PHY 252 Introductory Physics Laboratory II

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Experiments

Experiment 1

Equipotential and Electric Field Mapping

1.1 Objectives

1. Determine the lines of constant electric potential for two simple configurations of oppositely charged conductors.
2. Determine the electric field from lines of constant electric potential.
3. Set up an elementary circuit.
4. Measure the voltage in a circuit with a multimeter.

1.2 Introduction

We are surrounded by electric fields in our daily life. Electricity plays an essential role in the global economy, but we cannot sense small amounts directly, and sensing large amounts of it is a shocking experience. For small amounts of electric fields, we use tools to measure them. One tool is a multimeter, which can be set to measure many different aspects of electricity.

1.3 Key Concepts

In case you don't remember your PHY232 lecture material, you'll need to refer to the chapters in your text on Electrostatics and Electromagnetic Fields. As always, you can find a summary on-line at HyperPhysics[1]. Look for keywords: Coulomb's Law, Electric Field, Voltage, Work

Key concepts can be a part of a quiz and you'll really need to know them in order to succeed in this lab. Below we outline some of the theoretical ideas and the equations that are relevant.

To explore the relationship between electric charges, the electric fields they produce, and equipotential lines, you can play with a simulation from the University of Colorado.[2]

1.4 Theory

Force between 2 point charges

To understand where the concept of an *electric field* comes from, let's start with one of the simplist electric systems: two point charges, q_1 and q_2, separated by a distance r. The force that they exert on each other, F_E, is given by Coulomb's Law,

$$F_E = \frac{1}{4\pi\epsilon_0}\frac{q_1\, q_2}{r^2}. \tag{1.1}$$

If the charges were electrons, then $q_1 = q_2 = -e$, where e is the elementary charge. The force on one of the electrons is thus

$$F_e = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r^2}, \tag{1.2}$$

Negative charges repel other negative charges, so these electrons repel each other. If we want to hold those two electrons at that constant distance r, we must balance the repelling forces by exerting an equal force inward, a bit like a spring.

[1] http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

[2] http://phet.colorado.edu/sims/charges-and-fields/charges-and-fields_en.html

Electric potential

If we push them together, we must act against the force of these charges. Let's figure out how much energy we have to expend (how much *work* we must do) to get them closer to one another. According to the *work-energy theorem*, if one component in a closed system pushes or pulls on other components, those other components gains or loses energy. In this case, the energy of our pushing is "stored" as potential energy in the 2-electron system. Thus, the force between objects is related to the potential energy they have. Notice that if we push the electrons to be half as distant from one another ($r' = \frac{1}{2}r$), then the force to keep them there is 4 times as much.

To find that potential energy from knowing the force, recall that

$$W = F\,\Delta s. \tag{1.3}$$

That is, work is equal to the force F exerted times the distance Δs over which that force was exerted. That formula is pretty easy when the force is constant, like if you were pushing a sled at a constant velocity across a uniform surface (with constant friction). The force that you exert at any location is the same. On the other hand, Eq. 1.1 says that the force between two charges changes with distance. That makes the work equation, Eq. 1.3, very difficult to use without applying math that goes beyond the scope of this course.[3]

If we do the fancy math involved, we find that the potential energy U of a charge q_1 due to a charge q_2 that is r away is

$$U = \frac{1}{4\pi\epsilon_0}\frac{q_1\,q_2}{r} \tag{1.4}$$

Now we have the electric potential energy, the energy that an object has due to its position relative to a system of electric charges.

You may think we're already done - we set out to find the electric potential, right? Well, it turns out that "electric potential energy" is not the same as "electric potential". Physicists want to know what the potential field is of a charge q_1 without worrying about the amount of charge on q_2. So they made up the **electric potential** V, which is just the electric potential energy divided by q_2, the charge that is feeling the force:

[3] If you know how to do integration, the general work equation is $W = \int_a^b F\,\mathrm{d}s$, where $\mathrm{d}s$ is the differential length. You may find an extra factor of 2 compared to Eq. 1.4, because this energy is divided between the two charges.

$$\begin{aligned} V &= \frac{U}{q_2} \\ &= \frac{1}{4\pi\epsilon_0}\frac{q_1\, q_2}{r}\frac{1}{q_2} \\ &= \frac{1}{4\pi\epsilon_0}\frac{q_1}{r} \end{aligned} \tag{1.5}$$

Notice that the electric potential of a charge is independent of the charge used to measure it. So now if someone asks you what the electric potential is of a charge, you can answer them, without needing to know what they're measuring it with. In other words, instead of saying, "the electric potential energy of q_2 due to q_1," you can say, "the electric potential due to q_1". And if you draw a map of how much the electric potential is at different points, you can draw **equipotential lines** that connect all the points that have the same potential.

Electric field

Now we want to place a charge in an electric potential field and find out how much it is pushed and in what direction. To do this, visualize the potential field like a hill. The greater the potential, the higher the elevation. If we put a ball on the side of a hill, it will roll downward, from a higher to lower potential. Similarly, a positive charge will act the same way. If you walk along the side of the hill, without going up or down the hill, it is analogous to walking along an equipotential line. The steeper the hill, or the greater the change in potential over a certain displacement, the faster the ball (charge) will accelerate. This change in electric potential over a certain displacement is called the **electric field**. With a formula, the magnitude of the electric field E is given by

$$|E| = \frac{|V_1 - V_2|}{\Delta s} \tag{1.6}$$

Finally, to visualize the direction that the charge is pushed, we need only to draw a line that follows the "hill" of potential from high to low. That line is called an **electric field line**. Notice that since the equipotential lines run along the side of the hill, and the electric field lines run down the hill, they are perpetually perpendicular to one another. Note that both lines can and often do curve; at each point in space, the electric field line at that point is at a right angle to the equipotential line at that point.

1.5 In today's lab

In this experiment we will measure the electric potential in the vicinity of two different charge distributions and use that measurement to find the electric field.

Each charge distribution will consist of two metal objects mounted on conductive paper. We consider metals to be ideal conductors (same electric potential everywhere on the metal). If we wave the potential probe in the air between the conductors, we would not read any potential. This is because air is a very effective insulator and so electrons don't flow through it. On the other hand, the conductive paper is partly conductive, allowing us to travel partway down the "voltage escalator". Thus, the electric potential depends on the location of the point on the paper.

1.6 Equipment

- DC power supply (Fig. 1.1)
- Digital multimeter (Fig. 1.2)
- Conducting paper with charge distributions (Fig. 1.3)
- 2 grid sheets (graph paper) with 1 cm squares
- 3 banana-to-banana wires ("banana" is the term for a kind of plug on the end of a wire)
- 1 banana-to-probe wire (the probe is a plastic handle with a sharp metal point sticking out of it)

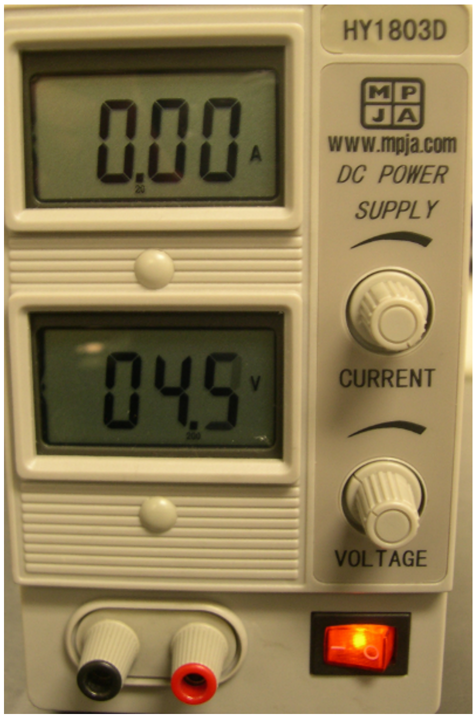
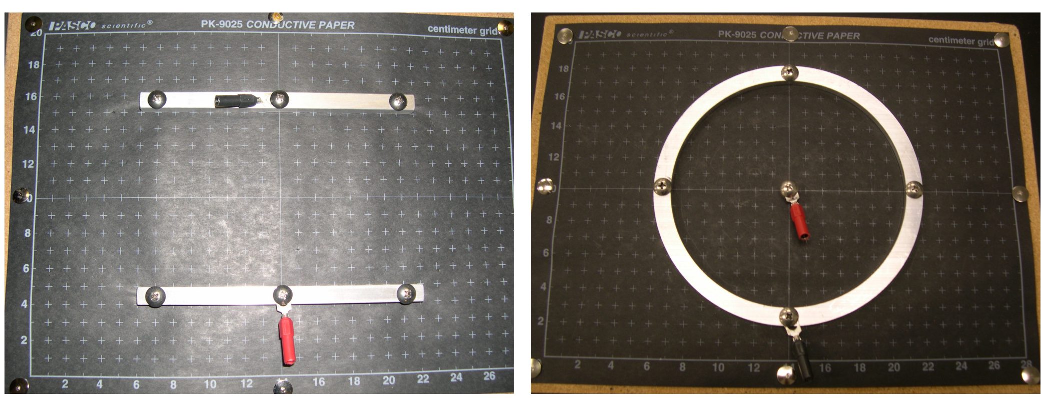


Figure 1.1: DC power supply

Figure 1.2: Digital multimeter



(a) Parallel plates.

(b) Ring and point.

Figure 1.3: Conductors mounted on semi-conductive paper.

1.7 Procedure

Safety Tips

- When plugging or unplugging wires, first **turn off all electronics that are connected** or will become connected to the circuit.
- When using the potential probe, **do not press hard** enough on the paper to make a dent or hole.

Two parallel conducting plates

The first distribution will consist of two parallel bars (or plates), seen in Fig. 1.3(a). This can be thought of as a 2D model of a parallel plate capacitor. A schematic of the parallel plate experiment is shown in Fig. 1.4. In this configuration, one of the two plates will be electrically connected to the positive terminal of the power supply and held at a constant positive electric potential. The other plate will be electrically connected to the negative terminal, or the "ground", of the power supply. All electric potentials are measured with respect to this electric potential (i.e. $V_{\text{ground}} = 0$ V). The ground terminal of the power supply will also be connected to the ground, or COM port of the multimeter. The probe used to measure the electric potential is connected to the "V" port of the multimeter.

1. **Setup:**

   a) Sketch the two conducting plates on a grid sheet provided by your lab instructor. *Each lab partner will turn in their own copy of the grid sheet.*

   b) Use a banana-to-banana wire to connect one of the parallel plates to the positive (red) terminal of the power supply.

   c) Use a second banana-to-banana wire to connect the second plate to the negative (black) terminal of the power supply.

   d) Connect the COM port of the digital multimeter to the negative terminal of the power supply using a third banana-to-banana wire.

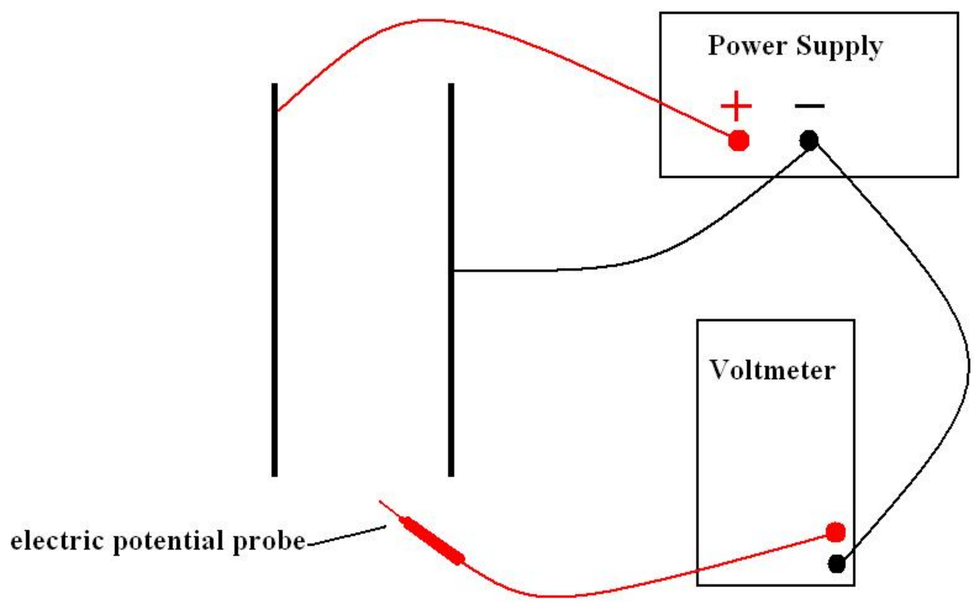


Figure 1.4: Schematic of experimental setup for parallel plates.

e) Connect the electric potential probe to the "V" port of the digital multimeter.

   Your setup should now look something like Fig. 1.5.

f) Adjust the power supply to an electric potential of 10 V.

g) Set the digital multimeter to measure DC electric potential (voltage) and press the "RANGE" button on the multimeter until the meter reads electric potential to the nearest tenth of a volt.

2. **Measure electric potential.** Use the electric potential probe to find at least six points having the same electric potential in the region between the plates (region A in Fig. 1.6) and record these points on your grid sheet. Then, find four points extending beyond the region of the plates having that same electric potential (two points in each region B shown in Fig. 1.6).

3. **Draw equipotential line.** Use a pencil to draw a smooth curve/line that intersects all of the points in Step 2.

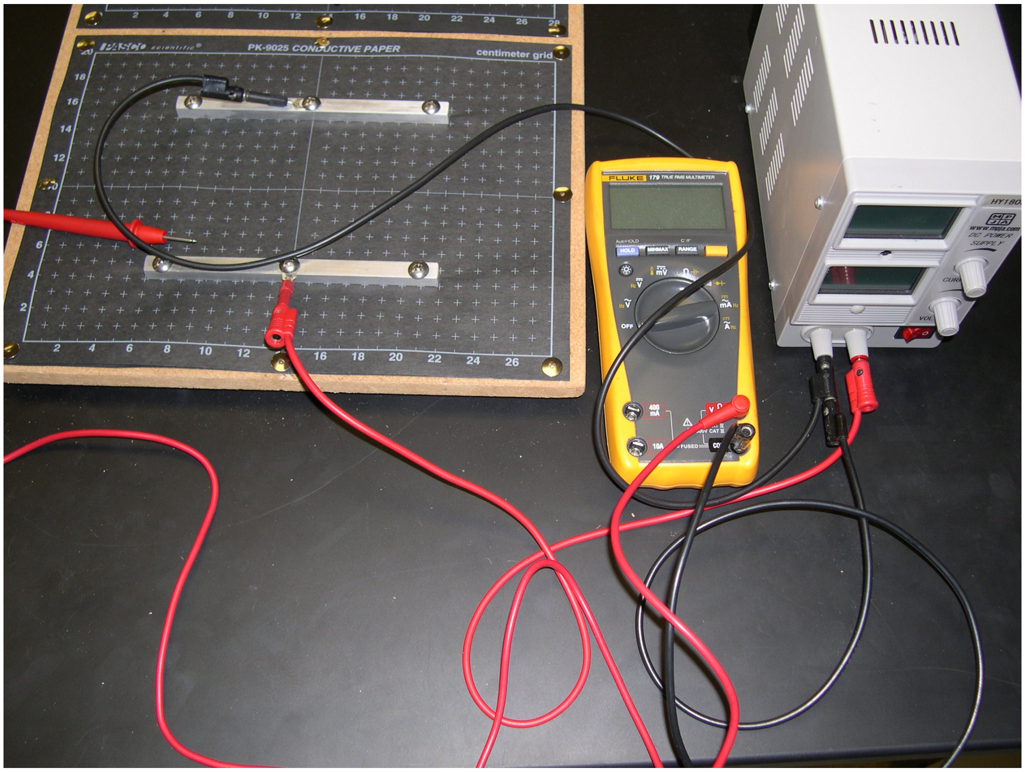


Figure 1.5: Photo of completed setup for the parallel plates.

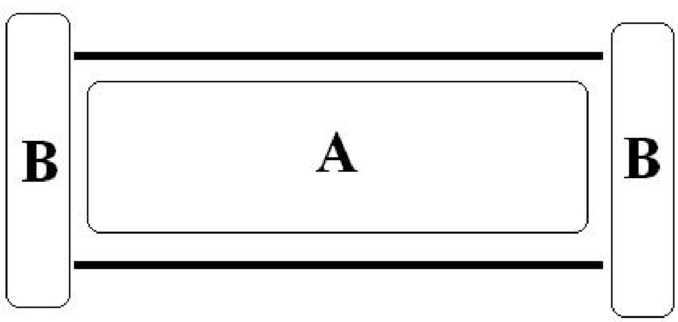


Figure 1.6: Regions near the parallel plates. Note that region A is between the two plates and region B is beyond the ends of the plates.

4. Repeat Steps 2 and 3 for at least two additional electric potentials.

5. Measure the distance s_{plates} between the parallel plates and assign a reasonable uncertainty to this measurement. Use this measured distance and the 10.0 V electric potential difference between the plates to calculate the electric field between the plates and its uncertainty (Question 1).

6. Measure the distance s_{lines} between two of your lines of equipotential; calculate the difference in electric potential between these two lines; calculate the electric field and its uncertainty using these measured values (Question 2).

7. **Draw electric field lines.**

   a) Draw and label at least eight electric field lines. You should include some near the edges of the parallel plates in region B.

   b) Indicate the direction of the electric field with an arrow on each of your electric field lines.

Ring and point

The second charge distribution will be a point source at the center of a ring. A schematic of this arrangement is shown in Fig. 1.7.

1. **Setup:**

   a) Sketch the ring and point on another grid sheet provided by your lab instructor. To help draw the ring, there is a spare ring in the lab that you can trace.

   b) Use a banana-to-banana wire to connect the point at the center of the ring to the positive (red) terminal of the power supply.

   c) Use a second banana-to-banana wire to connect the ring to the negative (black) terminal of the power supply.

   d) Connect the COM port of the digital multimeter to the negative terminal of the power supply using a third banana-to-banana wire.

   e) Connect the electric potential probe to the "V" port of the digital multimeter.

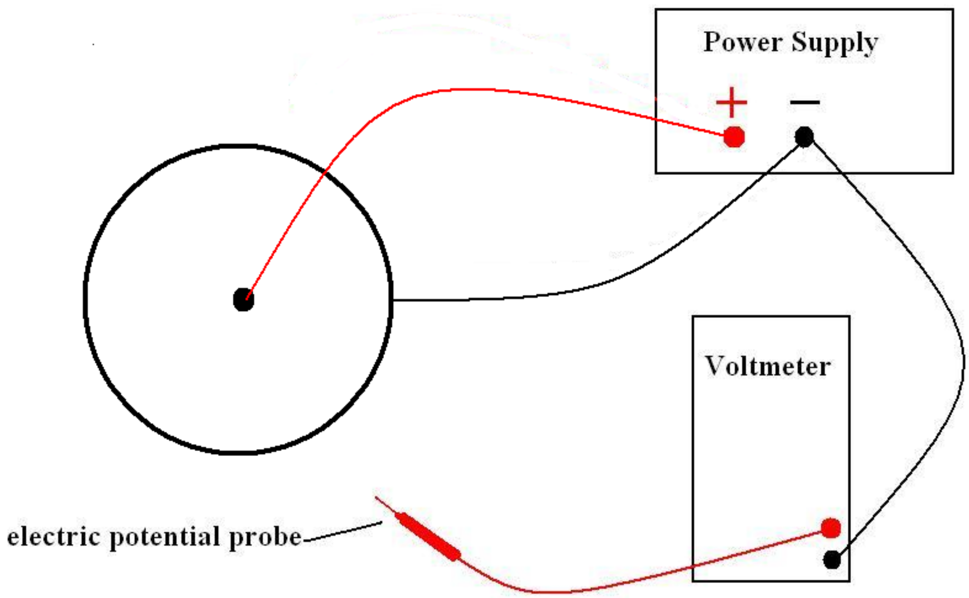


Figure 1.7: Schematic of experimental setup for point charge in ring.

f) Adjust the power supply to an electric potential of 10 V.

g) Set the digital multimeter to measure DC electric potential (voltage) and press the "RANGE" button on the multimeter until the meter reads electric potential to the nearest tenth of a volt.

2. **Measure electric potential.** Use the electric potential probe to find at least eight points having the same electric potential inside the ring. Record these points on your grid paper.

3. **Draw equipotential line.** Use a pencil to draw a smooth curve/line that intersects all of the points in Step 2.

4. Repeat Steps 2 and 3 for at least two additional electric potentials.

5. Draw and label the electric field lines (at least eight of them). Indicate the direction of the electric field with an arrow on each of your electric field lines.

1.8 Questions

1. Use the electric potential difference between the two parallel plates and Eq. 1.6 to calculate the magnitude of the electric field between the plates. In addition, calculate the uncertainty in the electric field. See Eq. A.2 to reference how to propagate uncertainty through a division of two values, or you can use the formula here: $\delta E = E\left(\left|\frac{\delta V}{V}\right| + \left|\frac{\delta s}{s}\right|\right)$.

   Electric potential between the plates: $V \pm \delta V =$

   Distance separating the plates: $s_{\text{plates}} \pm \delta s_{\text{plates}} =$

Your calculated magnitude of the electric field: $E \pm \delta E =$

2. Use the electric potential difference between two of your equipotential lines (between the parallel plates and not near the edge of the plates), the distance separating these two lines and Eq. 1.6 to calculate the magnitude of the electric field between the plates. In addition, calculate the uncertainty in the electric field. Do not use the plates themselves as the equipotentials in this question and show your work.

   Electric potential between the equipotentials: $V \pm \delta V =$

Distance separating the equipotentials: $s_{\text{lines}} \pm \delta s_{\text{lines}} =$

Your calculated magnitude of the electric field: $E \pm \delta E =$

3. Compare your results for the electric field obtained in Questions 1 and 2 using uncertainties. (If you have forgotten how to compare two values using their uncertainties, see Appendix A.3). Are your results consistent?

4. Given your answer to Question 3, how does the electric field inside the plates change with position (look at region A, not region B, of Fig. 1.6)?

5. Is the metal ring itself an equipotential? This should be verified by measurement. What did you do to make this measurement?

6. Now think about the region of space outside the circular ring in the second part of the procedure.

   a) Predict the magnitude of the electric field in the region outside the circular ring. Justify this prediction.

   b) Test your prediction experimentally and describe what you did. Was your predict accurate?

Experiment 2

Ohm's Law

2.1 Objectives

- Become familiar with the use of a digital voltmeter and a digital ammeter to measure DC voltage and current.
- Construct a circuit using resistors, wires and a breadboard from a circuit diagram.
- Construct series and parallel circuits.
- Test the validity of Ohm's law.
- Reduce a complicated resistance circuit to a simple one-resistor equivalent circuit.

2.2 Introduction

In the US, most of us use electricity every day. That electricity is handled in circuits, a closed loop of conductors travelling from power plants to neighborhoods to households and back again. That closed loop, with all of its many parts, forms one huge electrical circuit. Today we'll use the 3 essential parts of a circuit – power supply (or battery), wires, and resistors. We'll learn how resistors affect the current of electrons that flows through them, and how connecting resistors in different ways changes their behavior.

2.3 Key Concepts

As always, you can find a summary on-line at HyperPhysics[1]. Look for keywords: electricity and magnetism, ohm's law, resistor, resistor combinations

To play with constructing circuits and actually see how the electrons flow through a circuit, check out the online simulation "Circuit Construction Kit"[2] from the University of Colorado.

2.4 Theory

One of the fundamental laws describing how electrical circuits behave is **Ohm's law**. According to Ohm's law, there is a linear relationship between the voltage drop across a circuit element and the current flowing through it. Therefore the resistance R is viewed as a constant independent of the voltage and the current. In equation form, Ohm's law is:

$$V = IR. \tag{2.1}$$

Here, V is the voltage applied across the circuit in volts (V), I is the current flowing through the circuit in units of amperes (A), and R is the resistance of the circuit with units of ohms (Ω).

Eq. 2.1 implies that, for a resistor with constant resistance, the current flowing through it is proportional to the voltage across it. If the voltage is held constant, then the current is inversely proportional to the resistance. If the voltage polarity is reversed (that is, if applied voltage is negative instead of positive), the same current flows but in the opposite direction. If Ohm's law is valid, it can be used to define resistance as:

$$R = \frac{V}{I}, \tag{2.2}$$

where R is a constant, independent of V and I.

It is important to understand just what is meant by these quantities. The **current** (I) is a measure of how many electrons are flowing past a given point during a set amount of time. The current flows because of the

[1] http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html
[2] http://phet.colorado.edu/en/simulation/circuit-construction-kit-dc

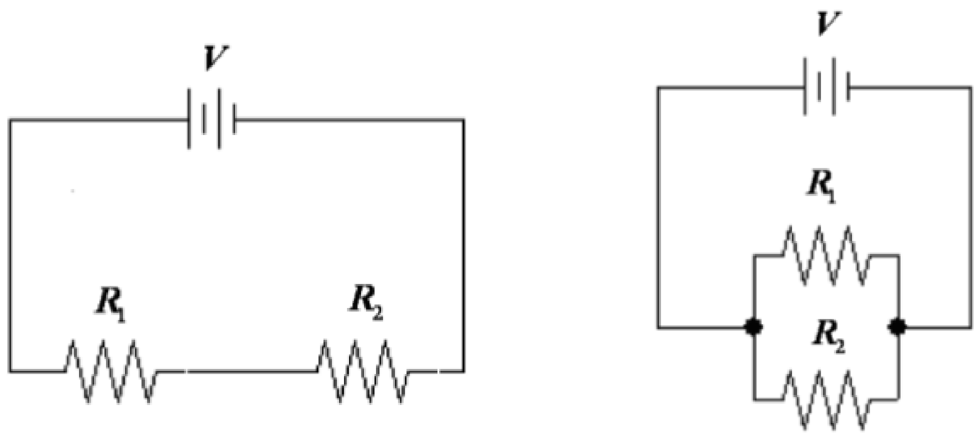
electrical potential (V), sometimes referred to as the **voltage**, applied to a circuit. In much the same way that a gravitational potential will cause mass to move, the electrical potential will cause electrons to move. If you lift a book and release it from a height (high gravitational potential) it will fall downward (to a lower potential). The electrical potential works in a similar way. If one point of the circuit has a high electrical potential, it means that it has a net positive charge and another point of the circuit with a low potential will have a net negative charge. Electrons in a wire will flow from low electrical potential with its net negative charge to high electrical potential with its net positive charge because unlike charges attract and like charges repel.[3]

As these electrons flow through the wire, they are scattered by atoms in the wire. The resistance of the circuit is just that; it is a measure of how difficult it is for the electrons to flow in the presence of such scattering. This resistance is a property of the circuit itself, and just about any material has a resistance. Materials that have a low resistance are called conductors and materials that have a very high resistance are called insulators. Some materials have a moderate resistance and still allow some current to flow. These are the materials that we use to make resisters like the ones we will use in this experiment. In short, the electrical potential causes the current to flow and the resistance impedes that flow.

Two or more resistors can be connected in series, connected one after another (Fig. 2.1(a)), or in parallel, typically shown connected so that they are parallel to one another (Fig. 2.1(b)). As long as the current must split, go through the resistors and then coalesce, they are in parallel.

When two resistors R_1 and R_2 are connected in series, the equivalent resistance R_S is given by $R_S = R_1 + R_2$. Thus, the circuit in Fig. 2.1(a) behaves as if it contained a single resistor with resistance R_S — that is, it draws current from a given applied voltage like such a resistor. When those resistors are connected in parallel instead, we use a different formula for finding the equivalent resistance. See Table 2.1 for all the necessary equations.

[3] Note that we say the current flows from high poential to low potential, but electrons flow from low to high. This is because current is defined as the flow of *positive* charges, and electrons are *negatively* charged. A negative charge flowing in one direction is like a positive charge flowing in the other. Yes, it's confusing, but we can't make the whole world start calling electrons positively charged, so we're stuck with it.



(a) Series (b) Parallel

Figure 2.1: Schematics of circuits illustrating resistors connected in series and in parallel.

Series	**Parallel**
$V_S = V_1 + V_2$	$V_P = V_1 = V_2$
$I_S = I_1 = I_2$	$I_P = I_1 + I_2$
$R_S = R_1 + R_2$	$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2}$ or $R_P = \frac{R_1 R_2}{R_1 + R_2}$

Table 2.1: Equations for two resistors in series and parallel.

Using these two relationships, a complex circuit can be redrawn as a circuit with a single resistor. You may wish to review the process of finding the equivalent resistance of circuits in your physics textbook.

2.5 In today's lab

Today we'll become accustomed to some standard electrical equipment: we'll figure out how to use the circuit boards, resistors, and wires to create series and parallel circuits. Then we'll learn how to measure the current through a wire, as well as the voltage between two points in a circuit. Finally, we'll verify that the equations that are presented in the theory section are actually correct.

2.6 Equipment

- DC Power Supply (Fig. 2.2)
- 2 digital multimeters (Fig. 2.3)
- breadboard (Fig. 2.6)
- several banana-to-banana wires

Safety Tips

- When plugging or unplugging wires, first **turn off all electronics that are connected** or will become connected to the circuit.
- If you are color blind or suspect that you are, you may find the color codes on the resistors difficult. Please consult your lab instructor for advice or help.

The DC Power Supply

A DC power supply is used to provide varying voltage to a circuit. The power supply used in this lab is shown in Fig. 2.2. The black and red connectors are the negative (−) and positive (+) output terminals, respectively. The voltage knob controls the power supply's output voltage. The current knob sets a limiting current. **Here, adjust the current control to its maximum setting (all the way clockwise) at all times.**

Note: Prior to making any change in the circuit, always turn the voltage knob to its minimum setting (all the way counterclockwise) and turn off the power supply! So the next time you turn on the power supply its output will be zero volts.

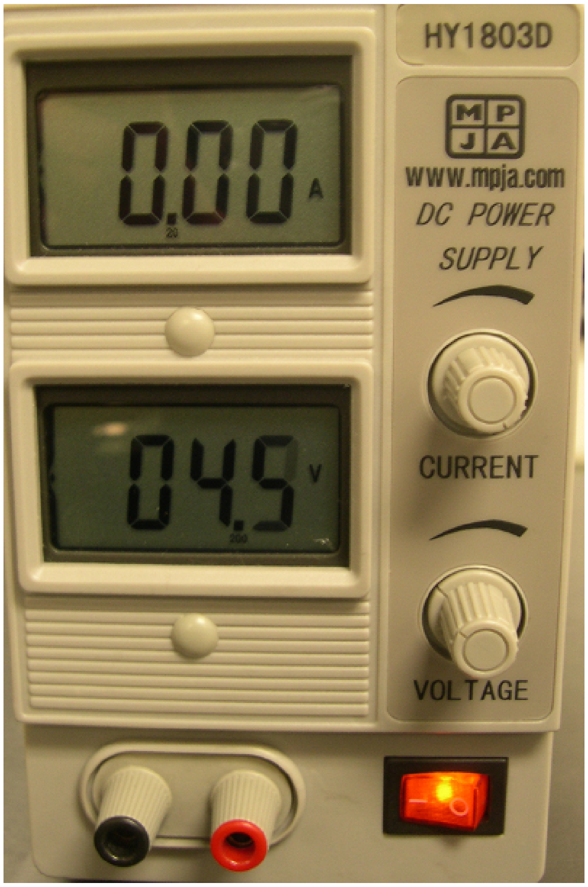


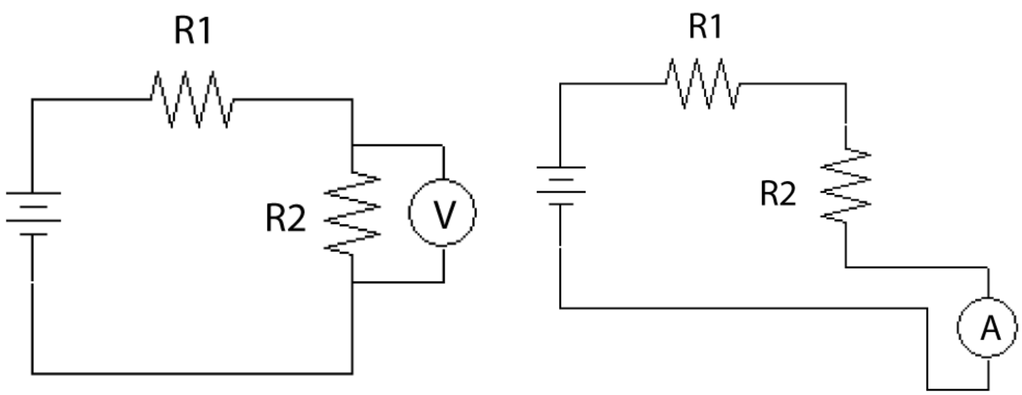
Figure 2.2: DC power supply

Figure 2.3: Digital multimeter

The Digital Multimeter

The digital multimeter is shown in Fig. 2.3. As its name suggests, a multimeter has multiple functions. It can be used for several different purposes, two of which are a voltage measuring device (a voltmeter) and a current measuring device (an ammeter). We will use these functions in this experiment.

To use the multimeter as a voltmeter, the dial selector is set to one of the positions labeled "V". The probing cables are then connected to the plugs labeled "VΩ" and "COM". There are two types of "V" settings. The setting with the tilde (∼) over it is used for measuring AC voltage. The other type of "V" setting has two lines over the V – one line is solid and



(a) Voltmeter connected in parallel (b) Ammeter connected in series

Figure 2.4: Schematics of meters being connected in a circuit.

the second line is dashed this indicates DC voltage. AC is an abbreviation for alternating current. An AC voltage is a voltage whose magnitude and polarity vary with time. DC is an abbreviation for direct current. A DC voltage is a constant voltage. During this experiment, only the DC setting is used. There are two DC voltage settings on the multimeter: "V" and "mV". When using the "mV" setting, the output of the multimeter will be in millivolts. Whether the multimeter is used to measure voltage (as a voltmeter) or current (as an ammeter), one cable is **always** connected to the COM plug. If the multimeter is used to measure current, the other lead is connected to either the 10A plug or the 400mA plug.

A voltmeter must be connected in parallel (across) to the circuit element of interest, as shown in Fig. 2.4(a). Since the voltmeter measures potential difference between two points, it is easy to connect. To measure the potential difference (voltage drop) across a resistor, use two cables to connect the plugs of the voltmeter to the circuit across the resistor (one cable before the resistor and a second cable after the resistor). A voltmeter typically has a very large internal resistance; therefore very little current will flow through it. Consequently, the current in the circuit will be approximately the same before and after the voltmeter is connected.

To use the multimeter as an ammeter, the dial selector is set to one of the positions labeled "A". Similar to the voltmeter settings there are AC and DC settings. Like the voltmeter, two cables must be connected to the ammeter. One of your cables MUST be connected to the plug labeled "COM". The second cable can be connected to one of two possible plugs —- either the "10A" plug or the "400mA" plug. If you have a large amount of current (anything above 400 mA), you **must** connect the cable to the terminal marked "10A". If you put it in the "400mA" terminal you could damage the multimeter. If you are unsure if you have too much current for the 400 mA plug, start with the 10A plug. If you do not get any reading at all (i.e. 0.00), you have a very small current and can then move the cable to the 400 mA plug.

An ammeter must be connected in series with the circuit element of interest, as shown in Fig. 2.4(b). This means that unlike measuring voltage, if you want to measure current you must break the circuit and wire the ammeter in. All of the current must flow through the ammeter in order for it to be measured. If you use your finger to trace the path of a charge in Fig. 2.4(b) after it leaves the power supply, you will see that it must go through both the resistor **and** the ammeter. In contrast, tracing the path of a charge in Fig. 2.4(a) you will see that it has two "parallel" paths through which it can go (do not connect an ammeter in this manner). An ammeter typically has a very small internal resistance. Therefore, the current in the circuit is approximately the same before and after the ammeter was connected, and you won't measure any current.

Standard electronic symbols are shown in Fig. 2.5. The positive side of a battery or power supply is indicated with the longer vertical line.

The Breadboard

The breadboard is designed for quick construction of simple electronic circuits and is shown in Figure 2.6. Electronic elements (e.g. resistors) are easily attached using the metal spring clips in the middle of the breadboard. Each metal clip is electrically connected to a plug connector by a metallic strip. The resistance between the metal clip and the plug connector is negligible; therefore, you can assume that these two points are at the same electrical potential (voltage) and the same point in a circuit. Circuits are constructed by connecting the electronic circuit elements and the power supply together using cables with banana plugs. The banana plugs fit securely into the plug connectors on the breadboard, the multimeter and the power supply.

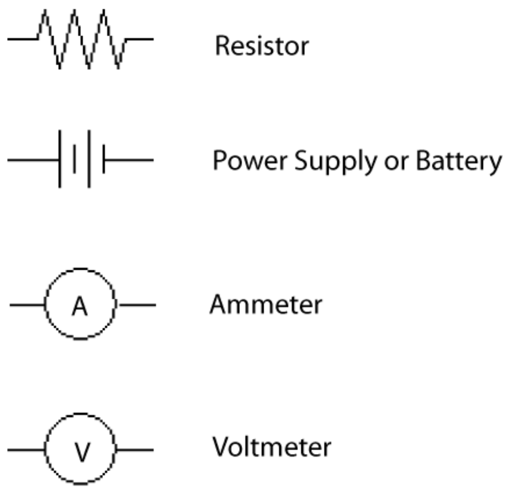


Figure 2.5: Standard symbols

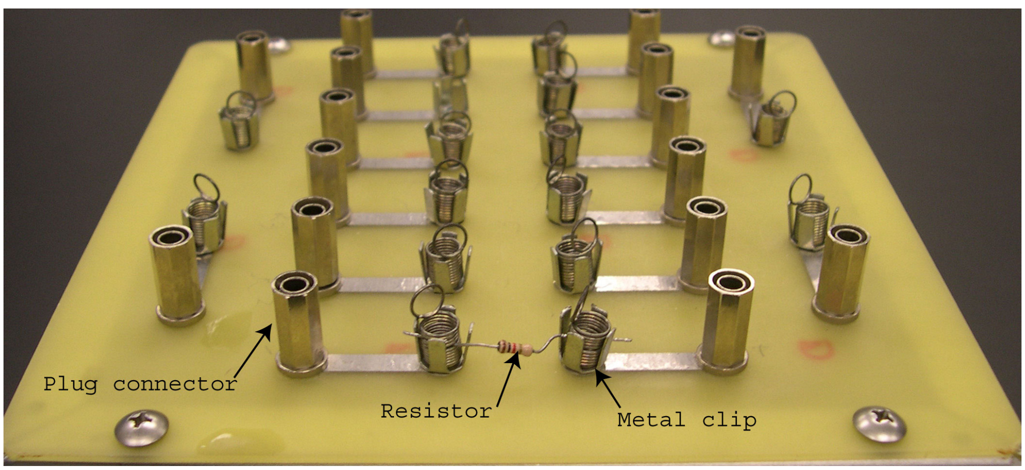


Figure 2.6: Breadboard

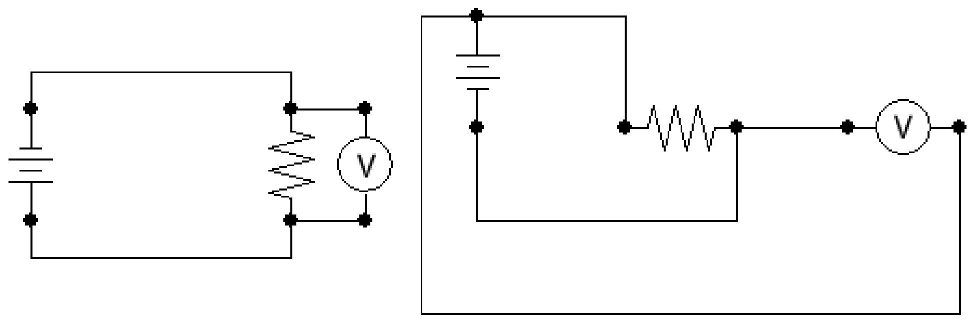


Figure 2.7: These two circuits are equivalent — they have the same configuration of elements and will act in exactly the same manner.

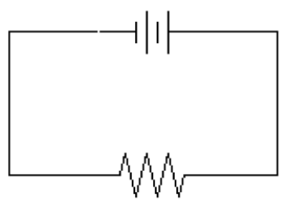
Wires

You will have to hook up wires to make the circuits described in the circuit diagrams. Each line without any circuit element should correspond to a wire in your circuit. A wire (or line in the diagram) represents a path where current can flow.[4] **All points on a wire/line have the same voltage.** Because of this, a circuit may be realized by several different arrangements of wire. For example, see Fig. 2.7.

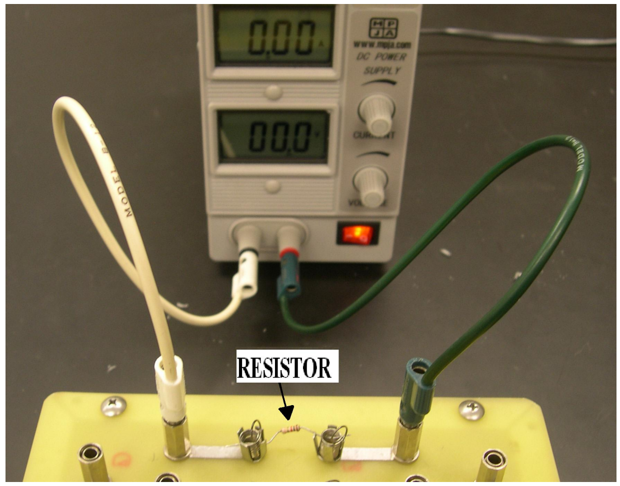
Suggestions for building circuits

The schematic representation of electronic circuits typically shows wires as straight lines and changes in the direction of the wires are indicated by abrupt bends in the wires. In practice, the flexible wires are not straight and as you might expect changes in direction are not abrupt 90 degree bends in the wires. Adding measuring devices (e.g. ammeters, voltmeters) to the circuit increases the circuit's complexity. The following steps will

[4]A wire is actually a resistor with very low resistance compared to the resistors we typically use in class. Therefore, we can usually neglect (ignore) any resistance that it has. On the other hand, this resistance is a big factor in long-distance electrical transmission lines, since there is so much wire involved.



(a) Schematic



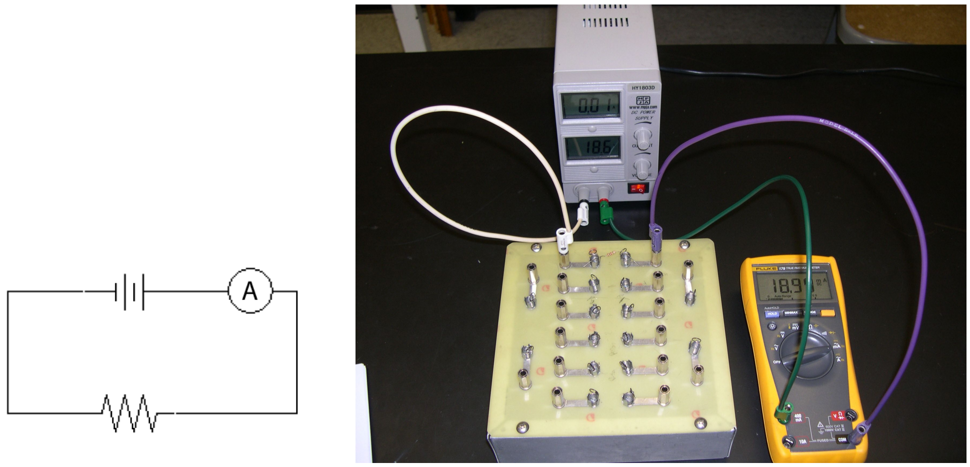
(b) In practice

Figure 2.8: Building a circuit that includes a power supply and resistor.

guide you through the construction of a simple circuit that includes an ammeter and a voltmeter. To avoid confusion, all of the wires used in the following example have different colors. The figures in this guide show both the circuit represented schematically and how the circuit actually looks in practice.

1. **Start by building the circuit without any meters.** Where two lines meet, you will need two wires. Although it may seem efficient to initially construct the circuit with the meters included, experience has shown that this method often leads to wiring errors. Figs. 2.8(a) (schematically) and 2.8(b) (in practice) show a simple circuit with a power supply and a single resistor. The green wire is connected to the positive terminal of the power supply and the white wire is connected to the negative terminal.

2. **Include an ammeter in the circuit to measure current.** Attach a single wire to the "COM" input of your ammeter; in this example, this is the purple wire. Identify the element in your circuit through which the desired current is flowing (in this case the resistor). Unplug the wire (or wires) leading into one end of that element and plug all of them into either the 400mA or 10A input of your ammeter, depending



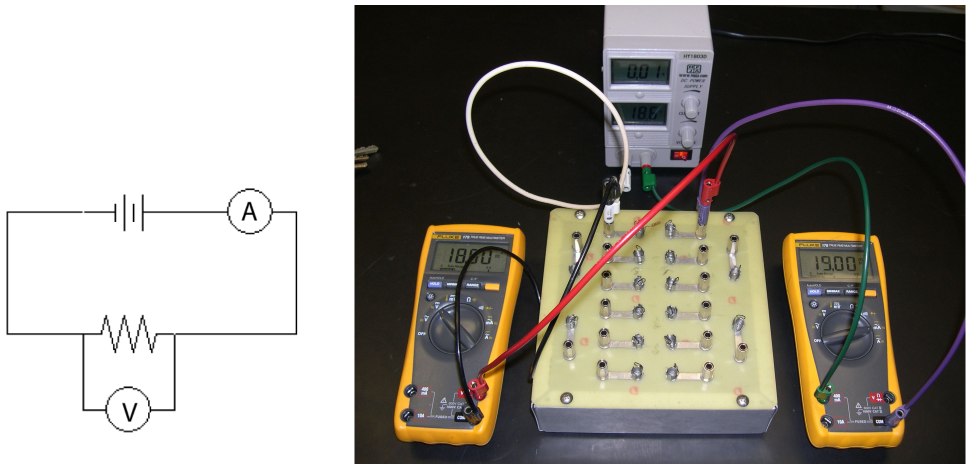
(a) Schematic

(b) In practice

Figure 2.9: Building a circuit that includes a power supply, ammeter, and resistor.

of the size of the current you are measuring. In this example, there is only one wire leading to the resistor (the green wire) and we are using the 400mA setting of the ammeter. Plug the free end of the purple wire into the plug on the breadboard where you removed the circuit's wire (or wires) — i.e. the place where the green wire was connected in Fig. 2.8(b). You have now forced all of the current carried by the wire (or wires) to go through the ammeter in addition to the circuit element of interest. The ammeter is now properly connected in series with the resistor. Figs. 2.9(a) (schematically) and 2.9(b) (in practice) show our simple circuit with a power supply, a single resistor, and an ammeter. Turn the dial to read mA or A. **By default, it is set to read AC current.** We have DC current, so press the yellow button to change the mode to DC. You'll have to this again if the multimeter turns off automatically.

3. **Include a voltmeter in the circuit to measure voltage.** Attach two wires to the voltmeter inputs. In the example below the red wire is connected to the "VΩ" input and the black wire is connected to the "COM" input of the voltmeter. Attach the free end of each wire across the points whose voltage you would like to measure – in this case the red wire is connected to the right of the resistor and the



(a) Schematic (b) In practice

Figure 2.10: Building a circuit that includes a power supply, voltmeter, resistor, and ammeter.

> black wire is connected to the left of the resistor. The voltmeter is now properly connected in parallel with the resistor, as seen in Fig. 2.10 – **never connect an ammeter in this fashion**.

Once you have constructed a circuit, no matter how complicated, you can use steps two and three to measure the current flowing through a given element in the circuit and the voltage across that circuit element.

Resistor color codes

Most resistors are coded with color bands around one end of the resistor body. Using the resistor color code system is similar to using scientific notation. Scientific notation uses a number between 0 and 9.9 multiplied by some power of ten. The resistor color code system uses a number between 01 and 99 multiplied by some power of ten. These color bands tell the value of the resistance. Starting from the end, the first band represents the first digit of the resistance value and the second band the second digit. The third band represents the power of ten multiplying the first two digits. The fourth band represents the tolerance. If the fourth band is absent, it means the tolerance is 20%. Table 2.2 is a color code chart, from which one can tell the resistance of a resistor.

Table 2.2: Resistor color codes

Color	1st digit	2nd digit	Power of 10	Tolerance
black	0	0	0	-
brown	1	1	1	-
red	2	2	2	-
orange	3	3	3	-
yellow	4	4	4	-
green	5	5	5	-
blue	6	6	6	-
violet	7	7	7	-
gray	8	8	8	-
white	9	9	9	-
gold	-	-	-	5%
silver	-	-	-	10%
none	-	-	-	20%

Example

Suppose the color code on a resistor is yellow, violet, orange and gold like the resistor depicted above in Fig. 2.11. What is its resistance and what is the uncertainty of this resistance?

The value of the resistance can be found from the first three colors. From the table above, the first digit is 4 (corresponding to the yellow band), the second digit is a 7 (corresponding to the violet band) and the power of 10 multiplier is 3 (corresponding to the orange band).

So, the resistance is

$$\begin{gathered}(\text{first digit})(\text{second digit}) \times 10^{\text{multiplier}}\,\Omega \\ 4 \qquad\qquad 7 \qquad\qquad \times 10 \quad {}^{3} \qquad \Omega \\ 47 \times 10^{3}\,\Omega \end{gathered} \tag{2.3}$$

The fourth color is used to calculate the uncertainty in the resistance. The tolerance of this resistor is 5% (corresponding to the gold band). So, we calculate the uncertainty thusly:

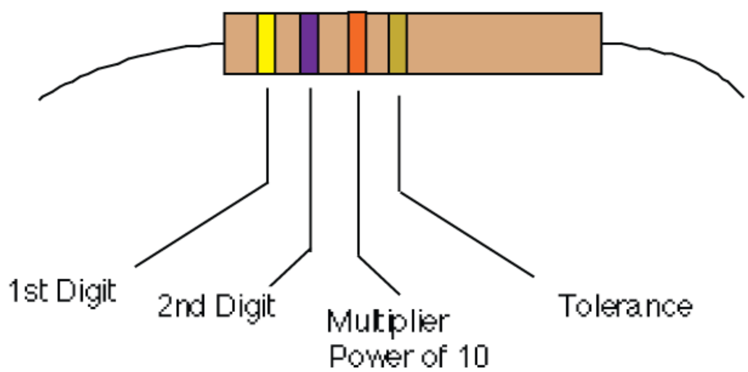


Figure 2.11: Example resistor.

$$\delta R = R \times \text{tolerance} = 47\,000\ \Omega \times \frac{5}{100} = 2\,350\ \Omega \tag{2.4}$$

The resistance of this particular resistor is $47\,000 \pm 2\,000\ \Omega$ or 47 ± 2 kΩ. Because the tolerance is only given to one significant figure, the uncertainty can only be known to one significant figure.

Different classes of errors

Manufacturer's tolerance

Suppose you purchase a nominally 100 Ω resistor from a manufacturer. It has a gold band on it which signifies a 5% tolerance. What does this mean? The tolerance means $\delta R/R = 0.05 = 5\%$, that is, the fractional uncertainty. Thus, $R = R \times 0.05 = 5$. We write this as

$$R = R_{\text{nominal}} \pm \delta R = 100 \pm 5\ \Omega \tag{2.5}$$

It says that the company certifies that the true resistance R lies between 95 and 105 Ω. That is, $95 \leq R \leq 105\ \Omega$. The company tests all of its resistors, and if they fall outside of the tolerance limits, the resistors are discarded. If your resistor is measured to be outside of the limits, either (a) the manufacturer made a mistake (b) you made a mistake or (c) the manufacturer shipped the correct value but something happened to the resistor that caused its value to change.

Reading a digital meter

Suppose you measure the voltage across a resistor using digital multimeter. The display says 7.45 V and doesn't change as you watch it. The general rule is that the uncertainty is half of the value of the least significant digit. This value is 0.01 V so that half of it is 0.005. Here's why: The meter can only display two digits to the right of the decimal so it must round off additional digits. So if the true value is 7.454 or 7.445 V, these values, or anything in between, will get rounded to 7.45. Thus the average value and its uncertainty can be written as 7.45 ± 0.005.

When you record this, be sure to write 7.45 V, not 7.450 V. Writing 7.450 implies that the uncertainty is 0.0005.

Note that in this example we assumed that the meter reading is steady. If instead, the meter reading is fluctuating, then the situation is different. Now, you need to estimate the range over which the display is fluctuating, then estimate the average value. If the display is fluctuating between 5.4 and 5.8 V, you would record your reading as 5.6 ± 0.2 V. The uncertainty due to the noisy reading is much larger than your ability to read the last digit on the display, so you record the larger error.

Combining uncertainties

Information on combining uncertainties is contained in Appendix A. As was done in Physics 251, KaleidaGraph can give you the uncertainty in the slope of a graph by choosing "Curve fit", then "General fit" and finally "fit1".

****Note!****

You will be asked about the consistency of results, or to compare values. Whenever this is asked, it is meant to be a quantitative answer. See Appendix A for the instructions on determining consistency.

2.7 Procedure

- The units of all quantities must be specified, i.e. Ω = Ohms, V = Volts and A = Amps.
- For unit abbreviations, the prefix “k” means “kilo” $= 10^3$ and “m” means “milli”$= 10^{-3}$
- Set the **current** control knob to its maximum setting at all times (full clockwise position).

Circuit with one resistor

1. **Construct the circuit shown in Fig. 2.12.** Refer to the Suggestions section above. Choose a resistor that has a resistance of at least 1000 Ω, so that we can neglect the ∼ 6 Ω internal resistance of the ammeter. Choose a voltage setting on the power supply, and read off the voltage and current from the meters. Then use Ohm’s Law (Eq. 2.1) to experimentally[5] determine the resistance. Record your measurements in Data Table 1 in your Excel spreadsheet. Refer to Eq. A.2 to calculate the uncertainty in your experimentally determined resistance. Compare your measured value (Ohm’s Law value) with the nominal value given by the color code (Question 1).

[5] Here we mean “experimentally” to mean that we are performing an experiment to measure the resistance, not that the method is “experimental” and thus not well-tested yet.

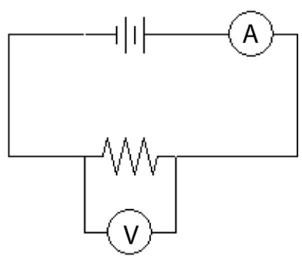


Figure 2.12: Schematic for Step 1

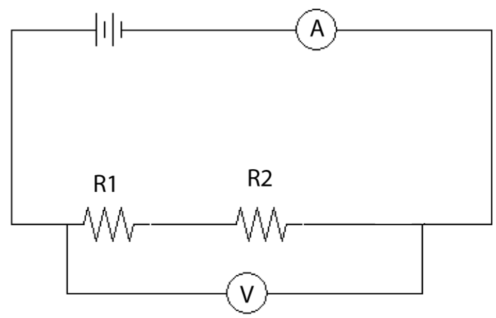


Figure 2.13: Schematic for 2 resistors connected in series.

2. **Graphical test of Ohm's law for a constant resistor.** Use the same circuit as in Step 1. Begin with a very small positive voltage and gradually increase the voltage. For five settings throughout the range, record both the voltage reading from the voltmeter and the current reading from the ammeter in the top half of Data Table 2. Decrease the supply voltage to its minimum value and change the polarity of the voltage (make the electricity flow in the opposite direction through the circuit). You do this by switching the wires connecting your circuit to the power supply. Again, gradually increase the supply voltage. For five settings throughout the range, record voltage and current measurements in the bottom half of Data Table 2. Using all of the data in Data Table 2, plot V (vertical axis) vs. I (horizontal axis). Have Kaleidagraph fit your data with a best fit line, display the equation of the best fit line and the uncertainties in the slope and intercept (don't forget to briefly comment on your graph). Record the slope and its uncertainty in your spreadsheet. Compare this to your value for the resistance determined by Ohm's Law (Question 2).

Two resistors connected in series

3. **Construct the circuit shown in Fig. 2.13.** Use two different resistors having resistances of approximately 1 kΩ and 2 kΩ. Set the power supply voltage to the middle of its range and record your measured voltage and current in Data Table 3.

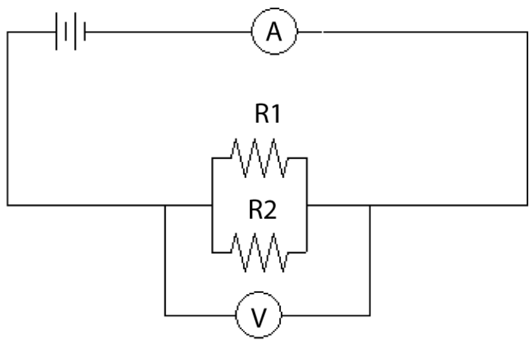


Figure 2.14: Schematic for 2 resistors connected in parallel.

Two resistors connected in parallel

4. **Construct the circuit shown in Fig. 2.14.** Use two different resistors having resistances of approximately 1 kΩ and 2 kΩ. Set the power supply voltage to the middle of its range and record your measured voltage and current in Data Table 4. For two resistors wired in parallel, the uncertainty of the equivalent resistance is given by Eq. 2.6.

$$|\delta R_{\mathrm{P}}| = R_{\mathrm{P}}^2 \left(\left| \frac{\delta R_1}{R_1^2} \right| + \left| \frac{\delta R_2}{R_2^2} \right| \right) \tag{2.6}$$

2.8 Questions

1. Discuss the consistency of the resistance found using the color codes and the measured resistance that was found using Ohm's Law.

2. Does the resistance found from the slope agree with the resistance found using Ohm's Law?

3. You used two experimental methods to determine the resistance. Explain which method is better.

4. Discuss the consistency of your nominal and measured effective resistance for two resistors connected in series.

5. Discuss the consistency of your nominal and measured effective resistance for two resistors connected in parallel.

6. Use your data from Data Table 1 to answer this question. What would happen if the ammeter (resistance = 6 Ω) was mistakenly connected in parallel with the resistor? Specifically, calculate the effective resistance of a parallel connection of the ammeter and the resistor. What current flows from the power supply if the circuit is connected in this fashion? **Never connect an ammeter in this way, it can damage the meter.**

7. Use your data from Data Table 1 to answer this question. What would happen if the voltmeter (resistance = 10 MΩ = 10^7 Ω) was mistakenly connected in series with the resistor? Specifically, calculate the effective series resistance of the voltmeter and the resistor. What current flows from the power supply if the circuit is connected in this fashion?

Experiment 3

Electrical Energy

3.1 Objectives

- Calculate the electrical power dissipated in a resistor.
- Determine the heat added to the water by an immersed heater.
- Determine if the energy dissipated by an immersion resistor is completely transferred to heat added to the water.
- Measure the resistance of an immersion heater.

3.2 Introduction

The Law of Conservation of Energy states that energy cannot be created or destroyed. But it can be converted. We convert electrical energy to other kinds of energy all the time, from using electric stoves to heat our food to the neurons in our brains using action potentials to activate neurotransmitters that control and regulate our bodies. Today we will be essentially modeling the electric tea kettle.

3.3 Key Concepts

As always, you can find a summary on-line at HyperPhysics[1]. Look for keywords: heat and thermodynamics (heat, specific heat), electricity and magnetism (electric power, power)

3.4 Theory

When a voltage is applied across a resistor, an electrical current will flow through the resistor. As an electron travels along, it occasionally collides with the ions of the resistor and causes these ions to vibrate with greater amplitude than they had before the collision. In this way, the collisions increase the vibrational amplitude and thus the vibrational energy of the ions. This increase in vibrational energy corresponds to a change in thermal energy (heat). Electrical energy has been converted into heat. This is an example of the conversion of energy from one form to another.

The electrical **power** (P) dissipated by a resistor is given by

$$P = IV, \tag{3.1}$$

where P is the power in watts (W), V is the voltage in volts (V), and I is the current in amps (A). From the power, we can calculate the **work** done by the resistor, which is given by

$$W = P\,\Delta t, \tag{3.2}$$

where W is the work in joules (J) and Δt is the time elapsed when the voltage is applied to the resistor.

Heat is a form of energy. Traditionally, heat is measured in units of calories (cal) instead of joules. One calorie is defined as the amount of heat necessary to raise the temperature of 1 gram of water by one degree Celsius (℃). The conversion factor between calories and joules is

$$1\ \text{cal} = 4.18\ \text{J}. \tag{3.3}$$

When a resistor is immersed in a cup of water and a current is passed through it, the electrical energy dissipated by the resistor will be converted

[1] http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

into heat, and the heat may be absorbed by the water, the cup, the resistor, etc. The amount of heat H added to an amount of water of mass m_{w} by changing its temperature by ΔT can be calculated by using the following equation:

$$H = m_{\mathrm{w}}\, c_{\mathrm{w}}\, \Delta T + S, \tag{3.4}$$

where c_{w} is the specific heat of water, $c_{\mathrm{w}} = 1.0\ ^{\mathrm{cal}}\!/_{\mathrm{g}\,^{\circ}\mathrm{C}}$. Note that to get the heat energy H in joules to compare it to electrical energy, **you'll need to convert it from calories to joules** using Eq. 3.3. $m_{\mathrm{w}}\, c_{\mathrm{w}}\, \Delta T$ is the heat absorbed by the water, while S represents the total heat absorbed by all other parts of the apparatus. The calorimeter is a very good insulator. Therefore, S will be very small compared to the heat gained by the water, so we will assume $S \approx 0$.

3.5 In today's lab

In this experiment you will calculate the electrical energy dissipated by a resistor immersed in water and measure the amount of heat added to the water, then determine if the energy conversion is complete.

We will use deionized water that has been refrigerated to cool it to below room temperature. We will not start to take data until the water is about 4 ℃ below room temperature. Then, we will continue to take data until the water as reached about 4 ℃ above room temperature.

We do this because our calorimeter (a cup) is not in fact a perfect insulator, and heat from the surroundings (i.e. the room) introduces a systematic error in our measurement. This way, heat absorbed by the water from the room while the water is below room temperature will be offset by the heat lost to the room while the water is above room temperature. Using this method balances out the systematic error and allows us to measure only the heat transferred to the water by the resistor.

We assume that energy will be conserved. If this is true, then the energy that was produced by the resistor will all be absorbed by the water. By comparing the electrical energy (work done) produced by the resistor and the heat energy gained by the water, we can verify this.

Figure 3.1: The calorimeter is a small "thermos bottle" with a screw-top lid in which a resistor is soldered (circled).

3.6 Equipment

- Calorimeter – the insulated cup and lid is a very good insulator, it is assumed that no energy is transferred out of such a container. It has a resistor in it that heats up. The calorimeter is shown in Fig 3.1
- digital multimeter, to measure voltage across the heating resistor
- thermometer (actually a multimeter set to read temperature), which is shown in Fig. 3.2
- power supply(which is different from the last lab and shown in Fig. 3.3

Figure 3.2: A thermocouple is a device that will respond to tiny changes in temperature (circled). It's attached to the multimeter.

Figure 3.3: The power supply is a high-current device. We'll use the 6V, 5A maximum scales which reads on the bottom of each of the windows. You connect to the resistor through the sockets on the top of the calorimeter and to the + and − "0 TO 6 V" connectors on the front (circled).

3.7 Procedure

Safety tips

- **Important!** When running electricity through the resistor, it will heat up, so keep it submerged in water so it does not overheat. You can desolder the resistor by running high current through it when it's "dry."

Taking Data

You'll use the spreadsheet for the Energy lab on your computer and fill in the various fields on the left, and then as you heat the water slowly, record your readings on the right.

1. **Measure the resistance of the resistor** that is attached to the lid of the calorimeter, using the multimeter set to read Ω. See Fig. 3.4.

2. **We need to know the mass of the water in the cup.** To do this measure the mass of the cup before and after adding the water on the digital scale in the back of the room. We want to start our experiment with water about 4 ℃ colder than room temperature. To get this, you'll mix chilled water from the refrigerator with room temperature water from the container provided. Fill your calorimeter with enough water to **completely** cover the resistor coil if the lid were on.

3. **Measure room temperature.** Instead of the liquid thermometer shown, we'll use a thermocouple[2] connected to a multimeter. Find the yellow icon of a thermometer on one of the settings of the multimeter that the probe is plugged into. Set the dial to point to that icon and press the yellow button below the screen to start reading in degrees Celsius. The probe takes some time to get to room temperature, so don't play with it too much before taking a room temperature reading. (To be sure that it's settled and makes sense, you can switch to Fahrenheit using the range setting...the room temperature should be around 70°F, but do your measurements in Celsius.)

[2] A thermocouple works via the thermoelectric effect. It has two dissimilar metals fused together and the temperature is then determined by measuring a temperature dependent voltage across this junction.

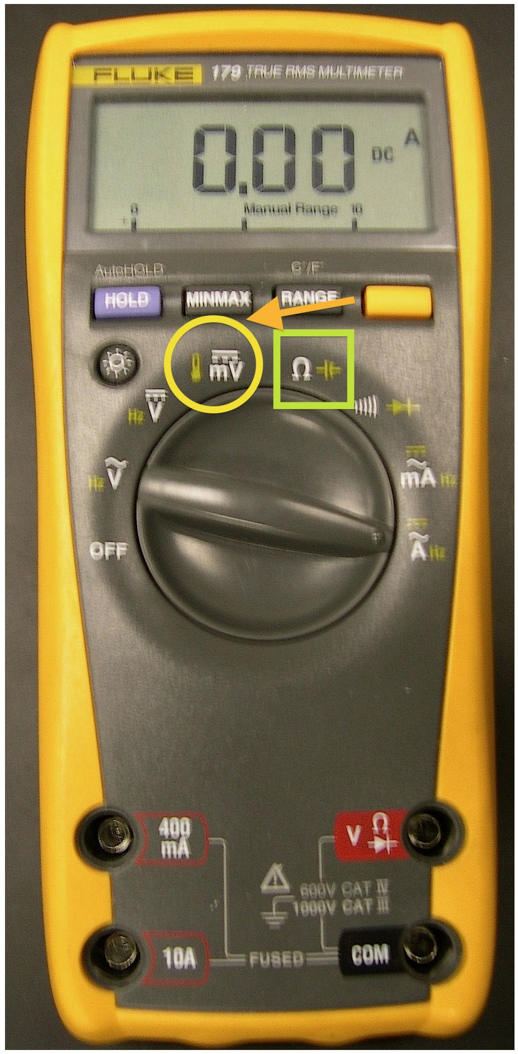


Figure 3.4: Digital multimeter with the green rectangle showing the setting for measuring resistance in ohms and the yellow circle showing the setting for measuring temperature in degrees Celsius. Notice that the latter setting will require the orange button to be pushed (to the right of the RANGE button.)

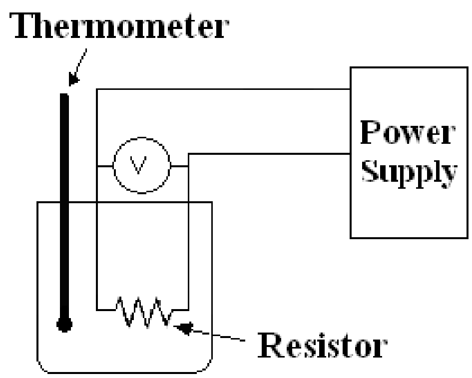


Figure 3.5: Setup.

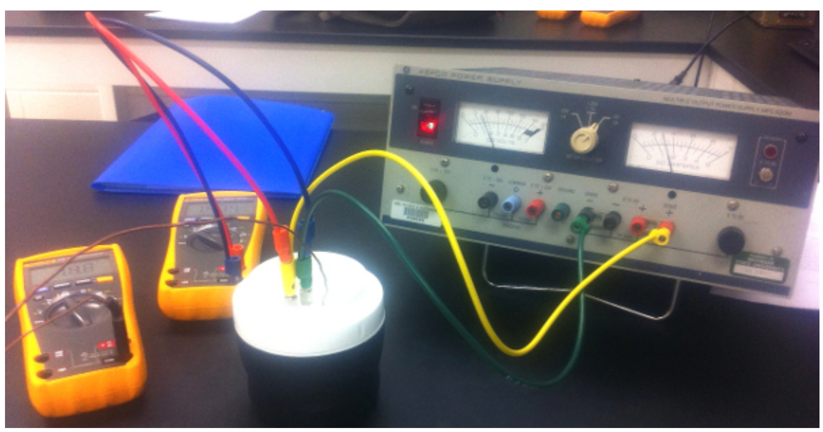


Figure 3.6: Setup.

4. **Connect the circuit as in Fig. 3.5.** One multimeter is now acting as the thermometer, and another is acting as a voltmeter. See Fig. 3.6 for a picture of a working setup.

5. **Once the resistor is covered with water and the lid is on the calorimeter, turn on the power supply and get ready to take data.** You'll record the temperature of the water every 30 seconds, so get ready to watch the clock or use a stopwatch (there are many

stopwatches on the Internet, if you want to use one of those). Turn the current knob (which is just a limit knob) all the way up and adjust the voltage until you have a current of approximately 3 A. Read and record the current from the power supply meter, and measure the voltage with the digital multimeter at the output of the power supply (V_{PS}) and at the calorimeter(V_{cal}).[3] Use the voltage at the calorimeter for your calculations.

6. **Collect data.** With the power supply on, wait to take data until the temperature of the water is between 3.0 and 4.0 ℃ less than room temperature. Record your starting temperature at time = 0 on your spreadsheet. **One member of the team must continuously and gently shake the cup to dissipate the heat uniformly in the water.** Otherwise the thermometer will not be reading the average temperature in the calorimeter. Continue collecting data until you reach as far above room temperature as you started below. So if you started collecting data at 3.5 ℃ below room temperature, continue until you reach 3.5 ℃ above.

[3] We are asking you to measure voltage at two points that are connected by a wire, so they should be the same voltage, according to what we know about circuits. You may find that they are different. See Question 4.

3.8 Questions

1. Calculate the temperature change (ΔT) and the time span (Δt) from start to stop. Also, calculate their uncertainties. For uncertainties, $\delta(\Delta T) = 2\,\delta T$ and $\delta(\Delta t) = 2\,\delta t$.

2. Calculate the power dissipated in the resistor, using $V_{\rm cal}$, and the associated error, using two methods: $P = IV$, $\delta P = P\,(\delta V/V + \delta I/I)$ and $P = V^2/R$, $\delta P = P\,(2\,\delta V/V + \delta R/R)$.

3. Which gives a more precise power value? Justify your response.

4. Were V_{cal} and V_{PS} different? Why? (Hint: What assumptions do we make about the effect of the wires on the circuit?) Why should you use V_{cal}?

5. Determine the work done by the resistor (in joules) and the associated error, using $W = P\,\Delta t$ and $\delta W = W(\delta P/P + \delta(\Delta t)/\Delta t)$.

6. Which uncertainty is more important, the uncertainty in time or in power? Justify your answer.

7. Construct a temperature versus time graph using your data.

8. Regarding your plot: remember that the equation of a straight line is $y = mx + b$. Let's unpack your straight line for these results into the straight line equation. So we need to figure out what x, y, and m (the slope) are.

   That is, write the equation of ΔT versus Δt in the "$y = mx + b$" form for your plot, with all of the right symbols, by combining the equations in the material above. It should include: $\Delta T, \Delta t, V, I, m$, and c_w. This is how the specific heat is measured.

9. Using your plot and your answer to the previous question, was the power constant? Justify your answer.

10. Calculate the heat added to the water using Eq. 3.4 and the associated uncertainty. The specific heat of water $c_{\mathrm{w}} = 1.0\ {}^{\mathrm{cal}}\!/\!{}_{\mathrm{g}^\circ\mathrm{C}}$. The uncertainty is $\delta H = H(\delta m/m + \delta(\Delta T)/\Delta T)$.

11. Compare the work done by the resistor and the heat added to the water. Is energy conserved? (You should take into account the uncertainties.) Was the heat energy found in the water less or more than the electrical energy? (Was energy lost or gained?) Discuss possible sources of apparent energy loss or gain in this experiment and its analysis.

Experiment 4

RC Circuits

4.1 Objectives

- Observe and qualitatively describe the charging and discharging (decay) of the voltage on a capacitor.
- Graphically determine the time constant for the decay, $\tau = RC$.

4.2 Introduction

We continue our journey into electric circuits by learning about another circuit component, the capacitor. Like the name implies, "capacitors" have the physical capability of storing electrical charge. Many things can be accidental capacitors. Most electrical components have some amount of capacitance within them, but some devices are specifically manufactured to do the sole job of being capacitors by themselves.[1] The capacitors in today's lab will lose their charge rather quickly, but still slowly enough for humans to watch it happen, but capacitors in electrical circuits can have very different characteristic times for charging and discharging.

[1] Batteries, in fact, are actually capacitors that discharge very, very slowly (they take a while to lose their charge) and can lose their overall effectiveness through that loss.

4.3 Key Concepts

As always, you can find a summary on-line at HyperPhysics[2]. Look for keywords: electricity and magnetism (capacitor, charging of a capacitor)

To play with building circuits with capacitors, or to get a head start on trying out the circuits for today, run the computer simulation at http://phet.colorado.edu/en/simulation/circuit-construction-kit-ac.

4.4 Theory

The Capacitor

A capacitor is a device that stores electrical charge. The simplest kind is a "parallel plate" capacitor: two flat metal plates placed nearly parallel and separated by an insulating material such as dry air, plastic or ceramic. Such a device is shown schematically in Fig. 4.1.

Here is how it stores electrical energy. If we connect the two plates to each other with a battery in a circuit, as shown in Fig. 4.1, the battery will drive charge around the circuit as an electric current. But when the charges reach the plates they can't go any further because of the insulating gap; they collect on the plates, one plate becoming positively charged and the other negatively charged. This slow buildup of charge actually begins to resist the addition of more as a voltage begins to build across the plates opposing the

[2] http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

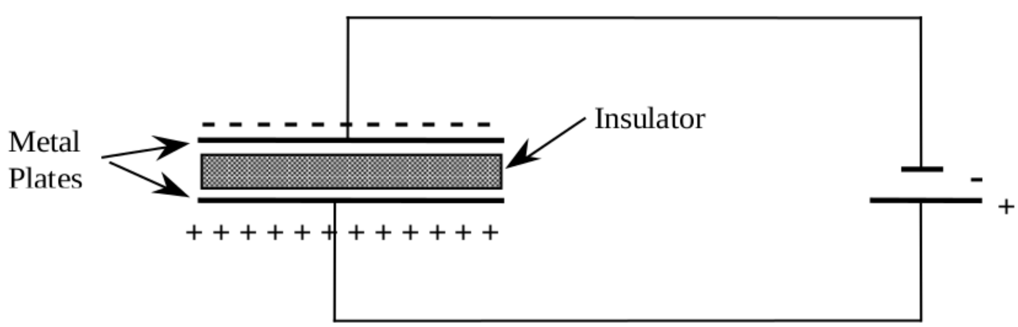


Figure 4.1: Schematic of a capacitor in a circuit with a battery.

action of the battery. As a consequence, the current flowing in the circuit gets less and less—it decays, falling to zero when the "back-voltage" on the capacitor is exactly equal and opposite to the battery voltage.

If we were to quickly disconnect the battery without touching the plates, the charge would remain on the plates. You could literally walk around with this charge stored. Because the two plates have different signs of electric charge, there is a net electric field between the two plates. Hence, there is a voltage difference between the plates. If, some time later, we connect the plates again in a circuit, say this time with a light bulb in place of the battery, the plates will discharge through the bulb: the electrons on the negatively charged plate will move around the circuit through the bulb to the positive plate until all the charges are equalized. During this short discharge period a current has then flowed and the bulb will light. The capacitor stored electrical energy from its original charge-up by the battery and then discharged through the light bulb. The speed with which the discharge process (and conversely the charging process) can take place is limited by the resistance of the circuit connecting the plates and by the capacitance of the capacitor (a measure of its ability to hold charge).

RC Circuit

An RC circuit is a circuit with a resistor (R) and a capacitor (C) in series connected to a voltage source (battery).

As with circuits made up only of resistors, electrical current can flow in this RC circuit, with one modification. A battery connected in series with a resistor will produce a constant current. The same battery in series with a capacitor will produce a time varying current, which decays gradually to zero as the capacitor charges up. If the battery is removed and the circuit reconnected without the battery, a current will flow (for a short time) in the **opposite** direction as the capacitor "discharges." A measure of how long these transient currents last in a given circuit is given by the **time constant** τ.

The time it takes for these transient currents to decay depends on the resistance and capacitance. The resistor resists the flow of current; it thus slows down the decay. The capacitance measures "capacity" to hold charge: like a bucket of water, a larger capacity container takes longer to empty than a smaller capacity container. Thus, the time constant of the circuit gets larger for larger R and C. In detail, using the units of capacitance which are "farads,"

$$\tau(\text{seconds}) = R(\text{ohms}) \times C(\text{farads}) \tag{4.1}$$

Isn't it strange that ohms times farads equals seconds? Like many things in the physical world, it is just not intuitive. We can at least show this by breaking the units down. From Ohm's Law, $R = V/I$. Current is the amount of charge flowing per time, so $I = Q/t$. Capacitance is proportional to how much charge can be stored per voltage applied, or $C = Q/V$. So,

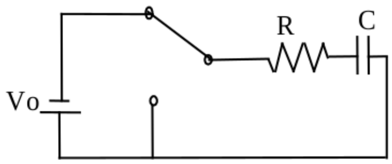
$$\begin{aligned} RC &= R \times C \\ &= \frac{V}{I} \times \frac{Q}{V} \\ &= Q/I \\ &= Q/(Q/t) \\ &= t \end{aligned} \tag{4.2}$$

The current does not fall to zero at time τ; τ is the time it takes for the voltage of the discharging capacitor to drop to 37% of its original value. It takes 5 to 6 τ's for the current to decay to essentially 0 amps. Just as it takes time for the charged capacitor to discharge, it takes time to charge the capacitor. Due to the unavoidable presence of resistance in the circuit, the charge on the capacitor and its stored energy only approaches an essentially final (steady-state) value after a period of several times the time constant of the circuit elements employed.

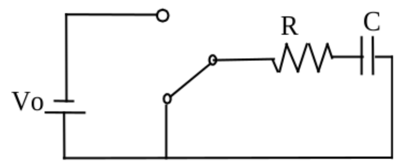
Charging and discharging the RC circuit

Charging

Initially, the capacitor is in series with a resistor and disconnected from a battery and so it is uncharged. If the switch is in the circuit and is opened, no current flows. Then, the switch is closed as in Fig. 4.2(a). The capacitor will charge up, and its voltage will increase. During this time, a current will flow, producing a voltage across the resistor according to Ohm's



(a) Charging



(b) Discharging

Figure 4.2: Schematics of charging and discharging a capacitor.

Law, $V = IR$. As the capacitor is being charged up, the current will be decreasing, with a certain time constant due to the stored charge producing a voltage across the capacitor and increasingly opposing the current.

In terms of $\tau = RC$, the voltage across the resistor and the voltage across the capacitor increases in time when the capacitor is charging looks like Fig. 4.3. Concurrently, the current through the resistor decreases in time as the current goes down with the charging capacitor.

While the capacitor is charging, V_C and V_R can be expressed as

$$V_C(t) = V_0\left(1 - e^{\frac{-t}{RC}}\right) \tag{4.3}$$

$$V_R(t) = V_0 e^{\frac{-t}{RC}} \tag{4.4}$$

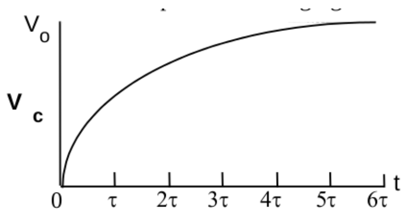
where e is an irrational number and is the base of the natural logarithm. The value of e is approximately 2.718.

When t is exactly equal to 1 time constant, $t = \tau = RC$, then

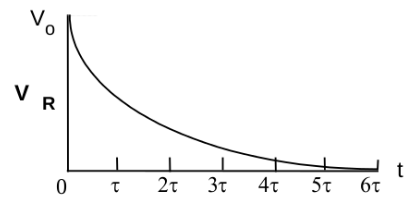
$$\begin{aligned} V_C &= V_0\left(1 - e^{-1}\right) \\ &\approx 0.63 V_0 \end{aligned} \tag{4.5}$$

$$\begin{aligned} V_R &= V_0\left(e^{-1}\right) \\ &\approx 0.37 V_0 \end{aligned} \tag{4.6}$$

So, after $t = RC$ seconds, the capacitor has been charged to 63% of its final value and the voltage across the resistor has dropped to 37% of its peak (initial) value. After a very long time, the voltage across the capacitor will be essentially V_0 and the voltage across the resistor will be, for all practical purposes, zero.

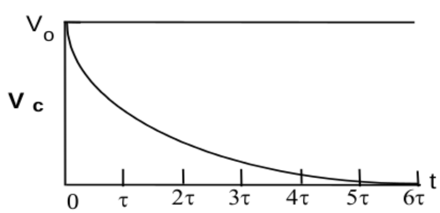


(a) Voltage across the capacitor V_C.

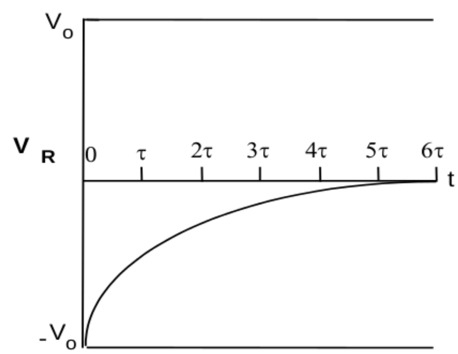


(b) Voltage across the resistor V_R.

Figure 4.3: Voltage in circuit components as a function of time, for the charging capacitor. Time constant $\tau = RC$.



(a) Voltage across the capacitor V_C.



(b) Voltage across the resistor V_R.

Figure 4.4: Voltage in circuit components as a function of time, for the discharging capacitor.

Discharging

If we flip the switch as shown in Fig. 4.2(b), we will discharge the capacitor. When it is discharging, the voltages follow Fig. 4.4.

The voltage of the resistor is exponentially increasing from $-V_0$ to zero. It is critical to remember that the total voltage between the capacitor and the resistor must add up to the applied voltage. If the circuit is disconnected from the power supply, then the sum of the voltage must be zero.

The voltage across a capacitor and a resistor in a discharging RC circuit is given by

$$V_C = V_0 e^{\frac{-t}{RC}} \qquad (4.7) \qquad\qquad V_R = -V_0 e^{\frac{-t}{RC}} \qquad (4.8)$$

We'd like to be able to plot this on a graph with a straight line. However, none of the lines in the graphs so far have straight lines — they're exponential. So we'll use the logarithm function to find an equation that looks like a straight line. First, we divide the voltage across the capacitor, V_C, by the initial voltage, V_0,

$$\frac{V_C}{V_0} = e^{\frac{-t}{RC}} \tag{4.9}$$

Then we calculate the natural logarithm[3] of both sides, yielding

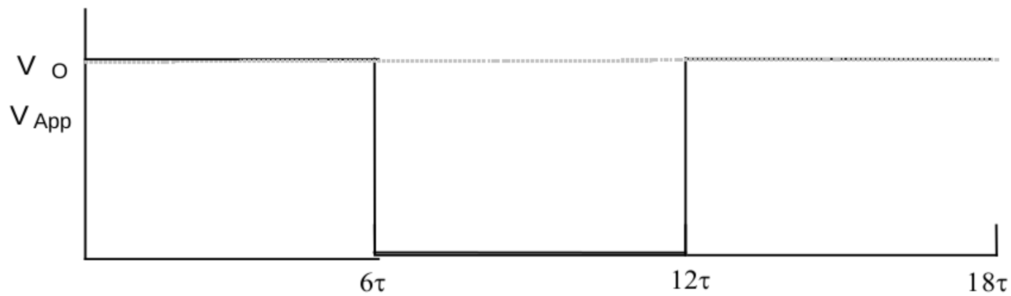
$$\begin{aligned} \ln\left(\frac{V_C}{V_0}\right) &= \ln\left(e^{\frac{-t}{RC}}\right) \\ \ln\left(\frac{V_C}{V_0}\right) &= \frac{-t}{RC} \end{aligned} \tag{4.10}$$

This last equation is a straight line, even though it may not look like one at first glance. If $y = mx + b$ is the equation of our straight line, then t is the independent variable x, the term with the voltage V_C that changes with time is the dependent variable y, and the slope m is everything that is multiplied by the independent variable t, so $m = \frac{-1}{RC}$ (You'll need this for Question 1). In this case, there is no term added to the t term, so the y-intercept b is zero.

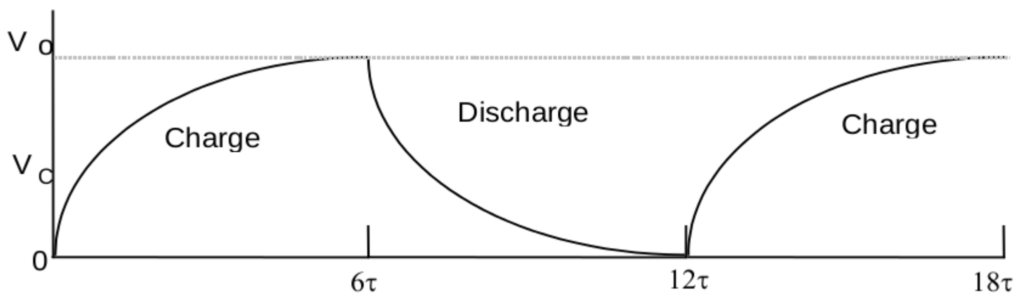
Repeated charging and discharging

If we now repeat this process and alternate the switch position every 6τ seconds, the voltages will look like Fig. 4.5. Notice that the voltage across the capacitor does not immediately match the voltage at the power supply, but rather it has some delay to get there. On the other hand, the voltage across the resistor changes very quickly to match the power supply voltage, but then dies down over time (as the capacitor gains charge and slows the current down).

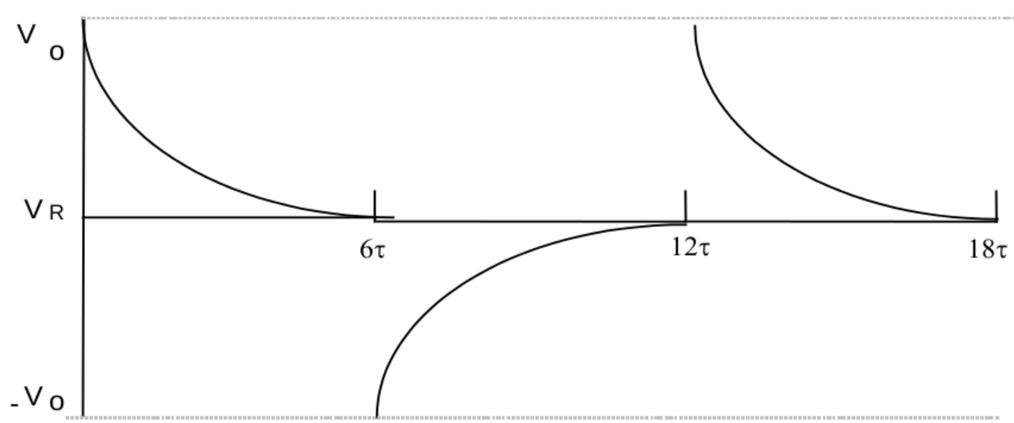
[3]The natural logarithm of x, $\ln(x)$, asks the question, "e raised to what power equals x?" For example, to find $\ln\left(e^2\right)$, we ask, "e raised to what power equals e^2?" e raised to the power 2 equals e^2, so $\ln\left(e^2\right) = 2$. We can thus use the natural logarithm to get just the power of e in an equation.



(a) Alternating voltage on and off at the power supply.



(b) Voltage across the capacitor.



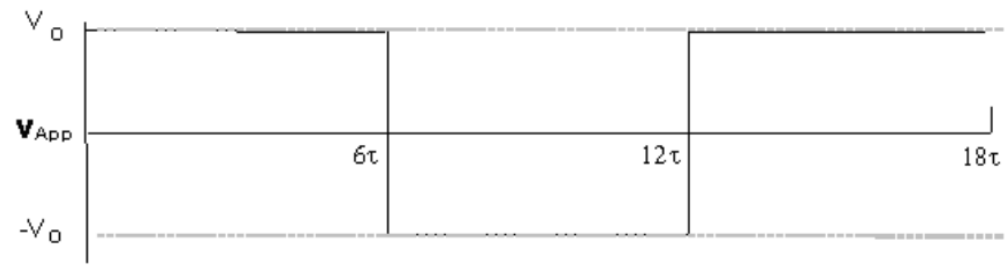
(c) Voltage across the resistor.

Figure 4.5: Voltage during repeated cycles of charging and discharging for (top to bottom) the battery (which is constant or off), the capacitor, and the resistor.

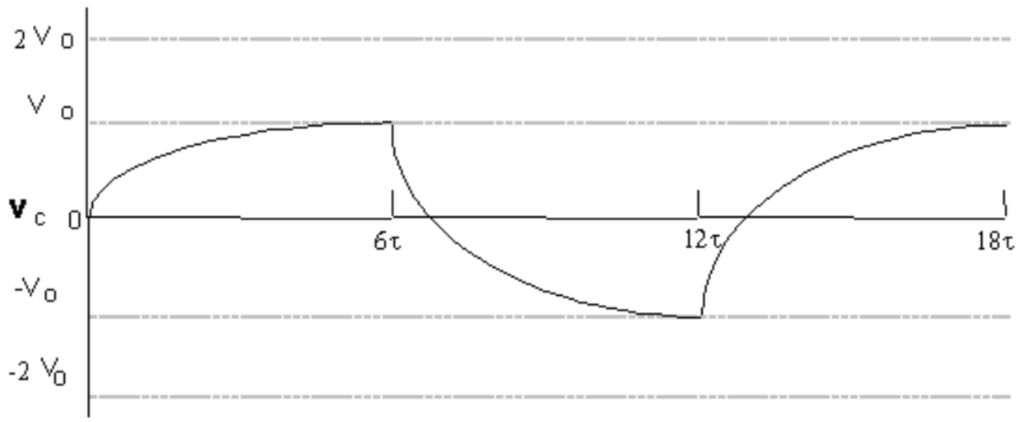
4.5 In today's lab

In this particular experiment, we are hooking up a wave generator to a RC circuit, which allows us to reverse the applied voltage. In effect, it will allow us to drive the circuit with alternating $+V_0$ and $-V_0$ as input voltage like in Fig. 4.5. The voltage as a function of time for both the resistor and the capacitor are shown in Fig. 4.6.

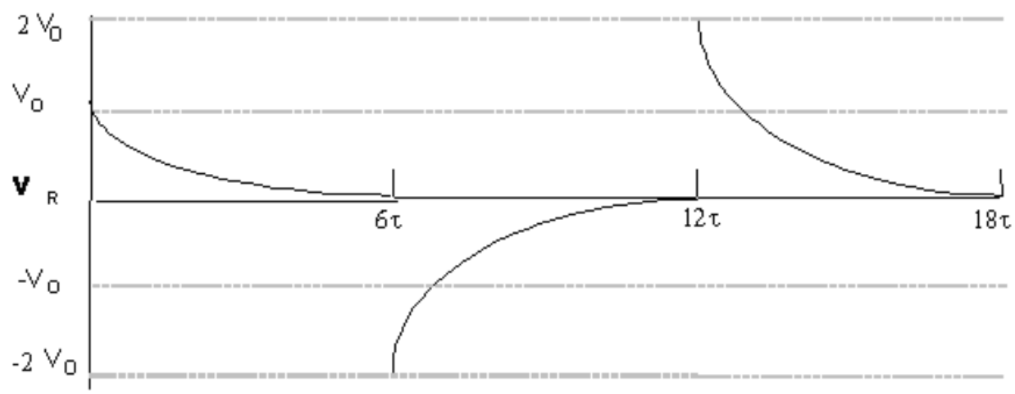
Then to see visually what is happening, we'll install a two-color LED that changes color when the current going through it changes directions.



(a) Alternating direction of voltage from signal generator.



(b) Voltage across the capacitor.



(c) Voltage across the resistor.

Figure 4.6: Repeated Charging and discharging with a signal generator.

4.6 Equipment

- Signal generator (see Figure 4.10)
- DC power supply
- Desktop timer (your own or the clock or something from the internet)
- Resistors and capacitors
- Two-color Light Emitting Diode (LED) (see Figure 4.11)
- Circuit breadboard

Safety Tips

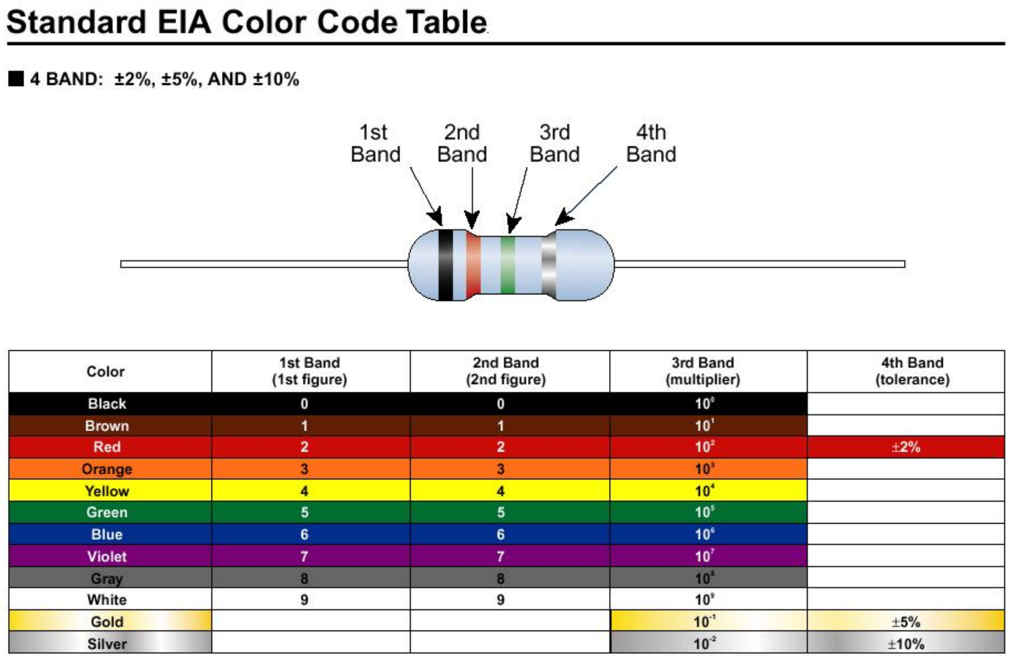
- When plugging or unplugging wires, first **turn off all electronics that are connected** or will become connected to the circuit. Today there is one instance where you will unplug first before turning off the power supply. Be sure to not touch the ends of the wires while or after you are unplugging them.

4.7 Procedure

Measuring the time constant

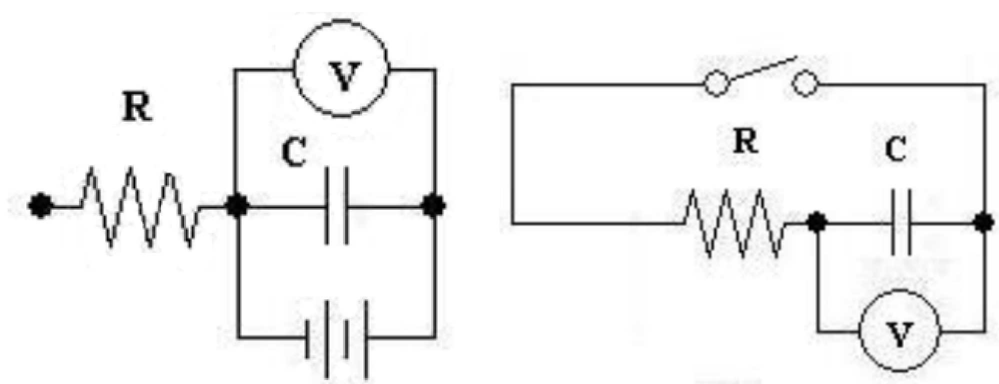
First we want to measure the time constant. This means we need to charge the capacitor fully, then let it discharge through a resistor as we measure the voltage as it changes over time.

1. Build the charging circuit shown in Fig. 4.8(a). Note that the resistor should only be attached at one end — it's dangling here. We place it in the circuit so that it is convenient to convert to the discharging circuit in Fig. 4.8(b). Be sure to set the multimeter to read DC voltage. Use the DC power supply, a 100 kΩ resistor, and a 1 000 μF capacitor. Check the color code of the resistor to verify that it is 100 kΩ; also check the tolerance of the resistor. Your instructor will tell you the tolerance of the capacitor, which is likely to be ±20%. The resistor codes can be found in Fig. **??**.



Color	1st Band (1st figure)	2nd Band (2nd figure)	3rd Band (multiplier)	4th Band (tolerance)
Black	0	0	10^0	
Brown	1	1	10^1	
Red	2	2	10^2	±2%
Orange	3	3	10^3	
Yellow	4	4	10^4	
Green	5	5	10^5	
Blue	6	6	10^6	
Violet	7	7	10^7	
Gray	8	8	10^8	
White	9	9	10^9	
Gold			10^{-1}	±5%
Silver			10^{-2}	±10%

Figure 4.7: Standard EIA (the Electronic Industries Alliance) resistor color codes for 4-band resistors. (from http://www.denizyildirim.org/mylibrary/)



(a) Charging. (b) Discharging.

Figure 4.8: Circuit schematics for measurement of RC.

2. Use the power supply to charge the capacitor to approximately 12–13 V. Then disconnect the power supply from the circuit **by unplugging the wires from the power supply, not turning it off**, and notice that the voltage across the capacitor slowly decreases — what could possibly cause this effect (see Question 3)? Disconnect the multimeter from the circuit, so that you have just the still-charged capacitor sitting there.

3. Build the discharging circuit shown in Fig. 4.8(b). Find a banana plug from a bucket in the front of the room. In this circuit, it will clip to another wire connector and make an effective[4] switch. After building the circuit shown in this figure — with your "switch" unconnected, or "open," the capacitor should still be charged from the previous step and you should still notice that the voltage is slowly decreasing.

4. Close the switch by connecting the banana plug, and you'll see the voltmeter start to register that the charge on the capacitor is decreasing as it discharges in the resistor. Let it go until the voltage across the capacitor has dropped to about 10 or 11 volts, then between the two of you start the timer and record the time and voltage in Table 1 in your spreadsheet. Continue recording the voltage across the resistor once every 10 seconds until your timer has reached 300 seconds.

5. Have Excel calculate $\frac{V_C}{V_0}$ and $\ln\left(\frac{V_C}{V_0}\right)$. Then, import your data into Kaleidagraph. Make a plot of the capacitor voltage ratio versus time.

6. Make a second plot of $\ln\left(\frac{V_C}{V_0}\right)$ vs. time. Have Kaleidagraph fit your graph with a best-fit line. Use the curve fit parameters to determine the time constant of the circuit and its uncertainty (Questions 1–2). You'll have to think about the slope of the line as you plotted it and the time constant as it appears in the formula Eq. 4.10.

Visualizing the RC circuit

In this part of the experiment you will build the circuit in Fig. 4.9 and use a square wave generator (Fig. 4.10) and a two-color light emitting diode

[4]We physicists use "effective" to mean "has the same effect as", rather than "useful". So here, an "effective switch" is a setup that has the same effect as a switch would. This makes for some good wordplay sometimes.

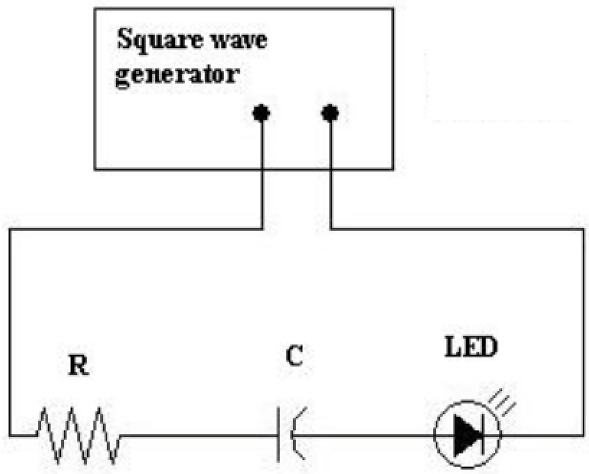


Figure 4.9: Schematic for an oscillating RC circuit with an LED.

("LED," in Fig. 4.11) to observe an RC circuit. The color which the LED displays depends on the direction of the current flowing through it. The brightness of the LED depends on how much current is flowing through it. The LED glows brighter for higher currents.

1. Use a **100 Ω** resistor (different from the first part of the lab!), a 1 000 μF capacitor, an LED, and a signal generator to build the circuit shown in Fig. 4.9.

2. When you turn on the the signal generator, it will default to a sine wave. Change it to a square wave. Set the amplitude of the signal generator to maximum and set the frequency to 0.500 Hz. Record your observations (Question 4).

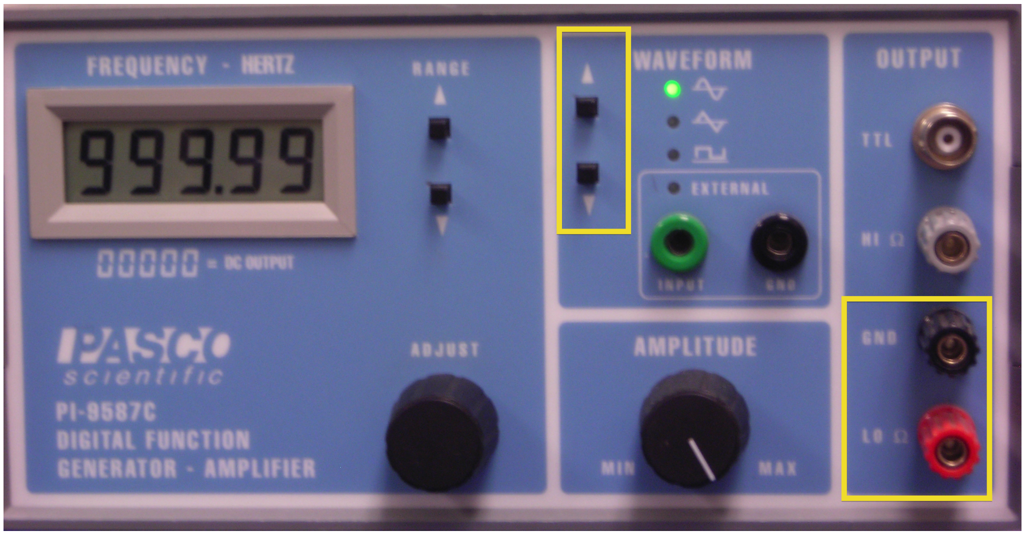


Figure 4.10: The Signal Generator produces output of a frequency you can control with the "Adjust" knob in the middle, reading out the frequency in Hertz in the window. It also generates signals of different shapes: sine wave, triangle wave, and square wave. You switch from one to the other with the buttons in the top yellow rectangle. You connect to the output of the Signal Generator at the red and black connectors shown in the lower right yellow rectangle.

Figure 4.11: The little white object on the left is a light-emitting diode for the second part of the lab. The blue object on the right is the capacitor that we'll use in this lab. Both are in the plastic bucket of parts.

4.8 Questions

Uncertainties

From the multiplication rule for uncertainties from Appendix A,

$$\delta(RC) = RC\left(\frac{\delta R}{R} + \frac{\delta C}{C}\right). \tag{4.11}$$

The uncertainty in the time constant τ obtained from the graph of $\ln\left(\frac{V_C}{V_0}\right)$ vs. time is given by

$$\delta\tau = \tau\frac{\delta(\text{slope})}{\text{slope}} \tag{4.12}$$

1. Use Eq. 4.10 to determine τ and $\delta\tau$ from your plot of $\ln\left(\frac{V_C}{V_0}\right)$.

2. Discuss the consistency between your measurement of τ from the graph and RC calculated from circuit values R and C.

3. After charging the capacitor and disconnecting the power supply, you observed that the voltage measured by the voltmeter across the capacitor slowly decreased. What are possible explanations for this observation?

4. What are your observations of the circuit involving the LED? Be specific about brightness and changes in brightness.

5. Qualitatively, how does your observation of the apparent brightness of the LED compare with your findings from the measurement of RC?

Experiment 5

The Oscilloscope

5.1 Objectives

- Explain the operation or effect of each control on a simple oscilloscope.
- Display an unknown sinusoidal electrical signal on an oscilloscope and measure its amplitude and frequency.

5.2 Introduction

So far, we've been using a voltmeter to measure a voltage. That's all well and good if the voltage is steady, DC electricity. But what if the electrical voltage you want to measure is varying rapidly in time? The voltmeter display may oscillate rapidly preventing you making a good reading, or it may display some average of the time varying voltage. In this case, an oscilloscope can be used to observe, and measure, the entire time-varying voltage, or "signal".

The oscilloscope places an image of the time-varying signal on the screen of a cathode ray tube (CRT) allowing us to observe the shape of the signal and measure the voltage at different times. If the signal is periodic (it repeats itself over and over) as is often the case, we can also measure the frequency, the rate of repeating, of the signal.

5.3 Key Concepts

As always, you can find a summary on-line at Hyperphysics[1] . Look for keywords: waves, oscilloscope

5.4 Theory

What the oscilloscope does

The oscilloscope plots voltage as a function of time.

There are two types of voltages: AC and DC. AC (short for "alternating current") indicates a voltage, the magnitude of which varies as a function of time. An AC signal is shown in Fig. 5.1. In contrast, DC (short for "direct current") indicates a voltage whose magnitude is constant in time.

The voltage is on the vertical (y) axis and the time is on the horizontal (x) axis. A constant voltage (DC) shows up as a flat horizontal line. The scope has controls to make the x and y scales larger or smaller. These act like the controls for magnification on a microscope. They don't change the actual voltage any more than magnification makes a cell on the microscope slide bigger; they just let us see small details more easily.

There are also controls to shift the center points of the voltage scales. These "offset" knobs are like the controls to move the stage of the microscope to look at different parts of a sample. You will learn about other adjustments in the course of the lab.

[1] http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

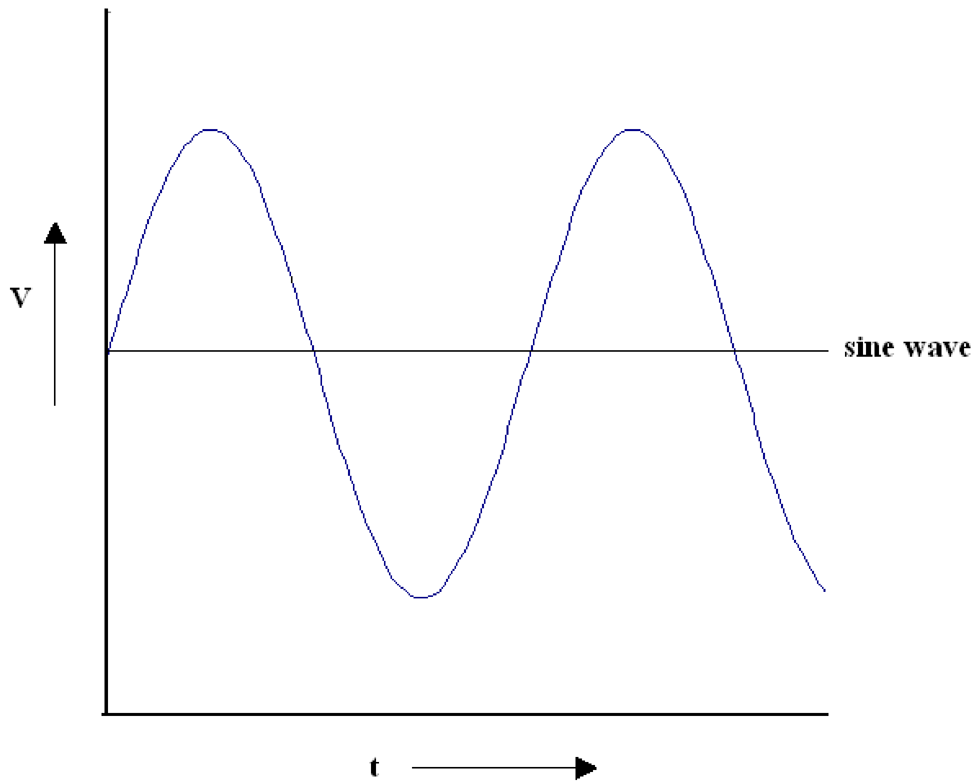


Figure 5.1: Graph of an oscillating voltage.

What the oscilloscope measures

There are two main quantities which can be measured with the aid of an oscilloscope that characterize any periodic AC signal. The first is the **peak-to-peak voltage** (V_{pp}), which is defined as the voltage difference between the time-varying signal's highest and lowest voltage (see the sine wave shown in Fig. 5.2). The second is the **frequency** of the time-varying signal (f), defined by

$$f = \frac{1}{T}, \tag{5.1}$$

where f is the frequency in hertz (Hz) and T is the period in seconds (s) (the period is also shown in Fig. 5.2).

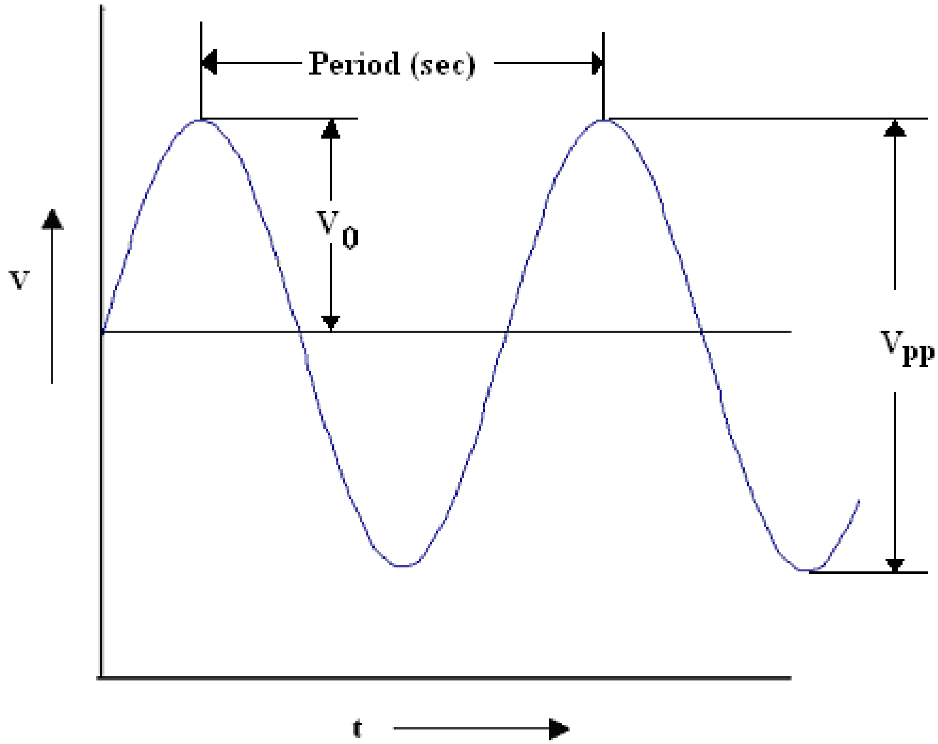


Figure 5.2: Graph of voltage vs. time, illustrating the parts of a sine wave.

Sometimes the angular frequency ω in rad/s is used instead of the frequency f in Hz.[2] They are related by

$$\omega = 2\pi f \tag{5.2}$$

The form of a standard AC signal is

$$V(t) = V_0 \sin(2\pi f t) + V_{\mathrm{DC}}, \tag{5.3}$$

where V_{DC} is an optional constant DC offset that shifts the sine wave up or down. Notice that the 2π makes it so that if the frequency f is 1 Hz, then

[2] Radian is a unit of angular distance. You are probably more familiar with degrees. While there are 360 degrees in a full circle, there are 2π radians.

the sine wave travels a full cycle in 1 s, which is what we would expect from that frequency.

The amplitude, V_0, is related to the peak-to-peak voltage V_{pp} of the signal by

$$V_{\mathrm{pp}} = 2V_0. \tag{5.4}$$

5.5 In today's lab

In this experiment you will familiarize yourself with the use of an oscilloscope. Using a signal generator you will produce various time varying voltages (signals) which you will input into the oscilloscope for analysis.

5.6 Equipment

- Oscilloscope.
- Signal generator.
- BNC-to-banana wire.

Safety Tips

- When plugging or unplugging wires, first **turn off all electronics that are connected** or will become connected to the circuit.

The oscilloscope.

An oscilloscope contains a cathode ray tube (CRT), in which the deflection of an electron beam that falls onto a phosphor screen is directly proportional to the voltage applied across a pair of parallel deflection plates. A measurement of this deflection yields a measurement of the applied voltage. The oscilloscope can be used to display and measure rapidly varying electrical phenomena. The internal subsystems of the oscilloscope are shown in Fig. 5.3 and the front panel of the oscilloscope is shown in Fig. 5.4. Because you'll need to be able to read the dials and markings, blowups of the left and right halves of the front panel are shown in Fig. 5.5 and Fig. 5.6.

A vertical amplifier is connected to the y-axis deflection plates. It serves to amplify the input signal to the y-plates so that the CRT can show an

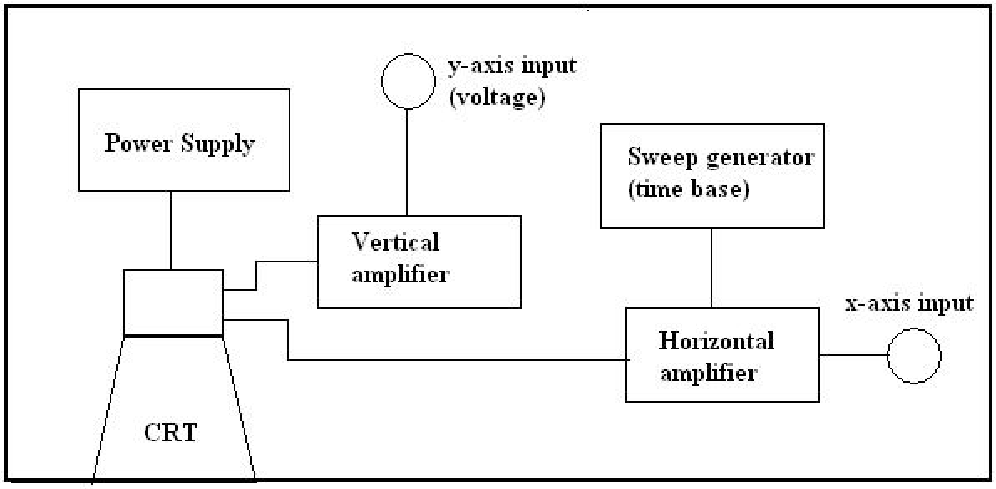


Figure 5.3: Diagram of subsystems in an oscilloscope.

Figure 5.4: Front panel of an oscilloscope.

Figure 5.5: The left side of the scope front panel.

appreciable vertical displacement for a small signal. The horizontal amplifier serves the same purpose for the x-axis plates and the horizontal display. Although an external input signal can be applied to the x-axis input, this function of the oscilloscope is not used in this course. Instead, a sweep generator internal to the oscilloscope is used to control the horizontal display. The sweep generator makes a beam move in the x-direction at a constant, but adjustable speed. The beam's speed is adjusted using the time base (TB) control knob. This allows the oscilloscope to display the external y-input signal as a function of time.

The sweep generator functions as follows. A saw-tooth voltage is applied to the horizontal deflection plates. A saw-tooth voltage is a time-varying periodic voltage and is shown in Fig. 5.7(a). The voltage first increases linearly with time and then abruptly drops to zero. As the voltage increases the beam is deflected more and more to the right of the CRT screen. When the voltage reaches its maximum value, the beam trace will be at the far right hand side of the screen (x = 10 cm). The voltage then abruptly

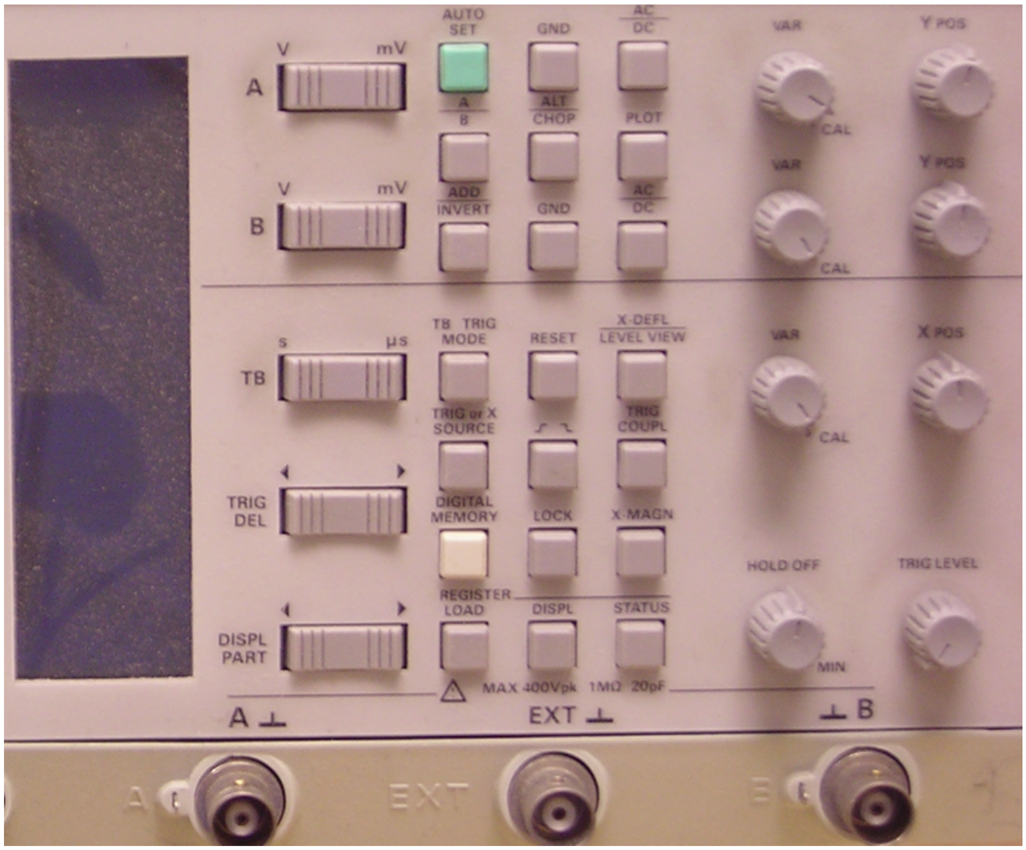
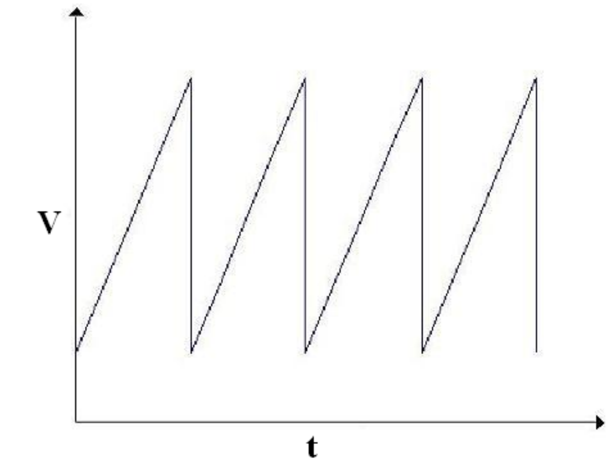
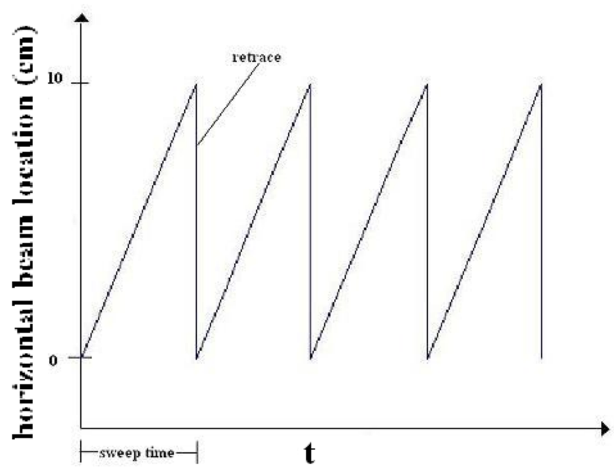


Figure 5.6: The right side of the scope front panel.

retraces back to zero — during this phase the signal is not displayed on the scope. The result is the beam spot sweeps across the screen with the same frequency as the saw-tooth signal. The horizontal position of the beam spot is shown in Fig. 5.7(b). Note: the time it takes the beam spot to move across the screen (sweep time) is equal to the period of the saw-tooth signal. The rate at which the beam spot sweeps across the screen is selected by using the time base (TB) selector knob and is calibrated in time/cm. Because both the phosphor screen and the human eye have some finite retention time, the beam spot looks like a continuous curve at frequencies higher than about 15 Hz.



(a) Voltage supplied to horizontal plates of oscillator.



(b) Deflection of beam on CRT of oscilloscope. The sweep time is one period of the saw-tooth wave.

Figure 5.7: Saw-toot input to oscilloscope.

Figure 5.8: The signal generator.

The signal generator

To investigate how the oscilloscope works in this first experiment, we will need to give it a test input signal. To accomplish this, we will be using a signal generator like the one pictured in Fig. 5.8.

It is important to understand the function of all of the dials and switches on the signal generator.

- The digital read out (upper left) displays the frequency that the signal generator is currently set to. This readout is in hertz (Hz).
- The RANGE buttons (to the right of the display) will move the decimal in the read out left or right. This means that by pressing the button once, we can change the frequency by a factor of ten. In the example pictured, one press of the button would change the frequency from 999.99 Hz to either 99.999 Hz or 9 999.9 Hz, depending on which direction we move the decimal. This will allow us to generate a large number of different frequencies quickly and easily. This only moves the decimal; it does not change the numbers that are displayed.
- If we wish to make a different numerical value, we need to turn the knob immediately below the range buttons, marked ADJUST. This

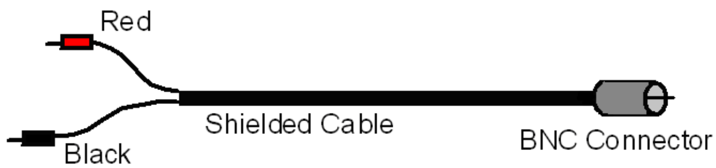


Figure 5.9: Cartoon of BNC-to-banana connector.

adjustment works in a rather unique way. If the knob is turned quickly the numbers change quickly. If we turn the knob slowly, the digits change slowly. So, with our frequency set at 999.99 Hz, as in the example above, if we wish to set it to 999.48 Hz, we could turn the knob slowly. If we wanted to set it to a 188.34 Hz, we could turn the knob the same amount, but just turn faster and the digits change faster. It may seem a little bit awkward at first, but it gives us quick access to a large range of frequencies.

- At the top is a setting labeled WAVEFORM. By changing this setting, we can create smooth sine curves, square waves or triangular waves. The LED will light up next to the type of wave selected.
- Below the waveform setting is a knob labeled AMPLITUDE. By rotating this knob, we can change the amplitude or height of our wave. This amplitude will be measured using the oscilloscope.
- The far right hand side is the OUTPUT of the signal generator. This is where we connect the cables to take the signal to an oscilloscope or an external circuit. We will use the two banana jacks at the bottom (the red and black ones) to connect banana plugs to a cable that has a BNC connector on the other end (the BNC connector is the round metal one that will connect to the "input" on the oscilloscope). The cable with the banana plugs and a BNC connector is shown in Fig. 5.9.

5.7 Procedure

It is extremely important that you learn how to operate the oscilloscope since it will be used extensively in several other exper-

iments this semester.

Helpful unit prefixes

- 1 millisecond = 1 ms = 1×10^{-3} seconds
- 1 microsecond = 1 μs = 1×10^{-6} seconds
- 1 millivolt = 1 mV = 1×10^{-3} volts
- 1 microvolt = 1 μV = 1×10^{-6} volts

1. **Set the Phillips PM3335 Oscilloscope to Mid-Range or "Nominal" Conditions.**

   a) First disconnect all input cables to your oscilloscope except the rear power cable.

   b) Find the controls listed in Table 5.1 and set their nominal values (see Fig. 5.4). (In the following, LCD refers to the Liquid Crystal Display screen to the right of the main screen.)

   c) Now press the AUTO SET button. This will automatically reset the internal electronics of the oscilloscope to reasonable nominal settings. Your oscilloscope should now display a horizontal line across the screen. If not, go back and recheck that each control is in the nominal position. If the horizontal line still does not appear ask your instructor for help. If you ever get lost later in the lab, you can return to the nominal settings. (The AUTO SET button does not necessarily give you the *best* configuration for your particular measurement; it gives *nominal* settings which are a good starting point. You will then use manual adjustments to customize the setup.)

2. **Adjustments.**

   a) Adjust the FOCUS and INTENSITY controls for a sharp and moderately bright line.

   b) Rotate the Y POS knob associated with the A-Channel (top knob) and move the horizontal line up and down on the screen. Set the line near the middle of the screen.

Control	**Setting**	**Notes**
inputs	disconnected	
POWER	on	(switch in, LCD light on)
INTENS(ity)	mid-range	
FOCUS	mid-range	
ILLUM(ination)	off	(knob fully counterclockwise)
DIGITAL MEMORY	on	(check LCD for “Digital Memory”)
Y-POS(ition)	mid-range	(both knobs: A and B channels)
X-POS(ition	mid-range	
VAR(iable)	**CAL**	**(fully clockwise, all three knobs)**
HOLD OFF	MIN(imum)	(fully clockwise)
TRIG(ger) LEVEL	mid-range	
LOCK	off	(button, check LCD for no “Locked”)

Table 5.1: Nominal settings for the oscilloscope

c) Set the display to Channel B: keep pressing the A/B button until you see ”B” (and no ”A”) indicated on the LCD. You can now adjust the Y POS knob of the B-Channel. Set the line near the middle of the screen.

d) Set the display to both Channel A and B simultaneously: “A” and “B” indicated on the LCD.

e) Rotate the Y POS knobs for both channels A and B. Notice that the signal moves up and down on the screen and note the independence of the two controls. Reset both to the center of the screen and then set the display for Channel A only.

3. **Digital and analog.** The oscilloscope can be operated in either digital or analog mode. Although you will use the digital side of the oscilloscope in all of the subsequent labs, we will briefly use the analog side of the oscilloscope first to help you understand how a signal is displayed on the oscilloscope. You can switch between the digital and analog modes by pressing the DIGITAL MEMORY button. In analog

mode the trace comes on the screen directly from the input (after some amplification or attenuation). The voltage of the input signal is given by the vertical displacement of the trace on the screen. To measure the voltage in analog mode, you need to know the sensitivity setting of the scope. The sensitivity V/mV is changed using the switch labeled A for signals on channel A and the switch labeled B for signals on channel B. The sensitivity setting is displayed on the LCD screen. The voltage and its uncertainty are then calculated by

$$V(\text{volts}) = \text{sensitivity (volts/cm)} \times \text{height (cm)} \tag{5.5}$$

with the uncertainty

$$\delta V = V \frac{\delta(\text{height})}{\text{height}} \tag{5.6}$$

The height is measured using the grid on the CRT's screen. Each of the 80 squares which make up the grid is 1.0 cm on a side. You should make a reasonable estimate of the uncertainty in the height when making a measurement in analog mode.

In digital mode, the oscilloscope automatically digitizes the input voltage. It quickly (up to forty million times per second) reads the input signal and stores its value in Volts in its electronic memory. The contents of the memory are then displayed on the screen (at 100,000 times per second or less). You can then calculate the voltage using the same method as you would in analog mode, or you can use the screen cursors (see Appendix E for outline) to help you to read the voltage directly off of the screen. You will use both methods in this experiment.

4. **View the oscilloscope without an input signal in analog mode.** Turn on the oscilloscope and make sure it is in analog mode. Use the switch labeled TB to set the time base to its largest possible value. The time base setting is displayed on the LCD screen. You should now see the beam move across the CRT screen. Using the time base, calculate how long it takes the beam to move across the screen. Also, estimate the uncertainty in the distance the beam travels (δ distance) across the screen and use it to calculate the uncertainty in your calculated time. In addition, directly measure the time the beam takes to move across the screen using a clock, watch or timer. Estimate the

uncertainty in this time. Record this data and show your calculations in Question 1 and answer Question 2.

$$t = \text{time base (s/cm)} \times \text{distance (cm)} \tag{5.7}$$

$$\delta t = t\,\frac{\delta(\text{distance})}{\text{distance}} \tag{5.8}$$

5. **View the input signal from the signal generator.**

   The signal generator produces a signal which is simply an electric voltage which varies with time. We will be using sine-wave signals in this lab. Here, the voltage varies in time like a sine wave oscillating between a positive and negative voltage at a particular frequency. Attach the output of the signal generator to the channel A input of the oscilloscope using a cable with banana jacks at one end and a BNC connector at the other.

   The signal generator produces voltage signals of different frequencies and peak-to-peak voltages. In order to use the signal generator effectively, we will have to learn something about its operation. Set the signal generator initially with frequency = 60.000 Hz, WAVEFORM being a smooth sine wave, and AMPLITUDE being approximately in the middle of the range.

   Change the oscilloscope to digital mode. Press the AUTO SET button on the oscilloscope. Adjust the sensitivity setting (A) so that the peak to peak signal fills most of the oscilloscope's screen, without extending above or below the grid. Also, adjust the time base so that one period of the signal fills most of the grid. NOTE: making these changes to the sensitivity and time base does not change the voltage or period of the signal; it only changes the scale the oscilloscope uses to display the signal.

   Sketch the signal displayed on the oscilloscope in Question 3.

6. **Using the cursors with the digital oscilloscope.** Inspect the CRT screen. If there is no writing at the bottom of the screen, press one of the blue keys just below the screen. If there is some writing and one of the soft keys has RETURN written above it, press the RETURN soft key and keep pressing it until RETURN is no longer

visible. This returns you to the highest menu level. You should now see:

CURSORS SETTINGS INTF TEXT_OFF

at the bottom of the CRT screen.

You can use these soft keys to help you measure voltages, times, periods and frequencies of input signals. Appendix E is an outline of the soft key structure.

a) **Measuring peak to peak voltage.**

We will use the soft keys to move the screen cursors (reference lines) to read voltages and times from the CRT screen. Press the CURSORS soft key. Press the MODE soft key to set up the cursors you wish to use. Press the V-CURS ON/OFF soft key to toggle the two horizontal cursors on and off: **you want these on to measure voltage.** Press the RETURN soft key to return to the main cursors menu. Press the V-CTRL soft key to control the two voltage cursors. Use the ↑REF↓ soft keys to move the bottom cursor up and down. Use the ↓ Δ ↑ soft keys to move the top cursor up and down. These two cursors are used to measure the peak-to-peak voltage of the input signal. The displayed voltage is the voltage difference between these two cursors; you move these cursors to make a measurement. To estimate the uncertainty in this measurement, use two clicks, or if the trace is larger than two clicks use the width of the trace. Measure the peak to peak voltage of your signal and record it in Question 4.

Using the sensitivity adjustment, you can change the height of the trace displayed on the screen without changing the actual input voltage. Change the sensitivity using the button labeled A on the oscilloscope. Re-adjust the cursors and measure the peak to peak voltage. Answer Question 5.

Change the sensitivity back to its previous setting.

The VAR knob varies the sensitivity in a continuous way, which cannot be interpreted by the electronics. Move the A VAR knob away from the full-right CAL position and observe what happens to the trace. Notice on the CRT a voltage is no longer displayed.

It should now only tell you how many divisions (cm) apart the cursors are placed. Also, on the LCD display next to the voltage sensitivity you should see a blinking ">" — this means the actual voltage sensitivity is something greater than the value indicated on the LCD screen. **When using the oscilloscope, it is very important that all three of the VAR knobs are set to the full-clockwise CAL position**. Return the knob to the CAL position.

b) **Frequency measurement.** The digital mode of the oscilloscope can be used to measure the period and frequency of a signal. As with the peak to peak voltage measurements you can use the soft keys to help you measure these values. Now, you will use the T-cursors. Go to the MODE menu and use the T-CURS/ON/OFF soft key to turn on the two vertical cursors. Then go to the T-CTRL menu to set the location of your cursors. Use the ←REF→ and ← Δ → soft keys to set the location of vertical cursors to correspond to one period of the input signal. At the top of the CRT screen you should see "$\Delta t =$" and "$1/\Delta t =$" corresponding to the period and the frequency of your signal. Record these in Question 6.

   Change the time base and re-measure the frequency. Answer Question 7.

   Return the time base to its previous setting.

7. **The features on the signal generator.**

   a) **The ADJUST knob.**
   Turn the ADJUST knob and observe what happens to the signal displayed on the oscilloscope. Sketch the trace before and after you turned the ADJUST knob. These need not be exact representations and you may change the scale (voltage sensitivity and time base) if you are unable to reasonably sketch the trace. Record these sketches (Question 8) and answer Questions 9–10.

   b) **The RANGE setting.**
   Push one of the two RANGE buttons and observe what happens to the signal displayed on the oscilloscope. Sketch the trace before and after you pushed the RANGE (Question 11) and answer Questions 12–13.

c) **The AMPLITUDE setting.**

Turn the AMPLITUDE knob and observe what happens to the signal displayed on the oscilloscope. Sketch the trace before and after you pushed the AMPLITUDE (Question 15) and answer Questions 15–16.

d) **The WAVEFORM setting.**

Turn the WAVEFORM knob and observe what happens to the signal displayed on the oscilloscope. Sketch the trace before and after you pushed the WAVEFORM (Question 17) and answer Questions 18–19.

5.8 Questions

1. While viewing the oscilloscope without an input signal in analog mode, record the following. **Include uncertainties** for all values except the time base setting. Show your work.

   time base setting:

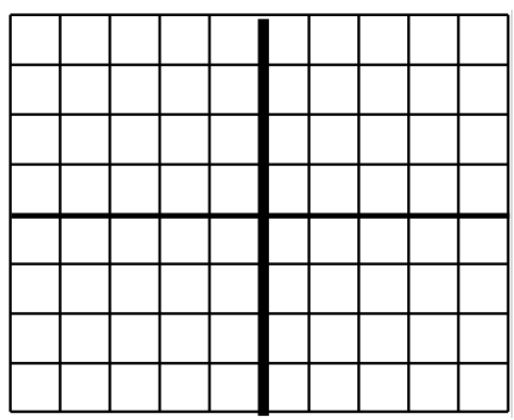
   distance traveled:

   time (calculated):

   time (measured):

2. Are the two times in Question 1 consistent? What is the meaning of this result?

3. After initially viewing the input signal, sketch the signal displayed on the oscilloscope on the grid below.



4. What is the peak-to-peak voltage V_{pp}? Don't forget to include the uncertainty.

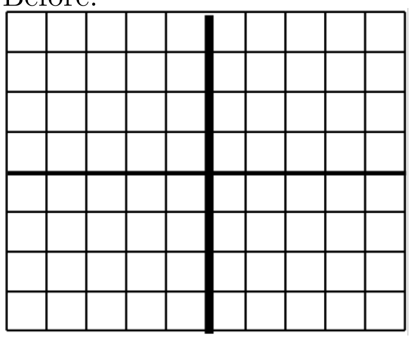
5. Did changing the voltage sensitivity on the oscilloscope change the peak-to-peak voltage? Explain.

6. What is the period and frequency of the wave? Use the Procedure Step 6b to find it. Don't forget uncertainties and units.

7. Did changing the time base change the frequency of the signal? Explain.

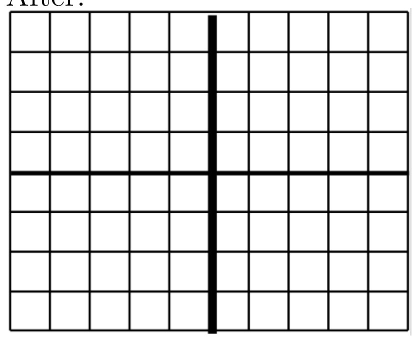
8. Sketch the trace before and after you turned the ADJUST knob. These need not be exact representations and you may change the scale (voltage sensitivity and time base) if you are unable to reasonably sketch the trace.

Before:



Volt/cm =
Time/cm =

After:



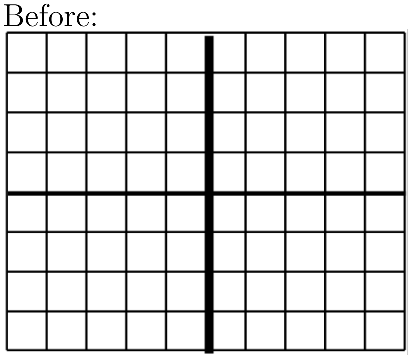
Volt/cm =
Time/cm =

9. After turning the ADJUST knob, use the cursors to measure V_{pp} and the frequency. What are they?

10. How did turning the ADJUST knob affect the signal?

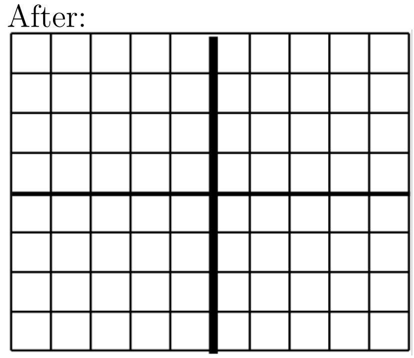
11. Sketch the trace before and after you pushed the RANGE. These need not be exact representations and you may change the scale (voltage sensitivity and time base) if you are unable to reasonably sketch the trace.

Before:



Volt/cm =
Time/cm =

After:



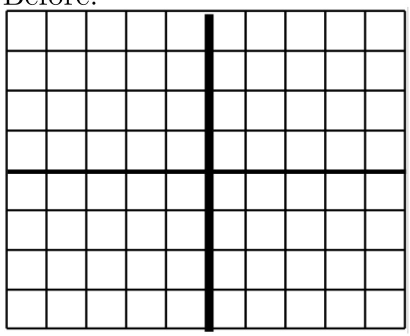
Volt/cm =
Time/cm =

12. After pushing the RANGE button, use the cursors to measure the peak to peak voltage and the frequency. What are they?

13. How did pushing the RANGE button affect the signal?

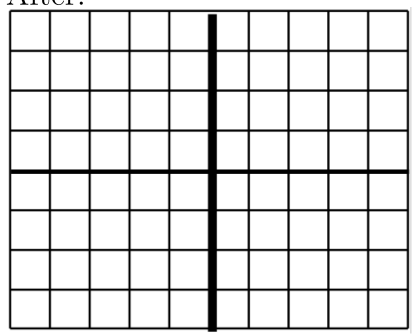
14. Sketch the trace before and after you turned the AMPLITUDE knob. These need not be exact representations and you may change the scale (voltage sensitivity and time base) if you are unable to reasonably sketch the trace.

Before:



Volt/cm =
Time/cm =

After:



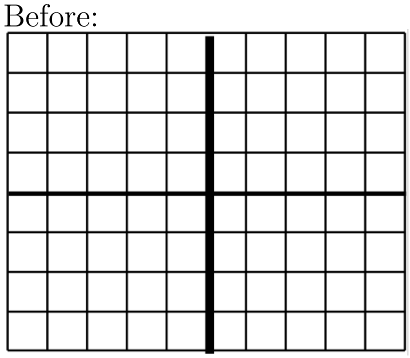
Volt/cm =
Time/cm =

15. After turning the AMPLITUDE knob, use the cursors to measure V_{pp} and the frequency. What are they?

16. How did turning the AMPLITUDE knob affect the signal?

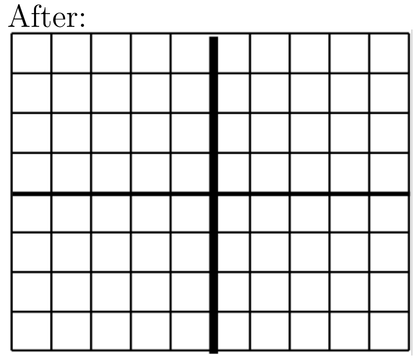
17. Sketch the trace before and after you turned the WAVEFORM knob. These need not be exact representations and you may change the scale (voltage sensitivity and time base) if you are unable to reasonably sketch the trace.

Before:



Volt/cm =
Time/cm =

After:



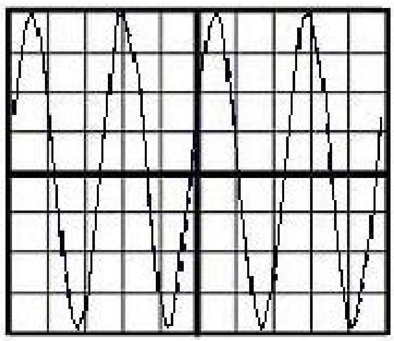
Volt/cm =
Time/cm =

18. After turning the WAVEFORM knob, use the cursors to measure V_{pp} and the frequency. What are they?

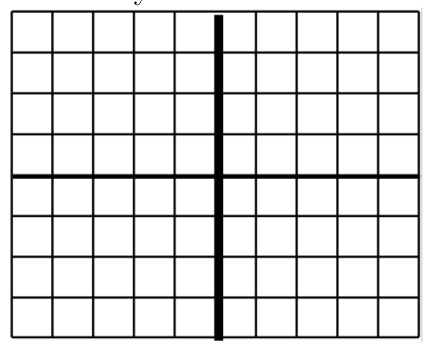
19. How did turning the WAVEFORM knob affect the signal?

20. The diagram below shows a signal on the CRT screen of an oscilloscope. Sketch the appearance of the trace if the voltage sensitivity scale setting on the oscilloscope is increased by a factor of 2.

Original display:

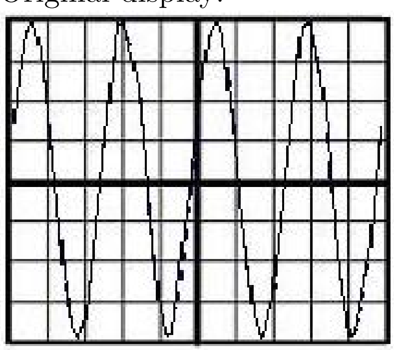


Sensitivity scale doubled:

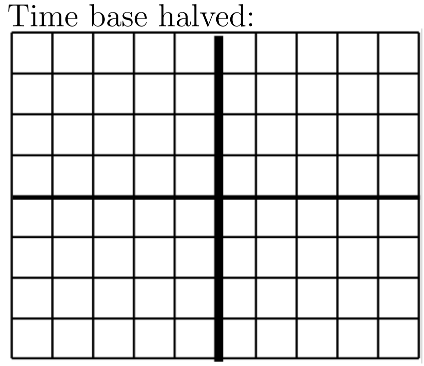


21. The voltage sensitivity is returned to its original setting, and then the time base is halved. Sketch the appearance of the trace after the time base has been decreased by a factor of 2.

Original display:



Time base halved:



22. If you wish to measure the frequency of the signal more accurately, which trace should you use (original or with the time base halved)? Why?

23. Suppose you have an unknown input signal. Briefly describe the steps you would take to view the signal appropriately and to make measurements of the frequency, period, and peak to peak voltage.

24. **Now do it:**
Measure the frequency and V_{pp} for the mystery signal from the white box. Here you will connect the output of an unknown box directly to the oscilloscope. You will not need the signal generator. Be sure to turn on the power supply connected to the unknown box. Remember to include uncertainties and units.

White box I.D. =

V_{pp} =

Frequency =

Experiment 6

The Amplifier

6.1 Objectives

- Understand the operation of the differential amplifier.
- Determine the gain of each side of the differential amplifier.
- Determine the gain of the differential amplifier as a function of frequency.

6.2 Introduction

When you go to purchase an audio amplifier for your home or car, there are a couple things you would like this amplifier to do. First, it will take a small signal and make it larger. The amount of this amplification can be varied using the volume knob on the amplifier. As you increase the volume, you would like the various frequencies of sound coming out of your system's speakers to increase uniformly. That is, you don't want low frequencies to increase in loudness significantly more (or less) than high frequencies. Furthermore, you want your amplifier to amplify the desired signal while ignoring background noise.

The frequency responses of audio amplifiers are available in the specifications of the amplifier. What does a frequency response of 20Hz–20kHz (+/− 3dB) mean? Well, over this frequency range, the power output does not increase (or decrease) by more than 3 dB. Although we will not measure gain in dB (decibels) in this lab, the dB is commonly used when specifying amplifiers. The dB scale is a logarithmic scale and a variation of 3 dB represents a change in power output of a factor of two (+3dB means the output power is doubled and −3dB means the output power has been cut in half). The frequency response of all real amplifiers is not flat, that is they do not amplify all frequencies equally well. The speakers in our audio systems also have frequency responses that are not flat, furthermore our ears cannot hear all frequencies equally well either.

Another frequently specified attribute of amplifiers is the signal to noise ratio. This is the ratio of desired amplified signal to the (undesired) background noise. This too, is commonly specified in dB. For example, a signal to noise ratio of 90 dB represents an actual (desired) amplified signal that is 10^9 or one billion times larger than the undesired noise!

6.3 Key Concepts

For this lab, we'll be making extensive use of the oscilloscope, so you might want to review the lab where we learned how to use it. It would be good to review voltage, too.

There aren't many references to amplifiers in introductory texts, as it not is typically covered. We are learning about them so we can use them to do an experiment with bio-electricity.

6.4 Theory

The differential amp compares two voltage signals with respect to ground (or reference), then takes their **difference** and amplifies this difference as its output. This allows the signal to be viewed on an oscilloscope or other recording device. We will see the usefulness of subtracting two voltage signals in next week's experiment when we use the differential amplifier to view cardiac signals.

A schematic diagram of a differential amp is shown in Fig. 6.1. The first red input lead has voltage V_a, the second has voltage V_b, and the black lead defines a reference voltage V_r. The reference voltage is usually ground. The input signals can be thought of as the voltage differences between the inputs and the reference:

$$A = V_a - V_r \tag{6.1}$$

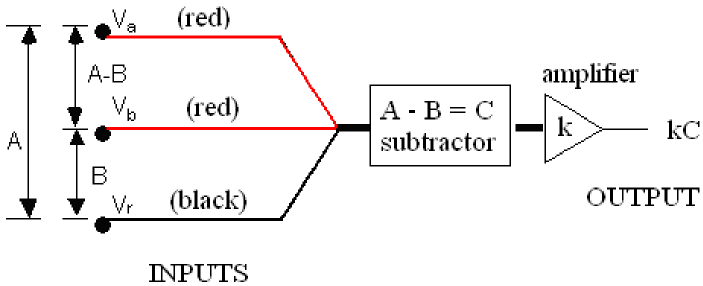


Figure 6.1: Schematic of a differential amplifier.

$$B = V_b - V_r \tag{6.2}$$

The subtractor part of the differential amplifier calculates the difference between the two input leads: $C = A - B = V_a - V_b$. The voltages here refer to voltages at any particular instant of time.

This signal $(A - B)$ is then sent through an amplifier and its amplitude is increased k times. The output signal of the amplifier is

$$\text{output} = k \times (A - B). \tag{6.3}$$

The value k is the "gain" of the amplifier,

$$\text{gain} = \frac{\text{output voltage}}{\text{input voltage}}. \tag{6.4}$$

The amplifier part of the differential amplifier makes voltages bigger at each moment. It cannot make the input voltage vary more or less quickly. Thus, an ideal amplifier has no effect on the frequency of its input signal $C = A - B$ or on the shape as a function of time. It only changes its size. Of course, the signal $A - B$ can be quite different from either A or B by themselves.

Stray electrical signals from outside sources, called noise, pervade the room where voltages V_a and V_b are measured. The amplitude of this noise is often much greater than the amplitude of the signals we wish to study. Since the noise may be much larger than the desired signals A and B, the arrangement that subtracts the voltage produces much less contamination of the output signal. The biological signals we will study in the next experiment would be completely obscured if not for this property of the amplifier,

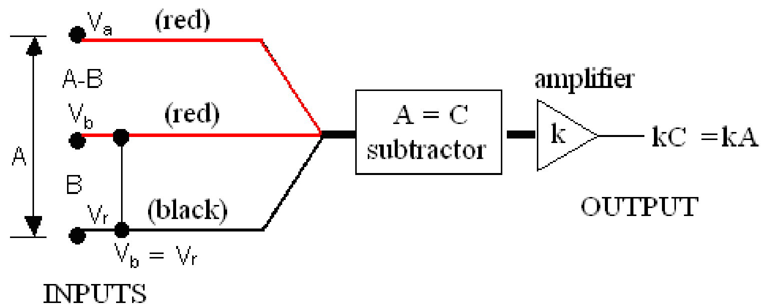


Figure 6.2: Schematic of an amplifier with the input signal set to zero.

which is known as Common-Mode Rejection, because it rejects signals sent in common to both of the input leads.

We will measure the characteristics of the amplifier by setting the input signal of B=0, that is, connected directly to the reference as shown in Fig. 6.2.

So, the inputs to the difference amplifier are

$$A = V_a \tag{6.5}$$

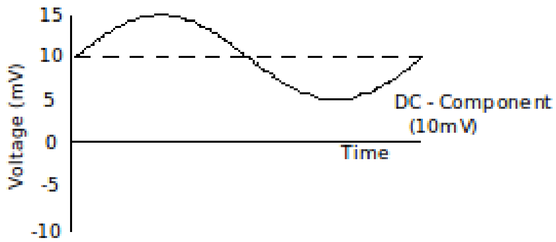
and

$$\begin{aligned} B &= V_b \\ &= V_r \\ &= 0. \end{aligned} \tag{6.6}$$

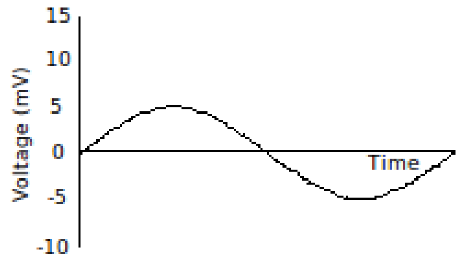
The output is

$$\begin{aligned} \text{output} &= k \times (A - B) \\ &= k \times (V_a - 0) \\ &= kV_a \end{aligned} \tag{6.7}$$

We could also connect the signal into channel A to the reference, with our input signal connected to B and get essentially the same result. The only difference would be a minus sign, i.e. output$(A = V_r) = -kV_B$. For AC signals, this minus sign presents itself as a 180° phase shift in the output signal.



(a) Without AC coupling.



(b) With AC coupling.

Figure 6.3: Output voltage with and without AC coupling, for input voltage that varies between 5 and 15 mV.

A second feature of the differential amplifier is that it can be **AC coupled**. This means that there is an electronic circuit that passes only input potentials varying fairly rapidly in time. The AC coupling circuitry will not pass a constant, DC voltage or slowly varying voltage at frequencies below 1/2 Hz. AC coupling thus removes any DC component from an AC signal. For example, a signal that varies from 5 mV to 15 mV at say, 10 Hz, is an AC signal with a DC component of 10 mV (See Fig. 6.3(a)). AC coupling will remove the 10mV DC component and pass an AC signal varying from −5 mV to +5 mV to the amplifiers, as in Fig. 6.3(b). AC coupling is accomplished by capacitors in the input circuit that act as a large resistance to DC signals. The differential amplifier may also be **DC coupled** with no restriction on the input. It amplifies whatever it sees at the input: AC, AC + DC, or pure DC. Note that the oscilloscope may also be AC-coupled; using the AC/DC button toggles the scope between AC coupling and DC coupling.

6.5 In today's lab

In this experiment it will be our goal to acquaint you with the differential amplifier and how the device can be used to measure small bio-electric signals. Before using the device as a tool in biological measurements, it will benefit you to have some idea of the basic structure of the differential "amp".

6.6 Equipment

- Differential amplifier
- Signal generator
- Oscilloscope
- Attenuator

6.7 Procedure

Setup

The apparatus that we will use consists of a differential amp, a signal generator, an attenuator and an oscilloscope. It is shown schematically in Fig. 6.4 and a photo is shown in Fig. 6.5. The attenuator is a device which decreases the amplitude of a signal. Today, we will use it to make small adjustments to the input voltage.

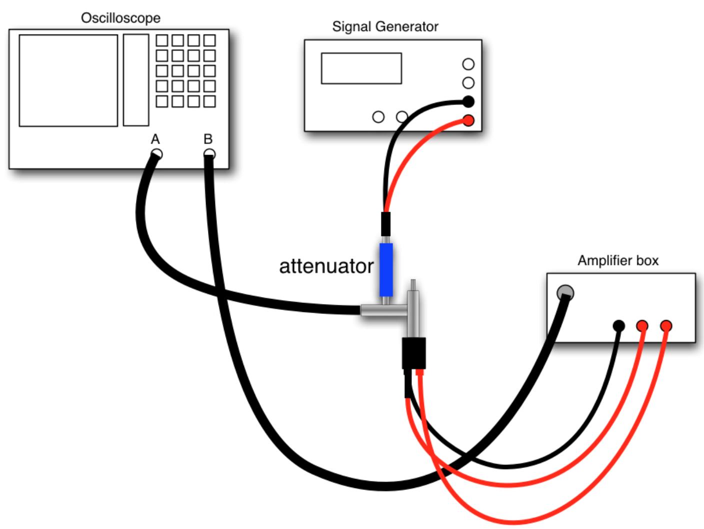


Figure 6.4: Schematic of setup.

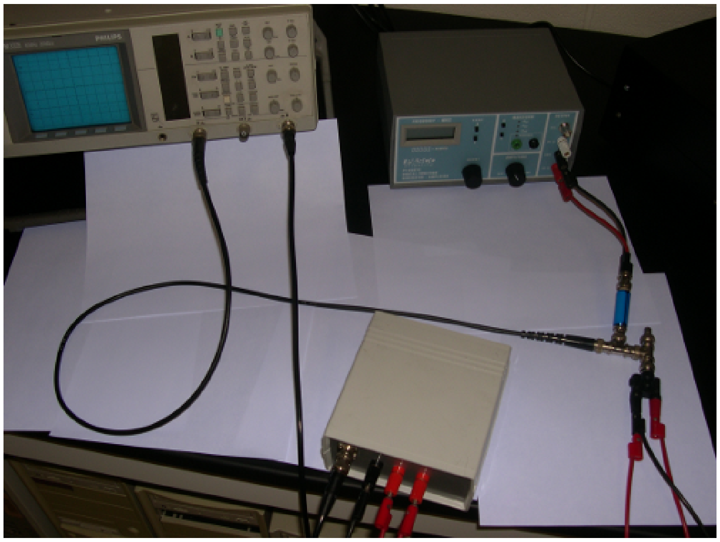


Figure 6.5: Photo of setup.

The differential amp is contained in an opaque plastic box. On the back of the box, there are three banana jacks. Two of them are red and the other one is black. The two red jacks are the INPUTS of the differential amp. The black jack is the ground or reference for the signals sent into the two red jacks. On the left side of box, there is a BNC connector for the OUTPUT of the amplifier. On the front, from the left, there are the OFFSET adjusting knob, a connection jack to charge the amplifier's battery, the High/Low gain selection switch, and the DC/AC coupling selection switch.

Retrieve an amplifier from the charger at the front of the room. If the amplifier is not connected to the charger, you should connect it to the charger and wait about 2 minutes for the amp's battery to charge. Record the number on the back face of your amplifier in your Excel Spreadsheet. You will need to know which amplifier you used for next week's lab. When you are finished with the experiment, return your amplifier to the front of the room and connect it to the charger.

Preparing the circuit.

1. Turn the OFFSET knob all the way counterclockwise. Set everything to AC coupling (both channels of the oscilloscope **and** the amplifier).

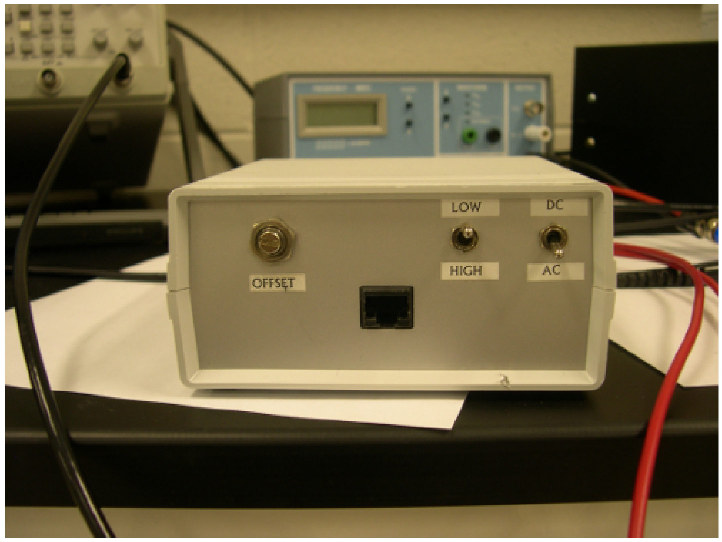


Figure 6.6: Setting the amplifier.

Make the following connections:

a) Set the amplifier coupling switch to AC and the gain of the amplifier to LOW as shown in Fig. 6.6.

b) The signal generator should be connected to the attenuator. Use a BNC cable to connect the output of the attenuator to channel A of the oscilloscope.

c) Connect the differential amplifier to the out put of the attenuator using banana plug cables as follows: One red jack on the amplifier is connected to the red jack on the attenuator. The other red jack on the amplifier is connected to the black jack on the attenuator. The black jack (reference) on the amplifier is also connected to the black jack on the attenuator. The attenuator and the connections to the amplifier are shown in Fig. 6.7.

d) Using a BNC cable, connect the output of the amplifier to Channel B of the oscilloscope.

e) Push the A/B button (circled in Fig. 6.8) until both channels are displayed on the oscilloscope.

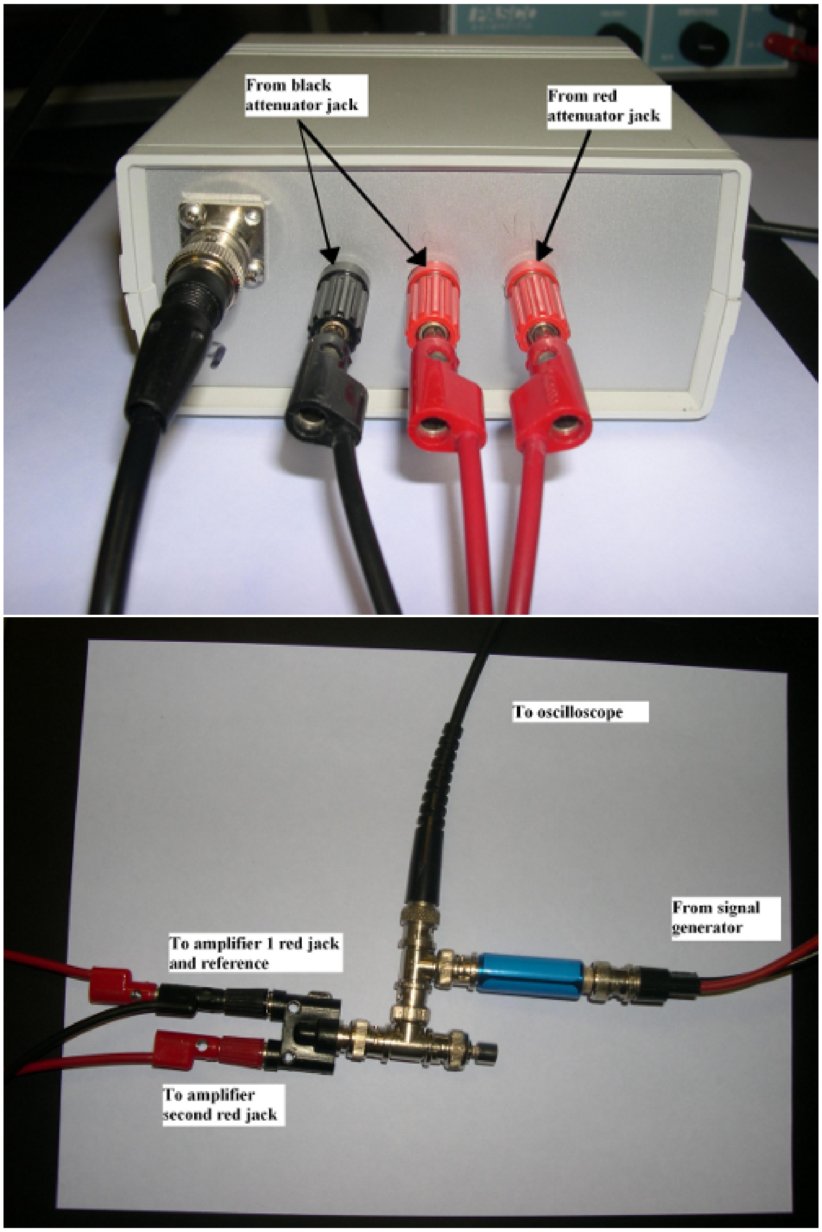


Figure 6.7: Connecting the cables to the amplifier (top) and attenuator (bottom).

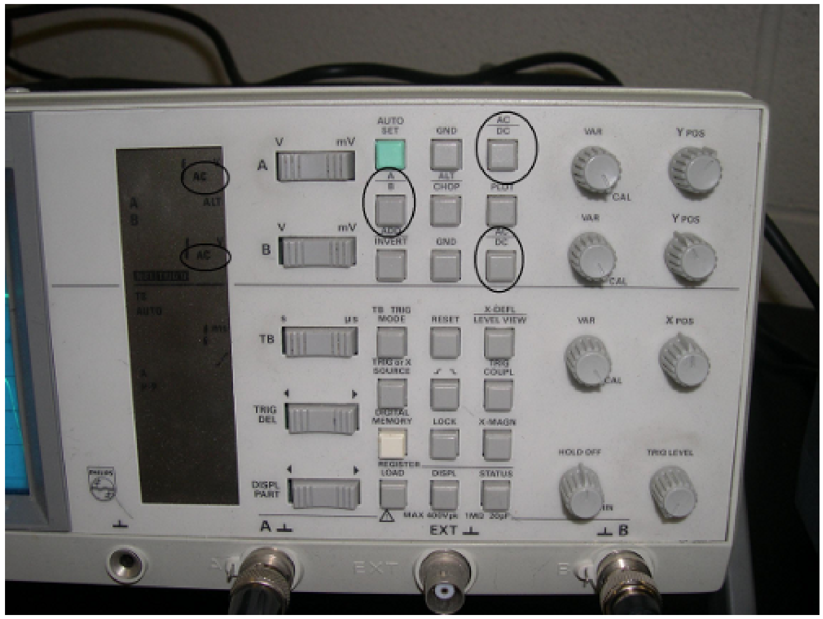


Figure 6.8: The scope is now set up to view the input signal on channel A and the output signal on channel B.

f) Use the AC/DC buttons (also circled) on **both** channels of the oscilloscope to set both Channels A and B to AC coupling. The LCD panel should now show AC for both channels (also circled).

2. **Triggering.** The triggering on an oscilloscope lets the oscilloscope know where on the signal it should start its trace. When set properly, the signal will start each trace in the same location. If not set properly, the signal will be very erratic and it will be extremely difficult to make any measurements. The output signal in this experiment is significantly larger than the input signal. Therefore, you want to set the oscilloscope to trigger on the output signal (channel B). Use should use the TRIG COUPL button on the oscilloscope until P-P is visible on the LCD panel. Then, push the TRIG x SOURCE button on the oscilloscope until "B" is visible just below the P-P on the LCD panel. Set the trigger level knob to the middle of its range.

3. With the current setup, turning the OFFSET knob on the amplifier should not affect the vertical position of the output trace on the

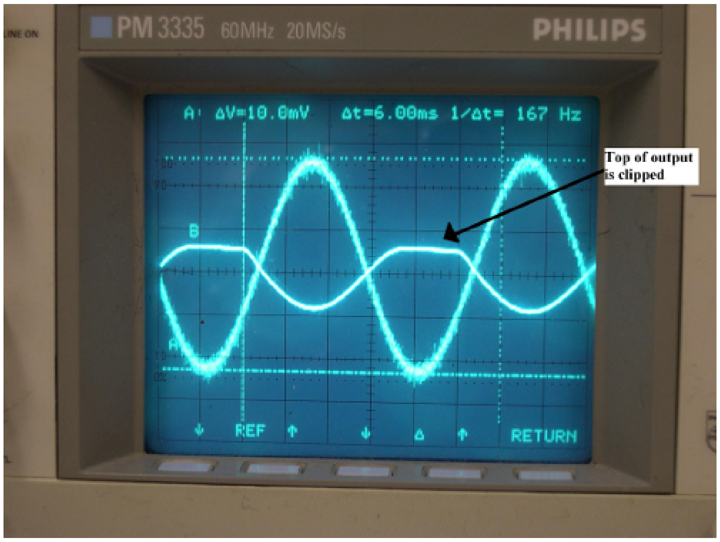


Figure 6.9: Output of amplifier is clipped.

oscilloscope (except momentarily).

4. If during any of your measurements the output signal looks clipped (that is, either the top or the bottom is cut off as in Fig. 6.9), you will have to adjust the OFFSET knob, until the entire signal is visible (see Fig. 6.10). Notice the amplifier output on the screen of the oscilloscope appears smaller than the input. This is because the voltage sensitivity for the output and the input are NOT set to the same level. If both the top and bottom are cut off (see Fig. 6.11), you most likely have the amplifier set to high gain, so switch it back to low gain.

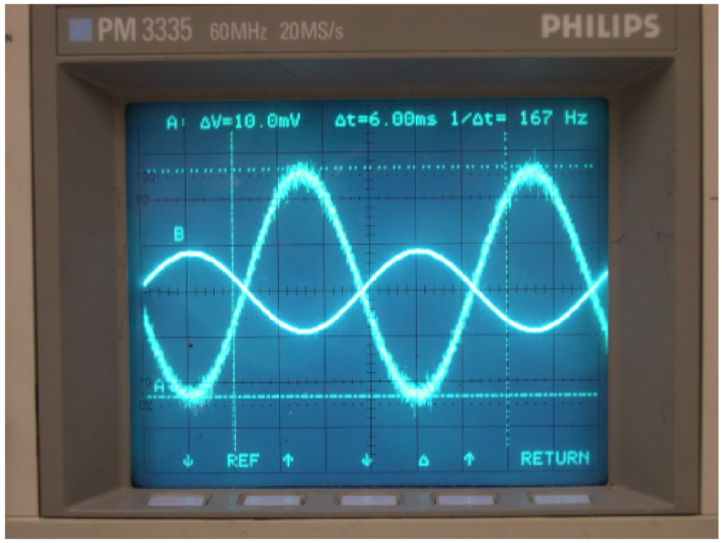


Figure 6.10: After adjusting OFFSET knob, output is no longer clipped.

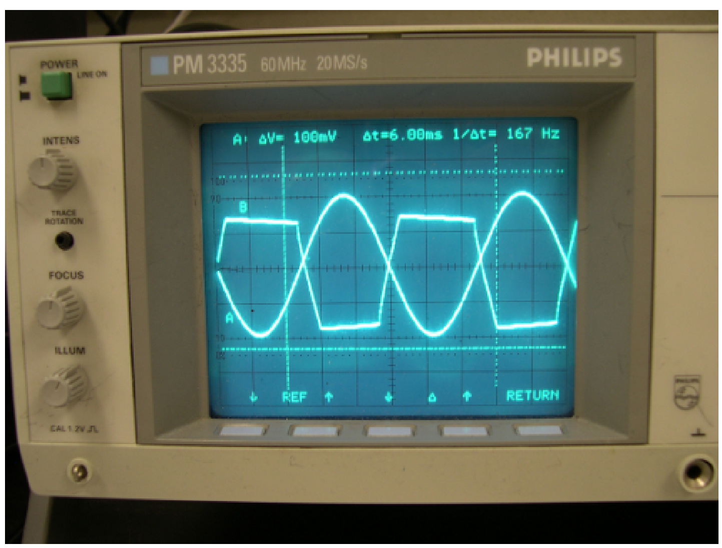


Figure 6.11: Top and bottom of output are both clipped (check input voltage and gain setting on the amplifier).

Part I. Gain of the differential amp (at a constant frequency $f = 200$ Hz)

1. Set signal generator frequency at 200 Hz.

2. Set the peak-to-peak voltage of the input signal to 10 mV. To set this, view channel A. Adjust the output amplitude knob on the signal generator to set the desired voltage. Set your 10 mV peak-to-peak limits with the cursors. Adjust the amplitude knob on the signal generator to increase or decrease your signal until it fits the cursor settings.

3. Measure the peak-to-peak voltage of the output. To measure the output voltage, view channel B on the scope and use voltage cursors to measure V_{pp}. Record the data in your Excel spreadsheet data table (under INPUT 1 = V_{IN}). Make sure the signal on Channel B of the oscilloscope has the same waveform as the input signal. If clipping occurs, adjust the OFFSET on the amplifier. Do not exceed an input voltage of 30 mV on Channel A.

4. Repeat the previous 2 steps for other input voltages shown in the data table.

5. **Plot** the output (vertical axis) vs. input (horizontal axis) voltage.

Part II. Gain as a function of frequency (at a constant $V_{\text{IN}} = 10$ mV)

1. Refer to your Excel spreadsheet for the lowest frequency setting in the second table and set the signal generator to that value. Set the input to 10 mV peak to peak. Measure and record the uncertainty in the input voltage (δV_{IN}) in your Excel spreadsheet.

2. Measure the output of the differential amp for each frequency shown in your Excel spreadsheet, from the lowest to the highest.

3. Measure the output of the differential amp for each frequency shown in your Excel spreadsheet, from the lowest to the highest.

4. **Plot** gain (vertical axis) vs. frequency (horizontal axis) on a semi-logarithmic[1] graph. Use a logarithmic scale on the frequency axis. To do this select "AXIS OPTIONS" from the PLOT pull-down menu in Kaleidagraph and then change the scale setting from linear to log.

[1] "semi-logarithmic" means that one axis is in log scale and the other is not.

6.8 Questions

Part I.

1. In practice, a linear gain amplifier is the goal. How did your amp do? This predicts a linear relation between V_1 and V_{out} . Does your data support a linear gain? How can you tell this from your data and graph?

2. Find the gain of your amplifier from the slope, including its uncertainty (you will need the gain of your amplifier for next week's experiment).

Part II.

3. Your frequency variation would have “passed by” 200 Hz again, which you used in Part I. Is your measured gain at 200 Hz consistent with your measurement in Part I? If not, suggest a possible explanation for the inconsistency. The equation for uncertainty in gain is

$$\delta(\text{gain}) = \text{gain}\left(\frac{\delta V_{\text{IN}}}{V_{\text{IN}}} + \frac{\delta V_{\text{OUT}}}{V_{\text{OUT}}}\right) \tag{6.8}$$

4. What happens to the gain of the differential amp at high frequencies?

5. Over what frequency range is the amplifier gain most reliably constant?

Experiment 7

Bio-Electric Measurements

7.1 Objectives

- Determine the amplitude of some electrical signals in the body.
- Observe and measure the characteristics and amplitudes of muscle potentials due to the heart muscles (EKG).

7.2 Introduction

Many biological systems, ranging from the single cell to the human body produce electrical signals that can be detected and recorded by sensitive electronic equipment. In recent years, the study of these signals has played an increasingly important role in the biological sciences, particularly in human medicine. Recently, there has been much interest in the electrical characteristics of plants. Even though research in this area is still in its infancy, there seems to be some evidence that plants change their electrical characteristics in response to changes in the environment.

While a complete explanation of the origins of electric phenomena in biological systems is not possible here, we will introduce the very basic concept of electricity produced by ionic diffusion. The weak electrical signals measured in this experiment are typical of those encountered in animal and plant cells. Through this experiment you will gain the basic knowledge of bio-electric measurements and the precautions necessary for obtaining meaningful data from biological systems.

7.3 Key Concepts

As always, you can find a summary on-line at HyperPhysics[1] . Look for keywords: bioelectricity, electrocardiogram, electric shock

7.4 Theory

When the heart is at rest, the inside of the heart muscle cells are negatively charged and the exterior of the cells are positively charged. The cells are said to be polarized. Depolarization and repolarization of the heart muscle cells causes the heart to contract and blood to be pumped throughout your system. Depolarization is accomplished when some of the positively charged ions move through the cell membrane, resulting in a lower potential difference between the exterior and interior of the heart muscle cells. Shortly after depolarization, positive ions move back to their original location and the heart cells are repolarized. Fig. 7.1 is an electrocardiogram (EKG) of two successive heartbeats.

The P-wave represents the depolarization of the two atrium chambers of the heart. The Q, R and S waves represent the depolarization of the two ventricle chambers of the heart. The T wave represents the repolarization of the two ventricle chambers. The atria are repolarized at the same time as the ventricles are depolarizing and are therefore obscured by the much larger ventricle depolarization.

The EKG can be measured by placing electrodes on the surface of your body. However, the resistance of dry skin is fairly high and it is necessary to reduce this resistance in order to obtain any measurements. This can be done by applying a conducting paste or gel to the skin. In this lab you will use adhesive, disposable foam, single use EKG electrodes which contain a hydrogel to reduce the resistance of your skin.

In addition to measuring cardiac signals in this experiment, you will observe AC noise, which your body picks up because it acts as an antenna.

[1] http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

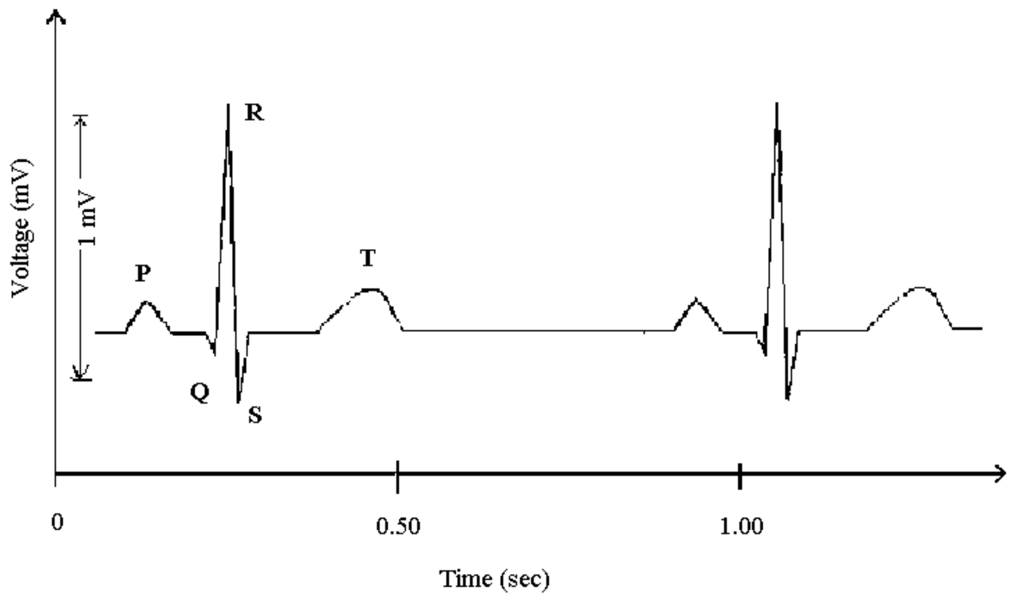


Figure 7.1: Electrocardiogram (EKG) of two successive heartbeats with different waves labeled.

7.5 In today's lab

In this experiment we will look at a specific biological measurement, the electrical potential produced by the human cardiac muscles. The heart puts out a signal varying from about -1 mV to $+1$ mV at a frequency of about $\frac{72 \text{ beats}}{60 \text{ s}} = 1.2$ Hz, corresponding to the contractions of the cardiac muscles. Customarily, placing an electrode on the skin of each arm makes this measurement. There is an arm-to-arm DC potential of about 20 mV due to the biceps and shoulder muscles. In addition, the whole body acts as an antenna picking up electromagnetic waves from the surrounding space. These signals are mostly 60 Hz from the 60 Hz power lines in the building. In a typical situation this may produce a potential between any two points on the body of 50–60 mV with a dominant frequency of 60 Hz. Thus, the cardiac signals are completely lost in the noise. Fortunately, we can use an amplifier to boost the signal from the cardiac muscle.

If the differential amplifier is connected to a subject as in Fig. 7.2 with an electrode on each arm and one on a leg, which is the common reference point,

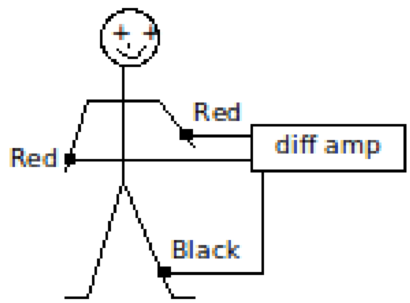


Figure 7.2: How we connect the amplifier to a person.

the cardiac muscle signals can be monitored. The AC coupling feature will remove the DC level from the input due to the large muscles in the body. The inputs to the amplifier are the AC potential differences between the right arm and right leg, and between the left arm and right leg. The difference will be the AC potential difference between the right arm and the left arm. The noise induced by EM waves passing through the body is common to both arm-leg inputs and thus is removed by the common mode rejection feature, with the leg input as the reference. The output is the amplified cardiac signal alone.

7.6 Equipment

- Differential amplifier
- Oscilloscope
- Disposable electrodes

Safety Precautions

Any time electronic equipment is connected to a human or animal subject, the matter of electrical shock must be considered. The severity of shock depends on the amount of current flowing through the body and the frequency of that current. See Figs. 7.3 and 7.4. The amount of current that will flow through the body is determined by Ohm's Law, $I = V/R$, where the voltage is fixed, and the current is determined by the body resistance.

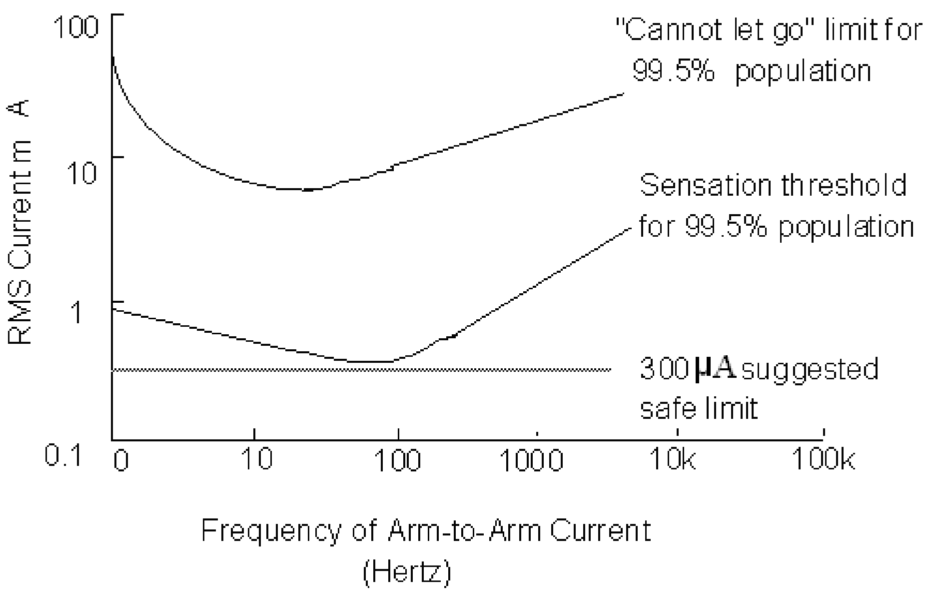


Figure 7.3: Thresholds for effects of current at different frequencies.

The arm-to-arm resistance with contacts on dry skin is of the order of 10^5 Ω. Sticking your fingers in the 120-volt wall outlet would let a current of 1–2 mA flow through your body — definitely painful. With dry skin, the maximum voltage you should even consider touching is 30 volts.

Using the disposable electrodes can reduce your skin resistance to as low as 5×10^{-3} Ω. Such a reduction in body resistance significantly raises the possibility of severe injury from an electric shock.

Electronic instruments used to amplify and measure voltages have no potential difference across their inputs, and therefore present no risk of shock. However, if some malfunction of the equipment were to transpire and allow a high voltage to be present at the inputs, a severe shock to the subject could result. Although the probability of such a malfunction is very small, even one incident of shock in thousands of subjects would be unfortunate. Therefore, the system you will use completely precludes the possibility of large voltages being present at the inputs of the differential amplifier.

The safety device used is known as an **optical coupler**. An optical coupler converts the output of the differential amplifier to an optical signal;

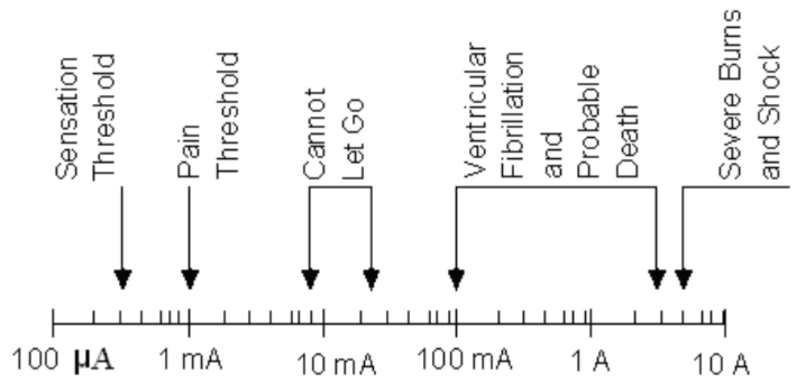


Figure 7.4: Effects of current that is oscillating at 60 Hz.

this optical signal is then detected and converted back to an electrical signal which can be displayed on the oscilloscope. Therefore, **no electrical path exists between the differential amplifier and the measuring device.**

7.7 Procedure

AC noise signal

First, we shall view AC noise voltages, which the body picks up from the surrounding power lines and cables. This forms a large portion of the signal which you would detect if you were to connect a set of electrodes from your body to the oscilloscope.

1. To observe the AC noise signal, touch the red end of the cable connected to the oscilloscope with your finger (as indicated in Fig. 7.5).
2. Adjust the voltage sensitivity and the time base on the scope to get a reasonable view of the signal.
3. Sketch the noise signal that you see on the scope (Question 1). You may want to press the "lock" button on the oscilloscope to freeze the scope's display (don't forget to push the lock button again to unlock the display afterwards).
4. Measure the peak-to-peak voltage and the frequency of the noise signal. Record this in Question 2 and answer Question 3.

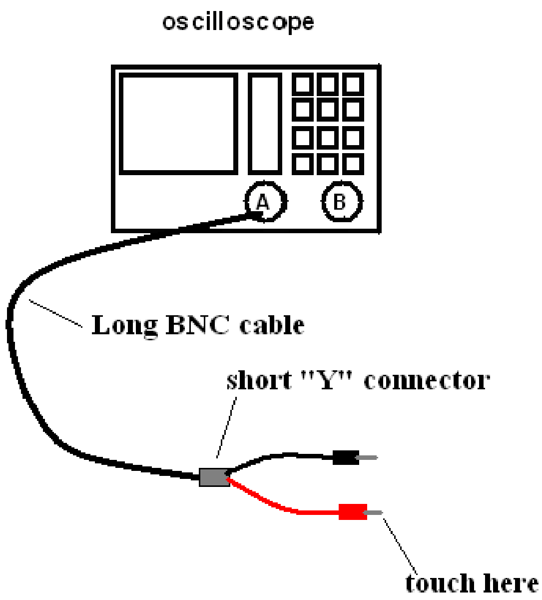


Figure 7.5: Setup to detect AC noise.

AC cardiac signal

Finally, we wish to observe and measure the cardiac signal (EKG). The connections to be made for this section are shown in Fig. 7.6.

1. Attach one electrode to each arm and attach one electrode to the ankle. Clip the red leads to the arm electrodes, and the black lead to the ankle electrode.

2. Connect AC output to channel A of the scope. Set both the scope and the amp to AC coupling. Because the heart muscle is constantly flexing and relaxing, the cardiac signal is a constantly changing voltage. Hence, for this measurement the amplifier should be in AC coupling mode to eliminate offsets due to steady DC potentials.

3. Adjust the voltage sensitivity and the time base on the scope to obtain a reasonable trace.

4. Sketch the cardiac signal (Question 4) that you see on the scope twice: once where you see several heartbeats and once where you can see the

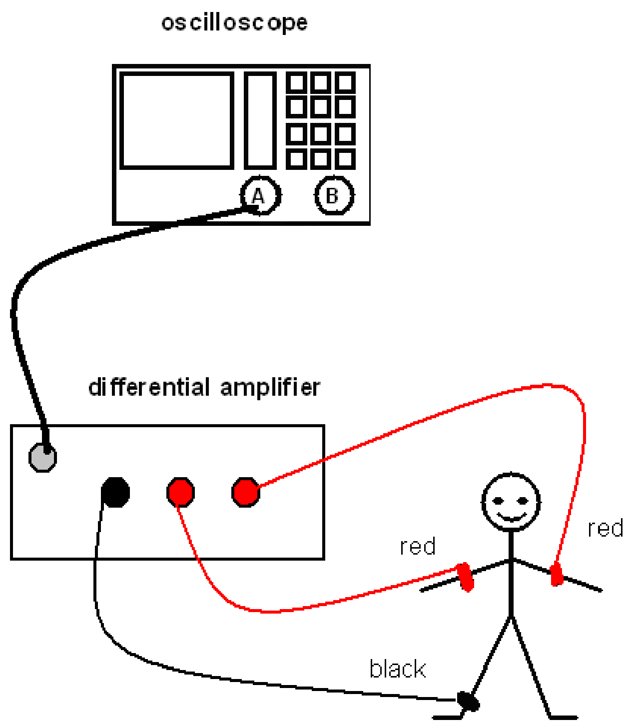


Figure 7.6: Setup to detect the AC cardiac signal.

detail of a single heartbeat. (You may want to freeze the trace by pressing the LOCK button on the scope.)

5. Determine the peak-to-peak voltage and the frequency of the cardiac signal (Question 5) and answer Question 6.

6. Interchange the two red leads. Readjust the amplifier OFFSET knob and observe the heart signal. Sketch what you see on the scope when set up to look at detail of a single heartbeat (Question 7) and answer Question 8.

7. Measure the cardiac signal for the other member(s) in your lab group. Record your results in Question 9.

7.8 Questions

AC noise signal

1. Sketch the noise signal that you see on the scope. You may want to freeze the trace by pressing the LOCK button on the scope.

2. What is the peak-to-peak voltage and frequency of the noise signal? Don't forget the uncertainties and units.

   $V_{\mathrm{pp}} =$

   Frequency =

3. Is the frequency of the noise signal consistent with 60 Hz (i.e. the frequency of electrical signal throughout the room)?

AC cardiac signal

4. Sketch the cardiac signal that you see on the scope twice: once where you see several heartbeats and once where you can see the detail of a single heartbeat. (You may want to freeze the trace by pressing the LOCK button on the scope.)

5. What is the peak-to-peak voltage and frequency of the noise signal? The uncertainty of the peak to peak voltage of the actual cardiac signal is given by

$$\delta V_{\mathrm{pp\ (actual)}} = V_{\mathrm{pp\ (actual)}} \left(\frac{\delta V_{\mathrm{pp}}}{V_{\mathrm{pp}}} + \frac{\delta(\mathrm{gain})}{\mathrm{gain}} \right) \tag{7.1}$$

V_{pp} read from the scope =

gain (from the amplifier lab, Exp. 6) =

actual V_{pp} =

frequency =

6. Predict what should happen to the output of a differential amplifier when its input leads are exchanged, recalling $C = k(A-B)$. Justify your prediction.

7. After interchanging the two red leads, sketch what you see on the scope when set up to look at detail of a single heartbeat:

8. Does this result agree with your prediction?

9. What is V_{pp} and frequency for the second group member?

   V_{pp} read from the scope =

   actual V_{pp} =

   frequency =

Third team member (if present):
V_{pp} read from the scope =

actual V_{pp} =

frequency =

Experiment 8

Diffraction and Interference

8.1 Objectives

- Observe Fraunhofer diffraction and interference from a single slit, double-slit and multiple-slit (a diffraction grating).
- Calculate the slit width, which produces the single-slit diffraction pattern, and observe how the slit width affects the diffraction pattern.
- Verify Babinet's Principle by observing the diffraction pattern from a thin wire.
- Calculate the slit width and the slit spacing for double-slit from the interference pattern produced by light passing through the double slit.
- Calculate the slit spacing of a diffraction grating and thereby determine the ruling density.

8.2 Introduction

The nature of light has been investigated for millenia. There were various theories about light being emitted from our eyes to see things, and light being one of the five elements. Eventually, the question was boiled down to two competing theories: is light a particle or a wave? While we know now that it can act as either a particle or a wave, depending on how you measure it, the diffraction and interference of light is clear evidence for its wave nature. Today you'll experience that evidence.

8.3 Key Concepts

As always, you can find a summary on-line at HyperPhysics[1] . Look for keywords: interference, diffraction, double slit, diffraction grating

There are many simulations of diffraction and interference on the web. Here are some of the author's favorites:

- http://ngsir.netfirms.com/englishhtm/Diffraction.htm. Single-slit diffraction. You can adjust the wavelength and slit width.
- http://ngsir.netfirms.com/englishhtm/Interference.htm. Double-slit diffraction.
- http://www.falstad.com/ripple/. Comprehensive "ripple tank" simulation. You can select which configuration you want from the top menu on the right, including single and double slit, as well as more complicated wave phenomena.

8.4 Theory

Wave Behavior Around Barriers and Slits

All of the phenomena in this lab result from the same physical consequence of wave interference. Recall that when two waves encounter one another, they add and subtract – they "interfere." In this lab we force light of a single wavelength (from a laser) to pass through slits or around obstructions near the laser and shine on a screen more than a meter away (except for the diffraction grating, where the screen will need to be much closer). Because the slits are of finite size, different "rays" come from slightly different places near the slits and so they might travel over slightly different path lengths to get to the screen. So depending on those path lengths, they might arrive in phase, a bit out of phase, or totally out of phase which results in a bright, dim, or no light. Constructive interference takes place at certain locations where two waves are in phase (for example, both waves have a crest). Destructive interference takes place where two waves are out of phase (for example, one wave has a crest, the other has a trough).

[1] http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

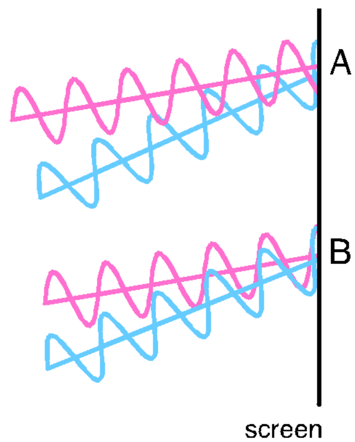


Figure 8.1: Two waves impinging on a screen from a slit arrangement (unseen from the left.

The two extremes are shown in Fig. 8.1. Each circumstance can result from rays of light emerging from two different slits (high or low) or two spots from within a slit (the top of it, the bottom of it, or anywhere inside).

At point A on the screen the two rays arrive out of phase (pink electric field vector going down where blue field is going up) and so the screen at A would be dark. Whereas in B, the two rays arrive with both pink and blue going up together, so they are in phase and the spot would be bright at B.

There are two physical consequences which are explored in this lab. The first is called **diffraction** which occurs when light passes by a single obstruction or through a tiny opening — a slit. The important quantities are the size of the opening or obstruction as compared with the size of the wavelength. Sound is the most common experience of this: it's not nice, but you can eavesdrop out of sight on what goes on around the side of a door and you can stand behind someone at a concert and still hear because the size of sound's wavelengths is comparable to the size of door openings or people: the waves of sound Diffract (or creep or bend) around the edges of these objects. Light's wavelengths (visible light, not AM radio "light") are short compared to openings or obstructions that we're used to in real life. So in labs like this one, we use machined slots and wires to make waves do their interference thing.

The first part of the lab studies diffraction through a single slit. The second part studies "interference"[2], and there's a famous physics story there.

The story is this: Isaac Newton was convinced that light was made of "corpuscles" because he was motivated by observing reflection of light, which to him seemed to be like mechanical bouncing of these corpuscles from a shiny surface. He knew about diffraction and he did a wild dance around that subject to make it fit his (wrong) idea. Rivals in continental Europe disagreed on this subject, notably Christiaan Huygens who insisted that light was a wave. Because the British were particular proud of Newton, they would not tolerate disagreement from his ideas and this bull-headedness persisted until the early 1800s.

Interference and diffraction from two slits

Suppose we have the situation with two slits, *but one is blocked* — so it's just a one-slit situation, like the first scenario we'll encounter during the lab.

[2]These phenomena are all effects of interference, but we reserve the word "diffraction" for these single-slit or single-obstruction phenomena and use the word "interference" for phenomena that involve passing a wave through multiple slits or obstructions.

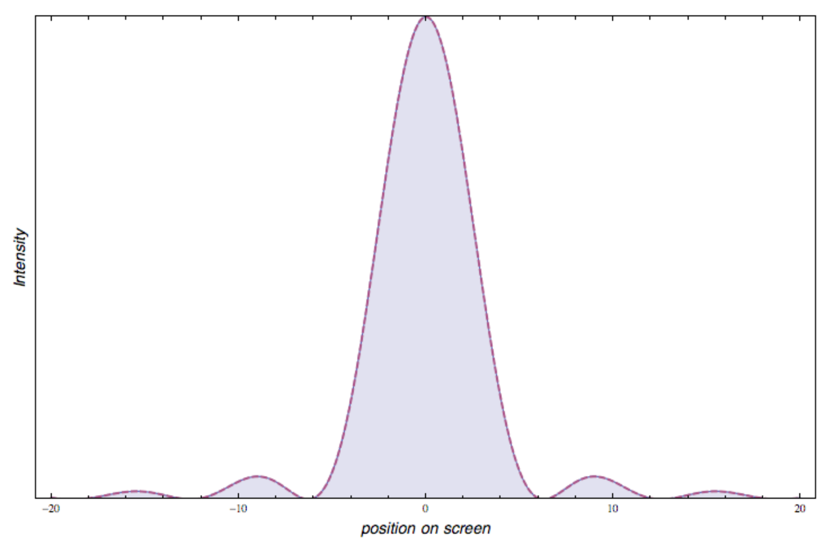


Figure 8.2: Intensity of light from diffraction through a single slit.

Fig. 8.2 shows the intensity of light which has passed through such a single slit and is diffracting. (The units are arbitrary, but all of the same scale.) In the lab, this is what you will see: dark and light places on the screen corresponding to where the wave on the figure goes to zero or is above zero, respectively, due to passing through a single slit. For a diffraction minimum to occur, the path length difference for the two waves must be an odd-integer-wavelength. This makes that the condition is

$$a \sin \theta_n = n\lambda. \tag{8.1}$$

Since $\theta_n = \arctan\left(\frac{x_n}{D}\right)$, we can write

$$\sin \theta_n = \sin \left[\arctan \left(\frac{x_n}{D} \right) \right]. \tag{8.2}$$

Therefore, combining Eqs. 8.1 and 8.2,

$$a = \frac{n\lambda}{\sin\left[\arctan\left(\frac{x_n}{D}\right)\right]}. \tag{8.3}$$

Here, a is the slit width, n is the order number of the diffraction minimum, λ ("lambda") is the wavelength of light, D is the distance from screen to slit, x_n is the distance from the principal maximum to the nth diffraction minimum, and θ_n is the angle from the center line to the n diffraction minimum. Eq. 8.3 is called the Diffraction Equation.

Note that x_n is a signed distance: it is positive for n positive, and negative for n negative. For small values of θ_n, $x_n \ll D$ and $\sin\theta_n \approx \tan\theta_n \approx \theta_n$. This is commonly called the **small angle approximation.** Using this equation, Eq. 8.3 reduces to

$$x_n = \frac{n\lambda D}{a}. \tag{8.4}$$

Now suppose you open the second slit: you would think that opening another "window" would add more light! But Fig. 8.3 shows what actually happens. (Remember, these are intensity plots. Where the blue curve is high, that means "bright" and where the blue curve is less high, "less bright", and where it's zero, that's "dark".

Where there was lots of light in the single slit case, in the middle between $x = -6$ and $+6$, there are now places where it's dark... there are lots of dots of dark spots next to dots of light. **Adding more light by opening**

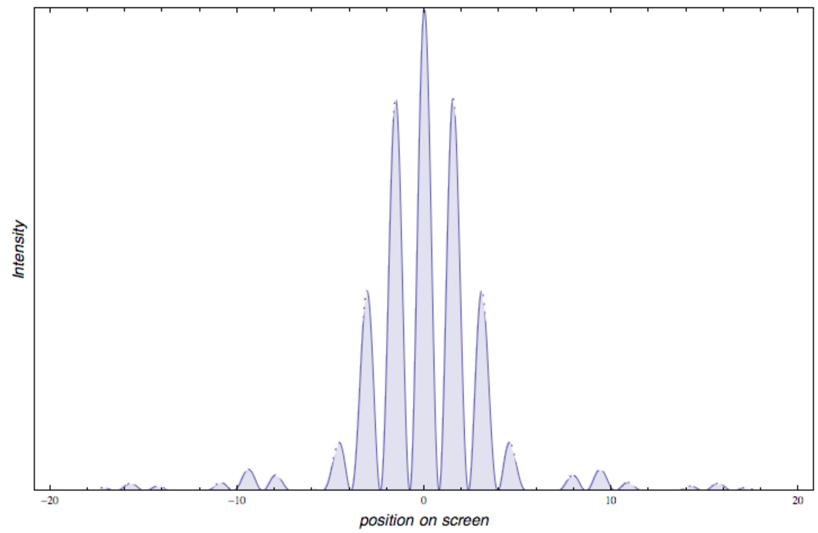


Figure 8.3: Intensity of light from diffraction through 2 slits that are close to each other.

the second slit leads to dark places! Only waves can do that and that was what the precocious Thomas Young tried to point out to his British colleagues about a century after Newton's death. He was so scorned and badly treated for this anti-Newton idea that he was basically forced to leave science. (He went into linguistics and deciphered the Rosetta Stone!) So what's going on here?

It's a combination of two things: interference of light from the **two slits** *plus* diffraction of light from **within each slit**.

Let's take the interference part first. Suppose that the slit dimensions are tiny, tiny, tiny relative to the distance between them. Then the light would pretty much interfere only due to their traveling to the screen from two different starting points (the two slits) and the intensity distribution would look like what's shown in Fig. 8.4. Lots of bright-dark-bright-dark fringes — a "picket fence" of intensity. This is what Young saw, and here's a link to a Java simulation of interference: `http://ngsir.netfirms.com/englishhtm/Interference.htm`.

But if we make the slits larger and larger so that they are not so small relative to the distance between them we get the image pattern in Fig. 8.3: The Interference effect competes with the Diffraction effect. I've reproduced

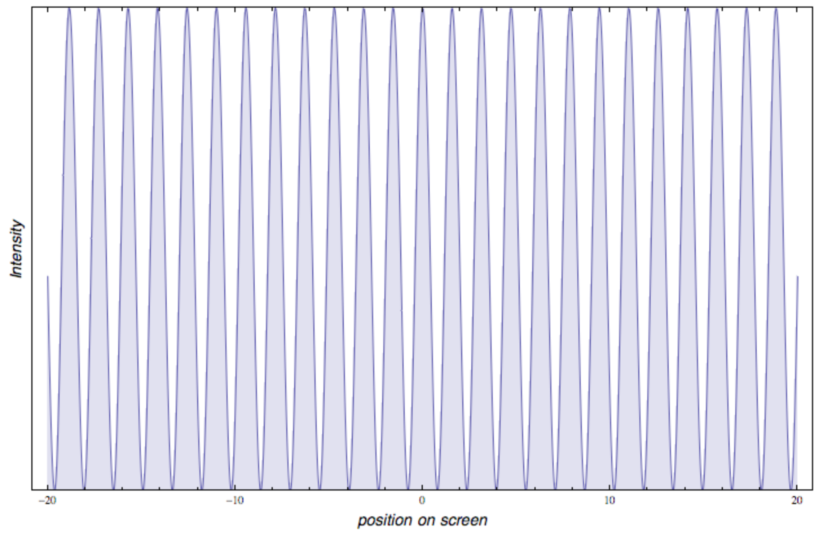


Figure 8.4: Intensity of light from only the two slits interfering with each other, not from the light from different edges of the same slit.

this in Fig. 8.5 where I've now plotted the Diffraction envelope due to the slit widths and overlaid it on the interference "picket fence" from the two slits themselves. Where there is no light reaching the screen because of the Diffraction, the picket fence goes to zero. Only where the Diffraction allows light to make it to the screen will the Interference pattern be visible.

If you look closely you'll see that as you go from the center peak to the right or left, the picket fence repeating pattern skips one. That's where the Diffraction takes over and doesn't allow any light to interfere from the two slits.

This actually may occur at exactly a picket fence point when

$$m = \frac{d}{a}, \tag{8.5}$$

where m is the order of interference *maximum* and d is the distance between the centers of the slits.

For the situation shown in Fig. 8.3, this happens exactly at

$$m = \frac{d = 4}{a = 1} = 4, \tag{8.6}$$

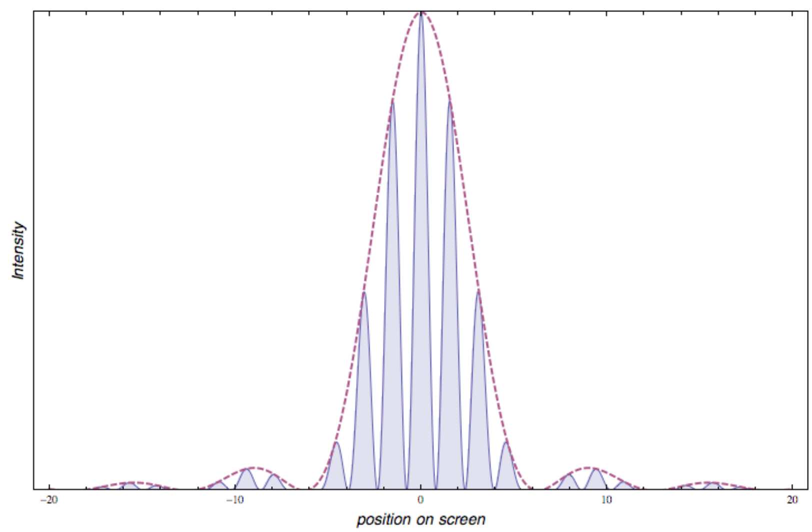


Figure 8.5: Intensity of light from the two-slit experiment, but with the one-slit diffraction pattern overlaid with the dotted purple line.

where the units of length are arbitrary in this calculation. The ratio refers to the 4th interference maximum from the center peak, which you can see is missing (remember that the counting starts with $m = 0$ at the center).glass, watch surface, jewelry, etc.

In this lab you will be able to see this happen. You'll see the picket fence and the places where the "slats" skip and then continue on. The distance from the central maximum to the mth interference maximum (a picket) is given by

$$x_m = \frac{m\lambda D}{d} \tag{8.7}$$

Both this equation and the equation for single slit diffraction (Eq. 8.4) use the small angle approximation, since there isn't a very big deflection of the laser.

Note that the algebra looks the same as for the Diffraction equation (Eq. 8.4), except that x_m refers to the location of **maxima**, not minima and d is the **spacing** between the two slits, not the width of the individual slits.

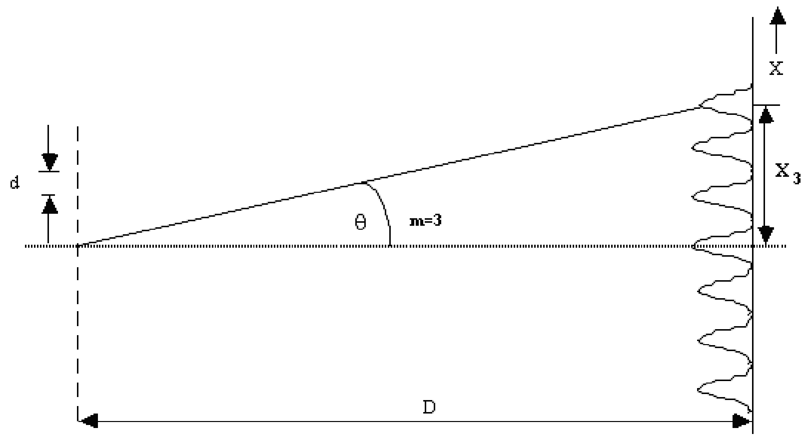


Figure 8.6: Pattern produced by a diffraction grating.

Multiple-slit interference and diffraction (a diffraction grating)

If you now use many, many slits, spaced extremely closely together, you get what is called a diffraction grating. Although a multi-slit grating is commonly referred to as a diffraction grating, a more appropriate name for it is an interference grating. The phenomenon that is observed, seen in Fig. 8.6, is interference and not, as its name suggests, diffraction. The condition here for interference maxima is the same as for double-slits, but the pattern may be very different because d (the slit spacing) for gratings is very small.

$$d \sin \theta_m = m\lambda. \tag{8.8}$$

Thus,

$$d = \frac{m\lambda}{\sin\left[\arctan\left(\frac{x_m}{D}\right)\right]}. \tag{8.9}$$

Note: the angles involved when using the diffraction grating are large; therefore, you cannot use the small angle approximation here.

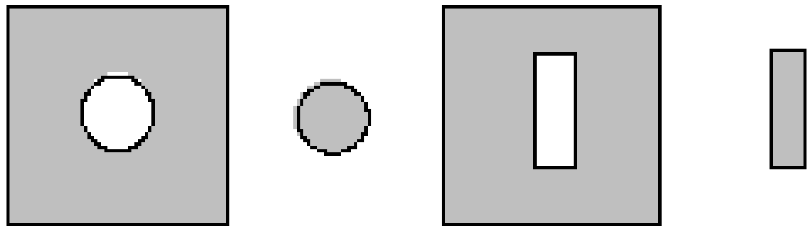


Figure 8.7: Examples of complementary screens. The gray regions are opaque and the white regions are transparent.

Babinet's principle

Two screens are said to be **complementary** when the transparent regions on one exactly correspond to the opaque regions on the other and vice versa. Fig. 8.7 shows two examples of complementary screens. Babinet's Principle implies that the Fraunhofer diffraction patterns from complementary screens are nearly identical. Thus, if a thin wire were placed in the laser beam, one would expect to obtain a diffraction pattern similar to that of a single-slit.

Why don't we see diffraction in daily life?

The peak spacing is **smaller** for **larger** object size. Common objects are much larger than the wavelength of light, so any interference effects are also usually too fine to notice. Further, in every day life, we use light with a variety of wavelengths, so that peaks of one wavelength tend to land on valleys of another wavelength. Thus diffraction effects are not only too small for our eyes to resolve, but are also smeared out because the wavelength is not a single well-defined value. Using small objects with a single well-defined wavelength helps us see these effects in the lab.

8.5 In today's lab

The simplest diffraction and interference patterns involve plane waves (collimated or parallel light beams). Diffraction patterns associated with plane waves are called Fraunhofer patterns, named after the German scientist who first explained the effect. In this experiment, we will use a laser as our light source. A laser produces collimated and coherent light beams at one wavelength, which makes the interference patterns crisp and easy to see.

8.6 Equipment

- optics bench
- laser mounted on bench, wavelength $\lambda = 650$ nm
- screen mounted on bench
- single slit diffraction wheel
- multi-slit diffraction wheel
- diffraction grating with mount
- rectangular frame with mount
- meter stick

Safety Tips

The laser is a device that can produce an intense, narrow beam of light at one wavelength. NEVER look directly into the laser beam or its reflection from a mirror, glass, watch surface, jewelry, etc.

8.7 Procedure

You will collect one set of data for the group. **Write the names of all group members on the data sheet(s) and attach to one group member's lab report.**

The single slit

As you do this part of the experiment, you should answer Questions 1–3.

1. Mount the single-slit wheel in the path of the laser beam (between the laser and the screen). The pattern is most easily seen with the slit near the laser and the screen far away. Try different slits and observe their diffraction patterns on the screen.

2. Choose a slit that gives a diffraction pattern of reasonable size. Measure the distance from the slit to the screen (D) and record the labeled slit width in an Excel spreadsheet.

3. Attach a piece of paper across the screen where you see the diffraction pattern. Mark carefully the positions of the center of the principal maximum and the center of several orders of **diffraction minima** on either side of it. Remove the paper from the screen and attach it to your lab report, writing the names of all the group members on it. Answer Question 1.

4. Measure the distance of each minimum from the principal maximum (x_n) and record them in an Excel spreadsheet. Have Excel calculate the slit width (a) using Eq. 8.4. *Use negative x_n and n for the positions to the left of the principal maximum.*

5. Have Excel calculate the mean value of the slit width and the standard deviation of the mean value. (The Excel formula for standard deviation of the mean is `=STDEV(cell1:cellN)/SQRT(N)`, where `N` refers to the total number of measurements). You can use the standard deviation of the mean value as the uncertainty in your slit width (δa).

Babinet's Principle

As you do this part of the experiment, you should answer Questions 4–7.

1. Place a thin wire in the laser beam.

2. Measure the distance between the wire and the screen (D) and record the labeled wire diameter.

3. Tape a piece of paper to the screen. Mark the positions of the principal maximum and the **diffraction minima**.

4. Measure the distance of each diffraction minimum from the principal maximum and record them in an Excel spreadsheet. Have Excel calculate the diameter using the appropriate equation.

5. Have Excel calculate the mean value of the wire diameter and the standard deviation of the mean value.

The double slit

As you do this part of the experiment, you should answer Questions 8–12.

1. Mount the multi-slit wheel in the path of the laser beam. Try different double-slits.

2. Choose a double-slit that gives a reasonable pattern. Measure the distance from the slit to the screen (D) and record the labeled slit width and slit spacing.

3. Tape a piece of paper across the screen where you see the pattern. Mark carefully the positions of the principal maximum, the **interference maxima**, and the **diffraction minima** on the paper. (You may want to distinguish the marks for each kind.) Remove the paper from the screen and attach it to your lab report and answer Question 8.

4. Measure the distance of each **interference maximum** from the principal maximum (x_n) and record them in an Excel spreadsheet. Have Excel calculate the slit spacing using Eq. 8.7.

5. Have Excel calculate the mean value of the slit spacing and the standard deviation of the mean value.

Multiple slit interference and the diffraction grating

Your lab instructor will tell you if you are to complete this section. As you do this part of the experiment, you should answer questions 13–14.

1. Place the grating in the laser beam (this time, **close** to the screen, not far away).

2. Measure the distance from the plane of the grating to the screen (D) and record it in an Excel spreadsheet.

3. Record the labeled ruling density (grooves/mm) in your Excel spreadsheet.

4. Tape a piece of paper across the screen. Mark carefully the positions of the principal maximum and the **interference maxima**. Remove the paper from the screen and attach it to your lab report (Question 13).

5. Measure the distance of each interference maximum from the principal maximum (x_n) and record them in your Excel spreadsheet. Have Excel use Eq. 8.9 to calculate the slit spacing (d) for each of the maxima. Calculate the ruling density, which is just the inverse of the spacing,
$$\text{ruling density} = \frac{1}{d}. \tag{8.10}$$

6. Have Excel calculate the mean value of the ruling density and the standard deviation of the mean value.

8.8 Questions

The single slit

1. Sketch the pattern you observed when the laser light passed through a single slit. Label some of the significant features.

2. How does the slit width affect the diffraction pattern?

3. Discuss the consistency of the mean value of the slit width with the labeled slit width.

Babinet's Principle

4. Is the position right behind the wire light or dark? Why is this surprising?

5. What is the equation you will use to calculate the diameter of the wire? Clearly define each quantity.

6. Discuss the consistency of the mean value of the wire with the labeled wire diameter.

7. Is your hair thicker or thinner than the wire? How did you find out?

The double slit

8. Sketch the pattern you observed when the laser light passed through a double slit. Label interference maxima and diffraction minima.

9. How is the double slit pattern different from the single slit pattern? Also, what causes the difference in the pattern?

10. How does the slit width affect the pattern?

11. How does the slit spacing affect the pattern?

12. Discuss the consistency of the mean value of the slit spacing with the labeled slit spacing.

Multiple slit interference and the diffraction grating

13. Sketch the pattern you observed when the laser light passed through a diffraction grating. Label the interference maxima.

14. Discuss the consistency of the mean value of the ruling density with the ruling density.

Experiment 9

Emission Spectra

9.1 Objectives

By the end of this experiment, you will be able to

- measure the emission spectrum of a source of light using the digital spectrometer.
- find the wavelength of a peak of intensity and its uncertainty.
- compare and contrast the spectra of various light sources.
- understand that a single color can be made of many wavelengths.

9.2 Introduction

We see very differently than we hear. With sound, we are able to listen to sound and pick out many different frequencies of sound, i.e. different pitches. For example, if we listen to music, we can pick out the drums and voice separately, even though they are happening at the same time. We don't have that capability with light. Instead, we end up seeing one individual color, which most likely is made up of many different wavelengths of light.

In order to see what wavelengths make up a source of light, we use a spectrometer.

9.3 Key Concepts

As always, you can find a summary on-line at Hyperphysics[1]. Look for keywords: "emission, quantum", electromagnetic spectrum

9.4 Theory

Light is either reflected from or emitted by an object. Broadly speaking, there are two types of emission of light: thermal radiation and luminescence.

Energy levels

The electrons of atoms and molecules exist in specific energy states. The energy emitted by the excitation of electrons is limited to differences between these states, thus specific energies of light are emitted. The color of a glowing LED, for example, is determined by the energy of the emitted light. The energy and wavelength of the light is described by the equation

$$E = \frac{hc}{\lambda}, \tag{9.1}$$

where λ is the wavelength, h is the Planck constant ($h \approx 6.63 \pm 10^{-34}$ J s), and c is the speed of light ($c \approx 3.00 \pm 10^{8}$ m/s). If you are measuring the emission spectrum of a gas trapped in a discharge tube, only certain wavelengths of light are emitted by the gas and the "pattern" that is produced is unique for that substance.

9.5 In today's lab

Today we'll be investigating the spectrum of light that is emitted from different sources in the room. First we'll use a diffraction grating to see with our eyes what that spectrum looks like. Then we'll use the digital spectrometer to give us a precise and detailed view of how intense different wavelengths are for a given source.

[1] http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

Figure 9.1: Digital spectrometer. Note the white USB cable and blue optical fiber.

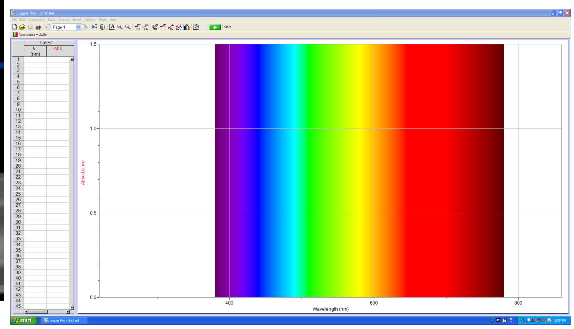


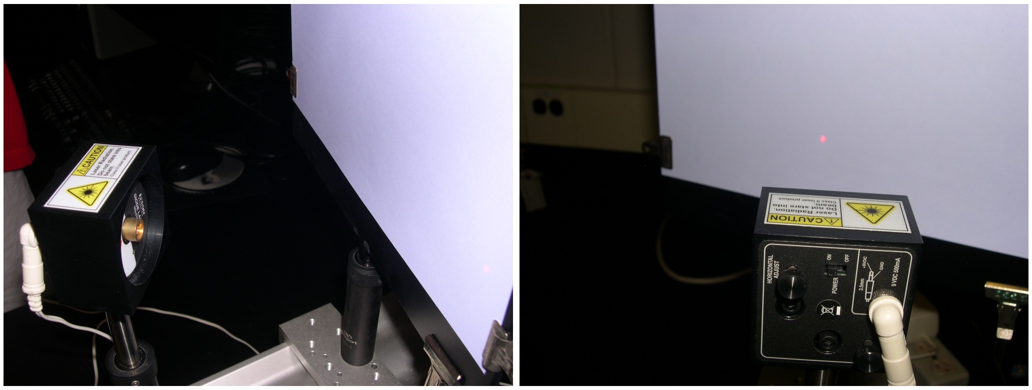
Figure 9.2: Screenshot of Logger *Pro*.

9.6 Equipment

- diffraction grating (Fig. 9.5)
- digital spectrometer with optical fiber (Ocean Optics USB650 Red Tide) (Fig. 9.1)
- Logger Pro (software) (Fig. 9.2)
- Diode laser (Fig. 9.3)
- gas discharge tubes (Fig. 9.4)

Safety Tips

- Gas discharge tubes get **very hot**. Be very careful to let them cool down before touching them.
- The laser is a device that can produce an intense, narrow beam of light at one wavelength. NEVER look directly into the laser beam or its reflection from a mirror, glass, watch surface, jewelry, etc.



(a) Front. (b) Back.

Figure 9.3: Laser mounted on optical bench.

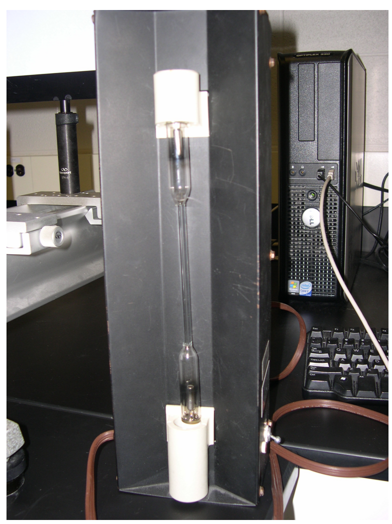


Figure 9.4: Gas discharge tube mounted in box.

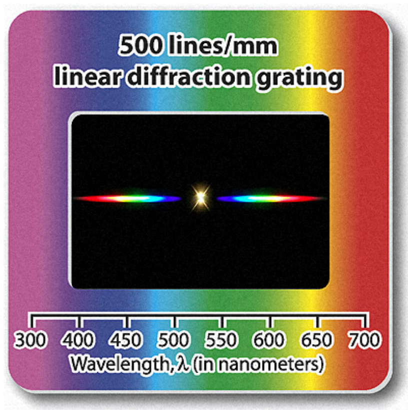


Figure 9.5: The diffraction grating.[2]

Diffraction grating

Seen in Fig. 9.5, a diffraction grating bends light that enters it, changing the light's outgoing direction. It bends lower-wavelength light more than it bends higher-wavelength light. Thus, it spreads out the incoming light according to its wavelength, allowing us to see the individual wavelengths that make up the incoming light.

9.7 Procedure

Setup

1. Connect the SpectroVis Plus spectrometer to the USB port of a computer. Start the data-collection program, and then choose `New` from the `File` menu.

2. Connect a SpectroVis Optical Fiber to the cuvette holder of the spectrometer.

3. To prepare the spectrometer for measuring light emissions: In Logger Pro, open the `Experiment` menu and select `Change Units` ▶ `Spectrometer:1` ▶ `Intensity`.

4. To set an appropriate sampling time for collecting emission data: In Logger Pro, open the `Experiment` menu and choose `SetUp Sensors` ▶ `Spectrometer:1`. In the small dialog box that appears, change the `Sample Time` to 60 ms, change the `Wavelength Smoothing` to 0, and change the `Samples to Average` to 1.

Observing light sources

You will investigate 5 different light sources — the laser, 2 different gas discharge tubes (helium (He) and mercury (Hg)), the overhead lighting, and your choice of an object that is not emitting its own light (just reflecting it). Pick an object that is not the same color as the overhead lighting.

Notes on specific sources

- **Laser.** The laser light is too intense to directly measure with the spectrometer. Instead, point the laser at a sheet of paper and aim the tip of the fiber optic cable at the laser spot on the white paper.
- **Gas discharge tube.** Your TA will show you how to safety insert tubes into the discharge box. The gas may take some time to heat up and emit its complete spectrum, so after turning it on, wait about 3 minutes, then make your observations.

Data Collection and Analysis

Do these steps for each light source after you've set it up.

1. **Observe the light source through the diffraction grating.** You may need to hold the grating at an angle to observe the interference pattern. This is the same method that the digital spectrometer uses to separate out the different wavelengths. **Do not look directly into the laser.** Instead, shine the laser on a piece of white paper and observe the spot on the paper. **Record your observations** using the data table at the beginning of the questions to do so.
2. **Start data collection** on the Logger Pro software. An emission spectrum will be graphed.

3. If the highest peak in the emission spectrum is higher than one, then the sensor is saturated and needs to receive less light. Try moving the detector away from or towards the light source until the highest peak is less than one, or point the optical fiber slightly off-center. If this doesn't help, stop data collection, repeat Step 4, and increase or decrease the `Sample Time`.

4. When you achieve a satisfactory graph, stop data collection. **Write down your observations** of the emission spectrum in the data table at the beginning of the Questions. Specifically, identify the 3 tallest peaks and their wavelengths (no uncertainty needed here), describe the range over which the peaks happen. Be sure to emphasize the features of each spectrum that distinguishes it from the other light sources that you tested.

5. **Print out a copy of the graph.** For the laser, zoom in to the peak. For the others, show the full visible spectrum, 400–700 nm.

6. For the laser and both gas discharge tubes, **find the wavelength of the highest peak** (the most intense light) and its uncertainty. To find the uncertainty, use the "half width at half maximum" (HWHM) of the peak. To assist you, label these points as seen in Fig. 9.6.

    a) The point of peak intensity. Label with the wavelength (x) and intensity (y) at that point.

    b) The two points on either side of the peak where the intensity is half of the peak intensity. Find the wavelength (x) and intensity (y) at those points and label them.

    Then, the HWHM, which is the uncertainty, is found by

    $$\delta\lambda = \frac{\lambda_{\text{max}} - \lambda_{\text{min}}}{2} \tag{9.2}$$

    Include a sample calculation of this for the laser light. Record all of this on each light source's printed graph.

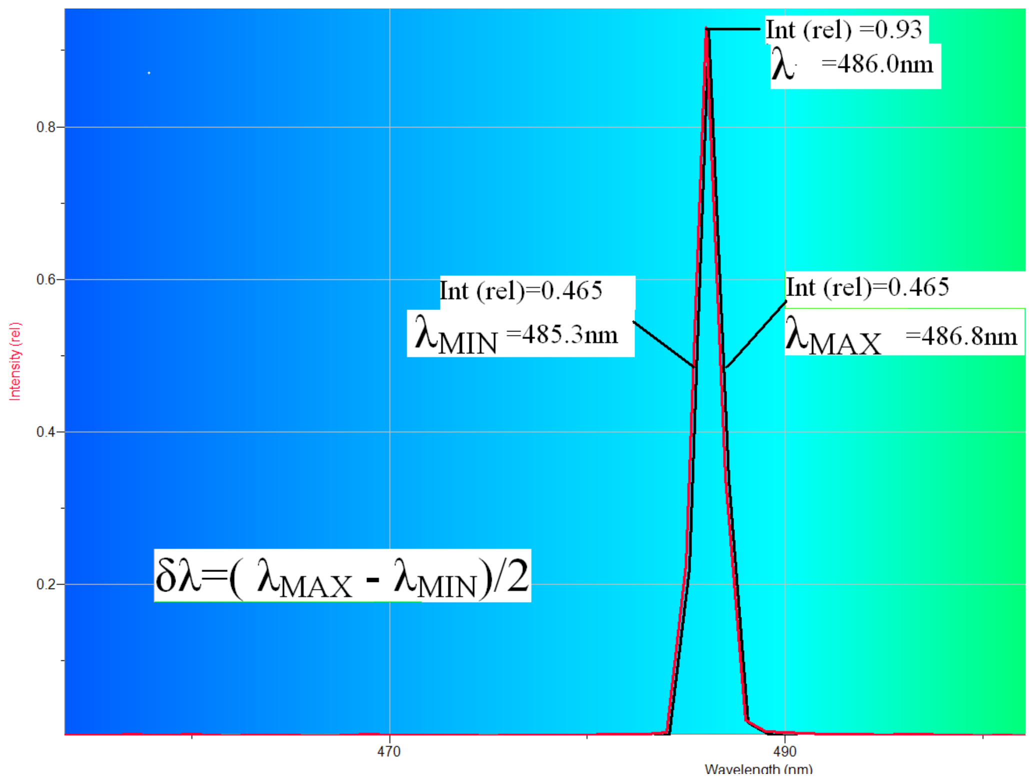


Figure 9.6: Example of how to label the graph of the laser emission spectra to find the HWHM.

9.8 Questions

Light Source	Peaks or unique features of the spectrum
laser	grating:
	spectrometer:
helium gas	grating:
	spectrometer:
mercury gas	grating:
	spectrometer:
overhead light	grating:
	spectrometer:
(reflected light)	grating:
	spectrometer:

1. Look at the overhead lighting. What color is it? Be as specific as you can.

2. Compare your measurement of the wavelength of the diode laser light with the manufacturer's value given to you by your instructor.

3. Compare the most intense wavelength of the helium spectrum to the theoretical value of 587.6 ± 0.05 nm.

4. Compare the most intense wavelength of the mercury spectrum to the theoretical value of 546.1 ± 0.05 nm.

5. Compare the spectrum of the overhead lighting to your answer to Question 1 (qualitatively). How close was your prediction?

6. Compare qualitatively the spectrum of the overhead lighting to that of the object you picked.

7. How many of the mercury peaks are found in the overhead lighting? Would you say there is mercury gas in the overhead lights?

Experiment 10

Color

10.1 Objectives

- Use the digital spectrometer to disperse white light into a continuous spectrum of color and determine the range of wavelengths in the visible spectrum.
- Observe the transmission properties of the three additive-primary color filters and the three subtractive-primary color filters.
- Observe and interpret the color sensations resulting from mixing additive-primary colors and mixing subtractive-primary colors.
- Be able to explain qualitatively the difference between additive and subtractive color mixing.

10.2 Introduction

Color is something we often take for granted (unless we are artists). Grass is green, the sky is blue (well, maybe not in the winter). But how are these colors formed? How can I mix two colors of paint and end up with a third color? I can hear two different sounds at the same time, but why does nothing look like two different colors at the same time?

Color is a complicated subject because it's a combination of physics (wavelengths, frequencies, atomic spectra, light, etc.), the physiology of color as perceived by humans, and history. It's somewhat muddled because through the history of painting and early attempts by Goethe and Newton to craft theories of color, some of the language stuck with use.

10.3 Key Concepts

As always, you can find a summary on-line at Hyperphysics[1] . Look for keywords: light and vision, color, color vision, additive color mixing

10.4 Theory

How do we see color?

White light is composed of light of all wavelengths in the visible range (400–700 nm). Our color vision comes from the fact that we have three different kinds of color receptors ("cones") in our retina. One kind of cone is most sensitive to red; another is most sensitive to green; and the third to blue (though there is overlap — see Fig. 10.1 where the curves are normalized to 1.0.). In fact in humans the number of cones sensitive to blue are fewer and the absolute sensitivity is shown in Fig. 10.2. Stop signs are red and not blue. These three colors are called the **additive primaries**, as they are typically combined to create other colors by combining together positively.

All receptors are sensitive to an overlapping range of colors, e.g. "blue" to violet, indigo, and blue. What color we see is dependent on how much the cones are stimulated with respect to each other. For example, when green and red cones are simultaneously stimulated, we can see orange or yellow, depending on how much more intense the red is with respect to the green. By mixing three additive primary colors with different intensities, we can generate all possible colors. You can convince yourself that Red and Green make yellow from Fig. 10.3.

In order for us to see anything at all, the light has to enter our eyes. The light can come directly from the light source, or it can be reflected from an object. The red light at a traffic signal is red because the light source is red. On the other hand, the red stop sign is red because it reflects red, and absorbs everything else. These represent two kinds of color mixing, additive and subtractive, respectively.

[1] `http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html`

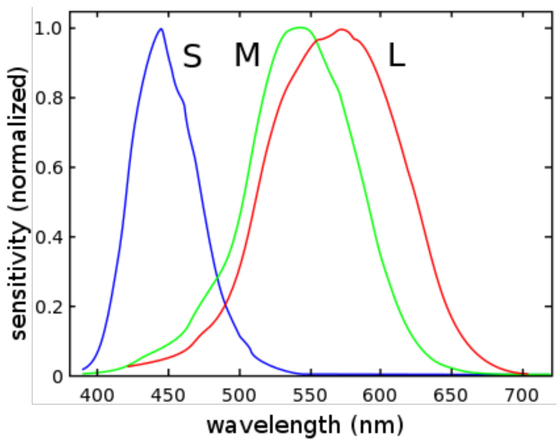


Figure 10.1: Normalized sensitivity vs. wavelength for each of the human eye's three cones[3], labeled S, M, L, and colored according to the primary color to which they are most sensitive. (Image credit: Vanessaezekowitz on en.wikipedia)

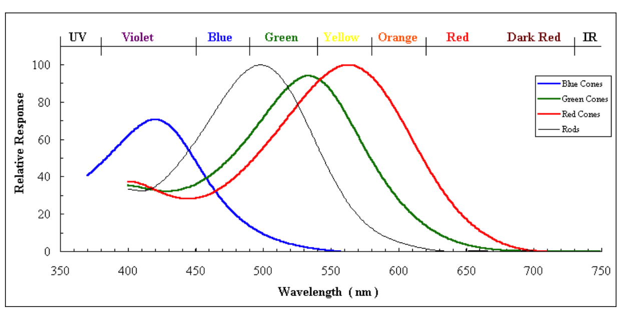


Figure 10.2: Absolute sensitivity vs. wavelength for each of the human eye's three cones. The rod sensitivity shown is not to scale, but is much reduced. (Image credit: E. Toolson)

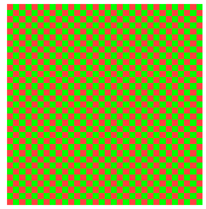


Figure 10.3: Squint at this and see yellow, yet no actual yellow color is in the picture. This is Ferris Bueller's moment with M. Seurat...and how comic books work.

Additive color mixing

When color combinations are additive – like in an older CRT ("cathode ray tube") display, the primaries used are red, green, and blue (from this point on, we'll call them R, G, and B). You start from black and add in the R, G and B colors to make the others. You cannot create black with the additive primaries, rather you can create white. Fig. 10.4 shows the additive color primaries at work. (You will mix these colors in the lab.)

The color wheel that you see on your computer, as in Fig. 10.5, shows the whole color spectrum. Notice that red, green, and blue are equidistant around the edges. You will play with additive colors by creating mixtures of them in a light projection box.

Subtractive color mixing

The earliest thinking about color came from trying to understand painting. Rather than the adding light colors like in our (older) TVs, they had to contend with how to make particular colors on a canvas. This is a **subtractive** process: light from a source, like the sun, falls on the surface of an object (or set of pigments) and is reflected.

But not all wavelengths are reflected; just some reach our eyes which we interpret as the color of that object as in Fig. 10.4. The painter's job is to mix the right pigments together in order to cause other humans to "see" the color he or she desired.

Said more specifically, the painter chooses the pigments necessary in order to take out the wrong colors from light that reflects from the surface leaving the desired color.

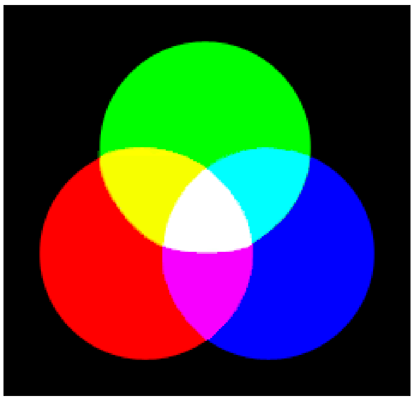


Figure 10.4: Colors adding together in a light projection box.

Figure 10.5: RGB color selection on a computer appropriate for viewing on a screen (additive).

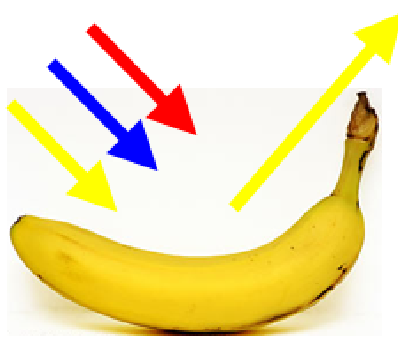


Figure 10.6: This is another way to make yellow: all colors fall on the surface of the banana and are absorbed except the yellow.

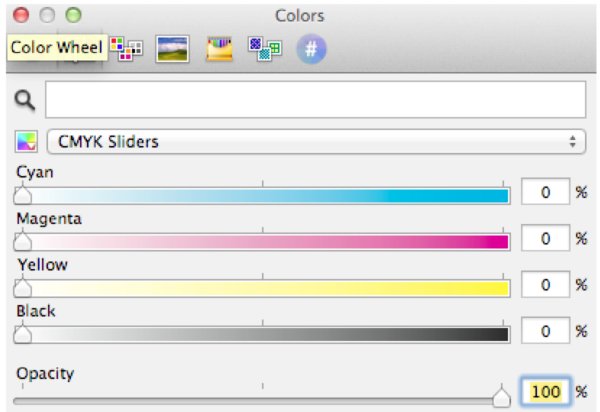


Figure 10.7: You've seen this on your computer as well. It's the color selection appropriate for printing (subtractive).

So color is not an attribute of just the object: it's a combination of the reflection or absorption of light (atomic physics) and our interpretation of that light through our highly-evolved eyeballs (physiology).

The **subtractive primaries** are a convention following a long history of painting and printing. They are now usually Cyan, Magenta, and Yellow, or CMY. Painters like them because you can get truest black using these three colors (which you'll do).[2]

Filters

A filter is a semi-transparent film which passes some wavelengths and not others. Let's deal with the Additive Primaries (R, B, G) and the Subtractive Primaries (C, Y, M) only. Remember: **White light is a mixture of all of the colors**, a controversial fact first worked out by Isaac Newton. So if I pass white light through a filter that removes all wavelengths but R. . . then you'd call that a Red Filter. Likewise, for B and G. Filters are not perfect: a red filter doesn't pass only a single wavelength, but rather a band of wavelengths which are reddish. You'll measure those bands in this lab.

Let's picture the effects of filters on the Additive and Subtractive Primaries in Figs. 10.8–10.9. In each, white light is incident from the left passes

[2]Sometimes you see printers using CMYK, where K stands for "key", which is not black, per se, but a printer-specific designation for the back "key" plate that prints the detail and is, in fact, black.

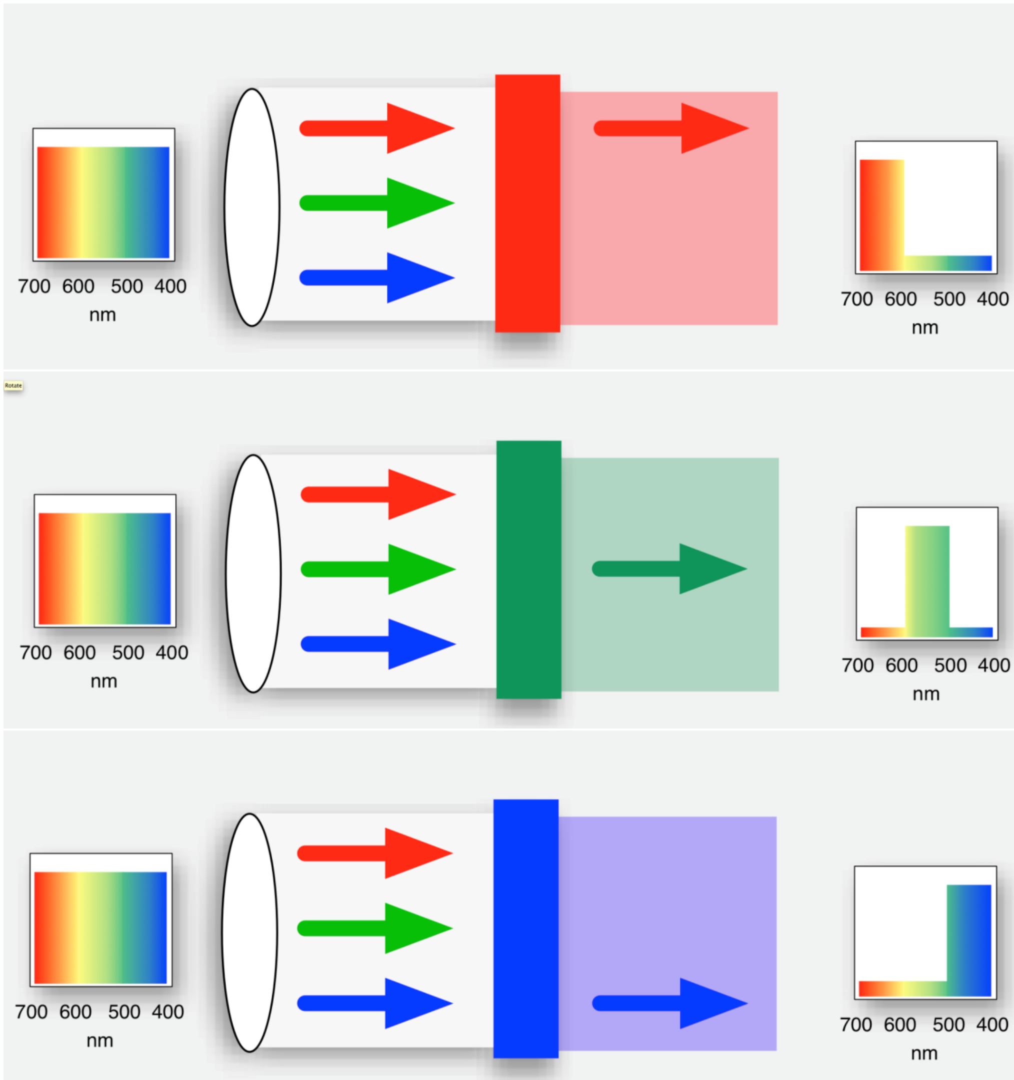


Figure 10.8: White light is incident on red (top), green (middle), or blue (bottom) filters.

through a filter, and only particular wavelengths emerge on the right. A little spectrum window shows the effects.

Maybe not too surprising, if you pass red light through a red filter, all you get is red. What happens if you pass red light through a blue filter?

The Subtractive Primaries can also be fashioned into filters, but here something different happens – both the physics and the perception is different. Fig. 10.9 shows those results. The white light enters from the left and passes through:

. . . a cyan filter — to produce cyan colored light. It does that by removing the longest wavelengths (reddish) leaving the rest – which is represented in the top as green and blue. (Look at the color wheel: the cyan filter removes its complementary color on the opposite side of the wheel – red.)

. . . a magenta filter — to produce magenta light. It does this by removing the middle wavelengths (greenish) leaving the rest which is represented in the middle as red and blue. It too removes its complementary color on the opposite side of the wheel.

. . . a yellow filter — to produce yellow light. It does this by removing the shortest wavelengths (bluish) leaving the rest which is represented in the bottom as red and green. Likewise, it removes its complementary color from the opposite site of the wheel.

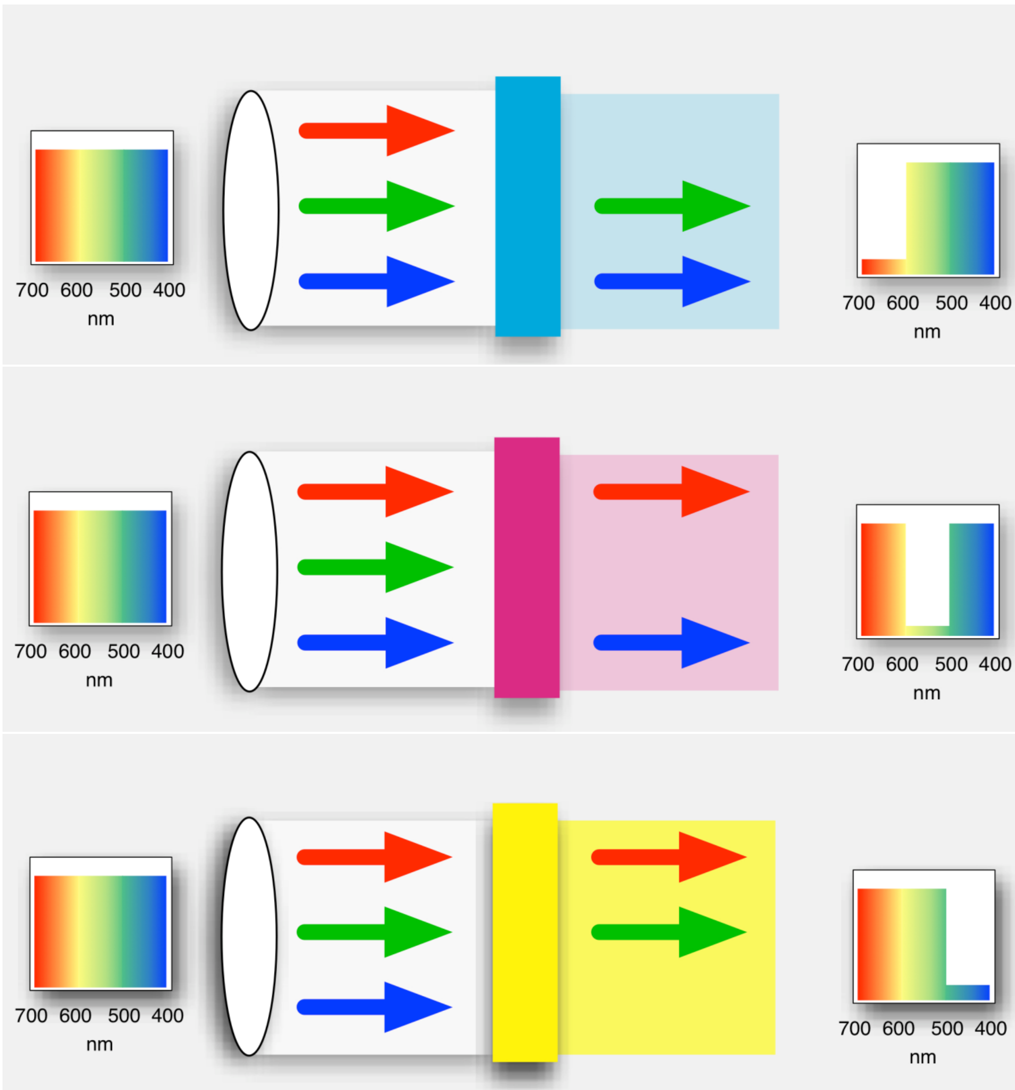


Figure 10.9: White light is incident on cyan (top), magenta (middle), or yellow (bottom) filters.

Table 10.1 demonstrates subtractive color mixing. White light is incident. Therefore, it contains red, green and blue light, the addition of primary colors. Each row shows a primary subtractive color. The table shows that each subtractive primary absorbs one additive primary color, as indicated by the shading. A mixture of magenta and yellow would absorb both green and blue, allowing only red to be seen.

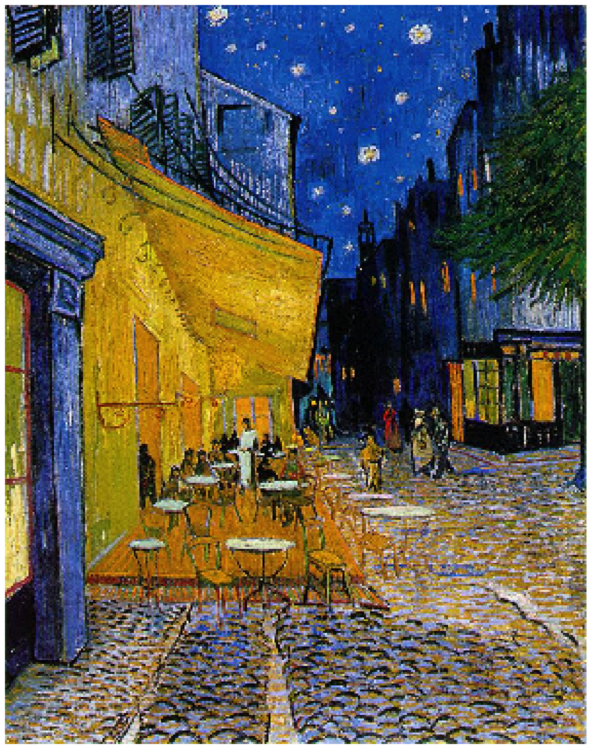
The same chart can be used to predict the result of additive color mixing. Blue and green is the same as white light with red absorbed. Looking for the shading on red leads you to the cyan row, so blue + green = cyan. This is how you see yellow in Fig. 10.3 since Red and Green on the bottom row are on the yellow subtractive primary line. Get it?

The subtractive primary colors can be thought of as adding two additive primary colors or subtracting one additive primary from white light.

white light **(contains all wavelengths)**	**red** long λ	**green** medium λ	**blue** short λ
subtractive primary:			
cyan (absorbs red)	red	green	blue
magenta (absorbs green)	red	green	blue
yellow (absorbs blue)	red	green	blue

Table 10.1: For a given subtractive primary color that subtracts from white light, this table shows which colors are absorbed and which are reflected/transmitted. Colors in a gray background are absorbed.

Van Gogh was the master of complementary colors, especially yellows with blues. One of the things about complementaries is that we see stark contrasts between them and we perceive a sense of stability. No physics here. It's physiology and psychology — artistic genius.



The Café Terrace on the Place du Forum, Arles, at Night,
by Vincent van Gogh (1888)

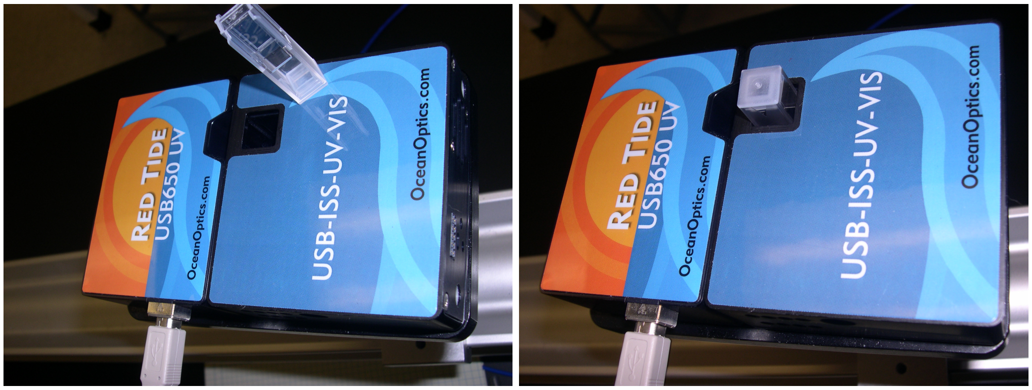
10.5 In today's lab

In this experiment, we will use subtractive color mixing by filters rather than by pigments, since filters are more easily manipulated in the laboratory. You will measure the bands of light that the filters allow through.

10.6 Equipment

- digital spectrometer like we had in the previous lab, but with an Absorptometer with integrated sampling system that creates light internally and passes it through insertable filters for digitization (Ocean Optics USB650 Red Tide, Fig. 10.10)
- computer with Logger *Pro* installed
- one empty cuvette[3] for calibration (the clear tube in Fig. 10.10(a))
- set of 3 additive-primary (RGB) filters in their own cuvettes, 3 subtractive-primary (CMY) color filters in theirs, and one cuvette with two filters in the same tube (there should be a total of 8 cuvettes at your bench)
- light projection box at the front of the room
- LED desk lamp

[3] A "cuvette" is a glass or plastic holder designed to hold objects destined for spectroscopic analysis. It's pronounced "coo-vette" as in "corvette."



(a) Cuvette (clear box) sitting on top (b) Cuvette inserted.

Figure 10.10: Digital spectrometer with integrated sampling system, shown with cuvette both uninserted and inserted.

10.7 Procedure

Setup

1. Connect the Ocean Optics Red Tide spectrometer to the USB port of the computer. Start the data-collection program Logger *Pro*, and then choose `New` from the `File` menu.

2. Calibrate the spectrometer:

   a) Place an empty cuvette in the square hole in the top of the spectrometer (see Fig. 10.10); make sure to align the cuvette so that the frosted sides are parallel with the long edge of the whole device (this ensures that the clear sides are facing the light source of the spectrometer).

   b) In Logger *Pro*, from the drop-down menus, choose `Experiment` ▶ `Calibrate` ▶ `Spectrometer: 1`.

   c) When the warmup period is complete, select `Finish Calibration`.

   d) Select `OK`.

Absorption spectra of filters

For each of the additive-primary color filters (red, green, blue),

1. Place the filter in the cuvette, insert the cuvette into the sample holder, press the "Collect" button in Logger *Pro*, and observe the spectrum that results. If the spectrum is not visible or is cut off at the top of the graph, right-click on the y-axis label `Absorbance`, select `Autoscale` ▶ `Autoscale`.

> Note that the plot is the **absorption spectrum**. A value close to one means that the wavelength in question was absorbed by the filter and not detected by the spectrometer. A value close to zero means that the wavelength was nearly totally transmitted.

2. Describe the colors transmitted. Record the wavelength ranges of the resulting absorption spectra. You may see a continuous band of colors (the "main" band), then a gap, and a narrower range of colors. Record these in Question 1 and answer Questions 2–3.

3. Place each of the three subtractive-primary color filters (cyan, magenta, and yellow) in the cuvette. Observe the resulting spectra in Logger *Pro*.

Print out your curves by overlapping different runs for the additive and subtractive filters. You can annotate your curves by going to `Insert` ▶ `Text Annotation`. A text box will appear and you can grab the end of the line with the mouse and point it at the curve that you've referenced.

Additive color mixing

In this part of the experiment you will use the light projection box to observe additive color mixing. The projector box is the large black box located at the side or in the back of the room. It contains three different independent light sources. The knobs on the sides let you adjust the intensity of each of the lights independently. For example, by adjusting the knobs so that the blue light is off and the red and green lights are of equal intensity, we can see what color we produce where they overlap. You can make accurate predictions for these colors using Table 10.1. **Make your predictions first**, then observe using the projector box, recording both in Question 4 and answering Question 5.

Subtractive color mixing

Now we will see how color by subtraction works differently. Here we will use the desk lamp on each table, which is approximately white. By stacking several color filters on top of each other, we can see what the resultant color is. Some of the filters are not very efficient (as we saw earlier), so you may want to use more than one of the same color (i.e. in the first one, stack two reds and two blues together). Make your predictions first, then observe holding the filters up and viewing the light passing through them using the desk lamp,[4] recording your predictions and observations in Question 6 and answering Questions 7–10.

[4] You saw during the last lab that the LED lamp is pretty close to white.

10.8 Questions

1. Record your observations below:

filter	**colors transmitted (note gaps)**	**range transmitted (main band)**	
		min	wavelength (nm) max
red			
green			
blue			

2. For an ideal "red" filter, what colors would be absorbed?

3. How well do the filters match the colors you would expect to see in red, green and blue light?

Additive color mixing

4. Record your predictions and observations in the following table.

light mixture	**predicted color**	**observed color**
red + green		
red + blue		
green + blue		
red + green + blue		

5. How well did your predictions agree with your results? Explain any differences.

Subtractive color mixing

6. Record your predictions and observations in the following table.

filter mixture	**predicted color**	**observed color**
red + blue		
blue + yellow		
cyan + magenta		
cyan + yellow		
magenta + yellow		
cyan + magenta + yellow		

7. Why does the red+blue give different results in this part of the experiment compared to the part with the projector box? Explain what caused the results for red + blue to be different in each case (that is, explain how each case worked).

8. Explain the results for cyan + yellow.

9. For blue + yellow, did the color you observe match your prediction? If it didn't, then why? What wavelengths must the filters let through?

10. Check this with the spectrometer by using the cuvette that has two filters in it—blue and yellow. Did you accurately estimate which wavelengths the filters let through? If not, which wavelengths did the filters let through? Print out your result.

11. Give a practical example from everyday life of additive and subtractive color mixing.

12. Why is it harder to think of examples of additive color mixing?

Appendix A

Dealing with uncertainty

A.1 Overview

- An uncertainty is always a positive number $\delta\mathbf{x} > \mathbf{0}$.
- If you measure x with a device that has a precision of u, then δx is at least as large as u.
- **Fractional uncertainty:**
  - If the fractional uncertainty of x is 5%, then $\delta x = 0.05x$.
  - If the uncertainty in x is δx, then the fractional uncertainty in x is $\delta x/x$.
- **Propagation of uncertainty:**
  - If $z = x + y$ or if $z = x - y$, then

$$\delta z = \delta x + \delta y. \tag{A.1}$$

  - If $z = xy$ or if $z = x/y$, then

$$\frac{\delta z}{|z|} = \frac{\delta x}{|x|} + \frac{\delta y}{|y|} \tag{A.2}$$

A.2 Concise notation of uncertainty

If, for example, $y = 1\,234.567\,89$ U and $\delta y = 0.000\,11$ U, where U is the unit of y, then $y = (1\,234.567\,89 \pm 0.000\,11)$ U. A more concise form of this expression, and one that is in common use, is $y = 1\,234.567\,89(11)$ U, where it is understood that the number in parentheses is the numerical value of the standard uncertainty referring to the corresponding last digits of the quoted result. This explanation is from Ref. [1]

A.3 Using uncertainties to compare data and expectations

Appendix B

Physical Constants

Name	**Symbol**	**Value(uncertainty)**	**Ref.**
electric constant	ϵ_0	$8.854\,187\,817\ldots$ (exact)$\times 10^{9}$ F m^{-1}	[1]
elementary charge	e	$1.602\,176\,565(35) \times 10^{-19}$ C	[1]
Planck constant	h	$6.626\,069\,57(29) \times 10^{-34}$ J s	[1]
speed of light in vacuum	c	$2.997\,924\,58$ (exact)$\times 10^{8}$ m s^{-1}	[1]

Appendix C

Oscilloscope cursor commands

Bibliography

[1] P.J. Mohr, B.N. Taylor, and D.B. Newell. The 2010 codata recommended values of the fundamental physical constants. (Web Version 6.0). This database was developed by J. Baker, M. Douma, and S. Kotochigova. Available: http://physics.nist.gov/constants [2012-07-03] National Institute of Standards and Technology, Gaithersburg, MD 20899., 2011.

[2] Rainbow Symphony, Inc. Diffraction Gratings Slides — Linear 500 line/mm. Available http://www.rainbowsymphonystore.com/difgratslidl1.html, 2012.

[3] Andrew Stockman, Donald I. A. MacLeod, and Nancy E. Johnson. Spectral sensitivities of the human cones. *J. Opt. Soc. Am. A*, 10(12):2491–2521, Dec 1993.