Chapter 2

Circuit Concepts, Elements and Terminology

As we have reviewed the technical mathematics to solve circuit problems, in this chapter we are going to learn the terms and symbols of each element that makes up a circuit. After learning the concepts of how the main components of electricity originate, such as current, voltage, and power, we are going to learn the elements and terminology of an electric circuit.

2.1. Circuit Concepts

2.1.1. Charge

The concept of electricity arises from an observation of nature. We observe a force between objects, that, like gravity, acts at a distance. The source of this force has been given the name charge. A very noticeable thing about electric force is that it is large, far greater than the force of gravity. Unlike gravity, however, there are two types of electric charge. Opposite types of charge attract, and like types of charge repel. Gravity has only one type: it only attracts, never repels.

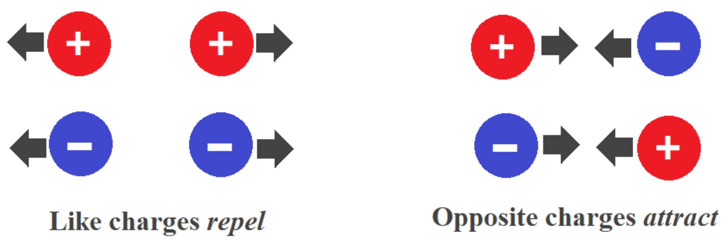

Figure 2.1 – Charges Exert Forces

2.1.2. Conductors, insulators, and semiconductors

Conductors are made of atoms whose outer, or valence, electrons have relatively weak bonds to their nuclei, as shown in this fanciful image of a copper atom.

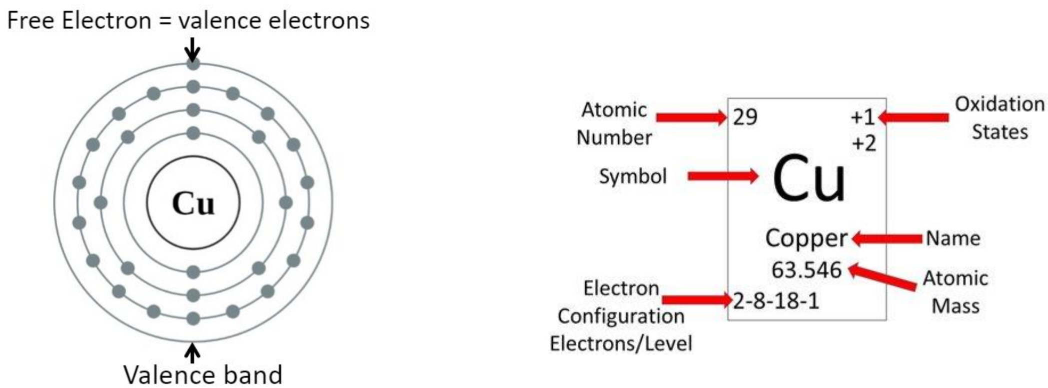

Figure 2.2 – Atom Structure of a Copper Atom

When a bunch of metal atoms are together, they gladly share their outer electrons with each other, creating a "swarm" of electrons not associated with a particular nucleus. A very small electric force can make the electron swarm move.

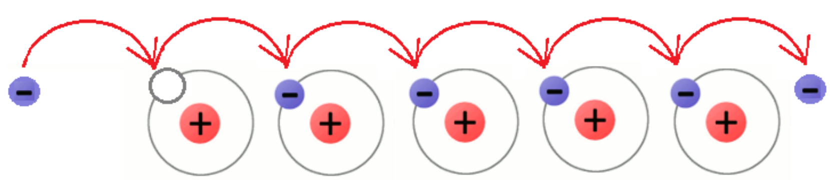

Figure 2.3 – Electron Movement of a Copper Atom

Copper, gold, silver, and aluminum are good conductors. So is saltwater. There are also poor conductors. Tungsten—a metal used for light bulb filaments—and carbon—in diamond form—are relatively poor conductors because their electrons are less prone to move.

Insulators are materials whose outer electrons are tightly bound to their nuclei. Modest electric forces are not able to pull these electrons free. When an electric force is applied, the electron clouds around the atom stretch and deform in response to the force, but the electrons do not depart. Glass, plastic, stone, and air are insulators.

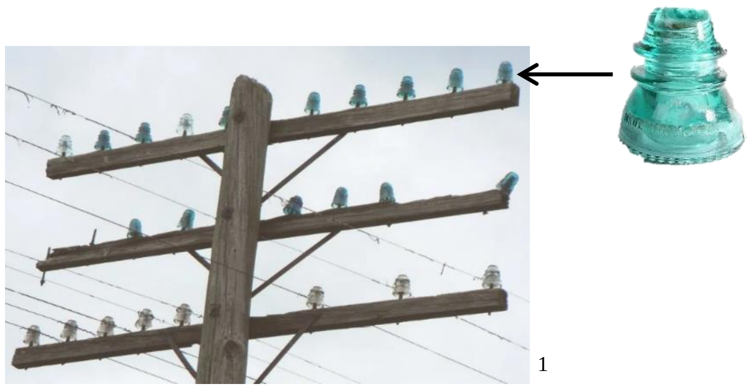
[1]

Figure 2.3 – Telegraph pole with glass insulators

Even for insulators, though, electric force can always be turned up high enough to rip electrons away—this is called breakdown. That's what is happening to air molecules when you see a spark.

Semiconductors are materials fall between insulators and conductors. They usually act like insulators, but we can make them act like conductors under certain circumstances. The most well-known semiconductor material is Silicon (atomic number). Our ability to finely control the insulating and conducting properties of silicon allows us to create modern marvels like computers and mobile phones. The atomic-level details of how semiconductor devices work are governed by the theories of quantum mechanics.

1 *"Telegraph pole with glass insulators along a railroad in Indiana*", General Overview on Glass Insulators – Basic Information. Image retrieved from https://www.glassbottlemarks.com/, 8/1/2020

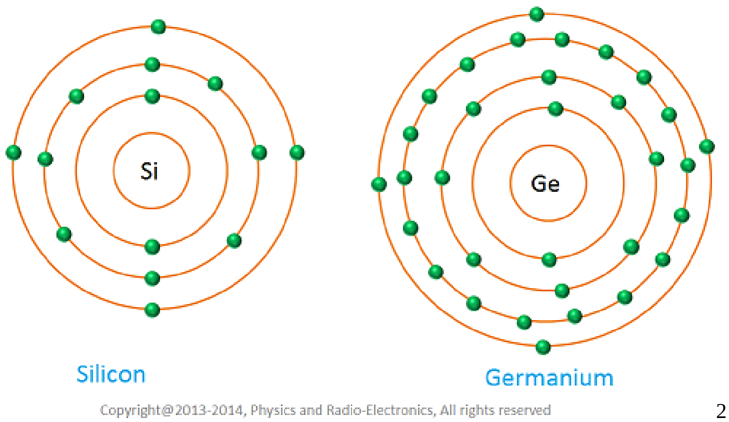

Figure 2.4– Atom Structure of a Semiconductor Material, Silicon and Germanium

2.1.3. Current

Current is the flow of charge. Current is reported as the number of charges per unit time passing through a boundary. Visualize placing a boundary all the way through a wire. Station yourself near the boundary and count the number of charges passing by. Report how much charge passed through the boundary in one second. We assign a positive sign to current corresponding to the direction a positive charge would be moving.

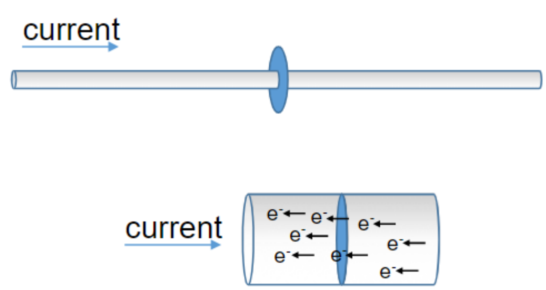

Figure 2.5– Electrons Flow in a Wire

Current is labeled with the letter *I* (for a fixed value) and *i* (for alternative values) and its measure unit is *Amperes, A.* Since current is the amount of charge passing through a boundary in a fixed amount of time, it can be expressed mathematically using the following equation:

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[2] *Intrinsic Semiconductor*, Physics and Radio Electronics, www.physics-and-radio-electronics.com, retrieved of June 20, 2020 https://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/semiconductor/intrinsic-semiconductor/atomic-structure-of-silicon-and-germanium.html

$$I = \frac{Amount\ of\ charge\ passing\ through\ a\ boundary\ (measure\ in\ Joules) = Q}{fixed\ amount\ of\ time\ (measure\ in\ seconds) = t}$$

$$I = \frac{Q}{t}$$

Formula 2.1 – Current Formula

A few remarks on current

- **What carries current in metal?** Since electrons are free to move about in metals, conductor materials, moving electrons are what makes up the current in metals. The positive nuclei in metal atoms are fixed in place and do not contribute to current. Even though electrons have a negative charge and do almost all the work in most electric circuits, we still define a positive current as the direction a positive charge would move. This is a very old historical convention.
- **Can current be carried by positive charges?** Yes. There are lots of examples. Current is carried by both positive and negative charges in saltwater: If we put ordinary table salt in water, it becomes a good conductor. Table salt is sodium chloride, NaCl. The salt dissolves in water, into free-floating Na^++start superscript, plus, end superscript and Cl^-−start superscript, minus, end superscript ions. Both ions respond to electric force and move through the saltwater solution, in opposite directions. In this case, the current is composed of moving atoms, both positive and negative ions, not just loose electrons. Inside our bodies, electrical currents are moving ions, both positive and negative. The same definition of current works: count the number of charges passing by in a fixed amount of time.
- **What causes current?** Charged objects move in response to electric and magnetic forces. These forces come from electric and magnetic fields, which in turn come from the position and motion of other charges.
- **What is the speed of current?** We don't talk very often about the speed of current. Answering the question, "How fast is the current flowing?" requires understanding of a complex physical phenomenon and is not often relevant. Current usually isn't about meters per second, it's about charge per second. More often, we answer the question "How much current is flowing?" all the time.

- **How do we talk about current?** When discussing current, terms like through and in make a lot of sense. Current flows through a resistor; current flows in a wire. If you hear, "the current across ...", it should sound odd.

2.1.4. Voltage

To move the electron in a conductor in a particular direction requires some work or energy transfer. This work is performed by an external electromotive force (emf), typically in electronics is represented by the battery. This emf is also known as *voltage* or *potential difference*. The voltage, V_{ab}, between two points *a* and *b* in an electric circuit is the energy (or work) needed to move a unit charge from *a* to *b*; mathematically: *(Alexander & Sadiku, 2013)*

$$V = \frac{Work\ or\ energy\ require\ to\ transfer\ charges\ from\ point\ a\ to\ b = W}{Amoung\ of\ charges\ transfered\ from\ point\ a\ to\ b = Q}$$

$$V = \frac{W}{Q}$$

Formula 2.2 – Voltage Formula

Voltage is labeled with the letter *V* (for a fixed value) and *v* (for alternative values) and its measure unit is *Volts, V.*

2.1.5. Resistance

Resistance is an electrical quantity that measures how the material reduces the electric current flow through it. The resistance is measured in units of Ohms (**Ω**)

What does resistance depend on?

Resistance depends on an object's size, shape, and material. In Figure 2.6 below, the cylinder's resistance is directly proportional to its length, ℓ. The longer the cylinder, the higher the resistance.

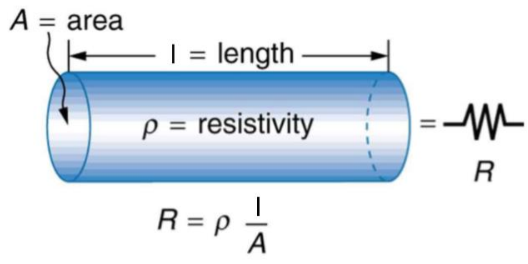


Figure 2.6. A uniform cylinder of length ℓ *and cross sectional area* ***A****. The longer the cylinder, the greater its resistance. The larger its cross-sectional area* ***A****, the smaller its resistance. Image credit: Adapted from OpenStax College Physics. Original image from OpenStax, CC BY 4.0*

Additionally, the resistance is inversely proportional to the cross sectional area **A**. If the diameter of the cylinder is doubled, the cross-sectional area increases by a factor of 4. Therefore, resistance decreases by a factor of 4.

The resistivity **ρ** of a material depends on the molecular and atomic structure, and is temperature-dependent. For most conductors, resistivity increases with increasing temperature. *(Current, resistance, and resistivity review, 2020)*

2.1.6. Power

Power is defined as the rate energy, *work,* is transformed or transferred over time. We measure power in units of joules/second, also known as watts.

$$P = \frac{Energy\ transformed\ or\ transferred = W}{Time\ takes\ to\ transferred\ the\ given\ energy = t}$$

$$P = \frac{W}{t}$$

Formula 2.3 – Power Formula

An electric circuit is capable of transferring power. Current is the rate of flow of charge, and voltage measures the energy transferred per unit of charge. We can insert these definitions into the equation for power:

$$P = \frac{W}{t} = \frac{W}{Q} \times \frac{Q}{t} = V \times I$$

$$P = V \times I$$

Formula 2.3 – Power Formula with Respect to Voltage and Current

Electrical power is the product of voltage times current, in units of watts.

2.2. Circuit Elements

Elements are the components and sources that make an electric circuit along with their connections. There are two types of elements found in electric circuits: passive elements and active elements. An active element is capable of generating energy while a passive element is not. Examples of passive elements are resistors, capacitors, and inductors. Typical active elements include generators, batteries, and operational amplifiers. For the first part of the electric circuit analysis study, we are aiming to gain familiarity with passive elements and independent sources.
(Alexander & Sadiku, 2013)

2.2.1. Passive Elements

A passive element is an electrical component that does not generate power, but instead dissipates, stores, and/or releases it. Passive elements include resistors, capacitors, and coils (also called inductors). These components are labeled in circuit diagrams as Rs, Cs and Ls, respectively. (Passive elements, 2020)

The electronics symbols a resistor, capacitor, and an inductor is as the following:

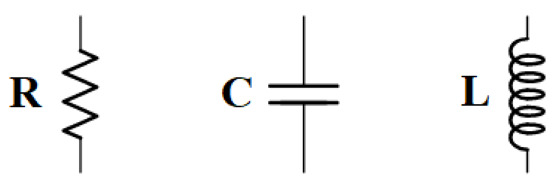


Figure 2.7 – Passive Elements: Resistor, Capacitor, and Inductor

2.2.2. Active Elements: Voltage and Current Source

The types of active circuit elements that are most important to us are those that supply electrical energy to the circuits or network connected to them. These are called “electrical sources” with the two types of electrical sources being the *voltage source* and the *current source*. The current source is usually less common in circuits than the voltage source, but both are used and can be regarded as complements of each other.

The electronics symbols for DC voltage and current source are as:

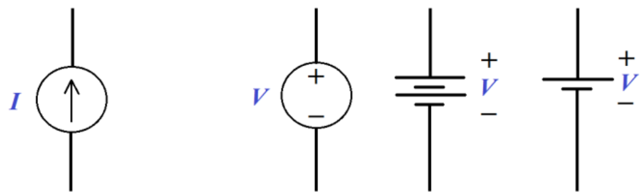


Figure 2.8 – Active Sources: DC current source (left symbol) and DC voltage sources (three right symbols)

An electrical supply or simply, “a source”, is a device that supplies electrical power to a circuit in the form of a voltage source or a current source. Both types of electrical sources can be classed as a direct (DC) or alternating (AC) source in which a constant voltage is called a DC voltage and one that varies sinusoidally with time is called an AC voltage. So for example, batteries are DC sources and the 230V wall socket or mains outlet in your home is an AC source.

Figure 2.9 – Examples of DC sources (left: batteries) and AC source (right: wall socket)

The electronics symbols for AC voltage and current source are as:

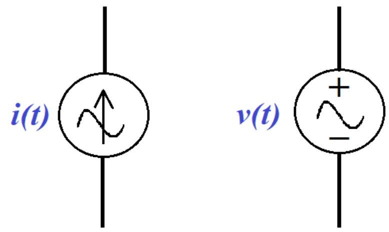


Figure 2.10 – Active Sources: AC current source (left symbol) and AC voltage sources (right symbol)

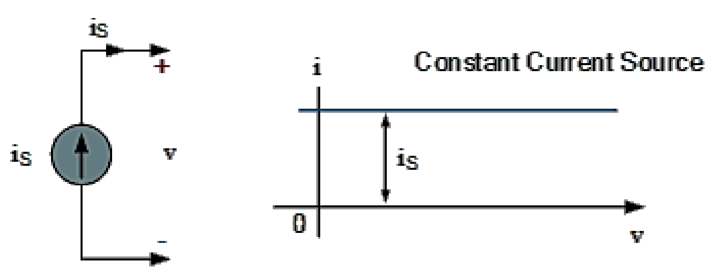
We said earlier that electrical sources supply energy, but one of the interesting characteristic of an electrical source, is that they are also capable of converting non-electrical energy into electrical energy and vice versa. For example, a battery converts chemical energy into electrical energy, while an electrical machine such as a DC generator or an AC alternator converts mechanical energy into electrical energy.

Renewable technologies can convert energy from the sun, the wind, and waves into electrical or thermal energy. But as well as converting energy from one source to another, electrical sources can both deliver or absorb energy allowing it to flow in both directions.

2.2.3. I-V characteristic of an Electrical Source

Another important characteristic of an electrical source and one which defines its operation, are its I-V characteristics. The I-V characteristic of an electrical source can give us a very nice pictorial description of the source, either as a voltage source and a current source.

Electrical sources are as:



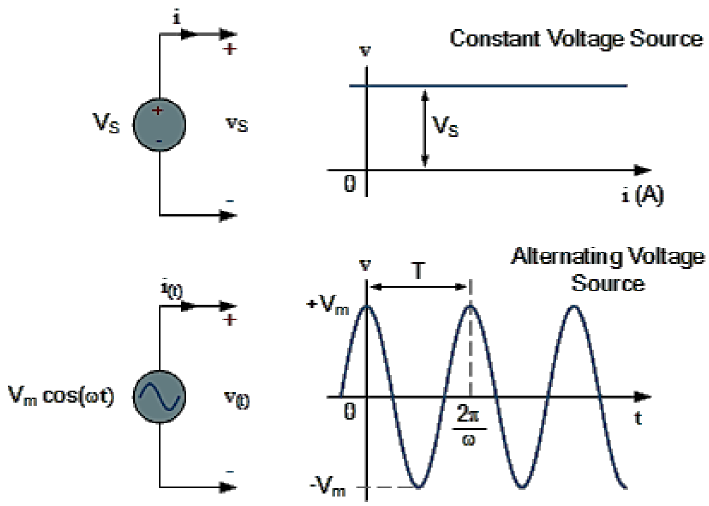


Figure 2.11 – I-V characteristics of a DC signal (top figure), of a DC voltage source (middle image), and of a AC voltage source (bottom image)

When dealing with circuit laws and analysis, electrical sources are often viewed as being "ideal", that is the source is ideal because it could theoretically deliver an infinite amount of energy without loss thereby having characteristics represented by a straight line. However, in real or practical sources there is always a resistance either connected in parallel for a current source, or series for a voltage source associated with the source affecting its output.

2.2.4. Independent and Dependent Sources

Electrical sources, both as a voltage source or a current source can be classed as being either *independent* (ideal) or *dependent*, (controlled) that is whose value depends upon a voltage or current elsewhere within the circuit, which itself can be either constant or time-varying (Voltage Source, 2020). In terms of electronic symbols, a diamond shape is used to represent a dependent source while a circle is used to represent an independent source:

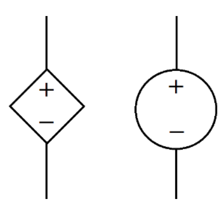


Figure 2.12 – Electronics symbols of a dependent DC voltage source (left figure) and an independent DC voltage source (right figure)

2.3. Circuit Terminology

Circuit terminology is a vocabulary use to talk about circuit. This vocabulary includes circuit terms and schematic terms.

2.3.1. Circuit Terms

Circuit: Circuit comes from the word circle. A circuit is a collection of real components, power sources, and signal sources, all connected so current can flow in a complete circle. A circle could be open or closed depending on its elements are connected.

- **Closed circuit**: A circuit is closed if the circle is complete, if all currents have a path back to where they came from.

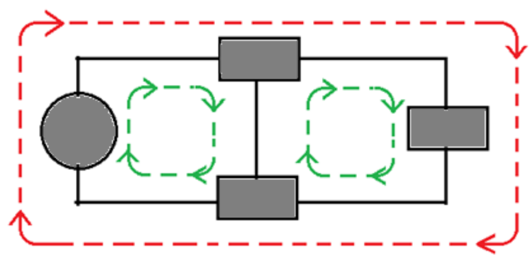


Figure 2.13 – Closed Circuit Representation

- **Open circuit:** A circuit is open if the circle is not complete, if there is a gap or opening in the path.

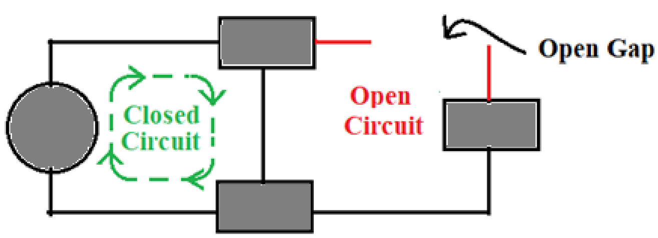


Figure 2.14 – Open Circuit Representation

- **Short circuit**: A short happens when a path of low resistance is connected (usually by mistake) to a component. The resistor shown below is the intended path for current, and the curved wire going around it is the short. Current is diverted away from its intended path, sometimes with damaging results. The wire shorts out the resistor by providing a low-resistance path for current (probably not what the designer intended).

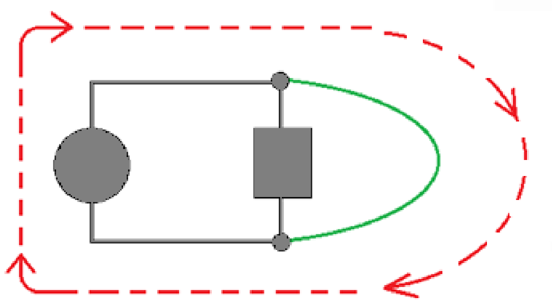


Figure 2.15 – Short Circuit Representation

- **Make or Break**: You **make** a circuit by closing the current path, such as when you close a switch (ON)

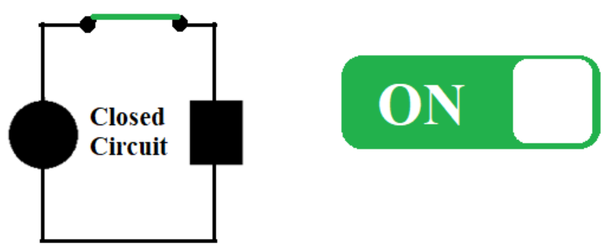


Figure 2.16 – Short Circuit Representation

Breaking a circuit is the opposite. Opening a switch breaks the circuit (OFF)

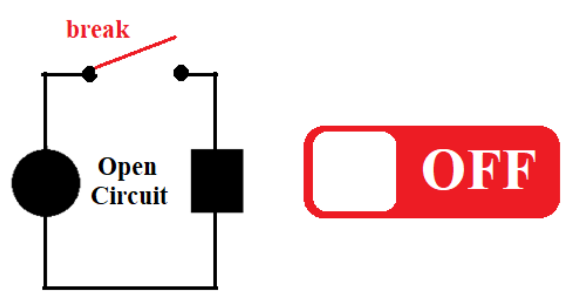
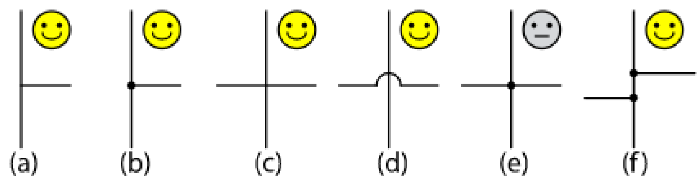


Figure 2.17 – Short Circuit Representation

2.3.2. Schematic

A schematic is a drawing of a circuit. A schematic represents circuit elements with symbols and connections as lines.

- **Lines:** Connections between elements are drawn as lines, which we often think of as "wires". On a schematic, these lines represent perfect conductors with zero resistance.
- **Dots:** Connections between lines can be indicated by dots. Dots are an unambiguous indication that lines are connected. If the connection is obvious, you don't have to use a dot. Some lines connection are drawn below:



(a) and (b) are both good. A solid dot means connection

(c) no solid dot indicates no connection

(d) also indicates no connection; the horizontal wire "hops" over the vertical wire. This connection is very clear but takes extra effort and space to draw.

(e) is acceptable to draw crossing lines, but risks looking too much like (c)

(f) is the better practice to draw crossing lines.

2.3.3. Node

A node is a junction where two or more elements connect is called a node. The schematic below shows a single node (the black dot) formed by the junction of five elements (abstractly represented by orange rectangles).

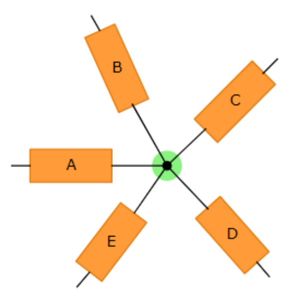


Figure 2.18 – Node Connection: A node connecting five elements

Since lines on a schematic represent perfect zero-resistance conductors, there is no rule that says lines from multiple elements are required to meet in a single point junction. We can draw the same node as a distributed node like the one in the schematic below. These two representations of the node mean exactly the same thing.

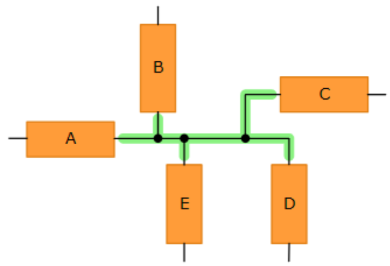


Figure 2.19 – Line representation of node connection of Figure 2.17

A distributed node might be all spread out, with lots of line segments, elbows, and dots. Don't be distracted, it is all just one single node. Connecting schematic elements with perfect conductors means the voltage everywhere on a distributed node is the same.
Here is a realistic-looking schematic with the distributed nodes labeled:

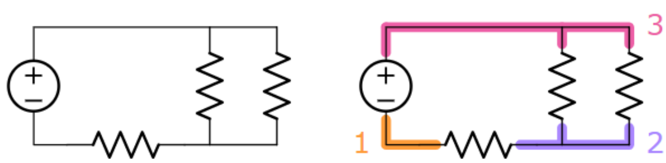


Figure 2.20 – Identifying Node Connection in an Electrical Circuit

The number of nodes in Figure 2.19 is **three.**

2.3.4. Branch

Branches are connected between nodes. A branch is an element (resistor, capacitor, source, etc.). The number of branches in a circuit is equal to the number of elements. For example, the circuit below has **four** branches:

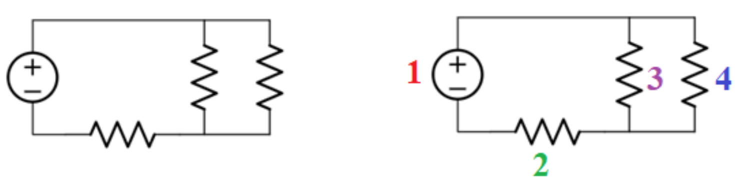


Figure 2.21 – Identifying Branches in an Electrical Circuit

2.3.5. Loop

A loop is any closed path going through circuit elements. To draw a loop, select any node as a starting point and draw a path through elements and nodes until the path comes back to the node where you started. There is only one rule: a loop can visit (pass through) a node only one time. It is ok if loops overlap or contain other loops. Some of the loops in our circuit are shown here. (You can find others, too. If I counted right, there are six.) Just from this simple example you can see the number of loops in a circuit can become quite large. Loop analysis can be quite a burden, so you will notice a fair amount of effort going into figuring out simpler methods.

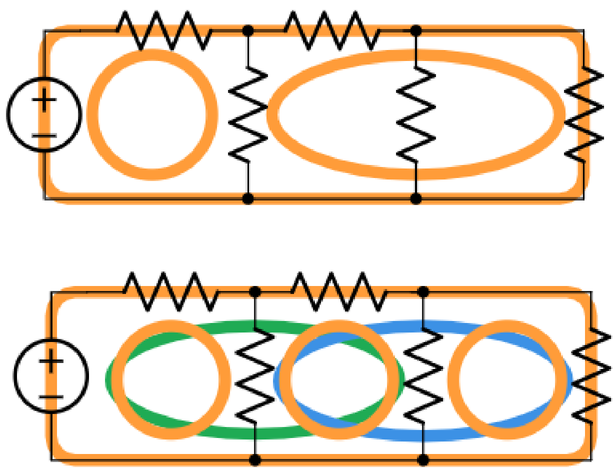


Figure 2.22– Identifying all Loops in an Electrical Circuit

2.3.6. Mesh

A mesh is a loop that has no other loops inside it, independent loop. You can think of this as one mesh for each "open window" of a circuit. For example, the circuit below has three meshes:

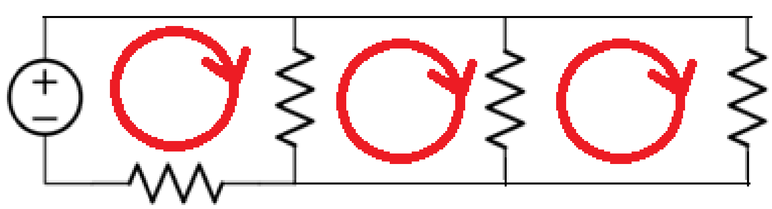


Figure 2.23 – Identifying Meshes in an Electrical Circuit

2.3.7. Reference Node

During circuit analysis we usually pick one of the nodes in the circuit to be the reference node. Voltages at other nodes are measured relative to the reference node. Any node can be the reference, but two common choices that simplify circuit analysis are, the negative terminal of the voltage or current source powering the circuit, or the node connected to the greatest number of branches.

2.3.8. Ground

The reference node is often referred to as *ground*. The concept of ground has three important meanings, ground is:

- the reference point from which voltages are measured.
- the return path for electric current back to its source.
- a direct physical connection to the Earth, which is important for safety.

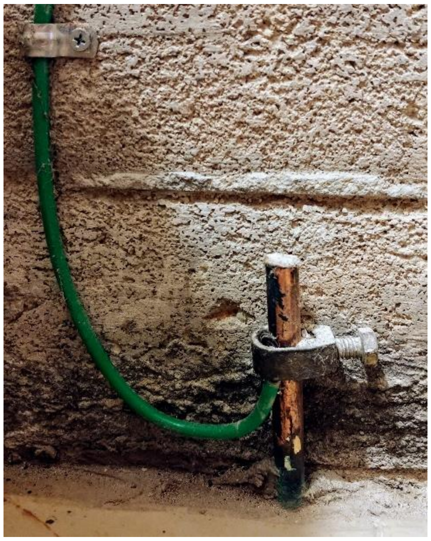


Figure 2.24– Residential Home Ground

You will come across various symbols for ground:

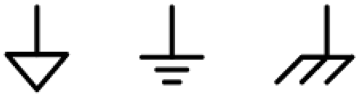


Figure 2.25 – Various Symbols for Ground: Common Ground(left), Earth Ground (middle), Chassis Ground (right)

2.3.9. Why is it important safety?

If an electric appliance or tool fails and accidentally creates a short circuit between high internal voltage and the metal surface of the appliance, it is much safer to direct the large dangerous current into the Earth rather than through you. The metal enclosure of an appliance is connected to a ground wire, which goes through the home's electrical system and out to Earth, thereby directing dangerous current to a safe place, away from people. When the appliance or tool is working properly, there is zero current flowing in the safety ground wire. *(McAllister, 2016)*

References

Alexander, C., & Sadiku, M. (2013). Circuit Elements. In C. Alexander, & M. Sadiku, *Fundamentals of Electric Circuits.* The McGraw Hill Companies.

McAllister, W. (2016). *Basic electrical quantities: current, voltage, power.* Retrieved from Khan Academy: https://www.khanacademy.org/science/physics/circuits-topic/circuits-resistance/a/ee-voltage-and-current

Passive elements. (2020). Retrieved from Renesan Electronics: https://www.renesas.com/us/en/support/technical-resources/engineer-school/electronic-circuits-01-passive-elements.html#:~:text=A%20passive%20element%20is%20an,%2C%20Cs%20and%20Ls%2C%20respectively.

Voltage Source. (2020). Retrieved from Electronics Tutorials: https://www.electronics-tutorials.ws/dccircuits/voltage-source.html