# Lab 2: Resistance, Current, and Voltage

## I. Before you come to lab...

- **A.** Read the following chapters from the text (Giancoli):
  - **1.** Chapter 25, sections 1, 2, 3, 5
  - **2.** Chapter 26, sections 1, 2, 3
- **B.** Read through this handout in its entirety.
- **C.** If you took PS2 last semester, or PS2 or Physics 11a in the fall of 2006, then you have already been introduced to Logger Pro, the software used for data collection and analysis. If not, you should take some time to acquaint yourself with the software:
  - **1.** Logger Pro for Mac or Windows can be obtained from
    http://www.fas.harvard.edu/computing/download
    You will need to log in with your Harvard ID and PIN. Logger Pro 3.5 requires Mac OS X version 10.3.9 or later, or Windows 2000/XP/Vista.
    If you have a PC or Mac but are unable to install Logger Pro, contact Joon for help. If you don't have a PC or a Mac of your own, or you don't want to install the software on your own computer, you can use Logger Pro on a computer in the Science Center computer lab.
  - **2.** Familiarize yourself with the software:
    - **a.**
      Start Logger Pro and click the  Open button.
    - **b.** Under the Experiments folder, find the sub-folder named "Tutorials."
    - **c.** Open the tutorial called "01 Getting Started."
    - **d.** Follow the instructions in the tutorial.
    - **e.** When you have finished, also complete the following subsequent tutorials:
      05 Manual Data Entry
      07 Viewing Graphs
      08 Stats, Tangent, Integral
      09 Curve Fitting
- **D.** Answer the questions at the end of this writeup and be prepared to turn them in at the beginning of lab.

## II. Background

- **A.** Circuit basics
  - **1.** In this lab, you will be exploring the behavior of electrical components connected in circuits. The most basic thing to keep in mind is that nothing interesting will happen at all unless there is a *circuit*—that is, a closed loop where charge can flow.
  - **2.** The two major concepts of circuits are current and voltage. Don't get them confused!
    - **a.** *Current* (abbreviated I) is the rate of flow of charge.
      - **(1)** It is measured in amperes (A), or amps for short. An amp is a coulomb per second. That is a very large current (remember how much charge 1 coulomb is), so in practice we will often be dealing with milliamps (mA) and microamps (µA).
      - **(2)** In a simple circuit consisting of one loop, current flows continuously—every circuit element in the loop has the same current flowing "through" it.
      - **(3)** The preposition "through" is a very useful memory aid—if you think of current as something that goes *through* a circuit element, then it makes perfect sense that the same current also goes through the next element in the loop. It's only at junctions that current divides or combines.
    - **b.** *Voltage* ($\Delta V$ or sometimes, sloppily, just V) is another name for potential difference, which is a quantity we have already encountered. Voltage is a measure of how much work it would take to move a unit charge from one place to another.
      - **(1)** It is measured in volts (also abbreviated V, which only adds to the confusion).
      - **(2)** Remember that potential is something which is a function of position. So a potential *difference* is something

that depends on *two* positions, or two points on a circuit. So we will often speak in terms like "the voltage drop from A to B" (which means "the potential at point A minus the potential at point B") or "the voltage across the resistor R" (which means "the potential at one end of the resistor minus the potential at the other end").

**(3)** Voltages are considered to be "across" rather than "through" circuit elements. So if you have two resistors in a row, they do not, in general, have the same voltage across them. However, if you add up all of the changes in voltage as you go around a closed loop, you must get a total of zero when you return to your original position, because the final potential is equal to the initial potential.

**3.** Ohm's law

**a.** In many circumstances, the current through and voltage across a circuit element are proportional to each other. That is, if you double the voltage, you would get twice the current. This empirical fact is known as Ohm's law.

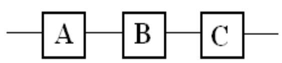
**b.** The proportionality constant between $\Delta V$ and I is called the resistance, R. Then Ohm's law can be stated quantitatively as: $\Delta V = IR$.

**c.** Resistance is measured in ohms ($\Omega$). An ohm is a volt per ampere. Because amps are so large, useful resistances are often on the order of kiloohms ($k\Omega$) or megaohms ($M\Omega$).

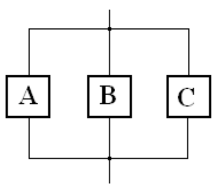
**d.** All real circuit elements have some resistance. However, when the circuit contains resistors or light bulbs, the comparatively small resistance of other circuit elements such as wires can often be neglected.

**4.** Series and parallel

**a.** Two or more devices which are in *series* are connected in the same branch. Therefore they have the same current passing through them (but not necessarily the same voltage).




**b.** Two or more devices which are in *parallel* are connected independently between the same two points. Therefore they have equal voltages across them (but not necessarily the same current).




**5.** Power

**a.** The electrical power (rate of change of electrical energy per unit time) of a device is equal to the current through it multiplied by the voltage across it: $P = I\,\Delta V$. Electrical power is measured in watts (1 W = 1 Joule/second), just like mechanical power.

**b.** Being very careful with the sign of electrical power leads to some useful insights:

**(1)** When the potential *decreases* in the direction that current is flowing, $\Delta V$ is negative, so that P is also negative. That tells us that electrical energy is being *lost* in that circuit element. This is always the case with resistors.

**(2)** When the potential *increases* in the direction that current is flowing, $\Delta V$ is positive, so P is also positive. This is usually the case with a battery.

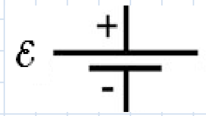
**c.** For resistive elements (resistors, light bulbs, heaters, etc.), the power is the rate at which electrical energy is being converted into heat or light. So we often talk about power "dissipated" in a resistor or bulb; as a result, the minus sign is often dropped with the implicit understanding that electrical energy is being lost or dissipated.

**d.** For a battery, P is the rate at which the battery is *supplying* electrical energy, which the rest of the circuit can use to do work. It is also the rate at which the chemical energy stored in the battery is being depleted.

**B.** Common circuit elements

**1.** Voltage source (battery)

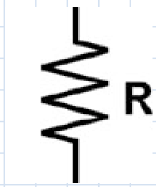
**a.** A battery can be considered as a source of constant voltage. The voltage it supplies is also called electromotive force, or emf, symbolized by $\mathcal{E}$. In circuit diagrams, a battery is represented by the following symbol:




- **b.** An ideal battery is just a voltage source; however, a real battery acts like an ideal battery in series with a small resistance, which is called the internal resistance of the battery.
- **c.** The internal resistance of a battery is usually less than 1 Ω. However, for a "dead" battery the internal resistance goes way up.

**2.** Resistor

- **a.** Resistors are just circuit elements that have resistance. They are indicated in circuit diagrams by the following symbol:




- **b.** Resistors obey Ohm's Law, so the voltage across a resistor is always equal to the instantaneous current through it multiplied by its resistance.
- **c.** Resistors connected in series add: $R_{eq} = R_1 + R_2 + ...$
- **d.** Resistors connected in parallel add inversely: $1/R_{eq} = 1/R_1 + 1/R_2 + ...$
- **e.** The power delivered to a resistor can be calculated by $P = I\,\Delta V = I^2R = \Delta V^2/R$ (all equivalent due to Ohm's law). This is the rate at which electrical energy is being converted to heat energy.

**3.** Wire

- **a.** A wire is the simplest possible circuit element. It is just a conductor which connects two points. A wire is represented by a straight line on a circuit diagram.
- **b.** A wire can be thought of as a resistor with a resistance of 0 ohms (in practice, they have a tiny but non-zero resistance). From Ohm's law, the voltage across it must be zero no matter how much current is passing through it.
- **c.** Thus we have the useful rule that **any two points in a circuit which are joined by a wire must be at the same potential**.

**4.** Voltmeter

- **a.** A voltmeter is a device used to measure the potential difference between two points in a circuit. Most commonly, it measures the voltage *across* a single circuit element, such as a resistor or a battery.
- **b.** To measure a voltage, connect the voltmeter in *parallel* across the device you are interested in knowing the voltage across. (Remember, parallel devices share the same voltage difference.) Putting the voltmeter in series with your circuit will cause the circuit itself to be drastically altered, and will give you meaningless results.
- **c.** A voltmeter basically acts like a very large resistor, usually on the order of megaohms. The larger the resistance, the less the voltmeter affects the circuit, because it is in parallel and parallel resistances add in *inverse*.
- **d.** The differential voltage probe (which is your voltmeter for this lab) acts like a 10 MΩ resistor when placed in parallel with a circuit.

## III. Introduction

**A.** In this lab, you'll learn familiarity with circuits by solving three "puzzles" involving measuring some unknown quantities. The key to solving these puzzles will be a good understanding of circuits, both on a theoretical and a practical basis.

**B.** Objectives for this lab:

- **1.** Learn the relationships between current, resistance, and voltage
- **2.** Learn about series and parallel components and how to take advantage of the rules regarding them
- **3.** Learn how to use a voltmeter to measure voltages in a circuit
- **4.** Develop practical circuit problem-solving skills
- **5.** Apply knowledge of experimental uncertainty to electrical measurements

## IV. Materials

**A.** LabPro interface with differential voltage probe

**1.** The differential voltage probe is basically just a voltmeter. Like the multimeter you used in Lab #1, it measures the potential at the red probe minus the potential at the black probe.

**2.** However, the Logger Pro software allows you to collect voltage data automatically. In particular, you can ask it to measure the voltage every few milliseconds and then display the voltage as a function of time. This capability will enable you to study circuits where the voltages are changing in time, such as RC circuits. (We won't need to use this capability until next week, though.) If all you want to do is take a single voltage measurement, however, you can just read it off the meter in the lower left corner of the Logger Pro window.

**3.** The differential voltage probe acts like a 10 MΩ resistor. So if you place it in parallel across something with a much smaller resistance, it draws very little current and changes the circuit only slightly; you can pretty effectively consider it to be of infinite resistance. This is not true, however, if the resistances that are in the circuit are very large themselves.

**4.** A note about uncertainty: chances are good that when you connect the voltmeter to make a measurement, the digital reading will jump around a bit (especially in the last decimal place) rather than staying perfectly constant. If this happens, you can estimate the uncertainly in the voltage reading by taking half the difference of the highest and lowest numbers that it jumps between. So if it is fluctuating between 1.248 V and 1.262 V, you would report the voltage as 1.255 ± 0.007 V.

**5.** If the reading does happen to stay constant, you can estimate the uncertainty as 1 in the last decimal place (so if it reads a constant 1.260 V, the uncertainty is ±0.001 V).

**B.** Selection of alligator clip leads

**1.** You'll use these as wires to connect different electrical components together into a circuit.

**C.** Battery pack

**1.** This is a pack containing two 1.5-volt batteries connected in series. It can be thought of as a single 3-volt battery.

**2.** The red lead connects to the positive terminal of the battery; the black lead connects to its negative terminal.

**D.** Selection of resistors

**1.** The resistance of a resistor is indicated by the set of four colored stripes on the resistor. The first two bands taken together indicate the first two digits of the resistance, the third band is the multiplier (power of ten), and the fourth band is the tolerance.

**Color Coding for Resistors**

| Color | Number | Multiplier | Tolerance |
|---|---|---|---|
| Black | 0 | 1 | |
| Brown | 1 | $10^1$ | |
| Red | 2 | $10^2$ | |
| Orange | 3 | $10^3$ | |
| Yellow | 4 | $10^4$ | |
| Green | 5 | $10^5$ | |
| Blue | 6 | $10^6$ | |
| Violet | 7 | $10^7$ | |
| Gray | 8 | $10^8$ | |
| White | 9 | $10^9$ | |
| Gold | | $10^{-1}$ | 5% |
| Silver | | $10^{-2}$ | 10% |
| Colorless | | | 20% |

**2.** So for example, the following resistor has a resistance of 26 (red-blue) times $10^5$ (green), within a tolerance of 5% (gold). So its resistance is 2.6 MΩ, give or take 5%.

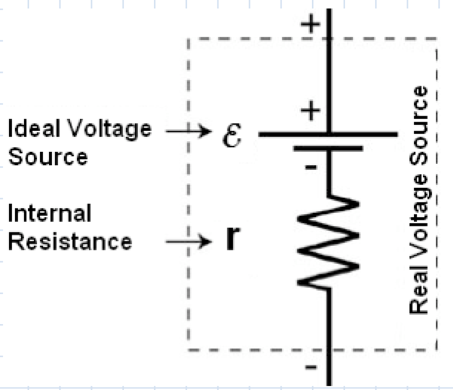
3. If you are not sure which end to start from, most resistors have a gold or silver band as their fourth band to indicate tolerance.

**E.** 1 "mystery" resistor

1. This is simply a resistor whose markings have been covered up with black tape. Your job in part of the lab will be to figure out a way to experimentally determine its resistance.

**F.** 1 two-terminal "ER" black box

1. This is a box containing a battery (emf) and a small resistor, connected in series. The two exposed metal contacts A and B are the + and - terminals, respectively, of the diagram shown below:




2. You will have to design an experiment to determine both the unknown emf and the unknown resistance r inside.
3. Everything inside the dashed lines is internal to the box. So you cannot measure, for instance, the voltage across just r, because you can't connect a voltmeter probe to the point in between r and the emf.

**G.** 1 three-terminal black box

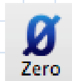
1. This box contains a network of three resistors, somehow connected to the three terminals of the box.
2. You will design an experiment to determine what the values of those three resistances are, and how they are connected to the terminals and to each other.

## V. Procedure

**A.** Before you begin...

1. Take a picture of yourselves using Photo Booth. Drag the photo into the space below:

2. Tell us your names:
   - **a.**
   - **b.**
   - **c.**
3. Open the file Lab2.cmbl in Logger Pro. You should see a digital readout in the lower left corner of the page. This is your "voltmeter" display. To ensure that it is properly calibrated, clip the two leads of the voltage probe to each other

and then click the 

button in the toolbar.

- **B.** Mystery resistor
  - **1.** General instructions
    - **a.** In this part of lab, you will attempt to determine the value of an unknown resistance by designing one or more circuits involving the mystery resistor and making appropriate measurements. It may seem trivial, but be forewarned: it's not trivial.
    - **b.** The tools you will be able to use to measure the mystery resistor are:
      - **(1)** A battery
      - **(2)** A selection of resistors of different (known) values
      - **(3)** LabPro interface with differential voltage probe and the Logger Pro software
    - **c.** Note that the only measurements you can make are *voltage* measurements. You cannot make direct measurements of current (or, of course, resistance)! However, if you are clever, you can figure everything out with just voltage measurements. For instance, if you measure the voltage across a *known* resistor, you can calculate the current through it using Ohm's Law.
    - **d.** These puzzles are designed to be challenging but fun. If you get stuck or find yourselves going around in circles, please don't hesitate to ask a TF for help! Your lab TFs are smart people who are experienced at working with circuits. They can provide you with useful hints.
    - **e.** Good luck and have fun!
  - **2.** Play around with the components at your disposal and see what you can measure. At some point, however, work with your lab partners to devise a systematic plan to determine the mystery resistance. Run it by a TF if you're not sure it'll work. Then put your plan into action!
  - **3.** Describe your procedure here; be specific! Include snapshots of circuit diagrams if you need to. Feel free to add as many steps as you need.
    - **a.**
    - **b.**
    - **c.**
  - **4.** Record your measurements and calculations here. Include uncertainty measurements, since we will want to know the uncertainty of your final answer.
    - **a.**
    - **b.**
    - **c.**
  - **5.** What is the mystery resistance R? What is the uncertainty in your measurement of R?
    - **a.** R = ?
    - **b.** uncertainty in R = ?
  - **6.** When you reach this part, talk to a TF before moving on. It's very important to understand how you solved this problem before tackling the next part.
- **C.** Resistor network black box
  - **1.** This box is the one with three terminals, labeled A, B and C. It contains three resistors of unknown resistances, arranged in an unknown fashion. Your task is to determine the layout of the resistors inside the box, and determine the values of the three resistances.
  - **2.** You can use all the same equipment that you used for the mystery resistor puzzle. Once again, you'll have to come up with your own procedure for determining the resistances in the box. As a hint, think about how your mystery resistor procedure could be useful to you again.
  - **3.** Record your procedure and all measurements here. Be specific about what you measured.
    - **a.**
    - **b.**
    - **c.**
  - **4.** What are the resistor values? How are they arranged relative to terminals A, B, and C? How did you determine them? (Don't worry about uncertainties for this part.)
    - **a.**

- **b.**
- **c.**

**D.** ER black box

- **1.** This part is slightly different. The other black box, labeled "ER," contains a "battery" which consists of a voltage source and a small-but-not-tiny "internal resistance." The battery is oriented so that terminal A is at a higher potential than terminal B. Your task is to determine the value of both the emf E and the internal resistance r.
- **2.** Because the box already contains a battery, we ask you **not** to connect an external battery to it. You can do everything using resistors, wires, and the voltmeter. However, you will need to make measurements of several different circuits in order to determine E and r. (Remember the pre-lab?)
- **3.** Record your measurements here:
  - **a.**
  - **b.**
  - **c.**
  - **d.**
  - **e.**
- **4.** The analysis of your measurements involves a determination of whether your data fits an equation with unknown parameters, and then calculating what those unknown parameters might be.
  - **a.** The equation you'll need was derived in the pre-lab; fitting your data to it is another matter altogether. By far the most convenient function to try to fit to is a straight line.
  - **b.** Hint: you want to rewrite the equation so that it is the equation of a straight line. You will not be able to do this if you stick to R and $\Delta V$ as your independent and dependent variables, but look what happens if you take the reciprocal of your equation. (You might need to simplify some fraction-like expressions.)
  - **c.** The great part about fitting data to a straight line is that it's easy to see whether it fits. Not only that, fitting data to a line gives you two independent parameters: the slope and the intercept. Your equation has two unknowns: E and r. Hmm...
  - **d.** You can use the data analysis features of Logger Pro to help you on this part. In fact, the data table there is already set up for your use.
- **5.** Record your results along with a copy of any graphs you used here:
  - **a.** E =
  - **b.** Uncertainty of E =
  - **c.** r =
  - **d.** Uncertainty of r =
  - **e.**

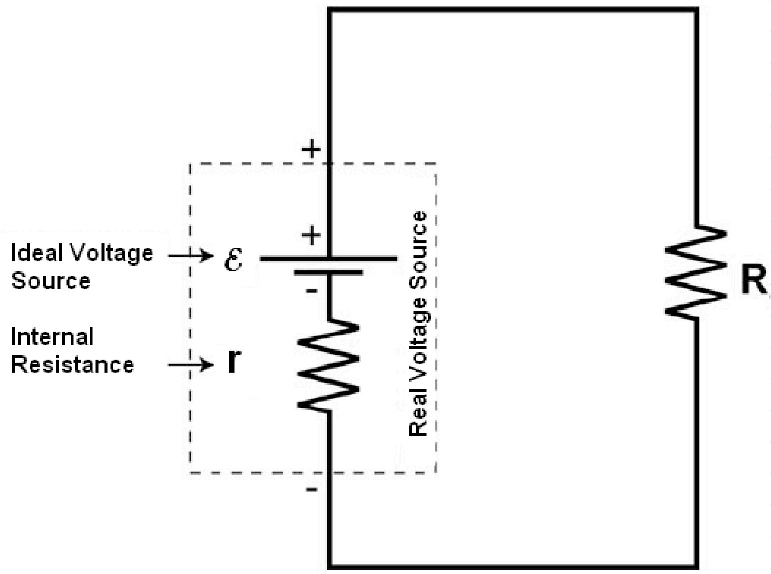
## VI. Conclusion

- **A.** You've reached the end of the lab. Congratulations!
- **B.** Save your work in this file and in Logger Pro.
- **C.** Submit the electronic copy of your lab report as you did for Lab 1. The instructions for doing so are on a laminated sheet by each computer.

### VII. Pre-lab assignment.

Answer the following questions on a separate sheet of paper *before* coming to lab. Remember to write your name, your TF's name, and your lab time on the sheet.

**A.** Consider the circuit diagrammed below.




**1.** You want to measure the voltage across R. On the diagram above, draw in the voltmeter (you can use a circle with a V in it to represent a voltmeter) in the appropriate place.

**2.**

Calculate the voltage across the resistor R, in terms of $\mathcal{E}$, r, and R.

**3.**

Suppose you are asked to experimentally determine the unknown values of $\mathcal{E}$ and r by measuring the voltage across

R for different values of R. How many different R values would you need to use to determine both $\mathcal{E}$ and r? Would it improve your results to take more data points than this?