University of Alabama
Department of Physics and Astronomy

PH 126 LeClair Fall 2011

# Electric potential, a.k.a. voltage

## 1 You will need

- a prototyping board
- an Arduino microcontroller [optional]
- a hand-held multimeter
- $1-20\,\mathrm{k\Omega}$ resistors (3-4)
- LED (1, loose)
- photoresistor (1, loose)
- various lengths of wire
- $1\,\mathrm{k\Omega}$ potentiometer (on protoboard)

## 2 Introduction

In today's lab, we will verify a few facts about electric potential, in particular the electric potential *difference* between various points in a circuit. These potential differences are commonly referred to as **voltages**. Potential difference tells us how much energy is available per unit charge for a circuit element to function, and is thus one of the two key parameters or analyzing circuit behavior (the other being how much charge is being affected). From what we know of electric potential so far, three key facts are important:

1. Electric potential is conserved
2. The electric potential difference between two points does not depend on the path taken
3. The electric potential about any closed path that returns to its starting point is zero

Actually, any one of these facts implies the other two, but it is important to keep all three in mind. How these three points apply to electrical circuits is the main task of today's lab.

## 3 Sourcing and measuring potential differences

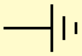
To the three facts above, we should add a two additional points relevant to circuits:

1. Every circuit needs a well-defined zero for potential, called the *ground* connection.
2. Voltage supplies create a constant potential difference between their two terminals

Both should be points you are vaguely familiar with – every circuit you've wired up so far had a connection to the ground point of the Arduino board, sometimes more than one. Every circuit had a connection to a 5 or 3.3 V source, a source of 5 or 3.3 V potential difference relative to the ground point of the Arduino.

## 3.1 Ground

The "ground connection" or "ground point" is the place in an electric circuit which is *purposely* connected to the earth, which we usually define to be our zero for electric potential $V = 0$. This is done not just to provide a convenient reference potential, it is a crucial safety feature we will discuss in later labs. The ground point (or just "ground") in a circuit or electrical diagram is usually shown like this:

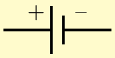
**Circuit diagram symbol for a ground point**: 

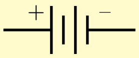
## 3.2 Voltage sources

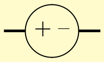
How do we actually change the electric potential – which we will usually just call voltage – of one object relative to another? Charging by induction or conduction are two ways, but somewhat cumbersome. A device known as a *voltage source* is a circuit element with two terminals, where a constant potential difference is supplied between these two terminals. Whatever you connect to the "negative" terminal of the source will have a voltage $\Delta V$ lower than the "positive" terminal. Using a "ground" point, one can also experimentally define one of the terminals as $V = 0$. If we "ground" the negative terminal, then the negative terminal is $V_{\text{neg}} = 0$, and the positive terminal has $V_{\text{pos}} = \Delta V$. If we ground the positive terminal, it has $V_{\text{pos}} = 0$, so the negative terminal must have $V_{\text{neg}} = -\Delta V$. We will see much more of this in the coming labs, and it will begin to make more sense!

Batteries are one example of a constant voltage source, and the wall outlets in your house are another example of a voltage source (though this voltage is not strictly constant). Ideal textbook voltage sources *always* supply a constant potential difference, $\Delta V$. Real voltage sources always have restrictions, a primary one being the amount of power that can be sourced. Below are circuit diagram symbols for constant voltage sources: the first two represents batteries, the last is a generic symbol for any more complicated sort of voltage source:

**Circuit diagram symbol for voltage sources:**

Batteries: 

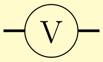


General constant voltage source: 

In most circuit diagrams (particularly those for the Arduino), the negative terminal will not be shown, you will just see a positive voltage label at some wire coming in to the circuit. This is a shorthand notation which implies that the terminal of the source that you don't see is connected to ground.

## 3.3 Measuring Voltage

A voltmeter is just what it sounds like – a device that measures voltage, or potential difference, between two points. A typical voltmeter has two input terminals, and one simply connects wires from these input terminals to the points within a circuit between which one wants to know the potential difference. If we wish to measure the potential difference across a particular component in a circuit, we connect the voltmeter in *parallel* with that component. In this lab, you will use a handheld voltmeter. When used on the proper setting (which we will show you), it simply measures the potential difference between the two probes coming out of it.

**Circuit diagram symbol for a voltmeter:** 

Of course, the idea is to measure the potential difference while disturbing the circuit as little as possible. For this reason, voltmeters have very high internal resistances[i] and no current flows through an ideal voltmeter. As an example, Fig 1a shows an incorrect use of a voltmeter – connecting the voltmeter in *series* with the resistor and battery. No charge flows through an ideal voltmeter, so connecting the voltmeter in this way essentially opens the circuit and nothing is measured. Figure 1b shows the proper use of a voltmeter – in *parallel* with the component to be measured, a resistor in this case. The voltmeter probes the potential on both sides of the resistor, but since no charge flows through it, it does not affect the circuit.

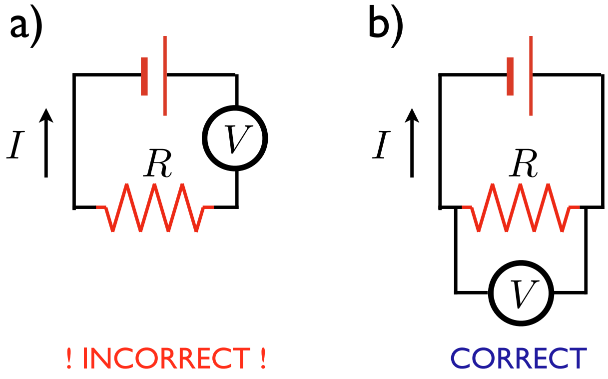


**Figure 1:** **(a)** *Incorrect connection of a voltmeter. Voltmeters have enormous internal resistances, current will not flow through them.* **(b)** *Correct connection of a voltmeter. The two input terminals of the voltmeter connect across the resistor, and draw no current.*

Real voltmeters are not ideal, you might have guessed. A real voltmeter has a finite input resistance, and, even when connected properly, draw a small amount of charge away from the circuit to be measured. We will dwell on this point more in later labs, for now you may assume your voltmeters are *practically* ideal.

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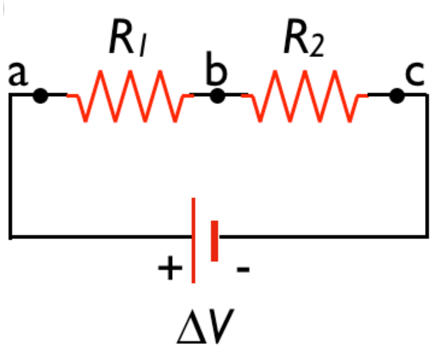
[i] Good laboratory voltmeters can have internal resistances on the order $10^{10}\,\Omega$ or more. For voltmeters, internal resistance is often called "input resistance."

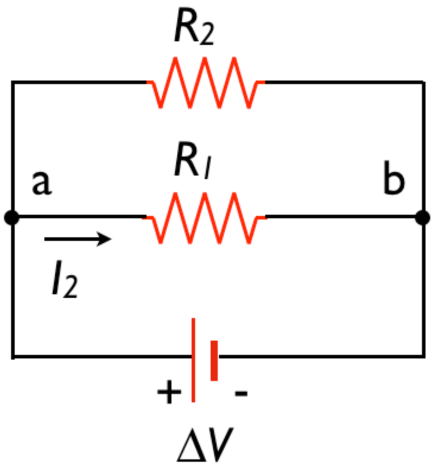
## 3.4 Series and parallel elements

The first three facts listed, arising from the fact that the electric force is conservative, lets us make key generalizations about circuits. Look at the circuit below, two resistors connected in *series* with a voltage source.



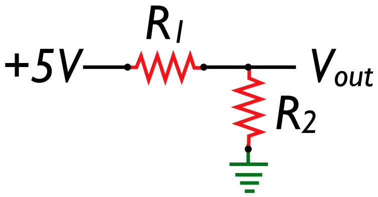
Since the electric force is conservative, the sum of potential differences around a closed loop must be zero. That means that if we "walk" around a circuit and get back to where we started, the potential differences across all of the elements encountered, added together, must be zero. Start at point c in the series circuit shown. Crossing the voltage source, we gain a potential difference of $\Delta V$ relative to where we started, since that is the function of a voltage source. If our wires are perfect, and no potential is lost, that means that the potential at a is $\Delta V$ higher than at c. If we continue walking around this circuit, we cross both resistors, and then get back to where we started.

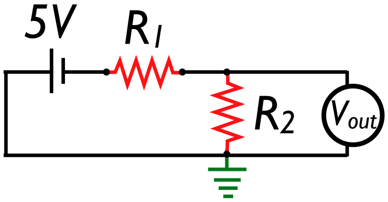
Since the sum of all potential differences for our trip must be zero, this means that the potential difference across the two resistors together must be $-\Delta V$. **In series, the elements share the supplied potential difference.** Now examine the *parallel* circuit below.



In this circuit, the same logic says that points a and b have a potential difference of $\Delta V$ supplied by the source. However, we can get from $a$ to $b$ in one of two ways: through $R_1$ or through $R_2$. That the electric force is conservative tells us both paths must give the same result, both must give a potential difference of $-\Delta V$ to complete the path back to $b$ where we started. **In parallel, elements have the same potential difference.**

This is a first glimpse into a general method of solving circuits: walk around the circuit, and add up the potential differences. The sum has to be zero, giving you a constraint on the circuit's behavior. Of course, if the "shorthand" notation is used, and the negative side of the source is not shown, you will have to remember to include it! The figure below shows both shorthand and full diagrams. What was labeled simply "+5 V" is a voltage *source* providing 5 volts relative to ground, and what was labeled "$V_{out}$" is an output voltage *measurement* (e.g., a voltmeter). Learning how to read the shorthand schematics will take a little practice, but not too much. If you look back at the Arduino circuits you've already wired up, it will probably be more clear already.





## 4 The lab

With this in mind, you have only a few tasks. **Turn in your measurements in response to the bulleted points below**, one report per group.

### 4.1 Identical resistors in series

Connect two identical resistors (say, somewhere between 1 and 20 kOmega) in series. Across these two resistors together, supply a potential difference of 5 V (either from the Arduino or the protoboard itself). Reference the series circuit above if you are unsure of how to do this.

- Verify that the potential between the two resistors is 2.5 V relative to ground.

Now connect two different resistors (varying by a factor of 2 or so) in series in the same way.

- How does the voltage split between the two resistors? Can you guess a mathematical relationship?[ii]

Now connect three identical resistors in series with the voltage source.

- Verify that the potential relative to ground splits evenly between the three resistors.

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[ii] Hint: it will be a fraction of the total supply voltage, something like (single resistor)/(sum of resistors).

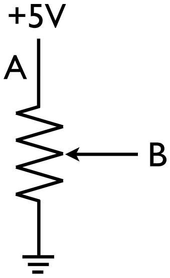
## 4.2 Identical resistors in parallel

Connect your three resistors in parallel (consult the parallel circuit above).

- Verify that the potential relative to ground is the same for all three resistors.
- Why would this be useful? Think about Christmas tree lights, and what happens when one bulb goes out.

## 4.3 Potentiometer

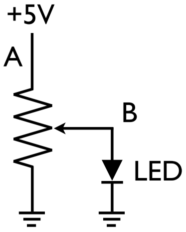
Connect one of the outer terminals a 10 kΩ potentiometer to ground. Connect the other outer potentiometer terminal to +5 V.



- Verify that the potential between difference from A to B plus the potential difference from B to ground is always 5 V, no matter the setting on the potentiometer.
- Verify that the potential difference between B and ground is always between 0 and 5 V.
- This is a simple way to provide an audio volume control. At which point would you plug in the audio source, and at which point the speaker?

## 4.4 LED plus potentiometer

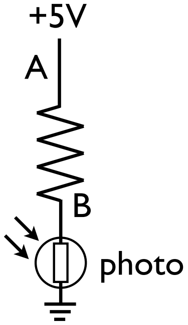
Connect an LED between the middle terminal of your potentiometer and ground, with the positive terminal of the LED (longer leg) to the potentiometer.



- How far do you have to turn the knob (%) to make the LED light up? What is the voltage between point B and ground when the LED lights up (note the color of your LED, it matters)?
- What does that imply about the threshold resistance of the LED?
- How do brightness and the voltage at point B relative to ground relate?

## 4.5 Photoresistor and fixed resistor

Connect a resistor of about $1\,\mathrm{k\Omega}$ and a photoresistor in series between $+5\,\mathrm{V}$ and ground.



- How does $V_B$ change with the relative illumination of the photoresistor?
- What would happen if you connected an LED between point B and ground when you illuminated the photoresistor or kept it dark?