

Resistors and Voltage Dividers

Resistors are frequently used components in electronic circuits. Their most frequent application is to control current flow and to adjust the available level of voltage so that it matches the requirements of other components of the circuit. It is important to understand the advantages and limitations of the various types of resistors. It is also important to be able to determine resistor specifications for a specific application. Electronic devices are supplied with dc power at a specified voltage. One very important use of resistors is to reduce that voltage to lower levels at specific points in the circuit. Resistors used for this application are called voltage dividers. This Tech Note will discuss the different types of resistors, specifications for resistors, how to obtain the values required for an application, and how to specify the resistor values in a voltage divider to obtain the voltage desired.

Characteristics of a Resistor: A resistor is a passive linear device that provides opposition to the flow of electrical charge. Current is the rate of flow of electrical charge and when current flows through a resistor a voltage develops across the resistor according to Ohm's law. (An exception is super-conductivity where below a critical temperature the resistance drops to zero for some materials.) The level of voltage drop for a set value of resistance depends upon the level of current. If several resistors are connected in series, the voltage drop across each resistor is determined by the ratio of the value of that resistor to the total of all of the resistors connected in series. The level of voltage across a resistor may change as the current changes, but the ratio of the voltage drop across each resistor will remain constant as illustrated in Figure 511.1.

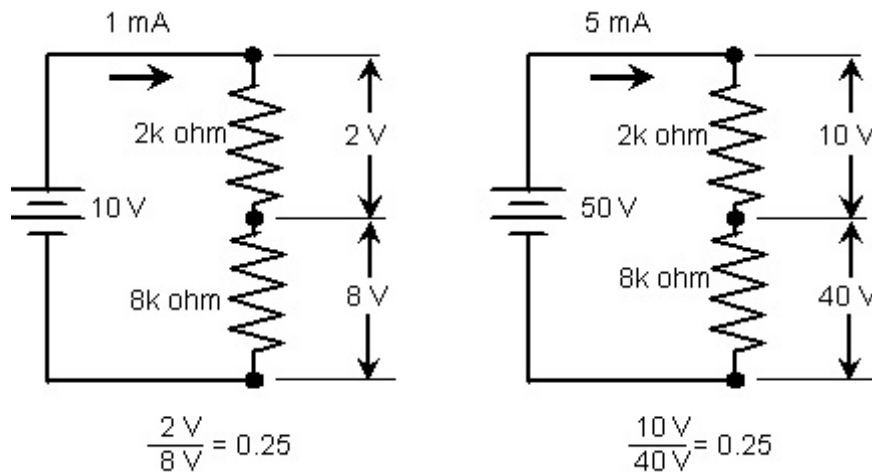


Figure 511.1 For constant values of resistors, the ratio of voltage across each resistor will remain constant even when the circuit supply voltage changes.

The standard symbol for a resistor is a zig-zag line as shown in Figure 511.1, and the unit of measure of resistance is the Ohm. Rather than writing out the word Ohm after a number the Greek letter omega (Ω) has been adopted as a replacement for the word Ohm such as 1k ohm. The quantities in Ohm's law are Volts (energy per unit charge), Amperes for current (flow rate of charge per second), and Ohms for resistance. It is important to note that for a resistor the voltage drop develops instantly when current flows and returns immediately to zero when current flow is interrupted. This is illustrated in Figure 511.2. Two other devices that offer resistance to the flow of electricity, capacitors and inductors, do not exhibit this same characteristic. Those devices store charge or energy and there is a time variable involved. Resistors do not store charge or energy.

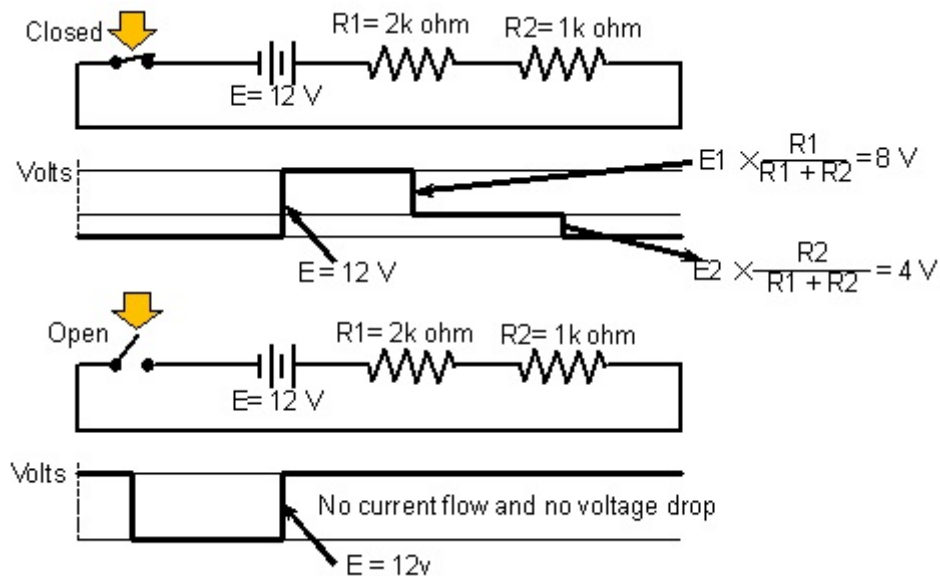


Figure 511.2 Resistors are passive linear devices that offer opposition to the flow of charge and for a series circuit the voltage drop across each resistor is in proportion to the value of the resistor to the total resistance of the circuit.

Another electrical principle at work when current flows through a resistor is the power formula. Heat is generated as current experiences resistance. The amount of heat produced is in proportion to the product of the current, voltage, and time in seconds. One Joule of heat is produced in a resistor if one ampere flows for one second through a resistor and produces a one volt drop across the resistor. One Joule of heat is also produced by a resistor when in one second 50 milliamperes (mA) of current results in a 20 volt drop across the resistor. Rather than knowing the total heat produced by a resistor over time, it is generally more practical to know the rate of heat produced. Energy per unit time is power, and for electrical circuits the unit of power is the Watt. One Watt is one Joule produced per second. In addition to a resistance rating in Ohms, a resistor will have a maximum wattage rating. In general this wattage rating should not be exceeded. Power expended in a dc circuit or electrical component is equal to the product of the voltage and current, Equation 511.1. Ohm's law can be substituted into the power formula to produce several important relationships. The power expended by a resistor is equal to the value of the resistor in Ohms times the square of the current flowing through the resistor (Equation 511.2). The power expended by a resistor is also equal to the square of the voltage drop across the resistor divided by the value of the resistor in Ohms (Equation 511.3). If the value of the resistor in Ohms and the power rating are known, the maximum current rating of the resistor and the maximum voltage drop permitted across the resistor can also be determined by rearranging these formulas Equation 511.4 and Equation 511.5).

$$P = E \times I \quad \text{Equation 511.1}$$

$$P = I^2 \times R \quad \text{Equation 511.2}$$

$$P = \frac{E^2}{R} \quad \text{Equation 511.3}$$

$$I = \sqrt{P/R} \quad \text{Equation 511.4}$$

$$E = \sqrt{P \times R} \quad \text{Equation 511.5}$$

Resistor Types: Several methods are used to construct resistors. The most common type of resistor used in electronic circuits consists of a small cylinder of carbon material. Powdered carbon is held together by a binding material and the value of the resistor depends upon the physical size and the ratio of carbon to binding material. **Carbon** resistors are rugged, inexpensive, and small. Their wattage rating is limited, generally not exceeding two watts. Common ratings are 1/10, 1/8, 1/4, 1/2, 1, and 2 watts. The wattage rating generally determines the physical size not the resistance rating. Most are too small to have the resistance value printed on the resistor, therefore, a color code is used to designate the resistance value. This will be discussed later in this Tech Note. As good as the manufacturing process may be, there will be variability in the values of resistors. The highest quality carbon resistors generally have a tolerance (accuracy) of no better than plus or minus five percent. Tolerance is also indicated on the resistor with a color band. If there is no tolerance indicated for a carbon resistor, the tolerance is plus or minus 20%. This means a 1k Ω carbon resistor may have a value as small as 800 ohm or as high as 1200 ohm. Resistors with very low tolerance values are available, but they are expensive. The value of a resistor will also change as the temperature of the resistor changes with the value increasing as the temperature increases.

Another way to make a resistor is to wind fine wire with a precise resistance around an insulating form such as a cylinder, then encasing the resistor in a nonconductive material that will dissipate the heat produced. This is known as a **wire wound** resistor. These resistors can be manufactured to a much lower tolerance. These resistors can have high wattage ratings. The physical size is larger than the carbon resistor and often the resistance value, wattage, and tolerance are printed on the resistor. These resistors are particularly well suited for applications where high wattage ratings are required. Because these resistors are actually a coil of wire they can take on the characteristics of an inductor (choke coil) if the current flowing through them is at a high frequency.

There is a type of resistor known as a **ribbon** or **film** type where a resistive material in the form of a thin ribbon or film is applied to an insulating form such as a cylinder. These resistors can have high power ratings, low tolerance, and minimal change of value with change of temperature while being more suitable for high frequency applications than the wire wound resistor. One type is made of a material called cermet which is a powdered metal mixed with glass or ceramic in a ratio that will yield the resistance value desired. The resistive element is applied to the insulating base cylinder as a paste then fired in a kiln to obtain the final product. The other type applies a spiral ribbon of vapor to the insulating base material to lay down the resistive element as a thin film. This film can be a carbon material or a metal type material. Resistors can also be made of a **conductive plastic**. This type is sometimes used for variable resistance applications where the value of resistance is adjusted frequently. Carbon power is generally mixed with a plastic resin to obtain the resistance characteristics desired.

Another way to classify resistors is by their function in a circuit. For the multitude of applications only a fixed resistance value is required and this uses a **fixed** resistor where the value is considered to be constant. One use of a resistor is as a voltage divider. This concept will be

discussed later in this Tech Note. A simple voltage divider is two resistors connected in series with a wire connected to the point where the two resistors join. This is illustrated in Figure 511.3. A voltage divider can be made using two resistors with the resistance values properly chosen or it can be done with one resistor with a tap made at the desired point. This is called a **tapped** resistor. The disadvantage is that the tap point cannot be adjusted. A slight modification of the tapped resistor is the **adjustable** resistor. The tap can be moved to the precise point for the application. This resistor is suited for applications where an adjustment is required after installation. Tools are generally required to make the adjustment of resistance.

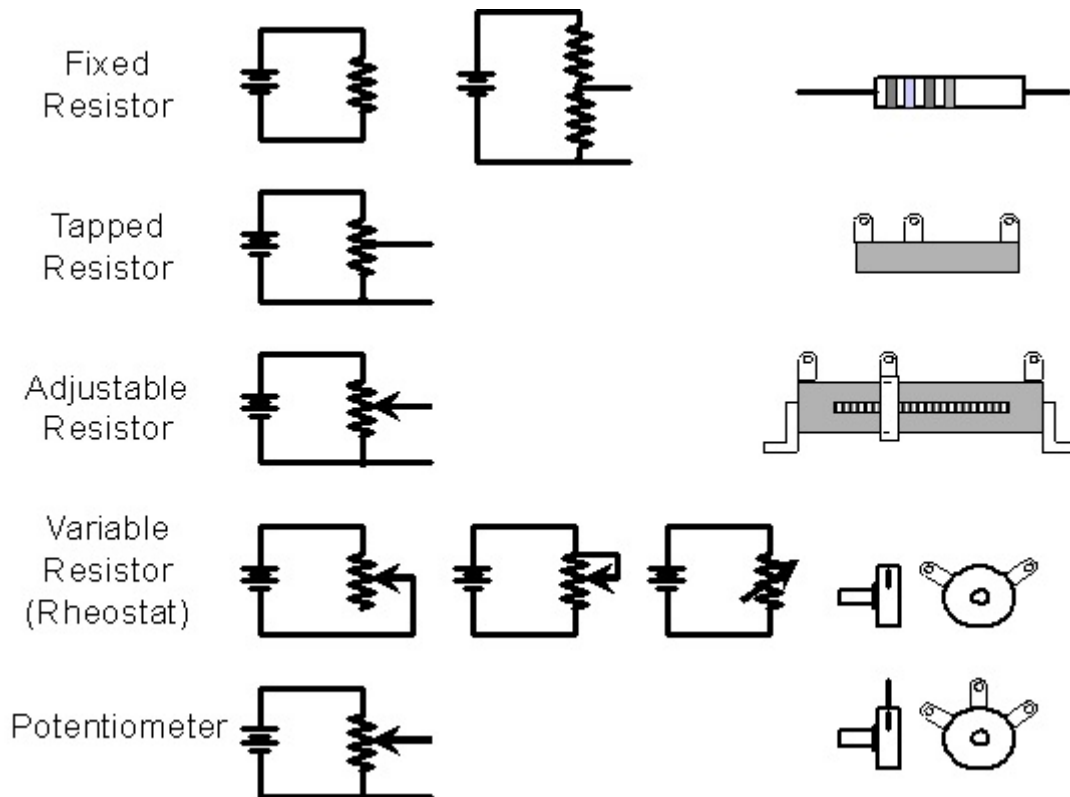


Figure 511.3 Symbols for different classifications of resistors are shown in typical dc circuits.

A **variable** resistor is one where the value can generally be easily changed. The adjustment may be as simple as turning a knob to using a tool to turn the adjustment. Another name sometimes used for this type is **rheostat**. The name rheostat is often associated with power applications where the name variable resistor is generally used for electronic circuit applications. A variable resistor or rheostat usually has only two terminals. This can be confused with another variable resistor with three or more terminals called a potentiometer. The symbols used in a circuit (shown in Figure 511.3) are different, but their physical looks may be similar. Potentiometers are used as voltage dividers where the voltage on the adjustable terminal can be easily changed by the turning of a knob. Some potentiometers do not have a knob and require a tool to make the adjustment. Note the similarity of schematic symbol for an adjustable resistor and a potentiometer. Adjustable resistors are generally used for power applications or where infrequent adjustments are required. The change of resistance for a potentiometer may be linear were a given number of degrees of turning result in a fixed incremental change in resistance. A potentiometer may be

exponential where the incremental change in resistance increases or decreases for a given incremental turning of the adjustment. Resistance range as well as precision of adjustment must also be considered for a potentiometer application.

Color Code: The value and tolerance of a resistor are frequently provided in the form of a color code. When a color code is used, there will be three color bands that give the value in Ohms and sometimes a fourth band that gives the tolerance. If the tolerance band is missing it is assumed that the tolerance is $\pm 20\%$. If the tolerance band is silver the tolerance is $\pm 10\%$. If the tolerance band is gold the tolerance is $\pm 5\%$. The position of the color bands is shown in Figure 511.4. The first band is the one closest to the end of the resistor. Gold or silver may be used in the third band, but their use in that band is quite rare. If used in the third band, gold is a multiplier of 0.1 and silver is a multiplier of 0.01.

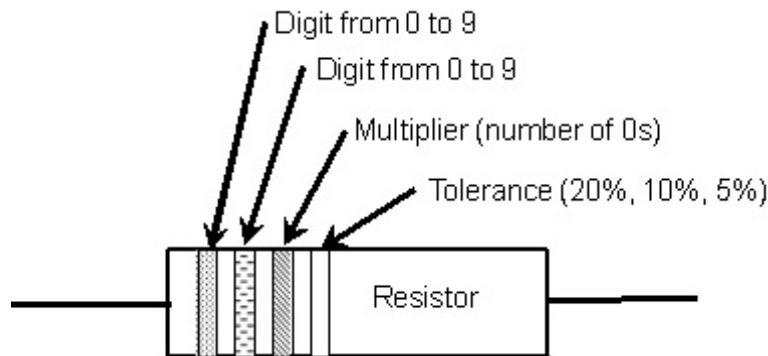


Figure 511.4 The value and tolerance of many resistors is provided in the form of color bands with the first two bands representing numbers and the third band giving the number of zeros (0) to place behind the first two numbers. The fourth color band, if present, gives the tolerance.

A person working with electronics needs to memorize the resistor color band numbering system. The numbers range from 0 to 9 and the multipliers range from no zeros to nine zeros added to the first two numbers. The trick is to memorize the colors and numbers in such a way that you will remember them after an extended period of time. One suggestion is to remember that the first two digits are black (0) and brown (1) and that the last two numbers are gray (8) and white (9). The colors between are the six colors of the rainbow; red (2), orange (3), yellow (4), green (5), blue (6), and violet (7). As an example determine the value of a resistor with the color bands blue, gray, orange. Blue is the number six (6) and gray is the number eight (8). Orange represents the number three (3), therefore, add three zeros to the first two numbers to get 68,000. For the next example determine the color bands to look for to find a 470 ohm resistor. The number four (4) is yellow, the number seven (7) is violet, and there is only one zero which is brown. The color bands will be yellow, violet, and brown. Here is a final example that can be somewhat tricky. What is the third color band of a 100,000 ohm resistor? Remember that the first two digits each have their own color band. The digit 1 is brown, and the digit 0 is black. With the left two digits eliminated there are four zeros remaining which is represented by the color yellow. The third color band is yellow and the color marking for this resistor is brown, black, yellow.

Carbon resistors are available in a wide variety of values, with more *standard values* available the lower the tolerance percentage. For 10% tolerance carbon resistors the common values are 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, and 82. These are the numbers of the first two color bands with higher values simply being times 10 multiples of these values. The number of zeros to add are indicated by the third color band.

Wattage and Current Ratings: All electrical components are only capable of dissipating the energy expended at a certain rate. As electrical current flows through a resistor heat is produced which must be dissipated to the surrounding environment. Multiplying the power determined with either Equation 511.1, 511.2, or 511.3 by time in seconds gives the heat produced in Joules by a resistor. It is very easy to direct attention to the desired effect to be accomplished by a resistor in a circuit and forget to make sure the resistor wattage rating is not exceeded. For example, assume a component in a circuit is frequently energized at 6 volts for an extended periods of time. Also assume the current to the component needs to be in the range of 20 mA to a maximum of 30 mA. A standard 220 ohm resistor will limit the current to 27 mA ($6V/220\text{ ohm} = .0273\text{ A}$). The minimum wattage rating must also be determined using either of Equations 511.1, 511.2, or 511.3. For this example the minimum requirement is 0.16 watts. A resistor with at least a 1/4 watt rating is required.

Sometimes it is necessary to determine the maximum current that a particular resistor can handle, or the maximum voltage drop that can occur across the resistor. These values can be determined by using Equation 511.4 or Equation 511.5. For example the maximum current rating of a 1k ohm, 1/2 watt resistor can be determined using Equation 511.4 and is 22mA ($\sqrt{0.5W/1000} = 0.022A$)

Obtaining the desired resistance for a particular application may require combining more than one resistor in either series or in parallel. This may be required because the value needed is not available or because the wattage requirement for the application exceeds the wattage rating of the resistor available. Knowing the rules for combining resistors in series or in parallel is a useful tool. When resistors are connected in series so there is only one path for current flow, the total resistance is the sum of the values of the individual resistors (Equation 511.6). Since the same current flows through each resistor connected in series, the voltage drop across each resistor will be in proportion to the value of each resistor. In Figure 511.5 two 150 Ohm resistors are connected in series with a total resistance of 300 Ohm. Using Ohm's law, the voltage across each resistor is the product of the value of the resistor and the current through the resistor. For the case of the series resistors of Figure 511.5, there is a 5 volt drop across each resistor which adds up to a total of 10 volts across both resistors.

$$R_{\text{TOTAL}} = R_1 + R_2 + R_3 \dots$$

Equation 511.6

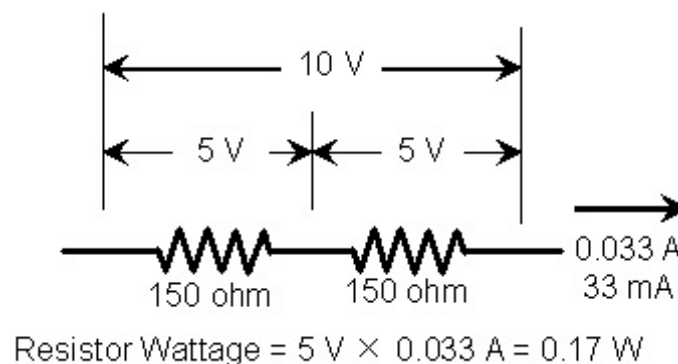


Figure 511.5 When resistors are connected in series the total resistance is the sum of the individual resistor values and the total voltage is divided across each resistor in proportion to the value of the resistor.

Assume that in a circuit a resistor ranging from approximately 300 to 350 ohm needs to be connected across 10 volts and that the only resistors available at the time are 1/4 watt resistors. A standard value 330 ohm resistor in this application will draw 30mA (0.030A). Multiply the current

by 10 volts drop across the resistor and the result is 0.3 watts (Equation 511.1). This is in excess of the rating of the 1/4 watt resistor (0.25W). By connecting two 150 watt resistors in series the total becomes 300 Ohm which is acceptable for this application and the current draw will be slightly higher at 33 mA. Since there are two resistors in series of equal value, each resistor will have only half the voltage or 5 volts across each resistor to add up to the total of 10 volts (Figure 511.5). Multiply the 33 mA by 5 volts (Equation 511.1) to determine the power dissipated which is 0.17 watts. Each resistor now is within the 1/4 watt maximum rating. Two quarter watt 150 ohm resistors connected in series can be used where if one 330 ohm resistor was used the rating would need to be one-half watt.

Another way to obtain the value of resistor required when the value is not available is to connect resistors in parallel. If two resistors of equal value are connected in parallel, the total or resultant resistance of the parallel combination is just half the value of the individual resistor. Equation 511.7 shows how to determine the total resistance when two or more resistors of equal value are connected in parallel. Divide the value of the individual resistor by the number of resistors in parallel. The total wattage rating of the parallel combination of resistors will be the resistance rating of one resistor times the number of resistors connected in parallel.

$$R_{TOTAL} = \frac{\text{Individual resistor value}}{\text{Number of resistors in parallel}} \quad \text{Equation 511.7}$$

Here is an example of connecting resistors in parallel to obtain the value desired. This technique also can be used to reduce the power requirement of each resistor when a high power requirement is necessary. Assume a value of resistance is needed in a circuit of 250,000 Ohm, but such a value is not immediately available. Assuming that 1M ohm resistors are available, as shown in Figure 511.6, four can be connected in parallel to obtain the desired resistance. Assume that the resistors used in this application have a 1/10 watt rating. Determine the wattage rating of the four resistors operating in parallel. The wattage is simply the sum of the individual wattage ratings for a total of 0.4 Watt.

$$R_{TOTAL} = \frac{1,000,000 \text{ ohm}}{4} = 250,000 \text{ ohm}$$

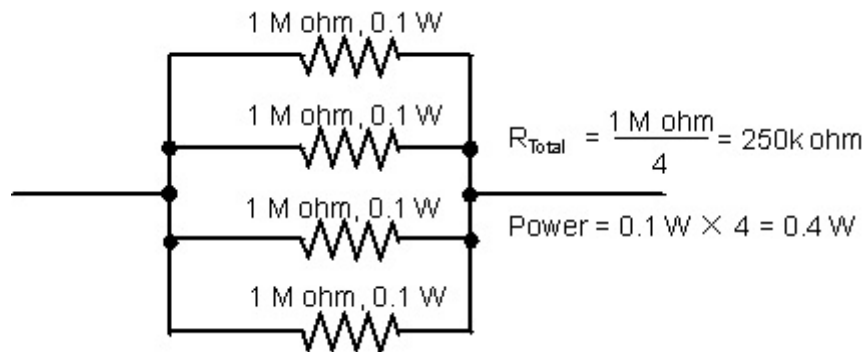


Figure 511.6 When resistors of the same value are connected in parallel, the resultant resistance is the value of one resistor divided by the total number of resistors, and the power rating is the power rating of one resistor times the total number of resistors in parallel.

Here is another example where the power rating of a resistor must be determined. A resistor with a value of 1 Ohm will be installed in a circuit and as much as 5 amperes will flow through the resistor for extended periods of time. First determine the power rating of the resistor in this application. Equation 511.2 will give the power in this case as 25 watts ($P = 5^2 \times 1 \text{ ohm} = 25W$). Assume the power resistors available only have a 10 Watt rating. It will take at least three to exceed the 25 Watt rating required. Assume also that the next higher rated 10 Watt resistor available is 5 ohm. Determine the number that must be connected in parallel to achieve 1 ohm. The answer is obviously five connected in parallel which will give a total power rating of 50 Watts.

Voltage Dividers: An electrical circuit supplied by a single voltage source often requires voltages of a lesser value at certain points in the circuit. When several resistors are connected in series and placed across a voltage source, the voltage drop across each resistor will sum to the supply voltage. The resistors connected in series form what is known as a voltage divider. The resistors divide the voltage into smaller values that add up to the total. This technique is illustrated in Figure 511.7. The circuit to the left has one resistor connected across a 12 volt supply. If the 2k ohm resistor is replaced with two 1k ohm resistors connected in series (Figure 511.7), the circuit will act the same as the original circuit. Note for the right hand circuit of Figure 511.7, there is 6 volts across each resistor. If a component of a circuit requires 6 volts then it can be connected across one of the resistors. The original 12 volt source was divided into two 6 volt components by the circuit of Figure 511.7. This voltage divider technique is used frequently in electronic circuits. An example may be where the output voltage from a sensor is too high to supply directly into an instrument. Assume the sensor voltage ranges from zero to 20 volts, but the maximum voltage that can be accepted by an instrument is 8 volts. To be on the safe side set 5 volts as the target maximum voltage. One way to make this transition is by using a voltage divider.

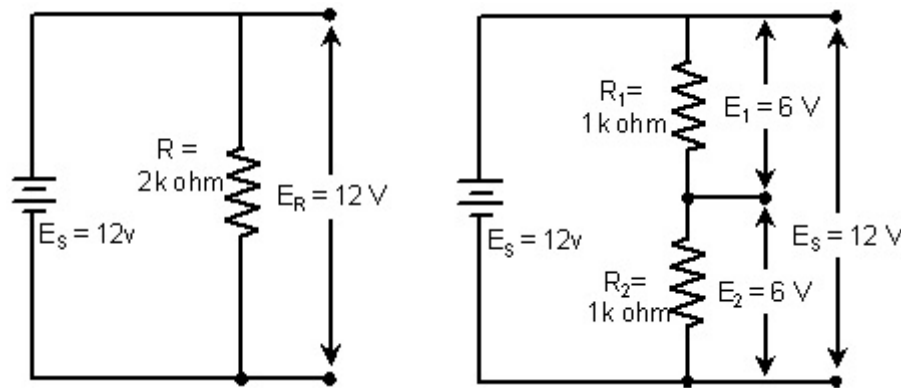


Figure 511.7 When two or more resistors are connected in series across a voltage source, the source voltage is divided in proportion to the ratio of the resistor over the total resistance. The voltage across each resistor in series will sum to the source voltage.

When resistors are connected in series to form a voltage divider, the voltage across any one resistor will be the ratio of that resistor value to the total series resistance times the supply voltage. The voltage divider technique is illustrated in Figure 511.8 for resistors of unequal values. If the values of the resistors and the supply voltage are known, use Equation 511.8 to determine the voltage across the desired resistor, R_x .

$$E_x = E_{\text{Source}} \times \frac{R_x}{R_{\text{Total}}} \qquad \text{Equation 511.8}$$

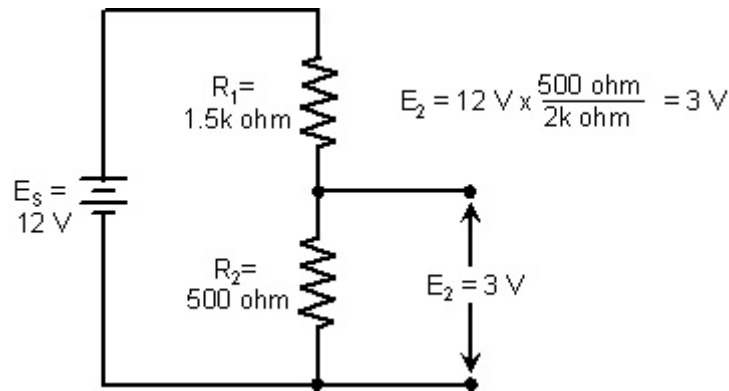


Figure 511.8 If the values of the resistors are known and the supply voltage is known, the voltage across each resistor can be determined using Equation 511.8.

Sometimes the value of one resistor to be connected in series is known as well as the source voltage and the desired voltage to be obtained across the unknown resistor. The question is what is the value of the resistor needed to obtain the desired voltage. A little rearranging of Equation 511.8 is required with $R_x + R_{\text{known}}$ substituted for R_{Total} . To find the value of resistor required to give the voltage needed, use Equation 511.9. This is illustrated in Figure 511.9. With a little practice, in many cases the value of resistor can be predicted.

$$R_x = R_{\text{known}} \times \frac{V_x}{V_{\text{Source}} - V_x} \quad \text{Equation 511.9}$$

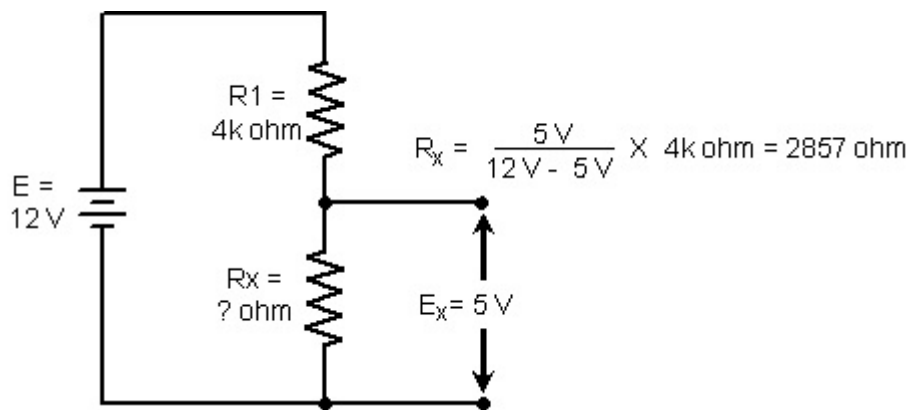


Figure 511.9 A value of resistor can be chosen in combination with a known resistor value that will divide the voltage to a desired level.

An example will illustrate the use of Equation 511.9 to determine the value of resistor required to provide the desired voltage. Assume that the source is 12 volts and a 4k ohm resistor is connected in series with a resistor of unknown value to provide 5 volts as illustrated in Figure 511.9. The voltage desired is less than half the supply voltage, so we know that the value of the

unknown resistor will be less than 4k ohm. Substituting the values into Equation 511.9 reveals that the value of the unknown resistor is 2857 ohm.

$$R_x = 4k \text{ ohm} \times \frac{5v}{12V - 5V} = 2857\text{ohm}$$

Wheatstone Bridge: In the 1830's it was discovered that by using the voltage divider principle very precise measurements of resistance were possible. The technique became known as the Wheatstone Bridge. There have been many modifications to the original bridge network over the years and today names other than Wheatstone are used for bridge networks. The basic principle of operation is similar and bridge networks can be used to measure capacitance, inductance, and impedance as well as resistance. The Wheatstone bridge uses the principle of voltage dividing to determine the value of an unknown resistance. Figure 511.10 illustrates the basic principle of the Wheatstone bridge. Bridge networks used today operate on the same principle as shown in Figure 511.10, but the values and arrangement of components may be different. The bridge network consists of two parallel branches. The left branch in Figure 511.10 has two resistors of equal value connected in series. These must be special high accuracy resistors. The right branch consists of a set of terminals where a resistor with an unknown value can be connected. The unknown resistor is connected in series with a highly accurate variable resistor. When the value of the variable resistor is exactly the same as the unknown resistor, points **A** and **B** in each branch will be at the same voltage. Points **A** and **B** are connected together (bridged) with a very sensitive ammeter called a galvanometer. Galvanometer needle deflection to the right or to the left of the zero point in the center indicates current flowing between points **A** and **B**. When points **A** and **B** are at exactly the same voltage there will be no current flow and the needle will point to zero. This condition indicates that the variable resistor R and the unknown resistance R_x are at the same value. There is a scale on the bridge to indicate the value of the variable resistor. This principle is used inside many measurement instruments.

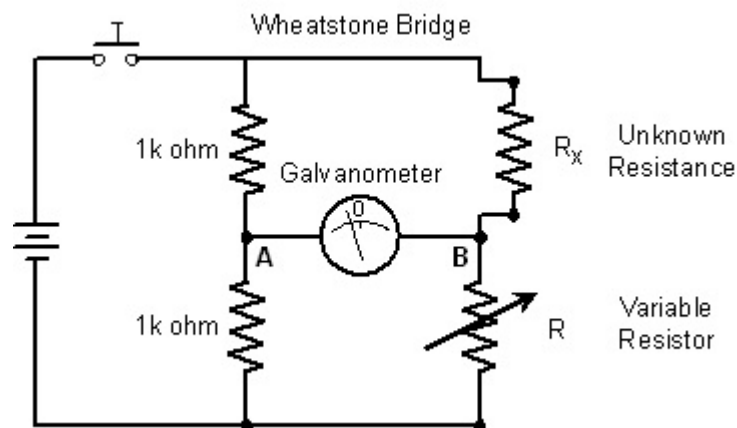


Figure 511.10 A Wheatstone bridge is used to determine the value of an unknown resistor which is connected in series with a variable resistor to form one branch of the network. For this example, the other branch consists of two highly accurate resistors of equal value. When the galvanometer connecting points **A** and **B** reads zero, the value of variable resistor and the unknown resistor are identical.