Electricity & Magnetism Lab Manual

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Last modified: January 19, 2015

January 19, 2015

This lab manual arose from its use at at Southampton College, part of Long Island University. It is made available online, and is freely usable. It is written in LaTeX, and the source is available upon request. If the materials here are extended or corrected, we ask that such additions and changes be sent back to its author at LIU so that everyone can benefit from the collective efforts of all users of this document.

Update Log:

Date:	Author:	Note:
June 20, 2003	SLL	Minor corrections with a few notes added
July 31, 2003	SLL	Added pix, resistor, scope, & cable appendices
August 27, 2003	SLL	Added to e/m lab
January 18, 2010	SLL	Revamped
January 18, 2015	SLL	Added Diffraction, Snell's, and Thin Lenses; Split circuits lab

Contents

Chapter 1

Introduction to Charge

1.1 Necessary Materials (per group)

balloon; cut-out paper holes from paper puncher; piece of wool; comb; clean, empty soft drink can; available water tap

1.2 Concepts Introduced

Force between charges; Charge separation

1.3 Introduction

Like charges repel and opposite charges attract. The forces between these charges are quite strong (for example, in comparison to the force of gravity). So when you look around at our world, you might expect things to be flying around due to these forces, yet you spent a whole semester learning mechanics without worrying about electricity and magnetism (E&M). Certainly E&M is important, however most things we observe in the world such as walls, carpet, dirt, paper are *not* charged. If they were charged, they would move towards objects with the opposite charge and neutralize the charge.

Instead, we have learned to tame the forces of E&M to our own purposes, and so we see those forces at work much more behind the scenes than gravity. However, when you shock yourself on a dry day touching metal or when you see lightening strike, you're seeing unharnessed E&M forces at work.

In this lab, we get exposed to charge and the forces between them. Keep in mind that in general most things are not charged, and it is only through rubbing that we can separate the positive and negative charges to *see* a net charge.

Despite being the first lab of the semester, this is not typical of future labs. You might even have fun. In any case, it's not a qualitative lab because electrostatics are, to be blunt, a pain. Humidity, what you're wearing, when you last showered can all have effects, and things tend not to be reproducible. There is some specialized (and expensive) equipment with which we could work, but even with them, things generally reduce to being simply qualitative.

1.4 Procedure

1.4.1 Activity 1

Blow-up a balloon to full size. After **rubbing** it vigorously on your hair (or a piece of wool), bring it near (without touching) the little disks of paper. **Describe** what happens including details such as directions, velocities, accelerations, and forces.

The balloon has been charged by your rubbing it, but **would** you say that the paper disks have a net charge? (why or why not?) Do some of the disks stick to the balloon or some bounce off? Why might either happen?

By this time, it is likely that much of the initial charge you gave the balloon leaked off the balloon through your hand. **Rub** the balloon again to charge it back up. **Place** the balloon against the wall and see if you can get it to stay against the wall.

To explain why the balloon does not fall to the ground, consider what you learned in mechanics with respect to forces (gravitational and frictional). However, there is now one more force and that is the electrostatic force between the wall and balloon.

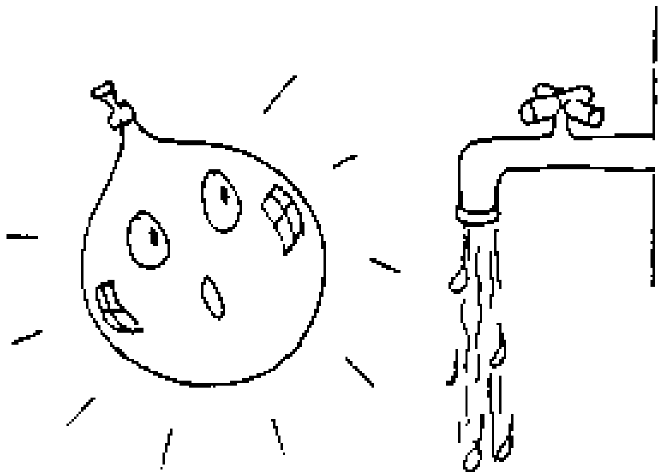
Draw the free-body diagram for the balloon including the forces acting on the balloon, and **explain** what forces are balanced to allow the balloon to stay against the wall.

Draw a diagram of the balloon–wall system similar to that seen in class with indications as to the locations of charge. In other words, indicate regions where the charge is locally more positive than negative with $+$ signs and likewise for negative charges with $-$ signs. You can indicate neutral areas by leaving them blank or with $\pm$ signs.

1.4.2 Activity 2

Rub a comb vigorously on a piece of wool. **Bring** the comb near the paper disks. **What** happens?

Bring the comb near an empty soft drink can that lies on its side. **Move** the can back and forth without touching it. **Attempt** to drag the can along without touching it. **Explain** how this process works. Is the can a conductor and does this matter? How is this different than what happens with the paper disks? If we had a can made of paper, would we see the same effect?



Turn on a small stream of water from the tap. Then **bring** the comb near the stream of water. **Is** that water stream attracted or repelled? **Is** the water charged? Why might the polar nature of a water molecule be important in explaining the reaction observed?

Now, **do** the same thing with a balloon instead of a comb. **Do** you notice any qualitative difference, and, if so, why might you suspect it occurs?

For these activities, **does** it matter whether the wool is taking away electrons from the balloon or comb or whether the wool is giving electrons to it?

All things being equal, consider a drop of water, a paper disk, and a ball of aluminum, all with the same mass. Rank them (and give your reasoning) as to which would be most attracted to the balloon.

When answering the questions above, you might first consider the question (though I don't need an answer to this):

If you brought the balloon near a big block of plastic (say a hairdryer), would you see the hairdryer move? Then why do the disks, the can, and the water move (the answers vary a bit).

1.5 Acknowledgments and References

The procedure of this lab came from the document *Charge That, Please!* by Harold Riggs.

Chapter 2

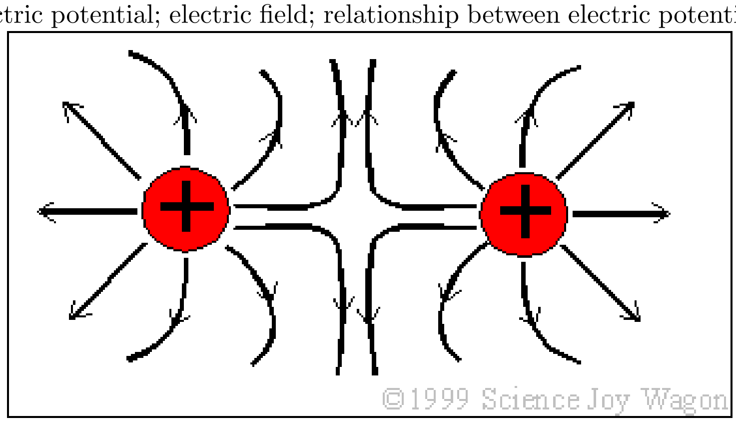
Electric Field Mapping

2.1 Necessary Materials (per group)

1 tray 1 transparent plastic sheet of printed graph paper 1 paper sheets corresponding to transparent sheet 3 different sets of metal inserts galvanometer 2 sets of connecting cables low-voltage power supply or battery

2.2 Concepts Introduced

electric potential; electric field; relationship between electric potential and field;



2.3 Introduction

The next step after understanding electric charge is the much more general and abstract idea of electric field. An electric field serves two roles. First, it helps us study and understand a variety of physical situations in a general way without being tied down to determining specific forces. In other words, we study an object's surrounding electric field and get a good idea of its properties without studying specifically the force between it and any particular charge. This should become clear as we progress in lecture. Secondly, and more fundamentally, the concept of an electric field is necessary to understand the dynamics of charges. It is through a dynamic field, that moving charges interact and through which a magnetic field is created. More tangibly, without a dynamic electric field, we would have no light!

2.4 The Method

Our goal here to get a picture of electric fields for a few situations to help you picture these (admittedly abstract) fields. To do so, we'll setup different patterns of conductors, and then by putting charge on these conductors, we will set up an electric field. We'll put charge on them using a power supply.

The next step is to be able to record the fields. We do this by first plotting equipotential lines. That is, we find the regions of the pattern that are at the same potential, say $1.0V$. We then look at regions that are $1.5V$, then $2.0V$, and so on. These equipotential lines are completely analogous to lines of constant elevation on a topographic map (such topographic lines are lines of constant *gravitational potential* instead of *electric potential*).

These equipotential lines give us information about the situation created by the pattern. They also tell us the geometry of the electric field lines because these lines are everywhere perpendicular to the equipotential lines. Electric field lines tell us where a positive charge would move toward. Continuing the analogy to a topographic map, the field lines tell the direction that a ball would roll when placed on a hill.

2.5 Procedure

1. Place the transparent sheet at the bottom of the tray.

2. Add water to the tray so that the depth is just a couple millimeters.

3. Place two, metal conducting pieces in the tray on top of the plastic sheet. Mark on a corresponding piece of graph paper where the two conductors are located.

4. Using the connector cables, connect the terminals of the power source (either a power supply that plugs into the wall or a battery) to the two conductors. It doesn't matter which polarity goes to which. If using a power supply, set it to just a couple volts before turning it on. Record this potential difference.

5. Set the digital multimeter (DMM) to DC voltage mode and connect one probe to the conductor attached to the negative side of the power source.

6. Take the other probe from the multimeter and touch the plastic sheet somewhere in between the two conductors. Note the voltage measured by the multimeter.

7. Now move this probe around and find the direction you can move it so that the multimeter does **not** change its value.

8. This point is one point on an equipotential line which you need to trace out on the paper. To do so, move the probe in a direction which keeps the voltage difference zero. Continue this while you trace out the line.

9. When you're done with this line, note on your paper the potential difference for this line (just the constant reading of the DMM).

10. Now put the probe somewhere else between the conductors and repeat for this new potential difference. You should have at least 4 equipotential lines for each pattern of conductors.

11. Repeat the above for three different patterns of conductors (for example, two round conductors, one round and one rectangle, and two rectangles).

12. On each of these sheets, draw the associated electric field lines. Recall that electric field lines are everywhere perpendicular to equipotential lines. One set of these "pictures" is needed per group, not per individual.

2.6 Questions to be answered

1. Why are equipotential lines near conductor surfaces parallel to the surface?

2. Is it possible for two different electric field lines to cross? Explain.

3. Sketch the field pattern of two positively charged conducting triangles that are identical in size.

2.7 Acknowledgments and References

The procedure and some of the questions here come from the book *Selective Experiments in Physics.*

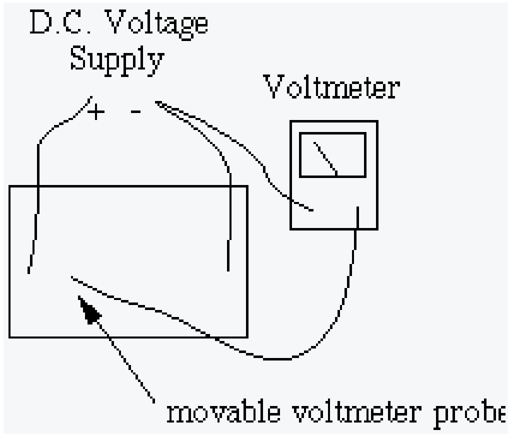
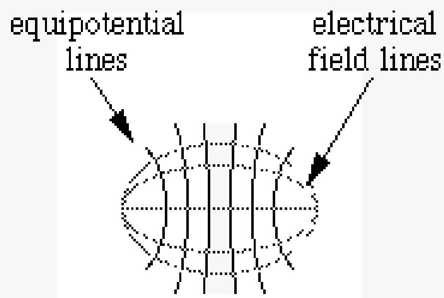

D.C. Voltage
Supply
+ -
Voltmeter
movable voltmeter probe

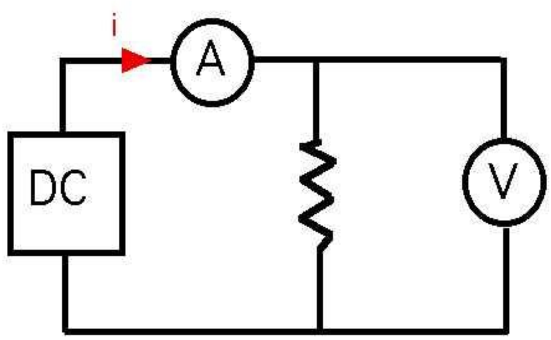
Fig. 1


equipotential
lines
electrical
field lines

Chapter 3

Introduction to Circuits I

3.1 Necessary Materials (per group)



digital multimeter (DMM); 1 ammeter; connecting wires; 4 resistors with roughly comparable resistances (within a factor of hundred); DC power supply; light bulb in a light socket

3.2 Concepts Introduced

Use of a voltmeter; Use of an ammeter; Use of a breadboard; Implementation of a circuit diagram; Kirchoff's Loop Law; Equivalent resistance of resistors in series and parallel; Ohm's Law

3.3 Introduction

We now enter the realm of moving charges, *i.e.* electricity. Here we use a power supply not just to provide charges to setup an electric field as in the previous lab, but also to provide a continuous supply of charges, *i.e.* a current.

There are a number of things to learn about circuits with much overlap with the lecture. In lab, you want to gain a real "practical" perspective which should help with some of the more abstract concepts from lecture.

A power supply has two *leads* which are at different potentials. The lead with a higher potential is usually colored red while the other is colored black. If there's another lead/input, it's generally the ground.

The charges on the lower potential lead (electrons) very badly want to get to the higher potential. If there's a conducting pathway by which they can get there, one has what is called a *closed circuit.* If there's no way for them to get there (because they would have to move through an insulator, say), then it is an *open circuit.*

Another important term related to these two terms, is the *short circuit.* This is very bad. This is what you see in the movies, when someone puts a bent paper-clip in the two holes of a wall socket. What it means is that a pathway with essentially no resistance is established between the red and black wires. What's bad is that the power supply has to provide a nearly infinite number of electrons to maintain its potential difference across its red and black leads (which is its sole mission in life). This nearly infinite supply of electrons means a large current which is dangerous and will likely break the power supply, hurt someone, or, at the very least, cause a really bad burning smell as the wire heats up.

To sum up, there are three kinds of circuits:

1. *open circuit* — infinite resistance between leads
2. *closed circuit* — finite resistance between leads
3. *short circuit* — zero resistance between leads

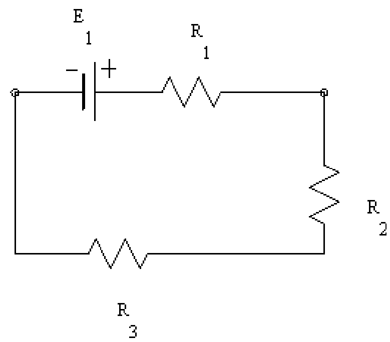
A *breadboard* is simple device which allows for connecting circuit elements (resistors, wires, etc) without much fuss. Every group of five holes in the breadboard are electrically connected underneath the surface so that if you want to connect two resistors just stick one end from each in a 5-grouping of the breadboard.

Perhaps the most fundamental rule in circuits is *Ohm's Law.* This law applies to resistors and says

$$V = IR \tag{3.1}$$

where V is the **voltage difference across** the resistor, I is the **current through** the resistor, and R is the resistance of the resistor. One should understand the difference in the two prepositions in bold above.

Another important law is **Kirchoff's Rule** which says that the sum of the potential differences around a circuit loop is zero. In analogy with gravitational potential, this law can be applied to a roller coaster which goes around in a loop going up and down. If you add up all the heights the coaster goes up and subtract all the depths it goes down, you must add up to zero. If you don't, then the coaster would end up at a different height when it picks up new passengers!



To **measure a voltage difference**, one simply puts the two leads of the multimeter at the two points in the circuit over which you want to know the potential difference. To measure the voltage difference across a resistor, you just put the two leads at the opposite leads.

To **measure the current through a particular part of a circuit** you **cannot** due as you would to measure voltage. Instead you have to actually **break** the circuit, and insert the ammeter to re-close the circuit. In this way, all the current has to go through the ammeter. To do otherwise, risks changing the circuit and blowing a fuse in the ammeter.

3.4 Procedure

3.4.1 Testing Kirchoff's Loop Law

Using the breadboard and a DC power supply,

1. construct a circular circuit with 4 resistors of different (but comparable, within a factor of 100 of each other) resistances. Also make sure that the resistances are less than $1M\Omega$ each.

2. Put roughly a 10 Volt potential difference across two opposite points on this circle being sure to measure precisely what the potential is.

3. Measure the four voltage drops, keeping the orientation of the probes of the voltmeter in the same order each time

4. Compute the sum of these potential drops

Questions & Discussion

1. Compare what would be expected by Kirchoff's loop law with what your measurement.

2. Calculate an error and percent error and comment on whether you have contributed to verifying the rule or contradicting it

3. Estimate your experimental uncertainty in your measurement and compare to your error.

3.4.2 Testing Ohm's Law

1. use a light bulb in a light socket, and measure its resistance with the multimeter

2. connect it in a circuit with the power supply by connecting the power supply to the connectors on the socket

3. make sure not much current is coming out of the power supply; keep the voltage low (around 1 volt)

4. then **carefully** insert your ammeter (you may have to use one of the analog ammeters if the current is greater than about $200mA$) into the circuit so that it is in **series** with the light bulb. (*make sure the fuse in your ammeter hasn't been broken, in which case your reading will stay at zero*).

5. connect your voltmeter **across** the light bulb so that you measure the voltage over the bulb

6. Record the voltage and current (make sure to record the resistance of the resistor as well.

7. Now, carefully and slowly increase the voltage a little bit. Record again the voltage and current. Repeat this for about 7 data points.

8. graph V versus I noting at what voltage the light bulb turned on.

9. find a best fit line and compute its slope (including units)

Questions & Discussion

1. Compare what would be expected for the slope from Ohm's law with what you got

2. calculate a percent error and comment on whether you have contributed to verifying the rule or contradicting it

3. comment on how linear the graph is, and whether you expected the graph to be linear

4. Would you expect the graph to be non-linear anywhere and why? Did you see this?

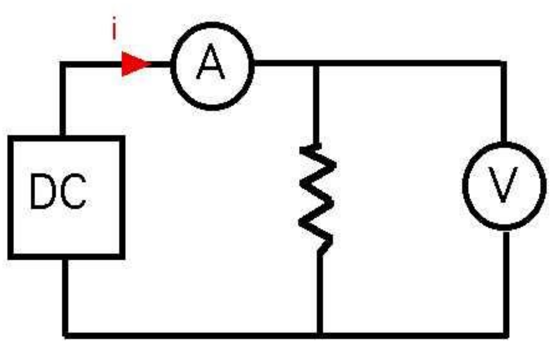
3.5 Acknowledgments and References

The document *Physics Laboratory Manual 116L* from The University of Texas at Austin served as a reference for this write-up.

Chapter 4

Introduction to Circuits II

4.1 Necessary Materials (per group)

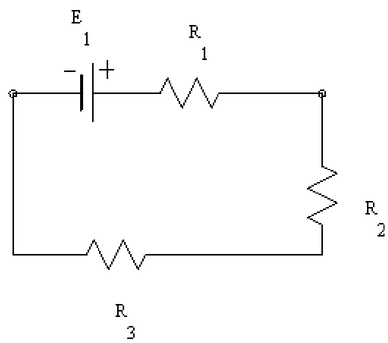


1 multimeter; connecting wires; 4 resistors with comparable resistances (within a factor of hundred); DC power supply

4.2 Concepts Introduced

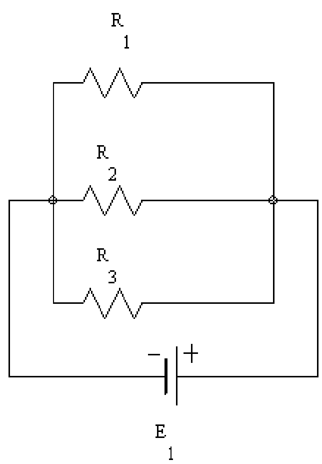
Use of a voltmeter; Use of an ammeter; Use of a breadboard; Implementation of a circuit diagram; Kirchoff's Loop Law; Equivalent resistance of resistors in series and parallel; Ohm's Law

4.3 Introduction



Resistors in Series
To connect resistors in series, simply grab a resistor's two leads with your hands. The lead in the left hand we'll say is the starting point. Then connect a second resistor to the first by connecting one of its leads to the lead of the original resistor in your right hand. Now grab the unconnected lead of the second resistor with your right hand. Your hands now hold the beginning and end points of the series combination and the resistance between these two leads in terms of the individual resistances will be:

$$R_{\text{eq}} = R_1 + R_2 + R_3 + \cdots .$$



Resistors in Parallel
To connect two resistors in parallel, grab a resistor's two leads with your hands. Now have someone grab a second resistor. Have them connect the lead in their right hand to the one in your right hand. Continue to hold the leads of the original resistor. Now have them connect the lead in their left hand to the

one in your left. If you continued to hold the original leads, you now have two resistors in parallel with a resistance which obeys

$$\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots .$$

To **measure a voltage difference**, one simply puts the two leads of the multimeter at the two points in the circuit over which you want to know the potential difference. To measure the voltage difference across a resistor, you just put the two leads at the opposite leads.

To **measure the current through a particular part of a circuit** you **cannot** due as you would to measure voltage. Instead you have to actually **break** the circuit, and insert the ammeter to re-close the circuit. In this way, all the current has to go through the ammeter. To do otherwise, risks changing the circuit and blowing a fuse in the ammeter.

4.4 Procedure

4.4.1 Testing the Series Rule for Equivalent Resistance

1. Choose four resistors of appropriate magnitudes, and measure their individual resistances with the multimeter.

2. Connect all four resistors in series with each other.

3. Measure the resistance of the series combination with the multimeter set for resistance.

4. Also hook this resistor network up to the power supply. Measure the current from and voltage across the power supply, and divide them to get the equivalent resistance.

Questions & Discussion

1. Compare what would be expected by the Series Rule with what your measurement.

2. Calculate an error and percent error and comment on whether you have contributed to verifying the rule or contradicting it

3. Estimate your experimental uncertainty in your measurement and compare to your error.

4.4.2 Testing the Parallel Rule for Equivalent Resistance

1. Choose four resistors of appropriate magnitudes, and measure their resistance with the multimeter (*you can use the same ones from Section 4.4.1*)

2. Connect all four resistors in parallel with each other.
3. Measure the resistance of this setup with the multimeter in resistance mode.
4. Also hook this resistor network up to the power supply. Measure the current from and voltage across the power supply, and divide them to get the equivalent resistance.

Questions & Discussion

1. Compare what would be expected by the Parallel Rule with what you got
2. Calculate an error and percent error and comment on whether you have contributed to verifying the rule or contradicting it
3. Estimate your experimental uncertainty in your measurement and compare to your error.

4.5 Acknowledgments and References

The document *Physics Laboratory Manual 116L* from The University of Texas at Austin served as a reference for this write-up.

Chapter 5

Capacitors and Equivalent Capacitance

5.1 Necessary Materials (per group)

2 capacitors rated for at least 15 V with identical capacitances at least $10\mu F$; 1 multimeter; timer; DC power supply;

5.2 Concepts Introduced

Capacitance; Equivalent Capacitance; Resistance of a multimeter

5.3 Introduction

We have seen the idea of *equivalent resistance*...that is that multiple resistors group together in either series or parallel can be considered equivalent to a single resistor of a certain resistance. Here, "equivalent" is used in the sense that the effects on the circuit will be identical.

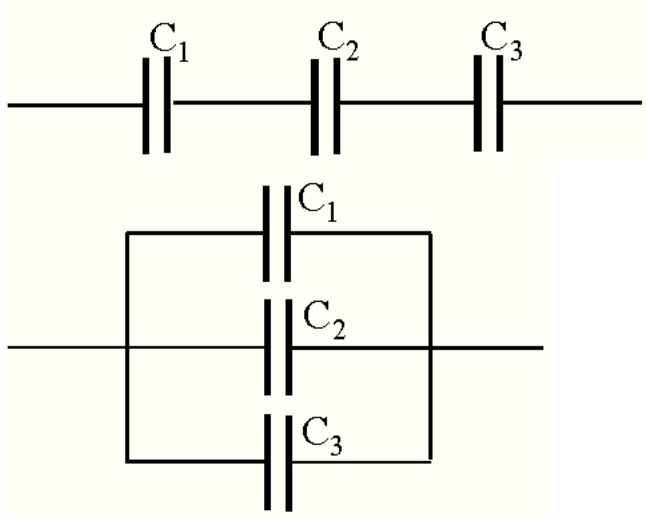
Likewise, here we will study *equivalent capacitance*. For this we will group two capacitors and study the effective capacitance.

The way in which we will study the behavior of capacitors is by charging them up, and then watching as they discharge. This discharge will follow exponential decay. To be more precise, we will put the capacitor in a circuit with a resistor R, and then, after charging it up to a voltage V_0, we'll measure the voltage across the resistor as it discharges. This voltage $V(t)$ that we read across the resistor should follow

$$V(t) = V_0 e^{-\frac{t}{RC}}. \tag{5.1}$$

By measuring the output voltage at various times, we can make a plot and extract the value of RC (in units of seconds).

What twist here is that instead of using a resistor, we will instead have the capacitor discharge across the voltmeter itself. So the multimeter will be both a measuring device and an active participant in the circuit!



We start with one capacitor so that we can determine the internal resistance of the multimeter (by knowing the capacitance of the capacitor C, once we have RC it should be easy to find R). We then move on to two capacitors. We hook them in parallel and series, measure the respective time constants $\tau = RC$, and divide out the (just determined) resistance of the multimeter. With this we can test the series law

$$C_{\text{eq series}} = \frac{1}{\Sigma_i \frac{1}{C_i}} \tag{5.2}$$

and parallel law

$$C_{\text{eq parallel}} = \Sigma_i C_i. \tag{5.3}$$

5.4 Procedure

5.4.1 Single Capacitor

1. Select two identical capacitors which are rated for at least 15 V and with a capacitance of at least $10\mu F$.

2. Connect the multimeter to measure the voltage across the capacitor.

3. Using the power supply, charge the capacitor up to $15V$ (make sure that they are rated for higher than the voltage you pick). You do this by placing two leads from the power supply across the terminals of the capacitor until it is charged (the multimeter should give a stable reading).

4. If you put too much potential difference across the capacitor, it will overheat, stink, and then explode!

5. Record the voltage decay in one of two ways: (1) Record the time at which the multimeter reads every other voltage, or (2) Record the voltage every couple seconds.

6. Plot V versus t.

7. Determine the time constant τ.

8. From τ determine the resistance of the multimeter using the value of C labeled on the capacitor.

5.4.2 Two Capacitors in Series

1. Connect the two identical capacitors in series, and using this assembly, repeat the above procedure to extract the time constant.

2. From τ determine the equivalent capacitance of the capacitors in series using the resistance found above.

3. Compute a percent difference between this experimental value and the theoretical value one would obtain using the series law.

5.4.3 Two Capacitors in Parallel

1. Connect the two identical capacitors in parallel, and using this assembly, repeat the above procedure to extract the time constant.

2. From τ determine the equivalent capacitance of the capacitors in parallel using the resistance found above.

3. Compute a percent difference between this experimental value and the theoretical value one would obtain using the parallel law.

Chapter 6

Snell's Law

6.1 Necessary Materials (per group)

a rectangular glass block; cardboard and pins; straight edge; protractor; scotch tape; small water tank assembly

6.2 Concepts Introduced

Snell's Law of Refraction; index of refraction;

6.3 Introduction

Light propagates at different speeds in different materials. We can characterize different materials by an *index of refraction* n where we define $n \equiv c/v$. Here c is the speed of light in vacuum (the maximum speed light can have) and v is the speed of light in whatever material you're computing the index for.

Light generally moves in straight lines (geometric optics), but when light goes from one medium to another, it turns (or bends). A good analogy for this is to picture a tank with the tank operator keeping everything constant. the tank goes from a concrete road onto the beach. The tank is propelled by two treads and as it goes from concrete to sand, one of the treads hits the sand first and slows down (because of less traction). The other treat is still on concrete for a short bit and therefore goes faster. The tank *turns* toward the sand simply because the change in speed of the two materials.

We'll measure the index of refraction of a certain glass and of water.

6.3.1 Index of Water

1. Fill the refraction tank about half full of water.

2. Choose a location for the vertical stripe on the front glass.

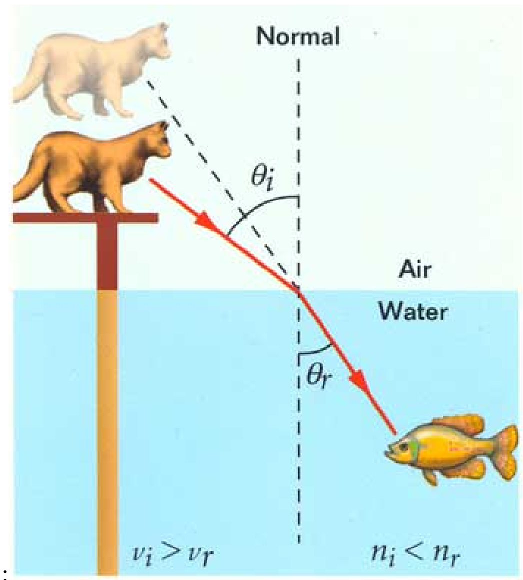


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Figure 6.1: Cartoon representation of what we're doing. We're measuring both θ_i and θ_r in the air. Note that the solid line represents the cat looking through the water (or glass black), while the the dashed line is just the geometric, straight line to the target (e.g. the fish or marker).

3. Turn the sweeping arm so that it lines up with vertical stripe on the front piece of glass and the mark on the rear glass. Measure the angle of incidence θ_i.
4. Move the seeping arm so that you line up with the *image* of the rear mark within the water. Measure the angle of refraction θ_r.
5. Repeat for a different location of the vertical stripe.
6. Compute the index of refraction using Snell's Law:

$$n_{\text{water}} = \frac{n_{\text{air}} \sin\theta_r}{\sin\theta_i}$$

   and compare to the usual value for water 1.33.

6.3.2 Index of Glass

1. We'll do a similar method as with the water, but it's a bit more tricky.
2. Tape a piece of blank paper to cardboard.
3. Place the glass block on the paper and outline it with a pencil. Be sure to keep the block in that same place throughout the following.

4. Place a pin against the rear edge of the glass. Call that point P.
5. Place another pin against the front edge of the glass. Call that point R. Make sure that the line connecting points P and R is not perpendicular to the front edge.
6. Sight *over* the glass to place a pin at point O in a line with points P and R.
7. Sight *through* the glass to place a pin at point O' in a line with points P and R.
8. Remove the glass block. Draw a straight line between points O and R. Draw another straight line between points O' and R. Also draw a line perpendicular to the front edge of the glass and through point R.
9. Using the protractor, measure the angles of incidence, θ_i, and refraction, θ_r.
10. Repeat for another pin location R.
11. Compute the index of refraction of the glass. Compare to a usual value for glass $n_{\text{glass}} = 1.5$.

Chapter 7

Focal Length of a Thin Lens

7.1 Introduction

Lenses are ubiquitous (e.g. telescopes, microsope, glasses, car lights).

We are going to study the properties of one of these lenses, but first we'll have to introduce three important quantities when imaging an *object*. The distance from the object to the lens is called, appropriately enough, the *object distance* which we denote by the variable o. A lens will produce an image of this object, and the distance from the lens to the image is called the *image distance*, denoted by i.

Finally, a property of the lens itself is the *focal length*, denoted f. The distances o and i will change depending on how you set things up, but the focal length is determined by the material used in the lens and its shape. If one shines parallel rays through a lens, the rays converge at a single point. The distance from this point to the lens is the focal length.

So, all three distances i, o, and f can have the same units since they are all lengths. Furthermore, the thin lens equation relates the three to each other

$$\frac{1}{f} = \frac{1}{o} + \frac{1}{i}. \tag{7.1}$$

It should only make sense that you can put an object anywhere you want (i.e. you pick the distance o), and that once you do so, then that distance and the type of lens you're using dictates where the image will be.

In this lab, we'll use a few different ways of finding the focal length to study a thin lens (we'll only be studying a converging lens). After we get these measurements, we'll want to compare them all to each other, and figure out our best measurement of the focal length.

7.2 Procedure

7.2.1 Distant Object Method

1. Mount the lens and the screen on the optical bench.
2. Point optical bench at a distant object. Usually you can find a good tree or lightpost visible through the window to image.
3. Adjust the position of the screen until you have a good, distinct image of the object.
4. Record whether the image is erect or inverted.
5. Estimate the object distance, o.
6. Measure the image distance i (from where to where?).
7. Calculate the focal length from the thin lens equation above letting o "go to infinity."

7.2.2 The Straightforward Way

1. Use the illuminated arrow as the object.
2. Mount the object at the far left of the bench.
3. Mount the lens "not too far" from the object.
4. Adjust the position of the screen (and possibly that of the lens) until a distinct image is formed.
5. Record the object and image distance.
6. Record properties of the image.
7. Using the thin lens equation, calculate the focal length.

7.2.3 The Method of Conjugate Foci

1. Mount the arrow at the far left as in Fig. 7.1.
2. Adjust the position of the lens and screen to get a distinct image.
3. Remember where the lens is now.
4. Keeping the object and screen in the same positions, move the lens toward the screen until a another image is formed on the screen.
5. Record the distance x through which you moved the lens.
6. Measure/record the distance D from the object to the screen.

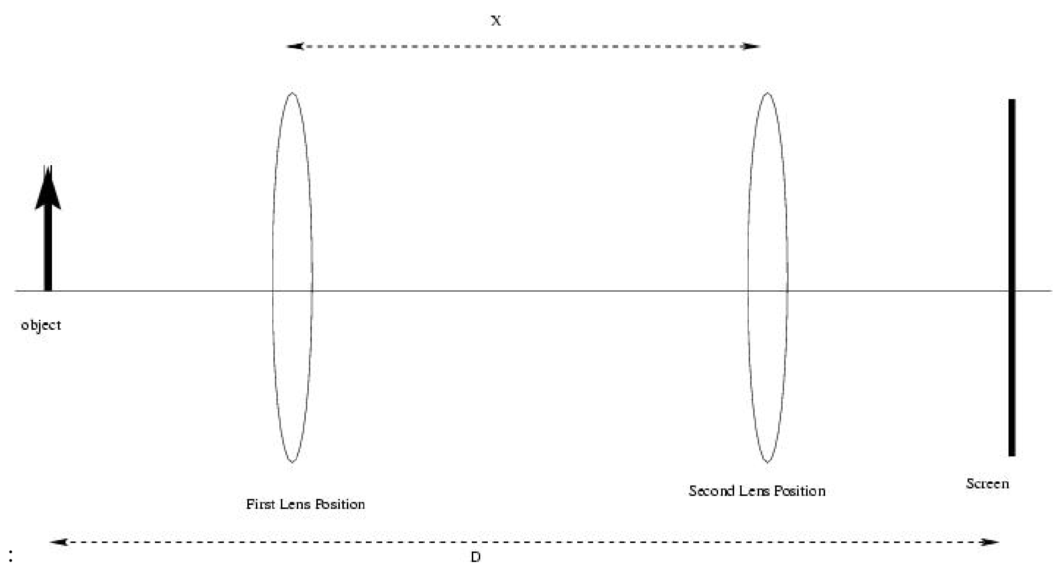


Figure 7.1: Diagram of the method of conjugate foci.

7. Calculate the focal length using the equation:

$$f = \frac{D}{4} - \frac{x^2}{4D} \tag{7.2}$$

7.2.4 Parallax Method

1. Mount the lens at the far right of the bench.
2. Mount the object on the bench at some convenient position inside the focal length of the lens.
3. Measure the object distance.
4. Bend down and look through the lens at the object. What you see is its image. We want to know where that image is.
5. While looking through the lens, hold your pen behind the lens so that you can see the object **through** the lens at the same time that you see your pen **over** the top of the lens.
6. Adjust the position of your pen (forward and back) so that as you move your eye right and left, there is no parallax between the image of the object and your pen. When there is no such parallax effect, then you pen is at the position of the image.

7. Measure the image distance as the distance from the pen to the lens. However, you should record this distance as a negative value. The reason for this is that the lens equations shown before works when the sign of i is defined in a particular way. When the image is on the opposite side of the lens as the object (the case for the three preceding methods), then the image distance is positive. If the image is on the same side of the lens as the object, then the image distance i should be negative.

8. Calculate the focal length.

7.2.5 Final Thoughts

1. Determine the **best** value for the focal length.

2. Once you've done so, compute the percent differences between each value and your best value.

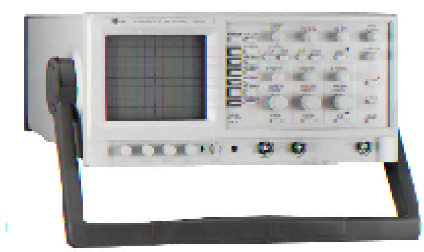
3. Form a confidence interval for the focal length. In other words, you want to say "I am confident than any optical scientist in the world who may come along and measure the focal length of my lens will find a value for the focal length in the range of $1.0cm$ to $100.cm$."

Chapter 8

Introduction to the Oscilloscope

8.1 Necessary Materials (per group)

1 oscilloscope; 1 function generator; coaxial cables, breakouts, and regular cables with banana plug terminations; microphone; speaker



8.2 Concepts Introduced

Use of an oscilloscope; AC current; Use of a function generator; Electronic representation of sound; Wave properties: period, frequency, angular frequency, peak-to-peak, amplitude, DC offset;

8.3 Introduction

Up until now, we have generally dealt with constant potentials, so called *DC* circuits. However, as you almost certainly know, all around us is *AC* power. So we need to understand what happens when voltages change, and how we can measure them. The standard tool for studying such changing voltages is the *oscilloscope.*

8.3.1 A Changing Voltage

First, let's discuss how a voltage can change in time. It might be periodic, meaning that it repeats itself in time. The length of time it takes for it to repeat is called the *period* (generally measured in seconds). The inverse of this is the *frequency* which says how many times it repeats per unit time. The standard unit for this is Hz which is the same as $1/s$.

Often times, the voltage will change as trigonometric function ($e.g$ sin or cos), in which case we might want to know the frequency in radians/s. This is called the *angular frequency* ω.

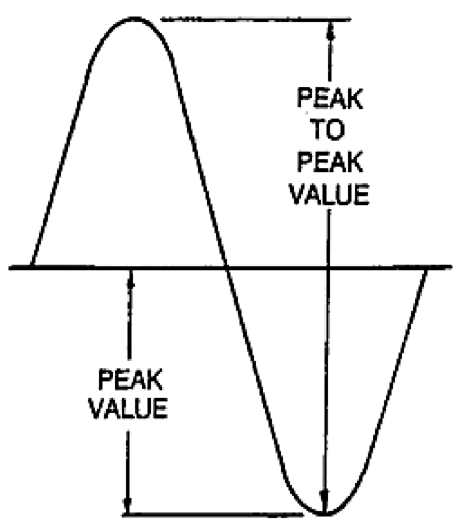
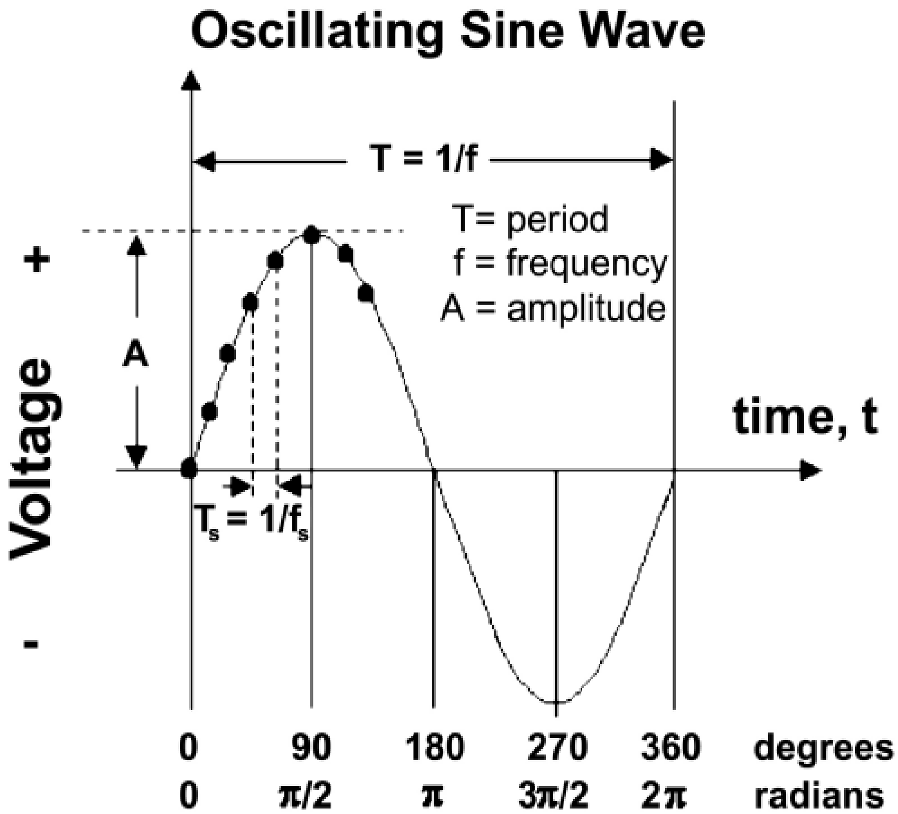


FIGURE 5-14. Peak and Peak-to-Peak Values.

The usual definition of *amplitude* applies for a varying voltage signal. The amplitude is just half the *peak-to-peak* voltage, which is the difference in the maximum and minimums of the voltage. A concept likely to be new is the *DC offset* which is the the time averaged signal. To picture this, imagine a sinusoidally varying voltage. If you average a sin function, you get zero so the DC offset would be zero. However, imagine taking the sin function and shifting it up the y-axis. The distance you shift it is the new average and hence the non-zero DC offset.



To put all this together, imagine a signal of the following form:

$$V(t) = A\sin(\omega t) + B. \tag{8.1}$$

You should be able to identify the amplitude A, the angular frequency ω, and the DC offset B. The "normal" frequency would then be $\omega/(2\pi)$ and the period would then be $2\pi/\omega$.

8.3.2 The Oscilloscope

The oscilloscope displays time varying voltages and uses a cathode ray tube (CRT) with a scanning beam of electrons to show them. Its screen has a grid of lines which allow measurements of the signal to be made. The various and numerous buttons and knobs are used to adjust the appearance of the signal on the screen and determine the scales of the on-screen grid.

Once turned on, the scope takes a few seconds to warm up. The focus and intensity can be adjusted to sharpen the trace (the signal seen on the screen). Sometimes, the trace may be "off screen" and you have to adjust its position to bring it into view. To see if this is the case, push the "beam find" button and it will show to which side the trace has been moved. The position knobs can be used to bring it back into view.

The scopes we use generally have two "channels," namely inputs for two different signals. You can view either one by selecting CH1 or CH2, or view both at the same time by choosing something such as "Dual Trace."

The normal way to use the scope is to plot the voltage on the y-axis and time on the x-axis. To determine the scale of the y-axis, you look at the "Volts/div" knob associated with the channel you're viewing. So, if the know points to $5V$, this means that each distance between two grid lines (a *division*) is $5V$. For example, if your amplitude stretches for two and half divisions, then you amplitude is $2.5div \times 5V/div = 12.5V$.

Likewise, there is (only one) knob which determines the time scale (for both channels). It should be marked with something along the lines of "sec/div." If a period of your signal stretches over 8 divisions, and your time knob reads $10\mu s/div$, then your period is then $8 \times 10\mu s/div = 80\mu s$.

8.3.3 The Signal Generator

Often, when dealing with AC circuits, you will want a pure sin wave with which to test the equipment. To give us such signals, we have the function generator. To operate one, you input the frequency, amplitude, and DC offset for the wave you desire, and it outputs one.

8.4 Procedure

In this lab, you should get familiar with the scope and be able to measure properties of AC signals.

You should also pick five frequencies on the function generator, record the frequency that the function generator claims is the output frequency, and then test these against your own measurements with the scope.

Keep in mind to record uncertainties associated with your scope measurements. In particular, you should expect some uncertainty determining how many divisions and the scale of the division for each measurement. Thus, your uncertainty for a given quanitity (say amplitude) will differ from measurement to measurement. Also, be aware that you won't be able to simply "guess" and uncertainty after completing this section.

A sample table might look like the following:

Amplitude (V)	DC Offset (V)	Period s	f_{meas} (Hz)	f_{theor} (Hz)	% Diff

Chapter 9

Spectral Lines & Diffraction

9.1 Introduction

Hot gasses tend to emit light. Most street lights use a hot gas to provide illumination. If you sent that light through a prism what would you expect to see? A rainbow? That's a pretty usual expectation. That generally one sees something very different from a continuous rainbow should really shock you. You're literally seeing the structure of an atom in the light that you do see. You're seeing *quantum mechanics* at work!

Various elements emit radiation with particular wavelengths, so-called *spectral lines*. It is precisely these lines that astronomers search for in the spectrum of celestial objects in order to determine their chemical makeup. Our goal here is to observe the spectral lines for a few different elements and to measure the wavelengths of these lines.

The first step is to produce the emission spectrum. We need a confined gas of each material and a means by which to excite the gas. To accomplish this we have fluorescent lamps with tubes of the different gases.

The second step is to then analyze the wavelengths of the light which is emitted. For that, we need to spread out the emission by wavelength, just as raindrops do for a rainbow. To do this, we pass the emitted light through a *diffraction grating*. If you've ever noticed a rainbow effect from looking at CD, then you've seen the effect of a diffraction grating.

A diffraction grating consists of a very large number of equally spaced parallel slits. Light which hits the grating passes through the slits. However, after passing through the slits, the beam consists of light from all the different slits which is now recombined. In some places the light recombines and adds to together (*constructive interference) whereas in other places the light recombines by subtraction (*destructive interference).

The net effect is that light of different wavelengths will be bright, due to constructive interference, at different angles from the grating. The mathematical formula which relates is

$$d \sin \theta_m = m\lambda \tag{9.1}$$

where d is the spacing between the slits, θ_m is the angle at which one measures a bright spot, and λ is the wavelength of the light. The integer m has no units and is called the *order*. What one finds is that you see a repeating pattern of bright spots, with each set described by an order starting with 1.

Thus if one passes the light through a grating with spacing $0.1mm$, and finds a bright spot at 15^o away from straight through, then we can compute the wavelength of that light as

$$\begin{aligned} \lambda &= d \sin \theta_1 && (9.2) \\ &= (0.1\ mm) \sin (15^o) && (9.3) \\ &= 0.026\ mm. \end{aligned}$$

9.2 Procedure

1. Place the grating in its holder and adjust its height until its center is at the same height as the center of the collimator and telescope lenses.
2. Illuminate the collimator slit and rotate the telescope until the first sharp image is obtained by focusing the telescope.
3. Locate a spectral line, and bring it to the location of the cross hairs. Record the angular position of the telescope.
4. Swing the telescope to the other side of the grating and locate the corresponding spectral line. Record this angular position. In your calculations, you'll average this angular separation with that obtained in the previous step. Also record the observed color of this line.
5. Repeat these two measurements of the angular position for each spectral line. In particular, if you can distinguish spectral lines for order 2, measure these as well.
6. Repeat the measurements of all the spectral lines for all the gasses (mercury, sodium, etc).
7. Finally, don't forget to record the number of lines per centimeter for your grating.

Once you've taken the data, you'll need to compute the wavelength for each spectral line. Compare these to accepted values and compute the percent difference.

Discuss what your results mean. Does this method represent a good way to measure wavelengths of spectral lines? Does it convince you that spectral lines are what we believe them to be...in particular, does the experiment give evidence in support of our use of spectral lines to analyze the content of stars?

If my Andromeda colleagues looked at the emission from mercury gas, would they see the same thing?

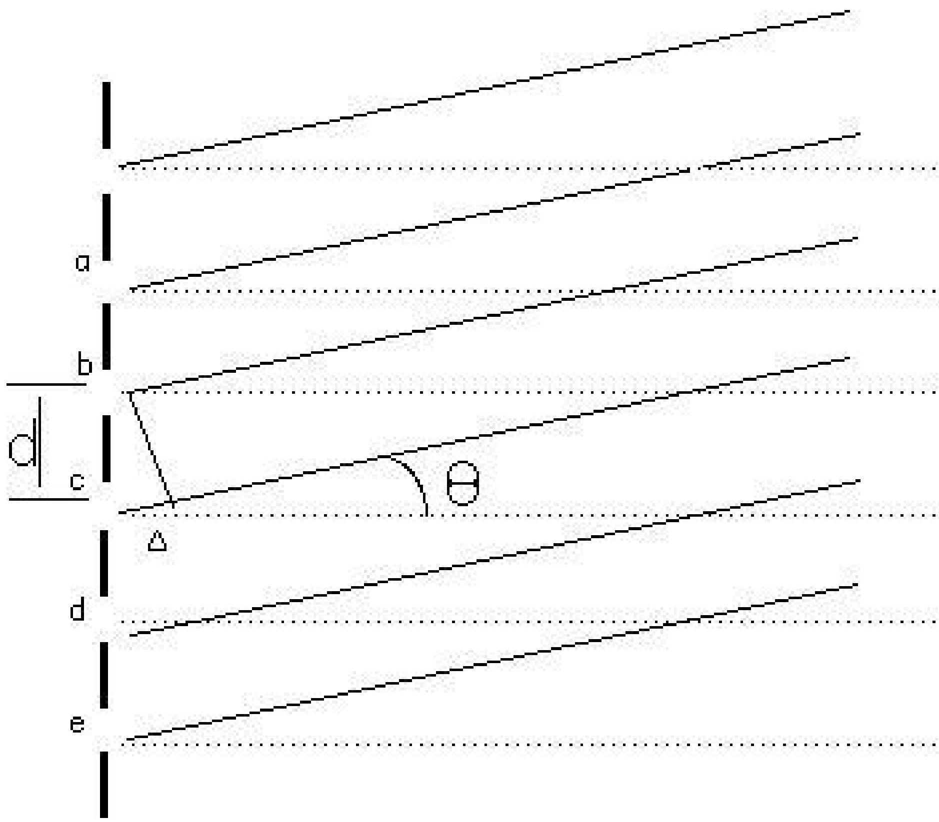


Figure 9.1: Diagram of interference with a diffraction grating. The vertical distance d represents the spacing between the slits of the diffraction grating. The angle θ represents the angular separation between the point of observation and the point straight through the grating. By forming the triangle with d as the hypotenuse, one can compute the difference in length of two adjacent paths for the light as $\Delta = d \sin \theta$. Where Δ is equal to the wavelength, one gets constructive interference.

Appendix A

Resistor Color Coding Scheme

A.1 Introduction

The following text and picture explains the color coding applied to electrical resistors and was obtained at the site
http://itll.colorado.edu/ITLL/index.cfm?fuseaction=ResistorChart.

A.2 Resistor Color Codes

Resistors are devices that limit current flow and provide a voltage drop in electrical circuits. Because carbon resistors are physically small, they are color-coded to identify their resistance value in Ohms. The use of color bands on the body of a resistor is the most common system for indicating the value of a resistor. Color-coding is standardized by the Electronic Industries Association (EIA).

Use the Resistor Color Code Chart (above) to understand how to use the color code system.When looking at the chart, note the illustration of three round resistors with numerous color code bands. The first resistor in the chart with 4 bands tells you the minimum information you can learn from a resistor. The next, a 5-band code, provides a little more information about the resistor. The third resistor a 6-band provides even more information. Each color band is associated with a numerical value.

A.2.1 How to read a typical 4-band, 5-band and 6-band resistor:

4-Band: Reading the resistor from left to right, the first two color bands represent significant digits, the third band represents the decimal multiplier, and the fourth band represents the tolerance.

5-Band: The first three color bands represent significant digits, the fourth band represents the decimal multiplier, and the fifth band represents the tolerance.
6-Band: The first three color bands represent significant digits, the fourth band represents the decimal multiplier, the fifth band represents the tolerance, and the sixth band represents the temperature coefficient.

A.2.2 Definitions of color bands:

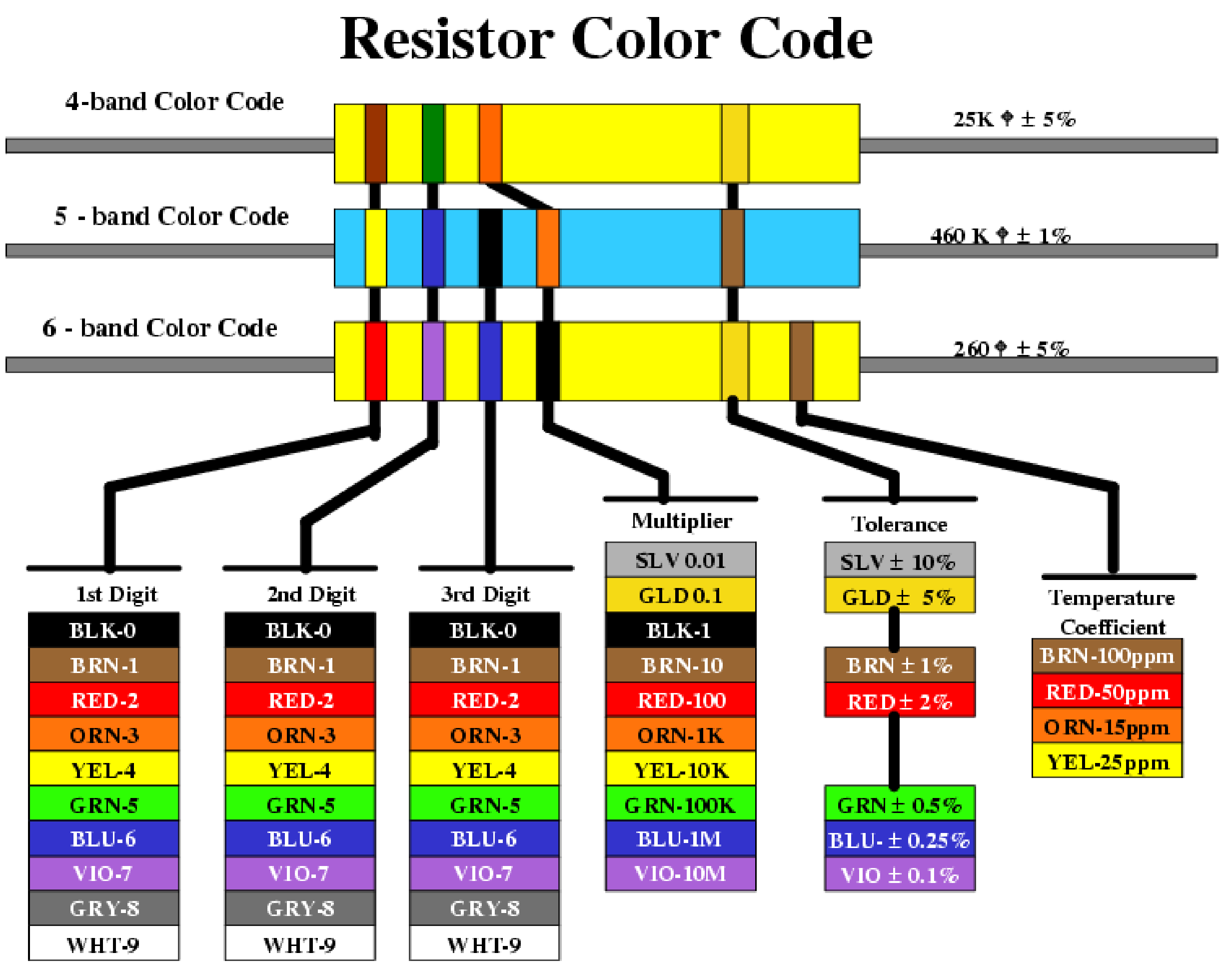
The color of the multiplier band represents multiples of 10, or the placement of the decimal point. For example: ORANGE (3) represents 10 to the third power or 1,000.

The tolerance indicates, in a percentage, how much a resistor can vary above or below its value. A gold band stands for +/-5%, a silver band stands for +/-10%, and if there is no fourth band it is assumed to be +/- 20%. For example: A 100-Ohm 5% resistor can vary from 95 to 105 Ohms and still be considered within the manufactured tolerance.

The temperature coefficient band specifies the maximum change in resistance with change in temperature, measured in parts per million per degree Centigrade (ppm/C).

A.2.3 Example (from chart)

Lets look at the first resistor on the chart. In this case, the first color band is RED. Following the line down the chart you can see that RED represents the number 2. This becomes our first significant digit. Next, look at the second band and you will see it is GREEN. Once again, follow the line down to the bar scale; it holds a value of 5, our second significant digit. Next, look at the third band, the multiplier, and you will see it is ORANGE. Once again, follow the line down to the bar scale; it holds a value of 3. This represents 3 multiples of 10 or 1000. With this information, the resistance is determined by taking the first two digits, 25 and multiplying by 1,000. Example: 25 X 1000 = 25,000 or 25,000 Ohms. Using the chart, the fourth band (GOLD), indicates that this resistor has a tolerance of +/- 5%. Thus, the permissible range is: 25,000 X .05 = +/- 1250 Ohms, or 23,750 to 26,250 Ohms.


Resistor Color Code
4-band Color Code
25K Ω ± 5%
5 - band Color Code
460 K Ω ± 1%
6 - band Color Code
260 Ω ± 5%
1st Digit
BLK-0
BRN-1
RED-2
ORN-3
YEL-4
GRN-5
BLU-6
VIO-7
GRY-8
WHT-9
2nd Digit
BLK-0
BRN-1
RED-2
ORN-3
YEL-4
GRN-5
BLU-6
VIO-7
GRY-8
WHT-9
3rd Digit
BLK-0
BRN-1
RED-2
ORN-3
YEL-4
GRN-5
BLU-6
VIO-7
GRY-8
WHT-9
Multiplier
SLV 0.01
GLD 0.1
BLK-1
BRN-10
RED-100
ORN-1K
YEL-10K
GRN-100K
BLU-1M
VIO-10M
Tolerance
SLV ± 10%
GLD ± 5%
BRN ± 1%
RED ± 2%
GRN ± 0.5%
BLU- ± 0.25%
VIO ± 0.1%
Temperature Coefficient
BRN-100ppm
RED-50ppm
ORN-15ppm
YEL-25ppm

Appendix B

Oscilloscope Tutorial

B.1 Introduction

An excellent tutorial is on the web at
http://www.cs.tcd.ie/courses/baict/bac/jf/labs/scope

I recommend in particular reading the sections on Terminology, Setting the Controls and Measurement Techniques. Keep in mind that scopes are sophisticated equipment, and we'll only be able to get limited experience with them. Some of the tutorial can be a bit overwhelming. Just look at the neat stuff! Also, come back and look at the tutorial after you've had your first lab experience with the scope. It will help fill in the gaps in your knowledge and won't be as intimidating.

Appendix C

Cable Types

C.1 Single Wire Termination Types

Above is shown a single wire with *banana plug* termination.

Above is shown an *alligator clip* termination for use on a single wire.

C.2 Dual Wire

This is a picture of coaxial cable stripped a bit so one can see the two wires contained within it.

Here is a diagram of a coaxial cable.

Above is shown a coaxial cable with *BNC* termination.

Above is shown a *BNC breakout* into two banana plugs.