Phys 15b: Lab 2: I-V Curves; Voltage Dividers

Due Friday, March 16\textsuperscript{1}, before 12 noon in front of Science Center 301

Note that this lab, like Lab 1, is to be done in SC305, at your assigned section times (Thursday, Mar. 1 or Mar. 15). There is no lab work to be done in the week of March 5 (and there will be no help labs), because of the hour exam scheduled for that week.

Attachments: LED data sheet; meter schematic.

Note: In this experiment, and others, there are questions, set off by the boldface label “Question:”, to be answered in the write-up. Please answer them in your notebook as you go along, with all work shown. Remember that you should include circuit diagrams, discussions, etc in your lab notebook so that someone who had never seen this handout would be able to understand exactly what you did in the lab. Please present your data in tables that include the units of the measurement, and the uncertainty or error. Also, please make your graphs large (at least half a page), with labeled axes and both horizontal and vertical error bars on your plots.

1 Purpose

1. To understand the voltage divider
2. To understand “bridge” circuits
3. To study the I-V characteristic of a light emitting diode
4. To study the I-V characteristic of an AA dry cell
5. To get some insight into the operation of your VOM as current meter and as voltmeter

\textsuperscript{1}Yes, this is a long way off. It’s a two-week lab, and we lose one week to an hour exam, as well.
2 Background

2.1 The Voltage Divider

The single most important d.c. (“direct current”) circuit configuration is called a voltage divider. It is used to produce a variety of desired voltages from one single source. This is important since the obvious alternative way to get a variety of voltages is clumsy and expensive: a “power supply” is required to convert the AC “line” voltage that comes from the wall plug into the DC level required by virtually every instrument. You don’t want to buy many heavy, expensive power supplies. Instead, you want to buy a handful of resistors to do the job. Here’s a voltage divider:

\[ \text{Figure 1: A Voltage Divider} \]

Given an input voltage \( V_{in} \), the output voltage \( V_{out} \) can be any fraction of \( V_{in} \), depending upon the values of \( R_1 \) and \( R_2 \). It is easy to find a formula for \( V_{out} \) beginning with two truths from Purcell, p. 151:

- the “condition” (no. 3 on p. 151) that the sum of the potential differences around a closed loop must be zero;
- the “condition” (no. 2, often called “Kirchoff’s current law”) that the currents into and out of a node add to zero, so top and bottom currents are equal. It follows that

\[
V_{in} = IR_1 + IR_2
\]

and...

\[
I = \frac{V_{in}}{R_1 + R_2}, \text{ (solving for } I) \]

Finally,

\[
V_{out} = IR_2 = V_{in}\left\{\frac{R_2}{R_1 + R_2}\right\}
\]

Depending upon the values of \( R_1 \) and \( R_2 \), the ratio in curly brackets can vary from 0 to 1 and the value of \( V_{out} \) can vary from 0 to \( V_{in} \). You will use the circuit twice in this experiment, and many times in others. Notice that the ratio of the voltages across the two resistors is simply:

\[
\frac{V_2}{V_1} = \frac{IR_2}{IR_1} = \frac{R_2}{R_1}
\]

That is, it is equal to the ratio of the resistors, a straightforward easy-to-remember result that you can use to design your voltage dividers.

**Question 1:** If you have batteries which give \( V_{in} \approx 6V \) and you want to make a voltage divider with \( V_{out} \approx 4V \), which of your resistors, or combinations of resistors, can you use, and hooked up in what circuit?
2.2 The Potentiometer

Very often, a device known as a potentiometer, or pot is used to make a voltage divider whose output voltage can be continuously varied:

![Potentiometer Diagram](image)

Figure 2: A “Potentiometer”

The pot is made of a length of resistive material (called “cermet,” in our case) with leads connected to its ends and with a third lead connected to a slider that can move along the resistor.

As the slider is moved from one end to the other, all ratios of $\frac{R_2}{R_1}$ are accessible, and all values of output voltage from 0 to $V_{in}$. Thus a pot can be used with a fixed voltage source (e.g. a battery) to provide a continuously variable voltage source (although a low quality one, as we shall: low quality in the sense that the output voltage will vary with the “load” that it drives). We will use the 100 $\Omega$ pot in this way many times throughout the course. Most knobs on electronic equipment turn pots.

**Question 2: (How to burn out a pot)** Consider what can happen if you connect a “short circuit” (e.g. a clip lead, or a stray wire) across the $V_{out}$ terminals of the pot. Suppose $V_{in} = 3V$, and the pot resistance is 100 ohms, with a maximum allowable power dissipation of 0.5 watts (you will use such a pot in this experiment). Now let’s look at two cases: one safe, the other not. Suppose the pot is initially set for $\frac{V_{out}}{V_{in}} = 0.5$, and then you short circuit $V_{out}$. Calculate the current that will flow in the circuit. You can use this current to calculate the power that will be dissipated by the pot. Or you can calculate the power dissipation using, instead the alternative power formula, $P = \frac{V^2}{R}$, where R is the segment of the pot that is carrying current. You can see how to get into trouble if you change your assumption about the pot setting: suppose the pot was set to $\frac{V_{out}}{V_{in}} = 0.9$. Now, if you repeat your calculations, you can see that your pot is not short-circuit proof.

2.3 A “bridge” circuit

The “bridge” circuit can be used to make very sensitive measurements given relatively crude measuring tools. You may recall that it was hard to use your meter to measure resistors with large values. A bridge circuit would have allowed you to make a much more accurate measurement. Bridge circuits are widely used in measuring devices, like thermometers. The basic idea is that you can get a much more accurate measurement by comparing the difference between an unknown thing and a known thing of nearly the same size, than by simply trying to measure the unknown thing itself. The circuit below is an example of a bridge circuit. It is designed to measure very small changes in $R_2$. It compares the voltage at A to the voltage at B by measuring the voltage difference between points A and B.
You can adjust the pot to make this difference, $V_{out1} - V_{out2}$, small, so that you can then measure it on the voltmeter’s most sensitive scale. Now, if the resistance $R_2$ changes, the corresponding change in $V_{out1}$ will be measured very accurately. The circuit is easier to understand if the two parts of the potentiometer above and below B can be labeled $R_3$ and $R_4$. It also simplifies the problem if you assume that the voltmeter has infinite resistance, so that you can draw the circuit without it.

When $V_{out1} = V_{out2}$, $V_{meter} = 0$. Such a reading indicates that the ratios of the two voltage dividers are equal: $R_1/R_2 = R_3/R_4$. If any of the resistors changes a little—say, $R_2$—then $V_{out1}$ changes a little, and V will show that change. Since the initial value of V was zero (dividers balanced), you can put the V meter on a high-sensitivity range and thus sense small changes in voltage that ride on a larger voltage. For example, $V_{out1}$ may be about 3V. If you tried to measure that voltage directly—and perhaps changes in that voltage—you would be obliged to use the meter’s 5V range. You would be limited to perhaps 0.1V resolution. If, instead, you use your meter on its 250mV range to measure only the difference between $V_{out1}$ and $V_{out2}$, you can easily get much higher resolution: perhaps 0.01V (10mV). This truth makes the circuit good for measuring small resistance changes. If, for example, $R_2$ were a temperature dependent resistor (or thermistor), the circuit could be used to make a sensitive electronic thermometer.

Another type of bridge circuit looks like the following:

![Figure 4: Differential Measurement Applied to Measure V of Battery](image)

Here the voltmeter is a “bridge” between the pot and the second voltage source, $V_2$. With the pot set to match $V_{out}$ to $V_2$, you can put the voltmeter on its most sensitive scale, and can easily detect small variations in $V_2$. You will use this sort of bridge circuit to measure the internal resistance of a battery later on in this lab.

In essence, a bridge circuit lets you make a differential measurement, where the main voltage is balanced out against a voltage that you manufacture (the pot voltage) so you can then measure small changes.

### 2.4 The Light Emitting Diode

In the early and middle parts of this century, a diode was a two-terminal vacuum tube device that conducted current in only one direction. Nowadays, solid state diodes are the rule (except for certain deranged audiophiles), widely used in the process of converting a.c. voltages into d.c. voltages. You will study this in the next experiment. A ubiquitous application of one kind of solid state diode is
as a small and efficient light source, light-emitting diode (LED). When a current flows through the
diode, light is produced because the charge carriers undergo an electrostatic potential energy drop
- not by inefficient thermal emission but very efficient photon production at a single wavelength.
Thus, unlike light bulbs, LEDs do not heat up in order to emit light. As with all devices the LED
has a limit to the amount of current it can safely pass. So, normally it is driven through a protective
resistor:

![Figure 5: LED Drive Circuit: R limits Current](image)

Note that even if the voltage across the diode were zero (which it is not), the maximum current
would be limited by the resistor to $V_0/R$ amperes. The diode voltage will actually be characteristic
of the semiconductor materials it is made from, ranging from about 0.5 to 2 volts. The diode’s
symbol includes an arrow to indicate the preferred direction of current flow.

2.5 The dry cell

Through the impenetrable wonders of electrochemistry, the dry cell maintains a characteristic po-
tential difference which we’ll call $V_0$ (roughly 1.6 volts for an alkali battery) between its terminals,
so long as little or no current flows through it. When the dry cell is connected into a circuit - to drive
a load - then current passes through it. The cell exhibits a change in voltage, which is ascribed to
its internal resistance, labeled $r$ in the sketch below:

![Figure 6: A “dry cell” shows non-zero output resistance](image)

At the terminals of the battery the voltage drops to $(V_0 - Ir)$. Thus, as a circuit element, a dry
cell can be represented as an ideal voltage source ($R_{out} = 0$) in series with a resistance. This
"resistance" may in fact be only an approximation to a more-complicated non-ohmic element, even
one whose voltage drop will vary depending on past use. However, a ball-park value, $r$,is very
helpful in deciding what kind of battery is needed to drive a given load. For example, the starter
motor of a car may draw 100 Amperes. Given that large $I$, the 12 volt car battery had better have an
internal resistance such that $Ir \ll 12V$ (which means $r \ll 0.12\Omega$). As a consequence, a car battery
is a set of big lead-acid wet cells (devices that show very low internal resistance).

**Question 3:** If a flashlight bulb uses 0.25 amperes, what internal resistance can a dry cell have if
the voltage at its terminals is to change by 0.15 volts or less when it lights the bulb?
3 Procedure

The 100 Ω pot in your lab kit is the one with a thin white base and a round blue top, with a “+” shaped slot for a screwdriver, and a code like “101X” written on the underside (can you understand the “101”, rather than say, “100”, in light of the resistor code discussed previously?). You can turn its top with your small screwdriver to move a slider along the resistive element. The two leads on one side of the base are the ends of the resistive element and the one opposite is connected to the slider.

Solder or breadboard? You can solder leads to the pot, or you can plug the device directly into your breadboard strip (the latter method is the easier!). Before you plug it in, be sure to use pliers to flatten each lead and then rotate the lead 90 degrees, so that the thin, flat leads fit the thin, flat gaps in your breadboard (they may look square from the top, but you know from the class video that the metal troughs underneath provide slots rather than square openings). After you have soldered the leads or plugged the pot into your breadboard, connect your ohmmeter across various pairs of terminals to check your understanding of which lead is which. See how the resistance changes as you turn the top, and find the total resistance, which may differ by 30% from 100 ohms.

3.1 An I-V curve for the LED

You will need to borrow a second meter from a friend, or collaborate with a partner on this part of the experiment. If you collaborate, you can share data, but each of you needs to put the data and a graph of it in his or her own notebook, and write it up independently. You can use a circuit with your pot as a variable voltage source, configured as shown below:

![Figure 7: A Circuit to measure LED's I and V]

Look at the LED data sheet attached to this write-up and find, in the table near the top, the absolute maximum DC current ("I_F(mA)"). For safety, at the start of your experiment pick an R from your resistor assortment or construct a series or parallel combination of your resistors, such that you cannot exceed this current, even at 4.5 volts. (But don’t limit the current to very small values or you won’t see the light.) After you have started the experiment you can change to a lower value of R and drive the current to the maximum so long as you are careful to keep the pot output voltage low enough not to drive the diode beyond its rated current.

Notice that the ammeter in the circuit above reads the total of the current through the LED and through the voltmeter. Were the voltmeter ideal, its current would be zero. Actually, on all voltage ranges your meter looks like a resistance of 20,000 ohms times the full scale voltage (e.g. 100 k Ω on the 5 volt DC scale). This is the same as saying that the meter draws 50 microamperes at full scale on all the voltage ranges, 25 microamperes at half scale, and so on. You may find the attached “schematic” or circuit diagram of the meter’s innards helpful.

Question 4: Sketch the circuit with the meters connected differently, so that the ammeter reads the true current through the diode and the voltmeter reads the voltage across the diode plus that across the ammeter. On all current scales, let us assume, the ammeter voltage is 0.25 volts full scale, 0.125
volts half scale, and so on (as we have said, this is not quite so; you can measure your full-scale drop on the 250mA scale, if you like—but we don’t mean to require you to do that: you would need access to a second meter). You should correct your voltage reading, using either the assumed “250mV-full-scale” value or your measured value. Using the meters this way is advantageous when you try to measure very small diode currents on your most sensitive (50 microampere) current scale, but uncertainty concerning the ammeter’s voltage drop will muddy your findings, of course.

Determine the I-V curve for both positive and negative voltages (i.e., reversing the diode in the circuit) and plot it. Note the points of interest on the plot – i.e. where the current first starts to flow in the LED, where the LED starts to light up, etc. Be sensible about the meter scales you use and the meter arrangements you use. Always correct for the effects of the meters. Adjust R to reach the maximum allowed current. Compare your data with the partial I-V curve of the data sheet.

Warm the diode by briefly heating one of its leads with the soldering iron; observe the effect on the current (in both directions) for a constant V—or vise versa. Semiconductor devices can be very temperature-sensitive. Note: we completely destroyed one LED with too much heat. The plastic that encloses the diode eventually melts if you overheat the lead for too long. Fifteen seconds, or so, should be all it takes to see any effect.

3.2 The internal resistance of an alkaline AA cell

Again, this is most conveniently a partnership experiment.

Your AA cell puts out about 1.6 V when no “load” is attached. If, however, you connect a “heavy” load (a small resistance joining the cell’s two terminals: confusing, eh? “small resistance” is “heavy load.” Sorry. The problem comes from the upside-down-ness of the concept of “resistance.”), then the cell will not be able to put its full 1.6V across the resistor. The voltage source (here, the AA cell) is then said to be “sagging” or ”drooping” under load. This occurs, as we’ve suggested above, because the cell has a finite resistance that is causing a significant voltage drop INSIDE the battery. If you disconnect the external resistor, the voltage across the battery should return to 1.6V. You have probably observed a similar effect when the house lights dim as a big appliance turns on, drawing a large current from the house wiring. Knowing the internal resistance of the battery allows you to determine how small a resistance you can place across the battery without causing sagging. You might try to measure the internal resistance \( r \) directly by measuring the battery voltage in the circuit below, with the switch opened and closed (a switch for us can be just connecting or disconnecting a clip lead):

![Figure 8: Load can cause measurable drop in cell's \( V_{OUT} \)](image)

When the switch is closed, current \( I \) flows through the series circuit of \( r \) and \( R \). Thus there is an \( Ir \) voltage drop inside the battery, and the voltage \( V \) is changed from \( V_0 \) with the switch open to \( (V_0 - Ir) \). Knowing \( I \) and the drop in voltage \( Ir \), we can find \( r \). If the drop in voltage is very small compared with the battery voltage, there will be a very small change on the meter, a drop that is
hard to determine accurately. You can do better if you use a bridge circuit like the one shown below. You can redraw the circuit with the two grounds (dashed arrows) connected together since they are the same point. **Note:** The word “ground” can be used in two distinct senses. One sense, the more common, simply refers to a local reference point for your circuit, a reference you have chosen to define as “zero volts.” This local potential could be millions of volts higher than the potential of the earth (the earth outside your building), which defines the other possible meaning of “ground.” Occasionally, someone will help you out by referring to the latter as *earth ground*. Most of the time, however, it’s up to you to figure out what “ground” means, from context! “Grounded appliances” have their cases connected to the third terminal of the three prong plug, which is connected to the earth (down in the basement, a copper spike is driven into the ground). You can tie your circuit ground to earth ground if you like, but you need not do so.

Here is the setup for measuring an AA cell’s output resistance:

![Figure 9: Circuit to measure cell’s ROUT](image)

Set your voltmeter to the 5V scale, and adjust the potentiometer until the voltmeter reads 0V. When this occurs, point $X$ is at the same voltage as the middle lead of the potentiometer (see section 2.3 re: the use of the *bridge* to make sensitive measurements). In other words, the potentiometer is now giving an output equal to the AA-cell’s voltage, $V_0$.

When you have adjusted the pot to equal $V_0$, you can safely switch the voltmeter to its most sensitive scale: 250mV.² With the meter on this most-sensitive range, you may want to fine-tune the potentiometer setting, to get a potentiometer voltage more exactly equal to the voltage at $X$.

If you now close the switch, the voltage at $X$ will fall somewhat, and the voltmeter will show you this. The meter reading will change by the drop across the AA-cell’s $r$. The voltage at $X$ a drops to $(V_0 - Ir)$ as current flows from the AA-cell through $R$. (The pot voltage changes by a negligible amount, because of a very small additional current that flows through the volt-meter. You can safely neglect this error.) If the meter reading drops below zero, adjust the pot so you start at a higher voltage. In this way you can determine $ir$ directly, on your most sensitive meter scale. The meter is being used to measure a small difference between a standard voltage you set with the pot and a nearly equal voltage $(V_0 - Ir)$.

Try various values of $R$ to get different values of $Ir$, and find the value of $r$ in each case. Does it

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²This scale is both 250 millivolts full scale and 50 microamperes full scale. You can use the meter, on this range as a sensitive voltmeter or ammeter. The meter is both, of course, and it’s up to you how to interpret what it’s doing for you. From the two full scale values, incidentally, you can also infer the meter’s internal resistance: $R_{\text{int}} = \frac{V_{\text{full-scale}}}{I_{\text{full-scale}}}$. 
look as if $R$ is an ohmic or “true” resistor? What is its value? Be sure to use at least some values of $R$ that produce an easily measurable $Ir$ voltage change. For small values of $R$, be alert to the possibility that $V_0$ may not stay constant because the battery is supplying a large current. If you want to go to an $I$ which exceeds the maximum for your current meter, notice that you can use it instead as a voltmeter to measure the voltage across $R$, and thereby calculate $I$, using Ohm’s Law.

And another fine point—this time a point that makes your job the easier!: you need make no correction for the voltage drop across the ammeter, this time, because we don’t care what the voltage across the load resistor, $R$ happens to be. We are interested in the load current, and the ammeter gives us a true reading of this quantity, despite its own internal voltage drop. (These are subtle points, in a simple experiment, aren’t they?!)

(meter sketch and LED data sheet follow)
Physics 15b Meter Schematic

The Radio Shack VOM is an inexpensive and fairly-simple meter—but a glance at the schematic below will show that it’s not entirely simple. The details are fussy. We’ll try to do the explaining with "balloons," and we’ll sketch some radically-simplified schematics of the meter switched so as to do particular tasks.

For AC:
- diode converts input (sinusoid) to bumpy DC;
- meter averages this mechanically to give RMS reading.

5V (DC) range:
- almost the same as "bare meter movement" with the important difference that current passes through 95K R in series with the bare movement’s 5K. So, 5V is required to move meter to "full scale" deflection. Rin, on this range, is 100k.

For protection:
- diodes limit voltage to about 0.6v in either direction, protecting meter movement against large overvoltage.

Bare meter movement:
- current passes from "+ V-ohms-A" terminal through "50μA" switch contact, to meter movement, and back out to "COM" ("common") terminal.

Figure 10: VOM innards
And here are particular configurations (determined by switch settings on the front panel of the meter): the meter looks like one or another of these circuits depending on what function you have selected:

**Particular Configurations of Volt**

**Bare Movement**

("250 mV" or "50 μA"
(Ohm's Law equivalents))

**Voltmeter:** DC, 5V full-scale

**Voltmeter:** AC, 10V full-scale

**Ammeter:** 250mA full-scale

(only here does fuse cause substantial error — and deviation from rule "250mV @ full-scale")

**Ohmmeter**
### TYPICAL ELECTRO-OPTICAL CHARACTERISTIC CURVES

- **Dotted lines indicate pulsed operation**
- **High efficiency Green**
- **High efficiency Red**
- **Instantaneous forward current (mA)**
- **Luminous intensity vs. forward current**
- **Spatial distribution**
- **Spectral distribution**

#### FEATURES:
- High efficiency GaP light source with capless lens package.
- Anode mounting on PC board or panel.
- Grounding of plastic base can be used as separate heat sink.
- Slide-in or solder-in assembly.
- Low power requirements.
- Compact, rugged high reliability.

#### ELECTRO-OPTICAL CHARACTERISTICS

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#### ABSOLUTE MAXIMUM RATINGS

- **Yellow**
- **H.E. Red**
- **Orange**
- **Green**

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<th>PARAMETER</th>
<th>UNIT</th>
<th>85 mW</th>
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<td>-55°C to +100°C</td>
<td>-55°C to +100°C</td>
<td>-55°C to +100°C</td>
</tr>
<tr>
<td>Lead soldering time at 260°C (See Note 2)</td>
<td>sec</td>
<td>5 sec</td>
<td>5 sec</td>
<td>5 sec</td>
</tr>
<tr>
<td>Continuous forward current at 25°C</td>
<td>mA</td>
<td>20 mA</td>
<td>35 mA</td>
<td>30 mA</td>
</tr>
<tr>
<td>Peak forward current (1 μsec pulse, 0.3 duty cycle)</td>
<td>mA</td>
<td>60 mA</td>
<td>1.0 A</td>
<td>90 mA</td>
</tr>
<tr>
<td>Reverse voltage</td>
<td>V</td>
<td>5.0 V</td>
<td>5.0 V</td>
<td>5.0 V</td>
</tr>
</tbody>
</table>

#### NOTES

1. The axis of spatial distribution are typically within a 10° cone with reference to the central axis of the device.
2. The leads of the device were immersed in molten solder, at 260°C, to a point 1/16 inch (1.6 mm) from the body of the device per MIL-S-750, with a dwell time of 5 seconds.

[END WHOLE LAB]