Basics of Electricity

Electricity for Construction Engineers

ICRC

Basics of Electricity

A quick introduction course

Coming from **Siemens Industry** STEP Online Courses

Contents

1. Introduction

Welcome to this course prepared by **S**iemens **T**echnical **E**ducation **P**rogram designed to prepare their distributors to sell Siemens Industry, Inc. products more effectively. This course covers **Basics of Electricity** and is designed to prepare you for further courses.

Upon completion of Basics of Electricity you will be able to:

- Explain the difference between conductors and insulators
- Use Ohm's law to calculate current, voltage, and resistance
- Calculate equivalent resistance for series, parallel, or series-parallel circuits
- Calculate voltage drop across a resistor
- Calculate power given from other basic values
- Identify factors that determine the strength and polarity of a current-carrying coil's magnetic field
- Determine peak, instantaneous, and effective values of an AC sine wave
- Identify factors that influence inductive reactance and capacitive reactance in an AC circuit
- Calculate total impedance of an AC circuit
- Explain the difference between real power and apparent power in an AC circuit
- Calculate primary and secondary voltages of single-phase and three-phase transformers
- Calculate the required apparent power for a transformer

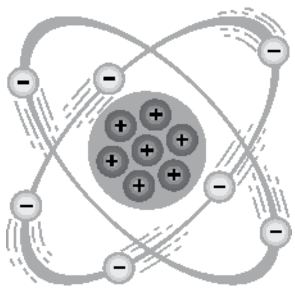
This knowledge will help you to better understand customer applications. In addition, you will better be able to describe products to customers and determine important differences between products.

At the end of each chapter, you will be able to complete a review by answering questions. These reviews will help you to ensure that the various notions have been acquired, and will prepare you for meetings with the course facilitators and online quizzes.

2. Conductors and Insulators

Elements of an Atom

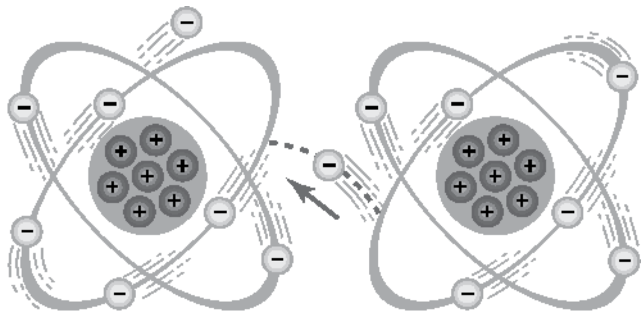
All matter is made up **atoms**. Atoms have a nucleus with electrons in motion around it. The nucleus is composed of protons and neutrons (not shown). **Electrons** have a negative charge (-). **Protons** have a positive charge (+). **Neutrons** are neutral. In the normal state of an atom, the number of electrons is equal to the number of protons and the negative charge of the electrons is balanced by the positive charge of the protons.



Free Electrons

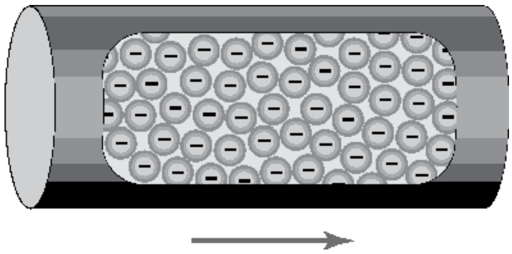
Electrons move around the nucleus at different distances. The closer to the nucleus, the more tightly bound the electrons are to the atom. Electrons in the outer band can be easily forced out of the atom by the application of some external force such as a magnetic field, friction, or chemical action.

Electrons forced from atoms are sometimes called **free electrons**. A free electron leaves a void which can be filled by an electron forced out of another atom.



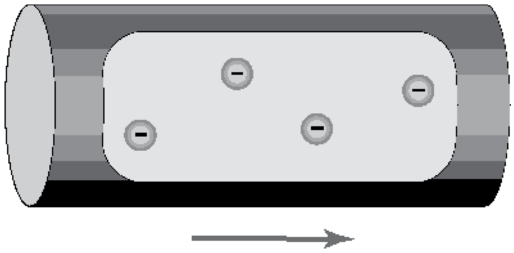
Conductors

An electric current is produced when free electrons move from atom to atom in a material. Materials that permit many electrons to move freely are called conductors. Copper, silver, gold, aluminum, zinc, brass, and iron are considered good conductors. Among these materials, copper and aluminum are the ones most commonly used as conductors.



Insulators

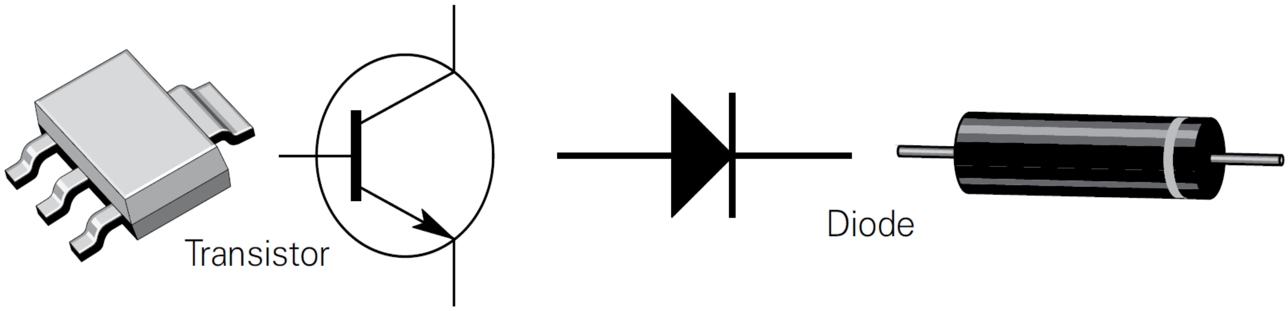
Materials that allow few free electrons are called **insulators**. Materials such as plastic, rubber, glass, mica, and ceramic are good insulators.



An electric cable is one example of how conductors and insulators are used. Electrons flow along a copper or aluminum conductor to provide energy to an electric device such as a radio, lamp, or a motor. An insulator around the outside of the copper conductor is provided to keep electrons in the conductor.

Semiconductor

Materials, such as silicon, can be used to manufacture devices that have characteristics of both conductors and insulators. Many semiconductor devices act like a conductor when an external force is applied in one direction and like an insulator when the external force is applied in the opposite direction. This principle is the basis for transistors, diodes, and other solid-state electronic devices.



Review 1

1. List the three basic particles of an atom and state the charge of each (positive, negative, or neutral).

Element	Charge
__________	__________
__________	__________
__________	__________

2. Materials that permit many electrons to move freely are called __________

3. Which of the following materials are good conductors?

a. copper
b. plastic
c. silver
d. rubber
e. aluminum
f. glass
g. iron
h. mica

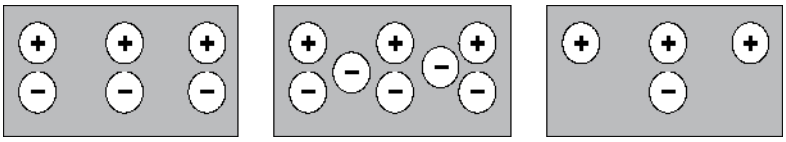
4. Materials that allow few free electrons are called__________

3. Current, Voltage, and Resistance

All materials are composed of one or more elements. An element is a material made up of one type of atom. Elements are often identified by the number of protons and electrons in one atom of the element. A hydrogen atom, for example, has only one electron and one proton. An aluminum atom has 13 electrons and 13 protons. An atom with an equal number of electrons and protons is electrically neutral.

Electrical Charges

Electrons in the outer band of an atom can be easily moved by the application of external force. When an electron is forced out of an atom, the atom it leaves behind contains more protons than electrons. This atom now has a **positive charge.** Atoms or molecules of a material can also have an excess of electrons, giving the material a **negative charge**. A positive or negative charge is caused by an absence or excess of electrons. The number of protons remains constant.

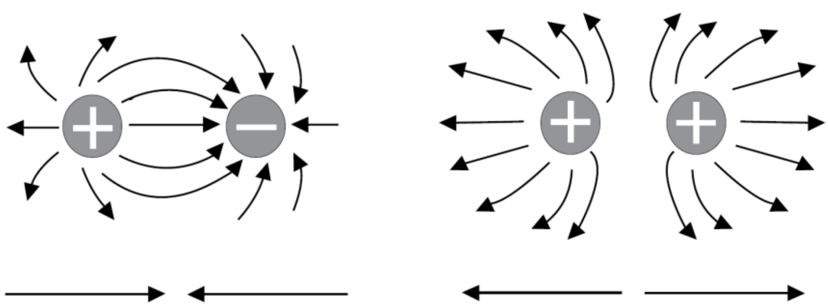


Neutral Charge Negative Charge Positive Charge

Attraction and Repulsion of Electric Charges

The old saying, “opposites attract,” is true when dealing with electric charges. Charged bodies have an invisible electric field around them. When two like-charged bodies are brought together, the force induced by their electric fields repels one body from the other. When two unlike-charged bodies are brought together, the force induced by their electric fields attracts one body to the other.

Unlike Charges Attract Like Charges Repel



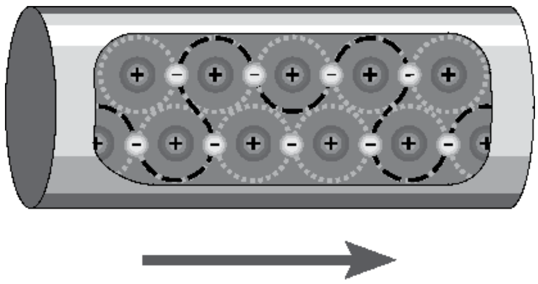
The interaction of electric charges depends on both the amount of each charge and the distance between them. The greater the amount of each charge the more charged objects attract or repel each other. However, this interaction is inversely proportional to the square of the distance between charges.

Current

The flow of free electrons in a material from one atom to the next atom in the same direction is called **current** and is designated by the symbol **I**. The amount of current flowing is determined by the number of electrons that pass through a cross-section of a conductor in one second.

Keep in mind that atoms are very small. It takes about 10^{24} atoms to fill one cubic centimeter of a copper conductor. This means that trying to represent even a small value of current as electrons would result in an extremely large number.

For this reason, current is measured in **amperes,** often shortened to **amps**. The letter **A** is the symbol for amps. A current of one amp means that in one second about 6.24×10^{18} electrons move through a cross-section of conductor. These numbers are given for information only and you do not need to be concerned with them. It is important, however, to understand the concept of current flow.

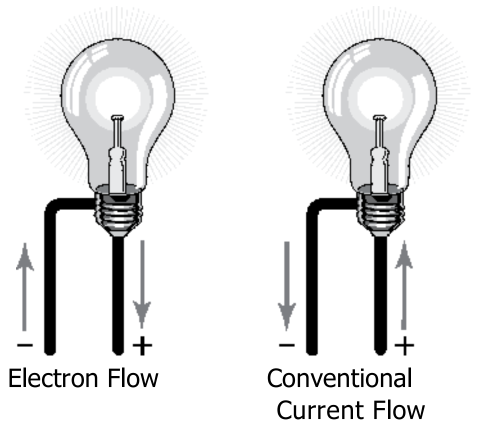


Because in practice it is common to find wide variations in the magnitude of electrical quantities, electrical units often have metric unit prefixes that represent powers of ten. The following chart shows how three of these prefixes are used to represent large and small values of current.

Unit	Symbol	Equivalent Measure
kiloampere	kA	1 kA = 10^{3} A = 1 000 A
milliampere	mA	1 mA = 10^{-3} A = 0.001 A
microampere	µA	1 µA = 10^{-6} A = 0.000001 A

Direction of Current Flow

Conventional current flow has the direction of positive charges moving from a positive polarity to a negative polarity. Since current is a movement of electrons with negative charges, the **conventional current flow is the opposite direction of electron flow**.

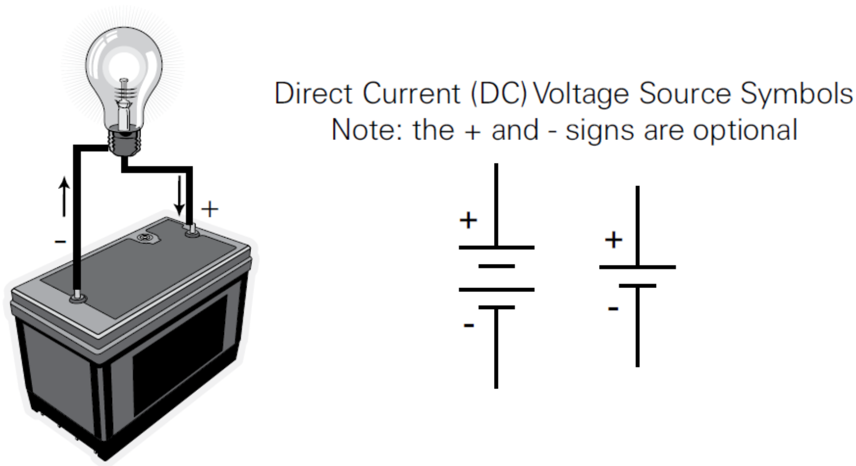


Voltage

The force required to make electricity flow through a conductor is called a **difference in potential**, **electromotive force (emf)**, or **voltage**. Voltage is designated by the letter **E** or the letter **U**. The unit of measurement for voltage is the **volt** which is also designated by the letter **V**.

A voltage can be generated in various ways. A battery uses an electrochemical process. A car's alternator and a power plant generator use a magnetic induction process. All voltage sources share the characteristic of an excess of electrons at one terminal and a shortage at the other terminal. This results in a difference of potential between the two terminals.

For a **direct current (DC)** voltage source, the polarity of the terminals does not change, so the resulting current constantly flows in the same direction.



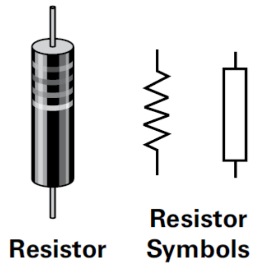
The following chart shows how selected metric unit prefixes are used to represent large and small values of voltage.

Unit	Symbol	Equivalent Measure
kilovolt	kV	1 kV =10^3 V = 1 000 V
millivolt	mV	1 mV =10^{-3} V = 0.001 V
microvolt	µV	1 µV =10^{-6} V = 0.000001 V

Resistance

A third factor that plays a role in an electrical circuit is **resistance**. All materials impede the flow of electrical current to some extent. The amount of resistance depends upon the composition, length, cross-section and temperature of the resistive material. As a rule of thumb, the resistance of a conductor increases with an increase of length or a decrease of cross-section. Resistance is designated by the symbol **R**. The unit of measurement for resistance is the **ohm** (Ω).

Resistors are devices manufactured to have a specific resistance and are used in a circuit to limit current flow and to reduce the voltage applied to other components. A resistor is usually shown symbolically on an electrical drawing in one of two ways, a zigzag line or an unfilled rectangle.



In addition to resistors, all other circuit components and the conductors that link components to form a circuit also have a resistance.

The basic unit for resistance is 1 ohm ; however, resistance is often expressed in multiples of the larger units shown in the following table.

Unit	Symbol	Equivalent Measure
megohm	MΩ	1 MΩ = 10^6 Ω = 1 000 000 Ω
kilohm	kΩ	1 kΩ = 1 000 Ω

Review 2

1. A material that has an excess of electrons has a ___________ charge.

2. A material that has a deficiency of electrons has a ___________ charge.

3. Like charges ___________and unlike charges ___________.

4. ___________ is the force that, when applied to a conductor, causes current flow.

5. Electrons move from___________ to___________.

6. Identify the basic unit of measure for each of the items shown below.

   a. Resistance ___________

   b. Current ___________

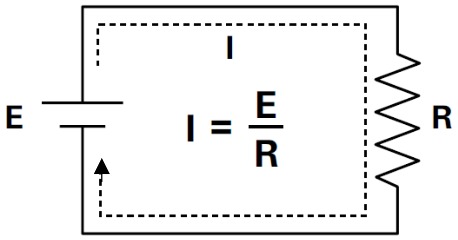
   c. Voltage ___________

4. Ohm's Law

Electric Circuit

A simple **electric circuit** consists of a voltage source, some type of loads and conductors, to allow electrons to flow between the voltage source and the load.

Ohm's law shows that current varies directly with voltage and inversely with resistance.



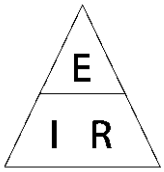
Current (I) is measured in amperes (amps) (A)
Voltage (E) is measured in volts (V)
Resistance (R) is measured in ohms (Ω)

There are three ways to express Ohm's law.

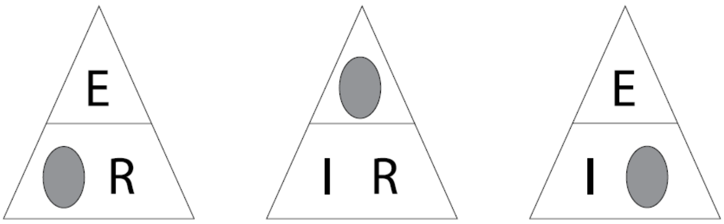
I = E / R E = I x R R = E / I

Ohm's Law Triangle

There is an easy way to remember which formula to use. By arranging current, voltage and resistance in a triangle, you can quickly determine the correct formula.



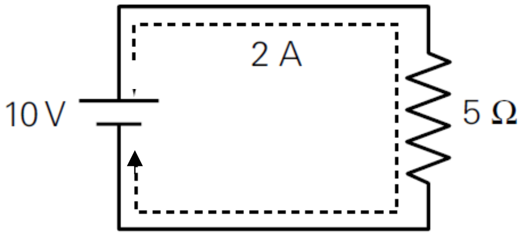
To use the triangle, cover the value you want to calculate. The remaining letters make up the formula.



I = E / R E = I x R R = E / I

Ohm's Law Example

As the following simple example shows, if any two values are known, you can determine the other value using Ohm's law.



$$I = \frac{E}{R} = \frac{10\ V}{5\ \Omega} = 2\ A$$

$$R = \frac{E}{I} = \frac{10\ V}{2\ A} = 5\ \Omega$$

$$E = I \times R = 2\ A \times 5\ \Omega = 10\ V$$

Use now a similar circuit, but with a current of 200 mA and a resistance of 10 Ω. To solve for voltage, cover the E in the triangle and use the resulting equation.

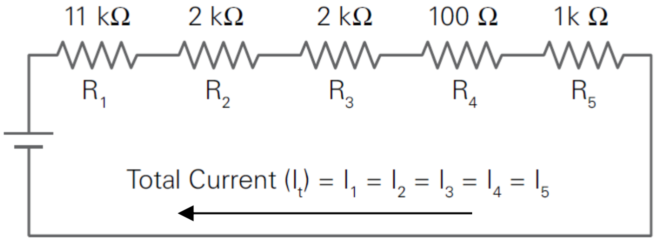
$$E = I \times R = 0.2\ A \times 10\ \Omega = 2\ V$$

Remember to use the correct decimal equivalent when dealing with numbers that are preceded with milli (m), micro (μ), kilo (k) or mega (M). In this example, current was converted to 0.2 A, because 200 mA is 200 x 10^{-3} A, which is equal to 0.2 A.

5. DC Circuits

Series Circuits

A **series circuit** is formed when any number of devices are connected end-to-end so that there is only one path for current to flow. The following illustration shows five resistors connected in series. Current flows from the positive terminal of the voltage source through the five resistors to the negative terminal.



$$\text{Total Resistance} = R_t = R_1 + R_2 + R_3 + R_4 + R_5$$

$$R_t = 11{,}000\ \Omega + 2000\ \Omega + 2000\ \Omega + 100\ \Omega + 1000\ \Omega$$

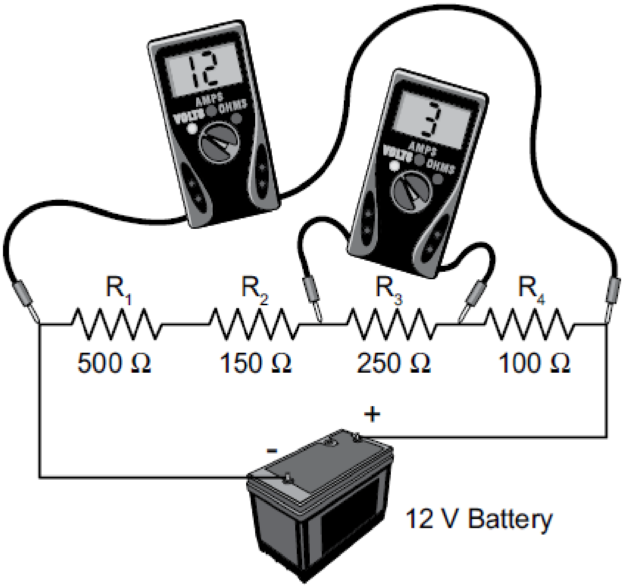
$$R_t = 16{,}100\ \Omega = 16.1\text{k}\ \Omega$$

The total resistance (R_t) in a series circuit can be determined by adding all the resistor values. Please note that **in a series circuit the total resistance is higher than each resistance**.
Although the unit for resistance is the ohm, different metric unit prefixes, such as kilo (k) or mega (M) are often used. Therefore, it is important to convert all resistance values to the same units before adding.

Current in a series circuit can be determined using Ohm's law. First, total the resistance and then divide the source voltage by the total resistance. This current flows through each resistor in the circuit.

The voltage measured across each resistor can also be calculated using Ohm's law. The voltage across a resistor is often referred to as a voltage drop. The sum of the voltage drops across each resistor is equal to the source voltage.

The following illustration shows two voltmeters, one measuring total voltage and one measuring the voltage across R3.



$$R_t = 500\ \Omega + 150\ \Omega + 250\ \Omega + 100\ \Omega = 1000\ \Omega = 1k\ \Omega$$

$$I = \frac{12\ V}{1000\ \Omega} = 0.012\ A = 12\ mA$$

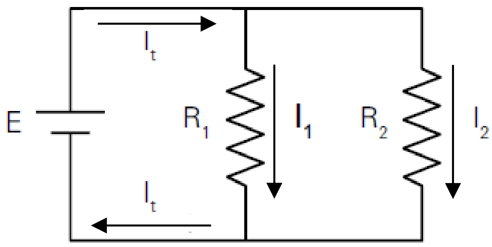
$$E_3 \text{ (The voltage accross } R_3) = I \times R_3 = 0.012\ A \times 250\ \Omega = 3\ V$$

$$E_t = E_1 + E_2 + E_3 + E_4 = 6\ V + 1.8\ V + 3\ V + 1.2\ V = 12\ V$$

Parallel Circuits

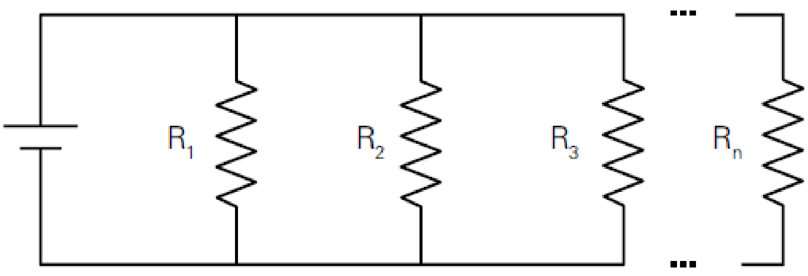
A **parallel circuit** is formed when two or more devices are placed in a circuit side-by-side so that current can flow through more than one path.

The following illustration shows the simplest parallel circuit, two parallel resistors. There are two paths of current flow. One path is from the positive terminal of the battery through R1 returning to the negative terminal. The second path is from the positive terminal of the battery through R2 returning to the negative terminal of the battery. The current through either resistor can be determined by dividing the circuit voltage by the resistance of that resistor.



$$I_1 = \frac{E}{R_1} \qquad I_2 = \frac{E}{R_2} \qquad I_t = I_1 + I_2$$

The total resistance for a parallel circuit with any number of resistors can be calculated using the formula shown in the following illustration.

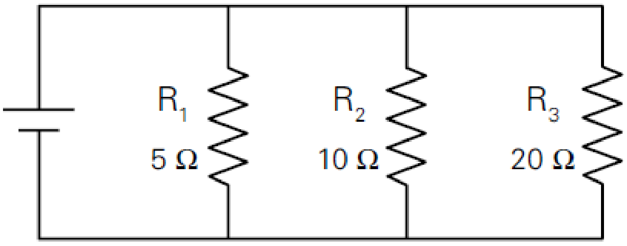


$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \cdots + \frac{1}{R_n}$$

$$R_t = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \cdots + \frac{1}{R_n}}$$

In the unique example where all resistors have the same resistance, the total resistance is equal to the resistance of one resistor divided by the number of resistors. Please note that **in a parallel circuit the total resistance is lower than each resistance**.

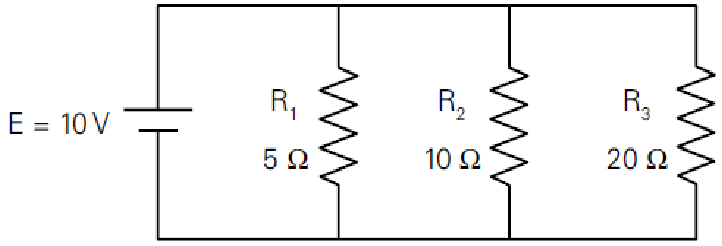
The following example shows a total resistance calculation for a circuit with three parallel resistors.



$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{5\,\Omega} + \frac{1}{10\,\Omega} + \frac{1}{20\,\Omega} = \frac{4}{20\,\Omega} + \frac{2}{20\,\Omega} + \frac{1}{20\,\Omega} = \frac{7}{20\,\Omega}$$

$$R_t = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{1}{\frac{7}{20\,\Omega}} = \frac{20\,\Omega}{7} = 2.86\,\Omega$$

Current in each of the branches of a parallel circuit can be calculated by dividing the circuit voltage, which is the same for all branches, by the resistance of the branch. The total circuit current can be calculated by adding the current for all branches or by dividing the circuit voltage by the total resistance.

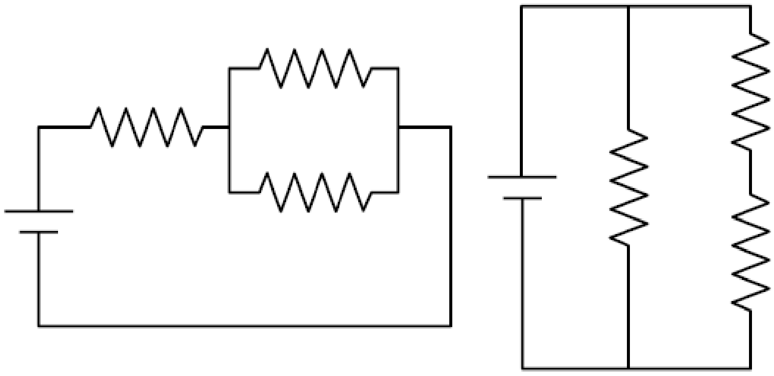


$$I_t = I_1 + I_2 + I_3 = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3} = \frac{10\,V}{5\,\Omega} + \frac{10\,V}{10\,\Omega} + \frac{10\,V}{20\,\Omega} = 2\,A + 1\,A + 0.5\,A = 3.5\,A$$

$$I_t = \frac{E}{R_t} = \frac{10\,V}{2.86\,\Omega} = 3.5\,A$$

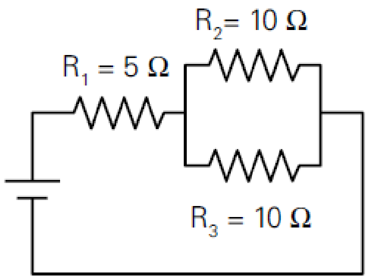
Series-Parallel Circuits

Series-parallel circuits are also known as compound circuits. At least three components are required to form a series-parallel circuit. The following illustration shows the two simplest series-parallel circuits. The circuit on the left has two parallel resistors in series with another resistor. The circuit on the right has two series resistors in parallel with another resistor.



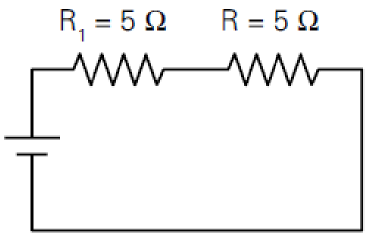
Series-parallel circuits are usually more complex than the circuits shown here, but by using the circuit formulas discussed earlier in this course, you can easily determine circuit characteristics.

The following illustration shows how total resistance can be determined for two series-parallel circuits in two easy steps for each circuit. More complex circuits require more steps, but each step is relatively simple. In addition, if the source voltage is known, by using Ohm's law you can also solve for current and voltage throughout each circuit,



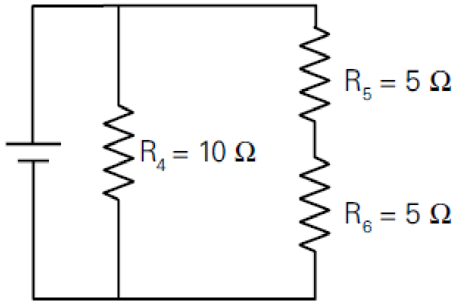
1. Combine the parallel resistors

$$R = \frac{1}{\frac{1}{10\ \Omega} + \frac{1}{10\ \Omega}} = \frac{10\ \Omega}{2} = 5\ \Omega$$



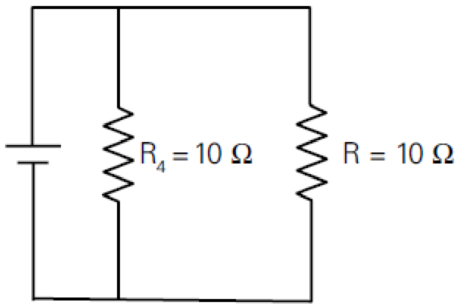
2. Add the series resistors

$R_t = 5\ \Omega + 5\ \Omega = 10\ \Omega$



1. Add the series resistors

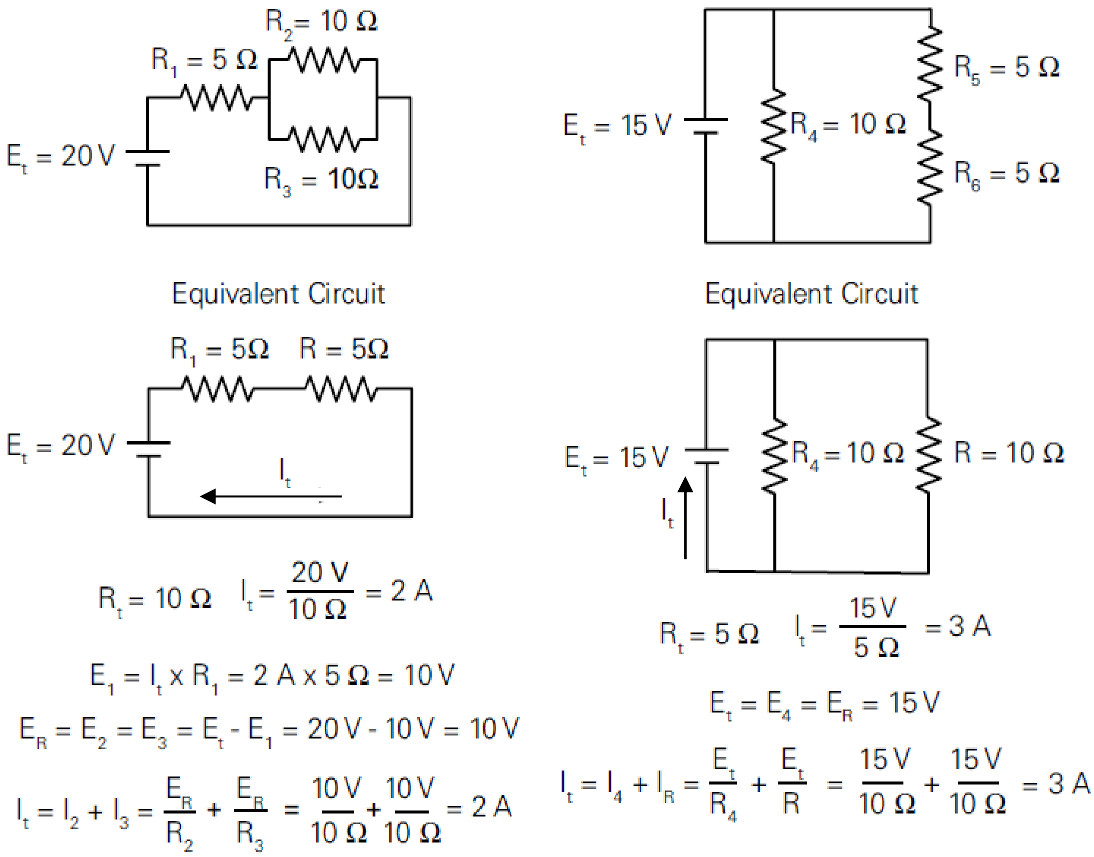
$R = R_5 + R_6 = 5\ \Omega + 5\ \Omega = 10\ \Omega$



2. Combine the parallel resistors

$$R_t = \frac{1}{\frac{1}{10\ \Omega} + \frac{1}{10\ \Omega}} = \frac{10\ \Omega}{2} = 5\ \Omega$$

Using the same two series-parallel circuits as in the previous example, but with source voltages included, the following illustration shows how Ohm's law can be used to calculate other circuit values.



Power in a DC Circuit

Whenever a force of any kind causes motion, work is accomplished. If a force is exerted without causing motion, then no work is done.

In an electrical circuit, voltage applied to a conductor causes electrons to flow. Voltage is the force and electron flow is the motion. **Power** is the rate at which work is done and is represented by the symbol **P**. The unit of measure for power is the **watt**, represented by the symbol **W**. In a direct current circuit, one watt is the rate at which work is done when 1 volt causes a current of 1 amp. You will learn later that there are other types of power that apply to alternating current circuits.

From the basic formula, Power is equal to current multiplied by voltage. Others formulas for power can be derived using Ohm's law.

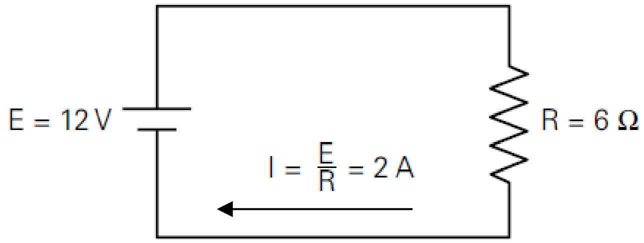
Direct Current Power Formulas **Ohm's Law**

$$P = I \times E = IE$$

$$P = IE = I(IR) = I^2R \qquad E = I \times R = IR$$

$$P = IE = \left(\frac{E}{R}\right)E = \frac{E^2}{R} \qquad I = \frac{E}{R}$$

The following example shows how power can be calculated using any of the power formulas.



$$P = IE = (2\ A)(12\ V) = 24\ W$$

$$P = I^2R = (2\ A)^2(6\ \Omega) = 24\ W$$

$$P = \frac{E^2}{R} = \frac{(12\ V)^2}{6\ \Omega} = 24\ W$$

Review 3

1. The total current in a circuit that has a voltage of 12 V and a resistance of 24 Ω is__________ A.
2. The total resistance of a series circuit with resistors of the following values:

   R1 = 10 Ω, R2 = 15 Ω, and R3 = 20 Ω is __________ Ω.
3. The voltage for a series circuit that has a current of 0.5 A and a resistance of 60 Ω is __________ V.
4. The total resistance of a parallel circuit that has four 20 Ω resistors is __________ Ω.
5. In a parallel circuit with two resistors of equal value and a total current flow of 12 A, the current

   through each resistor is __________ A.
6. For a DC circuit with a voltage of 24 V and a current of 5 A, the power is __________ W