Terminology and Definitions

English Units

English units are difficult to use since there's a different unit for each thing you measure. For example, each of the following are English units of length (source: Wikipedia)

Unit of Length	Value	Where it comes from
Inch	1"	The length of one digit.
Hand	4"	Width of your palm. Used with horses
Foot	12"	Length of a foot.
Cubit	18"	Fingertip to elbow
Yard	36"	Nose to finger tip
Ell	45"	Fingertip to to opposite shoulder. Used for cloth.
Fathom	6'	Fingertip to fingertip. Depth of water.
Rod	16.5'	Used for surveying
Chain	66'	Also used in surveying
Furlong	660'	The distance a team of oxen can plow without rest
Mile	5280'	8 furlongs
League	3 miles	The distance you walk in an hour

Table 1: A dozen ways to measure length using English units

These definitions are not precise - so it causes problems when trading between cities. It's also difficult to compare items in English units. For example, which is more:

- A person who is 5'10",
- A horse which is 20 1/2 hands, or
- A pond which is 1 fathom deep?

SI Units

Metric (or SI: System International) uses standard unit for everything (unless you are a chemistry major).

Name	Symbol	Parameter	Definition
Meter	m	length	Distance light travels in a vacuum
kilogram	kg	mass	mass of a the standard kilogram in Paris
second	s	time	Oscillations of a Cs_{133} atom
Coulomb	Q	charge	6.02E23 electrons
Kelvin	K	temperature	0K = -273 Celsius
radian		angle	180/pi degrees

Table 2: Base units used the metric system

Using these base units, some other units can be defined (termed derived units):

Name	Symbol	Parameter	Units
Newton	N	Force	kg m / s^2
Joule	J	Energy	Force * distance = kg m^2 / s^2
Watt	W	Power	Joule / second = kg m^2 / s^3
Amp	A	current	Q / s
Volt	V	Electric potential	Watts / Amp
Ohm	Ω	Electrical resistance	Volts / Amp
Farad	F	Capacitance	Q^2 s^2 / kg m^2 = Coulomb / Volt
Henry	H	Inductance	kg m^2 / Q^2 = Joules / Amp^2

Table 3: Derived units in the metric system

The nice thing about metric is that *everything* uses the same unit. It doesn't matter if you're measuring the distance a person walks, the distance an ox pulls, or the length of a piece of fabric: if you're measure length, the unit is meters.

When using a single unit of length, mass, time, or whatever, it can get rather clunky if you have to use very large numbers of very small numbers. To handle the very large and very small, metric uses prefixes that represent multiples of 1000 as show in Table 4.

Prefix	Symbol	Multiplier	Comments
Giga	G	10^9	Population of Earth = 7.5 billion
Mega	M	10^6	North Dakota = 0.7 million
kilo	k	10^3	NDSU = 14,000
milli	m	10^{-3}	Grain of rice = 1mm
micro	u	10^{-6}	bacteria = 1um
nano	n	10^{-9}	Sucrose molecule
pico	p	10^{-12}	Hydrogen atom = 100pm
femto	f	10^{-15}	

Table 4: Standard prefixes and their meaning

One nice feature of using metric units is even if you don't know the equation, you can usually get the right answer by getting the units to match up. For example, solve the following problem:

Determine the resistance of 100 meters of copper wire which has a cross sectional area of 1mm2. The conductivity of copper is

$$\rho = 1.68 \cdot 10^{-8} \Omega m$$

Solution: Even if you don't know what conductivity is, you can get the right equation.

You have

- $\rho = 1.68 \cdot 10^{-8} \Omega m$ conductivity
- $L = 100m$ length
- $A = 10^{-6} m^2$ cross sectional area

To get Ohms, multiply

$$R = \frac{\rho L}{A} = \frac{(\Omega m)(m)}{\left(m^2\right)} = \Omega$$

$$R = \frac{\left(1.68\cdot 10^{-8}\Omega m\right)(100m)}{10^{-6}m^2} = 1.68\Omega$$

Voltage / Current / Power:

Protons: Part of the nucleus of an atom. Protons do not move and are bound in place by chemical bonds.

Electrons: Part particle, part wave. Electrons are negatively charged particles which are locked in place in insulators and free to move in conductors. Note that current was discovered before electrons. The definition of positive current flow was somewhat arbitrary at that point. They got it wrong. (The direction of current flow is opposite of the direction of electron flow.)

Current: The flow of electrons. 1A = 6.02 * 10^{23} electrons per second.

Voltage: The force that causes current to flow, or, the energy released when current flows.

1 Amp of current flowing across 1 Volt produces 1 Joule.

Resistance: The resistance to current flow.

V = I R

1 Volt = 1 Amp flowing across 1 Ohm

An analogy which is often used is water flowing downhill.

- The pressure (or distance) the water flows downhill corresponds to voltage
- The actual flow of water corresponds to current
- The pipe which limits the flow of the water is resistance.

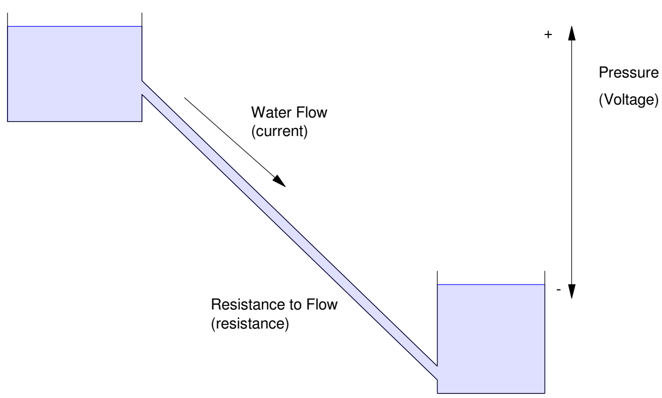


Figure 1: Water tanks are a common analogy for voltage (water head pressure), current (water flow), and resistance (size of pipe)

Note that for current to flow, there must be an inlet and an outlet (water in equals water out). The same holds for current.

Electrons (current) can neither be created nor destroyed. They can only be pushed around.

If you have a wire with only one end connected to a circuit, you know right away that the current is zero. The voltage can be anything - just the current is zero.

Power (Watts) and Energy (Joules):

Energy is a fundamental property in a system. Unless you are creating matter, energy is always conserved. Many techniques in engineering use this property: if you understand how the energy in the system is moving around, you've gone a long way in understanding the system.

There are several types of energy:

Thermal energy: The energy required to raise one CC of water one degree Celsius is 4.18 Joules

$$E = C \cdot m \cdot T \qquad \text{C = specific heat}$$

Potential Energy: The energy required to lift 1 kg 1 meter is 9.8 Joules

$$PE = mgh$$

Kinetic Energy: The energy required to accelerate 1 kg of mass up to 1 m/s is 1/2 kg

$$KE = \tfrac{1}{2}mv^2$$

Electric Energy: The energy released when moving 1 Coulomb of electrons across 1 Volt - or - the energy released when 1 Amp of current flows across 1 Volt for one second

$$w = \int v \cdot i \cdot dt$$

Power is the instantaneous rate of energy release

$$p = \tfrac{dw}{dt} = v \cdot i$$

$$w = \int p \cdot dt$$

The notation used in electrical engineering is for current to flow into the + terminal for voltage. With this convention, positive energy is energy absorbed (you're producing heat or charging a battery for example.) Negative energy is energy produced (typically by a battery driving a circuit).

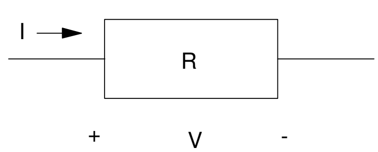


Figure 2: Standard definition of the direction of current and voltage for the relationship V = I*R

Circuit Notation:

Nodes:

A node is indicated by a solid line. It represents a wire (with a resistance of zero ideally). The voltage at any point on the wire is the same. The following circuit, for example, has four voltage nodes including ground.

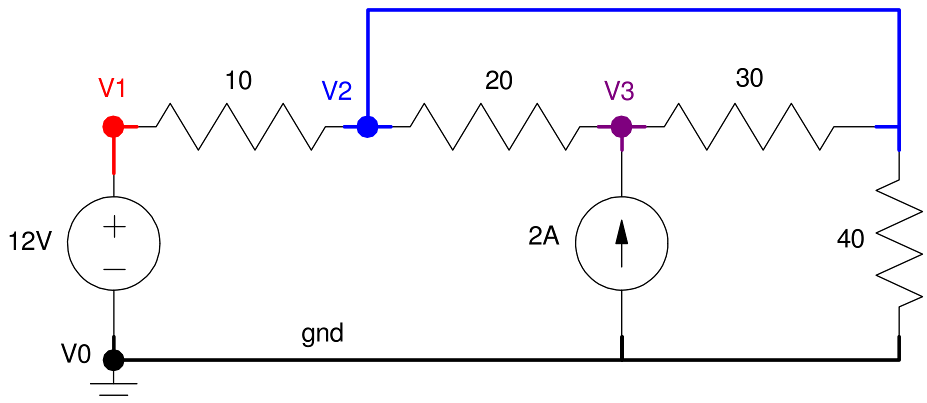


Figure 3: A voltage node is all points in a circuit which are connected with a wire (meaning they have the same voltage)

Ground:

Ground is a voltage node which all other voltages are referenced to. Usually, ground is the same as earth ground - it doesn't have to be, however. Birds sitting on a high-voltage line, for example, treat the 13kV line as their ground reference.

The symbol for ground is one of the following. If both are used in a circuit, it means that there are two reference voltages - which may be different. This can be important: if a person on the ground uses earth as his/her ground reference while a bird on the high-voltage line uses 13kV as her ground reference, everyone is OK as long as you keep the two grounds separate. If you connect the two, however, the bird goes poof.

Figure 4: Two dufferent symbols for ground. If both appear in a circuit, they may refer to different ground references.

Voltage Sources

Voltage sources are akin to batteries: they provide whatever current it takes to hold the voltage at a specified level. Voltage sources are very common. For example, many computers required a constant 3.3V or 5V power supply for them to operate. As another example, votlage specifies the speed of a DC motor (more voltage means the motor spins faster).

To get an idea of what voltage means, several votlages along with what that amount of votlage can do is presented in Table 1.

Voltage	Example	Enough voltage to...
1.5V	AA battery	Turn on a single LED
5.0V	USB Battery	Power a computer
13.2V	Car battery	Turn a motor (starter)
120V	Wall Outlet	Power a computer, hair dryer
13,200V	Residential transmission lines	Power a residential subdivision
345,000V	Long distance transmission lines	Power a small city

Table 1: Capabilities of various voltage levels

Voltage sources can be either independent or dependent.

- An independent voltage source outputs a constant votlage, sourcing or sinking whatever current it takes to maintain that votlage.
- A dependent voltage source, in contrast, can output a range of votlages. Some other signal controls the voltage output.

Several types of dependent votlage sources exist:

- Voltage controlled voltage source: This is similar to an amplifier for a speaker. A small votlage at the input sets the voltage at the output. Usually, the output voltage is an amplified signal.
- Current controlled voltage source: Sometimes, the output voltage is proportional to the current elsewhere in a circuit.

The standard symbols used for voltage sources in a circuit are presented in Table 2.

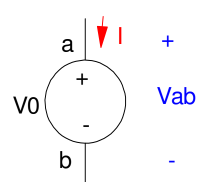
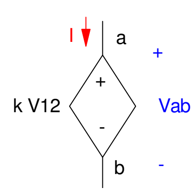
Element	Symbol	VI Relationship
Voltage Source (battery)		$V_{ab} = V_0$ $I = \text{any}$
Voltage Controlled Voltage Source (amplifier)		$V_{ab} = kV_{12}$ $I = any$

Table 2: Symbols and equations for different votlage sources

Current Sources:

Current sources provide a specified amount of current to a circuit. For some devices, current is what matters. For example, LEDs (light-emitting diodes) are current devices: the amount of light output by the LED is proportional to the current flowing through the LED. DC motors can also be current devices: the torque produced by a DC motor is proportiol to the current supplied.

Current specifies the thickess of the wire used to carry that current. Table 3 presents the relationship between current and wire thickness:

Current	Diameter of wire needed	Example
1uA	0.000 7mm	Sleep mode for a TV remote
1mA	0.021 mm	Power a single LED (dim)
1A	0.72mm	Charging a cell phone
10A	2.3mm	Hair dryer
100A	7.3mm	Welding

Table 3: Various current levels and the thickness of wire needed to carry this amount of current.

Like votlage source, two types of current sources exist: dependent and independent.

- Independent current sources: the current output is fixed. The current source provides whatever voltage is required to set the current level.
- Dependent current sources: the current output is proportional to some other circuit parameter, typically a voltage or current.

With dependent current sources, there are two main types:

- Voltage-controlled current sources: the current is proportional to an input voltage. A driver for an LED of DC motor would be an example of this. MOSFETs are another example of this.
- Current-controlled current sources: the current is proportional to some other current in a circuit. BJT transistors are examples of this.

The circuit symbold for a current source is presented in table 3.

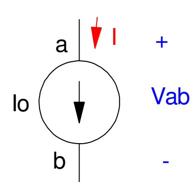
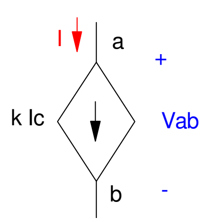
Element	Symbol	VI Relationship
Current Source (LED driver)		$I = I_0$ $V_{ab} = any$
Current Controlled Current Source (transistor)		$I = kI_c$ $V_{ab} = any$

Table 4: Circuit symbols for independent and dependent current sources

Passive Circuit Elements

Passive circuit elements are devices which do not need a battery for them to operate. Instead, the properties of the material or the way they are constructed sets their value.

In this class, three types of passive circuit elements are used:

- Resistors,
- Capacitors, and
- Inductors

The standard circuit sumbol for each of these and their votlage-current relationships are presented in Table 5

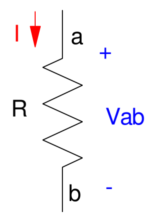
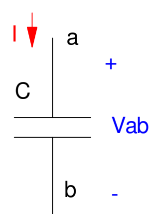
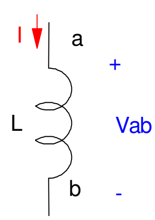
Element	Symbol	VI Relationship
Resistor (basic circuit element)		$V_{ab} = IR$
Capacitor (basis circuit element)		$I = C\frac{dV_{ab}}{dt}$
Inductor (basic cicuit element)		$V_{ab} = L\frac{dI}{dt}$

Table 5: Passive circuit elements and their VI relationships

Power:

Power (Watts) is a measure of energy absorbed per second (Joules per second). Examples of different power levels are presented in Table 7.

Watts	Example
1mW	power-on indicator LED
1W	Human Heart
10W	1000 Lumen LED Light Bulb
100W	Bicycling (300W = Tour de France)
1kW	Max output of elite athletes Hair dryer
10kW	Lawn Tractor (15.6hp)

Table 7: Examples of different power levels

Volt Meters - Ammeters - Ohm Meters

To measure voltage, current, and resistance, a multimeter is used with three settings.

Volt Meter: Volt meters are usually digital - meaning there is a microcontroller built in. The microcontroller has a high input impedance (typically 100MΩ or more). To measure a voltage, place the two probes across what you're trying to measure.

Voltage measurements are polarized. If you switch the leads, you get the opposite voltage (i.e. a 9V battery will read -9V).

To use a volt meter, connect the meter in parallel with what you are trying to measure, with the red (+) terminal goes to the + side.

Note that if you connect a volt meter incorrectly (i.e. in series), you stop all current flow due to the high impedance. Nothing breaks, you just end up measuring the voltage of the source (rather than the voltage across the 5k resistor).

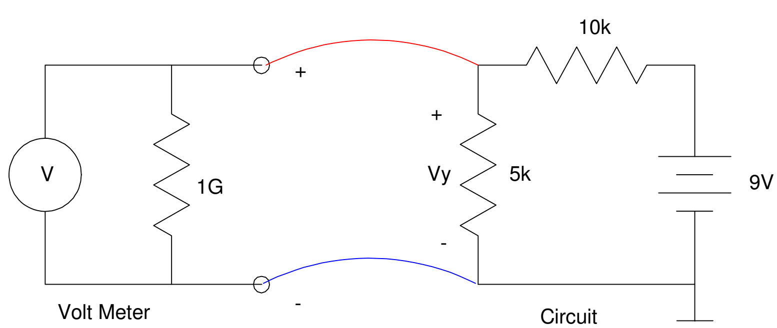


Figure 9: Volt meters have a large input impedance so they don't affect the voltages you are measuring

Ammeters: Ammeters measure current. The way they do this is they place a small resistance (0.1 Ohm typical) in series with a circuit and then measure the voltage across that resistor.

Current sensors are placed in series with the element you're trying to measure. This means:

- Current sensors are difficult to use. You have to be able to break open a circuit, inserting the sensor in series. This isn't always easy.
- Current sensors typically have blown fuses. If you (or someone before you) connect a current sensor in parallel by accident, you've shorted out what you're trying to measure with 0.1 Ohm. The low resistance creates large current, typically blowing the fuse.

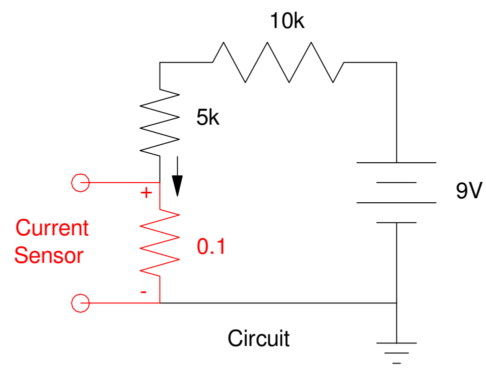


Figure 10: Ammeters typically add a small resistance in series with your load to allow you to measure current

Ohm Meters: Unlike voltage sensors and current sensors, ohm meters are active devices. To measure resistance, a small current is sent to the load. The resulting voltage drop is then used to compute the resistance. To get the most accurate reading, the resistance in the ohm-meter (the 10k shown below) should be close to the load resistance. Likewise, ohm-meters often times have different settings: these settings change the resistance placed in series with the load.

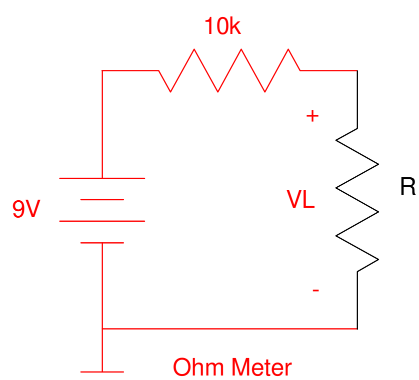


Figure 11: Ohm-meters typically apply a small test current to the load to produce a voltage and then compute the implied resistance

This means

- Ohm-meters cannot be used when the circuit is powered up. The power source will conflict with the test current the meter is using, creating erroneous readings.
- Ohm-meters are a little dangerous. If you try to measure the voltage or current produced by a firing cap, nothing happens. If you try to measure the resistance. the firing cap explodes.

Summary

From this point onewards, all courses in ECE, including this one, will be using the metric system for all units. The main units we'll be using in this course are

- V: Voltage (Volts): The force which tries to force current to flow
- I: Current (Amps): The flow of electrons (current) in a circuit
- R: Resistance (Ohms): The resistance to current flow, and
- P: Power (Watts): The amount of energy released per second.