A sine wave voltage display is shown in Figure 1.2.

It is worthwhile spending a little time with the oscilloscope and the function generator before you get started on the Learning Circuits. I can’t tell you exactly how to work the controls, as there are many different designs. You will have to hook up the oscilloscope to the function generator and play with the dials until it becomes clear. Don’t worry, you can’t hurt yourself or the equipment, so go ahead and experiment.

Figure 1.2  A sine wave displayed on an oscilloscope
An oscilloscope has one or two input probes. The probe tip is designed to connect to points in a circuit. The grounding clip on the probe is usually connected to the zero reference or ground of the circuit. At its other end (inside the oscilloscope) the grounding clip connects to the oscilloscope frame and to the power safety or green wire (the third plug in a three-pronged electrical plug). This connection to ground is required by the National Electrical Code.

A problem arises when you have both an oscilloscope and a function generator (or in more complicated circuits, multiple devices) all connected to one circuit. If two or more devices are connected to the power safety, you have multiple grounds. This is not desirable. For this reason, when you do have several devices connected to your circuit, use a “cheater plug” (a two-pronged plug) for all but one of your devices. In the Learning Circuits you will be using an adapter plug, which provides an additional level of isolation and safety.

**Voltages**

Throughout this book, the figures generally include a reference to a voltage source. The voltage source can be either ac or dc (see chapter 8). Voltage may come from a waveform generator, a battery, or the power utility.

The symbol used for a voltage source is either the letter $V$ in a circle or the symbol for a battery. A lowercase $v$ refers to a changing voltage. The polarity (plus or minus) of a dc voltage will always be indicated.

We will assume that the voltage source can supply the current demanded by the circuit without changing voltage. This is referred to as an ideal voltage source. In actuality voltage does change with load, but assuming an ideal source simplifies the discussion.

If the voltage is a step function or square wave, it will be clearly stated in the text.

**Resistors and Capacitors**

We are now ready to begin using our first electronic components, resistors and capacitors. These two components are found in most electronic
equipment because they do very basic and important jobs needed in every circuit.

Resistors are the most common electrical component (see chapter 8). They are used to limit the flow of current in a circuit. By comparison a conductor offers very little opposition to current flow. There are many types and sizes of resistors. In electronics, resistors are apt to be small cylinders that are about a half-inch long. This is the circuit symbol for a resistor:

\[ \text{Resistor Circuit Symbol} \]

Capacitors are the second most common component. Their basic function is to store electrical field energy. This field energy requires electric charge on the plates of the capacitor. (See chapter 8 for discussion of capacitors and electric charge.) The ratio of voltage to charge is called capacitance. Since it takes time to store energy, capacitors can be used to control frequency response, provide filtering action, provide timing, and store energy in power supplies. Capacitors are found in almost every circuit design. The circuit symbol for a capacitor is

\[ \text{Capacitor Circuit Symbol} \]

In the next sections we will be examining the way resistors and capacitors respond to various voltage waveforms. You will recall that a
waveform generator produces sine waves, square waves, and triangle waves. Sine wave voltages are the only waveform that keep the same shape in any combination of resistors and capacitors.

One way to study resistors and capacitors is to apply a “step function” to the circuit. A step function is a voltage that changes from one value to another. In many cases a low-frequency square wave can be used as a step function. Digital circuits make extensive use of square waves and step functions.

A common source of dc voltage is the battery. Batteries can be placed in series to increase the dc voltage. If two 9-V batteries are placed in series, the total voltage is 18 V. This series arrangement is shown in Figure 1.3.

If one of the batteries is reversed in polarity, the voltages subtract.

In practice, series batteries should be of the same type so that the batteries will last the same length of time.

Figure 1.3  Batteries in series
LEARNING CIRCUIT 1

Measuring Battery Voltages

You will need (in addition to your multimeter or oscilloscope):

2 9-V batteries

1. Set the multimeter to “volts” and to a scale appropriate (the voltage can be easily read on that range) for measuring 9 to 18 V (usually 25 V). Practice using the multimeter (which is now functioning as a voltmeter) by measuring the voltage of a battery. It should read 9 V.

2. Touch the batteries together in series, positive to negative, so the voltages add. Measure the total voltage. The reading should be 18 V.

3. Tie the common voltmeter lead to the connection between the two batteries. Note that the ends of the batteries are at +9 V and −9 V.

4. Do the same measurements using the oscilloscope. Note the trace moves across at different levels.

When batteries are placed in series, any one of the battery terminals can be called 0 V. If the midpoint or jumper between the two series 9-V batteries is called 0 V, then the other two terminals are at −9 V and +9 V. The potential difference between the outer terminals is 18 V.

Batteries may be placed in parallel provided their voltages are equal. Connect the plus terminals together and connect the minus terminals together. The resulting voltage is the same as one of the batteries, but the current capability is increased. A problem with this arrangement is that if one of the batteries becomes weak, the strong battery will drain into the weak battery.

AC voltage sources can be placed in series if they are voltages on separate windings or coils of a transformer. (Refer to chapter 8.) The voltages must be in phase (peak at the same time) if the voltages are to add. The coils of the transformer should have nearly the same dc resistance for this to be practical. In utility power generation, ac sources (generators) are placed in parallel on the power grid. Placing a power generator on line requires skill and a complex procedure.
When resistors are placed in series, their resistances add. If three 10-ohm resistors are placed in series, the total series resistance is 30 ohms. To calculate the total resistance, the units of resistance must agree. From this point on we will use the Greek letter $\Omega$ to mean ohm.

Consider a 300-$\Omega$ resistor in series with a 2-k$\Omega$ resistor. The 200 $\Omega$ must be expressed as k$\Omega$ or the 2 k$\Omega$ must be expressed as ohms. The answer is 2 k$\Omega$ + 0.3 k$\Omega$ = 2.3 k$\Omega$. The other solution is 2,000 $\Omega$ + 300 $\Omega$ = 2,300 $\Omega$.

The conductance of a resistor is the reciprocal of its resistance. You
calculate the resistance of parallel resistors by adding their conductances, and then taking the reciprocal of the total. Figure 1.5 shows two parallel resistors. A 10-Ω resistor has a conductance of 0.1 S, where S stands for sieman (a unit of conductance.) Consider a 5-Ω and a 2-Ω resistor in parallel. The conductances are 0.2 S and 0.5 S. The total conductance is 0.7 S. The total resistance is \( \frac{1}{0.7} \Omega = 1.429 \Omega \). This circuit is shown in Figure 1.6.

The equation relating the conductances of three parallel resistors is

\[
\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad (1.1)
\]

where \( R_T \) is the total resistance and \( R_1, R_2, \) and \( R_3 \) are the resistances of the three parallel resistors. This idea can be extended to any number of resistors.

When the resistors are in units of kΩ or MΩ, a convenient technique is to treat the values as if they were all ohms and at the end of the calcu-

The letter representing a resistor is usually a capital \( R \).

The unit of resistance is the ohm, abbreviated by the Greek letter \( \Omega \).

200 ohms can be written 200 Ω.

200 ohms can be written 0.2 kΩ where k stands for 1,000.

The parallel resistance of these two resistors is 181.81 Ω.

**Figure 1.5** Resistors in parallel
The 5-Ω resistor has a conductance of 0.2 sieman. The abbreviation for sieman is S. The 2-Ω resistor has a conductance of 0.5 S. The conductances add together and equal 0.7 S. The resistance is the reciprocal of the conductance, or 1.429 Ω. The voltage $V$ can be from a battery or a signal from a generator.

**Figure 1.6** A circuit with two parallel resistors

The answer is $6.66 \, \Omega$. With the correct units the answer is $6.66 \, \text{M} \Omega$.

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**LEARNING CIRCUIT 2**

**Combining Resistors in Series and Parallel**

You will need (in addition to your multimeter or oscilloscope):

- 3 1,000-Ω resistors

Set your multimeter to ohms $\times$ 1,000 (it is now functioning as an ohmmeter). Measure the resistances of two 1,000-Ω resistors in series and parallel combinations. Do the same thing using three resistors. How many combinations of series and parallel can you make with three resistors? See Figure 1.7.
The resistors in series provide a 3,000-Ω resistor from A to B.

This arrangement provides a resistance of 1,500 Ω from A to B.

These parallel resistors provide a resistance of 333.3 Ω from A to B.

**Figure 1.7** The three ways three 1,000-Ω resistors can be arranged
Voltages Applied to Resistors

When a voltage is placed across a resistor, a current flows in a loop formed by the voltage source and the resistor. This circuit is shown in Figure 1.8.

The current in the loop is given by Ohm’s law. By convention, the direction of the current is out of the positive terminal of the battery. The current level for a 6-V battery and a 1,000-Ω resistor is 6 mA. The power dissipated in the resistor is given by $V^2/R$. (See chapter 8 for discussion of these concepts.) To use this equation, the voltage must be expressed in volts and the resistor in ohms. The power is $36/1,000$ W or $36$ mW. If the voltage were 6 V ac, the answer would be the same.

Standard carbon resistors are commercially available that cover the range $10$ Ω to $22$ MΩ. These resistors are available in $1/4$-W, $1/2$-W, 1-W, and 2-W sizes. It is good practice to avoid using resistors at more than one-half their wattage rating. In most circuit applications it is convenient to use resistors of one wattage size, as $1/2$-W size is a typical power level. This means many resistors are rated higher than they need to be. The standard resistor values, with accuracy to within 20% of the stated value, in the range from 10 to 100 Ω are 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, and 82 Ω. These same multiples are available in every decade. For example, resistors are available at 22, 220, 2.2 k, 22 k, 220 k, 2.2 M and 22 MΩ. Resistors with accuracy to within 10% and 5% of their stated value are also available.

The value of a carbon resistor is noted in a rather esoteric way, by bands of color that encircle each end of the resistor. At one end of the
resistor, only silver and gold are used. Gold indicates that the resistor’s accuracy is to within 5% of the stated value and silver indicates 10%. No color on this end indicates accuracy to within 20%.

On the other end of the resistor, 10 different colors plus gold and silver are used, in three bands. The first two bands indicate numeric values and the third band indicates the number of added zeros. The numeric meaning of each color is listed in the following table. Note that gold and silver on this end have different meanings than they have on the other end.

<table>
<thead>
<tr>
<th>Color</th>
<th>Numeric Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0</td>
</tr>
<tr>
<td>Brown</td>
<td>1</td>
</tr>
<tr>
<td>Red</td>
<td>2</td>
</tr>
<tr>
<td>Orange</td>
<td>3</td>
</tr>
<tr>
<td>Yellow</td>
<td>4</td>
</tr>
<tr>
<td>Green</td>
<td>5</td>
</tr>
<tr>
<td>Blue</td>
<td>6</td>
</tr>
<tr>
<td>Violet</td>
<td>7</td>
</tr>
<tr>
<td>Grey</td>
<td>8</td>
</tr>
<tr>
<td>White</td>
<td>9</td>
</tr>
<tr>
<td>Gold</td>
<td>Divide by 10</td>
</tr>
<tr>
<td>Silver</td>
<td>Divide by 100</td>
</tr>
</tbody>
</table>

A resistor with bands of brown, black, and brown reads 100 Ω. The first brown is 1, the black band is 0, and the second brown indicates one added 0. The resistor with bands of brown, green, and green indicates 1,500,000 Ω. The brown is 1, the first green is 5, and the last green says that you add five zeros. Bands of green, blue, and gold indicate 5.6 ohms. Green is 5, blue is 6, and the gold says you divide by 10.

Another way resistors are made is by depositing a thin film of metal on a cylinder. A spiral is then cut into the surface of the cylinder. This cut defines the resistance—the closer together the spiral, the more resistance. These resistors are accurate to within 1% or 2%, and are more stable than carbon resistors.

For critical applications, precision wire-wound resistors are available with accuracies better than 0.1%. Metal film resistors are often coded by a stamped number. The last digit indicates the number of zeros.

If you have any doubt as to the value of a resistor, use your ohmmeter to verify the value.

Note that when you use your fingers to clamp the leads of the ohmmeter to the resistors, your fingers become part of the circuit. The resistance between your fingers can be as low as 10,000 Ω. The resistance depends on the individual, the surface area, the finger pressure, and the moisture and oils in the skin. For resistors over 1,000 Ω hold the ohmmeter by the plastic handles, and keep your fingers out of the circuit. When measuring a resistor, your fingers should not provide a parallel path for current flow, or the answer will be incorrect.
In many mass-produced products such as TV sets, the resistors are extremely small, have no leads, and are soldered directly onto the circuit board. At the other end of the spectrum, there are very large resistors that can dissipate 5, 10, or even 100 W. These resistors are made using a resistive alloy wire wound on a ceramic core.

The current that flows in an ideal resistor depends only on the instantaneous voltage. If the voltage is a sine wave, a step function, or a square wave, the current waveform is exactly the same. When the resistor value is very large or very small, there are exceptions to this statement. Resistors with low resistance values are influenced by their series inductance, and resistors with high resistance values are influenced by a shunt parasitic capacitance. These effects are important at high frequencies. For the circuits we will discuss in this book, these effects can be ignored.

The Voltage Divider

Two resistors in series across a voltage source form a voltage divider. This voltage divider circuit is shown in Figure 1.9.

One side of the voltage source is usually called the reference conductor or zero of potential. The voltage at the junction between the two resistors is a fraction of the total voltage. The purpose of the voltage divider is to produce this reduced potential. The ratio of voltage drops is equal to the ratio of resistance values. The sum of the two voltage drops is equal to the source voltage. In Figure 1.9 the negative side of the voltage source is the reference conductor. If the resistors are equal, the attenuation factor is 2. The current in this circuit is the voltage divided by the sum of the resistors, or \( I = \frac{V}{(R_1 + R_2)} \). The voltage across the first resistor is this resistance times the current, or \( V_1 = I \times R_1 = \frac{V \times R_1}{(R_1 + R_2)} \). The voltage across the second resistor is given by \( V_2 = \frac{V \times R_2}{(R_1 + R_2)} \). For example, if \( R_1 = 2 \, \text{k}\Omega \) and \( R_2 = 8 \, \text{k}\Omega \), their sum is 10 k\( \Omega \). If the voltage is 10 V, the current is 1 mA. The voltage across the 2-k\( \Omega \) resistor is \( I \times R_2 \), or 2 V. If the negative terminal of the battery is at 0 V, then the connection between the two resistors is +2 V. If the positive terminal of the battery is at 0 V, then the junction between the resistors is at −8 V.
For sine wave voltages or dc voltages, the power dissipated in each resistor can be calculated three different ways (see chapter 8). The voltage times the current, or $V \times I$, is the simplest way. The other two ways are $I^2R$ and $V^2/R$. The units must be in ohms, amperes, and volts to get an answer in watts. Using the equation $P = V \times I$, the power dissipated in $R_1$ is $2 \times 0.001 = 2 \text{ mW}$.

Sometimes it is necessary to select two resistors to obtain a required attenuation factor. The easiest way to solve this problem is to decide on a current level. The resistor values are simply the voltages divided by the current. For example, if 20 V is to be attenuated to 5 V, select a current of 1 mA. The resistor with 5 V is $5/0.001 = 5 \text{ k}\Omega$. The other resistor has 15 V across its terminals, so the resistor is $15/0.001 = 15 \text{ k}\Omega$.

If $R_1 = R_2$, then the voltage $V$ is 5 V. The voltage $V$ is always less than 10 V. The two resistors are often called a voltage divider.

**Figure 1.9** A voltage divider
When current is taken from a practical voltage source, the voltage drops. This is the result of current flowing in an internal resistance. An internal resistor and an external load resistor form a voltage divider (attenuator). The circuit is shown in Figure 1.10.

Internal resistance of any circuit at the point of interest is the ratio of voltage change to current change.

One approach to determining the internal resistance (also called the internal impedance) of a circuit is to add a load resistor and note the voltage change. The voltage before the load is applied is called the open circuit voltage. The change in voltage, or voltage difference, is the open circuit voltage minus the voltage when current is flowing. The change in current is the loaded voltage divided by the load resistance. The ratio of these two numbers is the internal resistance.

For example, assume the open circuit utility power is 120 V at 60 Hz. A 12-Ω load resistor drops the voltage to 119 V. The voltage difference is 1.0 V. The current is $\frac{119}{12} = 9.917$ A. The internal resistance
is $1/9.917 = 0.1008 \, \Omega$. The internal resistance of an ideal voltage source is zero. (Warning: Do not attempt to make this measurement on an open power connection. There is a good chance of electrical shock.)

It is sometimes useful to measure source resistance by using two different load resistors. For example, if the current varies from 15 to 35 mA and the output voltage varies from 9 to 8.98 V, the source impedance is $0.02 \, \text{V} / 0.02 \, \text{A} = 1 \, \Omega$.

The idea of source resistance can be extended to include inductance and capacitance. The term source resistance then becomes source impedance. The expression output impedance means the same thing. Impedance only has meaning for sine wave voltages and currents. The expression “output impedance” is in common use, but the value usually refers to a resistance.

The voltage divider in Figure 1.9 has an equivalent source resistance (series resistance) that can be determined by the ratio of open circuit
voltage to short circuit current. This is known as Thevenin’s theorem. The open circuit voltage is $V_O = \frac{V R_1}{R_1 + R_2}$. The short circuit current is $I_{SC} = \frac{V}{R_2}$. The ratio of $V_O/I_{SC} = R_1 R_2 (R_1 + R_2)$. This is the resistance of the two resistors in parallel, or the source resistance. In order to lower the source resistance, more current must flow in the divider. If both resistors are one-half of their first value, the source resistance would be one-half of its previous value. For example, consider a 20-V source where $R_1$ and $R_2$ are both $10 \, k\Omega$. The equivalent circuit is a 10-V source in series with 5 $k\Omega$. If $R_1$ and $R_2$ are each 5 $k\Omega$, the source impedance is 2.5 $k\Omega$.

Thevenin’s theorem can be very impractical. A short circuit on the utility power line to measure source impedance would blow the breaker.

### The Current Divider

When a voltage is applied across two parallel resistors as in Figure 1.11, the current in each resistor follows Ohm’s law.

The total current can be calculated two ways. The first way is find the current in each resistor and then add the values together. The second way is to compute the parallel resistance and then calculate the current. If the resistors are 2.5 $k\Omega$ and 5 $k\Omega$ and the voltage is 25 V, the currents are 10 mA and 5 mA. The total current is 15 mA. Using the second
The current splits so that a portion flows in each resistor. The current flowing in each resistor is given by Ohm's law. If there were three resistors, the current would split three ways.

Figure 1.11  Parallel resistors across a voltage source

Switches provide a mechanical means of making or breaking one or more electrical connections. The moving part of a switch is called a pole. A pole can make one or more connections in the throw of a lever or the rotation of a shaft. The abbreviation for pole is the letter $p$. If the pole makes one connection when the switch lever is thrown, the switch is called single-pole single throw, or SPST. A pole that transfers between two connections is called an SPDT, or single-pole double throw.

Switches are available with several poles, with connected or disconnected center positions and with spring returns. Size, style, current rat-
ing, and mounting arrangements are also variables. There are thousands of combinations available for the electronics designer. A few common switch arrangements are shown in Figure 1.12.

**Capacitors**

When capacitors are placed in parallel, the capacitances add. Capacitances must be expressed in the same units for addition. For example, a 0.001 µF capacitor is in parallel with 500 pF. The problem requires that the 500 pF capacitance be expressed in µF. This is 0.0005 µF. The total capacitance is 0.0015 µF.

Capacitors in series add like parallel resistors. The sum of the reciprocal capacitances is equal to the total reciprocal capacitance. For
example, consider a 0.2 µF in series with 0.4 µF. \( \frac{1}{0.2} + \frac{1}{0.4} = \frac{3}{0.4} \). The total capacitance is the reciprocal, or \( \frac{0.4}{3} = 0.133 \) µF. Again, to do a calculation all capacitances must use the same unit.

When a steady current (dc) flows into a capacitor, the voltage rises linearly. As an example, if a dc current of 1.0 mA flows into a capacitor for 1 ms, the charge is \( I \times t \) (see chapter 8, Equation 8.4). \( Q = 0.001 \times 0.001 = 10^{-6} \) coulombs. This much charge on 0.1 µF is a voltage \( V = \frac{Q}{C} = \frac{10^{-6}}{10^{-7}} = 10 \) V. The voltage rises linearly from 0 to 10 V in 1 ms.

A steady rise in voltage in a capacitor can be demonstrated using a square wave voltage and an oscilloscope. Consider the circuit in Figure 1.13.

The square wave voltage is set to 10 V peak. A 100-kΩ resistor connects the square wave voltage to a 0.1 µF capacitor. If the voltage on the capacitor never rises to more than 0.1 V, the current is essentially constant at 0.1 mA. The maximum charge \( Q \) is \( CV = 10^{-7} \times 0.01 = 10^{-9} \) C. This charge equals \( I \times t \) where \( I \) is \( 10^{-4} \) A. Solving for \( t \) yields \( 10^{-5} \) seconds. The square wave must stay positive for \( 10^{-5} \) seconds and return to 0 for another \( 10^{-5} \) seconds. This is a frequency of 50 kHz. The waveform across the capacitor will be a triangle wave, a voltage that rises and falls in a linear manner. This voltage can easily be seen on the screen of the oscilloscope.

### LEARNING CIRCUIT 5

**Observing Current Flow in a Capacitor**

You will need (in addition to your oscilloscope and function generator):

1. 1 100-kΩ and 1 50-kΩ resistor (use two parallel 100-kΩ resistors)
2. 2 0.1-µF capacitors

Connect a 0.1-µF capacitor and a 100-kΩ resistor to a square wave generator as shown in Figure 1.13. Set the frequency to 50 kHz and the amplitude to 10 V. Use the oscilloscope to observe and note the triangle wave across the capacitor.

Reduce the resistor to 50 kΩ and note that the amplitude of the triangle wave doubles. Now double the capacitance and note that the voltage returns to the first level.
Circuit to supply current to a capacitor

\[ V' = \text{square wave at } 50 \text{ kHz} \]
\[ 20 \text{ V peak-to-peak} \]

0.1 \( \mu \)F capacitor
100 k\( \Omega \) resistor

The voltage across the capacitor is a triangle wave.

The square wave is not shown to scale. It is shown to illustrate the timing.

The current supplied to the capacitor is constant in both directions. During the time the current flows in one direction, the voltage changes linearly.

**Figure 1.13** The voltage across the terminals of a capacitor when supplied a constant current for short periods of time
The RC Time Constant

When a dc voltage is switched on to a series resistor-capacitor (RC) circuit, the voltage across the capacitor rises as shown in Figure 1.14.

The voltage curve is called an exponential curve. At the moment of switch closure, the full voltage appears across the resistor. This means

![Diagram showing an exponential curve and a circuit diagram with a resistor and capacitor connected in series.]

\[ t = RC \]

The rise in capacitor voltage can be observed on a voltmeter.

**Figure 1.14** A circuit showing the rise of voltage in a series RC circuit
the initial current flow is $V/R$. As the capacitor receives charge, the voltage across the capacitor increases, taking away voltage from the resistor. At any moment in time the voltage across the resistor plus the voltage across the capacitor must equal the impressed voltage $V$. After a period of time, most of the voltage appears across the capacitor and there is very little current flow. The time it takes to reach 63% of final value is given by the product $RC$ where $R$ is in ohms and $C$ is in farads. This is called the RC time constant.

To show that $RC$ has units of time, we can use the following definitions. $R = V/I =$ volts/ampere and $C = Q/V =$ coulombs/volts. But coulombs = amperes $\times$ time. Therefore $RC = (\text{volts/ampere}) \times (\text{ampere/volt}) \times \text{time}$. As you can see, the volts and amperes cancel, leaving the unit of time.

---

**LEARNING CIRCUIT 6**

**Observing the RC Time Constant**

You will need (in addition to your multimeter or oscilloscope):

1. 9-V battery
2. 1 MΩ resistor
3. 1 µF capacitor
4. 1 SPDT switch

Construct the circuit shown in Figure 1.15. Select $C = 1 \mu F$ and $R = 1 \mathrm{M}\Omega$. The value of the time constant is $10^{-6} \times 10^6 = 1$ second. This rise in voltage is slow enough that it can be observed on a voltmeter. If a square wave generator is used as the voltage source, the rise time can easily be seen. Set the sweep frequency on the oscilloscope to 1 Hz. Set the square wave frequency to 1 Hz. Observe the time it takes the voltage to reach 7 V.

When a capacitor is discharged through a resistor, the falling voltage also follows an exponential curve. In this case the voltage falls to 37% in 1 time constant or 1 second. You can see this on the second half of the square wave cycle.
The idea of a time constant can be applied a second or even a third time to the same circuit. In the previous example the voltage falls to 37% in 1 time constant (10 seconds). The voltage will fall to 37% of 37% in 2 time constants (20 seconds). This is a value of about 13%. In 3 time constants or 30 seconds the value is about 5%.

The Impedance of a Resistor and a Capacitor in Series

When a sinusoidal voltage is applied to a series RC circuit (shown in Figure 1.17), the current that flows is sinusoidal. The voltage across the resistor peaks at the same time the current peaks. The voltage across the capacitor lags the current by 90°. Since the peaks of voltage do not occur at the same time, the voltages cannot simply add together. In Figure 1.16 the three voltages are represented by rotating pointers (see chapter 8).

Each pointer makes a counterclockwise rotation once per cycle. The height of the pointers above the horizontal axis represents the instantaneous voltages. The length of the pointer is the peak value of voltage. When the voltage across the resistor is maximum, the voltage...
across the capacitor is 0. When the pointer for the resistor voltage points straight up, the pointer for the capacitor voltage points to the right.

To solve for the impedance in this circuit, it is convenient to assume a current $I$. The peak voltage across the resistor is $IR$. The peak voltage across the capacitor is $IX_C$ where $X_C$ is the reactance of the capacitor (see chapter 8). To find the total voltage $V$ applied to the circuit, form a rectangle using the voltages across the resistor and capacitor as sides. The peak voltage $V$ is the length of the diagonal of this rectangle. The

![Diagram](image)

At time $= 0$ the voltage across the resistor is zero and the voltage across the capacitor is maximum.

The pointers rotate once per cycle.

![Diagram](image)

The three sine wave voltages displayed in time.

**Figure 1.16** The rotating pointers for a series RC circuit
length of this diagonal is the input voltage \( V = \sqrt{(IX_C^2 + IR^2)} \). The ratio of peak voltage to peak current is

\[
V/I = Z_{RC} = \sqrt{(X_C^2 + R^2)}
\]  

(1.2)

This ratio is the impedance of a series resistor and capacitor. If the reactance \( X_C \) of the capacitor is 300 \( \Omega \) and the resistor \( R = 400 \Omega \), the series impedance is 500 \( \Omega \).

The angles between the various pointers in Figure 1.16 are called phase angles. Sine waves that peak at different times are shifted in phase. To discuss phase relationships, the voltages must be sine waves at the same frequency. The current in a capacitor is always shifted 90° from the voltage across the capacitor. The current is said to lead the voltage. The voltage across a resistor is always in phase with the current. There is no phase shift in a resistor.

**The RC Low-Pass Filter**

A low-pass filter is a circuit that attenuates high-frequency sine waves and passes low-frequency sine waves. This filter might be used to limit high-frequency interference or reduce the high-frequency amplitude response of a voice amplifier. A first-order low-pass filter using an RC circuit is shown in Figure 1.17. This is exactly the same circuit we used to discuss the RC time constant in the previous section. This time our analysis involves sine wave voltages and not a step function.

The current flowing in the RC circuit is \( I = V_{IN}/Z_{RC} \). The output voltage is \( V_O =IX_C = V_{IN}X_C/Z_{RC} \). The ratio of output voltage to input voltage is

\[
V_O/V_{IN} = X_C/Z_{RC}
\]  

(1.3)

A low-pass filter is a voltage divider that changes the attenuated voltage depending on frequency. The ratio of output voltage to input voltage is called gain or attenuation factor. In this RC filter the gain is always less than 1.

To understand Equation 1.2 in more detail, let’s look at the extremes of frequency. As the frequency rises, \( X_C \) gets smaller and \( Z_{RC} \) reaches a limiting value of \( R \). At high frequencies the gain (attenuation) approaches \( 1/2\pi fR \). This means that the amplitude response falls off
inversely proportional to frequency. If \( f \) doubles, the amplitude is half its previous value.

At low frequencies \( X_C \) is large compared to \( R \). At the same time, \( Z_{RC} \) also gets greater. At low frequencies, \( Z_{RC} \) very nearly equals \( X_C \) and the gain ratio \( X_C/Z_{RC} \) approaches 1. This means there is little attenuation at lower frequencies. The frequency where \( X_C = R \) holds a special significance. The gain at this frequency is 0.707. This is called the –3 dB (dB stands for decibel) frequency or cutoff frequency of the filter (see chapter 8).
The amplitude response of this filter as a function of frequency is given in Figure 1.18.

The amplitude response has been normalized so that the $-3$-dB point is at a frequency of 1 Hz. To find a resistor and capacitor value for a specific cutoff frequency $f$, first select a resistor value like 10 kΩ. If the cutoff frequency is 15 kHz (see chapter 8), then we can find $C$ from the

![Amplitude response to sine waves for a first-order low-pass filter](image1)

![Phase shift of a first-order low-pass RC filter](image2)

**Figure 1.18** The amplitude and phase response of a first-order low-pass RC filter
In this example, \( \frac{1}{6.28 f C} = R = 10,000 \). Solving for \( C \), we obtain

\[
C = \frac{1}{6.28 \times 15,000 \times 10,000} = 0.0011 \mu F.
\]

The response curve in Figure 1.17 is still applicable. Simply multiply the horizontal scale by 15 kHz.

The phase shift through this normalized RC filter starts off near 0 degrees at frequencies well below 1 Hz. This is because the reactance of the capacitor is much higher than the resistor and the capacitor performs like an open circuit. Well above the cutoff frequency, the capacitor acts like a short circuit and the current is limited by the resistor. This means that the current is nearly in phase with the source voltage. The voltage across the capacitor lags this current by 90°. At frequencies well above the cutoff frequency, the phase angle between the input and the output voltages approaches 90° lagging. At the cutoff frequency, the phase shift is 45°. The phase shift for this first-order filter is shown in Figure 1.18.

There is a close relationship between phase shift and attenuation slope. In this RC filter, the amplitude falls off proportional to frequency above the cutoff frequency. If two RC circuits were to contribute to the attenuation, the amplitude would fall off proportional to frequency.
squared. In this situation the phase shift would double. In general, phase shift is closely related (proportional) to the attenuation slope.

The RC High-Pass Filter

When the roles of the resistor and capacitor are reversed in Figure 1.17, the output voltage is sensed across the resistor. The frequency and phase response are mirror images of the low-pass filter. This filter attenuates low frequencies and passes high frequencies. The circuit and the amplitude and phase response are shown in Figure 1.19.

The square wave response of a first-order high-pass filter is shown in Figure 1.20.

The voltage across the resistor plus the voltage across the capacitor must equal the square wave voltage. In other words, the two top curves in Figure 1.20 add up to a square wave. The leading edge of the square wave comes through immediately in a high-pass filter. The output voltage falls as the capacitor charges up. After the leading edge is coupled, the voltage waveform follows an exponential curve. The voltage drops to 37% of initial value in 1 time constant equal to the product $RC$.

A high-pass filter can be used to block an average offset voltage. The filter allows changing voltages to pass. An application of this filter might be to reduce the bass or low-frequency response in an audio amplifier. It might be used to pass a high-frequency carrier signal and reject an audio signal.

**LEARNING CIRCUIT 8**

**Constructing and Observing a High-Pass Filter**

Use the low-pass filter you constructed in Learning Circuit 7, but reverse the positions of the resistor and the capacitor. Find the amplitude response at the same frequencies. At what frequency does the amplitude reach 0.707 V? Observe the square wave response at 2 kHz.
A normalized phase response for a first-order high-pass filter

Figure 1.19  The amplitude and phase response of a normalized first-order RC high-pass filter
SELF-TEST

1. The terminals of the six individual cells of a 12-V battery are exposed. All the cells are in series. If the negative terminal is labeled 0 V, what are the voltages at the other cell terminals? What happens if the positive terminal is labeled 0 V?

2. Two 9-V batteries are placed in series. If the connecting point is 0 V, what are the other two voltages?

3. What is the maximum potential difference in problem 2?

4. Three resistors are in series. Their resistances are $910 \, \Omega$, $2.2 \, k\Omega$, and $3.3 \, k\Omega$. What is the total resistance?

5. Two resistors are in parallel. Their resistances are $1 \, k\Omega$ and $10 \, k\Omega$. What is the total resistance?
6. Two resistors 510 kΩ and 1.2 MΩ are in parallel. What is the parallel resistance in units of kΩs and MΩs? (Hint: First rewrite the resistor values using the same units.)

7. A 10-kΩ resistor measures 5% high or 10.5 kΩ. Show that a parallel resistor of 220 kΩ will reduce the resistor value to near 10 kΩ. What is the remaining error expressed as a percentage of 10 kΩ?

8. 20 V dc is placed across a 10-Ω resistor. What is the current? What is the power dissipated? What is the current direction?

9. In problem 8, what happens if the battery is reversed in direction?

10. 100 V ac is placed across a 2-kΩ resistor. What is the current? What is the power dissipation?

11. 10 V is placed across a resistor of 0.1 Ω. What is the current? What is the power dissipation?

12. 500 Ω and 1,000 Ω are in series across a 15-V battery. What is the current in the resistors?

13. In problem 12 the 500-Ω resistor connects to the negative terminal of the battery. If the negative terminal of the battery is at 0 V, what is the voltage at the junction between the two resistors?

14. In problem 13, if the positive terminal of the battery is at 0 V, what is the voltage at the junction between the two resistors?

15. Solve problem 13 if the resistor values are doubled.

16. A 12-V battery is loaded with a 1.2-Ω load resistor. The voltage drops to 11.92 V. What is the source resistance?

17. A 15-V dc power supply has a voltage divider consisting of three 2-kΩ resistors. What are the voltages at the two junctions? What is the source resistance at these two points?

18. Use the circuit of Figure 1.9. If R₁ is 300 Ω and R₂ is 100 Ω and the voltage is 10 V, what is the voltage at the junction of the two resistors?

19. The voltage in Figure 1.9 is 20 V. If the attenuated voltage is 6 V, what are the two resistor values if the current drawn is 1 mA? What are the resistor values if the current drawn is 5 mA?
20. A 9-V battery drops to 8.8 V when a 100-mA load is applied. What is the internal resistance?

21. A 12-V battery supplies three lamps in parallel. The lamps have resistances of 2 Ω, 3 Ω, and 5 Ω. What is the total current? Note: The filaments of a lamp are made from tungsten. The cold resistance of the filament is much lower than the hot resistance. This problem assumes that the given resistance values occur when the lamps are illuminated.

22. What is the total capacitance when 0.01 µF is paralleled with 0.1 µF?

23. What is the total capacitance when 330 pF is paralleled with 0.002 µF?

24. What is the total capacitance when 0.001 µF is in series with 500 pF?

25. A capacitor of 2 µF has a voltage of 15 V. What is the charge stored?

26. In problem 25 a current of 2 mA flows for 1 ms. What is the charge?

27. A capacitor of 0.001 µF is charged for 10 µs with a current of 20 mA. What is the voltage on the capacitor?

28. What is the time constant when the resistor is 100 kΩ and the capacitor is 0.01 µF? How long are 2 time constants?

29. What resistor forms a 0.1-second time constant with a 0.05 µF capacitor?

30. An RC circuit reaches 95% of final value in 0.1 second. What is the RC time constant?

31. An RC low-pass filter has a cutoff frequency of 20 kHz. If R = 10 kΩ, what is C?

32. In problem 31, what is the attenuation of a 1-MHz signal?

33. A designer wants to use a 0.01-µF capacitor for an RC low-pass filter at 20 kHz. What resistor value must he use?

34. A high-pass filter has a cutoff frequency of 10 kHz. The R is 100 kΩ. What is the capacitor value?

35. A high-pass filter is formed using 0.01 µF and 150 kΩ. A step voltage of 10 V is applied. How much time elapses before the voltage drops to 3.7 V?
36. In problem 35, how much time is required before the voltage drops to 0.5 V?

37. A high-pass filter has a cutoff frequency of 10 Hz. If the resistor is doubled in value, what change in capacitor value must be made to maintain the same cutoff frequency?

**ANSWERS**

1. The voltages are 2, 4, 6, 8, 10, and 12 V. If the positive terminal is 0, the voltages are −2, −4, −6, −8, −10, and −12 V.

2. The voltages are +9 V and −9 V.

3. 18 V.

4. 7,410 Ω.

5. 909 Ω.

6. 353 kΩ or 0.353 MΩ.

7. The resistor is corrected to 9.976 kΩ. The error is 0.024 kΩ or 0.24%.

8. The current is 2 A. The power is 40 W. The current flows from plus to minus.

9. The current flows in the opposite direction.

10. The current is 50 mA. The power is 5 W.

11. 100 A. 1 kW.

12. 10 mA.

13. 5 V.

14. −10 V.

15. −10 V.

16. The voltage changed 0.08 V. The current changed 9.93 A. The source impedance is 0.008 Ω.

17. The voltages are 5 V and 10 V. The source impedance in both cases is 2 kΩ in parallel with 4 kΩ. This is 1.33 kΩ.
18. 2.5 V.
19. 6 kΩ and 14 kΩ. 1.2 kΩ and 2.8 kΩ.
20. 2 Ω.
21. 1.2 A.
22. 0.11 µF.
23. 0.00233 µF.
24. 333 pF.
25. \( Q = CV = 2 \times 10^{-6} \times 15 = 30 \text{ microcoulombs.} \)
26. \( Q = I \times t = 0.002 \times 0.001 = 2 \mu C. \)
27. \( Q = I \times t = 0.02 \times 10^{-5} = 0.2 \mu C. \ V = Q/C = 0.2 \mu C/0.001 \mu F = 200 \text{ V.} \)
28. \( 10^{-8} \times 10^3 = 10^{-5} \text{ sec. Two time constants = 2 ms.} \)
29. \( RC = 0.1. \ R = 0.1/5 \times 10^{-8} = 2 \text{ MΩ.} \)
30. Three time constants = 0.1 second. One time constant equals 0.03 seconds.
31. 10 kΩ = \( 1/2\pi fC = 1/2\pi \times 20,000 \times C. \ C = 796 \text{ pF.} \)
32. The ratio of frequencies is 50:1. The attenuation factor is approximately 50.
33. \( R = 1/2\pi fC. \ R = 1/6.28 \times 20,000 \times 10^{-8}. \ R = 796 \Omega. \)
34. 100 kΩ = \( 1/6.28 \times 10,000 \times C. \ C = 159 \text{ pF.} \)
35. \( RC = 10^{-8} \times 150,000 = 1.5 \text{ ms.} \)
36. Three time constants or 4.5 ms.
37. The reactance must also double. This means the capacitance is half the value.