DC Circuits

We use electric circuits to convert electrical potential energy into other kinds of energy. It is through circuits that electricity becomes useful to us. Our lifestyle is not possible without the production, distribution, and use of current electricity.

Every electric circuit must have at least three elements:

source

load resistor(s)

 1. a source of electric current

2. a device that converts the electrical potential

energy produced by the source into some

other kind of energy – called a load resistor

3. conductors that connect the source and

load resistor(s) to make a complete, unbroken

path from the source through the load resistor(s)

and back to the source

There are several different types of souces of electric current:

 1. generator

 2. battery or electrochemical cell

 3. photovoltaic cell

 4. piezoelectric cell

 5. thermocouple

The source creates an electric field in all the conductors and resistors. The electric field exerts a force on the electrons in the conductor and resistors. The electromotive force, abbreviated EMF with symbol **E**, causes the mobile electrons to move through the conductors and resistors. This movement of electrons produces the electric current. The movement of electrons is not actually the current. The current is an electromagnetic wave that moves through the circuit, but it is much easier and accurate enough to visualize electric current as these moving electrons.

Good conductors of electricity have delocalized, mobile electrons which can move easily from one atom to another. Poor conductors and insulators have electrons which are held by their atoms and are not allowed to move from atom to atom. Metals are good conductors.

The source produces an electric field. The electric field can remain in the same direction at all times or it can reverse its direction periodically. If the field remains in the same direction, the current will flow in the same direction at all times. This type current is called **direct current** or **DC**. If the source field changes direction, the current will change its direction of flow every time the source field changes. This type current is called **alternating current** or **AC**.

Of the sources listed above, 2-5 can only produce DC. A generator can produce AC or DC depending upon the design of the generator. A generator cannot produce AC and DC at the same time. While the generator is operating, it will produce one or the other.

The current that we get from our wall outlets is 60 hertz AC. This current will change direction 60 times each second. Generators at regional power plants produce this current.

Most of the devices with which you are familiar operate on DC. Any device which can run on batteries uses DC since that is the only type of current a battery can produce. Devices which can run on wall current or batteries, convert wall current AC to DC for use in the circuits of the device.

The size of the current through a point in the circuit or through a resistor is determined by how many electrons move through the point each second. If 1 coulomb of charge moves through the point in 1 second, the current is 1 ampere or 1 amp. The symbol for the unit ampere is A. The current is therefore: I = 

I – current in amperes, A

Q – total charge of the electrons that move through the point in coulombs, C

t – time for the charge to move through the resistor in seconds, s

Since 1 C of charge is the total charge of 6.25 X 1018 electrons, a current of 1 A through a resistor means that 6.25 X 1018 electrons are moving through the resistor each second.

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Electrons move through the circuit because of the electromotive force of the battery. When the current moves through a resistor, the electrons lose electrical potential energy. The electrons move from a point of higher to lower electrical potential. The potential difference across a resistor is the voltage across the resistor. (Since energy cannot be created or destroyed, the energy lost by the electrons must be converted into another kind of energy and transferred to another object.) When we use the term “current” we will refer to **electron-flow current** which is in the direction in which the electrons move.

Every source has a positive terminal and a negative terminal. Since we will use **electron-flow current**, the negative terminal is at higher electrical potential than the positive terminal. Our current will flow through the circuit from the negative terminal of the source to the positive terminal. The potential across the terminals of the source is the voltage of the source. A 9-volt battery has a potential difference of 9 volts across the terminals. This is only true for in ideal source which is a source that has no internal resistance and produces no heat while operating.

A source converts some other kind of energy into electrical potential energy. A battery converts chemical energy into electrical. A photocell converts light into electrical. A thermocouple converts heat. A generator converts kinetic and magnetic energy into electrical.

The load resistor(s) (or simply called the load) converts the electrical energy of the charges that move through the resistor into some other kind of energy. A toaster or oven converts electrical into heat. A motor converts electrical and magnetic into kinetic energy. A LASER converts electrical into light.

The main idea in all circuit electricity is Ohm’s law. Ohm’s law states:

 **The current through a resistor is directly proportional to the electrical potential difference across the resistor and inversely proportional to the resistance of the resistor.**

As an equation: I =  or V = IR or R = 

I – current through the resistor in amperes, A

V – electrical potential difference across the resistor in volts, V

R – resistance of the resistor in ohms, Ω

Another way to think of Ohm’s law is that the resistance of a resistor is the ratio of the voltage

across the resistor that is needed to produce a certain current through the resistor. We speak of a resistor as ***drawing*** current from the source. Higher resistance draws less current from a source and higher resistance requires more voltage to draw the same current. The resistance of a device is determined by the design and materials in the device. The motor in an electric drill has a different resistance than the motor in an electric toothbrush.

**Electrical energy and power**

The amount of energy a resistor converts depends upon the amount of current that flows through the resistor, the drop in electrical potential across the resistor, and the amount of time the resistor carries the current. In equation form:

***EPE* = VIt** or ***EPE*** = **I2Rt** or ***EPE* = V2t/R**

*EPE* – electrical potential energy in joules, J

V – electrical potential difference in volts, V

I – current in amperes, A

t – time in seconds, s

R – resistance in ohms, Ω

Which of these equations you will use depends upon the information you know and want to determine.

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Electrical power is the rate at which electrical energy is converted into another kind of energy. Like mechanical power, it is the rate of conversion and is given by the general equation:

**Power = energy / time**

For electrical power, the equations become:

**P = VI** or **P = I2R** or **P = V2 / R**

P – power in watts, W

V – electrical potential difference in volts, V

I – current in amperes, A

R – resistance in ohms, Ω

The first equation, P = VI, is most useful to determine the power production of a source.

The second equation, P = I2R, is most useful to determine the power consumption of a resistor.

Another unit of energy is used only for electricity, the kilowatt-hour. A kilowatt-hour is the amount of energy a resistor uses if it converts 1000 watts of power for one hour. The symbol for kilowatt-hour is kWh. This is what you pay for when you pay the power company for your electrical energy usage. If Progress Energy supplies your electricity, the company provides you with a potential to convert energy. You determine how much energy you convert by how much of that potential you use (based on which devices you operate) and for how long you use that potential. A 100-W lamp used more energy each second than does a 50-W lamp, but a 50-W lamp burning for 3 hours uses more energy than a 100-W lamp burning for 2 hours.

**Resistance of a wire**

The resistance of a wire is determined by three factors:

 1. the type of material from which the wire is made

 2. the diameter of the wire

 3. the length of the wire

Some metals have lower resistance than other metals. Copper has lower resistance than iron. Silver has lower resistance than copper. We make wires from copper rather than iron because of copper’s lower resistance which wastes less heat and is more efficient. We make wires from copper rather than silver due to the cost of the materials. Silver wire wastes less heat, but not enough less to overcome the extra cost of the silver. This resistance is called resistivity. Higher resistivity means the material offers more resistance than lower resistivity. Gold connectors are sometimes used in electrical devices because gold has low resistivity and is very unreactive chemically and will not corrode or “rust” when exposed to water vapor and oxygen in the air.

Larger diameter wire offers less resistance than smaller diameter wire. The mobile electrons that move through a conductor are on the outside of the wire. Electrons on the interior of the wire generally do not move much. Wire with a larger diameter has more surface area and therefore more electrons which are able to move.

Electrons bump into other electrons as they move through the wire. The farther the electrons have to move, the more resistance they will encounter.

So resistance of a wire is directly proportional to the resistivity of the material of the wire, directly proportional to the length of the wire, and inversely proportion to the cross-sectional area of the wire.

A long, thin wire of high resistance material has high resistance.

A short, thick wire of low-resistance material has low resistance.

Electrical resistance in a wire converts electrical energy into heat. High resistance wire is used in the heating elements of toasters because you want to produce heat. In most electrical devices, you do not want to produce heat. The heat is wasted energy. In these devices, you want the wires to have as little resistance as possible.

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**A circuit with a single resistor**

Let us consider a circuit that has only one resistor. An analogy would be a two-battery flashlight or a plug-in lamp with one bulb. We would represent the circuit with the following diagram:

source

resistor

The source has a fixed EMF. This is the voltage of the source. If the circuit is the flashlight, the voltage of the source is 3 V, 1.5 V for each battery. If the circuit is the lamp, the voltage of the source is the voltage of the wall outlet, 120 V. **This voltage cannot change.** The voltage of the source is determined only by the design of the source. The voltage will not change when a different device is attached to the source. The wall outlet will still be 120 V if a radio is plugged in instead of the lamp.

The current in the circuit is determine by the voltage of the source AND the resistor that is attached to the source. A resistor is said to DRAW a certain amount of current from a source. The load determines how much current a given source is required to produce. Ohm’s law applies here. The current in a circuit is directly proportional to the voltage of the source and inversely proportional to the resistance attached to the source. In equation form:

**Vsource = Icircuit R** or **Icircuit = Vsource / R** or  **R = Vsource / Icircuit**

R – resistance of the load in ohms, Ω

Icircuit – also the current through the resistor in amperes, A

Vsource – also the voltage across the resistor in volts, V

A higher resistance load will draw a smaller current from the source. A lower resistance load will draw a larger current from the source.

A higher voltage source will send a larger current to a resistor. A lower voltage source will send a smaller current to the resistor.

For a circuit with ONLY ONE resistor:

**Vresistor = Vsource**

**Iresistor = Isource**

**Rcircuit = Rresistor**

**Presistor = Psource**

**EPEresistor = EPEsource**

A resistor may draw more current than a source can provide. In this case the source will usually be damaged. The source may overheat and burn or melt. This happens when the resistance of the resistor is too small. A load of zero resistance draws an infinite amount of current from a source. No source can produce an infinite amount of current. A resistance of almost zero is a “short circuit.” This is very dangerous because a large amount of heat is produced and may start a fire.

A source may send too much current to a resistor. The resistor may not be able to convert energy fast enough. The extra energy is converted into heat which may damage the resistor. This happens when the voltage of the source is too high.

You should match the device with its proper power supply. Operating a device on the wrong power supply may damage the device, the power supply, or both. If a device tells you to use a 1.5-volt battery, using a 9-volt battery will not make the device operate better! Connecting the device to a 9-volt battery will probably damage the device, perhaps permanently.

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**A circuit with two resistors**

**IF a circuit has only two resistors**, THEN the resistors will be connected in **series** or in **parallel**. You must be able to look at a circuit and identify when the resistors are in series and when the resistors are in parallel. A place in a circuit where two wires meet is called a junction or a branch. Think of a junction as an intersection for cars. When a car comes to an intersection the car can follow different roads.

**Series arrangement of two resistors:**

R1

R2

-

-

-

+

+

+

The two resistors are in series if the circuit has no junction between

the two resistors. There is only one path for the current to follow

from the source back to the source. See the example right.

The circuit does NOT branch between the two resistors.

The resistors are in series with each other. Each resistor is also

in series with the source. **The same amount of current MUST**

**flow through each resistor and through the source.**

# Parallel arrangement of two resistors:

R1

R2

-

-

-

+

+

+

junction not a junction

junction not a junction

The two resistors are in parallel if there are two junctions

in the circuit. See the example right. There are two branches

with one resistor in each branch. The current will have **two**

possible paths to follow from the source back to the source.

Each resistor is also in parallel with the source. **The potential**

**difference (voltage) across each resistor MUST be the same**

**and equal to the voltage of the source**

**Ohm’s law with two resistors in the circuit**

The equations for Ohm’s law and the equations for power and energy apply to each resistor in the circuit individually:

 and  and 

 and  and 

The Ohm’s law, power, and energy equations also apply to the source:

  and  and 

**Power and energy for a circuit with two resistors**

The power produced by the source will equal the sum of the powers consumed by the individual resistors.

The energy produced by the source will equal the sum of the energies consumed by the individual resistors.

  and 

**Notice that this is the same relationship whether the resistors are in series or in parallel!**

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**Combined or equivalent resistance**

The source cannot tell whether a circuit contains one resistor or more than one resistor. The source detects the total combined resistance of the circuit and supplies current for that resistance at the electrical potential difference of the source. The source produces the amount of current that the entire circuit draws from the source. The combined resistance of all the resistors in a circuit is called the resistance of the circuit, .

***Resistors in series and resistors in parallel combine their resistances differently!***

**combined resistance of two resistors in series**

Two resistors in series produce a higher-resistance combination than either individual resistor.

The combined resistance is the sum of the two resistances.

 

With increased resistance, the combined resistors will draw less current from the source than either individual resistor would draw from that source.

**combined resistance of two resistors in parallel**

Two resistors in parallel produce a lower-resistance combination than either individual resistor.

The reciprocal of the combined resistance is the sum of the reciprocals of the two resistances.

  or 

If you know *Rcircuit* and one of the other resistors, you can find *R1* or *R2* with one of these equations:

 to calculate the resistance of resistor 1 and

 to calculate the resistance of resistor 2

With decreased resistance, the combined resistors will draw more current from the source than either individual resistor would draw from that source.

**Kirchhoff’s laws for a circuit with two resistors**

***Loop Law: In any circuit loop that includes the source, the sum of the voltage drops across the resistors is equal to the voltage of the source.***

**For resistors in parallel**, this will mean that each individual resistor has the same voltage as the source. There are two circuit loops, one loop that includes one of the resistors and a second loop that contains the other resistor. The source is in both loops.

 and 

**In a series circuit with two resistors**, there is only one loop. This will mean that the sum of the two voltage drops across the resistors will equal the voltage of the source.

 

***NOTICE: This law does NOT say the voltage across resistor 1 is equal to the voltage across resistor 2!***

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***Junction Law: When current passes through a junction, the total current that enters the junction is equal to the total current that leaves the junction.***

For a circuit with two resistors in series: The junction law does not apply. There are no junctions in the circuit.

**For a circuit that has two resistors in parallel:** The circuit will have two junctions, one before the two resistors and one after the two resistors.

junction A

 ●

 junction B

●

R1

R2

In the circuit above, the current that comes into junction A is equal to the current out of the junction. The same is true at junction B.

At junction A: current into junction A = current through resistor 1 + current through resistor 2

At junction B: current through resistor 1 + current through resistor 2 = current out of junction B

This makes the current into junction A equal to the junction out of junction B.

***NOTICE: This law does NOT say the current through resistor 1 is equal to the current through resistor 2!***

For resistors in parallel, this will mean the current produced by the source will equal the sum of the currents through the individual resistors.

 

**Some relationships for two resistors in series and in parallel**

**series**

Two resistors in series MUST carry the same amount of current.

The resistor with the higher resistance will have the larger voltage drop across the resistor.

The resistor with the higher resistance will consume more power and more energy.

**parallel**

Two resistors in parallel MUST have the same voltage drop.

The resistor with the smaller resistance will carry a larger current.

The resistor with the smaller resistance will consume more power and more energy.

Circuit with two resistors

**Series arrangement Parallel arrangement**

$I\_{source}=I\_{1}=I\_{2}$ $V\_{source}= V\_{1}= V\_{2}$

$R\_{circuit}=R\_{1}+R\_{2}$ $I\_{source}=I\_{1}+I\_{2}$

$V\_{source}=V\_{1}+V\_{2}$ $R\_{circuit}=(R\_{1}^{-1}+ R\_{2}^{-1})^{-1}$

$I\_{source}=\frac{V\_{source}}{R\_{circuit}} $ $I\_{source}=\frac{V\_{source}}{R\_{circuit}} $

$P\_{source}=P\_{1}+P\_{2}$ $P\_{source}=P\_{1}+P\_{2}$

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**Circuits with more than two resistors**

**Circuit Analysis**

IF a circuit contains three or more resistors THEN you should follow the procedure given below.

**IF you are only given a description of the circuit THEN sketch the circuit from its description. I will usually give you a drawing of the circuit. After you have the circuit diagram, follow steps 1 & 2. You will need to do these two steps regardless of what other information I give you. Let us always assign current flow as clockwise through the circuit with the terminal of the source from which the current leaves as the negative terminal, N.**

STEP 1 – Show with arrows the flow of current through the circuit and label each current “segment.”.

We will show **electron-flow current** which is from negative to positive. We will show current flowing clockwise through the circuit. Mark each end of each resistor as N or P. The end of the resistor that current enters is the negative end, N. Label the other end of the resistor P. Identify and label the junctions in the circuit. When current encounters a junction (where two wires connect to each other) the current will split with some current flowing through each branch out of the junction. Show and label the voltage drops across each resistor and the voltage rise across the source. Identify and label all the loops in the circuit. A loop is a single path from source to source through the circuit. Each circuit must have at least one loop and most circuits will have more than one loop. **Time spent on this step will be rewarded later while working the problem!**

STEP 2 – Identify which resistors, if any, are in series or in parallel with the source. Identify which resistors, if any, are in series or parallel with each other.

**The test for whether a device (resistor or source) is in parallel with another device**: IF the positive end of one device is connected to the positive end of the other device with only wires between the two AND the negative end of the first device is connected to the negative end of the other device with only wires between the two THEN the two devices are in parallel. Any two devices in parallel with the same device are in parallel with each other.

**The test for whether a device (resistor or source) is in series with another device**: IF the same amount of current MUST flow through two devices regardless of where the two devices are in the circuit THEN the two devices are in series. A resistor is in series with the source if all the current the source produces MUST flow through the resistor. Any two resistors in series with the same resistor (or the source) are in series with each other.

When two resistors fail **BOTH** tests then the two resistors are neither in series nor in parallel with each other. These two resistors may in series or in parallel with other resistors (or the source) however.

How you proceed at this point depends upon what information I give you in the problem.

Generally I will give you these two combinations of information:

**combination A: two pieces of information (V, I, R, P) about one resistor or two pieces of information (V, I, P) about the source**

**combination B: all the resistances of the resistors in the circuit and one piece of information (V, I, P) about the source**

**If combination A:**

STEP 3: Calculate V, I, and/or R for the resistor about which you know two pieces of information or V and/or I for the source if you know two pieces of information about the source.

STEP 4: Assign the same V for all devices in parallel with this resistor or source. You identified these devices in STEP 2.

STEP 5: Assign the same I for all devices in series with this resistor or source. You identified these devices in STEP 2.

STEP 6: Use the loop law to find unknown voltages and the junction law to find unknown currents.

 You identified the loops and junctions in STEP 1.

**Each time you calculate a V or an I, revisit STEPS 4 & 5!**

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**If combination B:**

STEP 3: Assign the same V for all resistors in parallel with the source if you know V for the source. You identified these resistors in STEP 2.

STEP 4: Assign the same I for all resistors in series with the source if you know I for the source. You identified these resistors in STEP 2.

STEP 5: Calculate the total resistance (equivalent resistance) of the circuit. Start with series arrangements within parallel branches.

STEP 6: Calculate the current produced by the source or the voltage of the source using the equation:

 $I\_{source}= \frac{V\_{source}}{R\_{circuit}}$

STEP 7: Revisit STEPS 3 & 4

STEP 8: Use Ohm’s law or the power equations for individual resistors for whom you know two pieces of information (V, I, R, P).

STEP 9: Use the loop law to find unknown voltages and the junction law to find unknown currents. You identified the loops and junctions in STEP 1.

**Kirchhoff’s Laws for circuits with more than two resistors**

***Junction Law*** – ***The total current into a junction must equal the total current out of the junction.***

●

●

●

●

*J1*

*J2*

*J3*

*J4*

***I1***

***I2***

***I3***

***I4***

***I5***

***I6***

***I7***

At junction 1, *J1*: total current into = total current out

 *I1* = *I2* + *I3*

At junction 2, *J2*: total current into = total current out

 *I2* = *I4* + *I5*

At junction 3, *J3*: total current into = total current out

 *I4* + *I5* = *I6*

At junction 4, *J4*: total current into = total current out

 *I3* + *I6* = *I7*

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***Loop Law – In a circuit loop that contains the source, the sum of the voltage drops across the individual***

 ***resistors equals the voltage of the source.***

*R1*

***Loop A***

***Loop B***

*R3*

*R2*

*R4*

A circuit loop is a single unbranched path that goes from one terminal of the source through the circuit to the other

terminal of the source. The circuit above contains two loops, *A* and *B*.

Loop *A* contains the source, resistor 1, and resistor 2. The loop law for loop *A* tells us:

 $V\_{source}= V\_{1}+V\_{2}$

Loop *B* contains the source, resistor 1, resistor 3, and resistor 4. The loop law for loop *B* tells us:

 $V\_{source}= V\_{1}+V\_{3}+V\_{4}$

From these two equations we can also determine:

 $V\_{2}= V\_{3}+V\_{4}$