Understanding Analog & Digital Circuits

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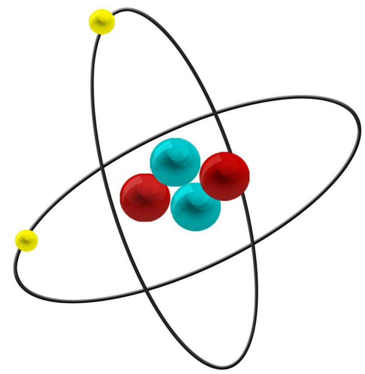
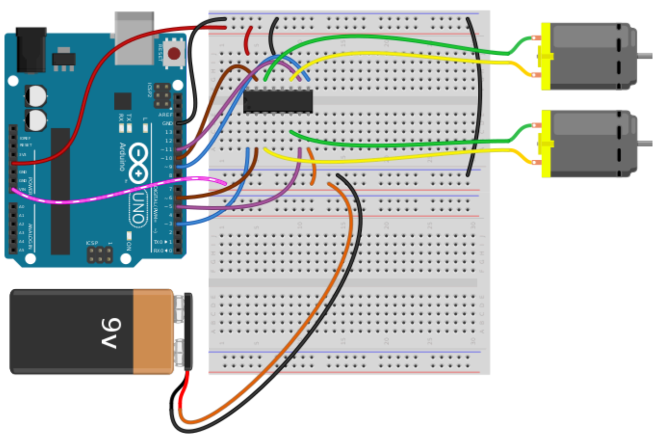
What are Electrical Circuits?



Electrical circuits or just "circuits" are fundamentally just a path for electrons to flow through; but understanding circuits in a practical way includes so much more. Before a full investigation of circuits can happen, everyone should have some basic understanding of an **atom**. The world is made of atoms, and there are three main subatomic particles. **Protons** and **Neutrons** 'live' inside the nucleus of the atom; and **electrons** [shown to the right in yellow] 'live' in the electron cloud, outside the nucleus. The electrons are held to the atom by an **electromagnetic force** which is pretty strong, but can be overwhelmed by forces from outside the atom. Atoms are complicated, but all you really need to know about them now is that the electrons can come loose and move around, independent of the atom. In some materials electrons move more freely than in others. If electrons can move freely between or among atoms, we call that type of material a **conductor** of electricity. If electrons can't easily move between or among atoms, we call the material an **insulator**.



Circuits provide a path for electrons to flow, and most of the time people build these circuits to achieve some sort of goal. [The circuit shown to the left appears to use an Arduino & integrated circuit to drive two motors, maybe for independent drive wheels to move a simple robot.] Over the past several hundred years, humans have started to better understand 1) that electrons are a part of the building blocks of the world 2) that electrons can be moved in predictable ways and 3) that the controlled flow of electrons can get matter to perform very specific actions. These understandings have been the main driver of recent technology, at all levels. This is even true, regardless of if the designer was fully aware of how these electron movements were a part of the technology (electrical engineers) or if the electron movement had been abstracted away from the things they had to worry about in designing new inventions (high-level software developers).

If anyone wants to build something totally new, or have it do any "physical computing" they need to be aware of how electrons move in a circuit. This requires understanding several core concepts of the mechanisms for circuits. In fact, some of the most interesting things circuits can do (touchscreens, memory storage, emitting light, wireless communication, etc.) require a robust understanding of these behaviors of electron movements. So we start at the beginning....

Electrons are what move in circuits

At first we didn’t know about electrons, so we imagined that positive charge flowed in circuits, like water in a river. All of our descriptions came from this river or plumbing analogy for the flow of electricity in circuits. Some people think this analogy is still useful to help with understanding.

Positive and Negative flow of charges in Circuits

Benjamin Franklin named the positives and negatives of electricity, possibly in a letter as early as May 1747. He understood these to be ‘types of pressure’ of a possible fluid that made electrical phenomena. At that point electrons hadn’t been discovered, and wouldn’t be for another 150 years; until J.J. Thomson was working with a cathode ray tube in April of 1897. Only after J.J. Thomson’s work could people understand that electrons are what really moved in circuits. Between Franklin and Thomson, key players in electricity research (like Michael Faraday and James Clerk Maxwell) selected to imagine that the positive charges moved throughout a circuit, so they could advance in their research. By the time Thomson discovered that it was really the electrons that moved in a circuit, we were too deeply entrenched into talking about the flow of positive charge in circuits to change how everyone wrote about them.

Properties of flowing Charges

The properties that are used to describe circuits also came from when we understood them as Benjamin Franklin did: flowing electrical fluids. This means that our descriptors: current, voltage, and power all need to be retrofitted to our understanding of electricity as the flow of discrete, electrically charged particles. This is where a proper physics course and a survey of static electrical forces (not-moving electrical forces) can be a great primer for studying electricity (moving/ flowing electrical forces). Luckily, one does not need all of the physics background to get started working with circuits. But it does help to have seen a few properties of electrons:

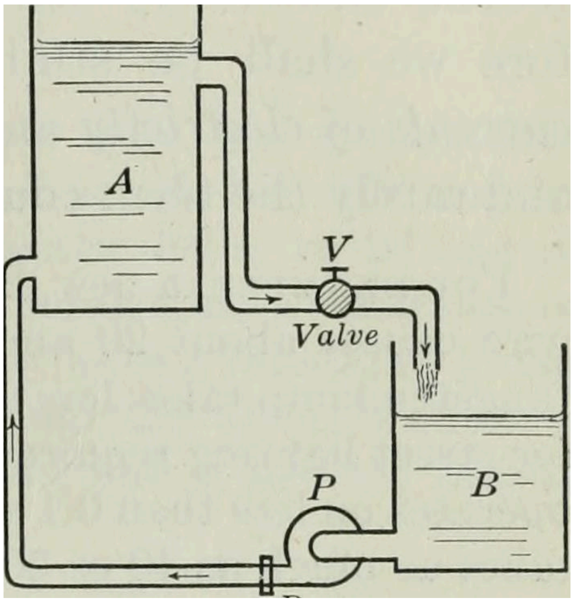
Properties of Electrons, as relevant to electrical circuits

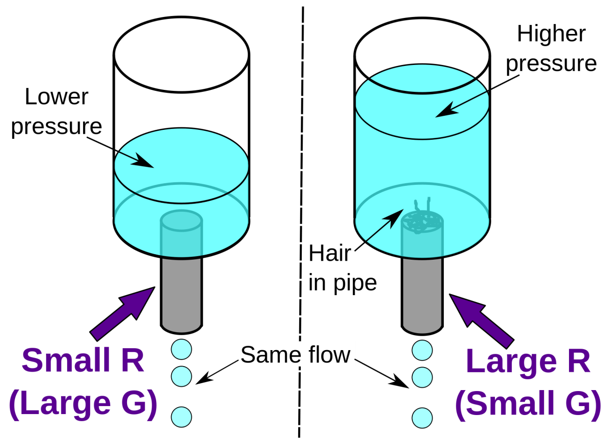
Property name	Value + Unit	Description
Mass	$9.10938356 \times 10^{-31}$ kilograms	This property is one we are used to thinking about, because it interacts with the force of gravity, but the effect is so small it doesn’t mean much for circuits….
Charge	$-1.60217662 \times 10^{-19}$ coulombs	This is the property that is relevant for circuits: electric charge. Notice that it is a negative charge for electrons, and that it is a very specific amount of charge that is carried by each individual electron.

*Since we talk about flowing positive charge, you can use the mental shortcut of taking the **absolute value** of the charge on an electron in most cases, while studying circuits.

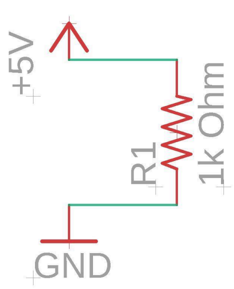
The Water Analogy for Circuits

Many people find circuits easier to think about, when they use water as an analogy for the flowing electric charge. It can be helpful to think about wires as though they were pipes, and the circuit in general as a plumbing system.



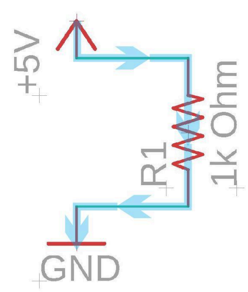


Battery: A pump (P) can move water around in a plumbing system.
Wires: The pipes of the plumbing system carry the water, with almost no resistance.
Resistors: A valve (V) or blockage (R) can slow the flow of water in the pipe.
Capacitor: A larger container (A and B) can hold a lot of water that stabilizes or delays the flow in other places in the plumbing circuit.
Voltage: The pressure in the pipes represents the amount of energy still held by the water.
Current: The flow rate (G) of the water describes how much water moves past a certain point.
Conventional Current: The flowing water molecules represent individual positive charges we imagine flowing (even though it is really negative electrons flowing in the reverse direction).



Imagining the current flow in a circuit can make its behavior more understandable. Everytime you see a new circuit, try to imagine how and where the current is flowing overlayed on the circuit diagram.

Thinking about this flow can also help you conceptualize connections that need made when hooking up components on a breadboard.



Representing Circuits: Schematics and Imagery

Schematics are a critical way to understand electric circuits, because they show how all of the components in a circuit are connected. To be clear, schematics show the order in which things are connected, but not necessarily how they are arranged. This means that schematics serve as a plan that help us ‘read’ a circuit or plan out how it will work.

Schematics have certain symbols that represent components.

More needs added here….

Current -- Amount of flowing charge in a circuit (indirectly: amount of individual charges)

The Unit for Current is:	Which is derived from a fraction of:	Which means current is:
Amperes	Coulombs	Amount of electric charge
	Second	Per second of time

Current is one of the main descriptions of circuits. It is a way to describe how much charge flows in a circuit. To be more specific, current is a description of how many electrons are moving in a circuit, but it describes the amount of moving electrons by their collective rate of electric charge moving throughout a circuit. The unit used to describe current in the **ampere** or 'amps' and this is a description of how much electrical charge passes through a point in a circuit per second.

Voltage -- Energy available for use from each flowing unit of charge

The unit for Voltage is:	Which is derived from a fraction of:	Which means current is:
Volts	Joules	Energy available
	Coulomb	Per unit of charge

Voltage is the property of circuits most people have heard of, and it describes the energy of the charges flowing through a circuit. Each electron will have a certain amount of energy associated with it as it moves along a circuit from the beginning to the end. But we describe this energy with respect to the flowing positive charges, and as the energy per unit of charge (notably not per electron or charged particle).

Power -- Energy use of the circuit that carries charges

The unit for Power is:	Which is derived from a fraction of:	Which means power is:
Watts	Joules	Energy used
	Second	Per second of time

As charge flows through the circuit, its energy gets used up. The rate that this energy is used is called the power (or power consumption/ power dissipation) of the circuit. This value is important to know because it often tells you how big & expensive the electric components need to be in order for the circuit to be able to operate without overheating itself during operation.

The Two Main Equations for Electric Circuits

$$V = IR$$

Ohm's Law describes the relationship between voltage, current and resistance in a circuit.
V is voltage, measured in volts (V).
I is current, measured in amps (A).
R is resistance, measured in ohms (Ω).

$$P = IV$$

The Power Law describes the relationship between power, current and voltage in a circuit.
P is power, measured in watts (W).
I is current, measured in amps (A).
V is voltage, measured in volts (V).

These two laws allow us to calculate most of the things that we need to know about circuits. All that is necessary is a little freshmen-level skill with algebra to use these to their fullest potential.

These equations can be used for many purposes. Below are a few examples:

Example 1:

You have just hooked up a resistive heater circuit, but you used a multimeter to measure the included resistor to be 30Ω before you powered anything. You just attached a 100 volt power supply, and things are getting as warm as expected.

You can use Ohm's Law to calculate the current flowing in the circuit (without needing to measure it directly with a multimeter).

You can use the Power Law to calculate the power used by the heater circuit.

Example 2:

You want to build an LED circuit, but the datasheet for the LED has a few limitations. The LED uses 2.1 volts of a supply, and can only handle a maximum current of 20 milliamps (mA). Given the current limitation of the LED, you will need to include a resistor in series in this circuit, along with the LED. The 2.1 volts used by the LED is subtracted from the 6 volts of the supply, which means your current-limiting resistor will have 3.9 volts applied to it in this circuit.

Given those 3.9 volts, what resistance value is the minimum needed to ensure that no more than 20 mA will flow through the LED?

Also, what power will be dissipated by this resistor?

Also, the power and current draw of parallel circuits is additive.

Example 3:

Three motors are hooked up to a microcontroller that can handle 0.25W of power usage. The microcontroller operates at a logic level of 5 volts, and each motor may draw up to 20mA of current. Would it be possible for these motors to overload the microcontroller? How do you know? What is the effective resistance of each of these motors?

Energy in Circuits

Energy is what drives the movement of charges in circuits. Electrons want to get from a place where they have an abundance of energy, to a place where they can live in a lower energy state. This is the main assertion of the second law of Thermodynamics - things ‘want to live’ in their lowest available energy state. So, electrons move through a circuit to get from high to low energy, and will do what they have to in order to get to the lower energy state.

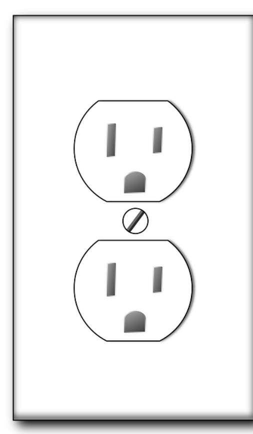
Energy sources

Energy in a circuit can come from a number of places. A battery is the most directly known and observable energy source for a **Direct-Current** circuit. A wall outlet is another common source of electricity, but these supply **Alternating-Current** and are a few steps removed from the actual energy supply that eventually makes it to an outlet at your home or school.

Chemical Batteries

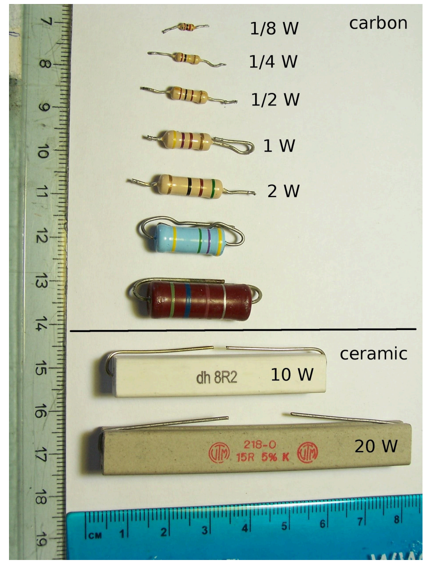
Batteries are interesting things. The infamous AA battery, delightfully rectangular 9 volt, or the high-tech LiPoly battery of a cell phone all have one thing in common: they are a chemistry experiment in a container. Some are **primary** batteries -- they can only be used once. A **secondary** battery can be recharged and used multiple times. Either way, these chemical reactions in a container have one ‘side’ that is higher anergy and one side that is lower energy for charges. If a battery is attached to a circuit, then the charges will flow so that they get to the lower energy state. If the charges have a very direct path, such as a wire connecting the two sides of the batteries, the charges will flow very fast and probably exceed the power ability of the battery or the wire. [Always remember: chemical batteries are driven by chemistry, and certain chemical reactions are slower than others…] Chemical batters are particularly useful, because they do not need to be attached to other power sources.

Electrical Grid Power



The electrical grid in most nations can be a great source of power, because it can be reliable and scalable for all sorts of energy needs. The one tricky part is that it is delivered as the alternating-current (AC) style of electricity [for many good reasons, beyond the scope of this document] and most basic electronics need that converted to a Direct Current (DC) supply for their purposes. Going from AC to DC is easy to do [compared to the vice versa] and is achieved effectively by any basic modern cell phone charger. The real downside for electrical grid power can be this need for a voltage transformer, an AC to DC converter, and that the electronics will remain tethered to the wall outlet in order to retain power.

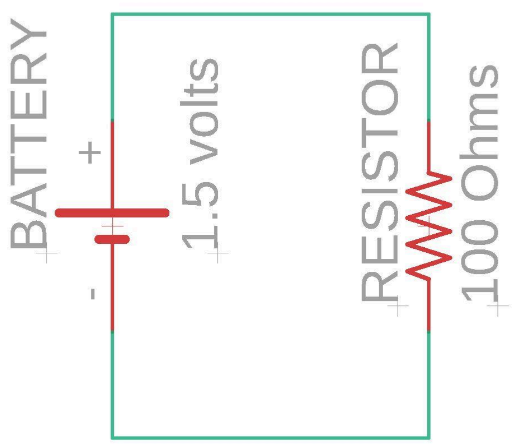
Power Rating of Components



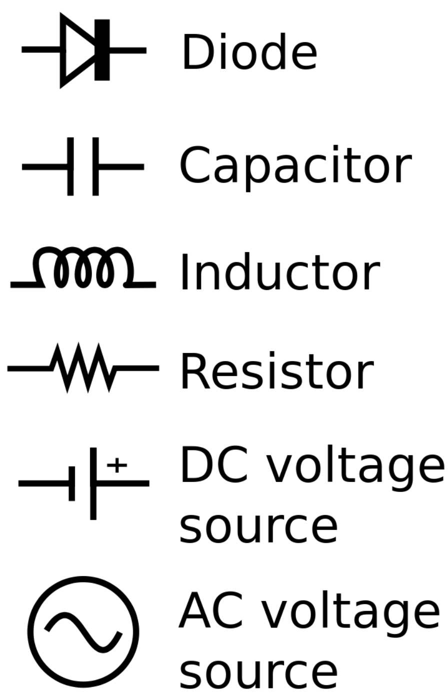
Lots of electrical components have different versions, depending on how much power they are intended to use. The image to the right are all different versions of resistors, to be used with different amounts of maximum power dissipation. It can be confusing at first to make sense of these versions of similar electrical components, but after some exposure to these applications (and destroying a few pieces by passing too much power through them) anyone will start to make sense of the power ratings of electrical components.

Representing Circuits with Diagrams

Circuits are often complex and, in order to convey meaning about what is involved, they are broken down into diagrams that show all of the important parts. Circuit diagrams are nearly universal and serve as the language to describe circuits graphically. Their importance cannot be overstated. The circuit diagrams shown in this document will all be created in [Autodesk Eagle.]



This is a simple circuit with a battery connected to a resistor, using all of the standard USA circuit diagram symbols. More of these standard symbols are shown to the right.



Measuring Electrical Circuits

> Measurement is the first step that leads to control and eventually to improvement. If you can't measure something, you can't understand it. If you can't understand it, you can't control it. If you can't control it, you can't improve it. [-H James Harrington]

The Multimeter

Measuring electrical circuits has progressed through several stages, and there are many different tools that are capable of measuring the basic (and advanced) properties of any circuit. Of these tools, the Multimeter is the most affordable and available for purchase [at most hardware stores]. Using a multimeter can be a bit tricky, and so some time will need to be spent figuring out how to use whichever version of these common devices you have in hand. Each brand/ model of multimeter seems to have its own quirks but there are some common themes:

- The wire probes need to be plugged into the right places for each different type of measurement
  - The black line often doesn't have to move
  - The red line may need moved to measure current and again for high current devices
- The number settings for each measurement represent a maximum readable measurement. Start at the largest reading option, and get more precise until you can't go any further without an error message. [error messages are often a 1 and nothing else]
- Voltage needs to be measured while the circuit is powered
- Resistance needs measured while the circuit (and possibly the component) is unpowered and/ or separated from the rest of the circuit
- Current is measured by 'injecting' the meter into the circuit. This means, breaking the circuit and reconnecting it with the meter itself -- but be careful not to blow a fuse…

Some great videos on how to use a multimeter:

[Google Search: How to use a Multimeter]
[Collin's Lab: Multimeters #Adafruit]
[How to use a Multimeter #Sparkfun]
[Basic Skills!: Multimeters iFixit Video]

By the way, here are some other videos worth watching if you're new to electronics:

[A Youtube Series on Electronics Knowledge]
[A single video on Some of the Electronics Hand Tools basics]

Inputs and Outputs

[Fab Academy Inputs](#)
[Fab Academy Outputs](#)

Sparkfun Video Series

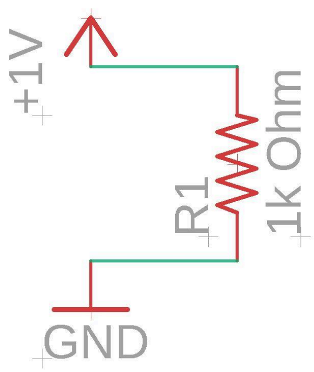
Adventures in Science! Playlist

1. Electric Current
2. What is Voltage?
3. Ohm's Law
4. Electric Power
5. What is a Battery?
6. Series and Parallel Circuits
7. Licking a 9V Battery
8. Bust a Capacitor
9. How to use a Multimeter
10. How to use a Power supply
11. How to use an Oscilloscope

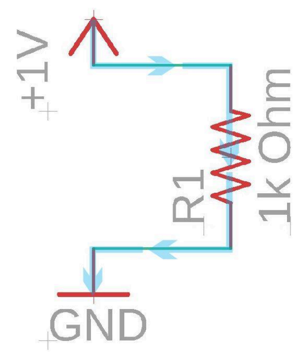
Example Circuits for Investigation

Different Voltages applied to a single Resistor (finding current, resistance & power)

The circuit as drawn in diagram



The current *shown over* the diagram

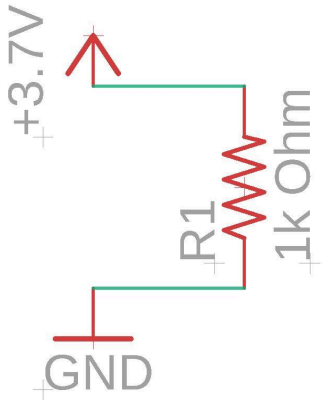


The circuit diagram shown twice above is an abbreviated circuit diagram. It shows the voltage source (and the voltage level) as well as the ground of the circuit [**electrical ground in DC circuits is the same as zero volts]. These abbreviated circuit diagrams represent important pieces of information you need, if you were going to try and build this circuit. By not showing the source of the voltage, the diagram implies it could be anything, for example a battery, solar panel, or power supply. Choosing to not include the battery like this starts to make it easier to think about segments of a circuit.

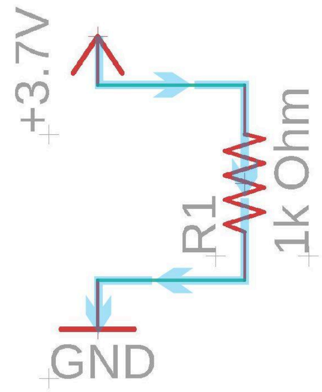
As you can see, this is a very simple circuit, with just a single one thousand ohm resistor in line between the voltage source and ground. This is the first of several abbreviated circuit diagrams you will see. In fact, most complex circuit diagrams are shown in broken-up forms such as this so they are more readable. Abbreviated circuit diagrams can also make it easier to draw the diagrams, once you level-up to that skill...

The slightly altered diagram on the right has blue arrows overlaid. These blue arrows represent the size and direction of the current flowing in the circuit. Every time you see a diagram (like the one on the left) you should imagine how the current flows through the circuit (as shown on the right).

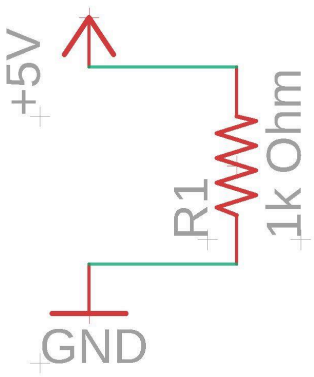
The circuit as drawn in diagram



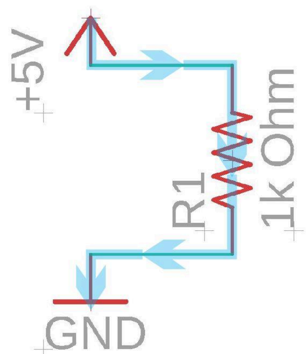
The current *shown over* the diagram



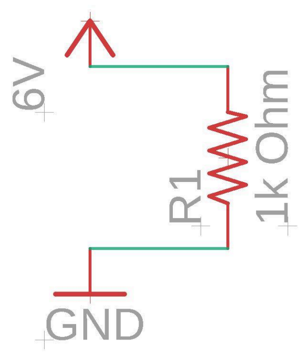
The circuit as drawn in diagram



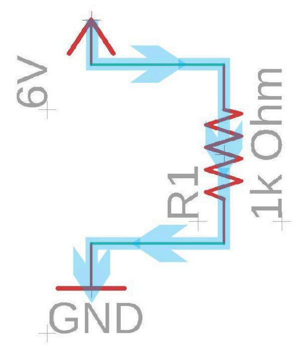
The current *shown over* the diagram



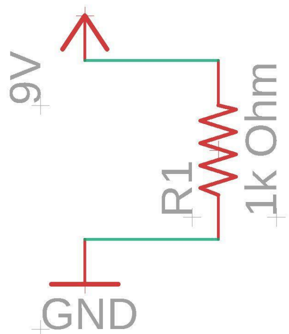
The circuit as drawn in diagram



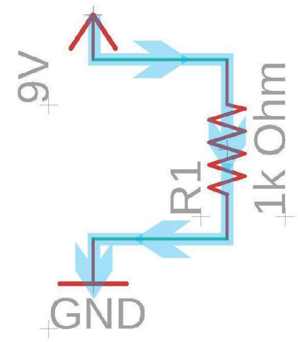
The current *shown over* the diagram



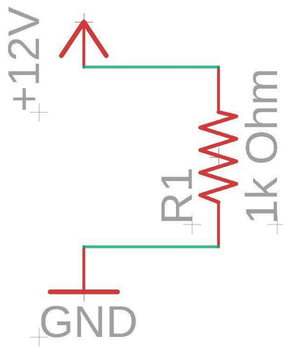
The circuit as drawn in diagram



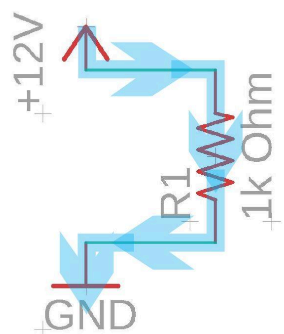
The current *shown over* the diagram



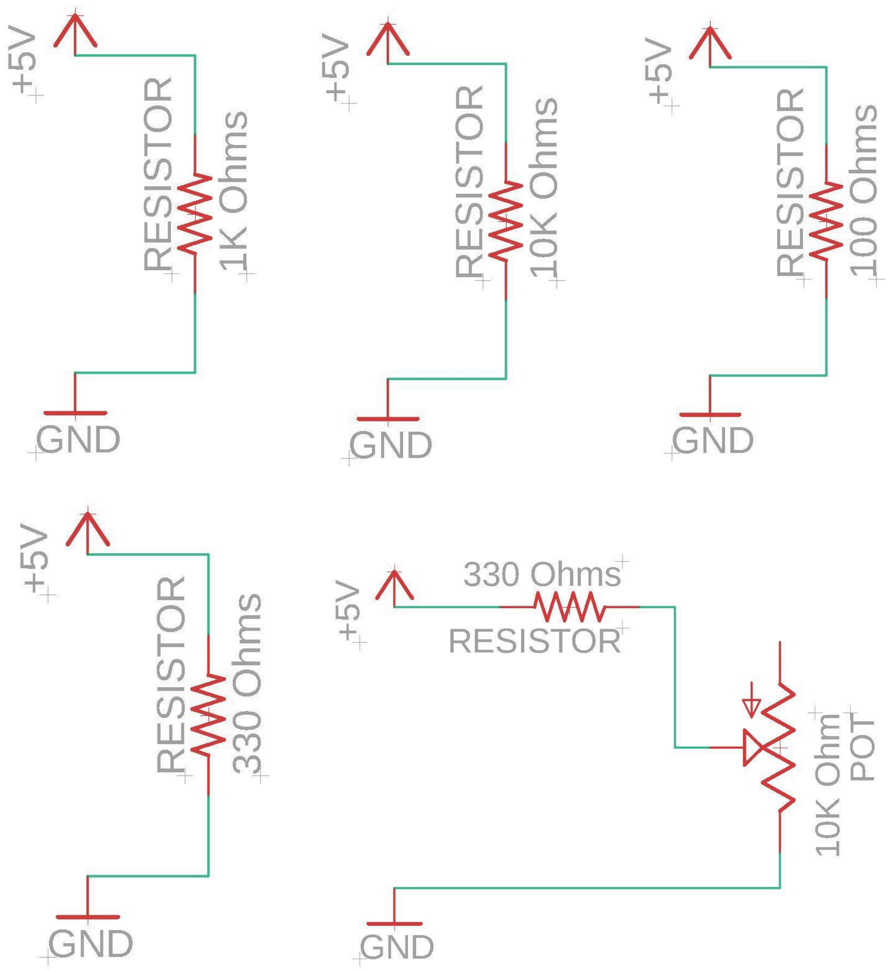
The circuit as drawn in diagram



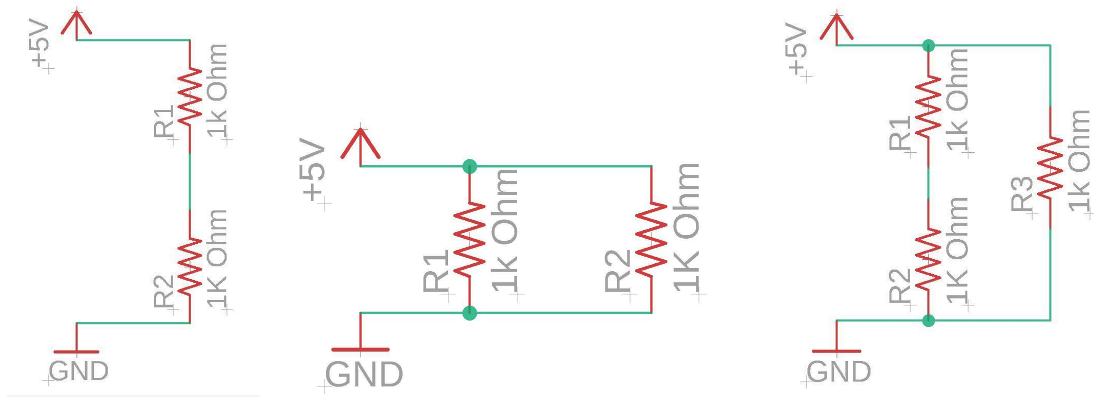
The current *shown over* the diagram



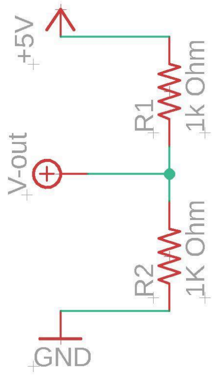
The same Voltage applied to Different Resistors
(finding current, resistance & power)

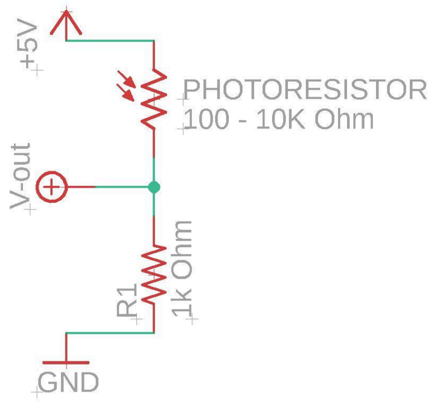


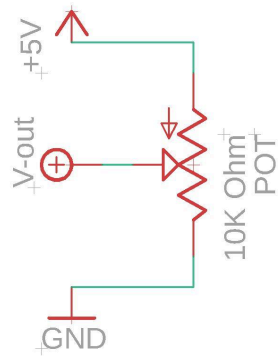
Series, Parallel and Mixed Circuits



Voltage Divider Circuits

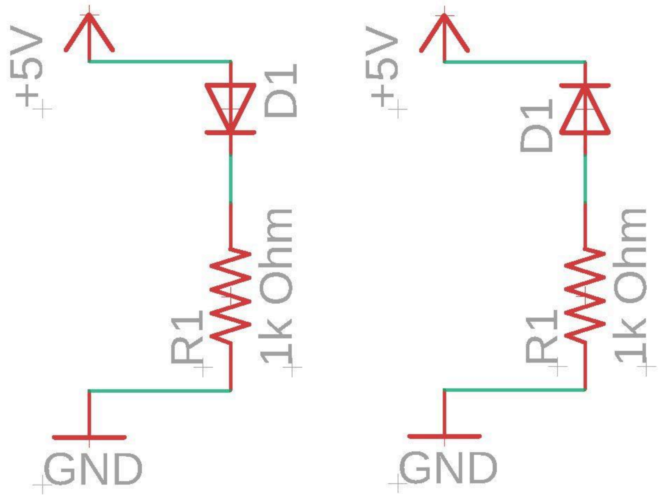




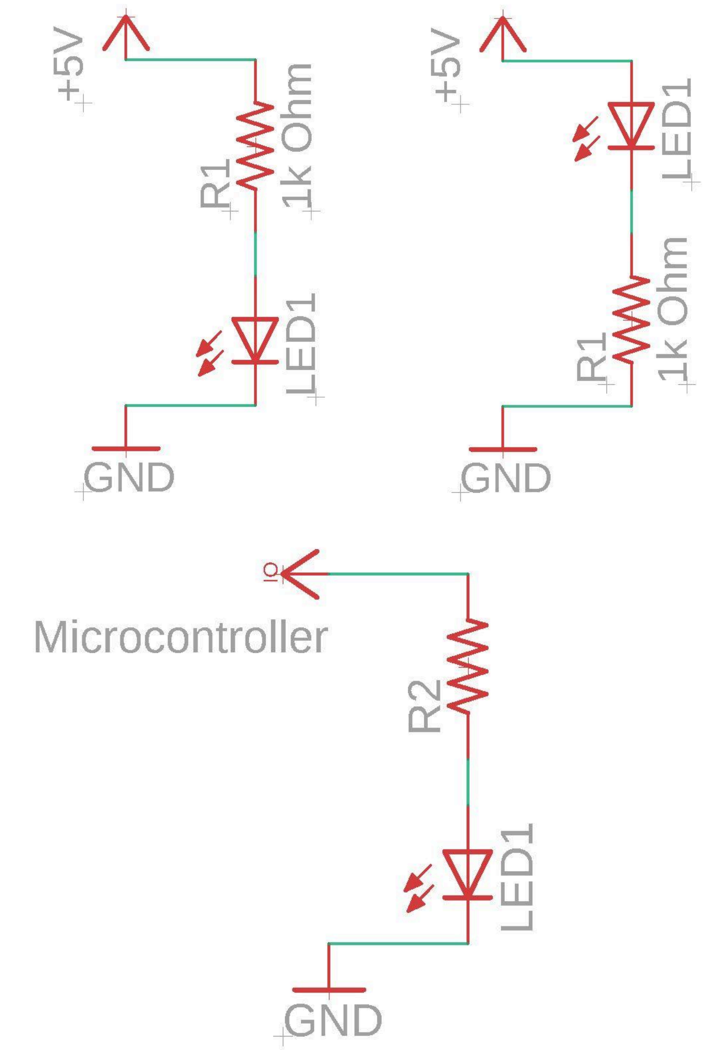


Non-Ohmic Devices

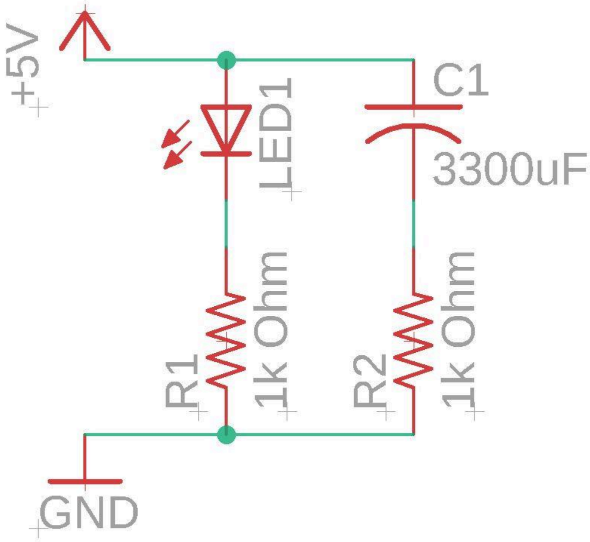
Diodes



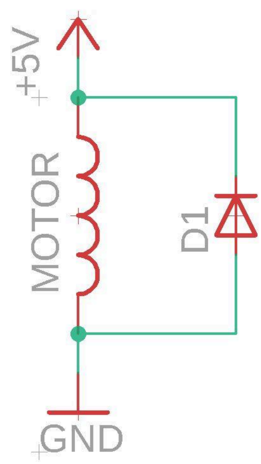
LED Basics


+5V
R1
1k Ohm
LED1
GND
+5V
LED1
R1
1k Ohm
GND
IO
Microcontroller
R2
LED1
GND

Capacitor Basics



Motors



Transistors