SUBARU®

Confidence in Motion

Technician Reference Booklet

Electrical Theory and Diagnosis

AUTOMOTIVE YES Youth Educational Systems® PROUD PARTNER

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This Technician Reference Booklet (TRB) is designed to be used in a classroom environment or as a guide for self study.
The TRB is not intended to be used as a supplement or substitute for the Subaru Service Manual. Always consult the appropriate Service Manual when performing any diagnostics, maintenance or repair to any Subaru vehicle.

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Electrical Theory and Diagnosis

Introduction

This training course introduces electrical safety, automotive electrical system theory, electrical component identification, automotive electrical circuit designs, and operation of a digital volt ohm meter (DVOM).

Course Objectives

Upon completion of this course, you will be able to:

- Identify safety practices associated with electrical service and repair
- Identify the components of an automotive electrical system
- Identify automotive electrical circuit types
- Operate a digital volt ohm meter (DVOM)
- Perform electrical measurements
- Identify electrical circuit fault types

Automotive Electrical Safety

Electrical Safety

There are many safety precautions that must be observed to prevent personal injury and damage to the automotive electrical systems. Always refer to the appropriate service information and observe all safety cautions and warnings prior to performing any service or repairs.

Personal Protection Equipment

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Safety Equipment

As a general warning, before attempting to service or repair any electrical system, wear the appropriate work clothing such as:

- Safety glasses with side shields
- Gloves (Chemical resistant)
- Subaru-approved uniform
- Protective shoes (Oil and slip resistant)

Additionally, cover or remove all metal objects including:

- Jewelry (watches, necklaces, rings, etc.)
- Belt buckles
- Zippers

Any metal that comes into contact with the vehicle can create a path for current to flow and possibly result in personal injury or damage to the vehicle.

Environmental Impact

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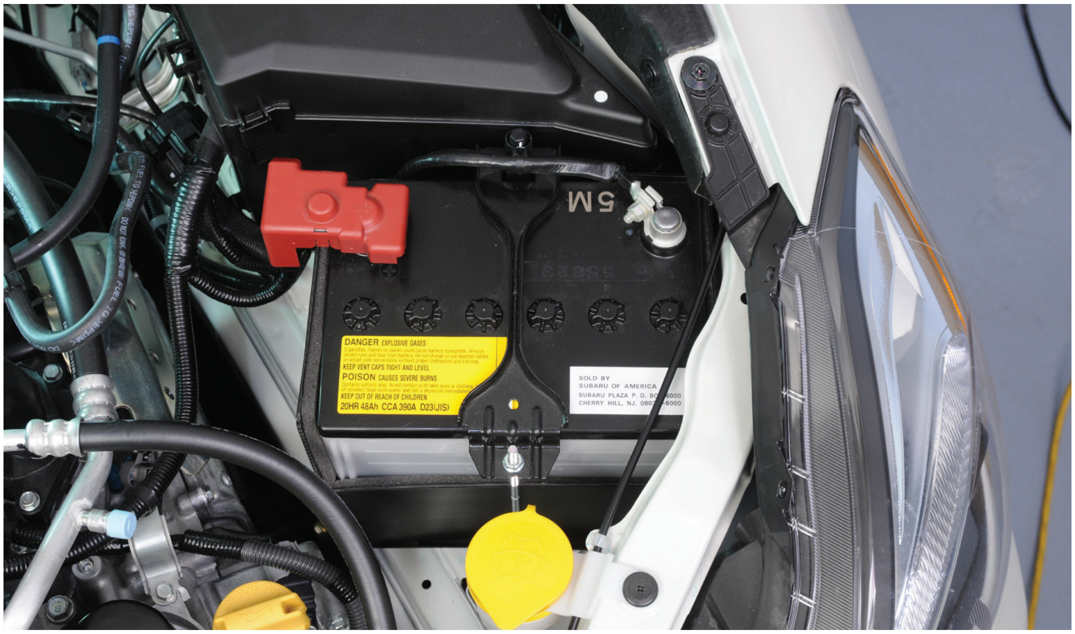
Environmental Impact

Automotive batteries may contain hazardous chemicals. Proper handling and disposal of automotive batteries are required to ensure personal and environmental safety standards are met.

The electrolyte found in typical automotive batteries is a corrosive acid that is also very toxic. Refer to OSHA Safety Data Sheet (SDS) for proper automotive battery handling requirements.

Periodically check the OSHA SDS for updates.

Battery Service Safety



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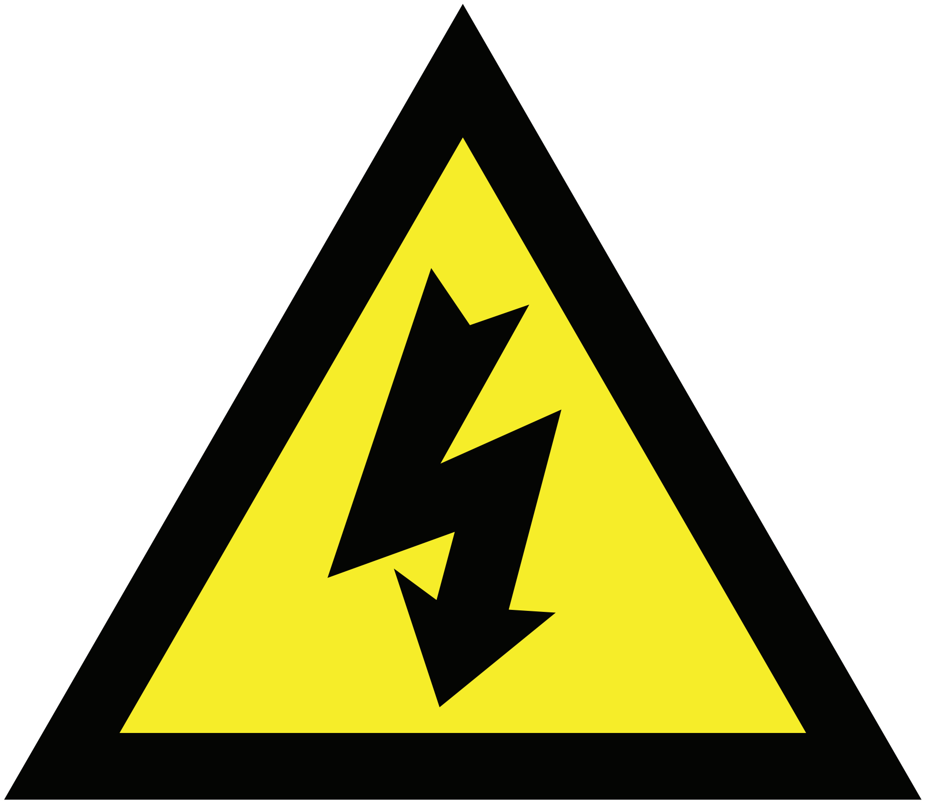
Battery Safety

To avoid personal injury or damage to the vehicle, follow the safety precautions listed below:

- Do not allow battery acid to contact your skin, eyes, or clothing.
- If battery acid should get in your eyes, rinse your eyes immediately with clean water and seek medical attention.
- If battery acid contacts your skin, wash the affected skin immediately with clean water.
- If battery acid is swallowed, drink large quantities of water or milk, followed by milk of magnesia and a beaten egg or vegetable oil.
- Always observe polarity when making battery connections.
- Always disconnect the negative battery cable first when disconnecting the battery.
- Always connect the negative battery cable last when connecting the battery.
- Keep open flames, sparks, and arcing away from the battery; the vapors created by cycling the battery are very explosive.
- Never smoke near the battery.
- Ensure the work area is well ventilated when using a battery charger.
- Never connect or disconnect a battery charger's leads while the charger is turned on.
- Do not wear jewelry when servicing the battery.
- Do not lay tools on the battery; if the tools contact both terminals of the battery, the battery will short out causing personal injury and possible damage to the battery, vehicle, and tools.
- Always wear the proper personal protective equipment when servicing the battery.

Electrical Safety Precautions



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WARNING: ELECTROLYTE IS CORROSIVE ACID, AND IS TOXIC; AVOID CONTACT WITH THE FLUID

WARNING: MAKE SURE THE ELECTROLYTE DOES NOT COME INTO CONTACT WITH SKIN, EYES, OR CLOTHING, ESPECIALLY THE EYES. FLUSH WITH WATER FOR 15 MINUTES AND GET PROMPT MEDICAL ATTENTION.

WARNING: IN ADDITION, BE CAREFUL NOT TO LET THE ELECTROLYTE MAKE CONTACT WITH THE COATED PARTS.

WARNING: BE CAREFUL WHEN HANDLING THE BATTERIES BECAUSE THEY PRODUCE EXPLOSIVE GASES.

WARNING: BE SURE TO KEEP THE BATTERY AWAY FROM ANY FIRE.

WARNING: FOR SAFETY, IN CASE AN EXPLOSION DOES OCCUR, WEAR EYE PROTECTION OR SHIELD YOUR EYES WHEN WORKING NEAR ANY BATTERY. IN ADDITION, NEVER LEAN OVER THE BATTERY.

WARNING: VENTILATE SUFFICIENTLY WHEN USING OR CHARGING THE BATTERY IN AN ENCLOSED SPACE.

WARNING: BEFORE STARTING WORK, REMOVE RINGS, METAL WATCH-BANDS, AND OTHER METAL JEWELRY.

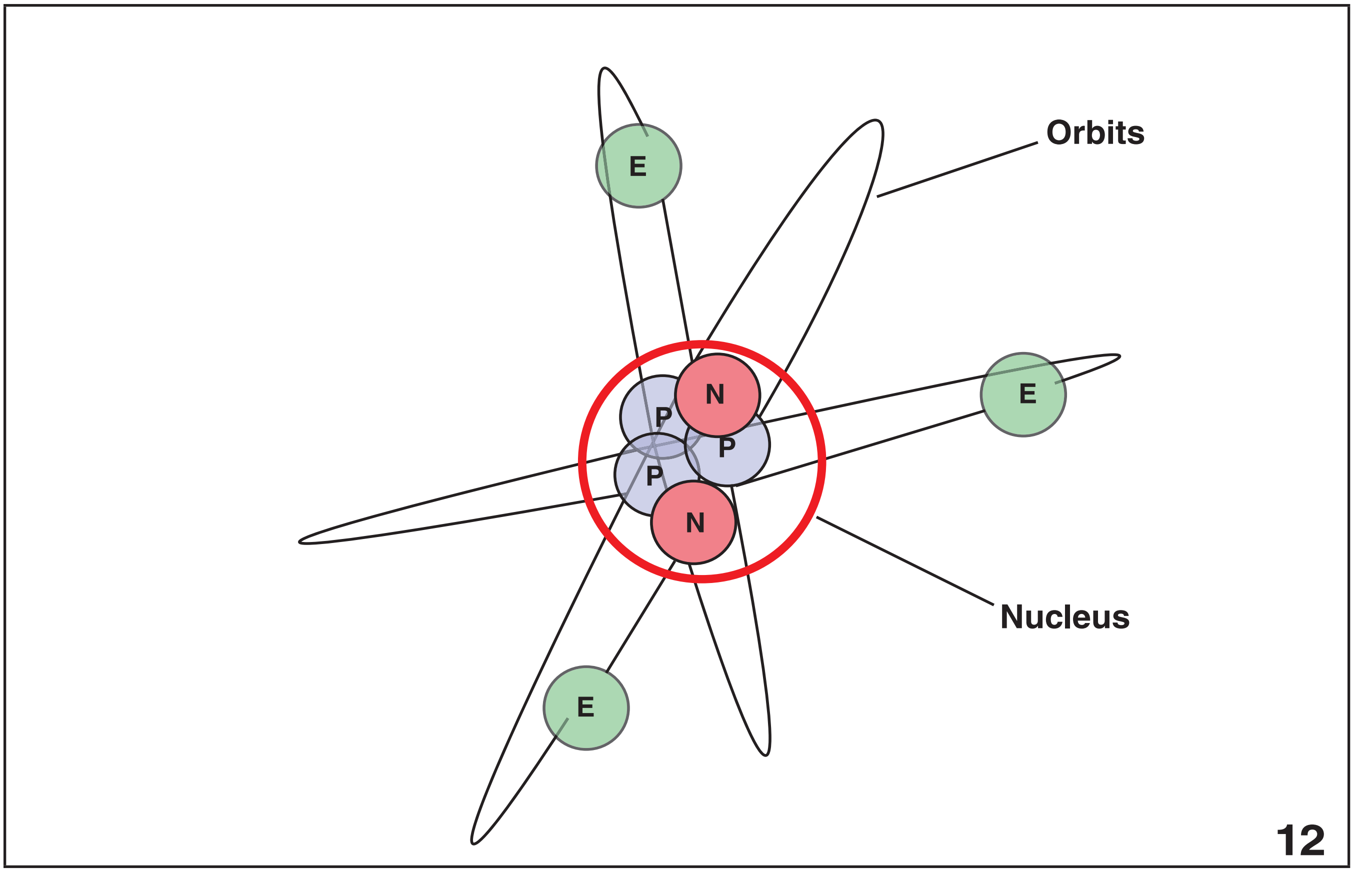
WARNING: NEVER ALLOW METAL TOOLS TO CONTACT THE POSITIVE BATTERY TERMINAL AND ANYTHING CONNECTED TO IT WHILE YOU ARE AT THE SAME TIME IN CONTACT WITH ANY OTHER METALLIC PORTION OF THE VEHICLE.

Note: **These WARNINGS and CAUTIONS may be re-emphasized as necessary throughout this course.**

Basic Electrical Theory

Theory

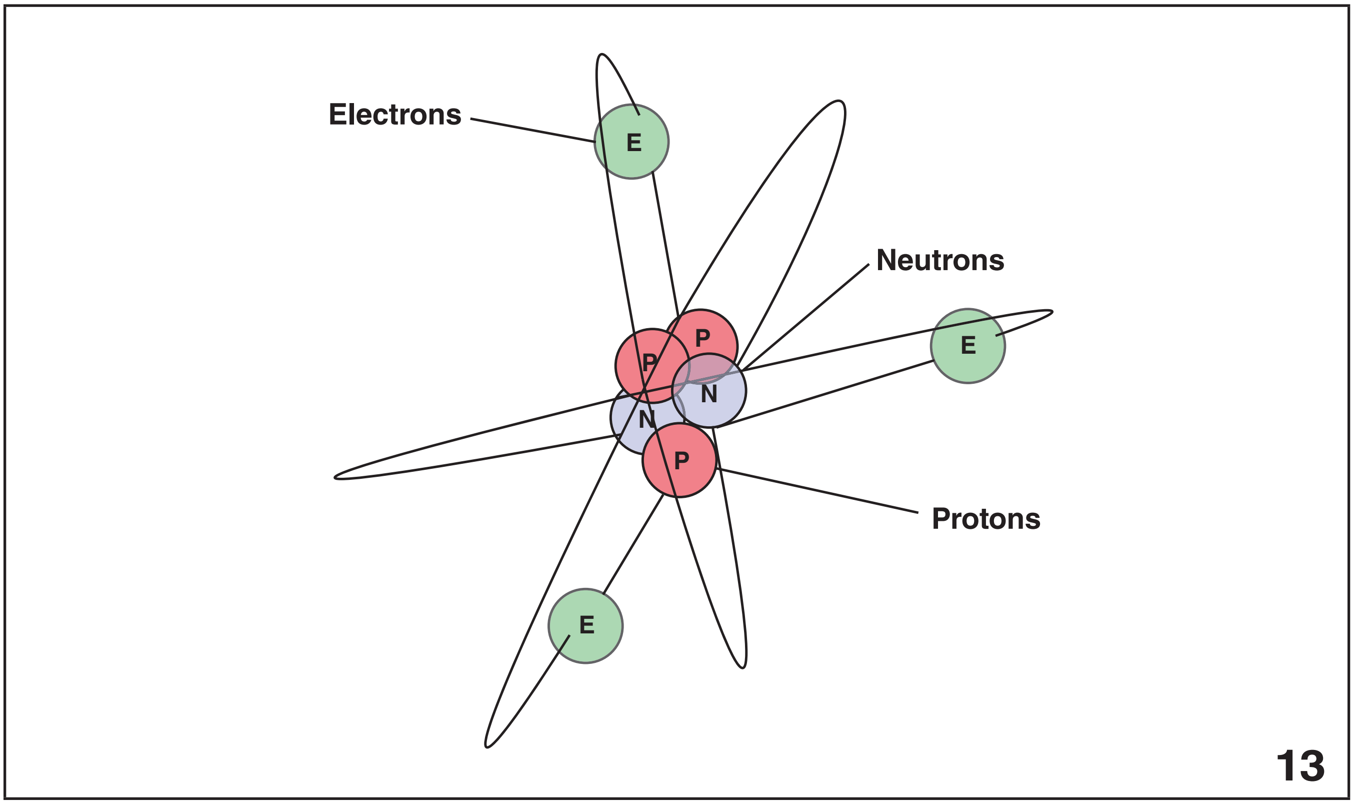
Atoms



Atoms

Atoms are the smallest particles of an element. Everything is made of atoms. An atom consists of positively charged protons, uncharged neutrons, and negatively charged electrons. At the center of an atom is the nucleus, which contains the protons and neutrons of the atom. The electrons orbit the nucleus on rings that surround the nucleus. The outer-most ring is called the valence ring, and the electrons on the valence ring are called free electrons. The number of free electrons on an atom determines whether the element is an insulator, conductor, or semiconductor.

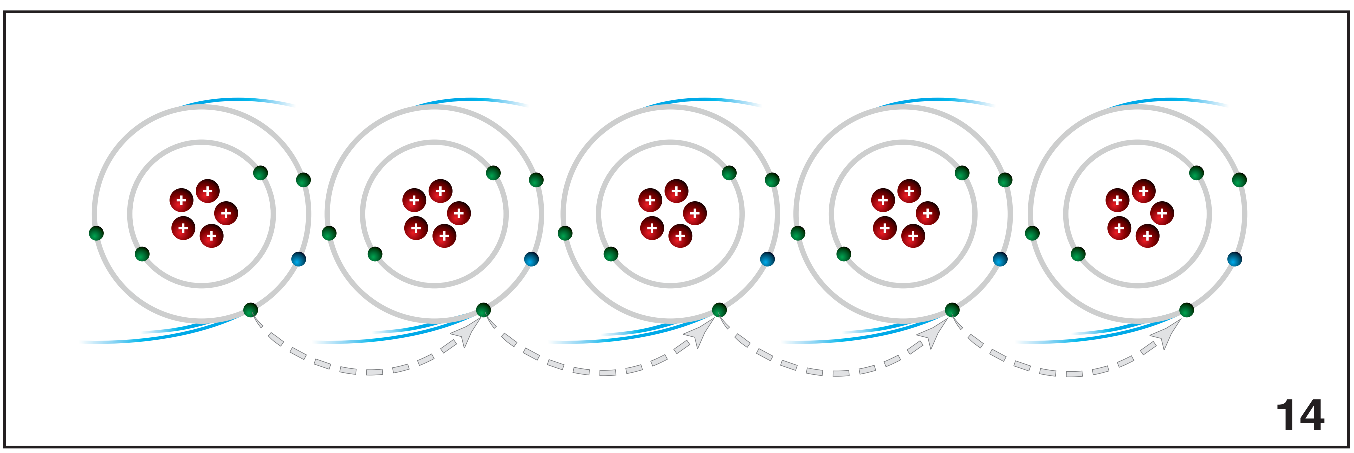
Electron Orbits



Electricity

Electrons orbit the nucleus because of the attracting forces created by the dissimilar electrical charges of the negatively charged electrons and the positively charged protons. Movement of the electrons around each ring of the atom is increased by the opposing forces created by the similar electrical charges of all the electrons on each of the atom's rings.

Unlike charges attract (or move toward one another) and like charges repel (or move away from one another).



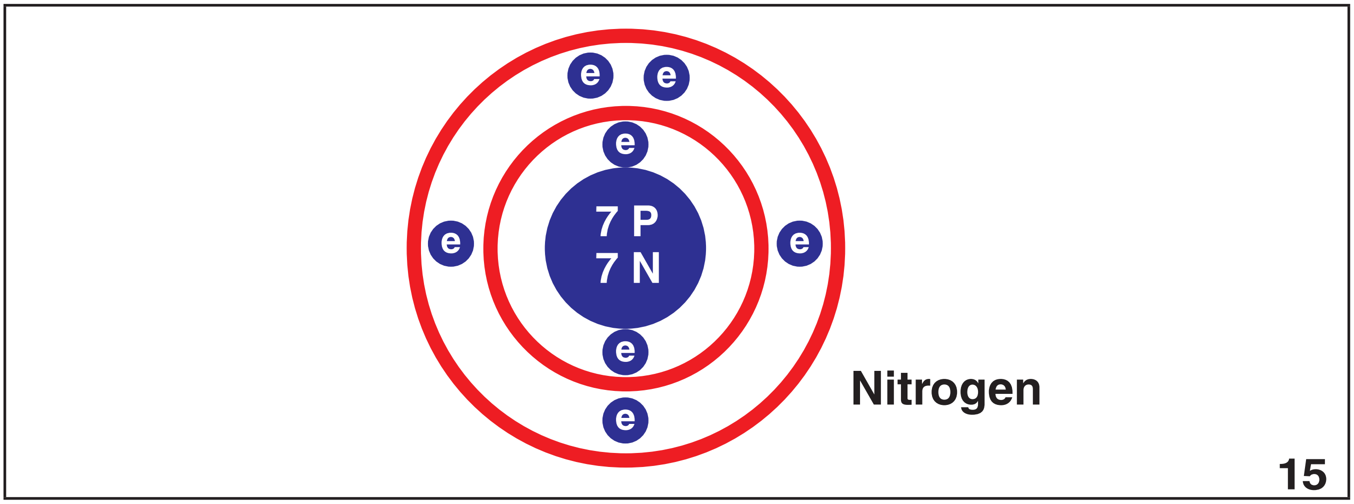
Free Electron Flow

Insulators, Conductors, and Semiconductors

Insulators

Insulators are elements that do not support the flow of electrons and have five or more free electrons in the valence ring.

Glass, plastic, rubber, latex, paper, wood, ceramic, nitrogen, and porcelain are examples of good insulators.

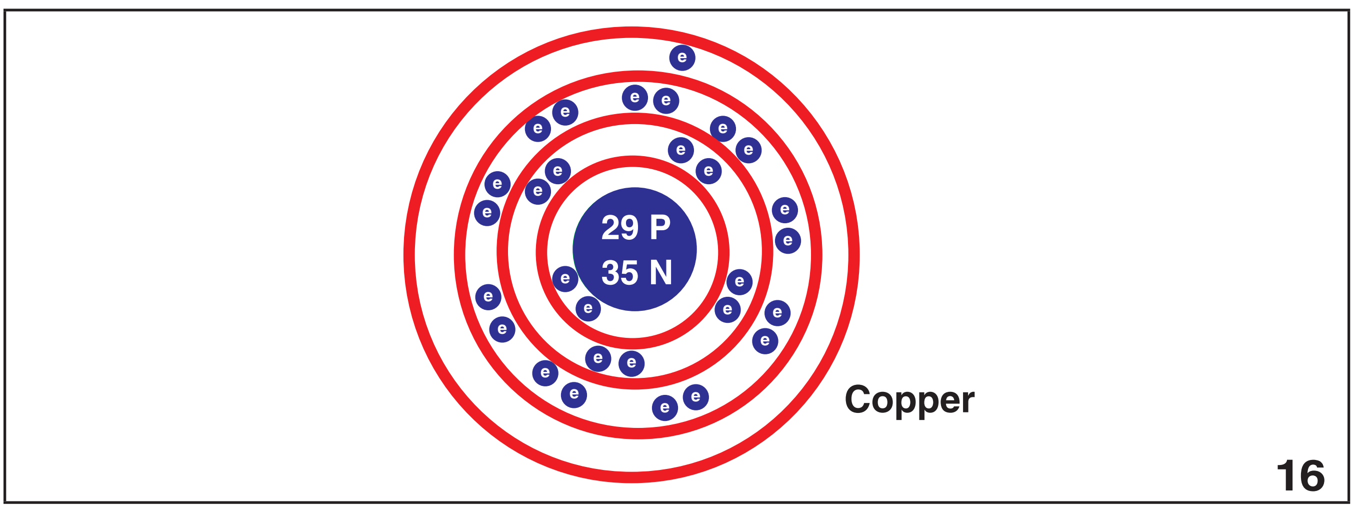


Nitrogen Molecule

Conductors

Conductors are elements or mixtures of elements that support the flow of electrons and have three or less electrons in their valence ring.

Copper, silver, gold, brass, iron, mercury, and aluminum are good examples of conductors.

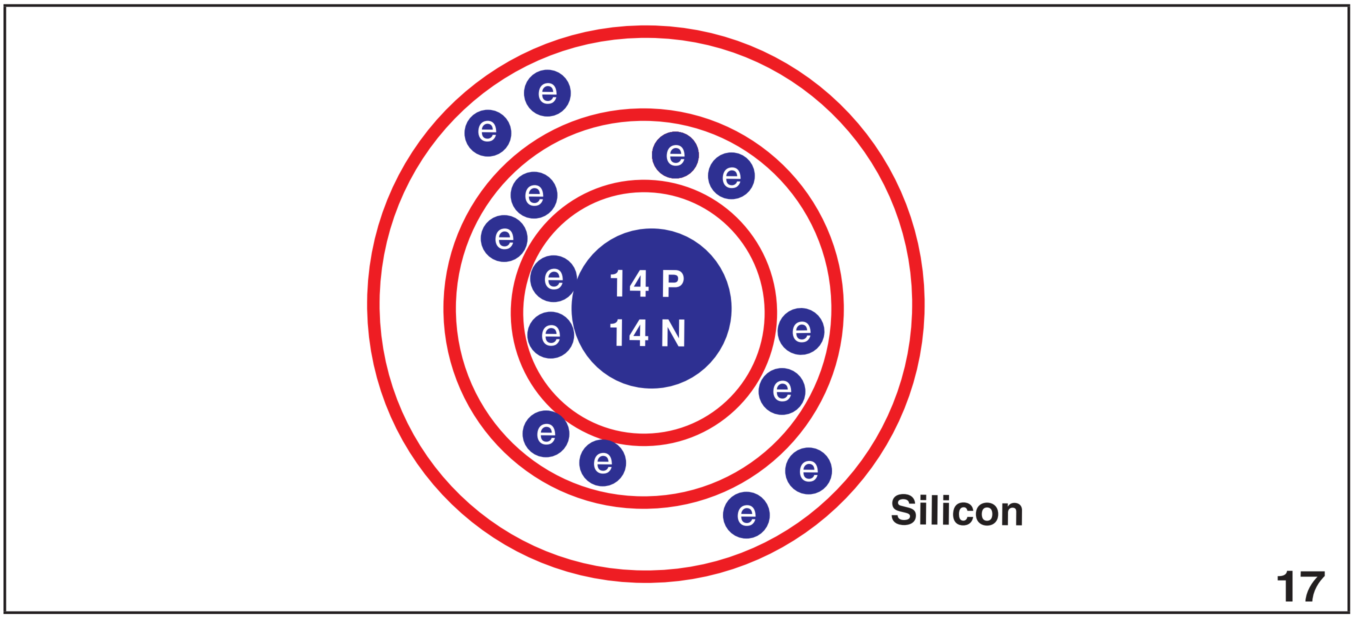


Copper Molecule

Semiconductors

Semiconductors are elements or mixtures of elements that are not good insulators or conductors and have four free electrons in their valence ring.

Silicon is the most popular semiconductor, and it is commonly found in sand.



Silicon Molecule

Electrical Theory and Diagnosis

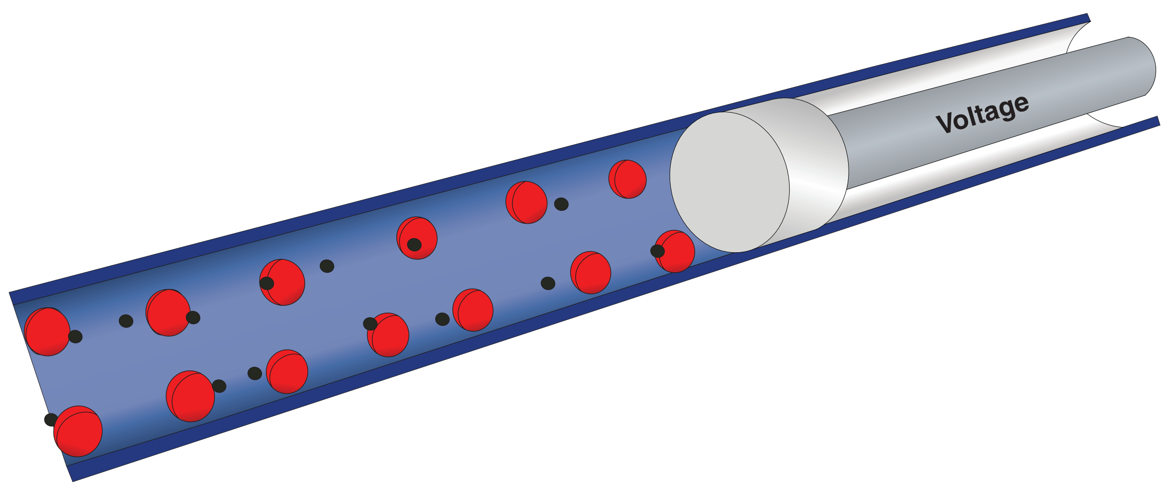
Electricity Defined

Electricity

Electricity is defined as the movement, or flow, of electrons through a conductor from one point in a circuit to another. The three basic outputs caused by electricity are heat, light, and magnetism.

Electricity is controlled by three basic units: voltage, amperage, and resistance. The results of electricity are easy to predict and measure because electricity is confined by the strict rules and relationships between voltage, amperage, and resistance.

Voltage (Electromotive Force)



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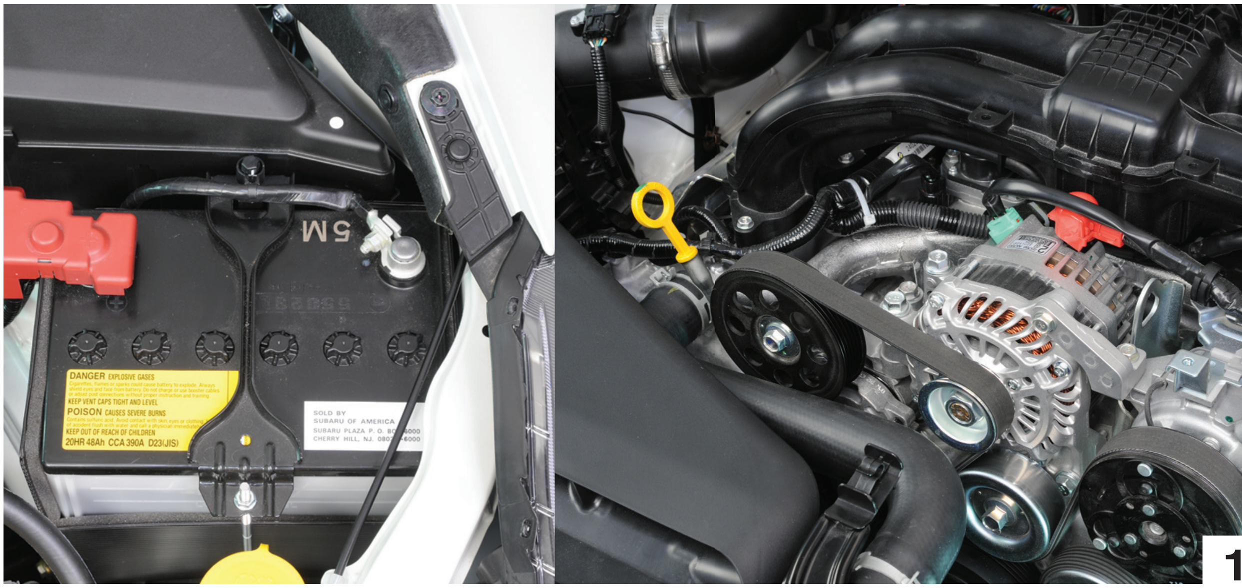
Voltage (Electromotive Force)

Voltage, also known as electromotive force (EMF), is defined as electrical pressure. Voltage is the electrical force that pushes the electrons from atom to atom through a conductor.

Voltage potential is the difference in electrical pressure between one end of a circuit and the other. The greater the difference in electrical potential (the difference between positive and negative), the greater the voltage force potential. Without this difference in voltage potential, current will not flow in a circuit. Voltage is consumed or used as it pushes the electrons through a conductor with resistance.

Voltage is measured in units called volts (V), using a voltmeter. Voltage measurements may commonly include the prefixes milli (m) or Kilo (K).

Voltage Sources



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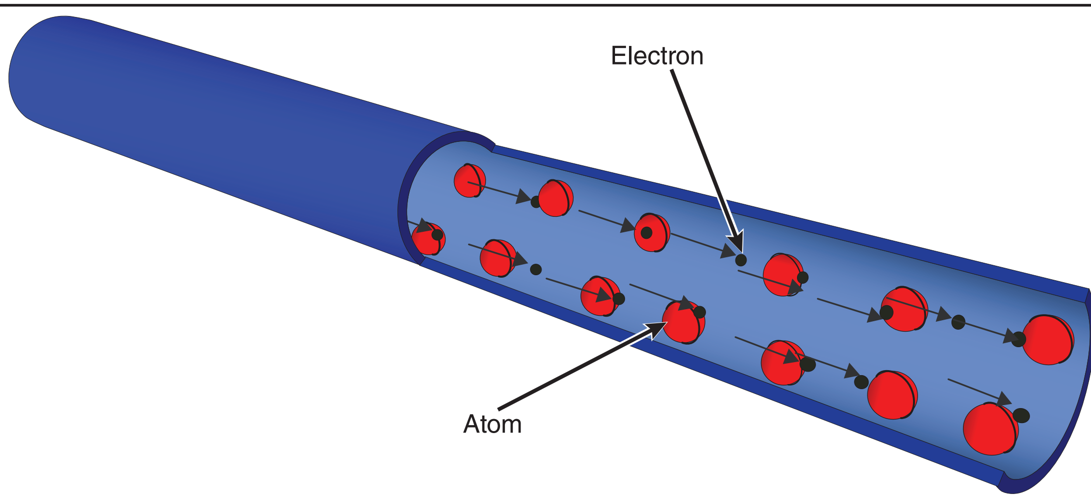
Voltage Sources

In automotive electrical systems, electrical potential is created by the electrochemical reaction that occurs within the vehicle battery and the electromechanical operation of the vehicle alternator. Other devices, such as piezo or thermocouples, may produce their own electromotive force in response to their particular environment.

Current (Amps)



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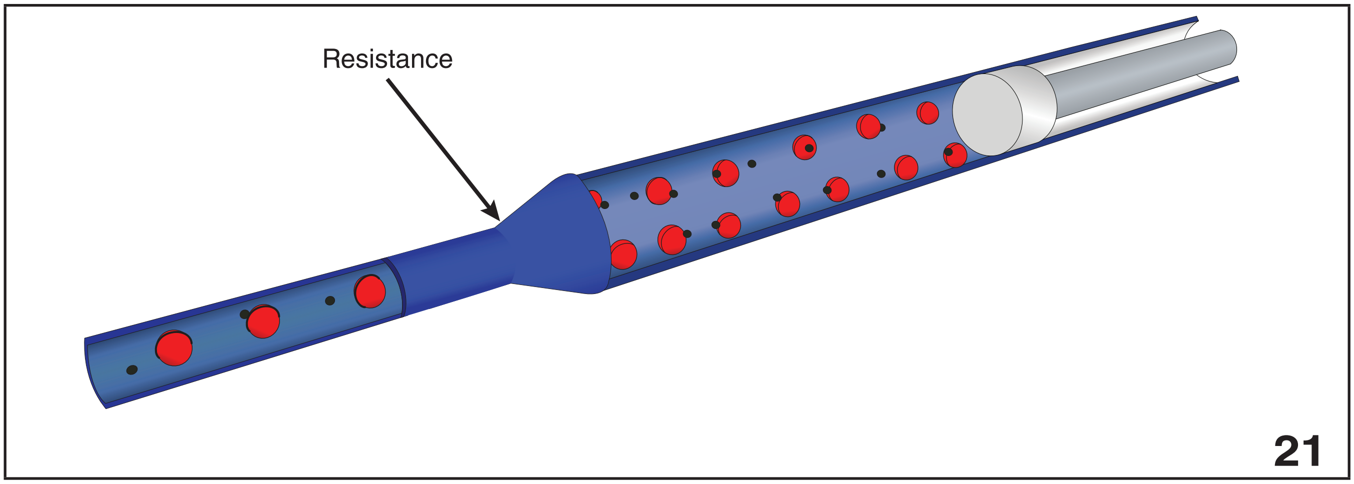
Current (Amps)

When electrons are flowing from one atom to another in one direction, an electrical current is created.

Current is the rate of electron flow past a given point in a circuit within one second. Current can only flow in a circuit that has a complete path. A circuit that contains an open will not allow current flow. Current is measured, in units called amps (A), using an ammeter. Current measurements may include the prefixes micro (µ) or milli (m).

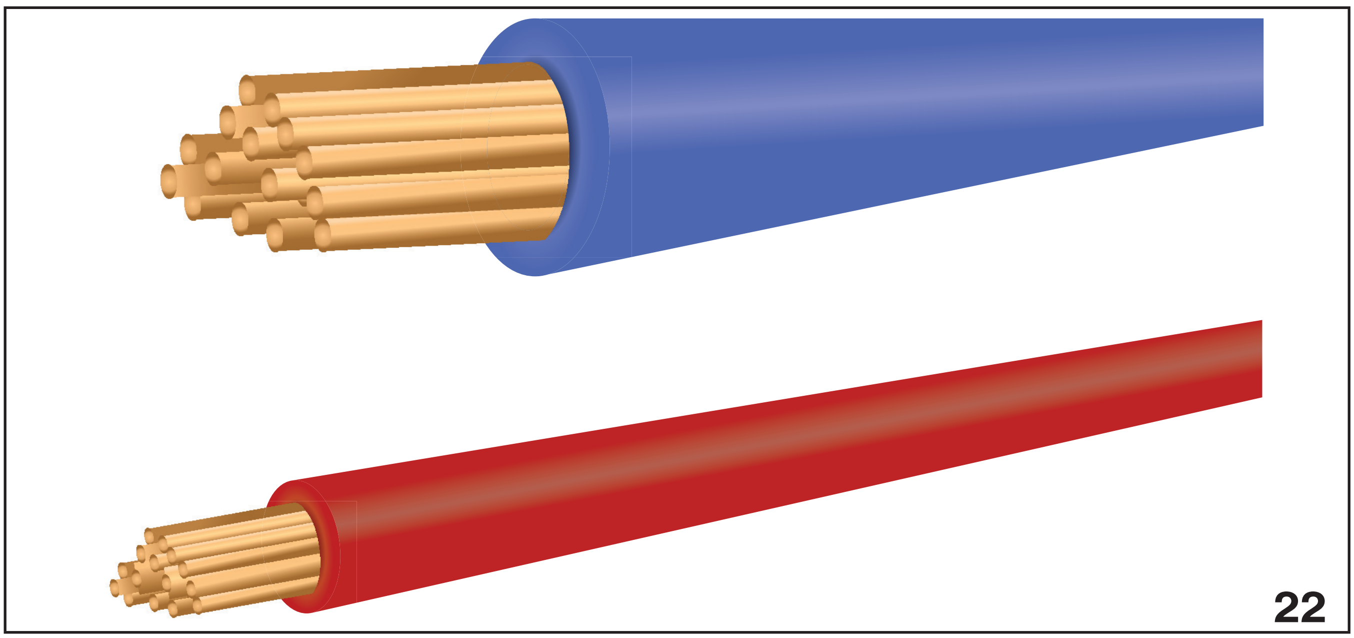
Resistance (Ohms)



Resistance (Ohms)

Resistance is the force that opposes or stops current flow in a circuit.

Resistance is measured, in units called ohms (Ω), using an ohmmeter. Resistance measurements may include the prefixes milli (m) kilo (K), or mega (M).

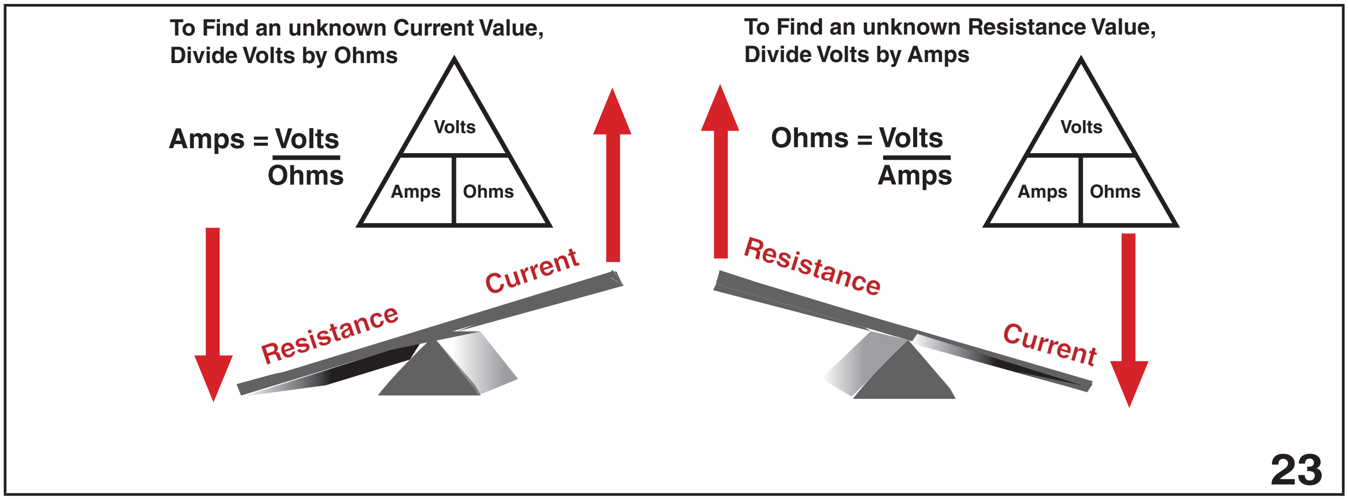


Conductor Size

Resistance can be affected by many factors, including the type of material used, condition of the material used, and the temperature of the material used. Additionally, the length and size of a conductor also affects resistance.

A shorter conductor will have a lower resistance than a longer conductor; if both conductors are the same gauge (size in diameter). In addition, a conductor with a smaller diameter has a higher resistance than a conductor with a larger diameter; if both conductors are the same length.

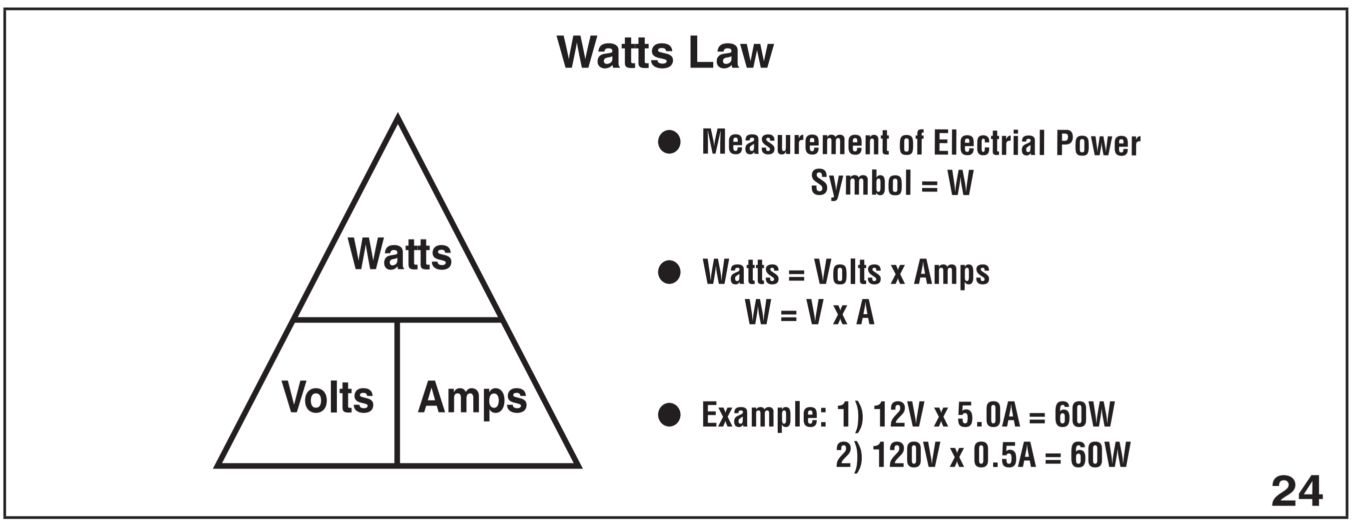
Two conductors with the same resistance may not have the same current carrying capability.



Resistance and Current

Ohm's law defines the relationship between voltage, resistance, and current. Ohm's law states that it takes one volt of electrical pressure to push one amp of current through one ohm of resistance. The formula for Ohm's law is typically expressed as (Volts = Amps x Ohms). As circuit resistance decreases, current flow increases; as circuit resistance increases, current flow decreases.

Power (Watts)



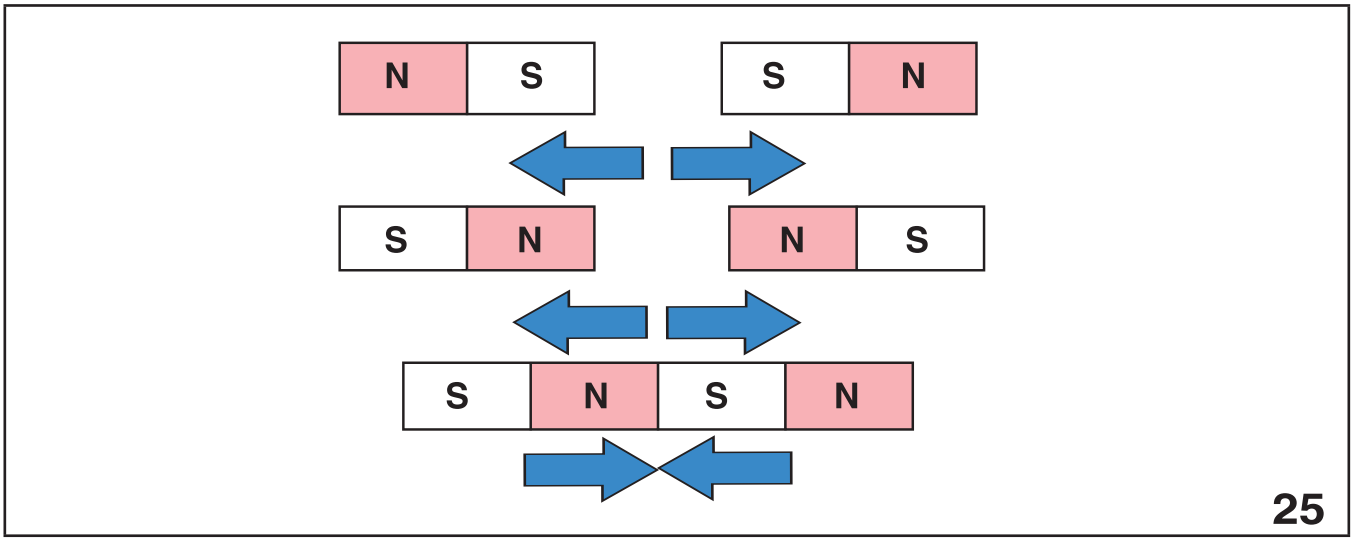
Power (Watts)

Power refers to the rate of doing work and is expressed in watts (W). A watt is equal to one volt multiplied by one amp. The mathematical formula for calculating power is expressed as Watts = Volts x Amps. The formula can also be interpreted as W = V x A.

Note: Some versions of the Ohm's law formula may use different values to represent electrical measurements however, the result remains the same. Examples of the variables uses are as follows:

Voltage (V)	**=**	**Electromotive Force (E)**
Amperage (A)	**=**	**Intensity (I)**
Ohms (Ω)	**=**	**Resistance (R)**
Wattage (W)	**=**	**Power (P)**

Magnetism



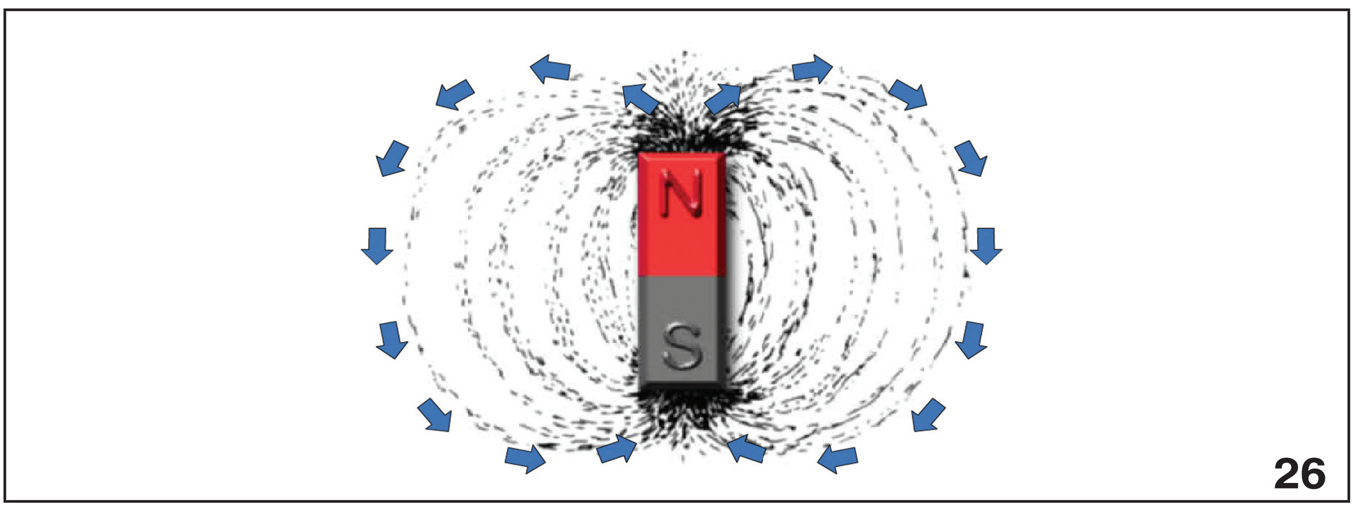
Magnetism

Magnetism is the force of attraction and repulsion caused by magnetic fields that are created by the movement of electrically charged particles. Magnetism naturally occurs in magnets and also occurs as a result of current flowing through a conductor.

Magnetism is the force used to create the electricity to recharge a vehicle's battery and make electric motors operate.

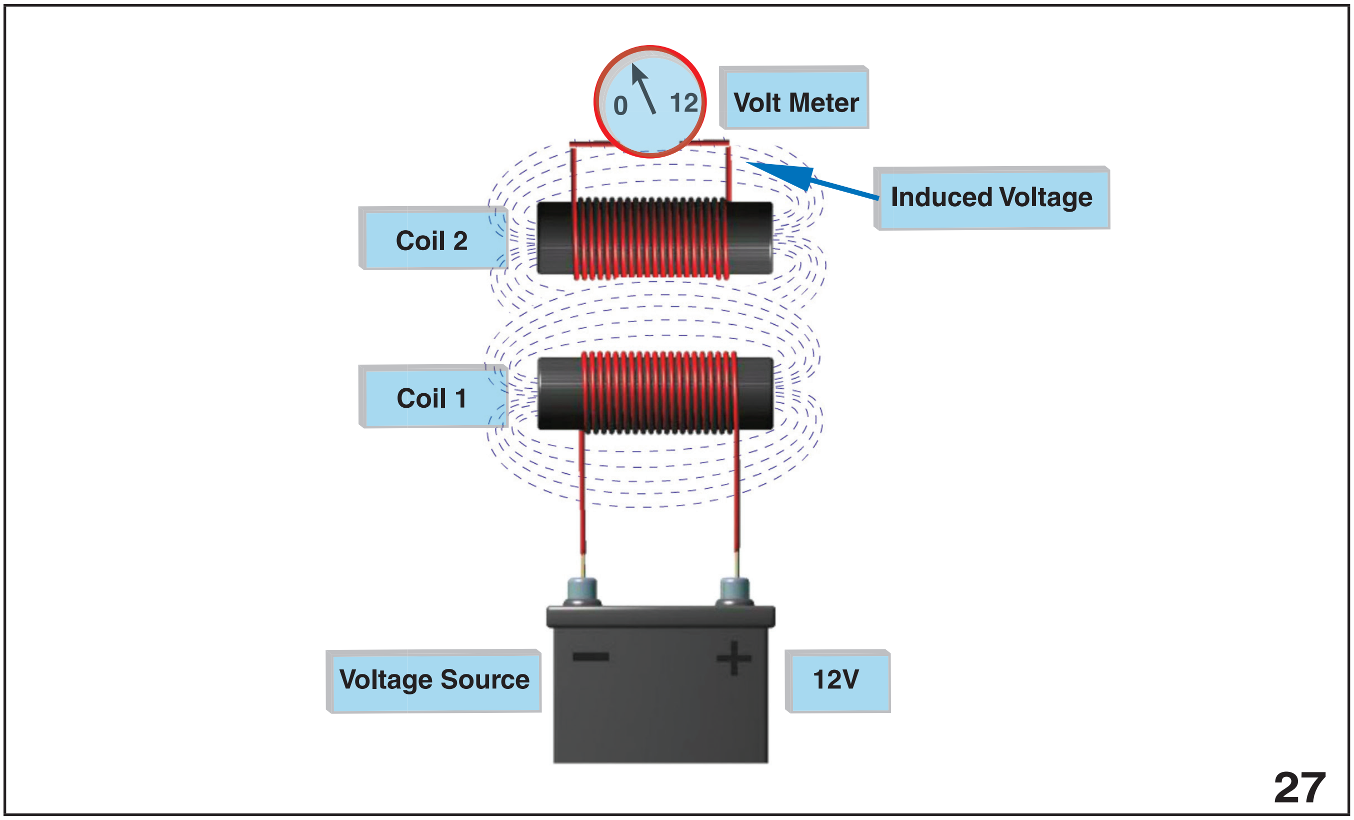
The two types of magnets commonly used in automotive applications include the permanent magnet and the electromagnet.

Permanent magnets do not require any assistance to keep their magnetic field, while electromagnets require an electric current to produce and maintain their magnetic field.



Lines of Magnetic Flux

Inductance



Induced Voltage

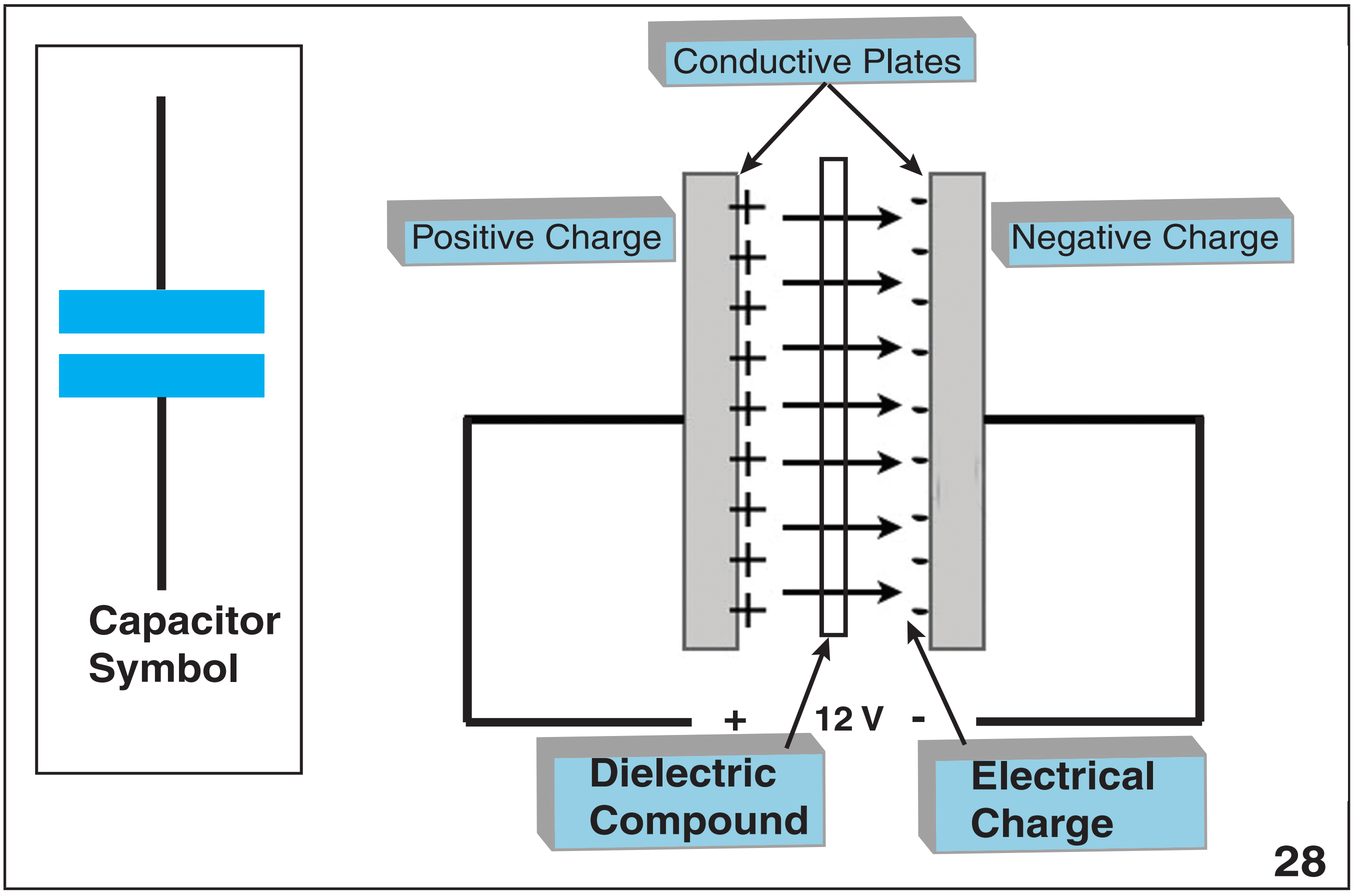
Inductance is a measurement of the effect of current flow in an electrical circuit when induction occurs. Induction is a magnetic process that produces a voltage in a conductor without directly contacting the conductor. Induction occurs by moving a conductor through a changing magnetic field or by moving the magnetic field across a conductor. Induction occurs when a change in the current flowing through a conductor changes the magnetic field that surrounds the conductor while current is flowing through it.

The changing of the magnetic field induces an additional voltage in the conductor (self-induction) and in nearby conductors (mutual induction). The current flow of the induced voltage occurs in the opposite direction of the current and magnetic field that generated the induced voltage.

Self induction is not ideal for automotive applications because of its tendency to cause voltage spikes and arcing. Self induction can occur when a current-carrying circuit is opened or switched off. Arcing can cause the contacts within switches to burn and even cause momentary operation of a circuit that was turned off. Self induction is also found in circuits with coils and electric motors. Capacitors and diodes are used in circuits where self induction exists to prevent voltage spikes and arcing from damaging the circuits.

Mutual induction is commonly found in automotive ignition coils, where the magnetic field created in the primary windings rapidly changes and creates a voltage in the secondary windings.

Capacitance



Capacitor Operation

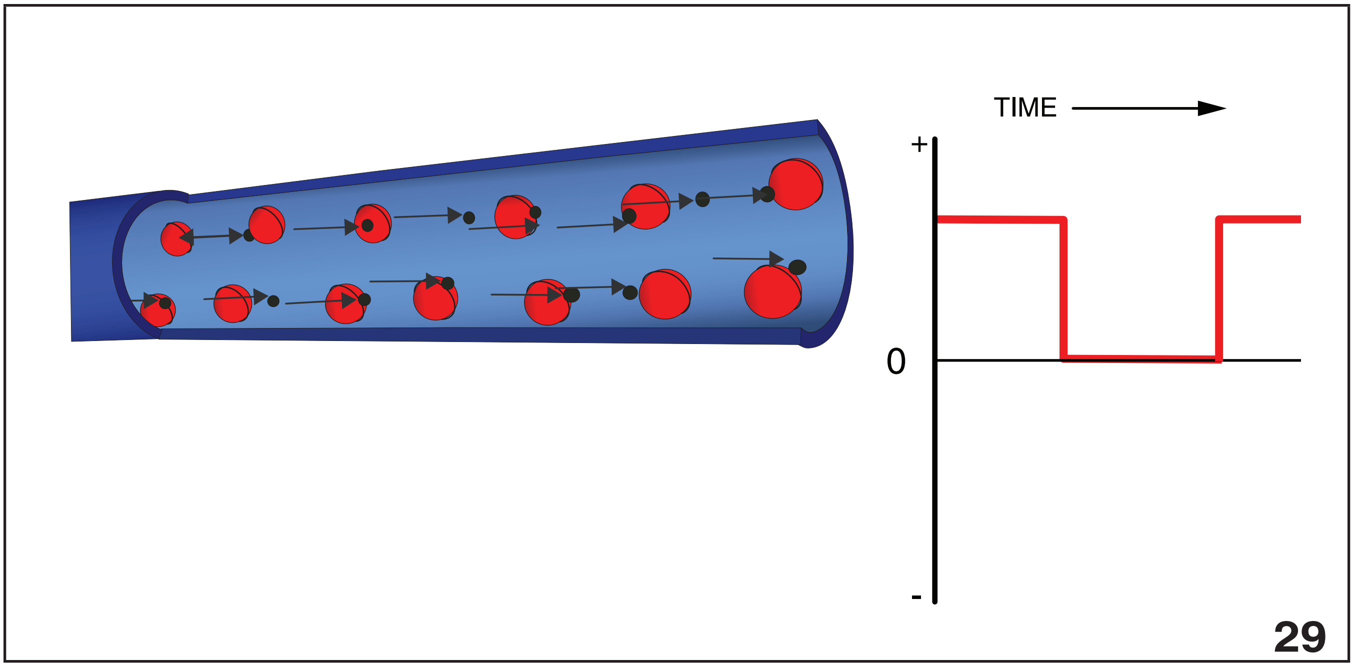
Capacitance is the ability of two conducting surfaces to temporarily store voltage. In some automotive applications, capacitors are used to store electrical charges.

Capacitance is measured and rated in farads. Microfarads are more commonly seen in automotive applications.

Current Types

Direct current and alternating current are the two types of electrical current flow.

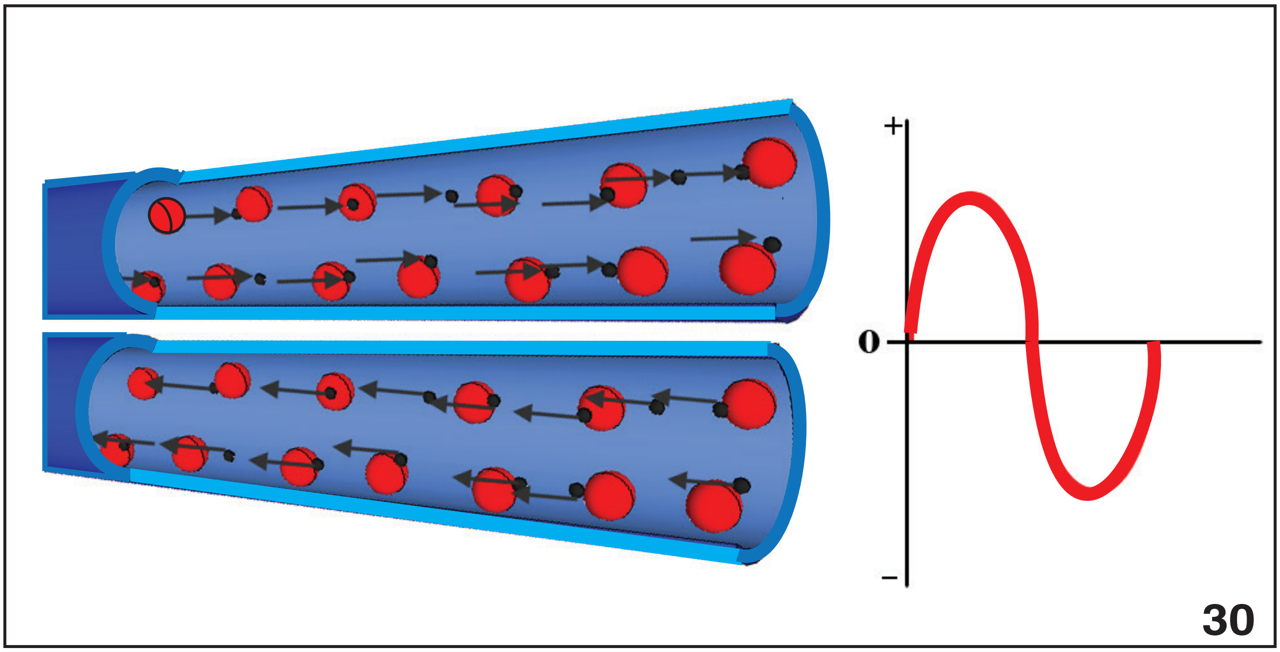
Direct Current (DC)



Direct Current (DC)

Direct current (DC) is produced by the difference in voltage potential between two point in a circuit. Direct current flows in one direction, and remains a constant value when the circuit is on (and a separate constant value when the circuit is off). Direct current produces a digital signal or a square waveform. One cycle of a digital signal occurs between two ON-times of a digital signal (or when the circuit is turned ON, turned OFF, and then turned ON again).

Alternating Current (AC)



AC Current (AC)

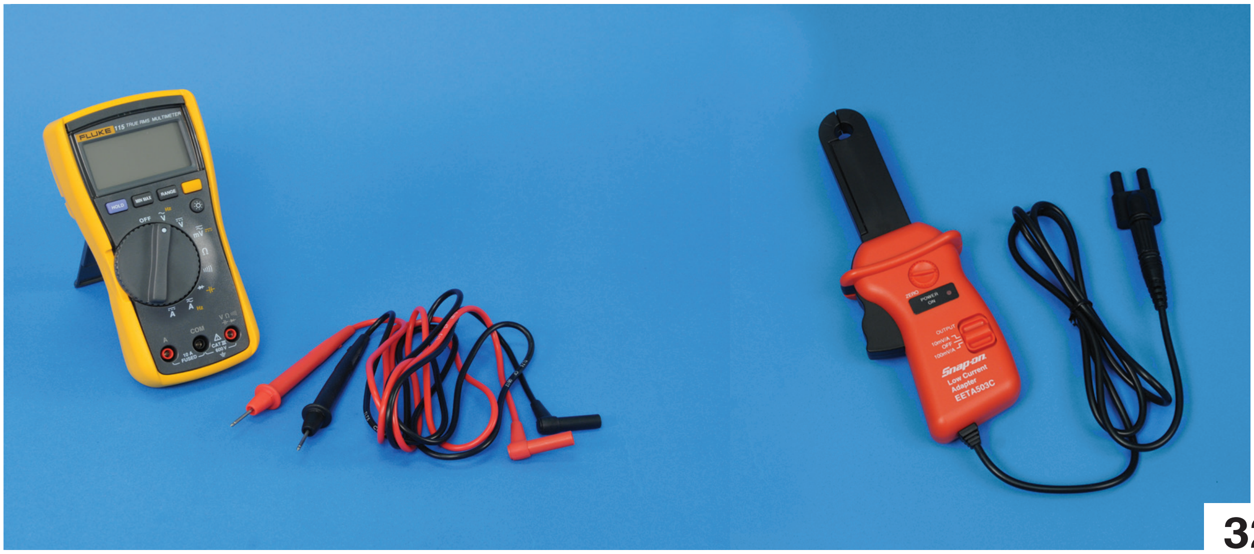
Alternating current (AC) is produced any time a conductor moves through a magnetic field, has a current that is not constant, and changes from positive to negative.

One cycle of an alternating current is called a sine wave. One cycle of a sine wave starts at zero, increases to a positive value, then falls to a negative value before finally returning to zero.

Digital Volt Ohm Meter (DVOM)

DVOM Overview

Purpose



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DVOM, Test Leads, and Inductive Clamp

DVOMs are diagnostic tools used to test the integrity of electrical circuits and circuit components. Typically, DVOMs have the ability to measure voltage, resistance, and current using a basic set of test leads. Some meters allow the use of an inductive amperage clamp as an alternate method for measuring circuit amperage. Additional features and accessories may be available depending on DVOM design and manufacturer. For this course, the Fluke 115 will be used.

DVOM Safety

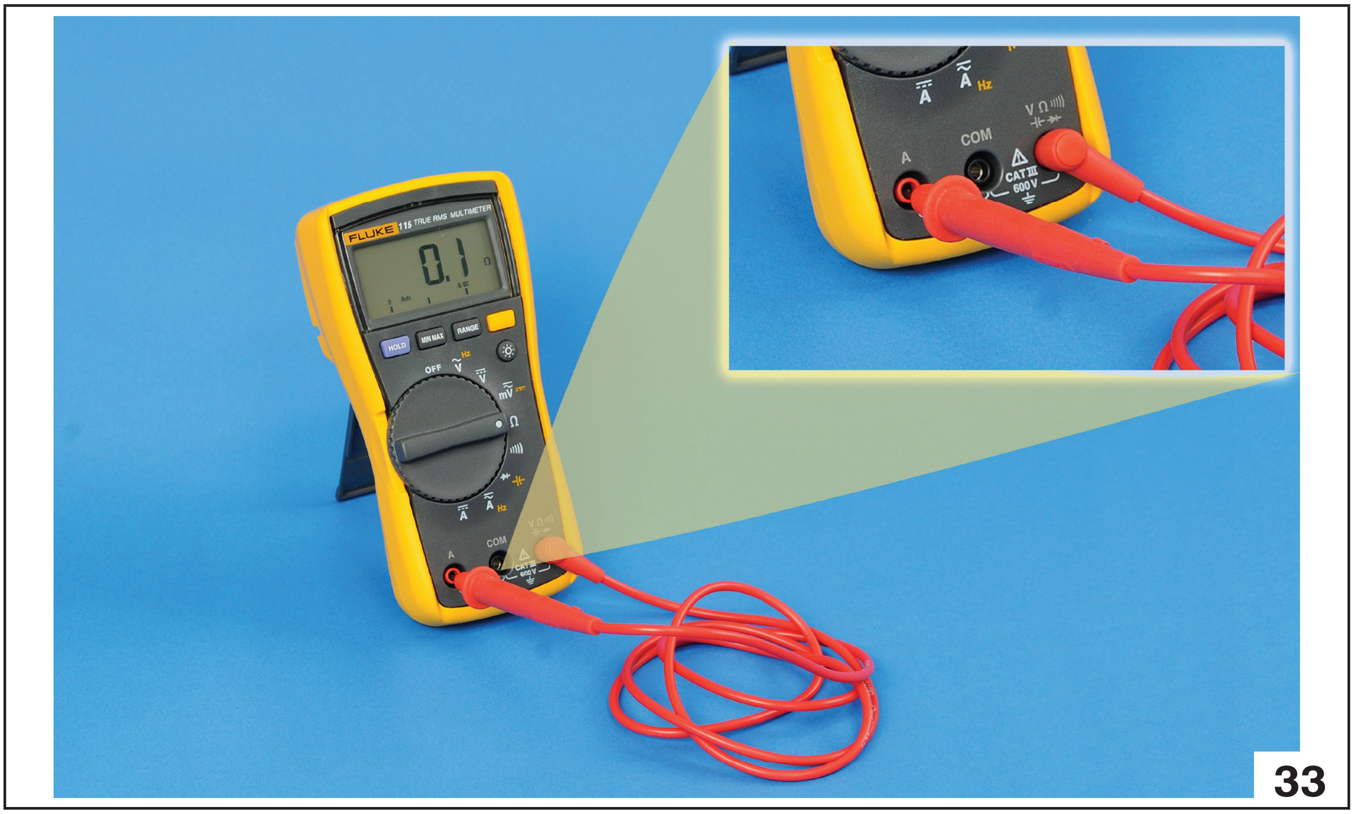
To avoid possible electric shock or personal injury, follow these guidelines:

Use the DVOM only as specified by the manufacturer, or the protection provided by the DVOM might be impaired.

- Verify DVOM operation prior to use.
- Do not use a DVOM that is not operating properly.
- Verify the integrity of the test leads by testing the leads for continuity prior to use.
- Do not use damaged leads.
- Do not use the DVOM if the readings are high or noisy.
- Always use the appropriate terminals, switch position, and range for the measurement being taken.
- Do not use the DVOM for measurements greater than specified by the manufacturer.
- Disconnect the circuit power and discharge all high-voltage capacitors before testing resistance, continuity, diodes, or capacitance.
- Do not use the DVOM around flammable gas or vapors.
- Some DVOMs provide circuit protection through the use of fuses built into the meter's internal circuit. If an over-current condition occurs, the fuse opens to prevent damage to the internal circuits of the DVOM.

DVOMs (by design) provide circuit protection while measuring circuits because they do not act as an additional load on the circuits being tested and prevent over-current events.

DVOM Testing



DVOM Testing

It is important to test the DVOM and the DVOM test leads prior to using the meter to take measurements. Failure to ensure the DVOM and leads are functioning properly can result in inaccurate measurements and possible personal injury.

There are various tests that can be performed to verify the integrity of the DVOM and all of its functions. Each set of tests may vary depending on manufacturer of the DVOM. At a minimum, testing the internal fuse(s) should be performed before each use to verify the integrity of the internal circuits.

Testing of the fuse on the Fluke 115 requires that the rotary switch is set to the Ω setting, and one test lead must be plugged into the port for measuring resistance. After the meter is set up, touch the test lead to the terminal in the 10A port to measure the resistance of the internal circuits. The measurement should be less than 0.5 ohms. If OL is displayed, then the fuse must be replaced and the test must be repeated. If any other measurement appears, the meter must be serviced.

DVOM Types

Low-impedance vs. High-impedance

Low-impedance vs. High-impedance

A DVOM's impedance is considered its operating resistance. When a meter is connected to a circuit, it behaves like an additional load on the circuit when current is flowing through it. A DVOM with a low impedance rating will draw current and act as an additional load on the circuit, which could affect circuit performance and result in inaccurate measurements.

To prevent adverse affects on circuit operation and the accuracy of circuit measurements, most DVOMs have a very high impedance rating, typically in the mega ohms scale. DVOMs with high impedance will have little or no current draw on the circuit and will result in more accurate measurements.

Low-impedance DVOMs should never be used to test electronic control modules, as the amperage draw caused by the meter being connected to the circuit could damage the circuit or circuit components.

DVOM Operation

DVOM Capabilities

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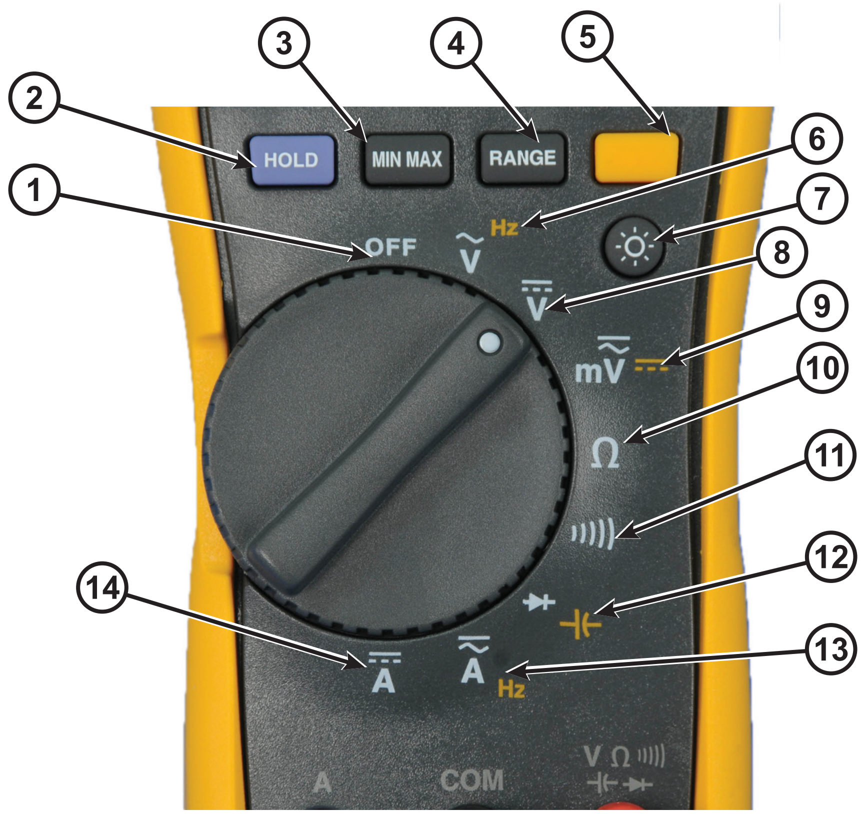
Fluke 115

The Fluke 115 meter has the following capabilities:

- Measure AC voltage from 6 mV to 600V
- Measure DC voltage from .1 mV to 600V
- Measure frequency from 5 Hz to 50 kHz
- Measure ohms from 0.1 Ω to 40 MΩ
- Measure AC current from 0.1A to 10A
- Measure DC current from 0.001A to 10A
- Perform a continuity check
- Perform a diode test
- Perform a capacitor check

DVOM Dial and Buttons



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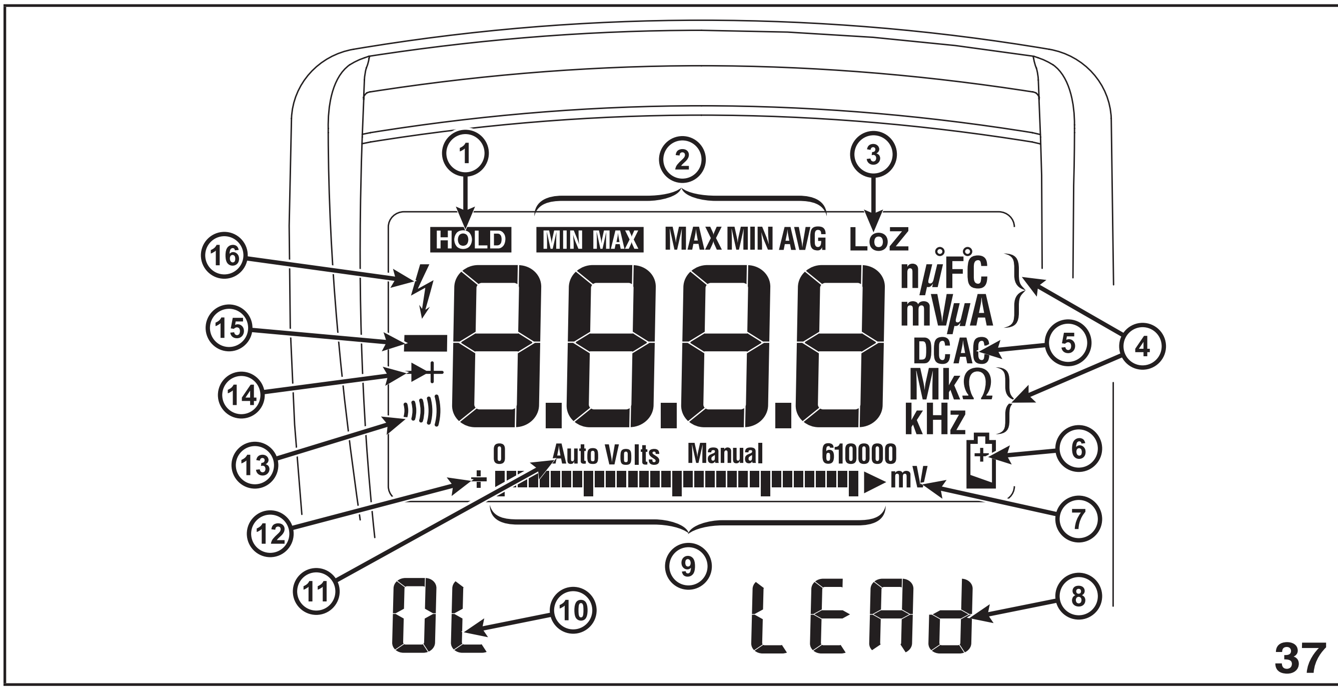
Fluke 115 Display

1	Off setting
2	Hold button used to freeze the meter display
3	Min/Max button used to capture the highest and lowest values
4	Range button used to change the display range between
5	The blank yellow button is used to disable automatic power-down
6	AC voltage setting (Hertz)
7	Backlight button used to toggle on and off the backlight
8	DC voltage setting
9	AC/DC millivolts setting
10	Ohms setting
11	Continuity setting
12	Diode test setting (Capacitance)
13	AC amperage setting (Hertz)
14	DC amperage setting

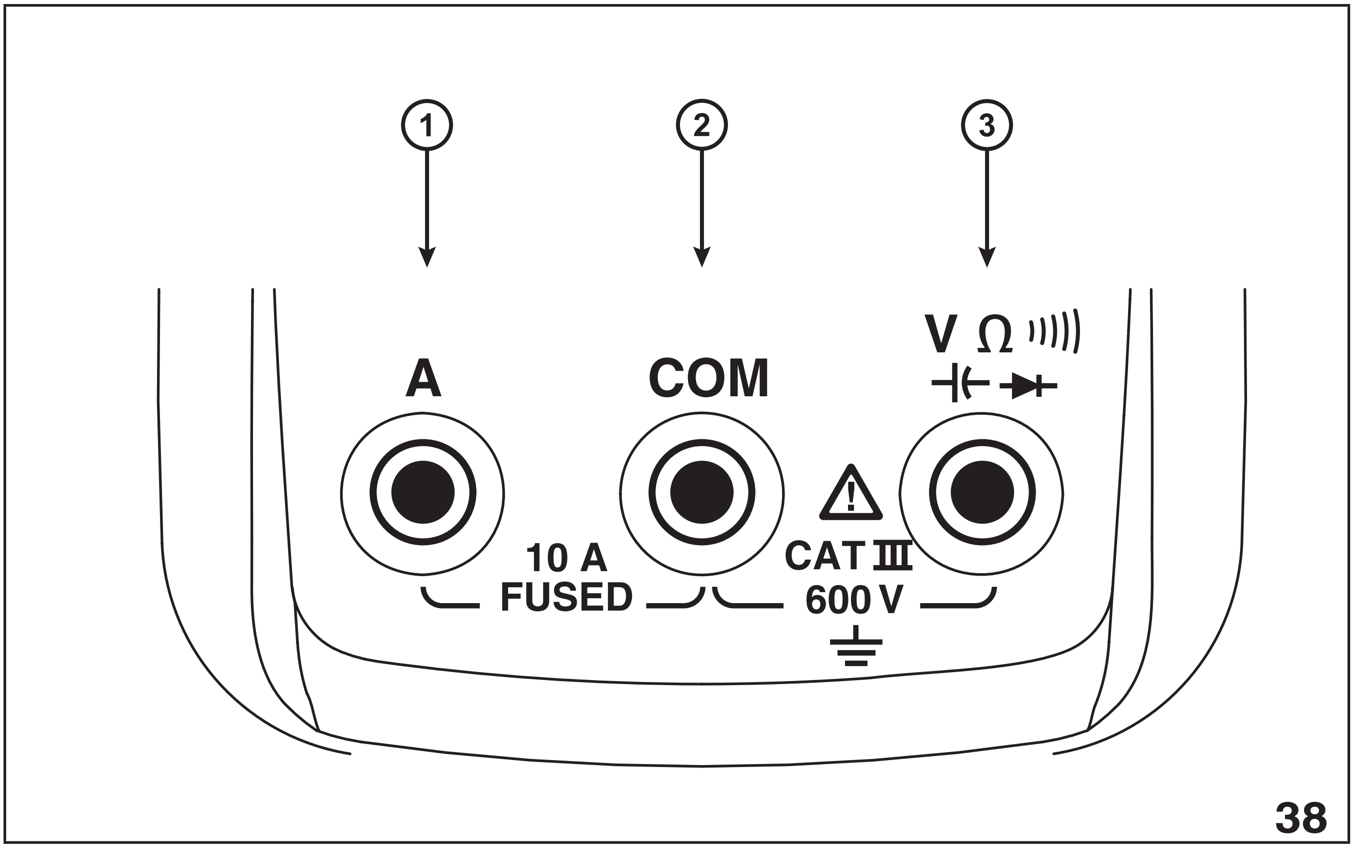
DVOM Display



Fluke 115 Display

1	Display hold enabled. Display freezes current measurement.
2	MIN MAX AVG mode enabled. Maximum, minimum, average or present measurement displayed.
3	The meter is measuring voltage or capacitance with a low input impedance.
4	Measurement units.
5	Direct current or alternating current.
6	Battery low warning.
7	Indicates the Meter's range selection.
8	(Symbol) Test lead alert. Briefly displayed whenever the meter's function switch is rotated to or from any A position.
9	Analog bar graph display
10	(Symbol) The input is too large for the selected range.
11	The meter is in the Auto Volts function. Auto ranging. The meter automatically selects the best resolution. Manual ranging. User sets the meter's range.
12	Bar graph polarity
13	The meter function is set to continuity
14	The meter function is set to diode test
15	Input is a negative value.
16	(Symbol) Unsafe voltage. Measured input voltage is greater than 30 V, or the voltage overload condition (OL).

DVOM Ports



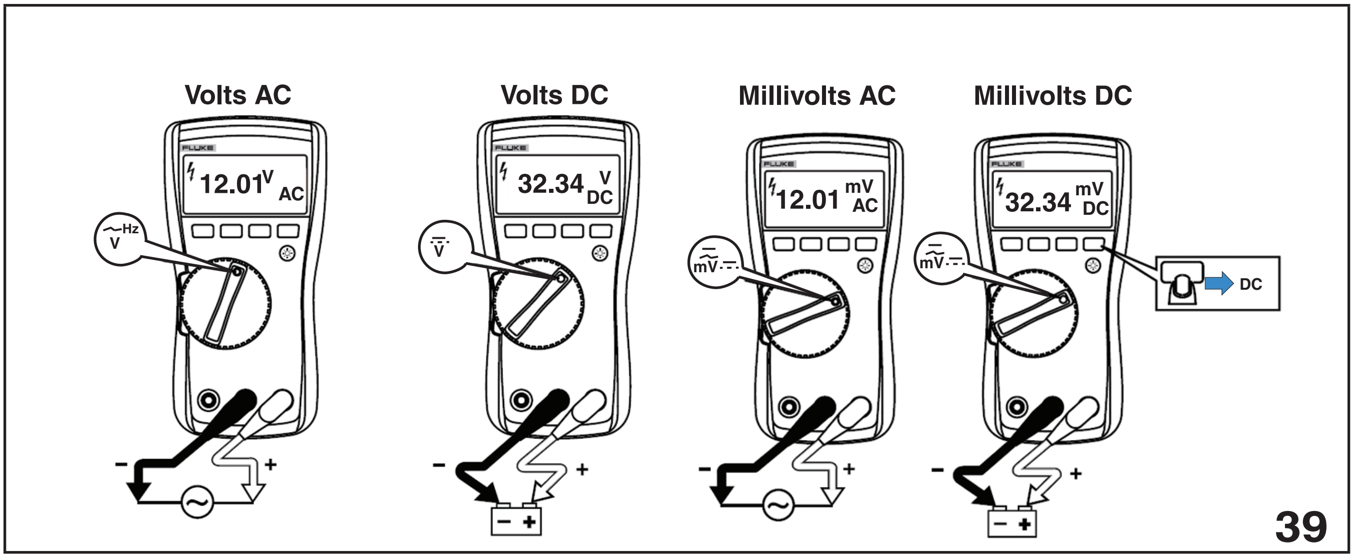
Fluke 115 Display

1	Input port used when measuring AC or DC amperage
2	Common port used for all measurements
3	Input port used when measuring voltage, resistance, continuity, capacitance, frequency, and testing diodes

Note: **Category III meters are primarily used on permanently installed loads such as distribution panels, motors, and three-phase appliance outlets.**

Electrical Measurements

Voltage Measurements



Volts

Voltage is a measurement of electrical pressure and is displayed using the letter (V). Voltage measurements may include one of the following prefixes: millivolt (mV), volt (V), kilovolt (kV), or megavolt (MV).

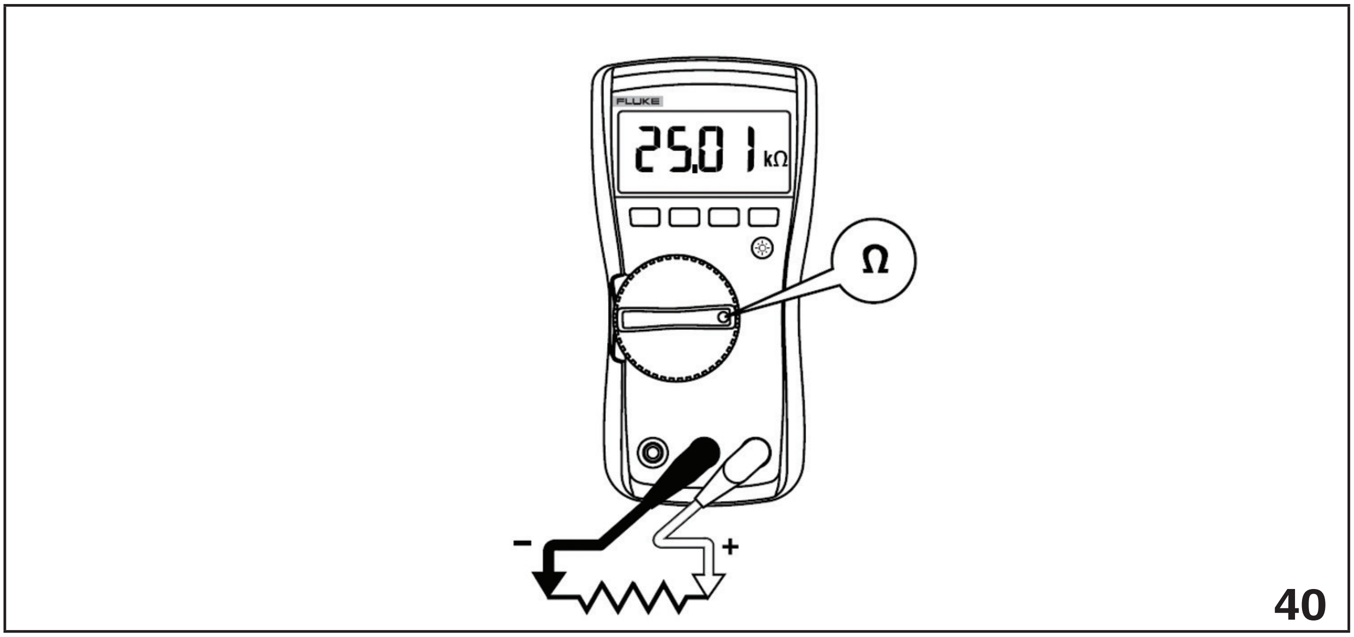
Voltage is measured with the meter leads placed in the appropriate ports on the DVOM and the dial set to measure DC or AC volts, depending on the circuit being tested. When measuring volts, the test leads must be connected in parallel or across the circuit (or portion of the circuit) being tested.

Available voltage is the number of volts present at any point in a circuit. To measure available voltage, place the COM lead of the DVOM at a known good ground and place the positive (red) test lead at any given point within the circuit. The measurement displayed on the meter indicates the amount of voltage that is present (or available) at the point where the red lead is placed.

Voltage drop is a voltage measurement that indicates a difference in voltage between two points in a circuit. Voltage drop measurements can be used in automotive diagnosis to pinpoint circuit and component faults. Circuit wiring will ideally have a voltage drop measurement of 0 volts, but are allowed to drop .01–.02 volts. In a normally operating circuit, the voltage drop measurement across a load device will equal the source voltage measurement.

Voltage drop can only be measured when current flow is present in the circuit being measured.

Resistance Measurements



Ohms

Resistance is measured in ohms and is displayed using the omega symbol (Ω). Resistance measurements may include one of the following prefixes: ohms (Ω), kilo ohms (kΩ), or mega ohms (MΩ).

Resistance is measured with the meter leads placed in the appropriate ports on the DVOM and the dial set to the omega symbol (Ω). When measuring resistance, the circuit must be off. Never connect an ohmmeter to a powered circuit/component. The test leads must be across the circuit or component when measuring resistance.

In order to measure resistance, the DVOM introduces current through the circuit and calculates the resistance by determining the amount of voltage dropped across the load.

Amperage Measurements

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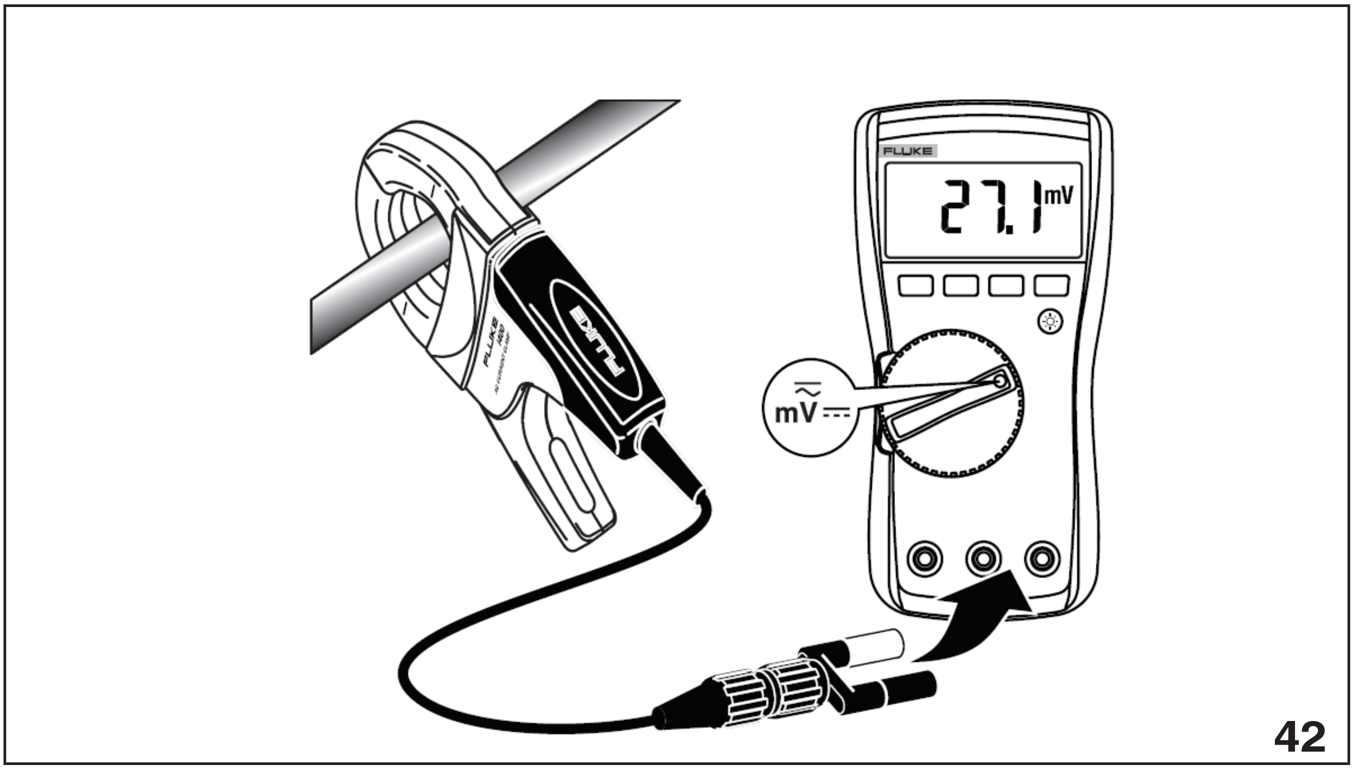
Amps

Amperage is a measurement of current flow and is displayed using the letter (A). Current measurements may include one of the following prefixes: microamp (μA), milliamp (mA), or amp (A).

Amperage is measured with the meter leads placed in the appropriate ports on the DVOM and the dial set to measure DC or AC amperage, depending on the circuit being tested. When measuring amperage, first turn the circuit off, then connect the test lead in series or in-line with the circuit being tested, and finally turn the circuit ON again.

Never connect an ammeter in parallel or damage to the meter or circuit may occur. Because a meter also acts as a load, connecting a meter in parallel creates an additional path in the circuit, and allows more current to flow in the circuit.

The easiest place to measure circuit amperage is at the circuit protection device or at an easy-to-access connector in the circuit. Remember that there will be zero current flow in a circuit that has an open condition.



Inductive Clamp

An inductive amperage clamp (also called an amp clamp) can be used as an alternative method for measuring circuit amperage. An amp clamp measures current flow based on the strength of the magnetic field created around the wire as current passes through it.

While using the inductive clamp, ensure the clamp is positioned around only one wire at a time, or current flow through additional wires in the clamp will interfere and result in an inaccurate measurement. To help prevent damage to the meter, always start with the meter set to the highest amperage setting first and then scale down until the proper setting is found. It is also good practice to measure amperage as close to the voltage source as possible to obtain the most accurate measurement when using an amp clamp.

Electrical Units

(M)	(K)				(m)	(µ)
Millions (Mega)	Thousands (Kilo)	Base	Tenths	Hundredths	Thousandths (milli)	Millionths (micro)
1,000,000.0	1,000.0	1.0	0.1	0.01	0.001	0.000001

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Electrical Units

Understanding the relationship of the number and the unit of the number being measured with the DVOM is important. The number scale illustrated above, which is based on the decimal place-value system, shows numeric values associated with electrical measurements based on the placement of the number in relationship to the decimal point.

The numbers to the left of the decimal represent whole numbers. The first three digits to the left of the decimal point are expressed as base units (V for volts, A for amps, and Ω for resistance). The first digit is the ones place, the second is the tens place, and the third is the hundreds place.

The 4th, 5th, and 6th digits to the left of the decimal are expressed in thousands and are displayed with the kilo prefix (KV for kilovolts and KΩ for kilo ohms). Amperage in automotive electrical systems do not reach the thousands scale.

The 7th, 8th, and 9th digits to the left of the decimal are expressed in millions and are displayed with the mega (M) prefix (MΩ for mega ohms). Voltage and amperage in automotive electrical systems do not reach the millions scale.

The numbers to the right of the decimal are considered fractions of a number or decimal numbers. The 1st digit to the right of the decimal is expressed in tenths (or 1/10) and is displayed in base units.

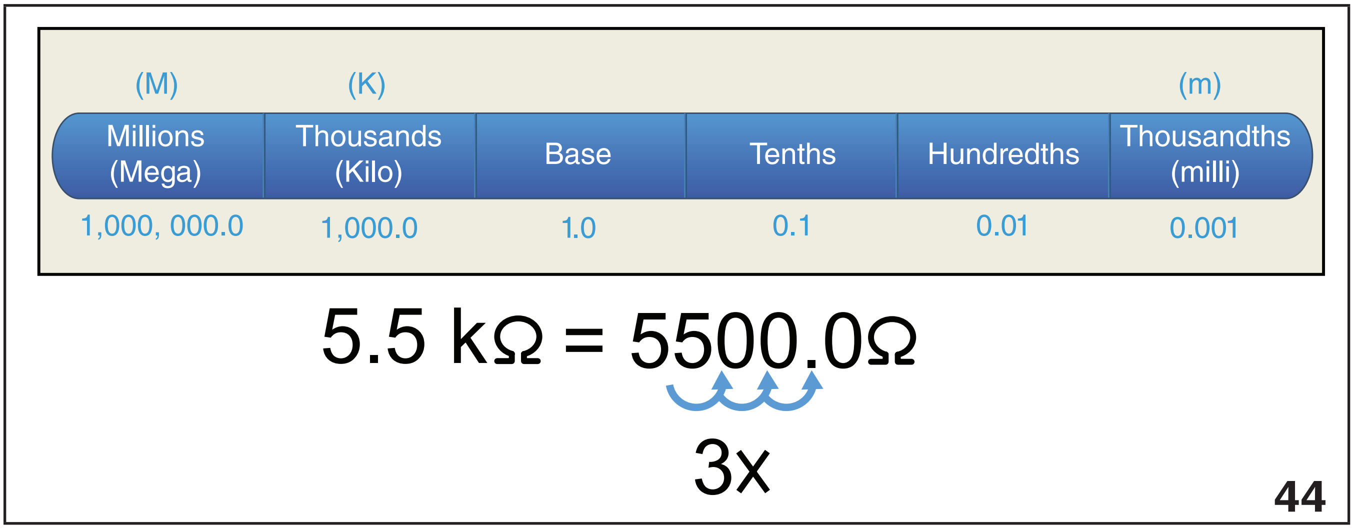
The 2nd digit to the right of the decimal is expressed in hundredths (or 1/100) and is also displayed in base units.

The 3rd digit to the right of the decimal is expressed in thousandths (or 1/1000) and is displayed with the milli (m) prefix (mV for millivolt, mA for milliamp, and mΩ milliohms).

Unit Conversions

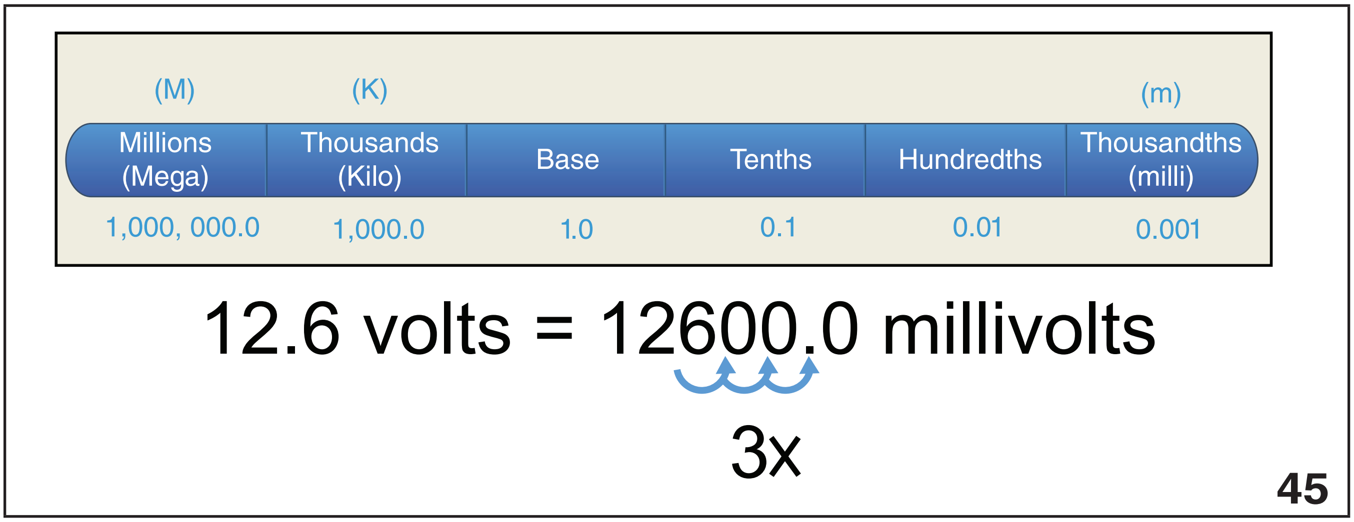
Unit conversions are important for comparing a measurement to a specification. Sometimes the measurement taken will be expressed in a unit that differs from the specification. Being able to convert the measured value to the same unit called out by the specification can make comparing the measured value to specification less difficult.

Unit conversion can be done by performing basic multiplication or division, or more simply, by moving the decimal place of the value that needs to be converted. The number of decimal place movements required is determined by the number of place values between the two numbers being compared.



Unit Conversions

To convert a smaller number to a larger number, multiplication must be performed or more simply the decimal place must be moved to the right. Converting a larger number to a smaller number is just the opposite and requires the use of division or a movement of the decimal place to the left.



Unit Conversions

For instance, to convert a number from volts (a larger number) to millivolts (a smaller number) requires that the number be multiplied by 1000 (because 1 volt is equal to 1000 millivolts). A simpler method for performing the same conversion is to move the decimal place of the number to the right three places (because there is a difference of three decimal places between the base unit volts decimal place and the millivolts decimal place, and the conversion is going from a larger number to smaller number).

Example

253 mV is measured and the specification is 0.0–0.2V.

253 mV = .253V (which indicates that the measured value is higher than specification)

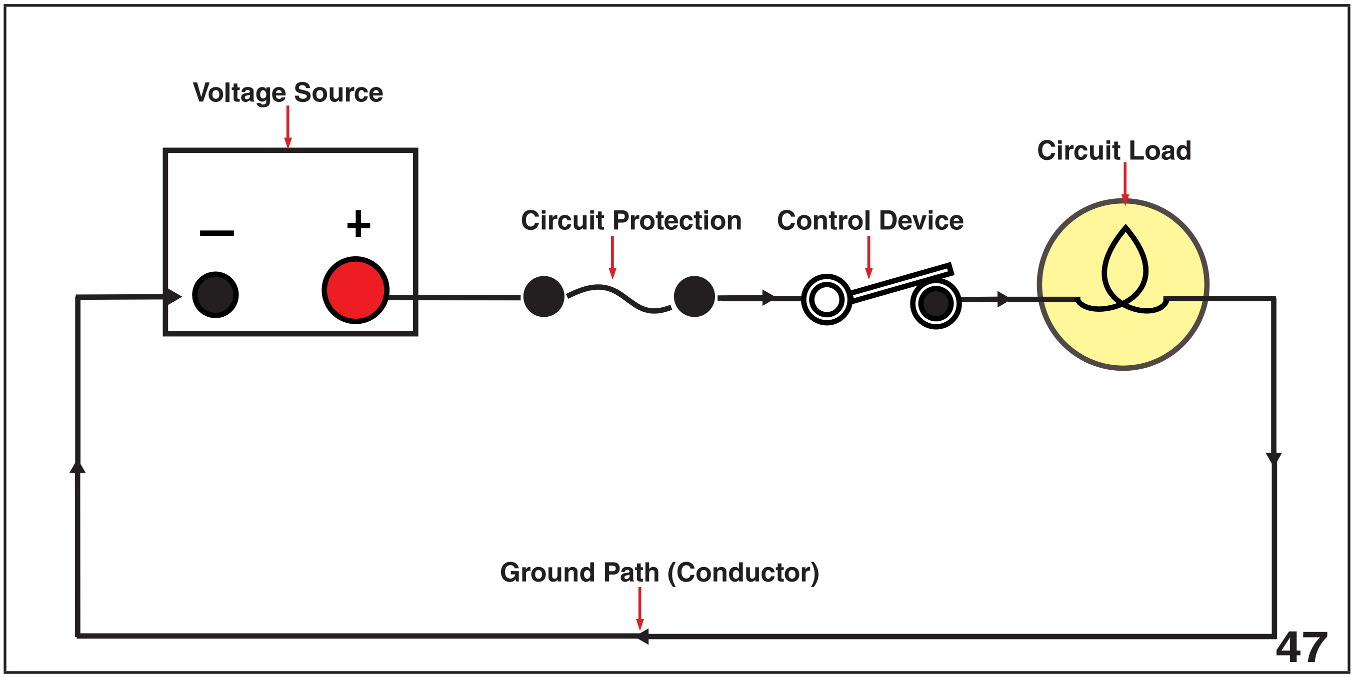
Example

.036V is measured and the specification is 34–38 mV

.036V = 36 mV (which indicates that the measured value is within specification)

Circuits

Basic Circuits



Basic Circuit

Basic Circuit Construction

A basic automotive circuit consists of a power source, a circuit protection device, a load device, a control device, and conductors that connect between each of the components.

In order for the basic circuit to operate, there must be a continuous path for current to flow from the power source through the load device and back to the power source.

Basic Circuit Operation

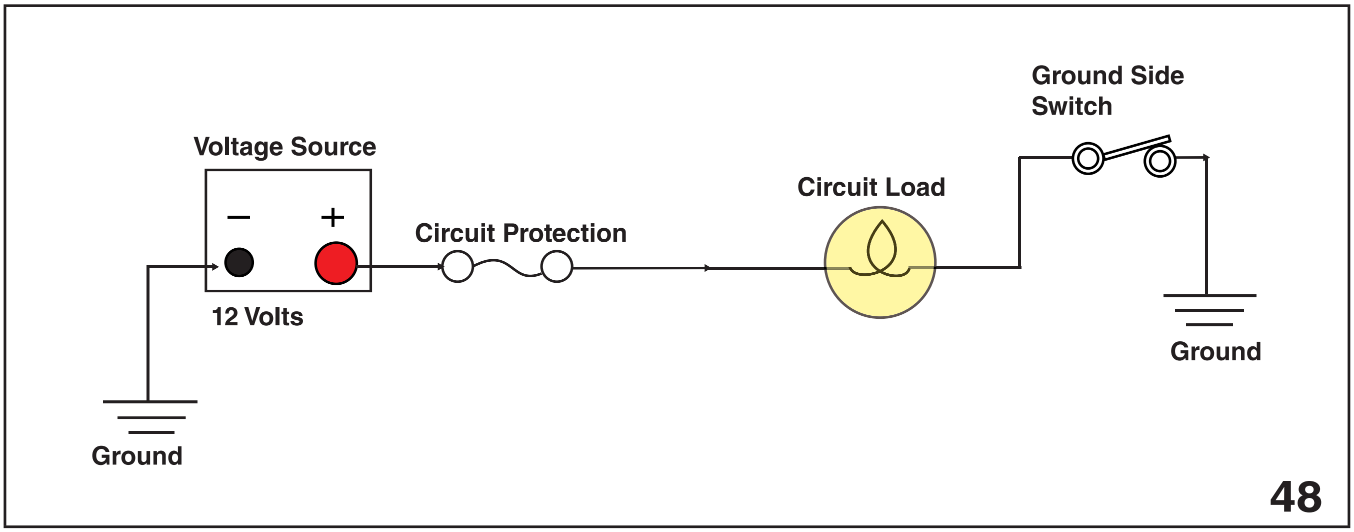
In the basic circuit shown, current only flows through the circuit when the switch in the ON position. With the switch ON, the circuit has a complete path for current to flow, and the circuit is referred to as a closed circuit. When the switch is OFF, current flow stops because the path is no longer complete, and the circuit is referred to as an open circuit.

With the switch ON, current flows from positive terminal of the battery through the load device and returns back to the negative terminal of the battery through a ground path.

Series Circuits

A series circuit consists of only one path for current to flow and includes one or more load devices. A failure of any one component in a series circuit will cause the entire circuit to not operate.

Series Circuit Rules

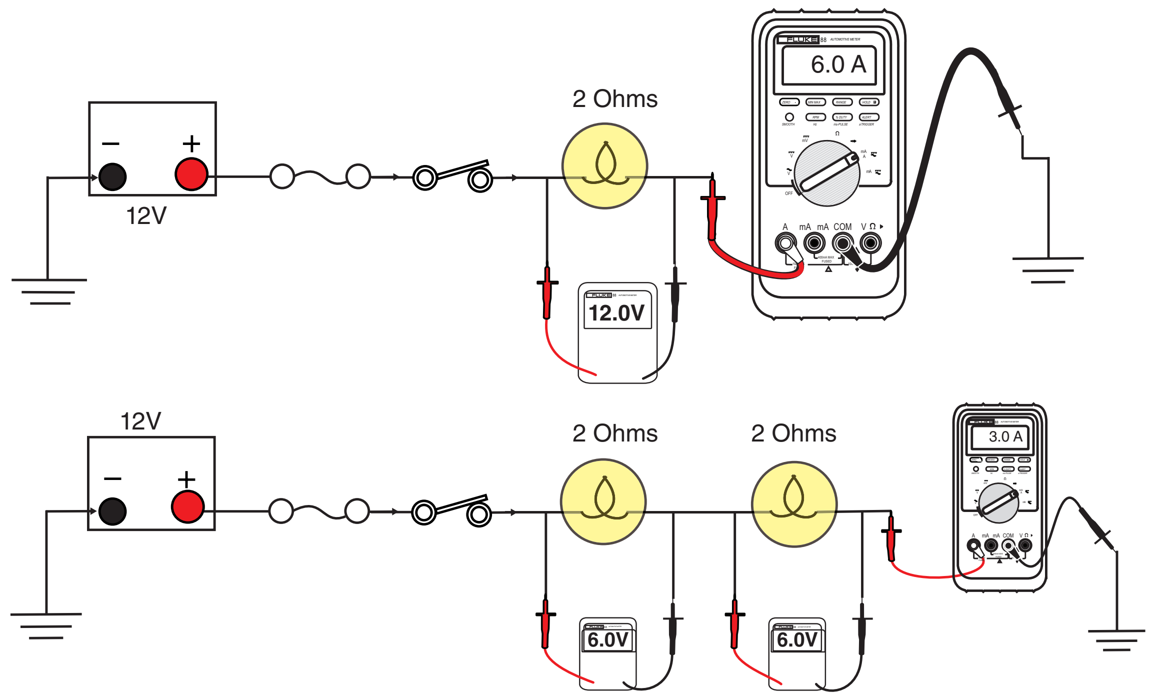


Series Circuits

Series circuit rules include:

- Total circuit resistance is the sum of all resistances
- Current is the same at any point within the circuit
- Voltage drop across each load device will vary according to it’s share of the total circuit resistance, i.e. half the resistance will drop half the voltage.
- The sum of the voltage drop of each load device equals source voltage

Ohm's Law and Watt's Law Relationship



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Ohm's and Watt's Law (Series Circuits)

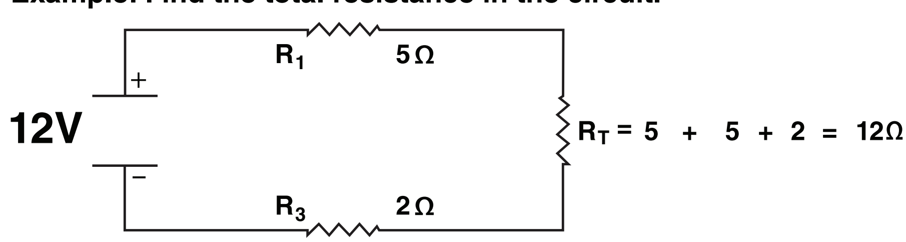
In a series circuit with a constant voltage, an increase in resistance (ohms) causes a decrease in current flow (amperage). Adding additional load devices to a series circuit reduces the performance of each load device within the circuit.

A series circuit supplied with 12 volts and a 1-ohm bulb will have a current flow of 12 amps and the bulb will operate at 12 watts. Adding an additional 1-ohm bulb to the same circuit increases the circuit resistance and reduces the current flow to 6 amps. Because each bulb has the same resistance value, each bulb operates at the same power; in this example, 6 watts each.

Calculating a Series Circuit's Total Resistance

$$R^T = R_1 + R_2 + R_3$$

Example: Find the total resistance in the circuit.



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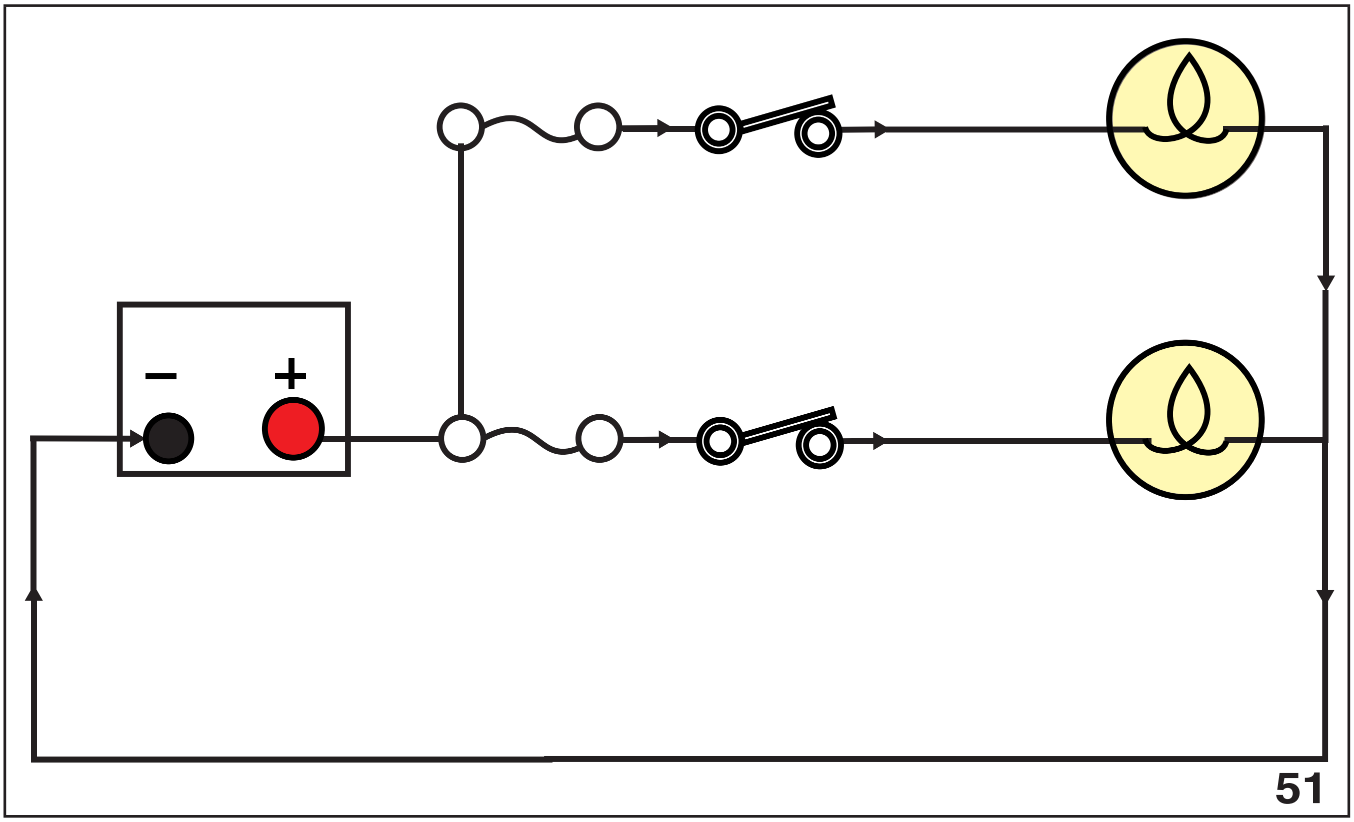
Series Resistance Formula

Parallel Circuits

A parallel circuit has more than one path for current to flow and includes one or more load devices in each path. A failure of a component in one path of a parallel circuit will not necessarily affect the operation of the load devices in the other parallel paths.

Parallel Circuit Rules

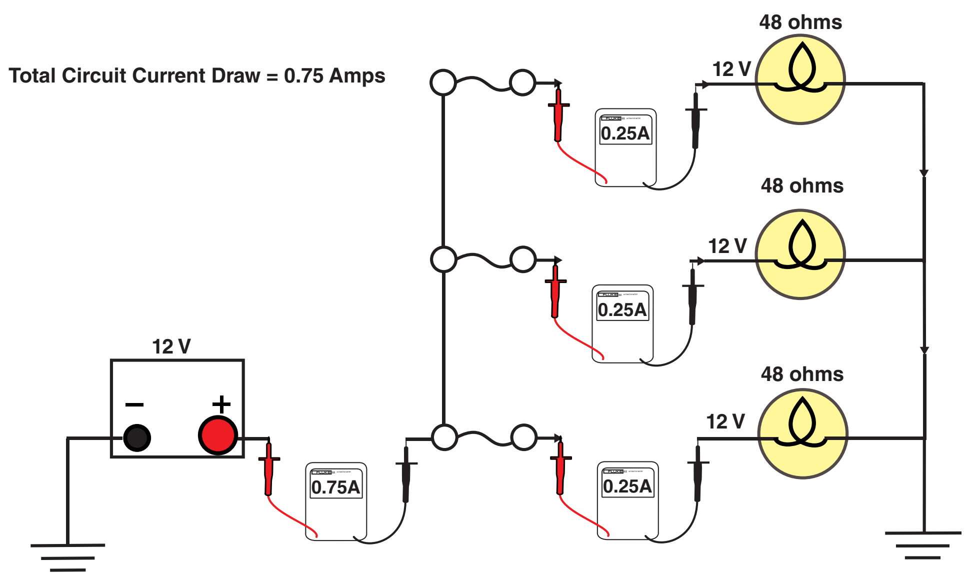


Parallel Circuits

Parallel circuit rules include:

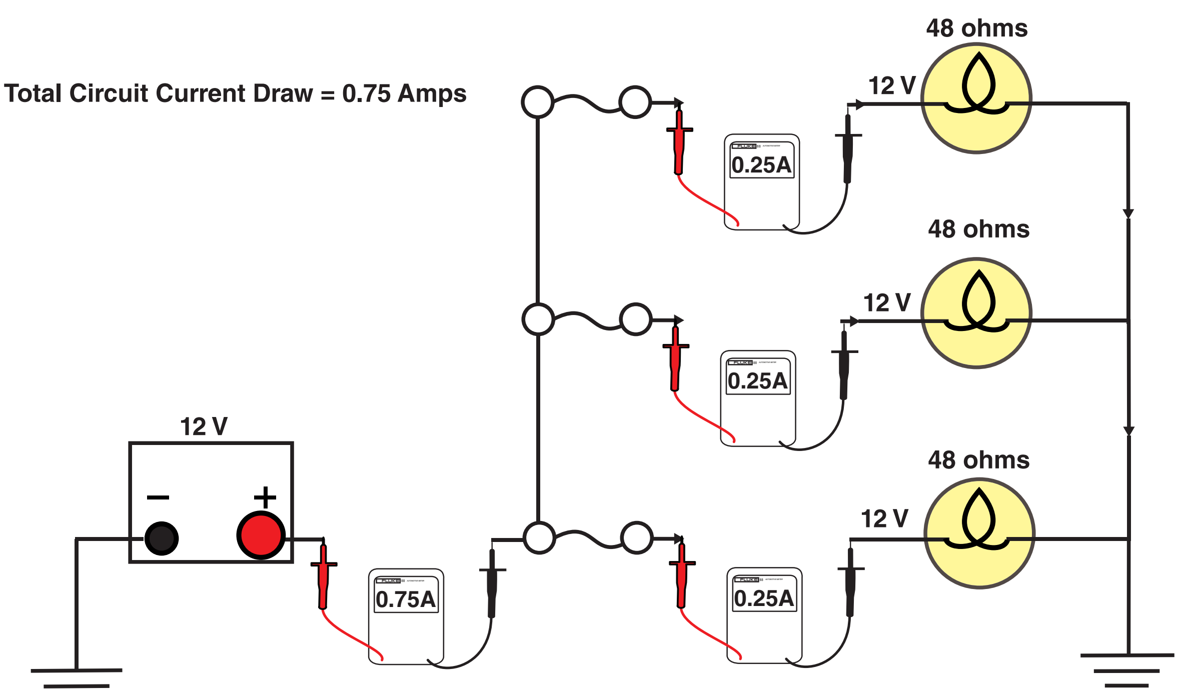
- Voltage applied to each parallel path is the same.
- Voltage consumed by each leg will be the same as voltage applied to each leg; however, if the path has more than one load device, the voltage consumed by each device will depend on the resistance of each load device in that path.
- Total parallel resistance is always less than the smallest resistance in any branch.
- Total circuit current equals the sum of the current in each parallel path.
- Current flow through each parallel path is dependent on the resistance of the load devices in each path.

Ohm's Law and Watt's Law Relationship



Ohm's and Watt's Law (Parallel Circuits) - Ohms

In a parallel circuit, voltage provided to each path is the same. The loss or addition of a path does not affect voltage applied to the other paths. However, total current flow of the circuit and the current flow in each parallel path are affected. Adding additional load devices to a parallel circuit reduces total circuit resistance and increases current flow in the circuit.

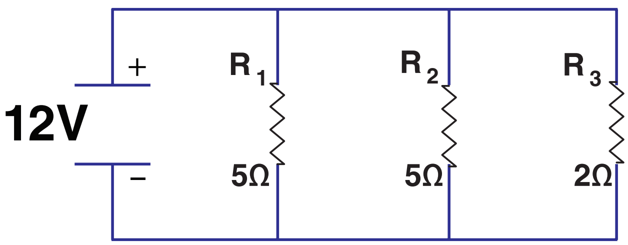


Ohm's and Watt's Law (Parallel Circuits) - Amps

Calculating a Parallel Circuit's Total Resistance

$$R^T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Example: Find the total resistance in the circuit below.



$$R_T = \frac{1}{\frac{1}{5} + \frac{1}{5} + \frac{1}{2}} = \frac{1}{.2 + .2 + .5} = \frac{1}{.9} = 1.11$$

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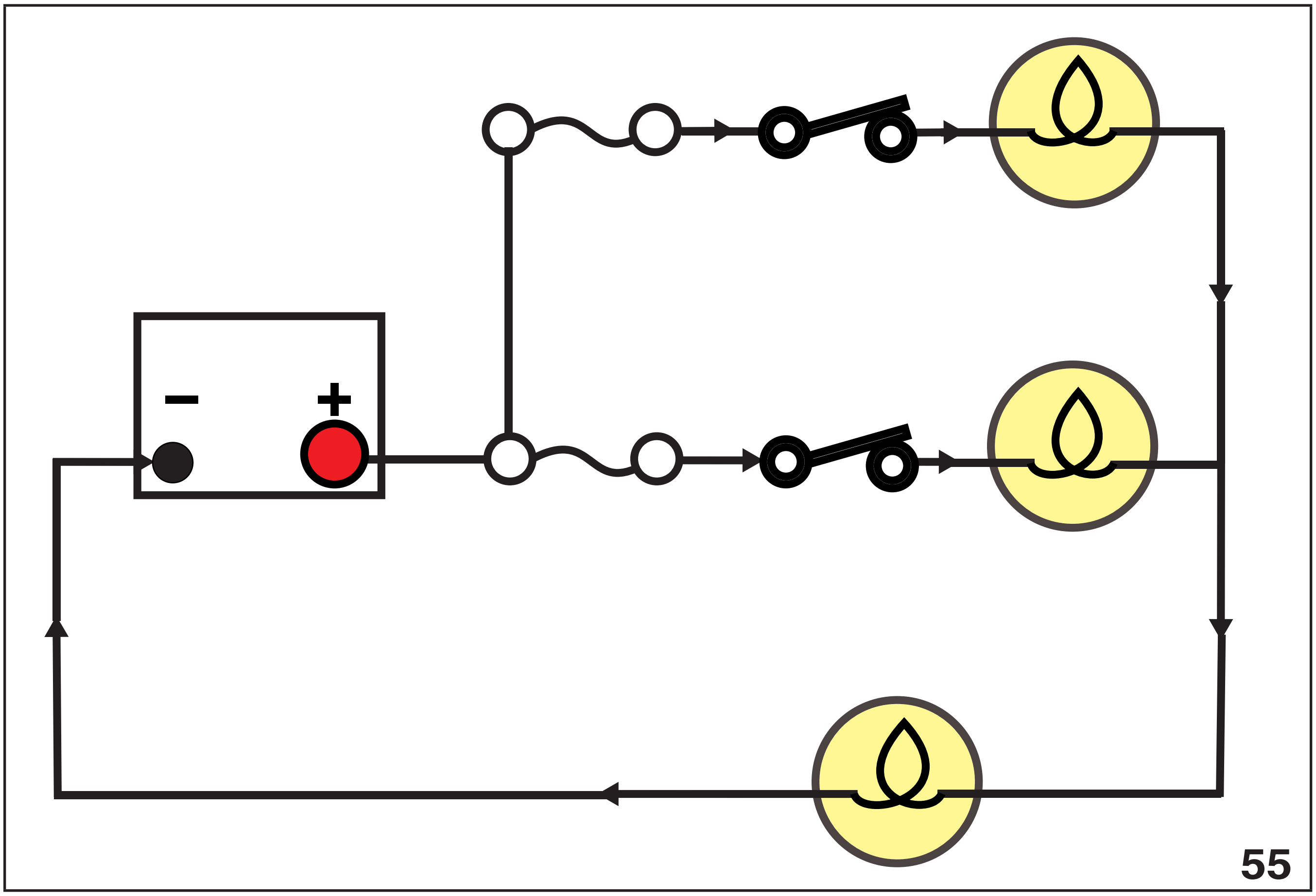
Parallel Resistance Formula (Reciprocal Method)

Combination Circuits (Series-parallel)

A combination circuit, also known as a series-parallel circuit, is a combination of both a series and a parallel circuit where some load devices are in series and others load devices are in parallel. A failure of any component in the series portion of the circuit will disable the entire circuit.

Combination Circuit Rules

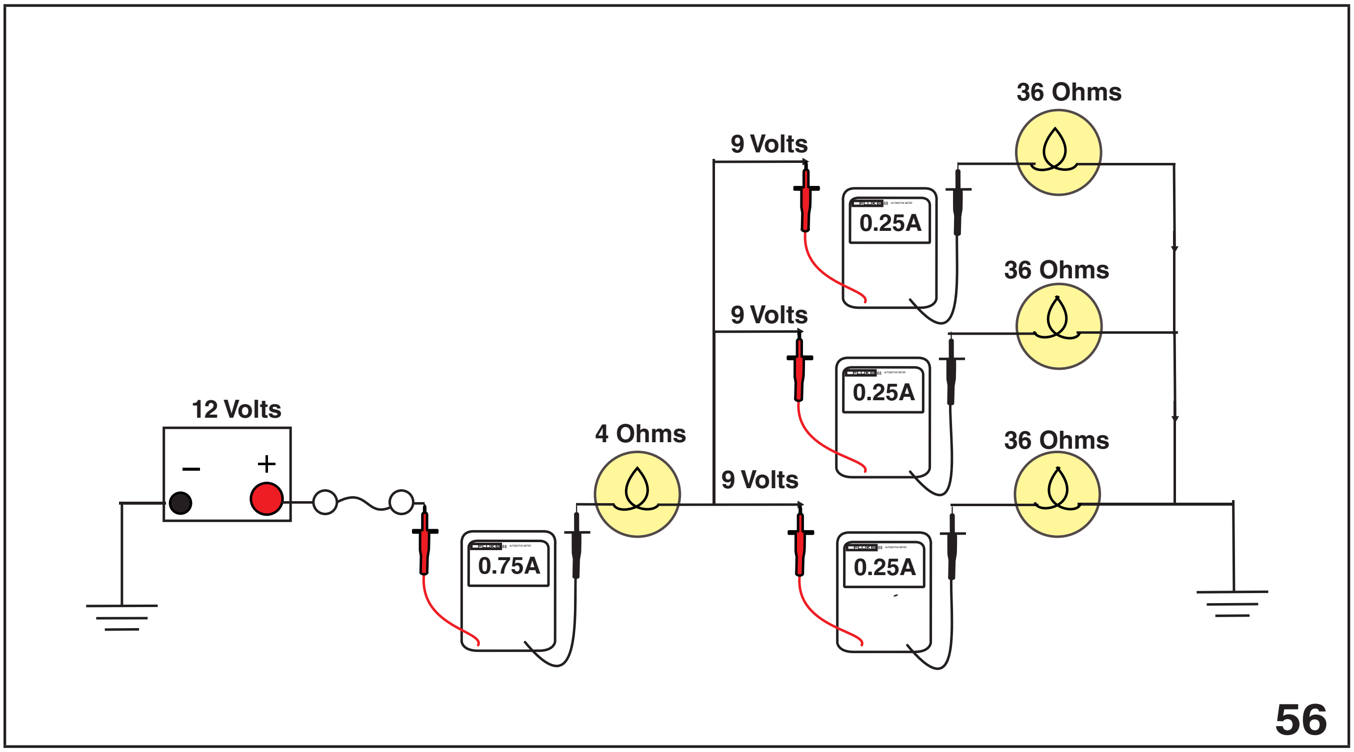


Combination Circuits (Series-parallel)

Combination circuit rules include:

- The available voltage to the parallel portion of the circuit is dependent on the resistance of the load devices in the series portion of the circuit.
- Total circuit resistance is the sum of the resistance of the parallel portion of the circuit and the resistance of the series portion of the circuit.
- Current in the series portion of the circuit is equal to the sum of the current in all parallel paths.

Ohm's Law and Watt's Law Relationship



Ohm's and Watt's Law (Combination Circuits)

In a combination circuit, an increase or decrease of resistance in the series portion of the circuit affects the entire circuit. A change in resistance in one parallel path affects the total circuit resistance, and current flow through the circuit. The resistance of the parallel part of the circuit will always be less than the resistance of any parallel path.

Circuit Faults

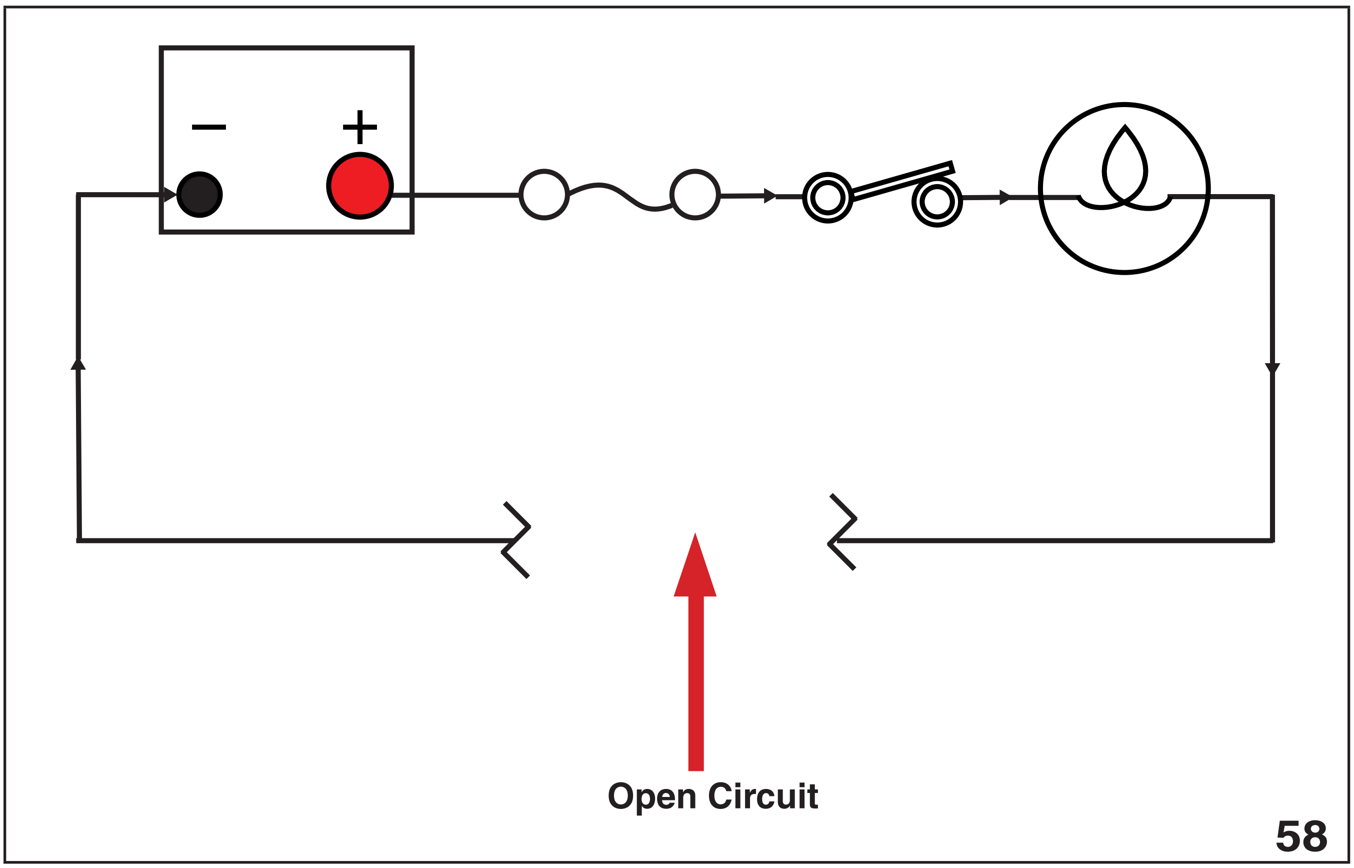
Circuit Faults

Circuit faults are electrical problems that can exist within electrical circuits. Circuit faults can change the operational behavior of a circuit or cause a circuit to become completely inoperative depending on circuit design and fault location.

The three basic types of faults include:

- Open circuits
- Short circuits
- High resistance

Open Faults

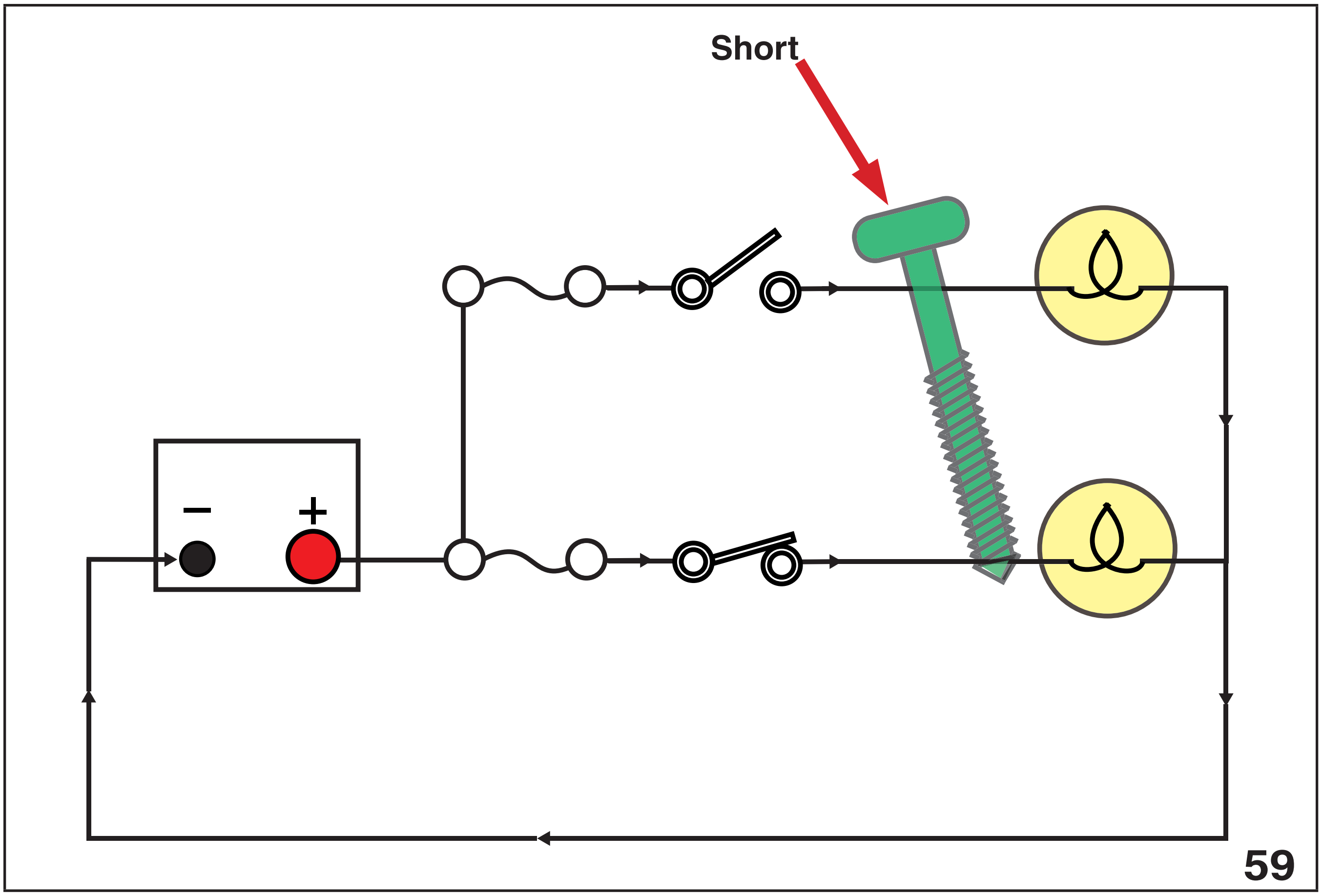


Open Fault

An open fault is an unwanted break in a circuit. Open faults can be caused by a break in a wire, a disconnected wire or connector, or anything that opens the circuit.

When a circuit is open, there is no current flow. No voltage can be used by load devices in a circuit without current flow. Voltage is always available within the circuit before the point in the circuit where the open exists. Voltage can even be measured after a load device if the open is located after the load device.

Short Circuit Faults



Short Circuit Faults

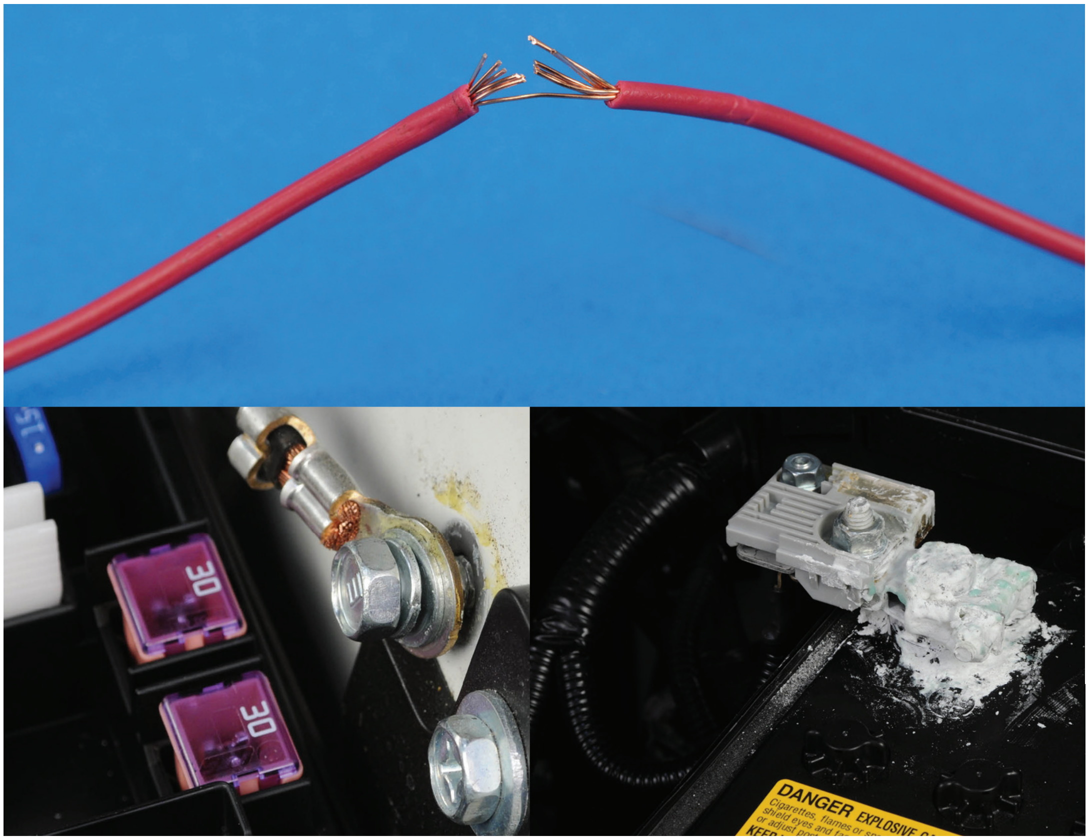
A short circuit fault is a condition where current flows through an untended path. These paths may include the power supply circuits, body/ground paths, or other vehicle circuits. Short circuits can occur in several portions of a conventional circuit causing a variety of symptoms. Shorts commonly manifest as a result of damaged insulation in a circuit or outside influences such as physical damage to the vehicle. Traditional short faults include:

- Short to Ground: In a short to ground fault, a portion of the circuit's conductor is exposed to ground source. This may occur on the power supply side, ground side, or within the load device itself.
- Short to Power: In a short to power fault, a portion of the circuit's conductor is exposed to an unintended voltage supply. This may occur on the power supply side, ground side, or within the load device itself.

Regardless of the short type, the symptoms/affects of the short depend on circuit construction and location of the short. Shorts to power or ground may cause a blown fuse/damaged components (due to excessive current flow) or continuous operation of a load device resulting in parasitic draw (dark current).

Note: **Blown fuses cause circuits to physically open, preventing circuit damage due to excessive current flow. A blown fuse should not be considered the root cause of the fault, but as an indicator that another fault is present within the circuit.**

High-resistance Faults



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High Resistance Faults

High-resistance faults are defined as circuits that have extra unwanted resistance. Corrosion, loose connections, partial broken wires, and even wrong wire sizes can cause high resistance faults within a circuit.

High-resistance faults cause reduced performance in circuit load devices. Slower-than-normal blower motor operation and dimmer-than-normal bulb intensity are examples of how high-resistance faults affect circuit load devices.

High resistance may be measured by two primary methods:

- Ohm Meter (Static Resistance): Use of an ohm meter calculates the resistance of a circuit by determining the amount of voltage drop across the measured segment. The source of the voltage in this instance is the DVOM itself. By itself, this voltage is relatively small and generally will not detect faults where conductor strands are broken as shown in the image above. Additionally, the circuit must be isolated from the power supply in order to perform this measurement. This method is commonly referred to as a Static Resistance measurement.
- Volt Meter (Dynamic Resistance): Use of a volt meter calculates the difference in potential voltage across the measured segment in the circuit. The source of the voltage is this method is the normal power supply for the circuit. As a result, the circuit can be evaluated under its normal operating conditions and the direct consequence of unwanted high resistance can be observed. This method is commonly referred to as a Dynamic Resistance or Voltage Drop measurement.

Electrical Components

Overview

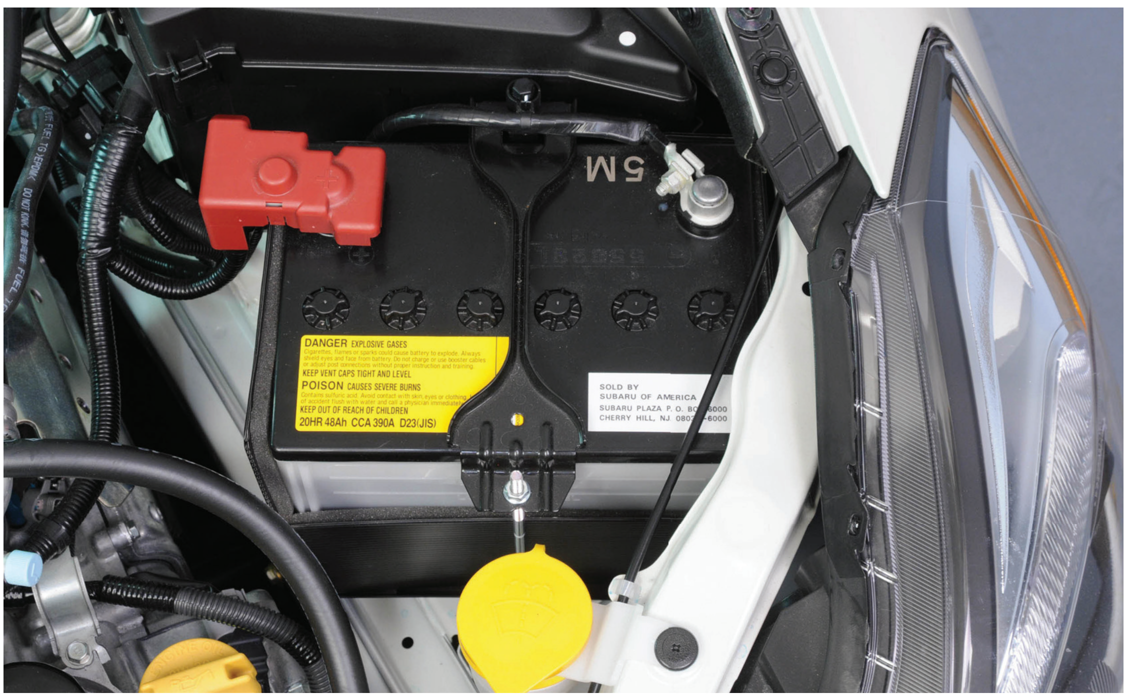
The five basic types of components used in electrical circuits include:

- Power sources
- Conductors
- Circuit protection devices
- Control devices
- Load devices

Power Sources

The battery and alternator are the two power sources commonly found in automotive electrical systems.

Battery



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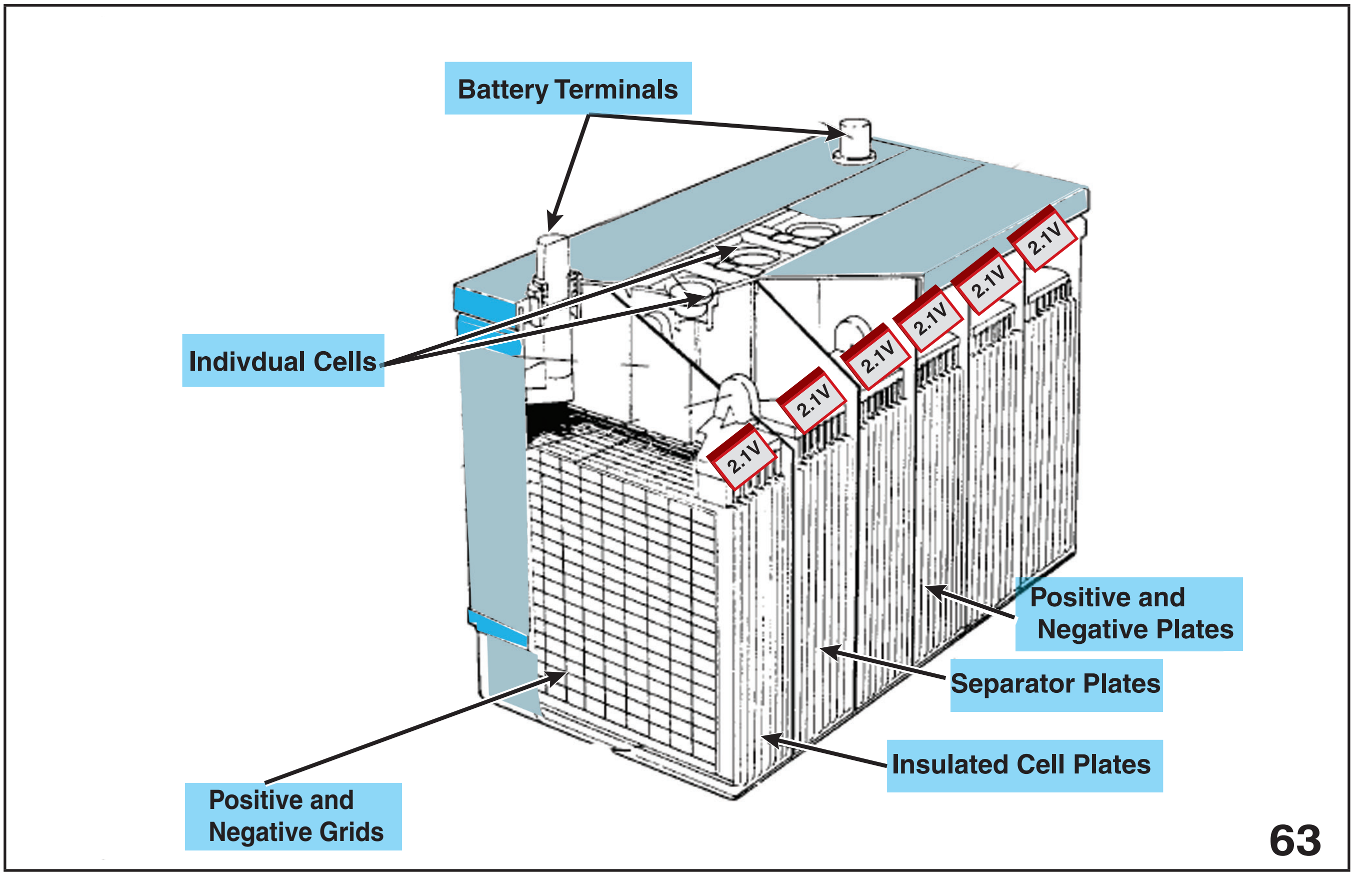
Battery

The battery provides the following functions:

- Stores energy in chemical (not electrical) form
- Converts the chemical energy into electrical energy
- Provides the source of energy for the engine ignition and starting systems
- Provides additional current when the demands of the electrical system exceed the output of the alternator
- Stabilizes voltage in the electrical system

Battery Construction



Battery

Automotive batteries normally have six cells, connected in series (positive of one cell to the negative of the next, and negative of that cell to the positive of the next. Each cell produces 2.1 volts; a six-cell battery produces 12.6 volts. The voltage output of the battery is determined by the material used in the construction of the plates and the quality and quantity of electrolyte (battery acid) in the battery.

Automotive battery cells are made of two dissimilar materials separated by a thin insulator. The positive plates of a cell are lead peroxide. Sponge lead is used for the negative plates. The number of plates in a cell does not increase the voltage capability of the cell or battery, but they increase the length of time the battery can produce current (amperage).

Without electrolyte, a battery is inactive and does not produce electricity. In automobiles, the electrolyte is a solution of water and purified sulfuric acid that allows the chemical reaction to occur between the plates. Generally, the percentage of sulfuric acid in a battery is 36% by weight and 25% by volume.

To determine the amount of charge in a battery, the specific gravity of the electrolyte is measured. A fully charged battery theoretically should have an electrolyte specific gravity of 1.299. However, a normally charged battery will most likely indicate specific gravity readings ranging from 1.260 to 1.280 at 80° F.

Specific gravity is the ratio of the weight (or mass) of the water to the weight (or mass) of the sulfuric acid. Thus, a specific gravity of 1.000 is equal to water. Specific gravity will change with changes in temperature of the electrolyte. For each 10° above 80° F, add .004 to the electrolyte reading. For each 10° below 80° F, subtract .004 from the electrolyte reading. Or you may use an electrolyte temperature correction chart or a temperature equipped hydrometer.

Note: The specific gravity readings must not vary more than 0.050 between cells. A variation of more than 0.050 indicates cell deterioration, and a need for battery replacement.

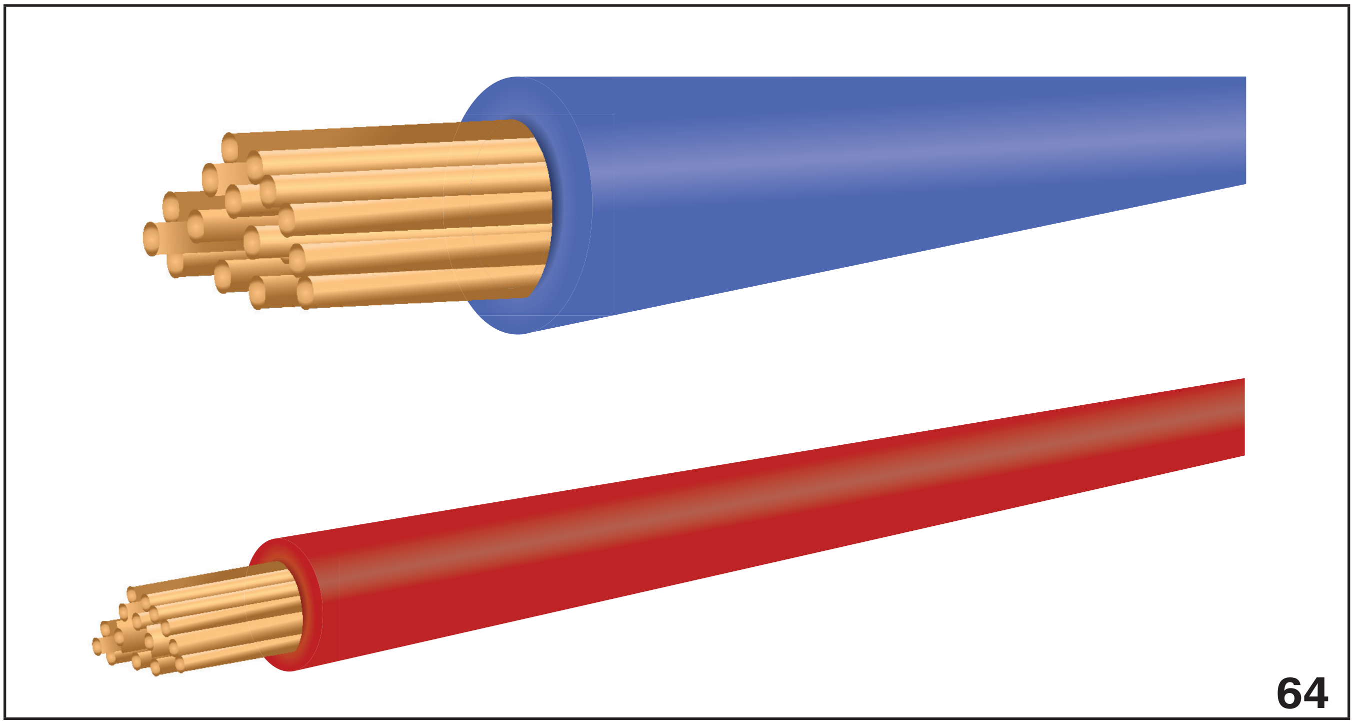
Conductors

Gold, silver, aluminum, tin-plated brass, and copper are some examples of conductors used in automotive applications. Copper is commonly used because it is readily available and low in cost. Silver is a better conductor than copper, but is higher in cost.

Conductors used in automotive circuits include:

- Wires (typically copper)
- Connector terminals
- Vehicle body, chassis, and frame
- Engine block, housings of metal parts, etc.

Wires



Wires

Wires in automotive applications fall into one of two categories: low-current carrying wires and high-current carrying wires.

Low-current wiring typically consists of smaller wires with thin insulation, while high-current wiring is typically larger and has thick insulation.

Most low-current wiring and some high-current wiring are made of stranded copper wire with insulation. Stranded wire consists of many single strands of copper wires wound together. The advantage stranded wires have over solid wires is that stranded wires have lower resistances due to the larger amount of exposed surface area and they are usually more flexible.

Wire size or wire gauge is designated by one of two standards: the American wire gauge (AWG) or metric.

The AWG standard designates a number that is based on the diameter of the wire. A wire with a smaller diameter is given a larger number while wires with a larger diameter are given a smaller number. For example a 16-gauge wire is smaller than a 4-gauge. Low-current-carrying automotive circuits use wires of a larger gauge (smaller diameter), while high-current-carrying circuits require wires of a smaller gauge (larger diameter).

The metric standard designates a size determined by the cross-sectional area of the wire and is expressed in square millimeters (mm^2). In the metric standard, a smaller number designates a smaller wire size and a larger number designates a larger wire size.

TOTAL APPROXIMATE CIRCUIT AMPERES	WIRE GAUGE (FOR LENGTH IN FEET)											
Constant 12 V	3'	5'	7'	10'	15'	20'	25'	30'	40'	50'	75'	100'
1.0	18	18	18	18	18	18	18	18	18	18	18	18
2	18	18	18	18	18	18	18	18	18	18	16	16
4	18	18	18	18	18	18	18	18	16	16	12	12
6	18	18	18	18	18	18	16	16	16	14	12	10
12	18	18	18	18	16	16	14	14	12	12	10	8
24	18	18	16	16	12	12	10	10	10	8	6	6

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Correct Gauge Size to Carry Current

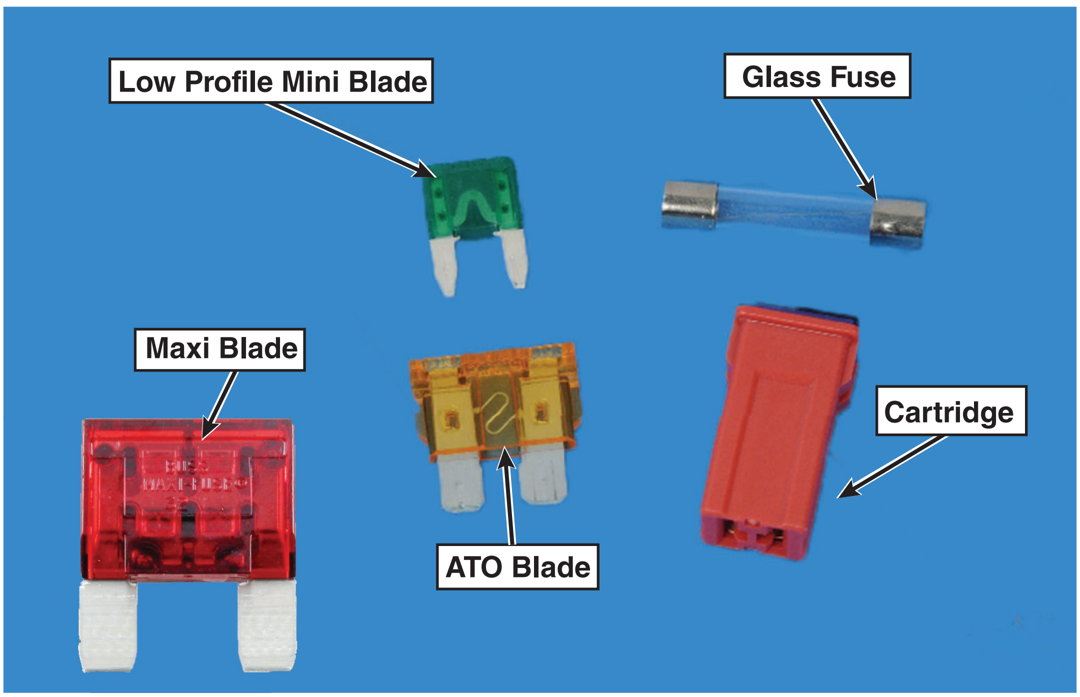
Diameter and length both affect the resistance of a wire. The chart above displays the length and gauge of a wire that is required to carry current for a given distance when circuit voltage is at a constant 12 volts.

Circuit Protection Devices

Circuit protection devices open the circuit when an over-amperage condition is present in the circuit. By opening the circuit, current flow through the circuit stops and prevents further damage to the circuit and circuit components. Types of circuit protection devices include fuses, fusible links, and circuit breakers.

Fuses

Fuses are the most commonly used circuit protection devices in automotive electrical systems. A fuse is a replaceable component that contains a strip of metal that melts at a specific amperage rating to stop current flow in a circuit when excessive current flow is present. A fuse with a melted strip indicates that a short circuit has occurred somewhere in the circuit. The short circuit must be repaired prior to replacing the fuse, or the metal strip in the new fuse will melt as soon as the circuit with the short is turned on. Only replace a fuse with a fuse of the same type and rating; never replace a fuse with a fuse that has a larger rating, or damage to the circuit may occur.



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Fuse Types

Fuse types include:

- Glass or ceramic
- Blade type
- Cartridge
- Glass and ceramic fuses can be found in older vehicles; however, blade and cartridge type fuses are common in modern vehicle applications. Blade type fuses come in a variety of sizes including the mini blade, auto blade, and maxi blade. Cartridge fuses are more common in European vehicles and have unique rounded metal strips.

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Fuse Locations

Fuses are typically located in a fuse panel, sometimes referred to as a fuse box, or main box. The fuse panels are located in various locations on the vehicle, but they are most commonly found in the engine compartment and in the passenger compartment, usually under the dash.

Slow Blow Fuses

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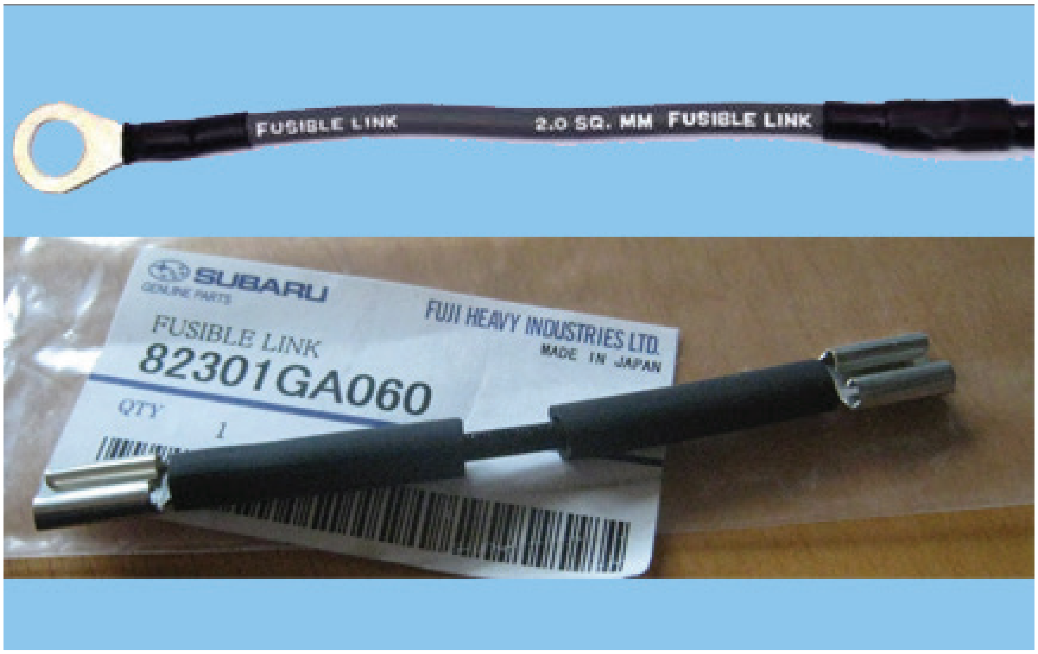
Slow Blow Fuses (SBF)

Slow blow fuses (SBF) are fuses that allow a current higher than their rating to flow for a short period of time before opening the circuit. Slow blow fuses are commonly used in motor circuits where an in-rush of current flow occurs as soon as the circuit is switched on, but then the current flow reduces as the circuit operates and becomes steady.

Fusible Links



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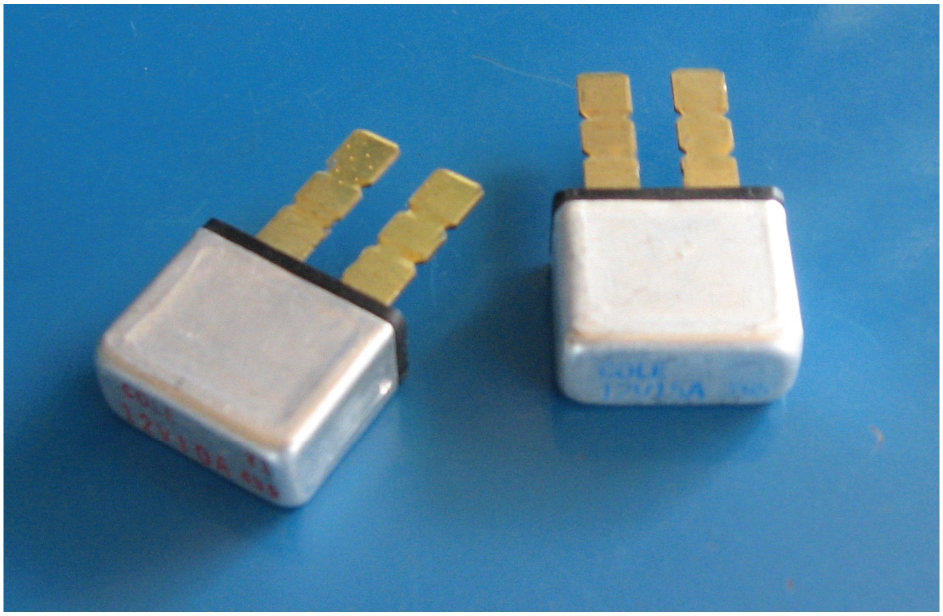
Fusible Links

Fusible links behave like a fuse, but they resemble a wire. Fusible links are made of a conductive material that melts when current in the circuit exceeds a specified current rating. The conductive material of a fusible link is wrapped in a heat-resistant insulator. Fusible links are typically found near a main connection close to the battery. Fusible links are a smaller wire size than the wires of the circuits they protect, typically 1/4 the size.

Circuit Breakers



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Circuit Breakers

Circuit breakers are thermal-mechanical devices that open the circuit when current is higher than the rating of circuit breaker. A bimetallic strip (made of two different metals) makes contact with the two terminals of the circuit breaker, allowing current to flow. When excessive current flows through the circuit breaker, the temperature of the bimetallic strip increases, causing it to bend and open the contacts. The bimetallic strip bends because one of the two metal strips reacts faster to the heat than the other, causing the strip to flex.

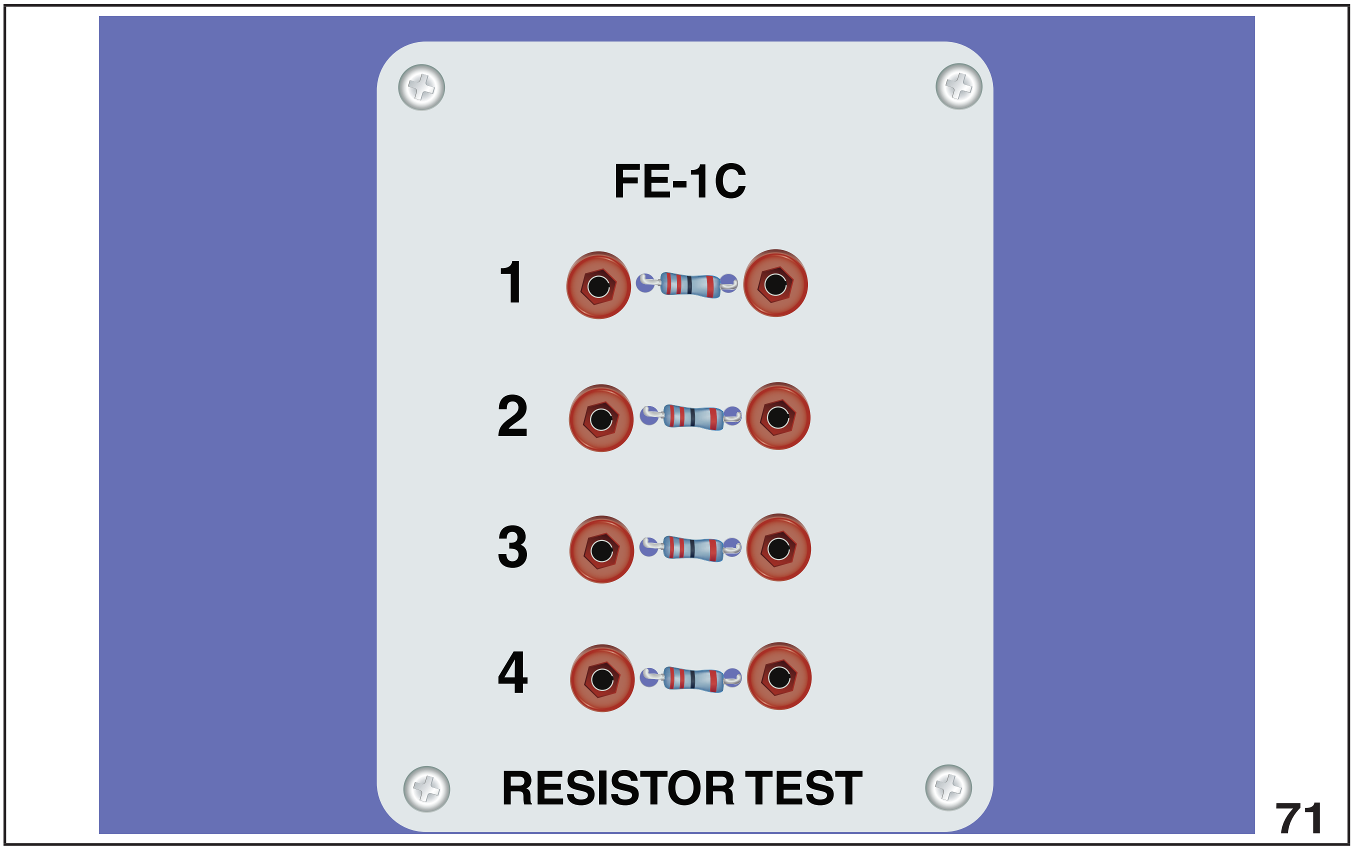
Some circuit breakers automatically reset as the bimetallic strip cools, while others require the breaker to be manually reset using a reset button on the circuit breaker assembly. Circuit breakers are used in circuits that are prone to excessive current draw like power windows, which can sometimes jam or be obstructed.

Load Devices

Load devices are the components in a circuit that perform work by changing electrical energy into other energy types, including heat, motion, light, or sound. During normal circuit operation, the load devices in a circuit will consume source voltage. Coils, lights, solenoids, electric motors, and heating elements are examples of load devices typically found in automotive electrical circuits.

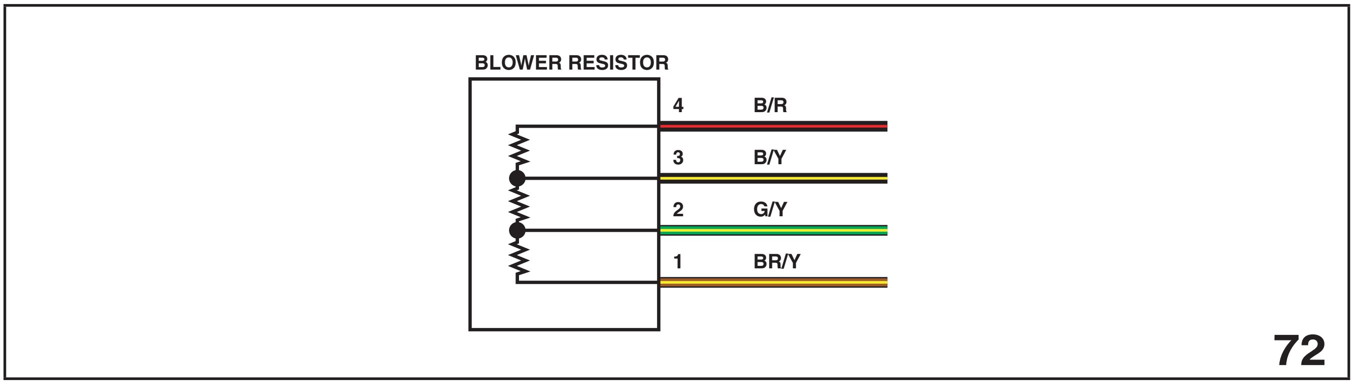
Resistors

Resistors are required in order for a circuit to operate. Resistors can be used to perform work or to control current flow. The resistors used to perform work are classified as load devices; resistors used to control current are classified as control devices. Fixed, stepped, and variable resistors are types of resistors used within circuits to control current.



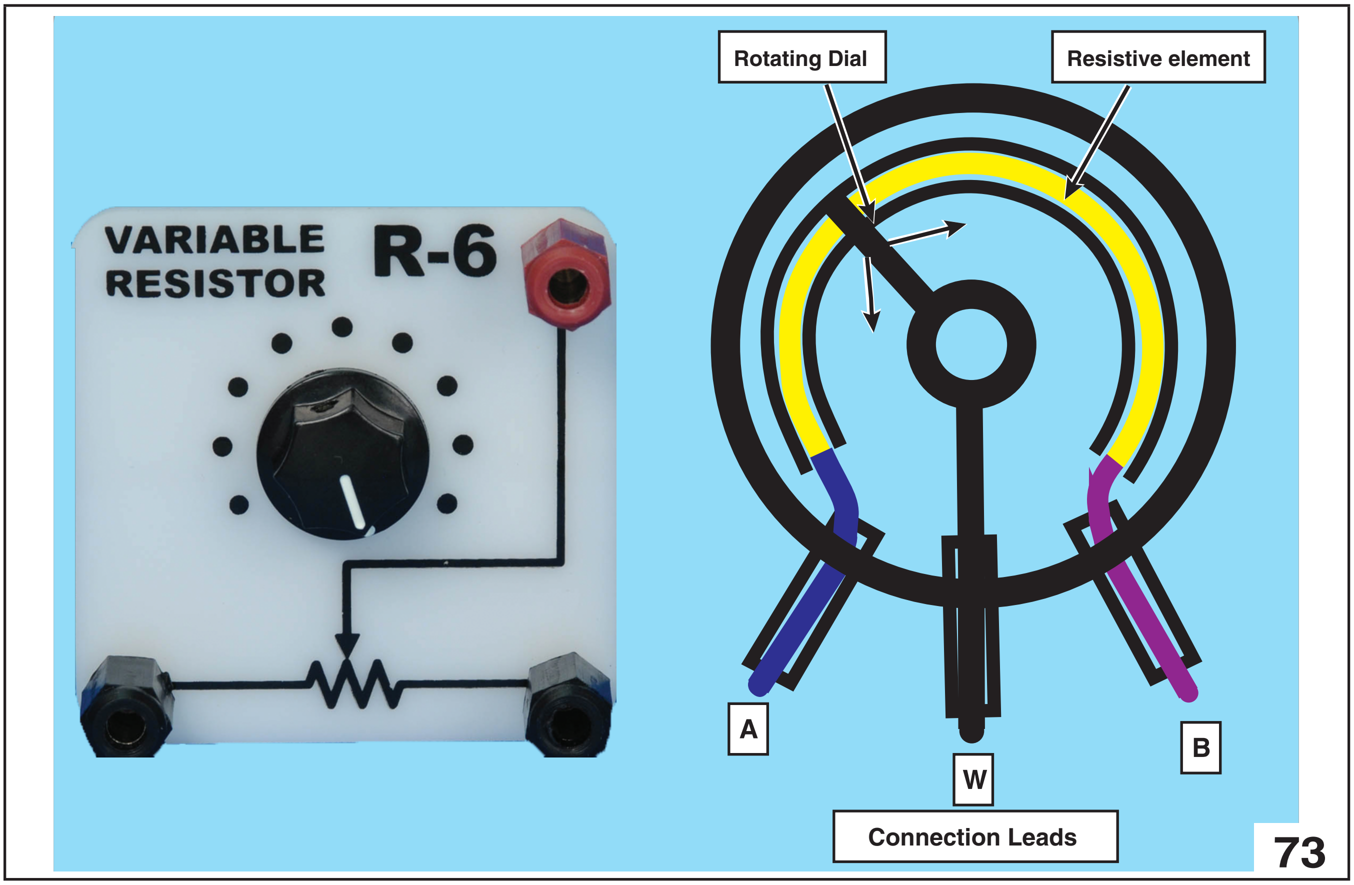
Fixed Resistors

Fixed resistors have a set resistance value that does not change.



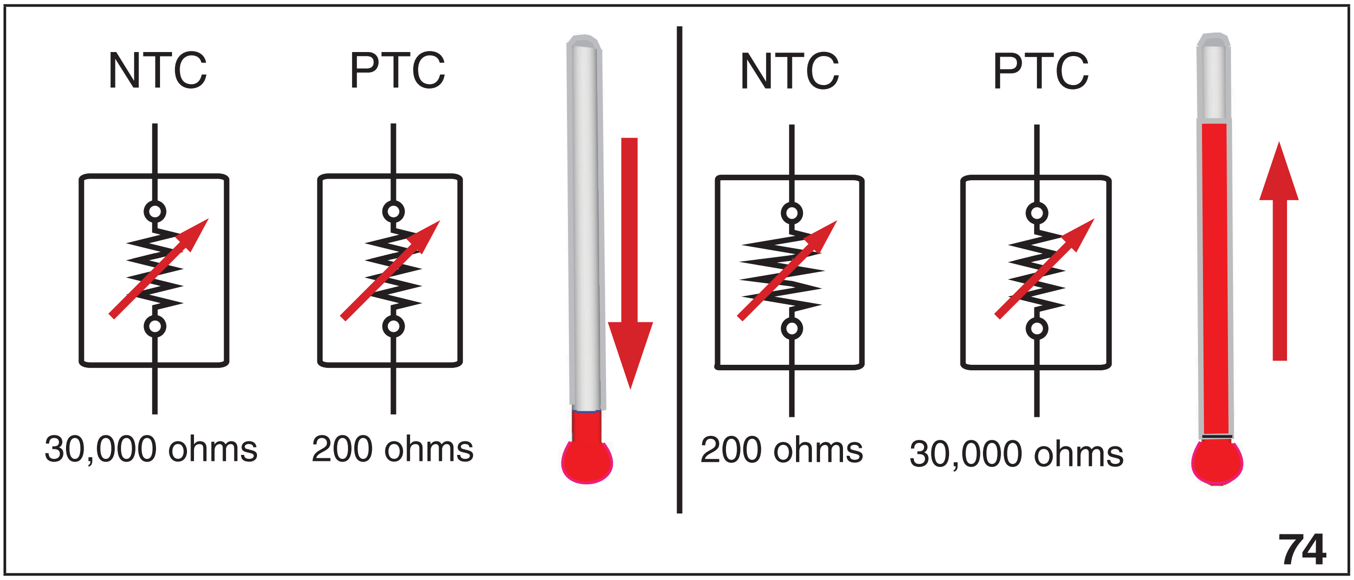
Stepped Resistors

Stepped resistors have two or more fixed resistance values that have an integrated switch or a switch wired in series. Stepped resistors are commonly used to control blower motor speed.



Variable Resistors

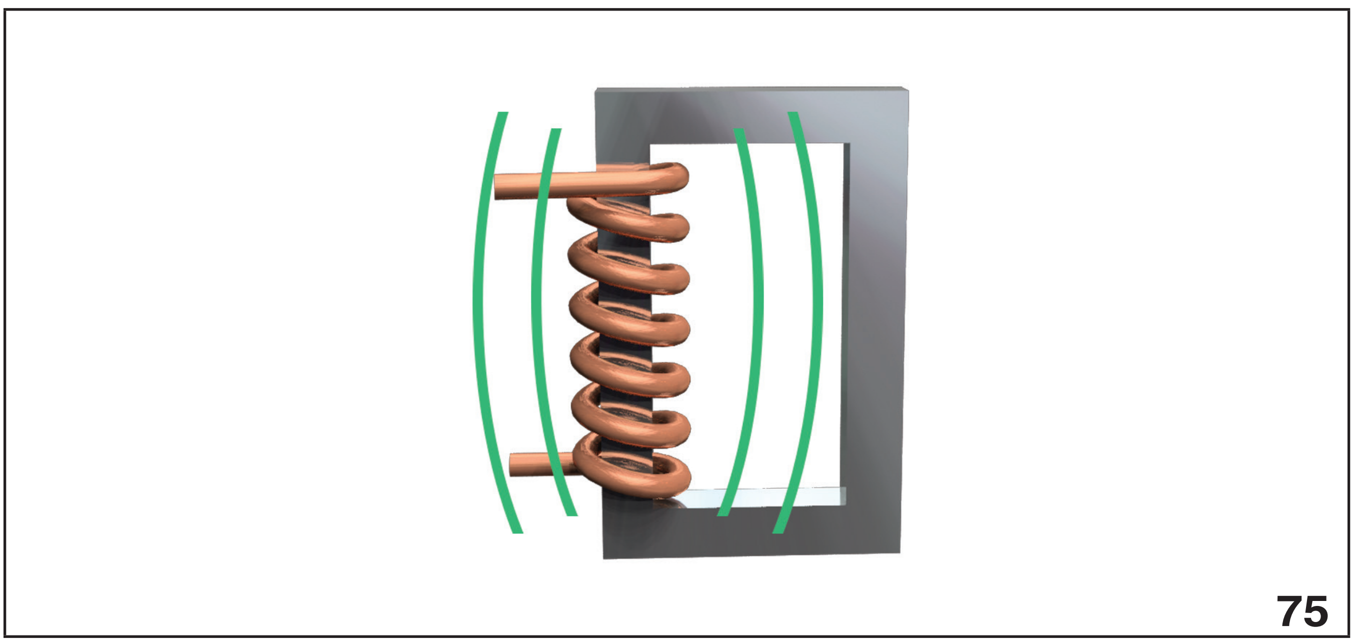
Variable resistors have an infinite number of resistance values within a given range and are commonly used in automotive applications in the form of a potentiometer.



Thermistor

Thermistors are variable resistors that are affected by changes in temperature. There are two types of thermistors: positive temperature coefficient (PTC) and negative temperature coefficient (NTC). PTC thermistors increase resistance as temperature increases. NTC thermistors decrease resistance as temperature increases.

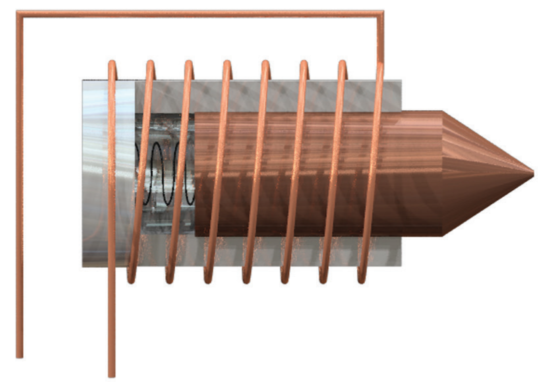
Coils



Coils

Coils are the most common electrical components used in load devices. Most load devices use a coil to perform work. Coils are made of many loops of wire that are wound around a metal core. As current flows through a coil, a magnetic field is created around the coil. The magnetic field created by the coil can be used to induce voltage and current flow in other circuits, and create motion. Ignition coils, fuel injectors, window motors, and relays are some examples of automotive components that use coils.

Solenoids



Solenoids

Solenoids are electromechanical devices consisting of a coil that surrounds a moveable iron core. When the coil is energized, a magnetic field is created causing the iron core to be attracted toward the coil. When de-energized, the return spring causes the iron core to return to its previous rest position. Fuel injectors, EGR valves, starter solenoids, and door lock actuators are examples of solenoids used in automotive applications.

Lights

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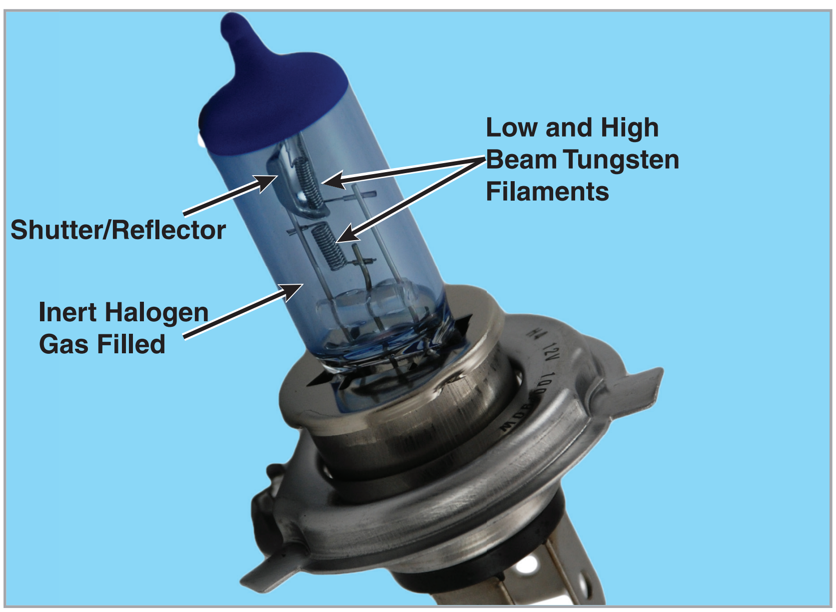
Lights

Lights are used in both interior and exterior applications in automotive electrical circuits. Traditional automotive light bulbs are simple coils within a glass bulb. Light-emitting diodes (LEDs) are replacing the traditional bulbs because they last longer and use less power.



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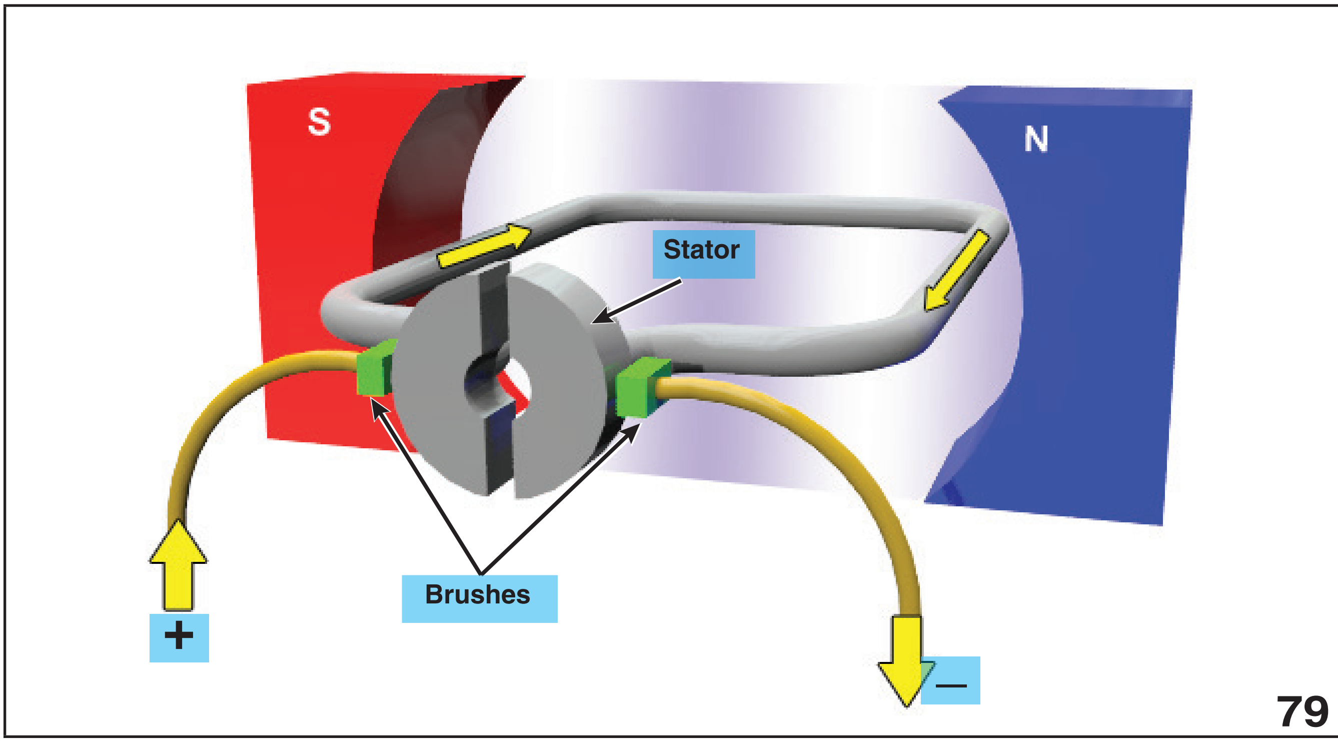
Dual Filament Halogen Headlamp Bulb

As current flows through the filament heat and light (incandescence) is created.

Electric Motors



Electric Motors

Electric motors are devices that use the magnetic fields created by current flow to create motion.

Electric motors consist of the following:

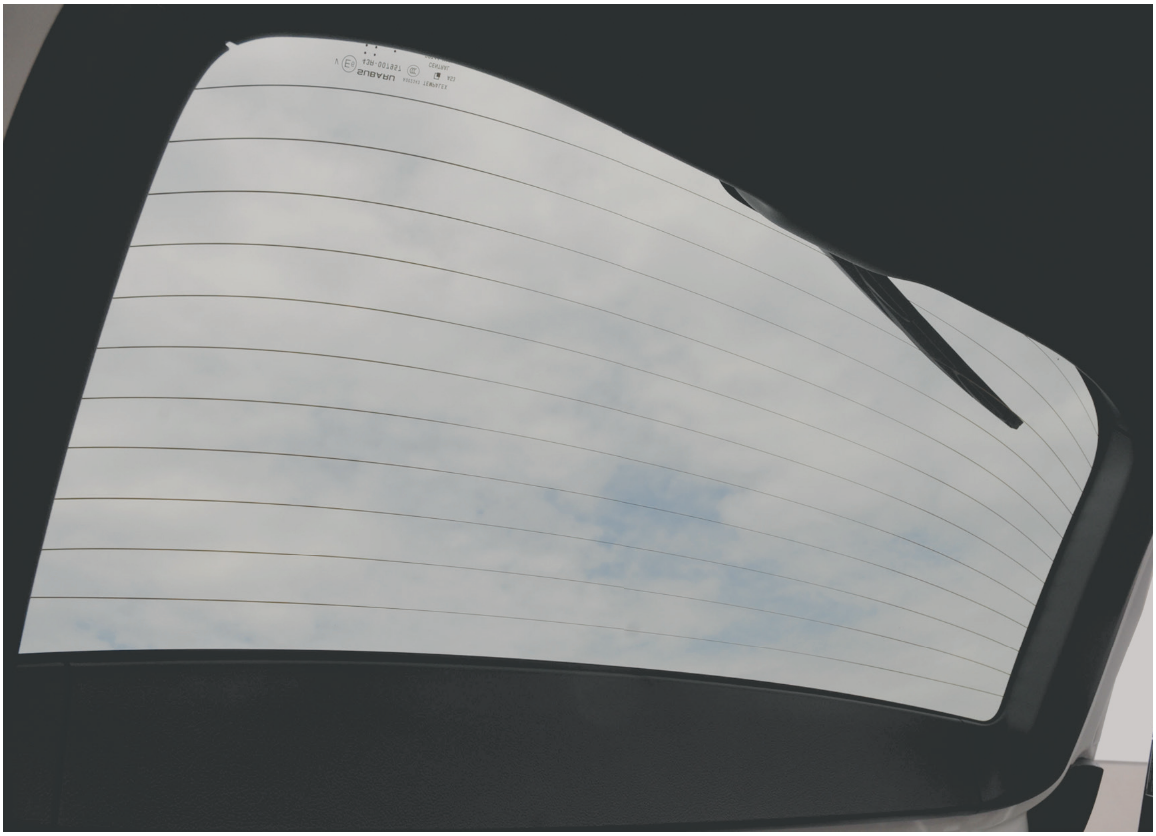
- Magnets (either stationary electromagnets or permanent magnets)
- Rotating armature with many windings
- Rotating commutator segments
- Brushes

Motion is created when current flows through an electric motor's brushes, commutator segments, and armature windings. As the current flows through the armature windings, a magnetic field is created. The magnetic field created by the armature winding is similar to the magnetic field created by the magnets in the motor's casing and causes an opposing force on the armature, forcing the armature to rotate.

The direction of motor rotation is determined by the direction of the current flow and magnetic fields created in the motor windings. A motor with more windings and commutator segments operates more efficiency and has higher possible speed and torque outputs.

Some motors operate in only one direction such as blower motors, while other designs allow forward and reverse motor operation such as power window and seat motors.

Heating Elements



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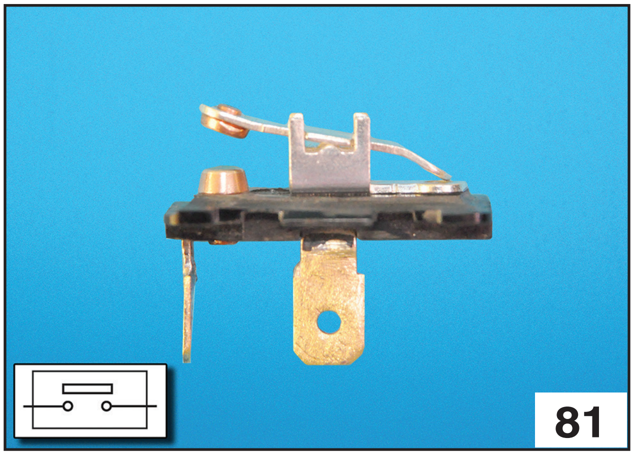
Heating Elements

Heating elements convert electrical energy into heat energy. Heating elements are commonly found in automotive applications such as rear window defrosters, heated seats, and heated mirrors.

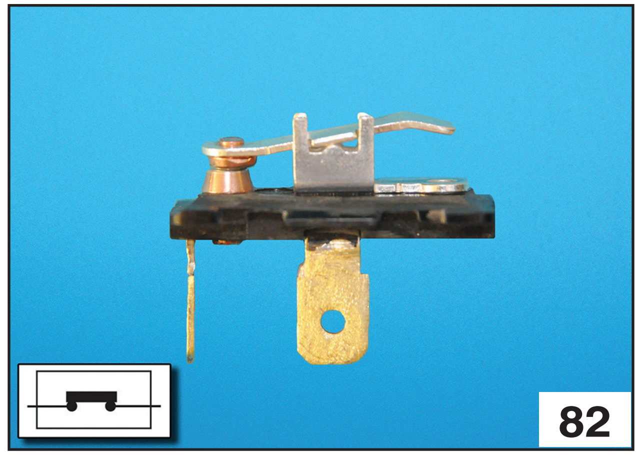
Control Devices

Control devices provide a means to control current flow in a circuit. Control devices can be used to switch current on and off, limit current, or control the direction of current flow in a circuit. Switches are the most widely known control devices. Other control devices include relays, resistors, and electronic control modules.

Switches



Switch Contact Open



Switch Contact Closed

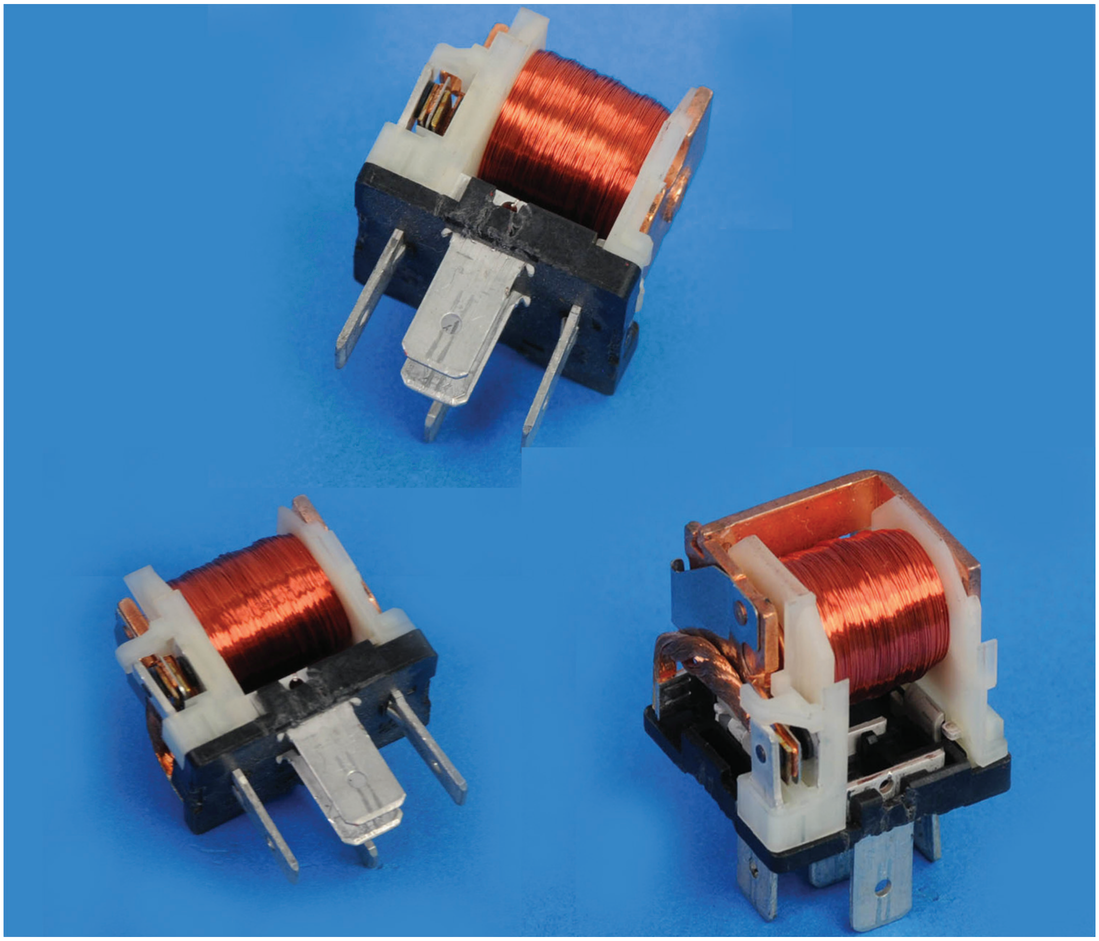
Switches provide a way to control electrical current flow to a load device. Switches toggle current flow on and off to a circuit, or direct current flow to various circuit paths.

There are several switch designs; some are manually controlled while others are automatically controlled. The most basic switch design consists of a pair of metal contacts that can be closed and opened to complete or break a circuit.

Other switch designs include:

• Single-pole	• Single-throw (SPST (S-1))
• Single-pole	• Dual-throw (SPDT)
• Single-pole	• Multiple-throw (SPMT)
• Multiple-pole	• Multiple-throw (MPMT)
• Momentary contact switches	• Relays (switched-side is the load side)
• Temperature-controlled switches	• Reed switches

Relays



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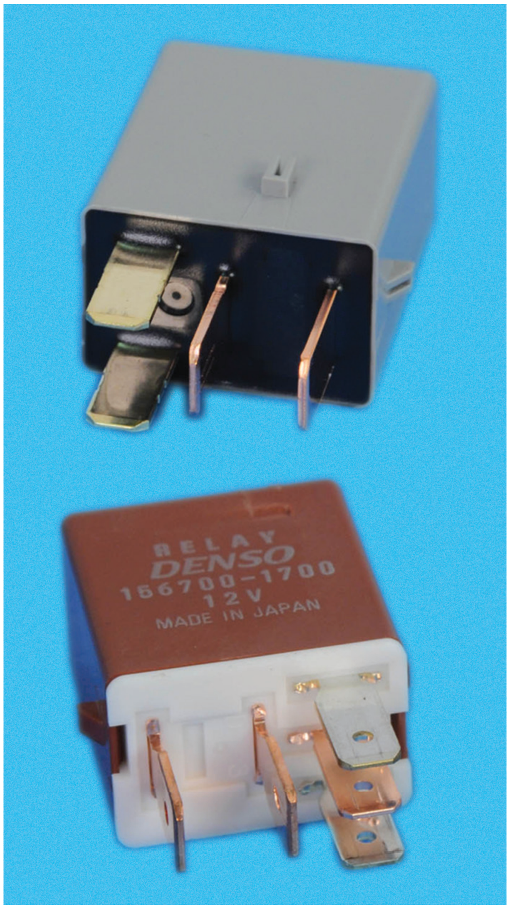
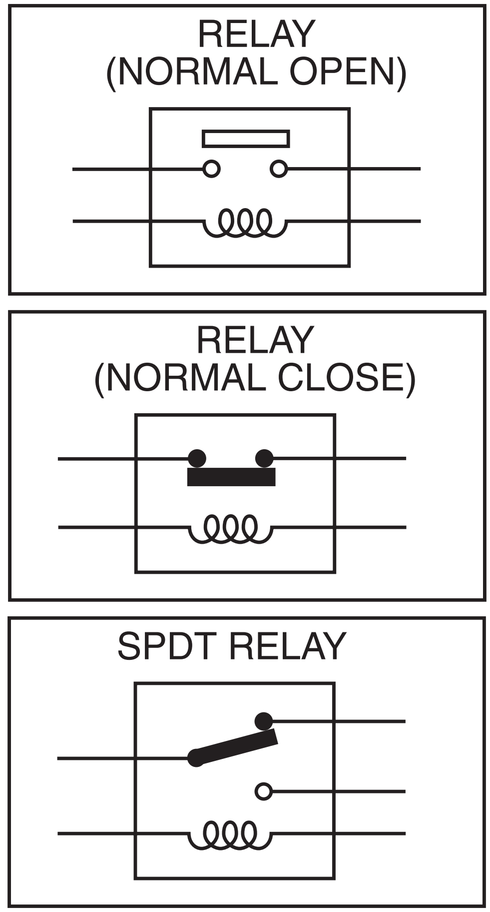
Relays

Relays are electromagnetic switches that use a low-amperage control circuit (coil side of the relay) to turn on and off a high-amperage load circuit (switch side of the relay).

Relays in automotive electrical systems include removable 4-pin and 5-pin relays, and non-removable relays located on the integrated circuits of electronic control modules and electronic component circuit boards.





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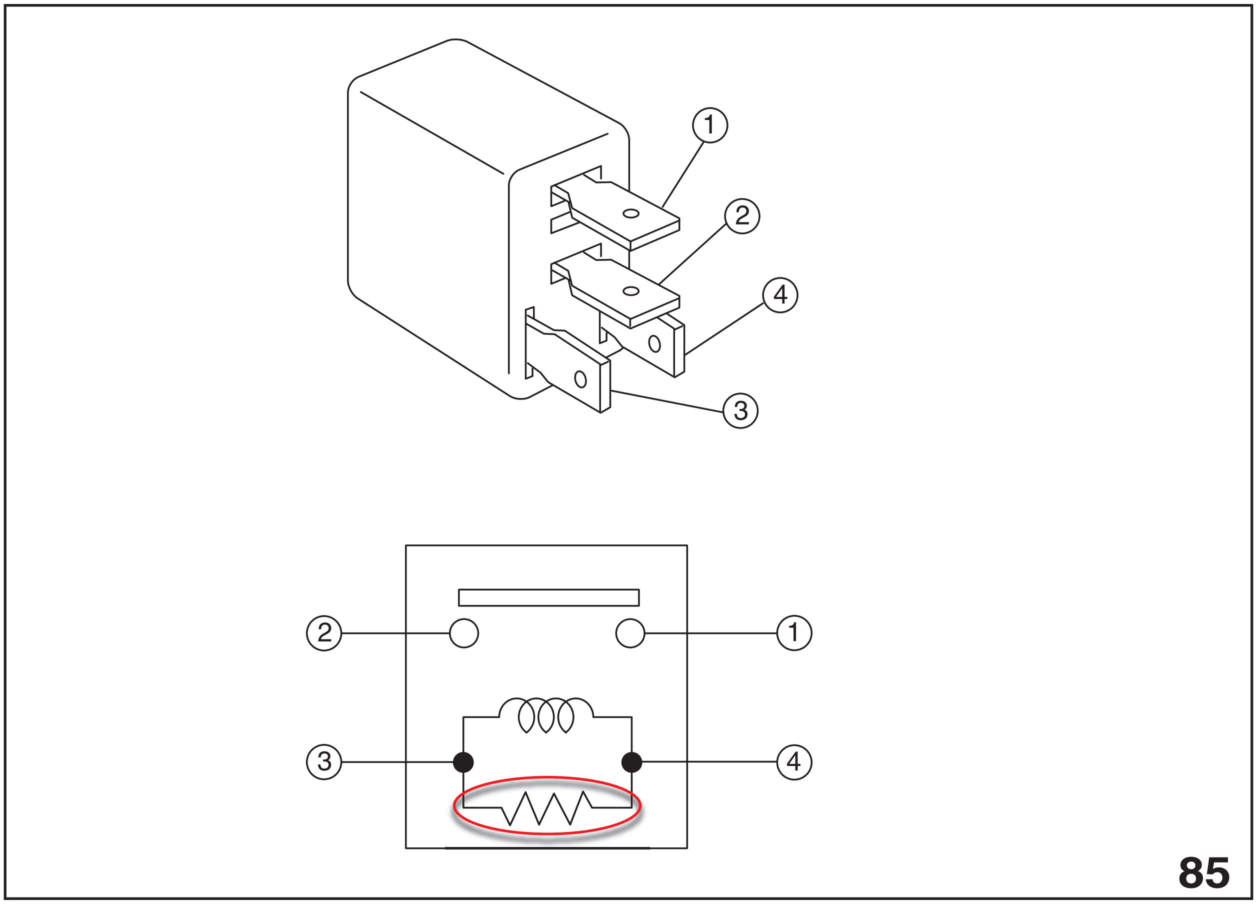
4-pin and 5-pin Relays

The 4-pin and 5-pin relays are commonly found in automotive applications. Relays typically have labeling on the top or side of the plastic housing that depicts the pins for the control (coil) side and the load (switch) side of the relay.

The difference between a 4-pin and 5-pin relay is that the 5-pin relay has two possible paths for current to flow while the 4-pin only has one path.

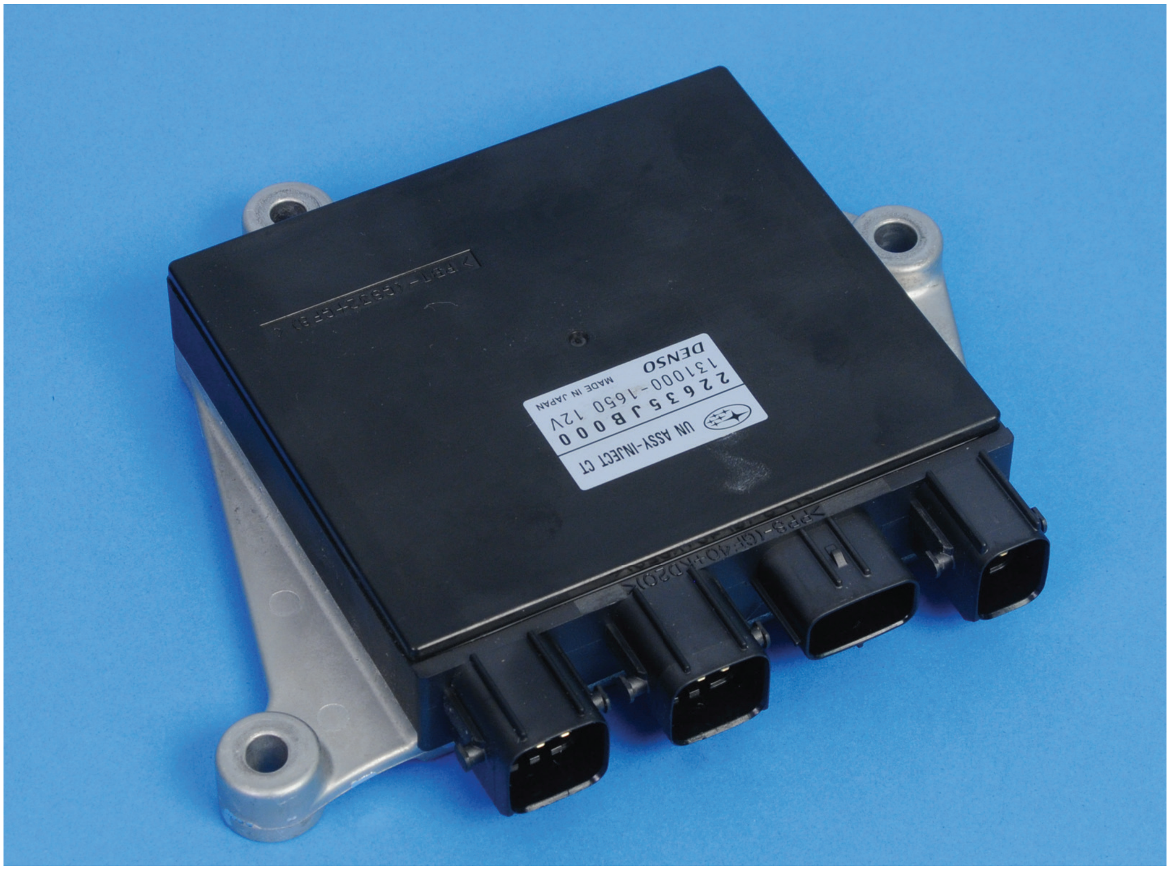
Voltage Suppressing Resistors



Voltage Suppressing Resistors

Voltage Suppressing Resistors (sometimes referred to as “Clamping Resistors”) are used as a form of circuit protection in circuits that are susceptible to damage (such as Control Modules) from voltage spikes. Voltage spikes regularly occur when the magnet field collapses within the relay coil windings. Voltage suppressing resistors are built into relay assemblies and are wired in paralleled with to the relay coil windings. These resistors create a restriction that limits the amount of current that flows through the circuit.

Electronic Control Modules



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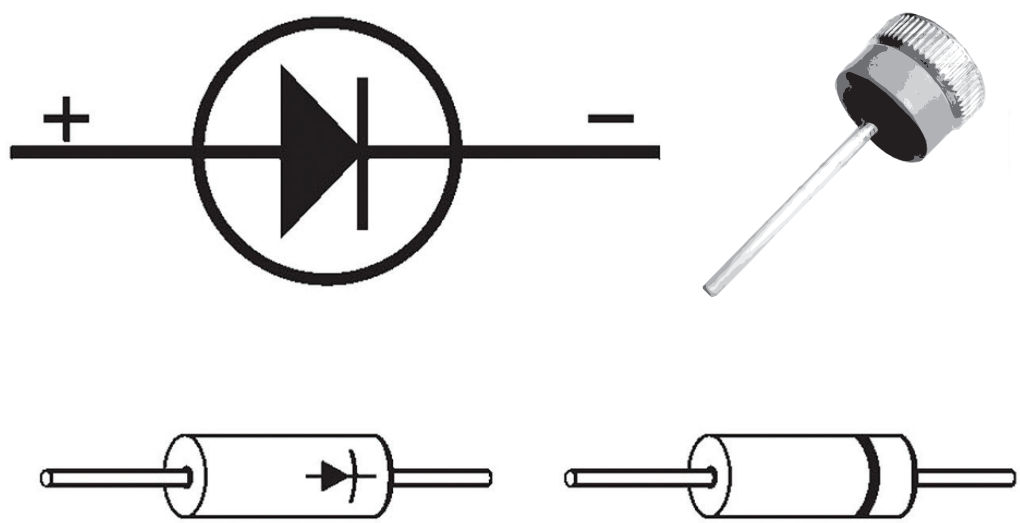
Electronic Control Modules

Electronic control modules also provide circuit control through transistors, which are essentially very fast switching devices. Electronic control modules are discussed in greater detail in another course.

Electronic Components

Diodes, light-emitting diodes (LEDs), and capacitors are some of the electronic components commonly found in automotive electrical circuits.

Diodes



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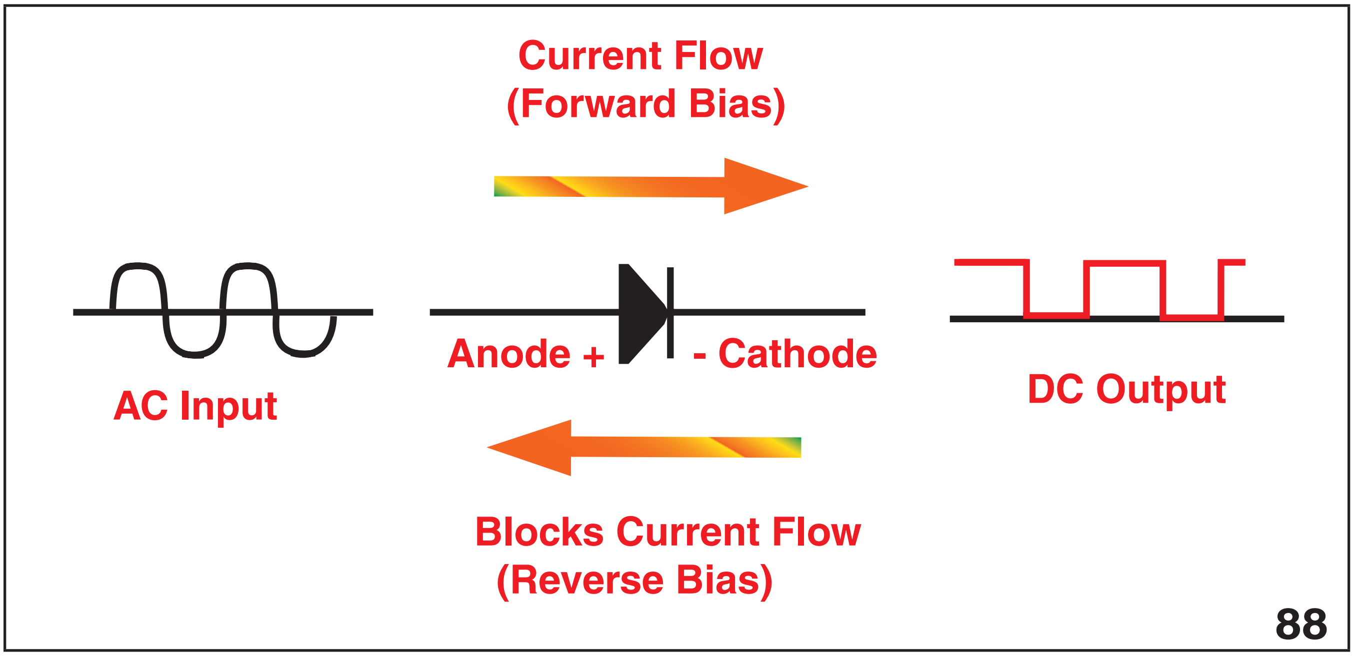
Diodes

Diodes are electrical one-way check valves that only allow current to flow in one direction. Diodes are semiconductors formed by joining two elements: one positive and one negative. The positive (P-type) material is called the anode, and the negative (N-type) material is called the cathode. The PN junction is the point where the anode and cathode meet. The cathode portion of the diode can quickly be identified by the painted stripe on the diode body. Diodes can be wired in one of two ways, either forward bias or reverse bias.



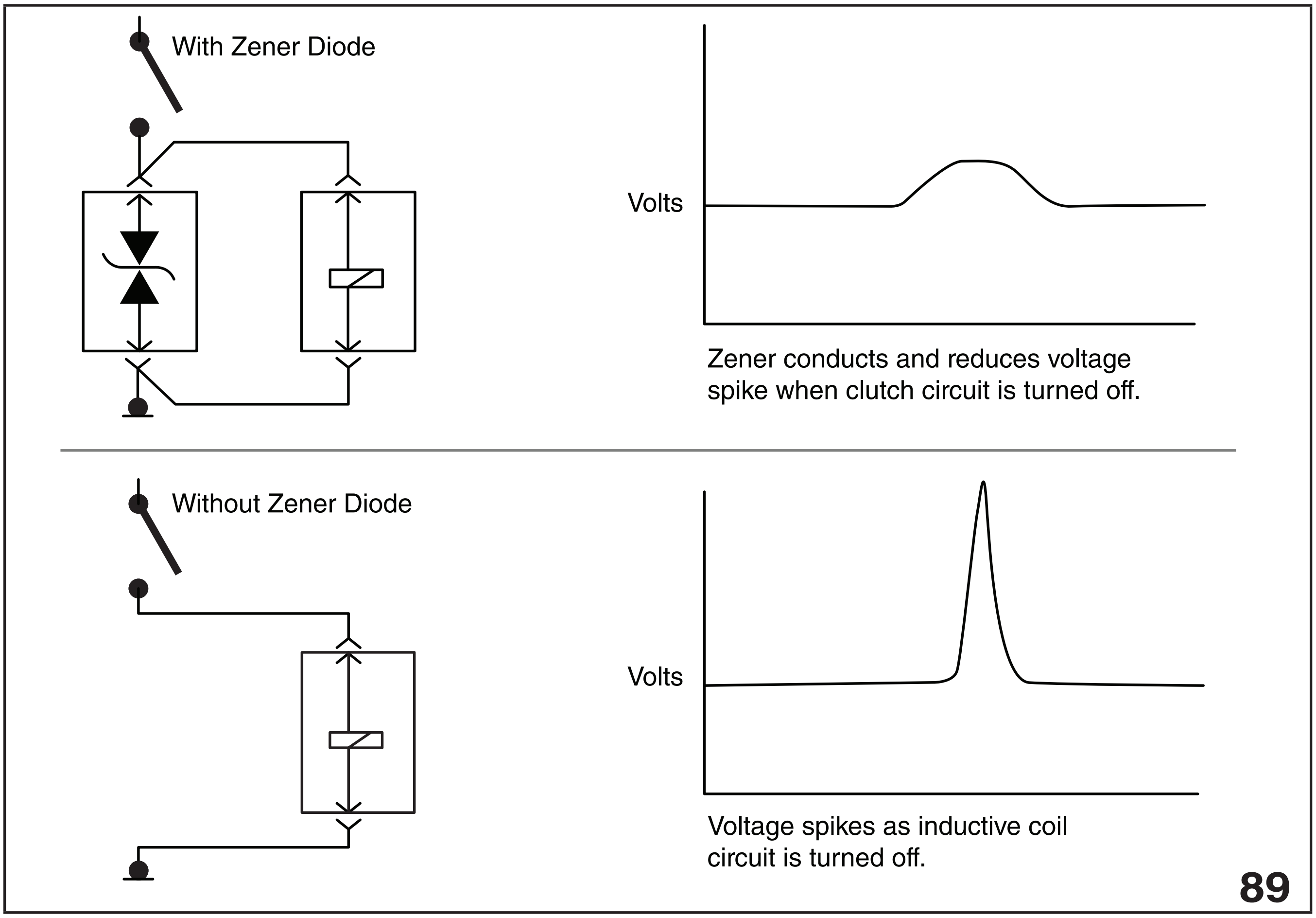
Forward Bias

Forward bias means that the diode is wired with the anode connected toward the positive side of the circuit and the cathode is connected toward the negative side of the circuit. When a diode is forward biased, it behaves like a conductor and allows current flow through the diode.

Diodes that are forward biased will use a small amount of voltage, typically around 0.5 volts. This voltage is considered the diode's turn-on voltage.

Reverse bias, as its name implies, means that the diode is connected in reverse, with the cathode connected toward the positive side of the circuit and the anode connected toward the negative side of the circuit. When a diode is reverse biased, it behaves like an insulator and prevents current flow through the diode.

Zener Diodes

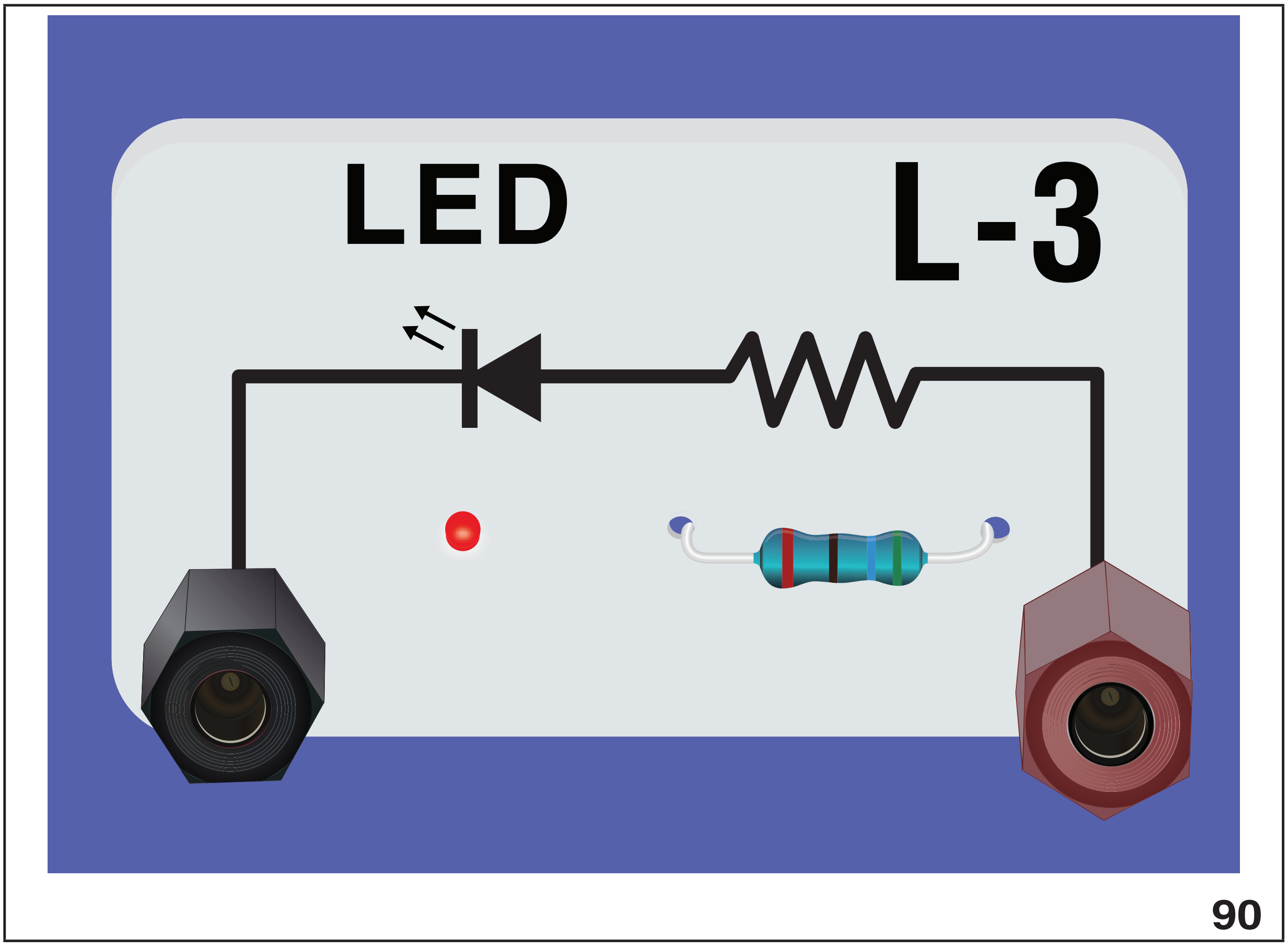


Zener Diodes

Zener diodes allow current to flow in reverse bias only when a specified breakdown voltage is reached, and they will not allow voltage to increase above the breakdown voltage. If circuit voltage is below the breakdown voltage, the Zener diode will not conduct in reverse bias and will prevent current flow. When the breakdown voltage is reached, a large current flow is created in reverse bias, preventing voltage from rising any higher.

A Zener diode rated at 13 volts will only allow current flow when the circuit voltage reaches 13 volts and will not allow the voltage to increase above 13 volts. If circuit voltage falls below 13 volts, the diode will not conduct and prevents current flow through the circuit. Zener diodes are excellent components for regulating circuit voltage.

Light-emitting Diodes (LEDs)



Light-emitting Diodes (LEDs)

Light-emitting diodes (LEDs) are diodes that produce light as current flows through them when they are forward biased. LEDs last longer than standard light bulbs because the light energy produced by an LED is electrical energy and not heat energy.

Capacitors

Capacitors are two-terminal electronic components constructed of a minimum of two conductors separated by insulators. Capacitors do not consume voltage; they only temporarily store it. Any voltage absorbed by a capacitor is returned to the circuit when the capacitor discharges. Capacitors are also used to absorb changes in circuit voltage and to prevent circuit damage caused by voltage spikes.

Notes

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