# ECE20007: Experiment 1

## Ohm's Law and Basic Measurement Equipment

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## 1 Application

**Welcome to ECE 20007, Electrical Engineering Fundamentals I!** In this lab, we will be going though a variety of different electronics principles to give you a practical understanding of where the principles are used, and how to actually use them.

In order to do almost anything in electronics, there is one fundamental principal that must be followed and understood, and that is Ohm's Law. Ohm's Law tells us the pure relationship between the three fundamental properties of any circuit voltage, current, and resistance, and will work for the vast majority of the principals and components that we will be using.

While understanding the math and theory as to why circuits do what they do is important, it is arguably equally important to be able to monitor and measure what a circuit is doing. One of the most useful measuring devices for electronics is known as the multimeter, as it can measure a wide variety of electrical properties, provided it is setup and wired properly in the circuit. Multimeters have been around for a long time, and have taken many forms, but all do the same thing, which is to measure voltage, current and resistance (and then some) in a circuit.

## 2 Experiment Purpose

While it is likely you have at least heard of Ohm's Law either through a high-school science course, personal research, or through ECE20001, it is incredibly important to experiment and tinker with Ohm's law to really understand what is going on and how to use these basic electronics principles in practice. The only issue (and it's a large one) is we cannot directly see what is happening in a circuit because we cannot see electric fields and electrons moving around. This idea makes it difficult for us to visualize what is happening in a circuit, so that is where our measurement equipment comes into play.

In this course, you will be using a piece of equipment called a breadboard to construct your circuits, and this lab will give you a brief introduction to using them. A breadboard allows us to make temporary circuit connections and then remove and rebuild at a later time. While breadboards use relatively simple principles to wire components in different ways, it does take practice. Breadboards are also somewhat fragile. Do not go shoving large wires or probes in your breadboard, as that will reduce the effectiveness of both the probes and the breadboard.

## 3 Important Notes about ECE20007

The other important part of this entire course is to encourage analyzing and troubleshooting. It is almost guaranteed that at some point or another a circuit in this course will not work as planned. Your task at that time is to go back through your circuit and figure out what went wrong. This takes time and practice. While it can be frustrating at times to not have a circuit work correctly, but the satisfaction of getting it working again is often worth it. This applies to all branches of science and life as well. If everything worked the first time with no issues, engineering probably wouldn't be a field worth studying.

As you move forward in this course, if something piques your interest and you want to go your own way and try something, DO IT! Do some research so you don't harm yourself or the equipment and give it a go. If you have reservations, ask questions. Everyone running this lab has unique experiences in electronics and will likely be able to help you in some fashion, or help you find someone that can. Tinker with your ideas, and don't be afraid to screw up. Again, make sure you are being safe; this is a top priority in this lab. Safety will be covered throughout this course as you learn to use different equipment and components safely and properly.

# 4 Current, Voltage, and Resistance

When analyzing any circuit, the three main things to look at are the current, voltage, and the resistance of the circuit. Nearly everything that is analyzed after these principles falls back to at least one of them at some point. Using current, voltage and resistance, we can determine the amount of power that a circuit is using, how the the circuit may be malfunctioning, and how it might be unsafe for people to interact with it.

## 4.1 Current

Current is often considered the most fundamental of the principles in electronics, as current is simply the flow of electrons through a medium. Ideally, this medium for current flow is a wire, but it doesn't have to be. This flow of electrons creates an electromagnetic (EM) field which carries energy to the load (the device that is using the energy) of the circuit. These EM field is also what allows for motors to spin, radios to broadcast and receive signals, and much more.

Current cannot flow inside of a circuit unless the circuit is a closed loop. Any break in the circuit, also called an "open circuit," does not allow current to flow. A light switch is simply a mechanism that opens and closes a circuit. When the circuit is closed, energy is able to flow to the light bulb, which allows it to illuminate.

The SI (International Standard) Unit for current is Ampere (A), or amps for short, named after one of the founders of electromagnetism, André-Marie Ampère. In equations, current is often denoted as $I$ also in tribute to Ampère, a French physicist who denoted it as "current Intensity" or "intensité du courant" in French. Mathematically, 1 amp of current is defined as 1 coulomb of charge passing through a surface in 1 second. This can be generalized to equation 1 to determine the total current flowing through a specific surface.

$$I = \frac{Q}{t} \tag{1}$$

Where $I$ is current in amps, $Q$ is charge in Coulombs, and $t$ is time in seconds. One Coulomb of charge is equal to the amount of charge of $6.24 \cdot 10^{18}$ electrons. The direction of current in a component inside a circuit is also often important, especially for devices we will look at later in the lab, such as diodes and certain types of capacitors.

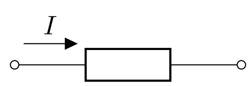



Figure 1: Arrows represent the direction current flows through a device.

**Note: Conventional Current versus Electron Flow Current** As mentioned above, Current is usually defined as the flow of electrons in a circuit. Electrons have a negative charge, which means that the charge from the electrons would flow from the negative side of a battery or power supply (often depicted with a "-" or black port) and work their way to the positive side ("+" or red port on most supplies). If we monitor a circuit by looking at current going in the same direction of the electrons, the term Electron Flow Current (EFC) is used. We often don't like thinking like this. We often prefer to look at a circuit with current flowing from the positive side to the negative side, as this tends to make more sense intuitively to us. This is called "Conventional Current." Unless denoted otherwise, we will be using conventional current in this lab, so current will flow from the positive side of the circuit to the negative side, and the current arrows will point in that direction too.

## 4.2 Voltage

Voltage, or Electromagnetic Force (EMF), is how much electric potential energy a circuit has. Voltage can be generated and stored in many ways. Touching two different metals together will generate a small voltage (this is how a thermocouple works). There are crystals that generate voltage when they bend (piezo crystal). Solar panels generate voltage with special silicon compounds which causes electrons to move when light shines on them. We most commonly associate voltage with batteries that store chemical energy, and when a reaction takes place between a metal and an acid, electrons are released which generates voltage. It is important to realize that voltage is generated; current is what happens when voltage has somewhere to go. While it is not completely the full story, thinking of voltage as the amount of pressure a battery or supply is pushing into a circuit might help visualize it. If you think about voltage like water pressure, the pressure is there whether there is flow (of “water” or charge in this case) or not. This means that voltage can be present even in an open circuit. Another term you will be hearing in regards to voltage is “voltage drop.” Voltage drop is used when a component “uses” a certain amount of voltage available in a path that the current can take.

Voltage has an SI unit of Volts (V), named after Alessandro Volta, who invented the electric pile, an early version of a battery. Voltage is defined as one joule per coulomb, or the amount of work we can get out of a single coulomb of charge as seen in equation 2.

$$V = \frac{j}{Q} \qquad \text{or} \qquad j = V \cdot Q \tag{2}$$

Where V is voltage, j is energy in joules, and Q is charge in coulombs. Both the equations in Equation 2 are the same, just rearranged. Solving for $j$ will become useful in a later section of the reading.

**Physics Note:** Work is defined as a change of energy ($\Delta E$) between two points, often in the form of force multiplied by a displacement. In electronics, electric fields store the potential energy which can then perform work on (moving) electrons and other objects that are in the field. When a circuit is closed, that electric field is able to move electrons at a certain current based on the amount of voltage (energy) provided by the source and the amount of resistance in the system.

When we measure voltage, we will be looking primarily at a “voltage difference” between two points. Another way to say this is we are looking at the change in potential energy between the two points we are measuring. If we measure voltage across a component, we are looking at the electric potential energy before the energy goes through the device, and seeing how much is left after. The difference between the two voltage measurements tells us how much energy the component is using by converting the electrical energy into a different form of energy such as heat (resistors), light (LEDs, lamps, and displays), movement (motors, relays, and solenoids), or some combination of the three. Since we are taking a difference between measurements, the direction in which the measurement is taken is important. Measuring voltage is done with two probes, which are often labeled with a “+” and “-”. The voltmeter, or a device that can measure voltage, will subtract the “-” probe from the “+” probe every time. Just like current, we can denote which direction we want the measurement to be taken, but instead of using an arrow, we will literaly just put “+” and“-” signs on either side of the component. We can also label the component directly along with nodes, or point labels on the circuit, to tell us which way we want to measure across a component. If we have a label of $V_{AB}$, we would put the “+” probe on $A$ and the “-” probe on $B$, like shown in Figure 2.

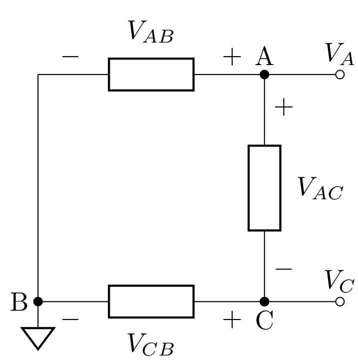



Figure 2: Using + and - to and labels to denote which way to measure voltage across a component.

When there are a lot of different components in a circuit, like almost any real-life circuit, it is often useful to have a common location where we can reference our measurements. This common place is often a “ground” location, or a place where the circuit returns to the source to complete a circuit. These locations will be usually denoted with one of the symbols in Figure 3 depending on the type of ground that is in the circuit. Looking at Figure 2, you will see a signal or “common” ground symbol attached to node B. This denotes a common location to measure from. If you see a voltage measurement such as $V_A$ with only one node to measure, the other is always going to be a ground, so $V_C$ will be measured from C to B in Figure 2. This means, using conventional current, we will always look at charges going from positive to negative, or high concentration to low concentration of charge.

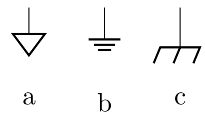



Figure 3: Different ground symbols: Common (a), Earth (b), and Chassis (c).

**Reality Check: What is Ground?** It may sound a bit misleading that we use the term “ground” for a common measuring point in a circuit, but more times than not, all the energy we use in electronics literally ends up in the ground. Looking at Figure 3, you will notice that one of the symbols is actually an Earth ground, and that literally means there is a metal spike, sometimes several feet long, going into the ground somewhere, and the circuit is attached to it at some point. The Earth is able to collect all of the charge that we use and dissipate it so the ground can always be used as a 0V measurement. This is also why lightning (almost) always goes downward to the ground, as the massive amount of charge in the air wants to go to a 0V location. A chassis ground is when you are literally using the metal shell of a piece of equipment or a large piece of metal to collect the extra charge. It is common to see a chassis ground eventually attached to an Earth ground at some point; if it isn’t, you will get a “tingling” feeling when you touch that piece of metal or equipment, and it can potentially cause damage to the equipment (and the person using the equipment) if the charge isn’t handled properly. Radios in cars rely on using the car itself as a chassis ground and the charge eventually finds its way to the Earth or the negative terminal of the battery. It is not uncommon to see amateur radio operators use a baking sheet or other large piece of metal such as a radiator as a chassis ground for their antenna if they are in a location that cannot get a good Earth or common ground. In our lab, rarely will we actually be connecting directly to ground, but instead using a common ground, which will be attached to the “-” side of our circuit. There are times you will see multiple ground symbols in a circuit. If they are all common grounds, ALL of those grounds are attached to the same common place, it might just be impractical to draw wires to have them all attached in a schematic. The same can be said about the Earth and chassis ground.

## 4.3 Resistance

Resistance is a fundamental property of literally anything that is put into a circuit. Anywhere there is movement or interactions between two objects, friction occurs as the the objects rub against each other. The same thing happens in circuits, where the electrons bump into each other and the atoms making up the component. This movement generates heat, and energy is lost in the system. In short, a resistor “resists” the flow of current through itself. Even wires have resistance, and there has been billions of dollars put into making materials with as little resistance as possible, now with the term “superconductor.”

A resistor in a circuit can take many shapes and sizes. Even humans can be used as a resistor. In this lab, we will mainly be using axial resistors, which are rolls of metal film. If there is more metal, the resistance decreases, and if there is more carbon, the resistance increases.

While resistance sounds like it may be a hindrance, resistance plays a large role in how we use electronics today, and we can use it to our advantage. Resistance is actually a critical component in many applications, such as sensor calibration. (Some of the most used sensors are just fancy resistors that change resistance in response to a certain stimulant,like light or temperature.)

Resistance has an SI unit of Ohms, often depicted by the Greek letter Ω. Resistance is named after Georg Ohm

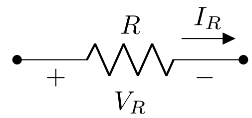



Figure 4: Schematic symbol for a resistor, a component that "resists" the flow of current.

who discovered that voltage and current changed proportionally based on the amount of resistance in a circuit, which is now known as "Ohm's Law."

# 5 Ohm's Law

As mentioned in the previous section, there is an encompassing law that allows us to make sense of current, resistance, and voltage all at once. Discovered by Georg Ohm, resistance is the ratio between the voltage applied to the circuit and the current flowing through it.

$$R = V/I \tag{3}$$

Where R is resistance in Ohms, V is voltage across the resistor, and $I$ is the current flowing through the resistor. Using basic algebra, we can rearrange this circuit equation to solve for any of the three variables. It is important to realize the **linear relationship** between the variables. There are no squares or radicals, so the relationship between the components will move up and down with each other in a linear fashion. Picture an X-Y plane with voltage on the X axis and current on the Y axis. This is called and I-V, or Current-Voltage Curve. If resistance stays constant, as a normal resistor does as voltage increases, so will current, creating a diagonal line through the middle of the plane, passing through the origin. The resistance of a resistor can change as it heats up; make sure to use components that can handle the current you are supplying!

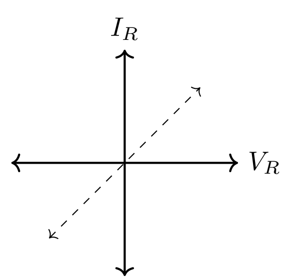



Figure 5: Voltage and current change proportionally through a resistor, making a standard I-V curve.

Ohm's Law can be applied to an entire circuit by looking at the total voltage, total current, and total resistance. It also applies a single component anywhere in the circuit, too. That said, there are components out there that do not follow Ohm's Law, such as diodes and transistors, but we will look at those at a different time. For now, we can assume that all components will follow Ohm's Law, which are called "Ohmic" components.

# 6 Power

While it is helpful to have current, voltage, and resistance as values we can easily determine in a circuit, they don't tell the full story individually. Sure, we can determine voltage if we know current and resistance in a circuit, but what does that mean for the wear and tear of the equipment or the electrical grid that circuit is working on? That is where power comes into play, as power allows us to determine the total amount of energy a circuit is using at a specific time.

Power is defined as the amount of work (change of energy, check note in Voltage section) over a period of time. If we look at our relationship of voltage and energy in Equation 2, we can see that Equation 4 can be made:

$$P = \frac{j}{t} = \frac{Q \cdot V}{t} = I \cdot V \tag{4}$$

Where $P$ is power in Watts, $j$ is energy in joules, $Q$ is charge in coulombs, $V$ is voltage in volts, and $t$ is time in seconds. Note that Equation 4 has charge over time, which is current (equation 1), so we can calculate power by multiplying the current in the system by the voltage. This is really important because a power supply, and even our entire power grid, only supplies the exact power that is needed at a specific moment, since we don't have a good way to store massive amounts of energy for extended periods of time. This is done by supplying a relatively constant amount of voltage (alternating, but stays at 120VAC within about 5%; we will talk about what this means more in depth in a future lab) and adjusting current accordingly. Equipment can usually only handle a certain amount of power, too. While equipment does have current and voltage limits, it is the total power going into the equipment that needs to be monitored. A lot of equipment will have control circuitry that will limit the power from being too high or too low, it is checks like this that allow power stations to communicate with each other, and draw power from each other during peak electricity hours such as around 4pm when everyone goes home and lights, computers, appliances, air conditioning units or furnaces kick on.

**Note: Watt Hours, and how we pay for power:** If you have looked at a power bill from your electricity provider, you will see that they provide you the amount of Killo-Watt-Hours (KWh) of electricity that was used in the past month, along with a price per KWh, and your total bill. Wait...Killo-Watt-Hours? Isn't a watt already energy over time, so multiplying it by time again just gives us energy, or joules? Yes. The bill you get from your electricity provider is actually an energy bill, not power. The reason we use KWh instead of joules is because a joule is an incredibly small amount of energy. It takes a little more than four joules of energy just to heat up one gram of water one degree Celsius (one calorie). If we were to give bills in joules, the numbers would be gigantic and difficult to rationalize for the majority of the population. Instead, we use KWh, which is equal to 3.6 Mega-joules, so the numbers on your bill are much smaller and can actually be somewhat understood. We can say a 60 watt light bulb being on for three hours uses 180 watt-hours of energy, or 0.18KWh, which is a lot easier to comprehend than calculating the charge difference on the bulb at 120VAC (or about 648,000 joules).

# 7 DC measurement Equipment: The Multimeter

There are many methods that we can use to measure or monitor different properties of circuits. Since there are three main values that we look at in a circuit (current, voltage, and resistance), it would make sense that we have ways of measuring all three. These devices are called ammeters, voltmeters and ohmmeters respectively. Fortunately, all three of these properties can be measured using the same basic device, a galvanometer, just in different configurations, so we can combine all three measurements into a single device, which we call the multimeter.

## 7.1 The Galvanometer

The Galvanometer is the basis for all of our basic circuit measurement equipment. In short a galvanometer is a device that can measure very small electric fields using a flexible coil of wire (similar to a spring coil that is used in mechanical watches) and some permanent magnets. When current (in the microamp ($\mu A$) range) passes through the coil of wire, it creates an electric field which interacts with the magnets, and the coil contracts, rotating around itself. When the coil contracts, a needle attached to the coil can then move about and point to a location on a scale depicting the current going through the circuit. Relatively simple math can be done to determine how much the coil will contract given a certain amount of current, so we can make a galvanometer fairly precise, and you will still see multimeters that use dials to measure current, voltage and resistance using a galvanometer like this. In digital galvanometers, a timing circuit is used to monitor how long it takes to charge a capacitor given a certain amount of current.

## 7.2 The Ammeter

An ammeter is a piece of measurement equipment that measures current in a circuit. Depending on the ammeter, it can often measure a wide range currents, most personal ones can measure from one miliamp to about 10 amps of current. Based on reading the section on the galvanometer, you might have realized that a galvanometer is essentially an ammeter than can only read very small currents, usually in microcamps. This isn't particularly helpful for most of our applications, as we usually have at least a few miliamps going through our circuits, so we need to find a way to allow more current in our sensor without destroying it. That is where we use a shunt resistor in parallel with the galvanometer as seen in Figure 8. A shunt resistor is a resistor that can take some of the current away from the main device as a form of protection. The resistance of the shunt resistor can be changed for different current ranges (that is what it means when you see an arrow going through a device in a schematic; it means the value is variable). The larger the resistance of the shunt resistor, the more current that goes through the galvanometer (current follows the path of least resistance). If the shunt resistor has a very low resistance, but can handle large currents, the majority of the current can go through the shunt resistor, and the galvanometer can measure the current that goes through it, and then be calibrated for the range of actual current. Many handheld multimeters will have a dial that will select a different shunt resistor depending on the range of current you want to measure.

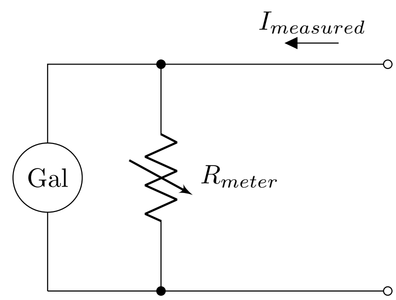


Figure 6: Basic schematic of an ammeter.

### 7.2.1 Measuring Current

As mentioned above, ammeters have very little resistance in them. Ideally, they would have 0Ω of resistance. This makes sense because we are trying to measure the current flowing through a device and we want the ammeter to have as little interference with that as possible. Because of this, we need to make sure that the ammeter is attached into the circuit **IN SERIES**. If the ammeter is attached in parallel, or across the component, a very low-resistance path would be created around the component, and all of the current would flow through the ammeter instead of the component. The way this is done is by physically breaking the circuit where you want to measure the current, and then attaching the probes of the ammeter to the circuit. It is always good practice to remove power from the circuit when you attach an ammeter (or any component for that matter). Since you are breaking a current path, more current will flow through other branches which might damage the components.

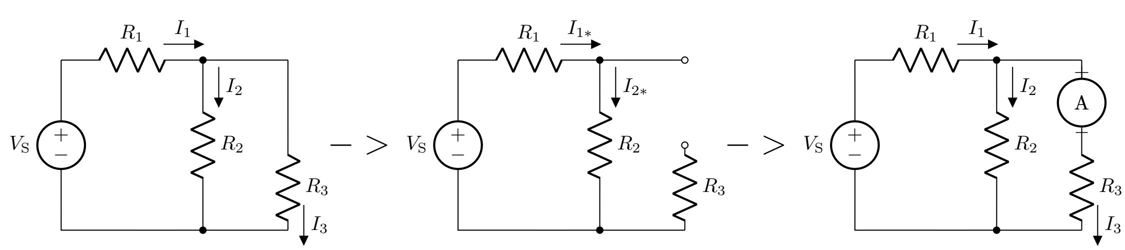


Figure 7: How to use an ammeter while measuring a circuit. The ammeter would be measuring the current through $R_3$ since it is now in the same path. Note that there is no current flowing through $R_3$ in the left schematic. In the right schematic, the ammeter completes the circuit so current can flow through $R_3$ and current can be measured.

### 7.3 The Voltmeter

A voltmeter, as the name suggests, measures voltage. This is done still using a galvanometer, but instead of using a shunt resistor, we will put a resistor in series with the galvanometer. If we know the resistor value, along with how much current is flowing through the resistor, we can calculate the voltage across the voltmeter using Ohm's Law. In the analog days, when voltmeters had dials just like galvanometers (because they were galvanometers), the scale was adjusted to say the voltage per an amount of current instead of the current value. In digital multimeters, the voltage is just calculated using an embedded math operation. Since there is no shunt resistor in a voltmeter, the meter resistor needs to be a fair amount larger when compared to the resistors in an ammeter, often around one mega-Ohm. Ideally, the resistance in a voltmeter would be infinite, or basically an open circuit. This also means that when you measure voltage, you put the voltmeter in parallel, or across the component you are measuring. The large resistance in the voltmeter will cause the vast majority of the current to flow through the component so an accurate reading can be made. Just like an ammeter, handheld voltmeters will have a dial (or auto-range) that can adjust the meter resistance to adjust the range of voltage being measured.

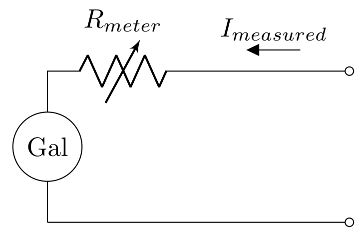



Figure 8: Basic schematic of a voltmeter.

### 7.4 The Ohmmeter

An Ohmmeter is a piece of equipment that can measure resistance. To keep things simple here, an ohmmeter is just a powered ammeter. A set voltage is supplied to the ammeter, and the resistor that is being measured will complete the circuit so the current can be measured. Since the voltage is known, and the current is measured, the resistance can be calculated using Ohm's law. When measuring resistance, make sure the circuit is not powered. Since the voltage is set in the calculation that the ohmmeter uses to determine the resistance, if the circuit is powered, that would skew the values and potentially damage the ohmmeter. If you are measuring the resistance of a single component in a circuit, make sure to physically remove it from the circuit in order to do so. If you try to measure the resistance of the component in the circuit, the resistance of the circuit will also be measured.

## 8 The Power Supply

Every circuit needs some sort of power. This is usually supplied in some shape or form by a voltage or current supply. This can be a battery, USB port from a computer, or a dedicated power supply unit (PSU) for a lab. For the majority of the labs in this course, we will be using lab-grade DC power supplies. We will be using function generators that can create AC signals, but we will get to those in a different lab.

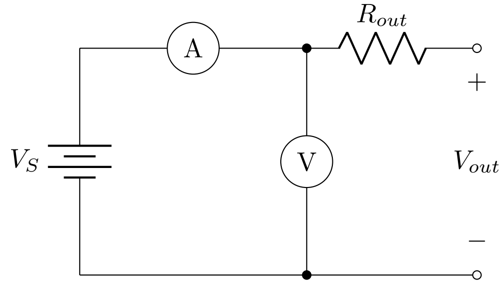



Figure 9: Basic schematic of a DC Power supply.

As seen in Figure 9, many power supplies, especially ones meant for lab settings, will have voltmeters and ammeters inside of them. This allows the PSU to display the voltage and current being supplied in a precise manner, and also allows the PSU to check itself and make sure it doesn't get overloaded. Many lab power supplies are able to produce multiple voltages at one time. While maintaining the same power, a PSU will have one supply that can supply a low voltage (usually maxing out around 6V) at high current, but then have a higher voltage (around 25V or even higher) supply at low current. Of course, depending on the needed application, supplies can be manufactured to provide almost any combination of current and voltage, but the price tag may change a fair amount too.

**Note:** The precision of the voltage and current will often depend on the supply and the ranges it can provide. If the PSU can provide multiple voltages at different ranges, the lower ranges will likely have higher precision which will be indicated in the manual and by how many significant figures are displayed with the internal voltmeter and ammeter.

**Current Limiting:** Current can cause a lot of damage to equipment if the current rating is exceeded, and can be dangerous to us as well. Most lab PSUs can limit the total amount of current that will be provided. Make sure you use this, especially when you are using a supply can can provide high current. If you mis-wired a circuit without setting the current limit, you can damage circuit components, equipment, and potentially hurt yourself.

## 8.1 Negative power?

If you take a look at a desktop computer power supply, or many PSUs that are in lab settings, it will be seen that they can provide a negative voltage value. For example, on many computer power supplies, the yellow wire coming out will be labeled "-12V." This may seem a bit odd, but it does have its uses. As a reminder, voltage is just the potential electric energy between two points. In Figure 10, you will see an example of how a power supply like this would be setup. You can even try this yourself with a few 9V batteries.

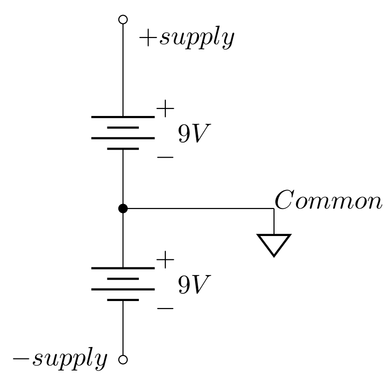


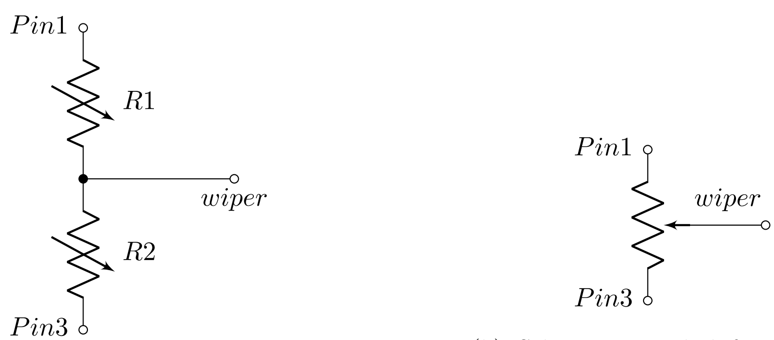

Figure 10: General schematic of a positive and negative supply.

Taking a look at Figure 10, you will see that the common ground is actually in the middle of the two batteries. This may seem odd, but remember that the common ground is just a common measuring point. This means that the "-" probe of the voltmeter would go on the common node. If we were to measure the voltage from the battery above the common ground by putting the "+" probe at the "+*supply*" node, we would get $9V - 0V = 9V$. Now do the same thing with the battery below the common ground. Keeping the "-" probe on the common ground, we will then take the "+" probe and attach it to the "$-$*supply*" node. Taking the difference between the probes would be $0V - 9V = -9V$. So we are not necessarily getting a negative voltage, moreso just attaching to the negative side of the supply. It is this idea that also allows us to get more than 9V out of the system. If we were to measure across the '+*supply*" and the "$-$*supply*," we would get $9V - (-9V) = 18V$. This is why adding batteries together in series allows us to get a larger voltage output, or allow a PSU to provide more voltage than that it can supply on one line.

It sometimes helps to think about this as a cliff over water. If we put our "0 meter" location at the top of the water/bottom of the cliff, we can drop a ball off the cliff, and it lands in the water and begins to sink. If we choose to measure the height of the ball in reference to the bottom of the cliff (0m,) as the ball starts sinking, it will have a negative location in that reference. If we were to calculate the total vertical height the ball has moved, we would combine the height of the cliff with how much the ball has sank to get our total displacement. The same thing is happening with our power supply.

# 9 The Potentiometer

For the first few labs you will be introduced to new equipment, such as the power supply and the multimeter, along with some components that will make our lives easier in electronics. The first of these devices is the potentiometer. A potentiometer is a device that acts like a pair of variable resistors in series. Inside of a potentiometer, there is a carbon strip with a pin called a wiper that moves across the strip. The amount of strip on either side of the wiper will determine the amount of resistance each resistor has. Using a dial or a slide, a potentiometer can adjust its resistance by decreasing one resistor and increasing the other. Every potentiometer will have a resistance label, such as 10K, which means that the total resistance of the resistors will always add up to 10KΩ. Potentiometers will have at least 3 pins, 2 for either side, and one for the wiper (usually the middle pin of the 3). Looking at Figure 11a, you can see how the layout of the pins relates to the resistors. Figure 11b shows how we usually draw a potentiometer in a circuit, replacing the pairs for a single resistor with the wiper in the middle.




(a) Internals of a potentiometer.

(b) Schematic symbol for a potentiometer.

Figure 11: Internal and usable schematic for a potentiometer.

It should be noted that all three pins of the potentiometer do not need to be used at all times. Attaching the wiper and pin 1 or 3 to a circuit will give you a single variable resistor that can be adjusted using the potentiometer dial or slide. This is called a Rheostat. Using all three pins can allow you to make a circuit called a **voltage divider**, which will be discussed in the next lab. It should also be noted that the direction of the potentiometer is often unimportant. Resistors are passive, and non-directional components, which means the direction that they are put into the circuit (flipping Figure 11a so pin 3 is on top instead of pin 1) is not important. For a potentiometer, the only thing that will change will be which direction the dial or slide needs to get moved in order to cause the resistance to increase or decrease when reading the wiper and one of the pins.

# In-Lab

Each lab in this course will have a similar layout, where you will start with a reading and then you will complete a lab portion. Every lab except for this one will also have a pre-lab section that will have you perform some calculations and simulations to better prepare you for the in-lab portion.

## 10 DC voltage measurement with a Digital Multimeter

1. Use the DC Power Supply to output both a 13V and a -13V output at the same time. Measure both of the voltages using a Digital Multimeter (DMM). Calculate the percent error for both of the measurements based on what is expected (the value shown on the power supply) versus what is measured on the DMM. Document expected values, the measurements, and the percent error in your lab notebook.
2. Determine how to get an output of 30V out of the DC supply. Document this procedure in your lab notebook. Measure the voltage output using a DMM and calculate the percent error. Document the values in your lab notebook.
3. Use the DC power supply to output a voltage of 5.125V. This may need to be done using a different mode or setting in your PSU. Measure the output using a DMM, and calculate the percent error. Document these values in your lab notebook.
4. Adjust the power supply until the DMM reads 5.125V. Again calculate your percent error, and document your measurements and calculations in your lab notebook. Are your errors between the PSU and the DMM adjustments close (within 5%?) Why is this the case?
5. Calculate the amount of current that will flow through a 220Ω resistor when there is 5V applied across its leads. Document this calculation in your lab notebook.
6. Adjust your PSU to output 5V with a current limit of 15mA. What do you expect to happen when a 220Ω resistor is placed as a load? Document your thoughts in your lab notebook.
7. Attach the 220Ω resistor to the outputs of the supply. What happened? Why did this happen? Document your thoughts in your lab notebook.
8. Calculate the minimum amount of resistance needed so that the current limit is not exceeded. Replace your 220Ω resistor with that value, and record the voltage and current through the resistor using a DMM. Compare the voltage and current to what is shown on the power supply. Which instrument should you rely on more for a more precise measurement? Why?

## 11 Verification of Ohm's Law

1. Set up your power supply with a current limit of 100mA.
2. Using your power supply, attach a 1KΩ to the voltage outputs.
3. Starting at 0V, and using step increments of no more than 0.5V, measure the current going through the resistor up to 5V. Document the voltage and current at each step in your lab notebook.
4. Plot an I-V curve of the current and voltage going through your resistor using MATLAB, Python, or a spreadsheet editor. Once you have the curve plotted, find the line of best fit. What is the value of the line of best fit? What does this represent? Document the values and your thoughts in your lab notebook.
5. Measure the resistance of the resistor using your DMM. Compare the measured resistance, expected resistance, and the line of best fit. What is the largest error between these? Does this seem like a reasonable error range? Why or why not? Document the values and your thoughts in your lab notebook.
6. Based on the tolerance band of the resistor you are using, are the ranges of the line of best fit or the DMM measurement in range? What are the maximum and minimum values that the resistor should be? Does the measured resistance fall within the tolerance labeled on the resistor?

## 12 Bonus Task: Using a Potentiometer as a Rheostat (+7%)

1. Using a 10K potentiometer, turn the dial all the way to one side until it will not move anymore. Measure the resistance between the middle pin and one of the outside pins. Also measure the resistance between the two outside pins. Document these values in your lab notebook.

2. Turn the dial all the way to the other side until it can no longer turn. Measure the resistance across the middle pin and the same pin as you did previously, along with the two outside pins again. What is the total range that the potentiometer can be adjusted? How much did the outside pins' resistance change? Does this make sense? Why or why not? Document these values and thoughts in your lab notebook.

3. Set up your power supply with a current limit of 100mA and a voltage output of 5V.

4. Turn your potentiometer all the way to the left.

5. Attach your power supply between one of the outside pins of the potentiometer and the wiper. Using the notch on your potentiometer dial, measure the current at each quarter turn of the potentiometer. Using the current, calculate the resistance of the potentiometer at each quarter turn. Document these values in your lab notebook.

6. Plot the resistance of the potentiometer versus the count of quarter turns completed using MATLAB, Python, or a spreadsheet editor (your first measurement is 0 turns, your second is 1 quarter turn, third is 2 quarter turns etc...). What visual relationship does the resistance of the potentiometer have with the amount that it is turned? (Linear?, exponential?, logarithmic?...) Think of where this might be useful. Think of where this might be a hindrance. *Hint: Perhaps where you want to adjust a value of something.* Document the plot and your thoughts in your lab notebook.

## 13 Bonus Task: Using a Potentiometer as a Voltage Divider (+3%)

1. Set up your power supply with a current limit of 100mA and a voltage output of 5V.

2. Using the same 10K potentiometer from the previous task, turn your potentiometer all the way to the left (the same way it was setup prior to measuring in the previous task).

3. Attach the + side of the power supply to one of the outside pins of the potentiometer, and attach the - side of the power supply to the other outside pin. Attach the wiper to the "+" probe of your DMM. Attach the - probe of the DMM to the same side of the potentiometer as the - side of the power supply.

4. Using the notch on your potentiometer dial, measure the voltage across the wiper at each quarter turn of the potentiometer. Document these values in your lab notebook.

5. Based on the voltage values read, why might this configuration be called a voltage divider? Where would this be helpful? Document your thoughts in your lab notebook.

6. Replace your DMM with a lamp from your lab kit. Turn the potentiometer. What do you notice happening with the lamp? What generalization can you make about the lamp brightness and voltage? Document your thoughts in your lab notebook.