**Lab 5: Resistance, current, and circuits**

You will complete four related investigations.

**PART A:**
- Build resistor circuits on circuit board, investigating current flow and voltages.

**PART B:**
- Measure resistance and determine resistivity of last week’s conductive paper.

**PART C:**
- Measure voltages and current flow in an extended medium (conductive paper).

**PART D:**
- Use the ideas of current flow in an extended medium to understand how an electrocardiogram obtains information about the heart through measuring the effects of currents in a living (conducting) body.

**Why are we doing this?**

So you can understand basic ideas about current, resistance, voltage, and electric fields in conductors and simple circuits, and so you see how to extend these ideas to more complicated systems that you might actually come across someday.

**What should I be thinking about before I start this lab?**

You should be thinking about what you have learned about work, electric potential energy, electric potential, and electric fields. Because in this lab you set up situations in which charges are continuously moving in conductors between points of different potential, and so something is doing work. You will see that this something is the “power supply”. That’s why it is called a power supply (or voltage supply), and why it needs to be plugged into the wall!

You might also be thinking that this contradicts the statement that a conductor in equilibrium has the same potential everywhere, and zero electric field. If the electric field is zero, why are the charges moving?
A. Resistor Circuits

Resistor circuits are made of two different types of conductors connected together, “wires” and “resistors”. Charges flow continuously through these conductors, so there are electric fields in the conductors, and the electric potential is not constant in them. These conductors are not in equilibrium.

The charge flow (current) is sustained by a voltage (power) supply. This supplies charge to the circuit, and drives it around the circuit. Ohm’s law says that the electric potential difference (voltage drop) between two ends of a conductor is proportional to the charge/unit time (current) flowing through it, \( V=IR \), with \( R \) the resistance.

A “wire” has very low resistance, so that the voltage drop across it is extremely small. A “resistor” has a larger, measurable, voltage drop.

You build circuits by plugging in elements to the circuit board shown below.

Holes connected by black lines are electrically connected by conducting wires, so all points connected by black lines are at the same electric potential. You build a circuit by plugging in resistors across the gap between crosses. The resistors are built into plastic blocks with banana-plug connectors that exactly bridge the gaps. After you plug in a resistor, there will still be unused holes in each cross. You will use the remaining holes to connect the variable voltage source to supply your circuit with charge, and to connect the digital multimeter to measure potential differences and currents at various points in the circuit.
1) Measuring current and voltage. Build the circuit below.

The digital multimeter (DMM) can be configured to measure current, voltage, or resistance. Here you want to measure current. Press the ‘A’ button for amps, then ‘2m’ for a 2 mA scale. The DMM now acts as an ammeter, and it displays how much current flows through it. In this mode it is very low resistance. So it acts like a connecting wire while measuring current, and doesn’t alter the properties of the circuit. Current flowing into the red terminal of the DMM and out of the black terminal gives a positive reading on the display.

Set the voltage supply to 10V: what is your measured current?

Which way do the electrons move?

How much work is done by the power supply to move one electron around the circuit?

Which way does the current flow out of the voltage source?
2) Now you will add a 10 KΩ resistor as shown below, and measure the current. Before you do this, predict your measured current in the space below. Remember Ohm’s law, and that wires have zero voltage drop across them.

Now build the circuit below. Here the ‘wire’ is a plug-in block that is a metal conductor.

What is your measured current?

Explain whether this agrees or disagrees with your prediction.
3) Voltage drops around the circuit, and measuring current with voltage drops. In part 2) you saw that the DMM can measure current directly, but it must be inserted in the path of the current so that current can flow through it. This makes it difficult to quickly probe current in different parts of the circuit.

If you press the ‘V’ button, the DMM will display the electric potential difference between its red and black terminals. In this mode, almost no current at all flows through the DMM – it acts like an extremely large resistor while measuring voltage.

Explain how you use the DMM to measure the current through a resistor by measuring electric potential difference (voltage drop) between the two ends of the resistor.

Now make the circuit below

Use the voltmeter to determine the current through each of the 10 KΩ resistors by measuring voltage drops. Write the current below.

Current through R1: 
Current through R2:
In the next step you will put a 10 KΩ resistor (call it R3) in parallel with R2. But before making the circuit, predict whether currents through R1 and R2 will increase or decrease.

Current through R1:  
Current through R2:  
Explain:

Now build the circuit below, and determine the voltages and currents.

Voltage across R1:  
Current through R1:  
Voltage across R2:  
Current through R2:  
Voltage across R3:  
Current through R3:  
Voltage across wire block:  
Current through wire block  

Explain how this agrees or disagrees with your prediction.

Explicitly verify that current is conserved at the node indicated above by showing that the current flowing into the node is the same as the current flowing out.
B. Resistivity and current flow

In part A of the lab, you looked at how resistors acted in series and parallel in electric circuits. In that case, there was only a certain path the current could take, namely through the resistors, and along the wires joining the resistors.

But most times things are more complicated. For instance in last week’s lab where you measured electric fields, the conducting sheet was like a resistor spread uniformly over a page of paper. You attached voltage leads, and current flowed throughout the page.

And you thought you were measuring electric fields!

Well in fact you were. An electric field in a conducting medium causes a current to flow. This happened in the conducting sheet, and in the circuits of part A) but it also happens in three-dimensional conducting media such as your body. For instance, ECG electrodes measure electric potential differences between different locations on the surface of your body. These are induced by currents flowing in your body generated by charges and electric potentials on your heart.

1) First you generate a current flow in the conducting paper. You can think of the conducting paper as a network of equal resistors of resistance \( r \) connecting each cross on the paper, as shown below. The ends are connected together by the very low resistance silver conducting bars drawn on the sheet. Indicate on the drawing below where you think the current will be flowing.

![Diagram of a grid of resistors](image.png)

Use the field-plotting board to connect the voltage supply across the silver bars, and probe with the DMM to measure the direction of the current at various places in the strip. (Remember that the current density is in the same direction as the electric field, and that \( \Delta V = \vec{E} \cdot d\vec{s} \)). Make sure there is no conducting material underneath the strip.

a) Measure the currents in the vertical and horizontal resistors? How do they compare?
2) Now measure the resistance of the various strips of conducting papers. They have silver electrodes painted along the edges to guarantee uniform current flow. Their thickness is 0.005 inches = 0.0127 cm. You use the multimeter on the ohms setting to measure the resistance, so you don’t need the voltage supply or the field-plotting board.

<table>
<thead>
<tr>
<th>Thickness (cm)</th>
<th>Width (cm)</th>
<th>Length (cm)</th>
<th>Resistance (Ω)</th>
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3) All the strips are made of the same material, but not all have the same resistance. This is because they have different geometrical shapes. In this part you determine the resistivity of the conducting sheet, which is independent of the shape.

Model the conducting paper as a network of resistors as shown previously, one connecting each cross on the conducting paper, and connected together at the ends by the silver bars painted on the strips.

a) Would the resistance increase or decrease if you were to make the strip wider by adding a row of resistors. Explain.

b) Would the resistance increase or decrease if you were to make the strip longer by adding a column of resistors. Explain.
c) Write down an expression for the resistance $R$ of the conducting sheets in terms of the number of resistors wide $N_w$ and the number of resistors long $N_l$, and the modeled resistance $r$ between crosses.

d) From your measured resistances in the previous table, determine the value of the resistance $r$. This $r$ should be the same for all sheets.

e) But don’t forget about the thickness. A twice-thicker sheet would have half the total resistance $R$, and half the $r$.

The resistivity, related to the imaginary resistors connecting the crosses as $\rho = rT$, is intrinsic to the material — it doesn’t depend on the thickness $T$.

Calculate the resistivity of the conducting paper in ohm-centimeters.

f) Write down an expression relating the resistance $R$ and the resistivity $\rho$ in terms of the length, width, and thickness of the conducting sheets. This is valid when the current flow is uniform.
C. Nonuniform current flow

1) In many situations, the current flow is not uniform. The position and shape of the silver-painted electrodes in part B) enforced uniform current flow by making the left and right edges of the paper equipotentials. Here you set up a more common situation, where the current flow is nonuniform. Imagine a sheet of conducting paper with two silver dots painted on it.

The configuration above is usually called a dipole, because the electric potentials in an infinite sheet are the same as that due to a charge dipole at the same location. The current flow is very nonuniform, as are the electric fields.

To answer the following questions, think about the currents, the electric fields, and the electric potentials. You will use these answers in the next section.

What will be the electric potential difference $V_A - V_B$?

How does the electric potential difference $V_C - V_D$ compare to $V_E - V_F$?

How are these related to the direction of the “dipole” moment?
Your heart is embedded in a conducting medium (your body), and is electrically active. This causes currents to flow in your body, and electric potentials develop throughout your body. An electrocardiogram measures potential differences at various points on the surface of your body, and tries to figure out what is happening at your heart.

In this section you set up a signal inside the conducting sheet, and try to get some information by looking at potential differences on the outside. This is very similar to the way that an electrocardiogram obtains information about your heart.

In a first approximation, the electrical activity of your heart can be characterized as an electric dipole, with a potential difference between the two poles. The electrocardiogram is trying to determine the orientation of a dipole in your heart by making measurements on the surface of your body.

How can a heart be a “dipole”?
When your heart beats, it establishes a very complicated charge and potential distribution that changes in time as different parts of the heart are stimulated. This is done by moving around positive and negative charge.

The total charge is always zero, just rearranged, so a dipole is a good approximation. The ‘fine-tuning’ charge distribution that differentiates the actual distribution from a dipole is not very important. It generates a potential that dies away rapidly as you move away from the heart. So from far enough away, the currents and potentials in the body due to the heart are indistinguishable from those produced by a dipole.

Here is a picture of the heart dipole at an instant 240 ms into the heartbeat, and a plot showing the tip of the dipole vector as a function of time (dotted path). The heart dipole changes both direction and magnitude during the heartbeat.
The three main leads of an electrocardiogram are usually called I, II, and III. These all give different views of the heart dipole.

Lead I: potential difference $V_{LA} - V_{RA}$
Lead II: potential difference $V_{LL} - V_{RA}$
Lead III: potential difference $V_{LL} - V_{LA}$

Download the Lab 5 settings file from the “Laboratories” page of the Physics 208 course web site. This should open DataStudio with the correct data acquisition settings.

You will use
- Input A of the Pasco interface for Lead I
- Input B of the Pasco interface for Lead II
- Input C of the Pasco interface for Lead III

Connect the 30V output of the DC power supply to the black and red probes. Connect a banana plug cable from the red terminal of red probe to the 30V red connection, and from the red terminal of the black probe to the 30V black connection. Do not connect anything to the black terminal of either probe.

Before you take data, set the voltage supply to 10V. This is your heart in its resting state.

Now have one of your lab group hold the probes to supply voltage to one of the (+,-) pairs of silver dots at the heart as labeled above. The voltage supply will simulate the heart potential.

Click ‘start’ on data studio, and use the knob on the voltage supply to increase the voltage to 20 or 25 volts, then back down again to 10V, to simulate a heartbeat (ba-bump!). Do this several times, and watch the traces on the screen.
Then use the other (perpendicular) (+,-) pair of dots, and take another set of ECGs.

For the two different orientations of the heart dipole at the center, measure the height (positive or negative) of the voltage signal signal for leads I, II, and III.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Lead I</th>
<th>Lead II</th>
<th>Lead III</th>
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</thead>
<tbody>
<tr>
<td>#1</td>
<td></td>
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To generate your data, you used a fixed heart dipole direction, and varied the magnitude of the dipole by turning the knob on the power supply. You also used a different dipole direction (~ perpendicular to the first one) that gave a very different set of ECG traces.

You obviously know the dipole directions you used for the two different data sets. But suppose you didn’t know, and you needed to use the ECG traces to determine the dipole direction and magnitude (pretend you are a cardiologist). For each of your data sets, use your work in part C) to qualitatively determine the direction and magnitude of the heart dipole. Print out your ECGs if it is easier for you to analyze them that way.

Explain in the space below how you used the ECG data to determine the dipole direction. Here are some questions to help you think about the problem.

Suppose one of the ECG leads gives a very small signal. How can you tell if this is because the dipole has a small magnitude, or because it has a particular orientation?

Suppose two ECG leads give almost the same voltage signal. What does this mean about their orientation relative to the dipole?

Suppose two ECG leads have the opposite sign of signal. How must the dipole be oriented?