Experiments with Electricity and Magnetism for Physics 336L

by

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Contents

Acknowledgments

A number of faculty and students at New Mexico Tech have contributed to the experiments for this junior-level laboratory class. The ones I know about are:

Prof. Marx Brook,
Prof. J. J. (Dan) Jones,
Prof. Paul Krehbiel,
Prof. Charles B. Moore,
Prof. William Rison,
Mr. Robert Rogers, and
Prof. William P. Winn

2018 Course schedule

Date	Lab	Due
1/22	Intro	
1/29	Circuits (1)	
2/05	Complex Imp. (2)	Circuits
2/12	BLMR (3)	Complex Imp.
2/19	Hysteresis (4)	BLMR
2/26	Hysteresis	
3/05	OpAmps (5)	Hysteresis
3/12	BREAK	—
3/19	Intro to Arduino (6)	OpAmps
3/26	Intro to Arduino	—
4/02	Digital to Analog Converters (7)	Intro to Arduino
4/09	Digital to Analog Converters	—
4/16	Diodes or Optional (8)	Digital to Analog
4/23	Optional (9)	
4/30	Optional	
5/5	Last day to submit lab report	

Table 1: This is the approximate schedule we will follow. Labs are due one week after they are completed.

0 Introduction

0.1 Course Goals and Time Committment

There are four purposes for this course.

- To give practical examples of concepts learned in Phys333/334
- To give you practice evaluating experimental errors.
- To let you experience some of the excitement (and confusion) of experimental physics.
- To give you a working comfort with basic electronics as it appears universally in a modern physics lab.
- To introduce you to *Physical Programming* (also called *Embedded Systems Programming*), a very useful experimental skill with a substantial future potential for employment.

Labs will take at least two hours to get through and understand. The course grade is based on your accurate completion and understanding of the labs. The individual measurements requested are frequently not time-consuming; that is intentional. The time you are not spending assembling circuits and making measurements is meant to be spent understanding your results and how they fit the basic electromagnetic theory that you have learned.

It will require one to three hours after each class session to complete the data analysis, perform the needed derivations, and do the background reading needed to understand your results.

0.2 Safety

- Shoes and socks are required for minimal safety.
- In case of emergency, campus police are available at 835-5434.
- Know the location of the nearest FIRE EXTINGUISHER. Can this fire extinguisher be used on electrical fires?
- Know the location of the nearest FIRE ALARM pull lever.
- Report defective or damaged equipment to the instructor.
- Construct experiments so they can not fall and so that people will not trip over wires.
- Do not energize any experiment outputting more than 30 V until the instructor has inspected it.
- Conventional lab protocol calls for no food or drink under any circumstances. I have loosened this ban because I have observed that science runs on caffeine. Thus, *black* coffee, tea, or bottled water are the *only* drinks allowed in the lab. Sugar and sweeteners are destructive to electronics, and many drinks (e.g. Coca-Cola) are corrosive. In the event of a spill of any type, you are responsible to promptly clean and dry any lab equipment involved. You may be required to dissassemble, dry, and retest your equipment if liquid has penetrated the case.
- Food and snacks are not permitted in the lab. If you are hungry, you may briefly excuse yourself after the daily introduction and finish your snack/lunch in the Workman lobby.

- Hazardous chemicals (e.g. lead) are associated with electronics. Thus, you *shall* wash your hands between working with lab equipment/components and eating.

0.3 Laboratory Protocol

- The Laboratory hours are 2 PM to 4:30 PM (1:30-4:00 or Thurs). Please arrive on time. Habitual lateness/absence will affect your grade. If you finish an experiment early, begin working on your analysis or on the next experiment.
- Conversations in the laboratory are encouraged but should be limited to the experiments.
- You are encouraged to help your fellow student learn the material or troubleshoot their experiment, but all are responsible for their own understanding.
- Lab reports using shared data or analysis, unless explicitly authorized and documented, will result in an automatic "F" for the report and possible disciplinary action.
- Feel free to bring computing devices/smart phones to assist in data plotting/analysis or for web research related to your analysis.

0.4 Required Supplies

Failure to bring the following supplies every time can result in grade reductions. (See section on grading).

- The lab manual, a printout, or an electronic copy of the day's lab.
- A lab notebook for your raw data and notes.
- A calculator or smart-phone/computing device that can act as a calculator. This allows you to do data analysis in lab.

0.5 Lab Reports and Grading

Lab reports must be typed, and will be uploaded as .pdfs. I need to be able to rapidly see that you did the work and that it is correct. Thus it must be well organized and neat. Raw data should be recopied into well-arranged tables. Figures (e.g. hand-written sketches or cell-phone pictures) should be digitally inserted into your report. In many cases, I have numbered each lab with items of data you should include. Please include these items in your report in that order, and with the appropriate number to make them easy to find.

I have posted LaTeXtemplates for a lab report on Canvas. I can give a short tutorial on LaTeXif you are interested in learning it. LibreOffice Writer or other word processors are also perfectly acceptable.

Your report should *NOT HAVE* an Introduction, Procedure or a Conclusions section. I should *ONLY* have the following sections:

0.6 Required report sections

1. **Heading** – In the following order, state
   (a) Your name

(b) The name of the experiment

(c) Date the report was written.

(d) Date the laboratory work was finished.

2. **Measured variables and data tables** – Numerical values should make clear how many significant figures you feel are appropriate. Thus:

```
2 Volts
2.0 Volts
2.00 Volts
2.000 Volts
```

mean very different things. If you list a measurement as 5 Volts, that tells me you think there is potentially 20% error in that measurement.

The column headings of your data table should list the name of the variable being measured and the units of the numbers contained. In theoretical courses, variables often represent quantities like $\vec{E}$ or $\vec{B}$ or ϵ. In the laboratory, variables represent the number of divisions on an oscilloscope or the voltage on a voltmeter. An imprecise table would have a column headed "Voltage (V)". A more precise table would indicate *the part of the circuit the voltmeter was connected to.* A well-defined variable could be called V_{AB}, where A and B are the two points on your circuit to which the voltmeter probes were applied. V_{AB} would be further defined by the inclusion of the circuit diagram with the table with A and B marked on it.

It is not unusual for raw data to be somewhat disorganized. For example, when measuring the amplitude of a resonant circuit vs. the frequency at which it is driven, one may take a number of data points that are not too interesting (because they are not near the resonance). You might also obtain data that you later decide are incorrect or ambiguous. For the lab report, you shall recopy the data table in a well-ordered way, omitting any dubious or redundant data points.

3. **Graphs** – Show data as points (not lines) and theoretical curves as lines. Use computer plotting software, or plot by hand in your notebook or on graph paper and scan in the plot. Axes should be labeled with tick-marks and and well-defined variables (described previously in discussion of tables).

4. **Answers to Numbered Questions** – Please number the questions in the same order they are asked in the lab manual. Often the questions will require either calculations or derivations. These should be done as follows:

Calculations: When numerical values are plugged into formulae or derived results, they should be explicitly written in your report. I know that you can plug ten numbers into a formula in your calculator and just write down the answer, but am explicitly asking that you not do that. You (or I) should be able to look at your calculations and see exactly what numbers you used at every step. This will help you find your mistakes and documents exactly what you did.

Derivations: If derivations require a figure; draw large, clear figures. Every derivation using the integral form of Maxwell's equations must have an accompanying figure that shows the locations of line integrals, surface integrals, and volume integrals.

5. **Error Discussion** – Calculations marked with a * in the lab require error analysis. The method I suggest is to make the relevant measurement at least five times, report mean and standard deviations and then do the calculation with mean values and "corner cases".

   Further, for each lab, specify what you think is the single largest source of error (e.g. reading the oscilloscope, uncertainty on the value of a component, simplifications made in the derivation or formulae used.)

0.7 Error Analysis

Types of Error

All experimental uncertainty is due to either random errors or systematic errors. *Random errors* are statistical fluctuations (in either direction) in the measured data. They may be due to the precision limitations of the measurement device, electrical noise, vibration or other uncontrolled variable. Random errors can also result from the experimenter's inability to take the same measurement in exactly the same way to get exact the same number. *Systematic errors*, by contrast, are roughly reproducible inaccuracies that are consistently in the same direction. Systematic errors are often due to a problem which persists throughout the entire experiment. Note that systematic and random errors refer to problems associated with making measurements. Mistakes made in a calculation are not counted as sources of error.

All measured quantities listed with a * should be recorded with error bars. It is all right to list the error at the beginning of a data table. (e.g. *All measurements are* $\pm 0.001V$).

Minimizing Error

Here are examples of how to minimize experimental error.

0.7.1 Random errors

You measure the mass of a ring three times using the same balance and get slightly different values: 17.46 g, 17.42 g, 17.44 g The solution to this problem is to take more data. Random errors can be evaluated through statistical analysis and can be reduced by averaging over a large number of observations.

0.7.2 Systematic errors

The cloth tape measure that you use to measure the length of an object had been stretched out from years of use. (As a result, all of your length measurements were too small.) The Ohm-meter you use reads 1 Ω too high for all your resistance measurements (because of the resistance of the probe leads). Systematic errors are difficult to detect and cannot be analyzed statistically, because all of the data is off in the same direction (either to high or too low). Spotting and correcting for systematic error takes careful thought into how your equipment works, and cleverness to measure how far off it is from correct.

0.7.3 Handling Errors

Note that uncertainties (Random or Systematic) are not obtained by comparing your results with the "accepted" values you find in the literature (or a lab manual). Instead, they are found in the following way:

1. Estimate the uncertainties in the measured quantities (e.g. voltages, resistances, frequencies, lengths, etc.) and
   - All instruments have an inherent accuracy which can only be determined by comparing the instrument to a more accurate instrument or to a "standard" for the quantity of interest. Explain what you compared your instruments to to determine this inherent accuracy.
   - Uncertainty in a length may be due to precision with which a scale can be read. Uncertainty in a time may be due to unknown reaction time for starting/stopping a timer.
   - Random uncertainties may be estimated by making the same measurement several times and calculating the standard deviation. Show such repeated measurements, and the standard deviation calculation, in your log-book.
   - Repeated measurements will not uncover systematic errors. This requires thought and calibration.
2. First correct systematic errors.
3. Next propagate the uncertainties in the measured quantities to find uncertainties in the calculated results.
   - Use the general formula for propagation of errors given on page 75 of Taylor's Error Analysis text. (See References section above – An excerpt follows)
   - Assume you are measuring the variable q which depends on the measured quantities, $x, \ldots, z$. If the uncertainties $\delta x, \ldots, \delta z$ are random, then the uncertainty in q is

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x}\delta x\right)^2 + \ldots + \left(\frac{\partial q}{\partial z}\delta z\right)^2} \tag{1}$$

0.8 Lab Grades

If you complete a lab and answer all the questions completely, you will get at least an "A-" for the lab. You can earn an "A" with exceptional clarity of presentation, wonderfully precise measurements, or a very good error discussion.

If you start omitting calculations, measurements or making errors in analysis, you are entering "B" territory. Significant omissions or confusions bring you to "C-land". Annoying your instructor by (for example) writing up the lab on a napkin in the 30 minutes before it is due can result in a grade below "C-".

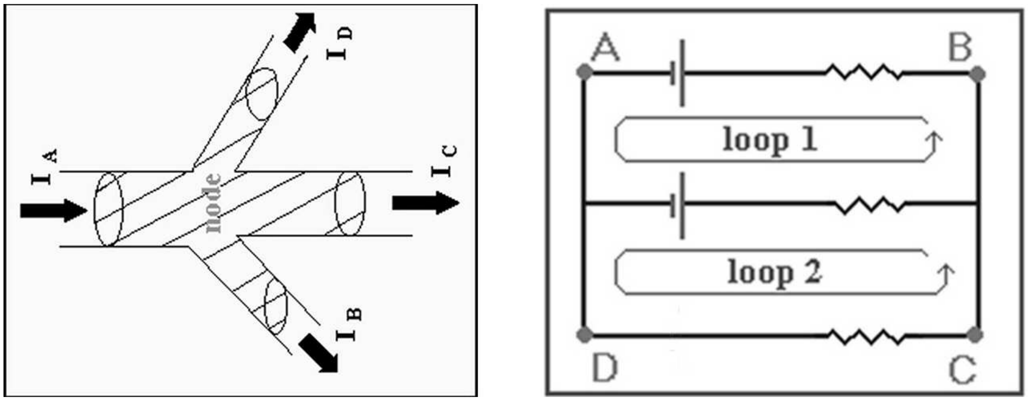


Figure 1: Kirchoff's Current Law: The sum of currents entering a node is equal to the sum of currents leaving it.
Kirchoff's Voltage Law: The sum of voltage around any closed loop in a circuit is zero.

1 Circuits (n=1)

1.1 Background theory

In Physics 333, you learned the basic principles you need to analyze any circuit.

1. Electrical charge is conserved. This leads to Kirchoff's current law.

2. The electrostatic force is a conservative force. This leads to Kirchoff's voltage law.

Kirchoff's famous laws for circuit analysis are stated above in the figure caption.

Referring to the left panel of Figure 1, we see that the current law means that $I_A = I_B + I_C + I_D$. This immediately leads to the useful corollary that in a series circuit (which has only one branch) the current is the same at all points in the circuit.

To understand the origin of the Voltage law shown in the right panel, consider that the definition of a conservative force is that the Work done is equal over any possible path between two points. Recalling that Voltage is just the work done per electron, we see that the voltage drop between any two points in the circuit must be equal no matter what path is taken. An equivalent way of stating this is that the closed loop voltage is 0 over any possible loop through the circuit.

Because they are derived from fundamental physical principles, Kirchoff's Laws are valid for any AC or DC circuit containing any combination of passive components, semiconductors and active components. For this lab, we will also need Ohm's law, $V = IR$. Ohm's law is an example of an IV characteristic. IV characteristics depend on the type of device being studied. A resistor fits Ohm's law exquisitely, while a light-bulb only approximately fits Ohm's law. Later in the course we will study the IV characteristics of diodes and transistors. For a diode, $I = I_r(e^{eV/nk_BT} - 1)$, which as you can see is not Ohm's law at all!

1.2 Basic Formulae for DC Circuits

$$V = IR \tag{1}$$

$$W = QV \tag{2}$$

$$P = IV \tag{3}$$

$$R_{eff} = R_1 + R_2 + R_3 + ... \quad (4)$$

$$1/R_{eff} = 1/R_1 + 1/R_2 + 1/R_3 + ... \quad (5)$$

Ohm's Law (eqn 1) is not fundamental. It happens to be true for materials called resistors. It is a simple case of an I-V curve or constitutive relation.

The Power dissipation formula (eqn 3) is merely a consequence of taking the derivative of equation 2, which is just the definition of voltage.

The series and parallel circuit laws (eqn 4-5) come directly from Ohm's law and Kirchoff's laws. A beautiful thing about these laws is that they generalize to complex impedances . Here "R" is replaced with "Z", which will be discussed in future labs.

In terms of fundamental physics, you need only conservation of charge and energy to derive all circuit laws. However, the simple formulae above come up so frequently in circuit analysis that they are worth memorizing.

1.3 Philosophy of Experimental Physics

An experimentalist spends a lot of time "thinking" as well. Results are almost never what you expect them to be, and apparatus is full of quirks that you need to learn via familiarity. In this experiment you will measure current and voltage in simple circuits with high accuracy. (Three figures is high accuracy for an experiment). Some obvious questions occur[1].

- How does one measure a voltage?
- How does one measure a current?
- How do you hook up a power supply?
- What value of resistor should I use?
- Why do the light bulbs behave differently than the resistors?

1.4 Series and Parallel Circuits with Resistors

You will build several simple series and parallel circuits and explicitly measure the voltage and current to verify Kirchoff's Laws and build up familiarity and confidence with the use of electrical equipment. This lab should serve to remind you of things you already know, and because it is relatively simple, you should be able to predict your results with three significant digits.

Using the power supply and several identical resistors of value R, build and study circuits *i*-*ii*.

(1) Set the power supply to roughly 6.00 V (Measure the actual value with a multimeter and record it). Before building circuit *i*, measure and record the resistor values you have selected (the two resistors will be slightly different even if nominally the same). Use this and the voltage to predict the current in the circuit.

(2*) Now build circuit *i*, measure (and record) the current at point A and point C. Should they be equal? Are they? Do they agree with your calculations? If they do not, you imost likely measured the current wrong.

[1] I am not asking you to explicitly answer these questions, but you will need to think about them to do the lab

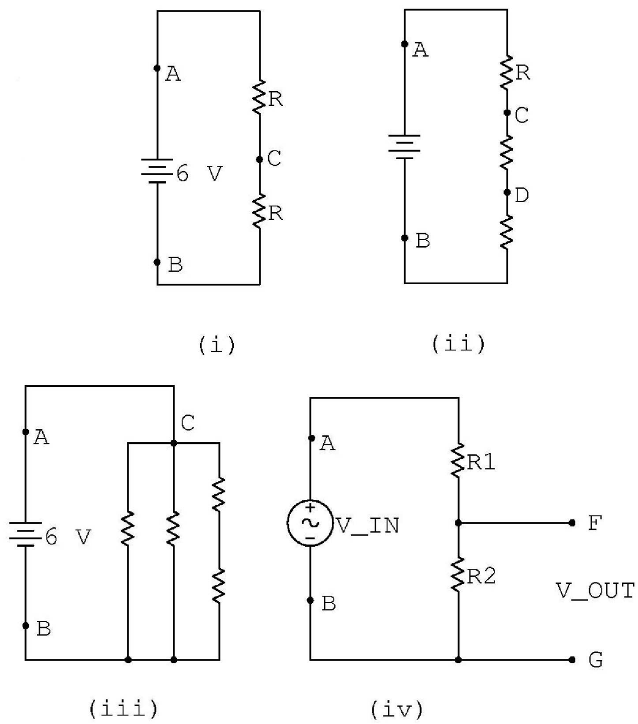


Figure 2: Circuits *i and ii* are simple series circuits. Circuit *iii* illustrates a combination of series and parallel circuits. Circuit *iv* is a very useful configuration called a "Voltage Divider".

(3) Before building circuit *ii*, measure and tabulate the three resistors to be used. You should now be able to predict the voltages for circuit *ii*. Make a table for circuit *ii* in which you include the predictions and measurements for V_{BD}, V_{BC}, and V_{BA}.

(4*) Build circuit *iii* and test Kirchoff's current law for node C. Make predictions of values for all the currents at node C and verify with measurements. It is more interesting to make predictions before doing the measurements. If you end up surprised, say so, then revise your predictions (without erasing the original ones).

(5) Circuit *iv* is called a "Voltage Divider". This is because $V_{OUT} = V_{FG}$ is always a fixed fraction of $V_{IN} = V_{AB}$. Design a 10:1 voltage divider (a circuit for which $\frac{V_{out}}{V_{in}} = \frac{1}{10.0}$.) You may not find resistors to provide an exact 1/10 ratio; it is sufficient to get between 1/9 and 1/11. Further, predict the division ratio of the circuit you actually build to three signficant digits based on the value of resistors you do find. Verify your prediction with three different values of V_{IN}.

Using resistance to measure temperature of a light-bulb

(6) Get two Ecko #46 lightbulbs out of the box and measure and record the resistance through each of them with your Ohmmeter. With some wire and a solder iron, solder the two lightbulbs into a series circuit (or connect them with alligator clips).

(7) Connect the two lightbulbs to the 6 V output of your power supply. Measure the current through the bulbs and the Voltage of the supply. Use this to calculate the resistance of two light-bulbs in series.

(8) Bypass one of the bulbs (just move your alligator clip so it is not in the circuit) so you can measure the current, voltage, and thus resistance of a single bulb.

(9) Make a table comparing the resistance of a single bulb measured with your Ohm-meter, of a single-bulb in a circuit with 6 V and of one of the double bulbs (in other words take the result from 7 and divide it by two. All three values will be very different. Why?

(10) The following formula allows you to calculate the resistivity of tungsten wire as a function of temperature. Assuming that room temperature is 300 K, calculate the temperature of the single bulb, and the double bulb. Light bulbs get very hot!

$$R = R_{ref} \times [1 + \alpha(T - T_{ref})] \quad \alpha = 4.4 \times 10^{-3} \quad 1/K \tag{6}$$

(11) Based on what you have learned, is it right to treat a lightbulb like a resistor? Why or why not?

1.5 For Advanced Students

(12*) A current meter has an equivalent series resistance (ESR), and it typically changes (increases) as you use the more sensitive current scales. Figure out the ESR for each of the three current scales on the device. You can achieve this by trying appropriate resistors in the circuit. Figuring out what "appropriate" means is your first task.

(13) If you are careful, you should be able to get within a factor of three of the ESR in step 12. To do better, you may need to better characterize the resistor and the voltage source you used in the measurement. Do we have standard resistors and voltage sources in the lab? Use them to refine your results.

Equipment

- HP 6235A Triple output Power Supply
- Proto-board or Spring Board
- Your Personal Multimeter
- Resistors

Laboratory Time

Two hours

2 Complex Impedance (n=1)

2.1 Motivation for the experiment

Since complex numbers are widely used in physics and electrical engineering, it is useful to see how a complex number can be measured. On the assumption that you have never seen complex impedance before, I explain it below, as succinctly as possible. I suggest following along with pencil and paper. If you want a longer explanation (or a different one), read Purcell and Morin, sections 8.3–8.5. I do not expect that on one reading you will really "believe" that it works, but it really does work and you can definitely use it to calculate. If you have seen either Fourier or Laplace transforms, then you have seen similar tricks before.

2.2 Background: Introduction to Complex Impedance

Voltages in a series circuit add. Engineers call this "Kirchoff's voltage law" (KVL). This applies to ANY circuit, whether it be composed of resistors, inductors, diodes, transformers, capacitors, etc. Physicists know that KVL is merely a consequence of the definition of voltage and its path independence around the circuit. Likewise, currents into any circuit "node" sum to the same value as currents leaving the node. Engineers call this "Kirchoff's current law" (KCL). Physicists realize that KCL is a consequence of the conservation of charge. In the last experiment, you used well-known rules for combining resistors in series and parallel, respectively.

$$R_{eff} = R_1 + R_2 + R_3 + ... \tag{1}$$

$$1/R_{eff} = 1/R_1 + 1/R_2 + 1/R_3 + ... \tag{2}$$

These rules came from combining KVL, KCL, Ohm's law and the following definition.

$$V_{source} = IR_{eff} \tag{3}$$

While KCL and KVL can be used to analyze ANY circuit, no matter what components it contains, the concept of effective resistance only works (simply) for linear devices (in practice this means Resistors, Inductors, and Capacitors, but not diodes, transistors, amplifiers etc.). However the concept of effective resistance CAN be extended beyond merely resistors. When applied to circuits with R's and L's and C's, we rename effective resistance (R_{eff}) to *effective impedance* (Z_{eff}) and we have the following formulae.

$$Z_{eff} = Z_1 + Z_2 + Z_3 + ... \tag{4}$$

$$1/Z_{eff} = 1/Z_1 + 1/Z_2 + 1/Z_3 + ... \tag{5}$$

$$V_{source} = IZ_{eff} \tag{6}$$

By analogy, you can see that these formulae apply to series and parallel combinations of R's, L's and C's. Furthermore, they can be mixed. You can have as many R's, L's and C's as you want, in any proportion. Here are the requirements to use effective impedance.

1. The power supply must be a sinewave (not a battery, and not some more complex function than a sine).

2. The impedance must be manipulated as a complex number.

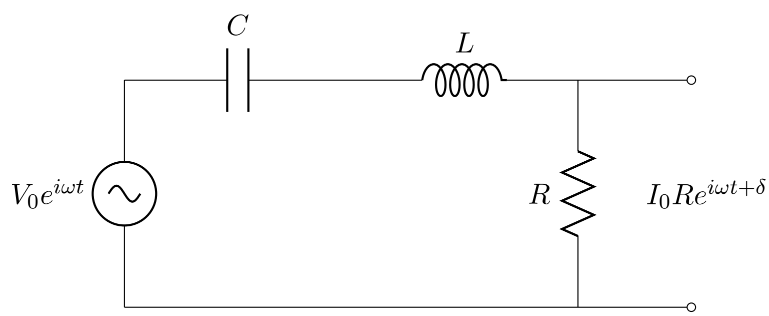
3. $Z_R = R$, i.e., the impedance of a resistor is just its resistance.

4. $Z_L = i\omega L$, i.e., the impedance of an inductor is proportional the angular frequency of the source, and is purely imaginary.

5. $Z_C = \frac{1}{i\omega C} = \frac{-i}{\omega C}$, i.e., the impedance of an capacitor is inversely proportional to the angular frequency of the source and to the capacitance.

2.3 Why does it work?

The circuit below is similar to what you will build in this experiment (except that you will have just the L or just the C, not both at once). The "trick" I develop applies to ANY combination of components, including ones with several parallel branches, but here we will just apply it to this particular circuit for concreteness. The differential equation for this circuit, expressed in terms of



the charge on the capacitor is:

$$V_s(t) = L\frac{d^2Q}{dt^2} + R\frac{dQ}{dt} + \frac{Q}{C} \tag{7}$$

If we require that $V_s(t) = V_0 cos(\omega t)$ then we expect $Q(t) = Q_0 cos(\omega t + \delta) + Q_{transient}$. Why do we expect this? Driven oscillators must respond at the driving frequency, but they do not have to respond in phase. Furthermore $Q_{transient} \to 0$ over several cycles, and will henceforth be ignored[2] Because of this property, we can rewrite

$$V_s(t) = Real[V_0 e^{i\omega t}] \tag{8}$$

$$Q(t) = Real[Q_0 e^{i\omega t+\delta}] \tag{9}$$

In analogy to Ohm's law, we want a relationship between voltage and current, not voltage and charge. For this simple form of Q(t), it is easy to calculate current. [3]

$$I(t) = \frac{dQ}{dt} = Q_0 i\omega e^{i\omega t+\delta} = i\omega Q(t) \tag{10}$$

By assuming sinuoidal variation, a derivative becomes as simple as multipling by $i\omega$. Furthmore, we can write

$$I(t) = I_0 e^{i\omega t+\delta} = i\omega Q_0 e^{i\omega t+\delta} \tag{11}$$

[2] I am assuming that you have solved enough similar equations to understand that this really is the characteristic of the solution.

[3] From here on out I will no longer show the "Real" operator. It is assumed.

Where $I_0 = i\omega Q_0$. Let us take individual derivatives and express them in terms of I_0.

$$\frac{dQ}{dt} = I_0 e^{i\omega t+\delta} \tag{12}$$

$$\frac{d^2Q}{dt^2} = I_0 i\omega e^{i\omega t+\delta} \tag{13}$$

$$Q = \frac{I_0}{i\omega} e^{i\omega t+\delta} \tag{14}$$

Replacing $Q(t)$ by appropriate forms of $I(t)$, equation 7 becomes

$$V_0 e^{i\omega t} = Li\omega I_0 e^{i\omega t+\delta} + RI_0 e^{i\omega t+\delta} + \frac{I_0}{i\omega C} e^{i\omega t+\delta} \tag{15}$$

Note that $e^{i\omega t}$ can be divided out of both sides, and $I_0 e^{i\delta}$ can be factored out of the right hand side. This leaves

$$V_0 = I_0 e^{i\delta}[Li\omega + R + \frac{1}{i\omega C}] \tag{16}$$

This is of the form $V = IZ_{eff}$ where

$$Z_{eff} = i\omega L + R + \frac{1}{i\omega C} \tag{17}$$

Note that Z_{eff} is just the sum of the individual Z's for the definitions of complex impedance given in the list at the end of section 2.2 above.

2.4 Overall Approach for the experiment

You will build the circuit shown below consisting of a function generator, connected to a capacitor (or inductor), connected to a resistor, connected to ground. All measurements will be made by connecting appropriate cables to the circuit and an oscilloscope. (You will NOT use your voltmeter to make these measurements except where directed.)

One can measure the impedance of a single component, or of an entire circuit. Regardless of what you are measuring, the following equation always applies:

$$V = IZ \tag{18}$$

All that changes in equation 18 is what parts of the circuit V, I, and Z apply to. Since we want to measure the impedance Z of the *entire circuit.* a good notation for this experiment is:

$$V_{FG} = I_R Z_{eff} \tag{19}$$

V_{FG} is the voltage measured between the output of the function generator and ground.

I_R is the current measured through the resistor. Since oscilloscopes only measure voltages (not currents) you will actually be measuring the voltage across the resistor (V_R). But of course $I_R = V_R/R$.

Once you know V_{FG} and I_R you can deduce Z_{eff}.

2.5 Make Measurements for RC Circuit

(1) **Measure components** – Measure and record the resistance (R_1) and capacitance you will use. (Your multimeter will do both!).

Use a T-connector and two cables to hook the function generator both to channel 1 of the oscilloscope and to the circuit of interest. Set the function generator to produce roughly 2 V amplitude at f=400 Hz.

(2*) **Record amplitude** – Read the actual amplitude of the function generator off the oscilloscope and record it.

(3) **Record frequency** – Read the period of the function generator off the oscilloscope, record it and calculate the frequency ($f = 1/T$) and well as the angular frequency ω.

Use a second cable connected to channel 2 of the oscilloscope to display the voltage between the resistor and ground. Now you should have two sine waves on the oscilloscope. They should have different amplitudes and they should have a time offset between them.

(4*) **Record amplitude, time delay, and phase of resistor voltage** – Record the amplitude across the resistor and the time delay of the voltage across resistor relative to the function generator. Calculate the phase (ϕ, in degrees) from the time delay. (You know how to do this ... think about it.)

(5) **Photograph or sketch the 'scope display** – Either photograph or sketch the oscilloscope display. Your photo/sketch should be clear enough that I can see both waveforms and be able to measure their amplitude and phase delays. This means the graticule must be visible, and the scales in time and voltage indicated.

2.6 Make Measurements for RL Circuit

(6) **Measure components** – Measure and record the resistance of the resistor R_2 AND of the inductor. (The inductor has a significant resistance ... and it must be included in your calculations).

As before, use a T-connector and two cables to hook the function generator both to channel 1 of the oscilloscope and to the circuit of interest. Set the function generator to produce roughly 2 V amplitude and change the frequency (f) to 1000 Hz.

(7) **Record amplitude** – Read the actual amplitude of the function generator off the oscilloscope and record it.

(8) **Record frequency** – Read the period of the function generator off the oscilloscope, record it and calculate the frequency f.

As before, use a second cable connected to channel 2 of the oscilloscope to display the voltage between the resistor and ground. You will notice the voltage across the resistor is much smaller than the function generator voltage. Feel free to change the vertical scales to make it easier to measure amplitude and phase.

(9) **Record amplitude, time delay, and phase of resistor voltage** Note that the time delay is opposite what it was for the RC circuit.

(10) **Photograph or sketch the 'scope display** – Be sure that the horizontal and vertical scales are clearly labeled or visible.

2.7 Do Calculations (R_1C)

(11) Calculate the magnitude $|Z|$ – From your measurements calculate the amplitude of the current through the RC circuit. Using $|V_{FG}| = |I_R|\ |Z_{Total}|$, what is the magnitude of Z_{Total}? (Hint: It will be similar to the resistance of the resistor, but somewhat larger).]

(12) Write Z_{Total} in polar form – $Z_{Total} = |Z|exp(i\phi)$. You have just calculated $|Z|$, and in step 4 you calculate ϕ from the time delay. (Actually, you calculated $-\phi$ (because the current and impedance have opposite phases) so throw a minus sign in there).

(13) Write Z_{Total} in cartesian form – Convert $|Z|exp(i\phi)$ to the form $x + iy$. Feel free to look at section 2.11 if you forgot how.

(14) Calculate experimental R_1 and C – Given an RC circuit, can you identify R and C with some function of x, y, and, perhaps ω? (Yes ... you can ... so do it.). At this point you should arrive at experimental values of R_1 and C.

(15*) Are your results within error tolerances? – Calculate R and C for the corner cases of your measurements. (State what the corner cases are and show the calculations as you did in the previous step.

2.8 Do Calculations (R_2L)

(16) Calculate the magnitude $|Z|$ – From your measurements calculate the amplitude of the current through the RL circuit. What is the magnitude of Z_{Total}? (Hint: It will be similar to the sum of resistances of the resistor and inductor, but somewhat larger).

(17) Write Z_{Total} in polar form – Same as step 12

(18) Write Z_{Total} in cartesian form – Same as step 13.

(19) Calculate experimental R_2 and L – Given an LR circuit, identify R and L with some function of x, y, and, perhaps ω. At this point you should arrive at experimental values of R_2 and L.

2.9 For Advanced Students

(20 – Filters Theory) The concept of complex impedance generalizes very nicely to the subject of filters. Calculate the theoretical amplitude and phase response of a single pole low-pass RC filter with a 3-dB point of 1000 Hz. Make Bode plots of amplitude and phase from 10.0 Hz to 1.00 MHz for this filter.

(21 – Filters Experiment) Build this filter and characterize it over the 10.0 Hz to 1.0 MHz frequency range footnoteYou might want to refer to the write-up entitled “Low-Pass Filters” for guindance.. Overlay the theoretical and experimental curves.

2.10 Equipment

- Oscilloscope
- Function generator
- Multimeter
- C=0.022μF Capacitor

- R_1=27 kΩ Resistor
- L=4.7 mH Inductor
- R_2=39 Ω Resistor

2.11 Refresher on Complex Arithmetic

Recall that for *any* complex number Z:

$$Z = x + iy = Z_0 e^{i\phi} = Z_0(cos\phi + isin\phi) \tag{20}$$

where $Z_0 = \sqrt{x^2 + y^2}$ and $\phi = atan(y/x)$. Also $Z_0^2 = Z^* Z$, where $Z^* \equiv x - iy$. Finally, it is useful to know that if $Z = \frac{1}{a+ib}$, then $Z^* = \frac{1}{a-ib}$

3 Magnetic Field, Inductance, Mutual Inductance, and Resonance (n=1)

3.1 Introduction

In this laboratory exercise you will learn

- how to calculate mutual and self inductance,
- how to measure the amplitude of an oscillating magnetic field,
- how a circuit behaves around a resonance, and
- how a transformer works.

This is a good time to review the concepts listed above in a junior-level textbook on electricity and magnetism.

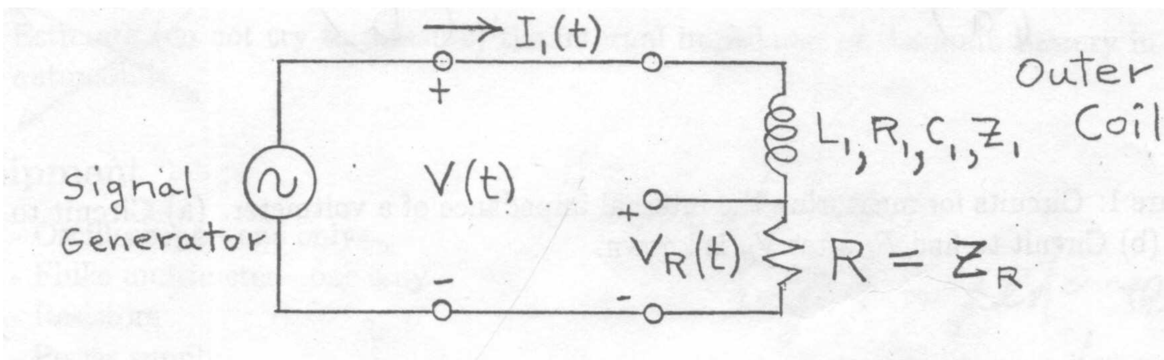


Figure 1: Circuit for measuring impedance and self-inductance and exploring what happens around a resonance.

3.2 Self Inductance

Set the function generator to 5 V amplitude (nominal) and f=1000 Hz. Hook up the circuit in the figure below. (*Note: The setup and the first four measurements below are identical to the LR circuit part of the Complex Impedance lab. Thus, I left out much of the explanatory detail.*)

(1) **Measure components** – Measure (with your multimeter) and record the resistance (R) of the resistor and the inductor.

(2*) **Record amplitude** – Record V_{FG} from channel 1 of O'scope.

(3) **Record period, frequency f, and ω** –

(4*) **Record amplitude, time delay, and phase of resistor voltage (V_R)**– Give phase in degrees.

(5) **Calculate the magnitude $|Z|$** – From your measurements calculate the amplitude of the current through the LR circuit. Using $|V_{FG}| = |I_R|\ |Z_{Total}|$, what is the magnitude of Z_{Total}?

(6) Write Z_{Total} in polar form –

(7) Write Z_{Total} in cartesian form –

(8) Calculate experimental R and L_1 – Identify R and L with terms in $x + iy$. Arrive at experimental values for L_1, R and R_L (the resistance of the inductor).

(9*) Estimate uncertainty in L_1, and $R + R_L$. First write down uncertainty in time-delay (How many percent is that). Translate this to degrees and add that many degrees to your calculated phase. Recalculate L_1 and $R+R_L$. What percent error in L_1 does this correspond to? How about $R + R_L$?

3.3 Resonance

(10) Observe a "null" resonance – Look for a resonance between 35 and 40 kHz. It will show up clearly as a null in your measurement of current. Measure this frequency to three significant figures.

(11) Observe phase shift through resonance – Compare the relative phases of $V_{FG}(t)$ and $V_R(t)$ at frequencies above and below the resonant frequency. Sweep back and forth through the resonance and note what you observe about the phase. This is not intended to be a precision measurement. You are merely trying to observe what happens to the phase as the circuit passes through resonance.

For the next part of the lab, we will set up the circuit as in Figure 2. Also, it is helpful to have three cables connected to the oscilloscope at once. First, connect V_{FG} to channel 3 of the 'scope. (It was probably on channel 1). Adjust the triggering to trigger on channel 3. (Alternately, you may put the function generator's "trigger output" on the "Ext Trigger" connector and switch to "Ext Trigger"). Connect channel 1 across the resistor to continue to measure V_R. Insert the search coil into the large coil and connect that to channel 2 of the 'scope. We will call this measurement V_2.

You are now prepared to study mutual inductance and also to obtain an "impossible" result at resonance.

3.4 Magnetic Field Amplitude and Mutual Inductance

(12) Measure the mutual inductance between the two coils – Set $f = 1000\ Hz$ and measure V_R and V_2. (Measure amplitude precisely, and make a note of approximate phase). From this you will calculate the magnetic field in coil 1 and hence the mutual inductance during the data analysis section of the lab.

(13) Get an "impossible" result – Now increase f back toward the resonance frequency and observe what happens to $V_2(t)$ and $V_R(t)$. Notice that while $V_R(t)$ (and hence the current through the circuit with the outer coil) is nearly zero at resonance, $V_2(t)$ is not. But $V_2(t)$ is proportional to dB/dt which is proportional to the rate of change of current in the Outer Coil.

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How can this happen when $V_R(t)$ is nearly zero?

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(It is likely we will discuss the answer to this question in class. Please answer it in your lab report as well).

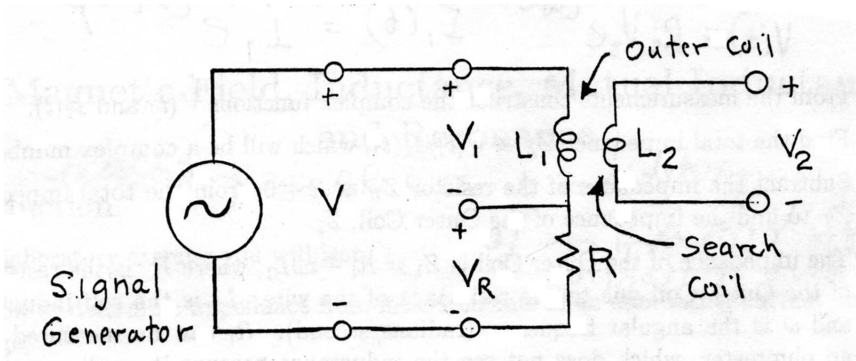


Figure 2: Circuit with Outer Coil and inner Search Coil. The Search Coil can be used to find the magnetic field from the Outer Coil. There is a mutual inductance between the two coils. As a unit, the two coils are a transformer.

3.5 Transformer

The two coils together are a transformer. In a transformer, power flows from the primary winding (Outer Coil in this case) to the secondary winding (Search Coil in this case). Remove the resistor from the primary circuit so that the function generator is connected directly to the primary winding (Outer Coil). And then, for calculations described below, do the following:

(14) Find the frequency range where the transformer equation will apply − Find and note the range of frequencies for which V_2 (the search-coil voltage) is nearly constant. (Hint, set your frequency to roughly 5 kHz and work your way down and up from there. The answer can be approximate, but you should include in your lab report how you defined *nearly constant.*

(15) Measure the transformer multiplication ratio − Having determined the frequency range over which V_2 is roughly constant, set the frequency somewhere in the middle of this range and measure and record the voltage $V_{FG} = V_1$ across the Outer Coil (primary winding) and the voltage V_2 across the search coil (secondary winding).

3.6 Calculations and analysis

(16) Find B Derive an approximate expression for the magnetic field strength B near the center of the Outer Coil when the current through that coil is I_1, the number of turns of wire is N_1, and the length of the coil is ℓ_1. Make the approximation that $B = 0$ outside the coil. The quantities I_1, N_1, and ℓ_1 have subscript 1 to indicate that they are associated with the Outer Coil (also called the primary of the transformer). Later, the subscript 2 will be used for variables associated with the secondary coil of the transformer (Search Coil).

(17) Find L_1 Derive an approximate expression for the self-inductance of the outer coil. Your expression will involve N_1, A_1, ℓ_1 and physical constants. A_1 is the area enclosed by one turn of wire in the coil.

(**18**) – Use the results in the previous items to estimate a numerical value for the inductance of the coil. Also estimate its impedance $Z_1 = i\omega L_1$ at a frequency $f = 1$ kHz.

(**19**) – Compare the inductance L_1 of the Outer Coil deduced from your measurements of voltage amplitude and phase with the value obtained from the equation for L_1 above. Can the discrepancy be explained by the uncertainty in the measured values? If not, can you come up with a systematic reason for the error, and can you perhaps come up with a way to calculate L_1 more accurately? Explain, and do it.

(**20**) – Starting with one of Maxwell's equations, develop the equations for determining B from the voltage induced in the Search Coil, given the cross-sectional area A_2 and number of turns N_2 of the Search Coil. Variables associated with the Search Coil will have subscript 2. Compare the B value derived from your measurements with that calculated as in (16) above, using the actual value of the current.

(**21**) – The combination of the Outer Coil and Search Coil constitutes a *mutual inductor*. Derive the following approximate equation for the mutual inductance between the Outer Coil and the Search Coil using the approximate expression for B above:

$$M_{12} = \mu_0 N_1 N_2 A_2 / \ell_1. \tag{21}$$

In addition, compute the induced voltage in the Search Coil.

(**22**) **Derive the transformer equation** – Derive the following expression for the ratio of voltages of a transformer:

$$\frac{V_2}{V_1} = \frac{N_2 A_2}{N_1 A_1}, \tag{22}$$

Compare your measured value (from step 15) with that predicted from the above expression.

(**23**) **Calculate coil capacitance** – Using the value for L_1 and the resonant frequency, calculate the capacitance of the coil.

Equipment

- L_1 – Outer Coil (2920 turns of 29 AWG wire (diameter $D = 0.29$ mm).
- L_2 – Search Coil (50 turns wound on wood)
- R – 310 Ω resistor
- Oscilloscope
- Function generator

Laboratory Time

Four hours

4 Hysteresis (n=2)

4.1 Introduction

A system is said to exhibit hysteresis when the state of the system does not reversibly follow changes in an external parameter. In other words, the state of system depends on the history of the system ("history-sis"). The classic examples of hysteresis use Ferromagnetic materials. The state of the system is given by the magnetic moment per unit volume, $\mathbf{M}$, and the external parameter is the magnetic field, $\mathbf{H}$. In this experiment, we explore hysteresis in the ferromagnetic core of a transformer by measuring both the magnetic flux density $\mathbf{B}$ and the magnetic intensity $\mathbf{H}$ in the core. The variable M can be deduced from $\mathbf{H}$ and $\mathbf{B}$.

The magnetic intensity vector $\mathbf{H}$ is *defined* by the equation

$$\mathbf{H} \equiv \frac{1}{\mu_0}\mathbf{B} - \mathbf{M} \; , \tag{23}$$

where $\mathbf{B}$ is the magnetic flux density (or magnetic induction), μ_0 is the magnetic permeability of free space and $\mathbf{M}$ is the macroscopic magnetization. The macroscopic and microscopic magnetizations are related by the defining equation

$$\mathbf{M} = \lim_{\Delta V \to 0} \frac{1}{\Delta V} \sum_i \mathbf{m_i} \; . \tag{24}$$

$\mathbf{M}$ is the vector sum of the atomic magnetic moments divided by the volume, ΔV, of the sample.

For an isotropic, linear material, $\mathbf{M}$ is linear in $\mathbf{H}$, as

$$\mathbf{M} = \chi_m \mathbf{H} \; , \tag{25}$$

where the dimensionless magnetic susceptibility χ_m is assumed constant. In this case equation (23) becomes,

$$\begin{aligned} \mathbf{H} &= \frac{1}{\mu_0}\mathbf{B} - \mathbf{M} && (26)\\ \text{so that} \quad \mu_0 \mathbf{H} &= \mathbf{B} - \mu_0 \chi_m \mathbf{H} && (27)\\ \text{and} \quad \mathbf{B} &= \mu_0 (1 + \chi_m) \mathbf{H} \; . && (28) \end{aligned}$$

By comparing this last equation with the free space equation,

$$\mathbf{B} = \mu_0 \mathbf{H} \; , \tag{29}$$

the magnetic permeability, μ, of the material is defined to be

$$\mu = \mu_0 (1 + \chi_m) \; . \tag{30}$$

The relative permeability K_m is defined as

$$K_m = \frac{\mu}{\mu_0} \tag{31}$$

$$\text{so that} \quad K_m = 1 + \chi_m \ . \tag{32}$$

In a ferromagnetic material, the magnetization is produced by cooperative action between domains of collectively oriented atoms. Ferromagnetic materials are not linear, so that

$$\chi_m = \chi_m(\mathbf{H}) \ . \tag{33}$$

However, the above equations are still applicable if we realize that μ is no longer a constant, that is

$$\mu(\mathbf{H}) = \mu_0[1 + \chi_m(\mathbf{H})] \tag{34}$$

and

$$\mathbf{B} = \mu(\mathbf{H})\mathbf{H} \ . \tag{35}$$

This behavior can be explained by examining the microscopic structure of a ferromagnetic material. The material actually is polycrystaline, consisting of many small crystals of the material. Each of these crystal grains is divided into groups or 'domains' of atoms. Within a domain, the magnetic moments of the atoms are all aligned parallel to each other. These domains, on the order of hundreds of Angstroms across, are essentially completely magnetized as long as the temperature remains below the Curie temperature of the material. In the absence of an externally-applied magnetic field, the magnetization vectors of the domains in a given grain can be aligned so as to minimize the net magnetization of that grain. Furthermore, the grains themselves can be randomly oriented as shown in Figure 1. Thus the macroscopic magnetization $\mathbf{M}$ is zero.

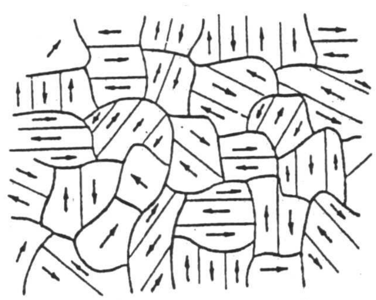


Figure 1: Magnetic domains in a ferromagnetic material when the applied field H is small.

If a weak external magnetic field is applied to a speciman with $\mathbf{M} = \mathbf{0}$, within each crystal grain the domains whose magnetization vectors are oriented more in the direction of the applied field will grow at the expense of the less favorably oriented domains. That is, the domain walls move and the material as a whole acquires a net macroscopic magnetization, $\mathbf{M}$.

For weak applied fields, movement of the domain walls is reversible and χ_m is constant. Thus the macroscopic magnetization $\mathbf{M}$ is proportional to the applied field,

$$\mathbf{M} = \chi_m \mathbf{H} \quad , \tag{36}$$

and

$$\mathbf{B} = \mu \mathbf{H} \quad , \tag{37}$$

where μ is constant.

For larger fields the domain wall motion is impeded by impurities and imperfections in the crystal grains. The result is that the domain walls do not move smoothly as the applied field is steadily increased, but rather in jerks as they snap past these impediments to their motion. This process dissipates energy because small eddy currents are set in motion by the sudden changes in the magnetic field and the magnetization is therefore irreversible.

For a sufficiently large applied field the favorably oriented domains dominate the grains. As the applied field is further increased, the magnetization directions of the less well oriented domains are forced to become aligned with the applied field. This process proceeds smoothly and irreversibly until all domains are aligned with $\mathbf{H}$. Beyond this point, no further magnetization will occur. The magnitude of $M = |\mathbf{M}|$ at this point is called the "saturation magnetization." A graph of $B = |\mathbf{B}|$ versus $H = |\mathbf{H}|$ for the above process is shown in Figure 2. This graph, which starts at $B = 0$ and $H = 0$, is called the normal magnetization curve.

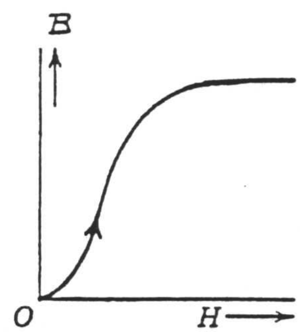


Figure 2: The normal magnetization curve of B versus H.

For large H, the domains appear as in Figure 3.

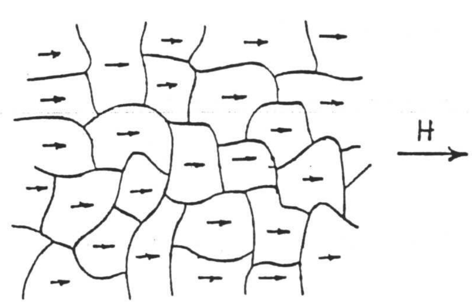


Figure 3: Ferromagnetic domains when the applied H is large.

The alteration of the domains and their direction of magnetization gives rise to a permanent magnetization which persists even after the applied field is removed.

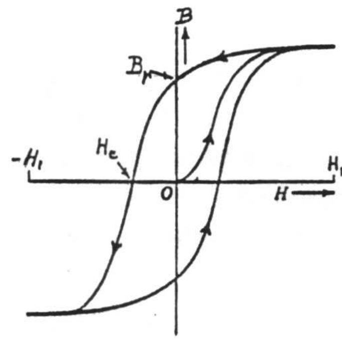


Figure 4: Magnetic hysteresis loop.

If we try to demagnetize the material by decreasing H, the B vs. H curve of Figure 2 is not followed. Instead, B does not decrease as rapidly as does H. Thus, when H decreases to zero, there is still a non-zero B_r, known as the "remnance." Only when H reaches the value $-H_c$ does B become zero. This value H_c is called the "coercive force." Continuing the cycle H_1, zero, $-H_1$, zero, and back to H_1, the B–H curve looks like that in Figure 4. Since B always "lags" behind H, the curve in the above graph is called a "hysteresis" loop (from the Greek "to lag").

The area inside the loop can be shown to be proportional to the energy per unit volume that is required to change the orientation of the domains over a complete cycle (Warburg's Law):

$$W = \int_{\text{vol}} \oint_{\text{cycle}} H dB \; d\tau \quad . \tag{38}$$

This energy goes into heating the specimen, and is in joules if H, B and v are measured in A/m, Tesla and m^3, respectively.

4.2 Applying Maxwell's Equations

Using the apparatus diagrammed in Figure 5, we can observe the hysteresis curve of a ferromagnetic material by the following technique. Suppose we wind two coils of wire on a torus of the material. Since ferromagnetic materials are good "conductors" of magnetic flux, the coupling constant between the two coils will be close to one.

Since both the magnetizing field H and the voltage drop across R_1 are proportional to the instantaneous magnetizing current, the horizontal deflection on the scope is proportional to H.

Faraday's Law (one of Maxwell's equations),

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad , \tag{39}$$

is what we need to calculate the voltage V_s across the secondary winding:

$$V_s = N_2 A \frac{dB}{dt} \quad . \tag{40}$$

Integrating gives

$$B = \frac{1}{N_2 A} \int V_s \; dt \quad . \tag{41}$$

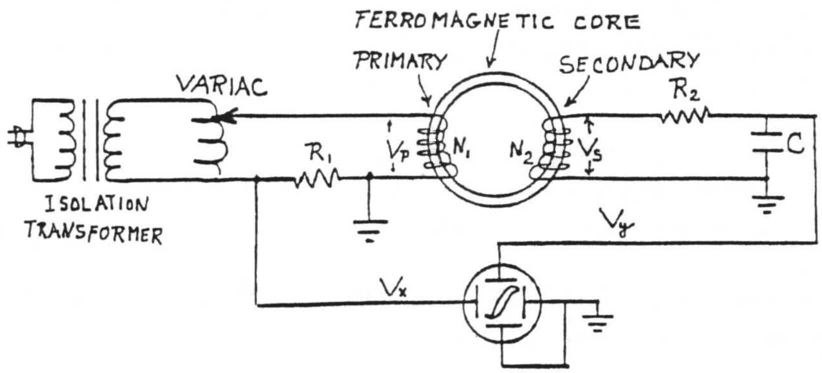


Figure 5: Schematic of apparatus to generate and display hysteresis loops.

R_2 and C across the secondary act as an integrator. If the resistance $R_2 \gg \frac{1}{\omega C}$, then the current in the secondary is determined almost entirely by R_2, so that we may write $i_s = V_s/R_2$. In the capacitor, the current is clearly $\frac{dq}{dt}$, so

$$\frac{dq}{dt} = i_s = \frac{V_s}{R_2} \quad . \tag{42}$$

Hence the potential difference across C at any instant is

$$V_y = \frac{q}{C} = \frac{1}{R_2 C}\int V_s \, dt = \frac{N_2 A B}{R_2 C} \quad , \tag{43}$$

so that the vertical deflection is proportional to B:

$$B = k_B V_y \quad . \tag{44}$$

An analysis of the transformer primary circuit begins with Ampere's Law, another one of Maxwell's equations,

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad , \tag{45}$$

and yields

$$H = k_H V_x \tag{46}$$

for the average of H around the iron core. after recognizing that the displacement current can be neglected at low frequencies.

4.3 Laboratory Measurements

Set up the apparatus using a 10Ω, 5W resistor for R_1, a 500kΩ resistor for R_2, and a 0.1μF capacitor for C. To display a hysteresis loop, run the oscilloscope in xy mode and display V_x on the x axis and V_y on the y axis. Be *sure* to include the isolation transformer (why?).

Starting with the Variac at zero, slowly turn up the voltage in increments such that each successive increment produces a hysteresis curve that is distinguishable from the previous one. Trace these curves, continuing until the material reaches saturation.

For the Variac setting that gives the largest hysteresis curve, measure the temperature rise in a one-minute time interval.

4.4 Calculations and Analysis

1. Transformer Primary: Start with Ampere's Law in differential form (equation 45). First, show how you put it into integral form. Then continue to derive (46) and find an expression for k_H. For your derivation to be complete, it should include a large figure the shows the path for the line integral and the area of the surface integral implied by Ampere's law in integral form.

2. Numerical value for k_H: Plug in relevant constants and come up with a numerical value for k_H for your experiment.

3. Transformer Secondary: Start with Faraday's Law in differential form (equation 39). First, show how you put it into integral form. Then continue to derive (40), (41), (43), and (44). Draw a large, clear figure that shows the path for the line integral and the area for the surface integral implied by Faraday's law in integral form.

4. Numerical value for k_B: Plug in relevant constants and come up with a numerical value for k_B for your experiment.

5. Choose one of your largest hysteresis loops and, using Warburg's law, calculate the energy loss per cycle due to hysteresis, the temperature rise of the core per cycle and the number of cycles and elapsed time necessary to raise the temperature of the core by 1°C. Be careful doing this calculation; it will take time; be sure your result is reasonable.

6. Plot the normal magnetization curve using the end points of the hysteresis loops.

7. From the normal magnetization curve (B vs. H), plot the relative permeability μ/μ_0 of the material as a function of H.

8. What is the theoretical limiting slope of the magnetization curve $B(H)$ when $H \to \infty$? (Hint: start with the most fundamental relation between H and B: $\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$.) Estimate the error in your measured value. Compare the theoretical value with your measured value and explain why they differ.

Vocabulary

◇ Hysteresis Loop
◇ Soft magnetic material
◇ Saturation Magnetization
◇ Remanence

Equipment list

- Isolation transformer
- Variac
- AC patch cord
- Ferromagnetic Torus (Rowland Ring)
- Resistor R_1 (10 Ω, 5 W) and Resistor R_2 (470–530 kΩ)
- Capacitor C (0.1 μF)
- Plastic film & fine-tip "sharpie" marker for tracing oscilloscope pattern
- Thermometer and insulation

5 Operational Amplifiers (n=1)

Background

5.1 Uses of Operational Amplifiers

Measurements in every branch of science and engineering typically begin with a transducer that changes whatever parameter is being measured into an electrical signal for further amplification and processing. Because of their versatility, superb performance, ease of use, and low cost, operational amplifiers (op amps) have become the main building block for amplification and processing of electrical signals before they are digitized and ingested by a computer (such as an Arduino). Operational amplifiers are used in circuits to perform the following functions:

- Amplifying
- Buffering
- Adding, subtracting, and multiplying
- Integrating and differentiating
- Detecting peaks and holding them
- Filtering (low pass, high pass, and band pass)
- Modulating and demodulating

Books listed under References below show many useful circuits using operational amplifiers and explain how they work in more detail than we give in the next section.

5.2 What Operational Amplifiers Do

As you would expect, an amplifier increases some electrical quantity, usually voltage. In general, $V_{Output} = A \times V_{Input}$ where the factor A is called the *Gain* of the amplifier. An integrated circuit operational amplifier such as we will be studying in this lab amplifies the voltage difference $v_+ - v_-$ between its '+' and '−' inputs (see Figure 1). The output voltage is

$$V_2 = A_{OL}(v_+ - v_-) \ , \tag{47}$$

where A_{OL} is the *open-loop* voltage gain of the amplifier.

Two properties of operational amplifiers make them particularly useful:

- The open-loop gain A_{OL} is large (typically 10^5 at low frequencies).
- The resistance R_{in} between the + and − inputs is large (typically 10 MΩ for operational amplifiers which use bipolar junction transistors (BJT) amplifiers, and 10^{10} Ω or higher for operational amplifiers which use field effect transistors (FET's)).

Operational amplifiers are used by providing negative feedback (usually resistance) from the output to an input, which substantially reduces their gain from its open-loop value. This new gain is called the *closed-loop gain* and we will denote it as G. So long as $G << A_{OL}$, G is independent of it and the OpAmp is said to be *ideal*.

5.3 The Golden Rules

An ideal operational amplifier can be analyzed by adding the following two simple rules to the usual rules for circuit analysis:

1. The + and − inputs are at the same potential.
2. No current flows into either input.

The above rules are so generally useful that they are sometimes call *The Golden Rules of Op-Amp behavior*. One implication of these rules, for an ideal operational amplifier is that the closed loop gain G depends only on the feedback elements and not on its open-loop gain A_{OL} nor on its internal resistance. Thus an amplifier with poor open-loop tolerance can be made as precise as resistors can be (which is very precise, even 0.1% if you want to pay for it!). (see Figure 1).

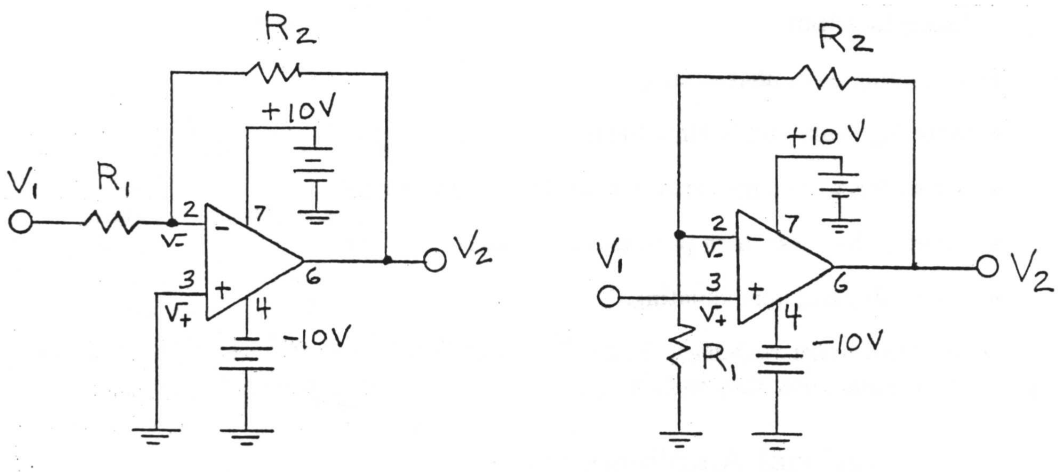


Figure 1: Inverting and non-inverting configurations.

Experiments

You will do five mini-experiments on op-amp circuits. In the first, you will see an op-amp work properly (ideally). You will then learn some of the limitations of op-amps and see some non-ideal behavior by observing *clipping*, *slew-rate limit*, and *band-width limit.* In the fifth mini-experiment, you will quantitatively test the OP-AMP GAIN HYPOTHESIS for DC voltages where op-amps behave *almost* ideally. Your write-up should have an entry corresponding to each experiment and the numbered measurements or calculations below.

This lab calls for a lot of sketching. It is still an important skill. Please don't use your cell-phone camera. Actually do sketches. A ruler can be helpful!

5.4 A. Proper operation of an Op-Amp

Build an inverting amplifier. Refer to the left-panel of figure 1 and build that circuit. You should choose $1000\ \Omega <= R_1 <= 100\ k\Omega$ and $R_2 \sim 10 \times R_1$.

Set proper Power and Signal voltages Op-amps are "active", they need power, as well as inputs and outputs. We call the power voltages V_{PS} (PS for power-supply). We call the input and output voltages ("signal voltages") V_1 and V_2. In Figure 1, $V_{PS} = \pm$ 18 V. On your function generator, set the amplitude of V_1 to 1.5 V and the frequency to approximately $f = 100\ Hz$.

(1) Determine approximate gain (G) Apply sine wave and triangle waves at the inputs (V_1) and measure/report the amplitude of input and output of the OpAmp. What is the closed loop gain factor G? Why do you think this is called an *inverting amplifier*?

(2) Sketch the appearance of the output waveforms. Draw one sketch for sine and one for triangle wave. You are doing this because in the next part you will see various ways they are distorted. Do the sketch large enough that you can clearly add to it. Draw only a single cycle of the wave.

5.5 B. *Clipping* of an Op-Amp

Reduce $V_{PS} = \pm$ 11 V. Leave the frequency and amplitude as in part A.

(3) Sketch the appearance of the sine and triangle waves under these conditions. Draw the new curves where they differ from the ones you drew in question (2). Indicate the differences with a dotted line or a different color of pencil.

(4) Set $V_{PS} = \pm$ 13 V Add another layer to the sketches from #2 and #3.

(5) Why do you think this phenomenon is called *Clipping*? Look up *Maximum Output Voltage Swing* on the data sheet for these Op-Amps. Does this help you understand what is going on?

5.6 C. *Slew rate* of an Op-Amp

Increase V_{PS} so that you no longer see clipping. Next, switch your function generator to a square wave and, increase f until you begin to notice that the vertical edges of the square wave stop being perfectly vertical.

(6) Sketch the appearance of the square wave at two different frequencies . Use the frequency at which you first clearly saw the edges tilting and also try a frequency about 3X as great. Draw a single period and normalize the x-axis so that the waves have the same "wavelength" in your sketch. You are trying to show how the shape of a single cycle changes with frequency. Indicate on your sketches what frequencies you are drawing.

(7) Return your function generator to 100 Hz, change to sine-wave, and repeat your observatio Use the same two frequencies as above. Do a new set of sketches for the sine wave.

(8) What's a slew rate? Based on your observations, what's a slew rate? Look up the slew rate in the data sheet.

(9) Determine slew rate experimentally. Use your square wave measurements from question (6) to determine an experimental value of the slew rate. (It will probably be higher than the data sheet says).

5.7 D. *Bandwidth* of an Op-Amp

The *bandwidth* of an amplifier is defined as the range of frequencies over which the amplifier performs correctly. Your Op-Amps operate all the way down to zero frequency, therefor their bandwidth is defined as the maximum frequency at which they operate correctly.

The word *correctly* can be defined in several ways. The typical definition is that the bandwidth of an amplifier is the frequency at which the output (for a sinewave input) is 3 dB lower than it is at low frequencies (beyond the bandwidth, the output generally keeps decreasing). The location of the 3 dB point is often called the "knee" of the amplifier frequency response. A loss of 3 dB is equivalent to a reduction in Amplitude of roughly a factor of 2. Therefor, if you determined that your amplifier had a gain of 10 at low frequencies, the bandwidth would be the frequency at which the gain of the op-amp was 5.

One of the reasons you learned about slew-rate, is, for larger inputs, the slew-rate distorts the waveform at lower frequencies than the bandwidth does. Thus, for larger inputs, the bandwidth cannot be measured correctly. To be sure of getting a proper bandwidth measurement, you should use the smallest possible input, such as V_1 =5–20 mV_{pp}.

(10) Measure the bandwidth of your op-amp Once you have set V_1 properly, increase the frequency to measure the bandwidth using a sinewave.

(11) Compare to GBWP Multiply your measured bandwidth by your gain G and compare it to the Gain Bandwidth Product (GBWP) listed in your data sheet.

(12) Check effect of BW on non-sinewaves Try putting in triangle waves or square waves (you pick) at different frequencies. Select 3 frequencies which best illustrate (judgement call) the increasing distortion in output waveform you see as you pass through the op-amp bandwidth. Explain these distortions. Also, explain why the sine wave didn't distort (or did it? ... the effect is more subtle with a sine wave.)

5.8 E. Theoretical *Gain* of an Op-Amp

In the last sections you got the approximate gains of the Op-Amps at low frequency, however it is hard to measure the Gain precisely using an oscilloscope, so we will do it instead using DC voltages and a voltmeter.

Hook up the op-amp input (V_1) to the 6 V output of your power supply and vary (V_1) and measure V_2. Use two multimeters to get measurements of V_1 and V_2 to three significant figures. Make a table of your results for V_1 and V_2 and calculate the precise op-amp gain.

After doing this, rebuild your circuit to make a *non-inverting* op-amp (Figure 1, right-hand panel). Repeat the measurements from the previous paragraph and tabulate these as well. Now use your two tables (and the measured values of R_1 and R_2 to evaluate the truth of the following statement:

> OP-AMP GAIN HYPOTHESIS: "The closed-loop gain of an inverting amplifier is $G = -R_2/R_1$ and the gain of an non-inverting amplifier is $G = R_2/R_1$."

Does the inverting amplifier agree with this hypothesis? To what precision?

Does the non-inverting amplifer agree? If it doesn't agree, is this measurement error, or is the hypothesis wrong?

5.9 Analysis

(13) Derive Gain of Op-Amps using Golden Rules Use the Golden Rules of Op-Amps to arrive at a formula for the gain of inverting and non-inverting op-amps. Show your work. Feel free to consult other sources to help you in your analysis.

(14) Compare your new analysis with the measured gains.

References

Powers, Thomas R., *The Integrated Circuit Hobbyist's Handbook,* High-Text Publications, Solano Beach, California, 1995.

Horowitz, Paul, and Hill, Winfield, *The Art of Electronics,* Cambridge University Press, New York City, 1989.

Equipment

- Operational Amplifier (LT1001)
- Oscilloscope
- ±15 volt power supply
- Resistors: R and 10R ($R > 2000\Omega$)
- Ohmmeter

Laboratory Time

Two hours

6 Introduction to Arduino (n=2)

A Background:

The goal of this, and following labs, is to introduce you to the important concepts of digital electronics in a fun and entertaining way using the Arduino microcontroller. By doing these experiments you will develop knowledge and skills that will help you in future employment and your research careers.

Arduino is a family of microcontrollers (tiny computers) and a software creation environment that makes it easy for you to create programs (called sketches) that can interact with the physical world. The most popular type of Arduino is the UNO, shown in Figure 1. A microcontroller is unlike a conventional computer in that it has hardly any memory, no operating system, and no keyboard, mouse or display. Its purpose is to control things by interfacing with sensors and actuators. For instance, you might attach a sensor to measure the temperature and a relay to control the power to a heater.

Installing the Software:

If you want to bring your own laptop, the software installation instructions are on page 2 of the SparkFun inventors Guide (which is page 5 of the pdf mentioned below. If you want to add more examples (to a Linux Arduino installation) and have them immediately accessible from the Arduino IDE, add them to the directory `/usr/share/arduino/examples.`

Equipment:

Arduino, USB Cable, Power adaptor, Oscilloscope, LEDs, resistors, Protoboard, jumper wires, multimeter.

To use an Arduino, you will need a conventional computer. This can be a Mac, Windows PC, Linux PC, etc. This computer will have the Arduino IDE *Integrated Development Environment* installed. The IDE allows you to write programs, download them to the Arduino board, and get serial debugging data back from the Arduino.

The userid of the computers in our lab is `Workman193`, the password is one blank character.

References:

The Arduino is programmed in a variant of the C language called "sketch". If you are not familiar with C, an ultrashort introduction is on pages 4–5 of the SparkFun Inventors Guide. The SparkFun Inventors Guide and the Sketch Programming Language Reference are installed on the computers in room 193 and are also available at `http://kestrel.nmt.edu/~rsonnenf/phys336L/`

You will largely be given the code, and the modifications you will be asked to do should be logical if you read the sample code carefully. A very good way to learn proper syntax is simply to look through the examples.

A.1 Introduction to the Arduino UNO Microcontroller Hardware:

Connect the USB cord to your Arduino to turn it on. You should see a green power LED on the Arduino board light up steadily. The little yellow "RX" and "TX" LEDs might flash a little too. There is also another LED which may start blinking (depending what state the Arduino was left in).

The major input/output components of the Arduino UNO are identified in Figure 1. These are described briefly in the list below. There is an appendix at the end of this document that contains additional technical information and specifications for the UNO.

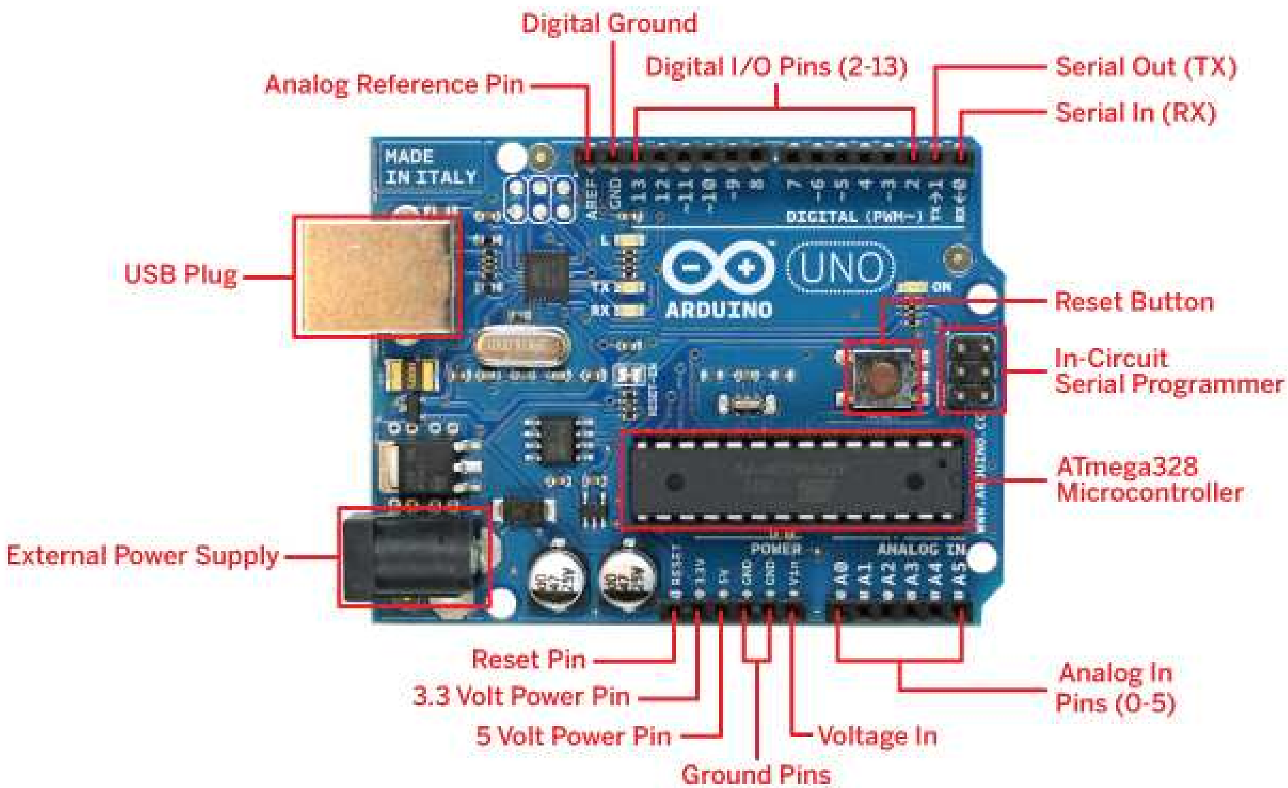


Figure 1: Arduino UNO microcontroller: Note the three LEDs to the left of the Arduino logo, they are labeled "TX", "RX", and "L".

USB plug: Connects the Arduino to the host computer and is used to download programs (called sketches) to the Arduino, communicate between Arduino and host computer, and power the Arduino.

External Power plug: Connects the Arduino to a DC power supply or battery (between 7.5 and 12 V) so the Arduino can operate without the host computer. The Arduino only uses about 40 mA, so a small 9 V battery (600 mAh) can power it for 10 15 hours. The sketch is stored in nonvolatile memory, and is not lost when the Arduino is powered down.

Reset: This pin, or the Reset Button, allows you to reboot the Arduino. Setting this pin momentarily to low (connecting it to GND) restarts any program the Arduino is running. Reset happens automatically when you powerup the Arduino.

3.3 Volt Power: Provides 3.3 V power to external devices and circuits.

5-Volt Power: Provides 5 V external power.

Ground pins: GND is the voltage to which all other voltages on the board are referenced.

Analog In pins (A0 A5): Allows a sketch to measure the voltage of a sensor. Note that the Arduino can only measure positive voltages in the range 0 to 5 V (see Table 1). Although labeled as analog inputs, these pins can also be used as digital inputs or outputs.

Digital I/O pins (2–13): Used as either digital inputs or outputs. Digital inputs and output have only two values: High and low (see Table 1, the ranges for high and low indicate the tolerances for these binary levels). When used as an input, these pins allow the sketch to read the status of a switch, or other device. When used as an output, the sketch controls the value of the pin and can turn an LED, or other device, on or off.

Serial Out (TX) / Serial In (RX) : Digital pins dedicated to transmit (TX) and receive (RX) serial data to/from the USB Plug.

Table 1. Analog and Digital Values

Type	Range of Values	Arduino Range of Values
Analog	Continuous	0-5 V Discrete (10 bits)
Digital (TTL)	High (5 V) Low (0 V)	High (5 V) Low (0 V)

A.2 Introduction to the Arduino UNO Microcontroller Software:

`Sketch` is a simplified form of `C`; it can be learned by examining some pre-written programs. The blinking LED sketch demonstrates how you can use the Arduinos digital output to control an external device. Load the *Blink* sketch from the Arduino IDE menu as follows:

`Files > Examples > 01.Basic > Blink`

The listing should look as below:

```
1  /*
2    Blink
3      Turns on an LED for one second, then off for one second, repeatedly.
4
5      written by Zachary Augenblick, Feb. 2014 */
6
7  int  ledPin = 13; //LED connected to digital pin 13
8
9  //the setup function runs once when you press reset or power the board;
10
11 void setup()  {
12   // Initialize the LED pin as an output
13   pinMode(ledPin, OUTPUT);
14   }
15
16 // The loop function runs over and over again forever
17 void loop()  {
18    digitalWrite(ledPin, HIGH);  // Turn LED on, HIGH is voltage level.
19    delay(1000);
20    digitalWrite(ledPin,LOW);
21    delay(1000);
```

A sketch includes the following:

Opening Comments (lines 1–6): These state the purpose of the sketch, provide some information about the circuit that it accompanies, and give the authorship and date of last modification.

Global Constants and Variables (line 7): These identifiers are known everywhere in the sketch and do not need to be passed as parameters in functions.

Setup Function (lines 11–14): This function is executed only once when the Arduino is powered up, or when you press the reset button. It is used to configure the sketch by specifying pin assignments and pin modes (input/output).

Loop Function (lines 17–21): This function is executed repeatedly, forever, and is used to input data from sensors and output control commands to actuators.

The Arduino IDE automatically color codes (shown in **bold** in this manual) predefined items in the sketch to improve its readability. These include variable types (e.g., `int` and `void`), builtin function names (e.g., `setup, loop, pinMode, digitalWrite, delay`), and predefined constants (e.g., HIGH, LOW, and OUTPUT). Notice also the use of capitalization. Names of variables and functions begin with lower case and capitals are used to separate words (called camel case). Names of constants are in all caps. Indentation is optional but improves readability. All loops, ifs and functions must be enclosed in curly brackets, like this ...`{ }`.

Look again at the example sketch and note several important characteristics of both C and Sketch:

- Every statement is terminated by a semicolon `;`
- Multistatement blocks are enclosed in curly brackets `{ }`
- Comments are preceded by `//` or enclosed between `/*` and `*/` delimiters
- Variables, constants, functions (all known as identifiers) must be defined before they can be used. Defining an identifier means specifying its name and type (`int, float, void`).

B Digital Output: Blinking LED

Run the sketch by clicking on the rightarrow button at the top of the IDE.

The LED marked "L" should start blinking slowly off and on.

(1) Hook your voltmeter up to GND and Pin 13: (Use the Jumper wires I provided) measure and record the two voltage levels you observe.

(2) Slow the arduino down: It may be a little difficult to measure the voltage since your voltmeter does not quite settle down in one second. Look at the Blink1 code. Maybe you can change the delay statements so that the LED is on for 5 seconds and off for 5 seconds.

(3) Upload the changed program: Record the voltage levels you observe.

(4) Speed the flash up: Shorten both the delays to make the LED blink faster. How short must you make them until you can no longer see the LED blinking?

(5) Time the HIGH and LOW intervals with 'scope: Now that you have made the flashing too fast to see, take the voltmeter off and use the oscilloscope to measure Pin 13 relative to GND. How long does Pin 13 spend being high and how long low (for the setup of step 4.) What blink frequency does this correspond to?

(6) Determine delay units: Based on your measurements in (5), if the instruction says "delay(30)", how many seconds is that?

(7) Determine maximum Arduino speed: Change the delay intervals to zero. (Alternately, you can comment the delay statements out with // characters). In principle this should make the Arduino infinitely fast, but the computer still takes time to execute instructions. Using the oscillscope, you can determine the fastest that the Arduino can make the LED blink. What is the ON/OFF period (and frequency) with zero delays?

(8) Light an external LED: Stick an LED into a protoboard and connect it to pin 13 and ground. Restore the program back to one second blinks. Your external LED should now be blinking. Once this works, move the external LED to some other digital output pin and make it blink. What line in the Blink program did you change to make this work?

(9) Create two flashing LEDs: Add a second LED to your program. Attach each LED to a different output pin. (Any pins are good except don't use pin 0). Make sure both LEDs blink together. Then change the code so that LEDs alternate (one goes on when other goes off). Put your name on this code. Photograph it with your cell phone, and include it in the lab report. (You can also save it. Use "Save As", then save it under "Sketchbook". You will see your program will now appear under Sketchbook.)

C Digital Input: Switch

Remove all Jumper wires from the Arduino and then insert a single jumper wire into the Arduinos Digital I/O Pin 2. Leave the free end of the jumper wire unconnected.

Load and run the *Button* sketch from the Arduino IDE menu.

`Files > Examples > 02.Digital > Button`

Watch the LED while you move your hand around in the vicinity of the Arduino. Try grabbing the free end of the wire or running your fingers slowly up and down it. Try to make the LED flicker a bit.

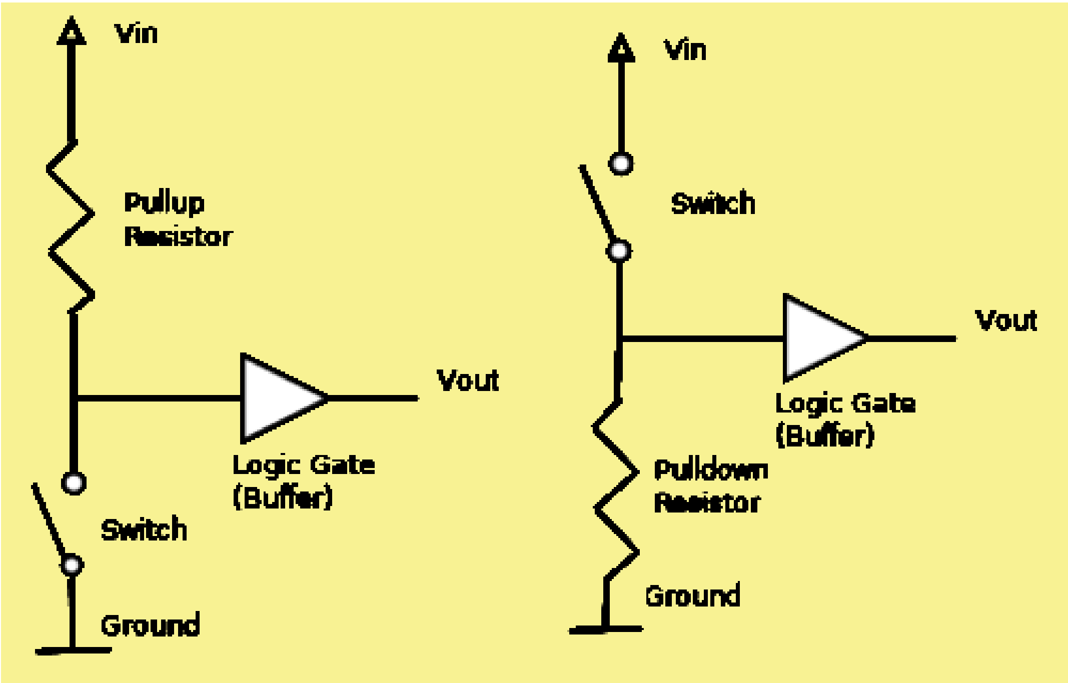


Figure 2: Pull-up resistor (left) and Pull-down (right).

(http://playground.arduino.cc/CommonTopics/PullUpDownResistor)

(10) Discover why a *floating* input is problematic: Connect the free end of the jumper wire to the Arduinos 5 V Power Pin and then to the GND pin: Which of those two pins makes the LED turn on? Note that it no longer matters whether you wiggle the wire around.

You have just learned the important lesson: A floating digital input will have an unpredictable value. If you want it to be high, you must connect it to 5 V. If you want it to be low, you must connect it to 0 V. This is done by using pullup and pulldown resistors, as shown in Figure 3. Pullup and pulldown resistors are often used with switches to ensure that the state of the digital input is determined whether the switch is open or closed. The engineering convention for pull-up and pull-down resistors is 10 $k\Omega$, but any value within a factor of two either way will work just as well.

(11) Use a switch to turn the pin 13 LED on and off: You will need a switch (with two jumper wires already attached), a protoboard, two additional jumper wires, and a 12 kOhm resistor. Use either the ”pull-up” or the ”pull-down” configuration. Your Arduino is still running the ”Button” program, so there is no need to change it. Figure out your connections and see your switch work reliably. Draw a circuit diagram of what worked. Indicate all connected pins.

(12) Modify the ”Button” code: Change the code so that what used to be the ”on” position of the switch now becomes the ”off” position. You don't need to move any connections. That's the point. Like many consumer devices today, you are ”fixing the problem in software”. What line did you have to change?

To fully realize that you have just created a fully standalone embedded system (if a simple one), disconnect the USB cable from the Arduino. Now connect an external power supply (only). You will see the Arduino works just like it did before. The switch still works.

D Analog Input: Potentiometers

This experiment demonstrates how the Arduino can read an analog voltage, and in part D we will use that voltage to control an external device.

Open a new blank sketch. Type, then upload the following code:

```
void setup() {
        Serial.begin(9600);
}

void loop() {
            int sensorValue=analogRead(A2);
            Serial.println(sensorValue);
}
```

The sketch above uses the `Serial.println` command to send data back to the host computer from the Arduino. It uses the serial monitor which operates over the USB port. After you upload the sketch to the Arduino, click on the magnifying glass icon in the upper right corner of the Arduino IDE to open the serial monitor.

(13) Digitize three different known voltages: Use a jumper wire to connect the appropriate analog input to the 5.0 V output of the Arduino, then connect the analog input INSTEAD to the 3.3 V output. Finally, connect the analog input to the GND. Record the three numbers that you get.

(14) Calibrate the Analog to Digital Converter (ADC): ADCs give integers which you then need to convert to real physical quantities. Based on 13, complete the linear mathematical equation below (that is ... find "K"). `voltageActual = K * analogRead()`.

(15) Add the ADC Calibration to your code: Now that you have figured out how to change `analogRead` to actual voltage, modify your code to do this for you. To make it more accurate, you must declare voltageActual as a float. Write down your modified code.

(16) Check your calibration: Check that your modified code actually reads the correct voltage from the 3.3 and 5.0 V outputs. (Record what voltages you get)

(17) Understand ADC resolution: How many different voltage levels can be measured using 10 bits? (This is a calculation, not a measurement).

(18) Understand quantization error: Given that you are measuring from 0 to 5 V, what is the smallest voltage change the Arduino can measure? (This is called the "least significant bit" or LSB, and the difference between this and the actual voltage is the quantization error).

(19) Figure out how to use a potentiometer: to vary your analog input. Potentiometers (or "pots") are used to vary voltages (or potentials ... thus the name). Pots usually have three pins. The resistance between two of them is fixed (to something like 10 KOhms). The third pin is connected to a "wiper" which slides along the windings of the other pins. The result is a voltage divider with a constant "R1+R2" but a variable "R2". Figure this out using your HP power supply and your voltmeter. Figure out how to hook up a potentiometer so that as you turn the knob the voltage varies from 0 up to the voltage of your HP supply. Sketch the circuit you arrived at indicating where each of the 3 pins on the "pot" were connected.

(20) Add a pot to your Arduino: Instead of using the +6V and common outputs of the HP supply, you will be using the 5 V and GND outputs of the Arduino. MAKE SURE NOT TO USE THE HP SUPPLY ANYMORE!!... YOU CAN BLOW UP THE ARDUINO!! PLEASE DON'T!! As you turn the knob, you should see voltages varying between 0 and GND on your Arduino.

E Analog Output: Controlling LED Brightness

We will modify the circuit constructed in Part C to vary the brightness of the LED using the Arduinos analog output. The word analog is in quotation marks because the Arduino cannot generate a true analog output. Instead it uses PWM as an approximation.

Attach the positive lead of an LED to Digital I/O Pin 9. This will allow you to use PWM output (note symbol in front of the 9 on Digital I/O Pin 9).

Open a new sketch in the Arduino IDE and copy the code below into it.

```
int sensorPin = A0;           // select the input pin for the potentiometer
int ledPin = 9;               // select the pin for the LED
int sensorValue = 0;          // variable to store the value coming from the
sensor
int ledValue = 0;             // variable to store the value for the LED

void setup() {
  // declare the ledPin as an OUTPUT:
```

```
  pinMode(ledPin, OUTPUT);
}

void loop() {
  // read the value from the sensor:
  sensorValue = analogRead(sensorPin);
  // map input range (0, 1023) to output range (0, 255)
  ledValue = map(sensorValue, 0, 1023, 0, 255);
  // write analog value to LED
  analogWrite(ledPin, ledValue);
  // wait 2 milliseconds
  delay(2);
```

(21) Run the sketch: Describe what happens when you turn the potentiometer knob.

(22) Use an oscilloscope to observe the output voltage: Use an oscilloscope to monitor digital I/O Pin 9. Record (photograph or sketch) the waveform for a dim (but not off) and a bright (but not maximum brightness) LED intensity.

(23) Explain how the LED brightness is being controlled: Explain in words what you observed on the 'scope. Why does this change the brightness of the LED as you turn the potentiometer know?

(24) Why do you think it is called analog PWM? (feel free to websearch it)

(25) What is the PWM frequency?

```
Appendix: UNO Specifications
============================
(http://arduino.cc/en/Main/arduinoBoardUno )

Summary
=======
 Microcontroller                         ATmega328
 Operating Voltage                       5V
 External Input Voltage (recommended)    712V
 External Input Voltage (limits)         620V
 Digital I/O Pins                        14 (of which 6 provide PWM output)
 Analog Input Pins                       6
 DC Current per I/O Pin                  40 mA Source or Sink
 DC Current for 3.3V Pin                 50 mA Source or Sink
 DC Current per VCC and GND Pins         200.0 mA
 Flash Memory                            32 KB (ATmega328) of which 0.5 KB used by
                                         bootloader

 SRAM                                    2 KB (ATmega328)
 EEPROM                                  1 KB (ATmega328)
 Clock Speed                             16 MHz
 Length                                  68.6 mm
 Width                                   53.4 mm
```

```
 Weight                                 25 g
 Power

Power
=====
The Arduino Uno can be powered via the USB connection or with an external
power supply.  The power source is selected automatically.

External (nonUSB) power can come either from an AC to DC adapter
(wallwart) or battery.  The adapter can be connected by plugging a
2.1 mm center-positive plug into the board's  power jack.
Leads from a battery can be inserted in the Gnd and Vin pin headers of the
POWER connector.

Memory
======
The ATmega328 has 32 KB (with 0.5 KB used for the bootloader).
It also has 2 KB of SRAM  and 1 KB of EEPROM
(which can be read and written with the EEPROM library).

Input and Output (I/O)
======================
Each of the 14 digital pins on the Uno can be used as an input
or output, using pinMode(),  digitalWrite(), and digitalRead() functions.
They operate at 5 volts. Each pin can provide or
receive a maximum of 40 mA and has an internal pullup resistor
(disconnected by default) of 20--50 kOhms.

The Uno also has 6 analog inputs, labeled A0 through A5, each of which provide 10 bits of
resolution. By default they measure from ground to 5 volts,
though is it possible to change the upper end of their range using the AREF pin and the
analogReference() function.

Special Pins
============
In addition, some pins have specialized functions:
     Serial: 0 (RX) and 1 (TX). Used to receive (RX) and transmit (TX) TTL serial data.
        These pins are connected to the corresponding pins of the ATmega8U2 USBtoTTL
        Serial chip.
     External Interrupts: 2 and 3. These pins can be configured to trigger an interrupt
        on a low value, a rising or falling edge, or a change in value. See the
        attachInterrupt() function for details.
     PWM: 3, 5, 6, 9, 10, and 11. Provide 8bit PWM output with the analogWrite()
        function.
     SPI: 10 (SS), 11 (MOSI), 12 (MISO), 13 (SCK). These pins support SPI
        communication using the SPI library.
     LED: 13. There is a builtin LED connected to digital pin 13. When the pin is HIGH
        value, the LED is on, when the pin is LOW, it's off.
```

AREF: Reference voltage for the analog inputs. Used with analogReference().

Reset: Bring this line LOW to reset the microcontroller. Typically used to add a reset button to shields which block the one on the board.

7 Digital to Analog Converters (n=2)

A Saving your data and code

You will be asked to save your data and your code in certain cases throughout this lab. Please include your name in any data or code files you generate. Please bring a USB-drive to save your data and code to. I will be erasing data and code after each class.

B Motivation for the experiment

All fundamental physical phenomena are ”analog” in that they can vary by an arbitrary amount (so long as their intensity is far above quantum limits). Computers only work on discrete (digital) numbers. Thus any measurement taken by a computer must first go through an ADC (Analog to Digital converter). Similarly, computers may control analog devices by using a DAC (Digital to Analog converter). The Arduino has built-in ADC's, but there are no DACs (except for PWM DACs, which have limitations). Thus we will learn how to build a DAC, in preparation for driving future experiments.

C Overall Approach for the experiment

You will build a 5-bit $R-2R$ resistor ladder, as shown in figure 1 using 5% tolerance resistors.

You will test the ladder initially with a power supply and a voltmeter, then you will develop an Arduino-based binary counter, then you will adapt the binary counter code to drive the $R-2R$ network, then you will digitize the analog waveform you created and check its linearity. Finally, you will use a professional $R-2R$ network to make an 8-bit DAC for use in future experiments.

D Build a 5-bit Ladder

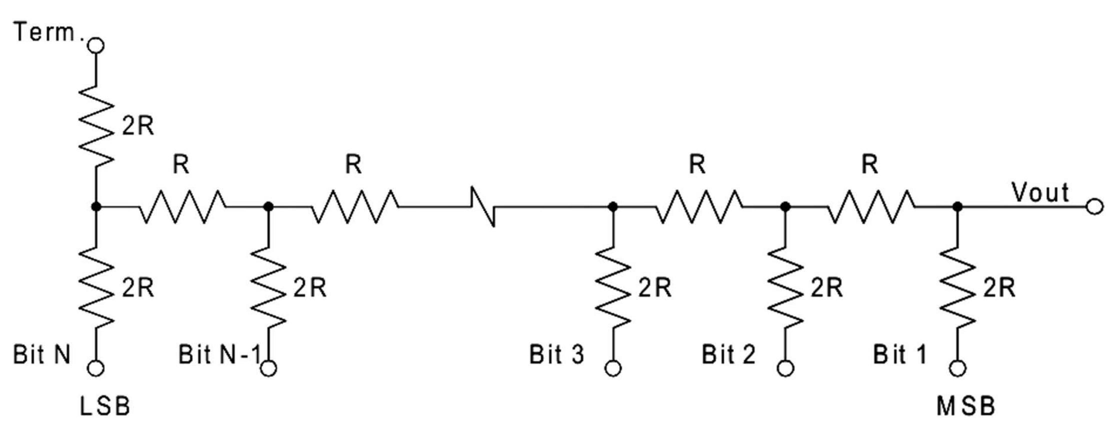


Figure 1: An R-2R, ladder network for N-bits.

D.1 Build a ladder using 16 identical resistors

The circuit diagram shows how to build an N-bit ladder, but we will only build a 5-bit ladder so as to avoid tedium and also to see more clearly how large the least signifcant bits (LSB's) are. For starters, build only the first 3-bits. Use the same value resistor for all parts. Use the 5 % precision resistors provided. For branches that say $2R$, use two resistors in series. Keep in mind that the central groove on the proto-board separates the two halves. This can be used to your advantage. Try to make your circuit well organized. The bits should form a recognizable somewhat repetitious pattern. This will make it less likely that you make a mistake.

Ground (or COMMON) every open-dot you see in the figure *EXCEPT* for the one that says V_{out}.

(1) Measure resistance between V_{out} and ground for a 3-bit ladder: Use a multimeter to measure the resistance between V_{out} and ground on your 3-bit A/D.

(2) Measure resistance between V_{out} and ground for a 4-bit ladder: Add another stage to your 3-bit ladder, and measure resistance to ground again from your newly created V_{out} position.

(3) Measure resistance to ground for a 5-bit ladder: Complete your ladder and again measure resistance to ground.

(4) Explain your results: Using a combination of circuit diagrams and words, I suggest analyzing the circuit beginning right at the least significant bit and then proceeding recursively to explain your results.

(5) Measure the effects of voltage applied at different bit positions: You have grounded all the pins except V_{out}. Now also unground the open circle labeled LSB (which is also Bit 5) and connect 16.0 V (measure it) from your HP supply at that point. Measure the voltage at V_{out}. Now reground the LSB and apply 16.0 V to Bit 4. What is V_{out} now? Continue to measure all the bits up to Bit 1. (Always make sure to keep all the bits you are not using grounded). Make a table of results.

(6) Explain what pattern you observe: There should be a regular pattern apparent in your results from step 5. State what the pattern is. If you don't see a regular pattern, maybe you did not build the circuit correctly.

E Build a 5-bit binary counter with the Arduino

Do not disassemble the resistor ladder (It will be used again). To the proto board on which you have built the ladder, add five LEDs. Connect each of the LEDs positive side through a 300 Ohm resistor to five different digital output pins of the Arduino. Connect all five grounds to the same ground pin on the Arduino board.

Load up the example code for Sparkfun_Circuit_04 ("Dance, LEDs, Dance!"). It was written for 8 LEDs. Modify it for your five LEDs. Exercise the 5 different functions suggested by the Sparkfun code. (Note that this program uses an array called *ledPins*. You remember arrays from Matlab, at least.)

Until now, your Arduino programs have only had the two functions *setup* and *loop*. Those are ALWAYS required, but you are allowed to add as many additional functions as you like. You will be adding two more functions, *bin_digit* and *greater*. Since *bin_digit* is slightly advanced, I provide the code below:

```
int bin_digit(int base10, int this_bit, int number_bits)
    /* PURPOSE: bin_digit converts base10 to binary, one bit at a time.
    bin_digit returns either 0 or 1.
```

```
    So, if you need to convert a number to 5-bit binary, you need to call
    bin_digit 5 times.  More detail follows.*/
    /* USAGE: bin_digit(178,3,8) returns the 4rd least significant
    bit of decimal 178 converted to 8-bit binary.
    bin_digit(178,0,8) returns the LSB
    bin_digit(178,5,6) returns the MSB at 6 bit resolution
    If this_bit=0, then return the LSB (or 1's bit) of base10 number.
    If this_bit=3, return the 2^3 or 8's bit
    */
{
    int kk, bind, twopower; //kk is a counter,
      // bind='binary digit', twopower='power of two'
    for (kk = number_bits; kk > this_bit; kk--)
      // kk-- is C shorthand for k=k-1  (what do you think kk++ does?)
      {
           twopower = 1 << kk;  //note that << means 'shift-bit left'.
                                //1 << kk raises 2 to the kk power.
           base10 -= greater(base10, twopower) * twopower;
      }
    bind = greater(base10, 1 << this_bit);
    return bind;
}
```

Note that this code makes use of the additional function *greater*. I provide the header for *greater* below

```
int greater(int x,int y)
/*USAGE  greater(2,1) returns 1
         greater(1,2) returns 0
         greater(2,2) returns 1
*/
```

It is up to you to write the code that makes *greater* actually work.

Modify *setup* and *loop* appropriately so that your LEDs light up to represent binary 13. Do not do this by just telling which LEDs to light up. Instead, call *bin_digit* five times in a for loop and have the Arduino decide which LEDs to light.

(7) Photograph your setup: Photograph your handywork (including the ladder network and the LEDs lit up to show binary 13 (the LSB should be on the right).

Now that you can light proper LEDs for any 5 bit number, add code so that your program repeatedly counts from 0 to 31. Your LEDs should now be counting in binary from 0 to 31. Make the count slow enough that you can check that the binary is correct.

(8) Submit your code: Submit the finished code for *loop* and *setup* as well as the code for *greater*

F Build a 5-bit DAC

Your counter is now almost a DAC. Move the wires that went to the 5 LEDs (without the series resistors) and put them in the appropriate place on the DAC circuit. Now run your count program and look at V_{out} with your meter. (You may need to increase the delay to give your meter time to stabilize between counts).

(9) Check your program output: Submit the first 5 voltages you measure, corresponding to first five counting #s.

(10) Digitize your DAC output: Connect V_{out} to A_0. Add code to read the analog voltage every time you count to a different number. Use Serial.print() to send the digitized analog voltage to the serial monitor.

(11) Improve your serial output: Add a column to your serial data so that you have two columns, the decimal number you sent to the DAC and the analog readback that corresponds to it.

(12) Improve your serial output further: Add a third column to your serial data that gives the voltage value that the DAC count corresponds to.

(13) Submit your output: You can make a text file out of the serial monitor by just highlighting the text and pasting into a new text file. You need only submit the output of step 12 (as steps 10 and 11 are included in it.)

(14) Plot your output: Make a plot (MATLAB, Excel, etc.) from the text file you just created. Is the DAC you built perfectly linear? It should be close unless you made a mistake, but it is probably not perfectly linear because you used 5% resistors to build it.

(15) Analyze the goodness of fit: Use Matlab, Excel or some other program to measure the R-value of the line. Since it is really quite accurate, report the R-value to at least 7 decimal places. Congratulations, you built a DAC!

G Build an 8-bit DAC using a ladder chip

You know what to do. You already have the code (except you need to change it to 8-bit code.) The instructor should have provided you with an R-2R ladder chip at the beginning of the lab. Do NOT build the 8-bit DAC with individual resistors! Hook the provided chip up correctly and you will have an 8-bit DAC.

(16) Set the DAQ to 1, 127, 255: Measure the output voltage with your multimeter. Compare what you got against the LSB, half of full-scale, and full-scale minus one LSB. If the results are not within 1% of correct, you made a mistake.

(17) Count from 0 to 255: Run your counting code from 0-255, capture the output on the serial port, and measure the goodness of fit (R-value) of your new DAC. Compare the R-value to the previous DAC. Keep it setup. You will use it in the next lab.

- Arduino Uno
- LEDs
- Protoboard
- 5% resistors
- R-2R ladder chip

8 Diodes (n=1)

A Measuring the Constitutive Relation of a Diode

A diode is an example of a non-linear electronic device. Doubling the input does not give you twice the output.

Current starts to flow in the forward direction (the direction of the arrow in circuit symbols) through diode junctions when the voltage across the junction reaches a threshold, which you will determine in this lab. The base-emitter and collector-base junctions of transistors are also diodes.

The diode we will use is the emitter-base junction of a NPN transistor. The flat side of the transistor has labels for the three pins: e, b, c, for emitter, base, collector.

1. Set your function generator to produce a sinewave of 400 Hz frequency and 1.5 V amplitude and attach it to the circuit of Figure 1. (I recommend using a 10–20 kΩ resistor in place of the 4.7 kΩ shown in the circuit diagram). Sketch (or photograph) $V_1(t)$ and $V_R(t)$ from the oscilloscope; use the same voltage scales and the same zero position for both $V_1(t)$ and $V_R(t)$.

   Next we will use our Arduino to quantify the current from the diode vs. the applied voltage. You already have a circuit with an 8-bit DAC on a chip from the previous lab.

2. Replace the function generator from the previous part with the Arduino DAC output. Again, sketch (or photograph) $V_1(t)$ and $V_R(t)$ from the oscilloscope. You may need to change the delay in your Arduino counter code to make the counter run faster so you can easily view the waveforms on the oscilloscope.

3. Next disconnect the oscilloscope completely and use the Arduino to take data. Run the output of the DAC (which is now $V_1(t)$) into A0 on the Arduino and run $V_R(t)$ into A1. Modify your code to produce a table of V_R vs. V_1 as your counter runs through a full cycle. Capture this data and make a plot of it.

4. Of primary interest is the current through the diode $I(t)$ vs. the voltage across the diode V_{BE}. You are already taking the correct data, but you have to crunch it slightly to turn V_1 and V_R into V_{BE} and I. A little bit of thought on your part should tell you what calculation to do. Once you have figured it out, upgrade your Arduino code to four columns. The first two are V_1 and V_R. The next two are V_{BE} and I. Capture the four column table and make a plot of I vs. V_{BE}. This plot is called the *constitutive relation* for a diode. (More casual folk just call it an "I-V Curve".)

5. To complete the constitutive relation we must turn the diode around. Make the same measurements as in the previous step with the diode reversed (V_{EB} instead of V_{BE}). Modify the code to show V_{BE} as a negative voltage and I as a negative current. ALSO, because the currents in the reverse bias direction are so small, you should change the resistor to around 250 kΩ. Combine these results with the current table. (Not asking you to do that with the Arduino itself ... this is a cut and paste request!) Capture the data and plot the full constitutive relation of a diode. (You may want to do two plots since the reverse bias current probably appears to be zero on the scale where you can see the forward current).

6. Explain what you saw in step one of the lab based on the constitutive relation. In particular, why is the rectified waveform not an an exact copy of the top half of the input waveform?

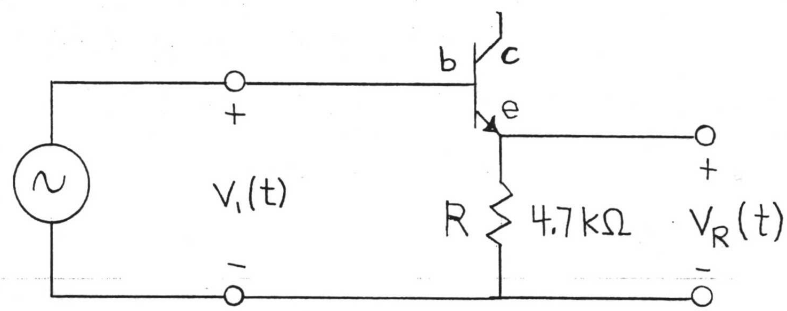


Figure 1: Circuit to rectify a voltage.

7. EXTRA CREDIT: We are used to defining resistance by Ohm's law, $R = V/I$. However for an highly non-linear device like a diode, this formula must be generalized. One can consider a "differential resistance" defined as $R_{eff} = dV/dI$. If you are clever, you can extend your code to produce a fifth column of data which is the approximate differential resistance of the diode. If you think you have it, submit a five column table for the diode returned to its "forward bias" position.

Equipment list

- Function generator
- Arduino with DAC chip attached
- NPN Transistor: 2N4401 or MPSW01
- Oscilloscope
- 15 kΩ Resistor
- 250 kΩ Resistor

Laboratory Time

Two hours

9 Index of Refraction of Air (n=1)

Even though the wavelength of light in air is only slightly smaller than the wavelength of light in a vacuum, it can be measured.

Measurements

1. Use the equipment listed below to determine the index of refraction of air.
2. Extrapolate your results to predict the index of refraction at 1 atmosphere (1013.25 millibars) and 0^o C.
3. What measurement uncertainty leads to the largest uncertainty in the index of refraction? What is the resulting uncertainty in the index of refraction?

Calculations

4. From your data and the ideal gas law, find out how the ratio of pressure to absolute temperature, p/T, depends on the fringe number N_f. The fringe number N_f is defined in the following way: fringe number 1 is the fringe you see at the beginning. As new fringes appear as you decrease (or increase) the pressure, number them 2, 3, 4, etc.
5. From theory derive the function $N_f(n)$ where n is the index of refraction.
6. From the above, find the function $p(n)$ relating pressure and index of refraction. Then find a relation between $1 - n$ and $p(1) - p(n)$. Put in numbers to get $1 - n$. Then find n.

Equipment list

- Hand vacuum pump
- Chamber with flat windows
- Pressure sensor
- Laser
- Michelson Interferometer
- Thermometer

Laboratory Time

Two hours

10 Low-Pass Filters (n=1)

We will learn about and apply the concept of “filtering”. We will predict and measure the time constant of an RC circuit in an AC environment. Finally, we will use what we know to predict and then measure the capacitance of a home-made parallel-plate capacitor.

The experiment

We revisit the series circuit of resistor and capacitor to understand, time-constants, Bode plots, and low-pass filters.

Filters and Frequency response

1. Sketch the circuit you intend to build. It consists of resistor R_1 connected to the center pin of the BNC of a function generator, followed in series by capacitor C_1. (N.B. The circuit is slightly different than the one you built for the Complex Impedance lab. There the resistor was connected directly to ground. Here the capacitor is connected directly to ground).

2. Build the circuit and probe the total voltage from the function generator V_{FG} on one 'scope channel.

3. Measure the Voltage across the capacitor V_C at about a dozen different frequencies between 1 Hz and 3 MHz. The frequencies should be roughly uniformly spaced in a logarithmic sense, but more tightly focused on the range of frequencies where there is a noticeable change in the behavior of the circuit. The savvy physicist surveys the frequencies of interest before taking the time to do detailed measurements.

4. Measure the relative amplitude and phase of V_{FG} and V_C for each frequency. *Hint: Get both signals on the oscilloscope at once. Trigger on the input voltage and set the trigger level to 0V. This is a way to easily quantify the phase shift between the applied voltage and current.*

   Make a table with columns (1) f_{FG}, (2) V_{FG}, (3) V_C, (4) $\frac{V_C}{V_{FG}}$,and (5) ϕ_C. Make a plot on log-log paper of column 4 vs. column 1 and a plot on semilog paper of column 5 vs. column 1. Such paper is provided for you on next page. This type of plot (log-log and semilog for amplitude and phase vs. frequency) is called a “Bode Plot”. *Note: Measuring ϕ_C is somewhat time-consuming. You can first survey the frequency range of interest and decide where to concentrate your effort measuring ϕ accurately. At other frequencies, you can just approximate it.*

5. Using what you already know about complex impedance, write down the complex voltage divider equation for this new circuit in which V_{FG} is the input and V_C is the output. Solve for the ratio $\frac{V_C}{V_{FG}}$. If you do this correctly, the expression R_1C_1 should appear somewhere in your ratio. Define the variable $\omega_1 \equiv \frac{1}{R_1C_1}$ and calculate its value. ω_1 and the corresponding f_1 are often called the “corner frequencies”. (Note the “corner” in your amplitude Bode plot at about this frequency). Note that the corner frequency ω_1 is also the reciprocal of the time constant of the circuit, RC.

6. Using your voltage divider equation, what is the amplitude ratio for $\omega = \frac{1}{R_1C_1}$? Finding a frequency that gives such an amplitude ratio is a quick way to find the corner frequency.

You have just created and analyzed a "low-pass filter", so called because it attenuates high frequencies, without much affecting the low frequencies (thus "passing them"). Circuits like these were (until recently with all-digital technology) attached to the bass and treble knobs of your stereo system. Filters are still important throughout science and technology. Turn your scope up to maximum sensitivity and then push the "BW limit" switch to see a low-pass filter in operation.

Filters and Music

Before the advent of digital technology, the base and treble knobs on stereo systems merely changed the resistance of an RC filter like the one you just created. It is worth listening to the effect your filter has on music. Bring an iPod or similar player and design a filter that cuts out frequencies above 100 Hz. Play your iPod through a speaker (we have some you can use) and note how the low-pass filter affects it.

Can you design a high-pass filter that only plays music *above* 1000 Hz? Try it and see how it sounds. (You get credit for this part of the lab just by demonstrating it to your instructor.)

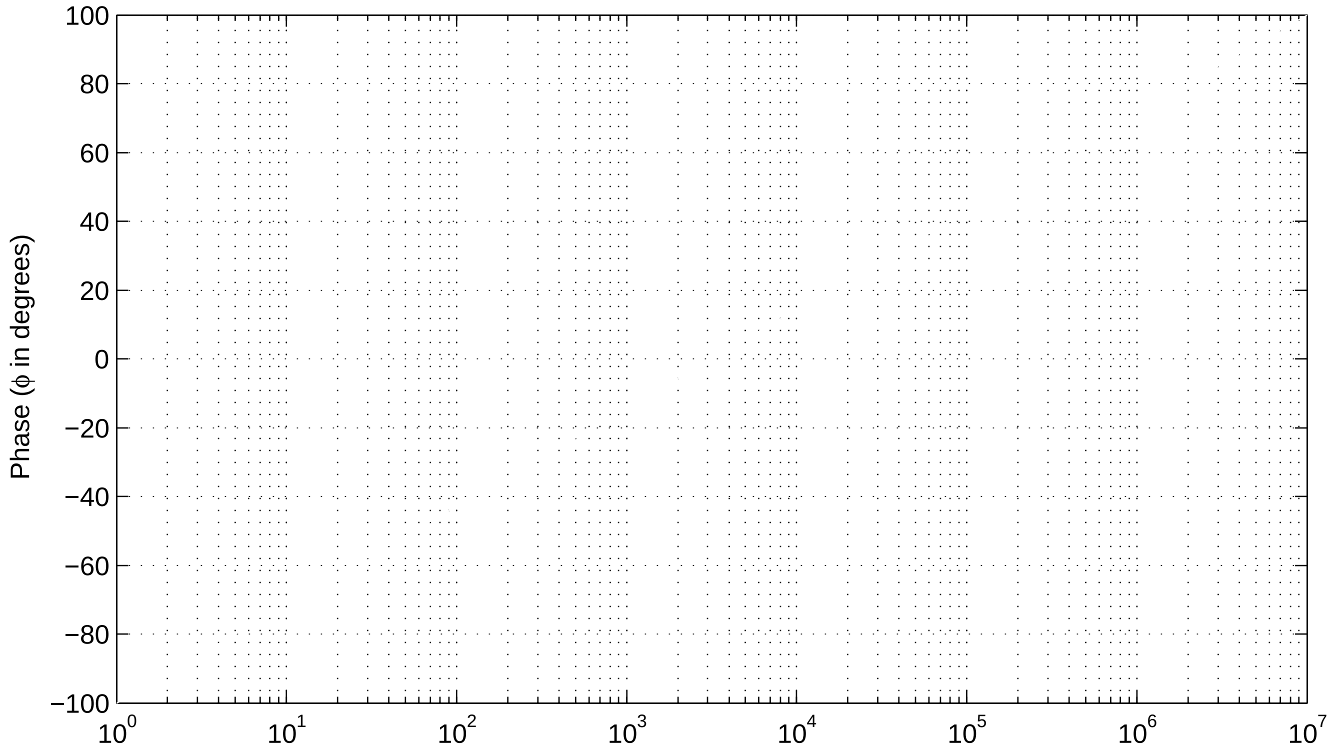
You should know in your designs that the output impedance of an iPod is about 30 Ω. You must include this series resistor when designing your filter.

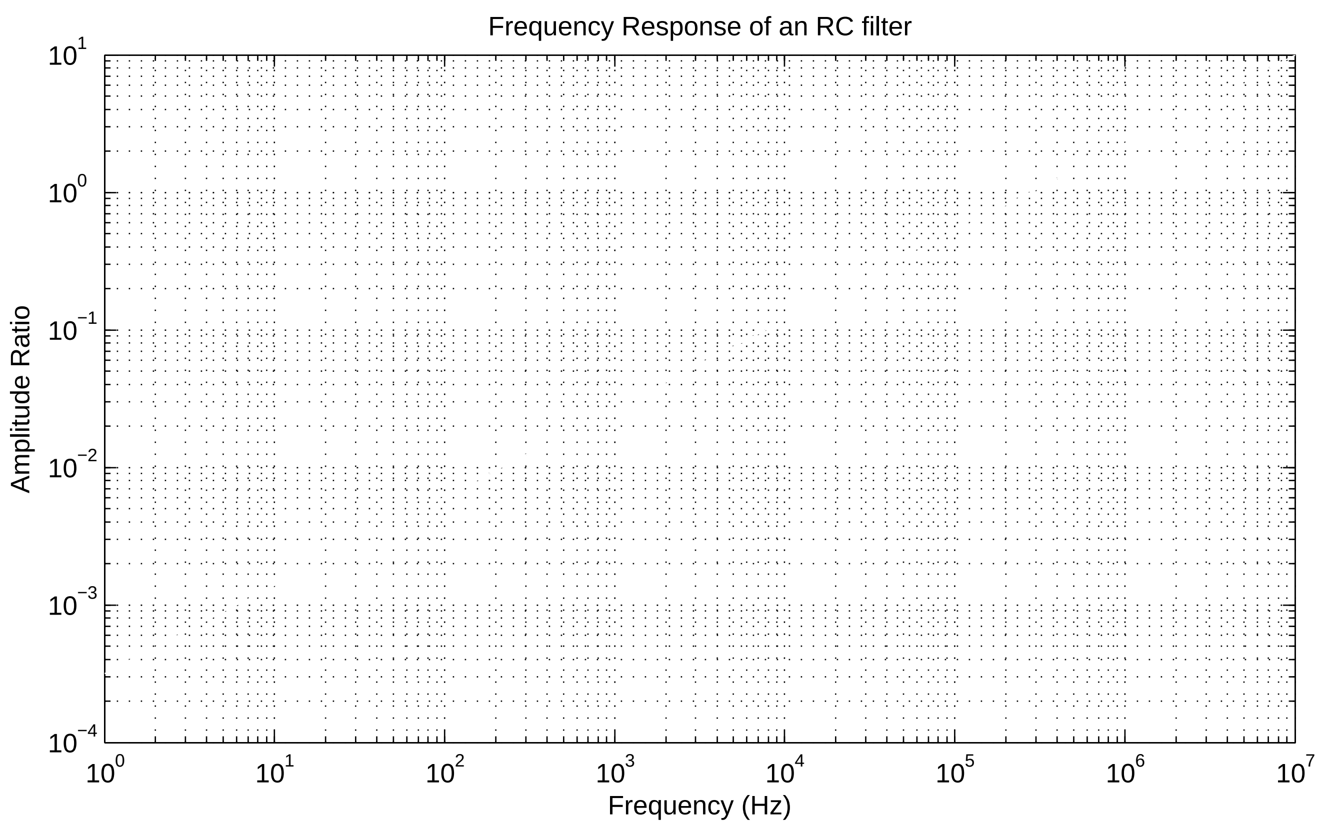
Equipment

- Oscilloscope
- Function generator
- Capacitance meter
- Ohmmeter
- R_1=3.3 kΩ Resistor
- R_2=You select it Ω Resistor
- C_1=0.047μF Capacitor

Laboratory Time

Two hours


Phase (φ in degrees)
100
80
60
40
20
0
−20
−40
−60
−80
−100
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7


Frequency Response of an RC filter
Amplitude Ratio
10^1 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4}
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
Frequency (Hz)

11 Electric Field, Capacitance, Dielectric Constant (n=1)

Laboratory Work

Measure the dielectric constant of liquid nitrogen.

Some of the effort in this laboratory project will be designing the experiment. You will need to make calculations to see what kinds of equipment the experiment will require. The first measurements should be done quickly and simply to uncover unsuspected problems.

Report

In addition to describing your laboratory work and the results, consider the subtle effect leading to the Clausius-Mosotti formula in Problem 4.38, Page 200 of D. J. Griffiths, *Introduction to Electrodynamics*, Third Edition, Prentice Hall, Upper Saddle, NJ, 1999. Can the Clausius-Mosotti formula explain the descrepancy between your measurement and the accepted value of liquid nitrogen? (You should be able to find the polarizability of one nitrogen molecule from the dielectric constant of gaseous nitrogen.)

Equipment

- Liquid Nitrogen
- Air-variable capacitor
- Styrofoam containers
- Miscellaneous electronic equipment

Laboratory Time

Two hours

12 Negative Resistance (n=1)

Introduction

In linear devices such as ordinary resistors, "resistance" could be defined either as dV/dI or as V/I; in either case the resistance of the device would have the same value. What definition should be used for non-linear devices such as diodes, neon lamps, and spark gaps? There is some advantage in defining resistance for these kinds of devices as dV/dI. Because of this definition, these devices exhibit negative resistance, and because of the negative resistance they can be made to oscillate in special circuits.

Laboratory Work

1. This experiment will use a high voltage power supply; ask the instructor to look at your circuit before turning on the supply.

2. Find the relation between voltage V and current I for a neon lamp. This relation is called the "constitutive relation" for the neon lamp.

3. Use the constitutive relation to design and construct an oscillator. A capacitor and a resistor will be required in the circuit. Draw a diagram of your circuit. Measure the frequency of the oscillator. (HINT: The capacitor needs to be put in parallel with the lamp, while the resistor needs to be in series with the combination. Based on your measurementsso far, you should be able to pick a resistor and capacitor that will work well.)

4. Now that you have seen the oscillator work once, you are more likely to understand what is going on. Select a different resistor or capacitor with the goal of either doubling or halving the oscillator frequency (you decide which you want to do. If your first frequency came out small, you might want to double it, but if the flashing is pretty rapid, you might aim to halve the frequency.)

Calculations and Analysis

5. From the values of the capacitor and the resistor and the voltage at which the neon lamp becomes conducting, calculate the frequency of the oscillator. Compare your calculated frequency with the measured frequency. Repeat the calculation for the second resistor/capacitor set you choose.

Equipment list

- High voltage supply
- Voltmeters
- Neon lamp
- Assorted parts

Laboratory Time

Two hours

13 Serial Ports (n=1)

Background

Serial data communications is important in many scientific instruments. If you build an instrument yourself, or need to automate a commercial instrument, you will likely need to understand it.

Like so much else in electronics, serial communications have advanced and proliferated since the PC revolution of the early 1980's. You have probably heard of USB (Universal serial bus), and SATA (Serial ATA, for hard drives), which are high performance interfaces for commercial computers. There are also many serial interfaces used at the chip or subsystem level, among these are I2C (Inter-IC bus) and SPI (Serial Peripheral Interface).

The grandparent of all serial-protocols is the RS-232 protocol, often simply called "the serial port protocol". Despite its antiquity (a variant was first used in teletypes for telegraphy in the early 20th century), it is still used by GPS devices and various scientific instruments and is available on your laptop computer via a "terminal program". In particular, because if its simplicity, it is a good protocol to learn. The other modern protocols previously mentioned have much in common with it, and you can understand their more sophisticated features more easily if you already understand RS-232.

Connectors and pin definitions

The RS-232 protocol was used most heavily for PC's to communicate with modems. Because modems interfaced to telephones, they had a lot of complexity. They had to detect dial tones and know when the line was clear for data. In fact the full RS-232 interface defined a 25-pin connector. Early on PC-manufacturers cut this down to 9-pins, and used a "9-pin D connector" (see Figure below). This is still more complicated than needed for most applications. In practice, one needs only the "RX" (Receive) and "TX" (Transmit) wires, plus ground, and sometimes power. When you read descriptions of RS-232 and serial ports on line, you will run into references to arcane signals like request to send (RTS), clear to send (CTS) and data terminal ready (DTR) that were important in modem and telephone days. Fortunately, you need none of these things for this lab. You only need to understand RX and TX.

In this lab, you will be using only RX, TX and ground. The RS-232 specification says that pin 2 is RX (receive). Pin 2 is sometimes called RD (Receive data). Pin 3 is TX (transmit), also known as TD (Transmit data). Pin 5 is ground (by now you know that you always need a ground!). Looking at the diagram below, you will see that the "male" and "female" connectors are mirror images. Thus what you think is Pin 2 may be Pin 4, while Pin 1 may be Pin 5. To make matters worse, there are two types of cables in common use for serial ports.

Experiment

Connect an oscilloscope to the serial port of a laptop computer and analyze the waveforms that come out of MINICOM or HYPERTERM. Figure out how to translate oscilloscope waveforms into letters. This article will be extremely useful. (*http://en.wikipedia.org/wiki/RS-232*).

It is your job to figure out the connectors and how to connect to the appropriate pins. After that, the waveform analysis is straightforward.

Your report should include a sketch of the waveforms of your initials shown at 19200 baud and at 2400 baud. Indicate what changes as you change the baud rate of MINICOM or HYPERTERM.

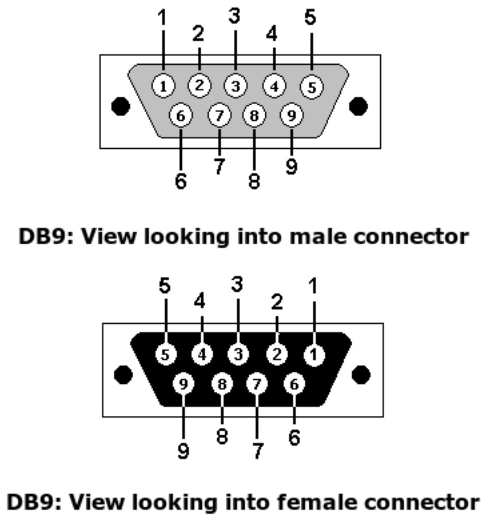


Figure 1: 9-Pin "D" connectors: They are called "D" because of their shape. This type of connector is also referred to as a "DB9". They are the same size and shape as the video (SVGA) connector on the back of your computer, but they have fewer pins. Notice that pin 2 on the "male" connector becomes pin 4 on the "female" connector. This causes endless confusion.

You should figure out how to decode all the capital letters and all the numbers on a computer keyboard. When you are ready, I will type you a 10 character or less secret message. Decode this and include it in your report.

1. A "straight" cable connects every pin on one end to the same numbered pin on the other end. You would think this is obvious, but there is another common option.

2. A "cross-over" cable connects pin 2 on one end to pin 3 on the other end.

If you undertand why cross-over cables exist, you will understand more about serial ports. In principle, you only need one wire (plus ground) to send data. In fact this is correct. For a computer to send serial data, it merely triggers a line The concept of a cross-over vs. a straight through cable also applies to Ethernet, where it also causes much confusion among beginning engineers and scientists.

Equipment

- Laptop computer with working serial ports
- Tektronix TDS-1002 Digital Oscilloscope
- Serial port cables

Laboratory Time

Two hours

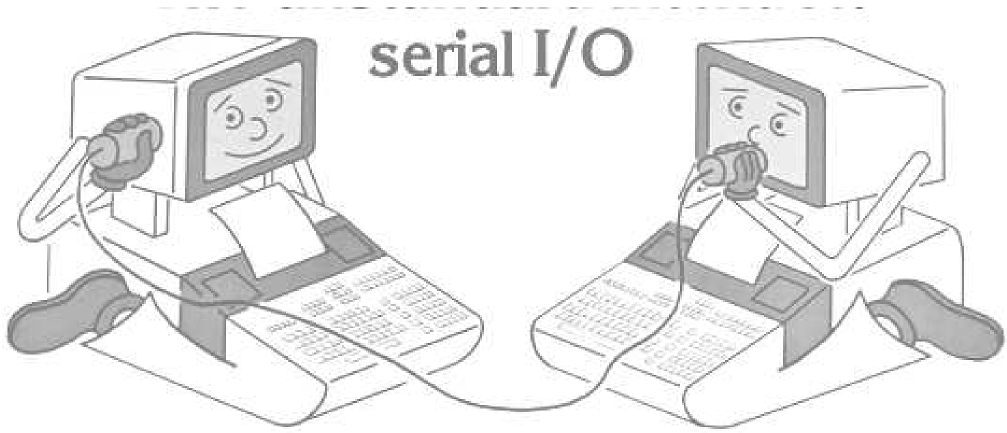


Figure 2: Why you need a crossover cable: The computer on the right is "talking" into its TX line. The computer in the left is "listening" to its RX line. If the left computer wants to "talk", it wiggles it's TX line, which must obviously be connected to the RX line of the computer on the right.

Equipment

- Laptop computer with working serial ports
- Tektronix TDS-1002 Digital Oscilloscope
- Serial port cables

Laboratory Time

Two hours

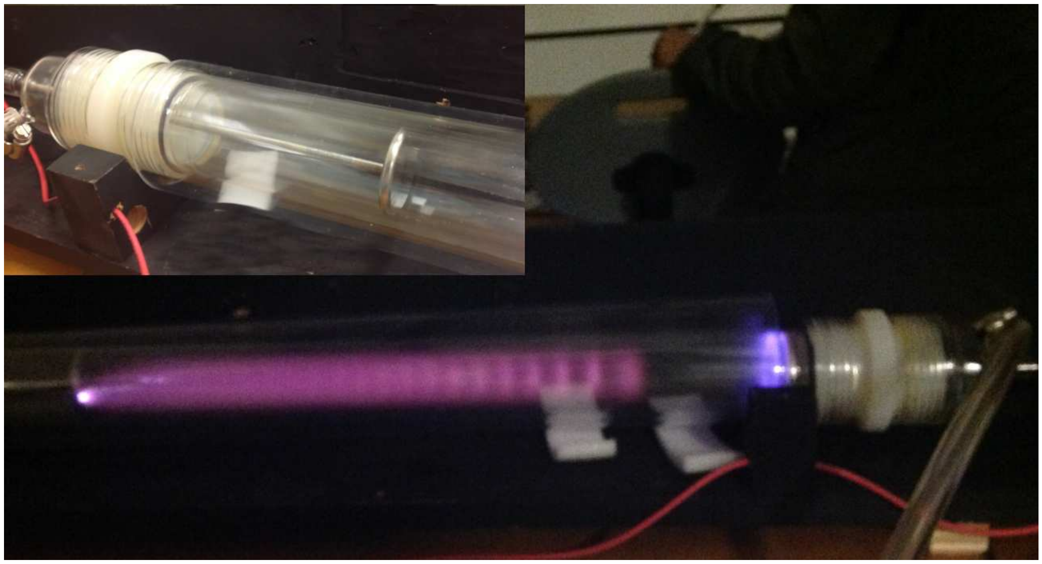


Figure 3: A glow discharge tube with a Nitrogen plasma.

14 Miscellaneous Experiments (n=various!)

Some of these experiments require advance notice because I will have to procure needed supplies. The amount of notice required is indicated on each.

The following experiments are not completely described. Part of each exercise is to identify the core scientific objective. Most are n=2 or more because of the work of figuring out what to do and perhaps assemblying supplies. I will help you with these and can decide on their value in advance.

A Arduino Experiments

The Arduino can measure or control a vast quantity of experiments and there is code for the taking out on the net.

B Plasma Physics

In room 199 we have the plasma apparatus shown on the next page. Once built, one can observe beautiful effects on the glow as a function of pressure (see photo). One can do spectroscopy and measure the temperature of the plasma, or study Paschen's law, which relates the voltage necessary to break down the gas to the pressure inside the tube and the gap between the electrodes. One can also demonstrate the pinch effect and see how magnetic flux is ”frozen in” to plasmas. All of these experiments are outlined in a paper by S. Wissel, A. Zwicker, J. Ross, and S. Gershman*American Journal of Physics, 81(9)*, pp. 663-670, 2013. If the experiment is built, it will take about two weeks to do.

C The Radio Spectrum

A spectrum analyzer and a simple antenna allow one to see the emissions of your cel phone and to find all the radio stations currently broadcasting near Socorro. In the write-up for this n=1 experiment, measure the frequency and amplitude of the 5 strongest radio stations and two different cel phones.

D Lightning Location

A lightning flash actually consists of millions of tiny sparks that can be individually located in the sky. This is done by putting out a half dozen antennas and measuring when the radio pulse from each spark arrives. You can do a simple version of this test with two cables. Move a sparker back and forth between them and measure its location by correlating the peaks on an oscilloscope.

E Lock-in Amplifiers

This project has a lot of physics and is *not* lethal. We have both a lock-in amplifier and a mechanical chopper. The "chopper" when applied to a laser beam or LED, can allow you to see a weak light from an LED in an otherwise brightly lit room. Perhaps you can even make a laser motion detector out of this apparatus.

F TV remote control

This requires only one week advance notice.

Using a phototransistor or photodiode, look at the infrared light signal emitted by a remote control unit for a television set. See if you can determine the control codes.

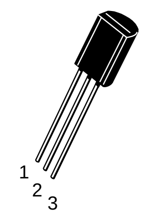
Appendix – Data Sheets

One Watt High Current Transistors

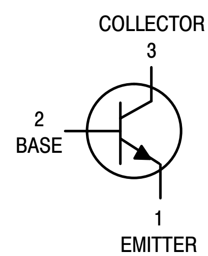
NPN Silicon

MPSW01
MPSW01A*

*ON Semiconductor Preferred Device



CASE 29–10, STYLE 1
TO–92 (TO–226AE)



MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Collector–Emitter Voltage MPSW01 MPSW01A	V_{CEO}	 30 40	Vdc
Collector–Base Voltage MPSW01 MPSW01A	V_{CBO}	 40 50	Vdc
Emitter–Base Voltage	V_{EBO}	5.0	Vdc
Collector Current — Continuous	I_C	1000	mAdc
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	1.0 8.0	Watts mW/°C
Total Device Dissipation @ T_C = 25°C Derate above 25°C	P_D	2.5 20	Watts mW/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	–55 to +150	°C

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Ambient	$R_{\theta JA}$	125	°C/W
Thermal Resistance, Junction to Case	$R_{\theta JC}$	50	°C/W

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic		Symbol	Min	Max	Unit
OFF CHARACTERISTICS					
Collector–Emitter Breakdown Voltage(1) (I_C = 10 mAdc, I_B = 0)	 MPSW01 MPSW01A	$V_{(BR)CEO}$	 30 40	 — —	Vdc
Collector–Base Breakdown Voltage (I_C = 100 μAdc, I_E = 0)	 MPSW01 MPSW01A	$V_{(BR)CBO}$	 40 50	 — —	Vdc
Emitter–Base Breakdown Voltage (I_E = 100 μAdc, I_C = 0)		$V_{(BR)EBO}$	5.0	—	Vdc
Collector Cutoff Current (V_{CB} = 30 Vdc, I_E = 0) (V_{CB} = 40 Vdc, I_E = 0)	 MPSW01 MPSW01A	I_{CBO}	 — —	 0.1 0.1	μAdc
Emitter Cutoff Current (V_{EB} = 3.0 Vdc, I_C = 0)		I_{EBO}	—	0.1	μAdc

1. Pulse Test: Pulse Width ≤ 300 μs, Duty Cycle ≤ 2.0%.

Preferred devices are ON Semiconductor recommended choices for future use and best overall value.

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted) (Continued)

Characteristic	Symbol	Min	Max	Unit
ON CHARACTERISTICS[1]				
DC Current Gain	h_{FE}			—
(I_C = 10 mAdc, V_{CE} = 1.0 Vdc)		55	—	
(I_C = 100 mAdc, V_{CE} = 1.0 Vdc)		60	—	
(I_C = 1000 mAdc, V_{CE} = 1.0 Vdc)		50	—	
Collector–Emitter Saturation Voltage (I_C = 1000 mAdc, I_B = 100 mAdc)	$V_{CE(sat)}$	—	0.5	Vdc
Base–Emitter On Voltage (I_C = 1000 mAdc, V_{CE} = 1.0 Vdc)	$V_{BE(on)}$	—	1.2	Vdc
SMALL–SIGNAL CHARACTERISTICS				
Current–Gain — Bandwidth Product (I_C = 50 mAdc, V_{CE} = 10 Vdc, f = 20 MHz)	f_T	50	—	MHz
Output Capacitance (V_{CB} = 10 Vdc, I_E = 0, f = 1.0 MHz)	C_{obo}	—	20	pF

1. Pulse Test: Pulse Width ≤ 300 μs, Duty Cycle ≤ 2.0%.

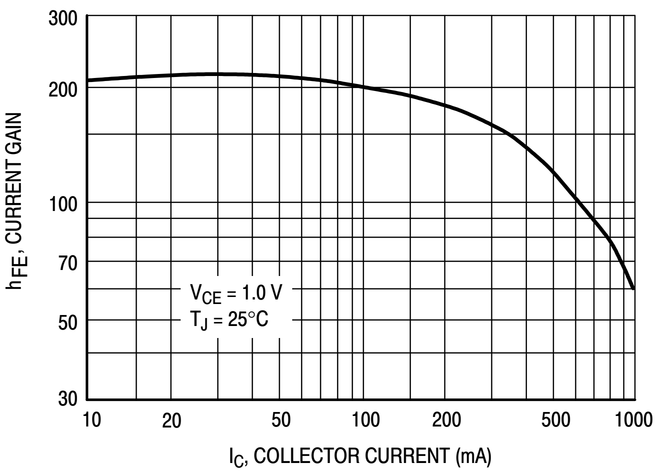


Figure 1. DC Current Gain

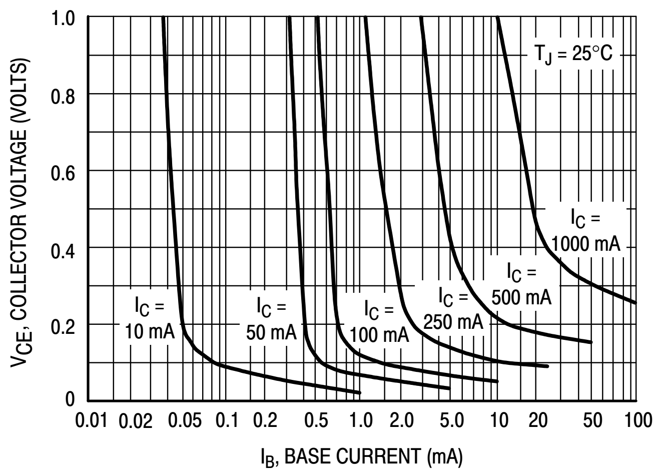


Figure 2. Collector Saturation Region

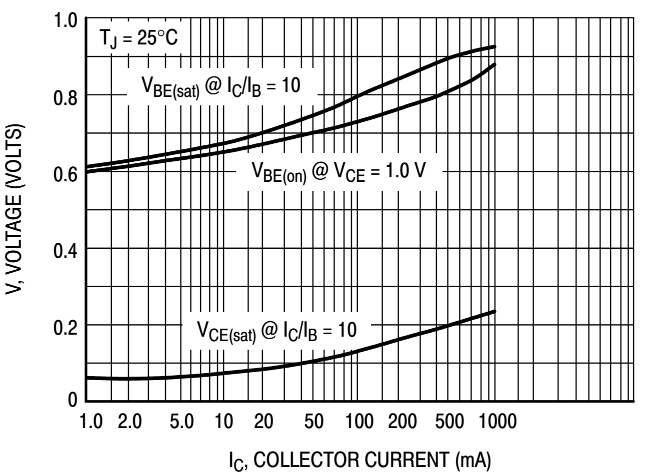


Figure 3. “ON” Voltages

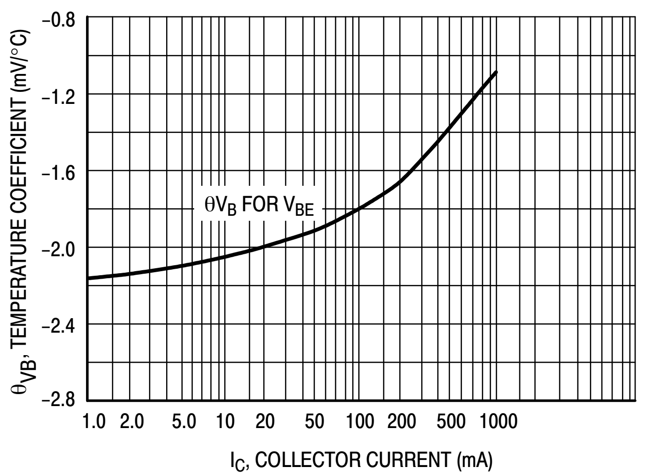


Figure 4. Temperature Coefficient

Precision Operational Amplifier

FEATURES

- *Guaranteed* Low Offset Voltage
  - LT1001AM 15μV max
  - LT1001C 60μV max
- *Guaranteed* Low Drift
  - LT1001AM 0.6μV/°C max
  - LT1001C 1.0μV/°C max
- *Guaranteed* Low Bias Current
  - LT1001AM 2nA max
  - LT1001C 4nA max
- *Guaranteed* CMRR
  - LT1001AM 114dB min
  - LT1001C 110dB min
- *Guaranteed* PSRR
  - LT1001AM 110dB min
  - LT1001C 106dB min
- Low Power Dissipation
  - LT1001AM 75mW max
  - LT1001C 80mW max
- Low Noise 0.3μV$_{P-P}$

APPLICATIONS

- Thermocouple amplifiers
- Strain gauge amplifiers
- Low level signal processing
- High accuracy data acquisition

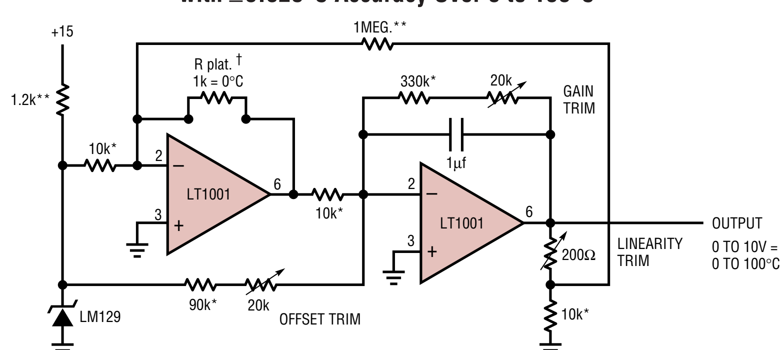
DESCRIPTION

The LT®1001 significantly advances the state-of-the-art of precision operational amplifiers. In the design, processing, and testing of the device, particular attention has been paid to the optimization of the entire distribution of several key parameters. Consequently, the specifications of the lowest cost, commercial temperature device, the LT1001C, have been dramatically improved when compared to equivalent grades of competing precision amplifiers.

Essentially, the input offset voltage of all units is less than 50μV (see distribution plot below). This allows the LT1001AM/883 to be specified at 15μV. Input bias and offset currents, common-mode and power supply rejection of the LT1001C offer guaranteed performance which were previously attainable only with expensive, selected grades of other devices. Power dissipation is nearly halved compared to the most popular precision op amps, without adversely affecting noise or speed performance. A beneficial by-product of lower dissipation is decreased warm-up drift. Output drive capability of the LT1001 is also enhanced with voltage gain guaranteed at 10mA of load current. For similar performance in a dual precision op amp, with guaranteed matching specifications, see the LT1002. Shown below is a platinum resistance thermometer application.

TYPICAL APPLICATION

Linearized Platinum Resistance Thermometer with ±0.025°C Accuracy Over 0 to 100°C

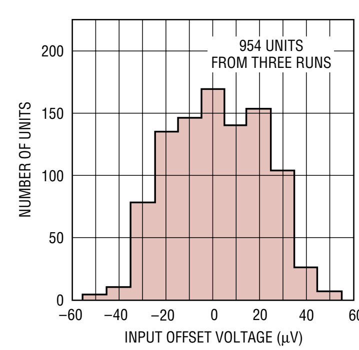


* ULTRONIX 105A WIREWOUND
** 1% FILM
† PLATINUM RTD 118MF (ROSEMOUNT, INC.)

‡ Trim sequence: trim offset (0°C = 1000.0Ω), trim linearity (35°C = 1138.7Ω), trim gain (100°C = 1392.6Ω). Repeat until all three points are fixed with ±0.025°C.

1001 TA01

Typical Distribution of Offset Voltage $V_S = \pm15V$, $T_A = 25°C$



1001 TA02

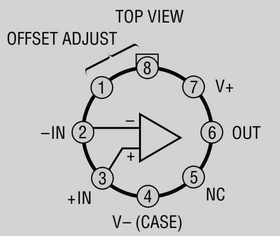
ABSOLUTE MAXIMUM RATINGS

(Note 1)

Supply Voltage .... ±22V
Differential Input Voltage .... ±30V
Input Voltage .... ±22V
Output Short Circuit Duration .... Indefinite

Operating Temperature Range
LT1001AM/LT1001M **(OBSOLETE)** .. –55°C to 150°C
LT1001AC/LT1001C .... 0°C to 125°C
Storage: All Devices .... –65°C to 150°C
Lead Temperature (Soldering, 10 sec.) .... 300°C

PACKAGE/ORDER INFORMATION



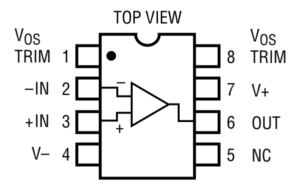
H PACKAGE METAL CAN

T_{JMAX} = 150°C, θ_{JA} = 150°C/W, θ_{jc} = 45°C/W

ORDER PART NUMBER
LT1001AMH/883 LT1001MH LT1001ACH LT1001CH

OBSOLETE PACKAGE

Consider the N8 and S8 Packages for Alternate Source



N8 PACKAGE
8 PIN PLASTIC DIP

S8 PACKAGE
8 PIN PLASTIC SO

T_{JMAX} = 150°C, θ_{JA} = 130°C/W (N)
T_{JMAX} = 150°C, θ_{JA} = 150°C/W (S)

ORDER PART NUMBER
LT1001ACN8 LT1001CN8 LT1001CS8
S8 PART MARKING
1001

J8 PACKAGE
8 PIN HERMETIC DIP
T_{JMAX} = 150°C, θ_{JA} = 100°C/W (J)

ORDER PART NUMBER
LT1001AMJ8/883 LT1001MJ8 LT1001ACJ8 LT1001CJ8

OBSOLETE PACKAGE

Consider the N8 and S8 Packages for Alternate Source

Consult LTC Marketing for parts specified with wider operating temperature ranges.

ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at T_A = 25°C. V_S = ±15V, unless otherwise noted

SYMBOL	PARAMETER	CONDITIONS		LT1001AM/883 LT1001AC MIN	TYP	MAX	LT1001M/LT1001C MIN	TYP	MAX	UNITS
V_{OS}	Input Offset Voltage	Note 2	LT1001AM/883		7	15		18	60	µV
			LT1001AC		10	25				
$\frac{\Delta V_{OS}}{\Delta Time}$	Long Term Input Offset Voltage Stability	Notes 3 and 4			0.2	1.0		0.3	1.5	µV/month
I_{OS}	Input Offset Current				0.3	2.0		0.4	3.8	nA
I_b	Input Bias Current				±0.5	±2.0		±0.7	±4.0	nA
e_n	Input Noise Voltage	0.1Hz to 10Hz (Note 3)			0.3	0.6		0.3	0.6	μV_{p-p}
e_n	Input Noise Voltage Density	f_O = 10Hz (Note 6) f_O = 1000Hz (Note 3)			10.3 9.6	18.0 11.0		10.5 9.8	18.0 11.0	$nV/\sqrt{Hz}$ $nV/\sqrt{Hz}$
A_{VOL}	Large Signal Voltage Gain	$R_L \geq 2k\Omega$, V_O = ±12V $R_L \geq 1k\Omega$ V_O = ±10V		450 300	800 500		400 250	800 500		V/mV V/mV
CMRR	Common Mode Rejection Ratio	V_{CM} = ±13V		114	126		110	126		dB
PSRR	Power Supply Rejection Ratio	V_S = ±3V to ±18V		110	123		106	123		dB
R_{in}	Input Resistance Differential Mode			30	100		15	80		MΩ

ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at T_A = 25°C. V_S = ±15V, T_A = 25°C, unless otherwise noted

SYMBOL	PARAMETER	CONDITIONS	LT1001AM/883 LT1001AC MIN	TYP	MAX	LT1001M/LT1001C MIN	TYP	MAX	UNITS
	Input Voltage Range		±13	±14		±13	±14		V
V_{OUT}	Maximum Output Voltage Swing	R_L ≥ 2kΩ R_L ≥ 1kΩ	±13 ±12	±14 ±13.5		±13 ±12	±14 ±13.5		V V
S_R	Slew Rate	R_L ≥ 2kΩ (Note 5)	0.1	0.25		0.1	0.25		V/µs
GBW	Gain-Bandwidth Product	(Note 5)	0.4	0.8		0.4	0.8		MHz
P_d	Power Dissipation	No load No load, V_S = ±3V		46 4	75 6		48 4	80 8	mW mW

V_S = ±15V, –55°C ≤ T_A ≤ 125°C, unless otherwise noted

SYMBOL	PARAMETER	CONDITIONS		LT1001AM/883 MIN	TYP	MAX	LT1001M MIN	TYP	MAX	UNITS
V_{OS}	Input Offset Voltage		●		30	60		45	160	µV
$\frac{\Delta V_{OS}}{\Delta Temp}$	Average Offset Voltage Drift		●		0.2	0.6		0.3	1.0	µV/°C
I_{OS}	Input Offset Current		●		0.8	4.0		1.2	7.6	nA
I_B	Input Bias Current		●		±1.0	±4.0		±1.5	±8.0	nA
A_{VOL}	Large Signal Voltage Gain	R_L ≥ 2kΩ, V_O = ±10V	●	300	700		200	700		V/mV
CMRR	Common Mode Rejection Ratio	V_{CM} = ±13V	●	110	122		106	120		dB
PSRR	Power Supply Rejection Ratio	V_S = ±3 to ±18V	●	104	117		100	117		dB
	Input Voltage Range		●	±13	±14		±13	±14		V
V_{OUT}	Output Voltage Swing	R_L ≥ 2kΩ	●	±12.5	±13.5		±12.0	±13.5		V
P_d	Power Dissipation	No load	●		55	90		60	100	mW

V_S = ±15V, 0°C ≤ T_A ≤ 70°C, unless otherwise noted

SYMBOL	PARAMETER	CONDITIONS		LT1001AC MIN	TYP	MAX	LT1001C MIN	TYP	MAX	UNITS
V_{OS}	Input Offset Voltage		●		20	60		30	110	µV
$\frac{\Delta V_{OS}}{\Delta Temp}$	Average Offset Voltage Drift		●		0.2	0.6		0.3	1.0	µV/°C
I_{OS}	Input Offset Current		●		0.5	3.5		0.6	5.3	nA
I_B	Input Bias Current		●		±0.7	±3.5		±1.0	±5.5	nA
A_{VOL}	Large Signal Voltage Gain	R_L ≥ 2kΩ, V_O = ±10V	●	350	750		250	750		V/mV
CMRR	Common Mode Rejection Ratio	V_{CM} = ±13V	●	110	124		106	123		dB
PSRR	Power Supply Rejection Ratio	V_S = ±3V to ±18V	●	106	120		103	120		dB
	Input Voltage Range		●	±13	±14		±13	±14		V
V_{OUT}	Output Voltage Swing	R_L ≥ 2kΩ	●	±12.5	±13.8		±12.5	±13.8		V
P_d	Power Dissipation	No load	●		50	85		55	90	mW

Note 1: Absolute Maximum Ratings are those values beyond which the life of a device may be impaired.

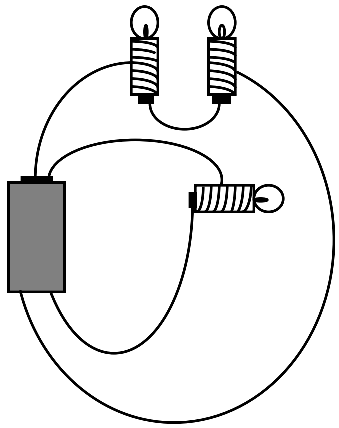
Note 2: Offset voltage for the LT1001AM/883 and LT1001AC are measured after power is applied and the device is fully warmed up. All other grades are measured with high speed test equipment, approximately 1 second after power is applied. The LT1001AM/883 receives 168 hr. burn-in at 125°C. or equivalent.

Note 3: This parameter is tested on a sample basis only.

Note 4: Long Term Input Offset Voltage Stability refers to the averaged trend line of V_{OS} versus Time over extended periods after the first 30 days of operation. Excluding the initial hour of operation, changes in V_{OS} during the first 30 days are typically 2.5µV.

Note 5: Parameter is guaranteed by design.

Note 6: 10Hz noise voltage density is sample tested on every lot. Devices 100% tested at 10Hz are available on request.



Determining and **I**nterpreting **R**esistive **E**lectric Circuits **C**oncepts **T**est

Version 1.2

Instructions

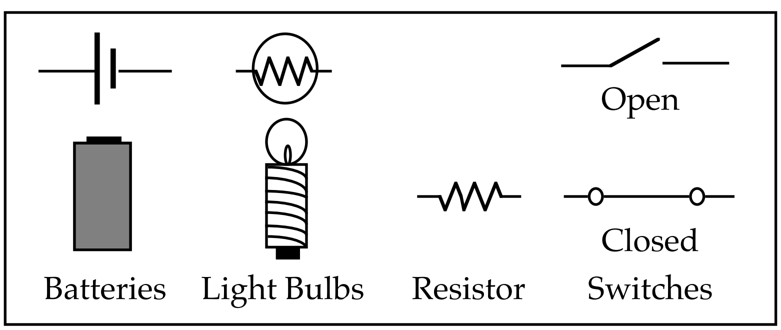
Wait until you are told to begin, then turn to the next page and begin working. Answer each question as accurately as you can. There is only one correct answer for each item. Feel free to use a calculator and scratch paper if you wish.

Use a #2 pencil to **record your answers** on the Opscan sheet, but please **do not write in the test booklet**.

You will have approximately 30 minutes to complete the test. If you finish early, check your work before handing in both the answer sheet and the test booklet.

Additional comments about the test

All light bulbs, resistors, and batteries are identical unless you are told otherwise. The battery is ideal, that is to say, the internal resistance of the battery is negligible. In addition, the wires have negligible resistance. Below is a key to the symbols used on this test. Study them carefully before you begin the test.



by Paula V. Engelhardt and
Robert J. Beichner
North Carolina State University
Department of Physics
Raleigh, NC 27695-8202
(919) 515-7226
Beichner@NCSU.edu

1) Are charges used up in the production of light in a light bulb?

(A) Yes, charge is used up. Charges moving through the filament produce "friction" which heats up the filament and produces light.

(B) Yes, charge is used up. Charges are emitted as photons and are lost.

(C) Yes, charge is used up. Charges are absorbed by the filament and are lost.

(D) No, charge is conserved. Charges are simply converted to another form such as heat and light.

(E) No, charge is conserved. Charges moving through the filament produce "friction" which heats up the filament and produces light.

2) How does the power delivered to resistor A change when resistor B is added to the circuit? The power delivered to resistor A _____.

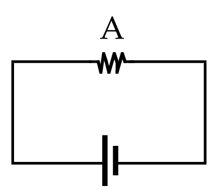
(A) Quadruples (4 times)

(B) Doubles

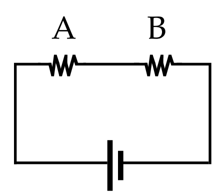
(C) Stays the same

(D) Is reduced by half

(E) Is reduced to one quarter (1/4)



Before



After

3) Which circuit or circuits have the GREATEST energy delivered to them per second?

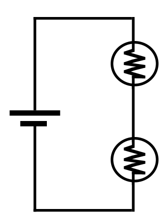
(A) Circuit 1

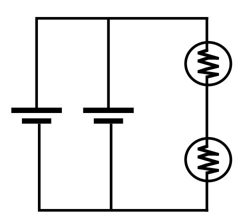
(B) Circuit 2

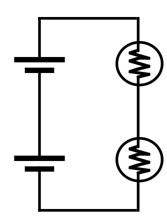
(C) Circuit 3

(D) Circuit 1 = Circuit 2

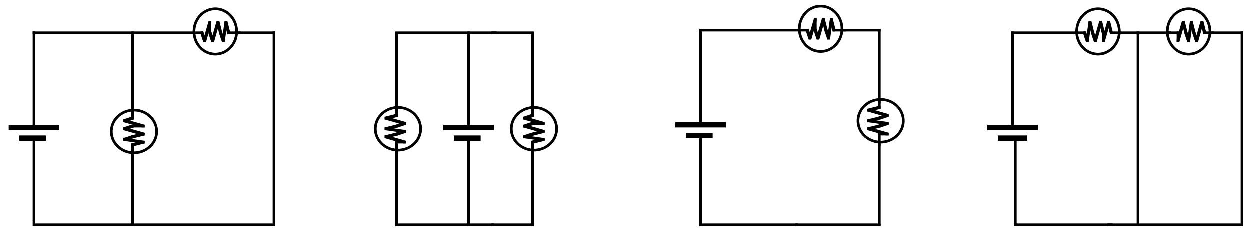
(E) Circuit 2 = Circuit 3


Circuit 1


Circuit 2


Circuit 3

4) Which circuit or circuits below represent a circuit consisting of two light bulbs in parallel with a battery?



Circuit 1 Circuit 2 Circuit 3 Circuit 4

(A) Circuit 1

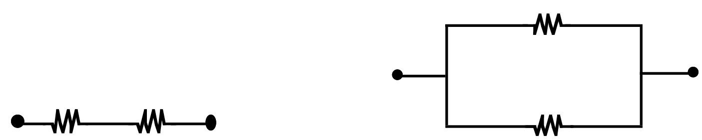
(B) Circuit 2

(C) Circuit 3

(D) Circuits 1 and 2

(E) Circuits 1, 2, and 4

5) Compare the resistance of branch 1 with that of branch 2. A branch is a section of a circuit. The resistance of branch 1 is _____ branch 2.



Branch 1 Branch 2

(A) Four times

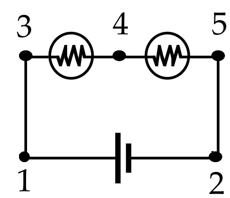
(B) Double

(C) The same as

(D) Half

(E) One quarter (1/4)

6) Rank the potential difference between points 1 and 2, points 3 and 4, and points 4 and 5 in the circuit shown below from HIGHEST to LOWEST.



(A) 1 and 2; 3 and 4; 4 and 5

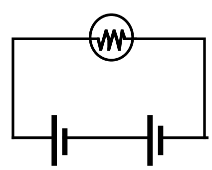
(B) 1 and 2; 4 and 5; 3 and 4

(C) 3 and 4; 4 and 5; 1 and 2

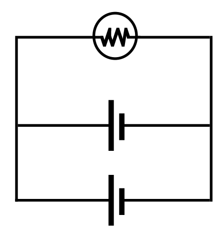
(D) 3 and 4 = 4 and 5; 1 and 2

(E) 1 and 2; 3 and 4 = 4 and 5

7) Compare the brightness of the bulb in circuit 1 with that in circuit 2. Which bulb is BRIGHTER?



Circuit 1



Circuit 2

(A) Bulb in circuit 1 because two batteries in series provide less voltage

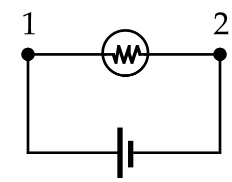
(B) Bulb in circuit 1 because two batteries in series provide more voltage

(C) Bulb in circuit 2 because two batteries in parallel provide less voltage

(D) Bulb in circuit 2 because two batteries in parallel provide more voltage

(E) Neither, they are the same

8) Compare the current at point 1 with the current at point 2. At which point is the current LARGEST?



(A) Point 1

(B) Point 2

(C) Neither, they are the same. Current travels in one direction around the circuit.

(D) Neither, they are the same. Currents travel in two directions around the circuit.

9) Which circuit(s) will light the bulb? (The other object represents a battery.)

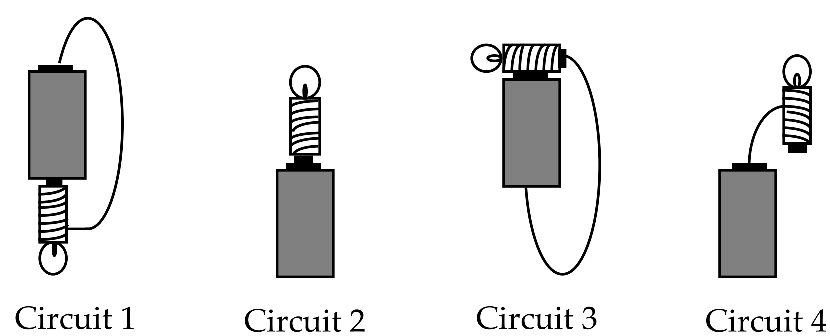
(A) Circuit 1

(B) Circuit 2

(C) Circuit 3

(D) Circuits 1 and 3

(E) Circuits 1, 3, and 4



10) Compare the brightness of bulbs A, B, and C in these circuits. Which bulb or bulbs are the BRIGHTEST?

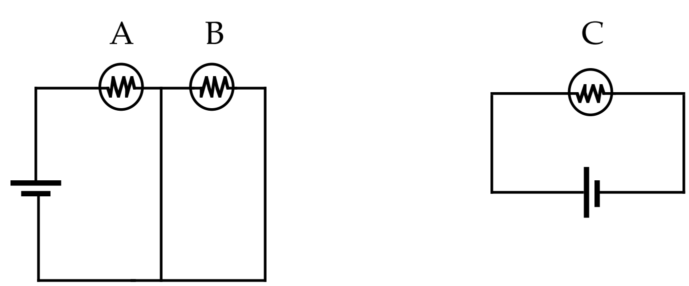
(A) A

(B) B

(C) C

(D) A = B

(E) A = C



11) Why do the lights in your home come on almost instantaneously when you turn on the switch?

(A) When the circuit is completed, there is a rapid rearrangement of surface charges in the circuit.

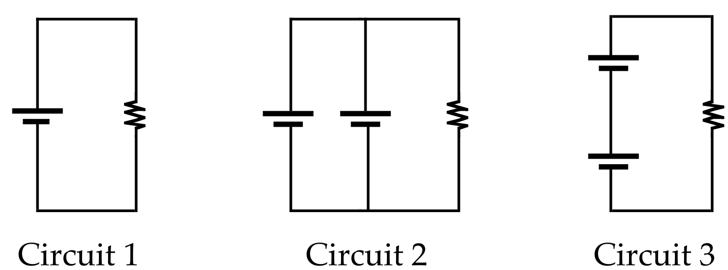
(B) Charges store energy. When the circuit is completed, the energy is released.

(C) Charges in the wire travel very fast.

(D) The circuits in a home are wired in parallel. Thus, a current is already flowing.

(E) Charges in the wire are like marbles in a tube. When the circuit is completed, the charges push each other through the wire.

12) Consider the power delivered to each of the resistors shown in the circuits below. Which circuit or circuits have the LEAST power delivered to them?



(A) Circuit 1

(B) Circuit 2

(C) Circuit 3

(D) Circuit 1 = Circuit 2

(E) Circuit 1 = Circuit 3

13) Which schematic diagram best represents the realistic circuit shown below?

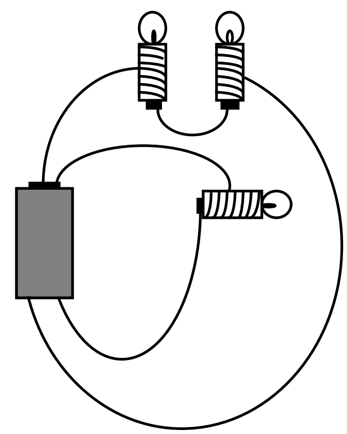
(A) Circuit 1

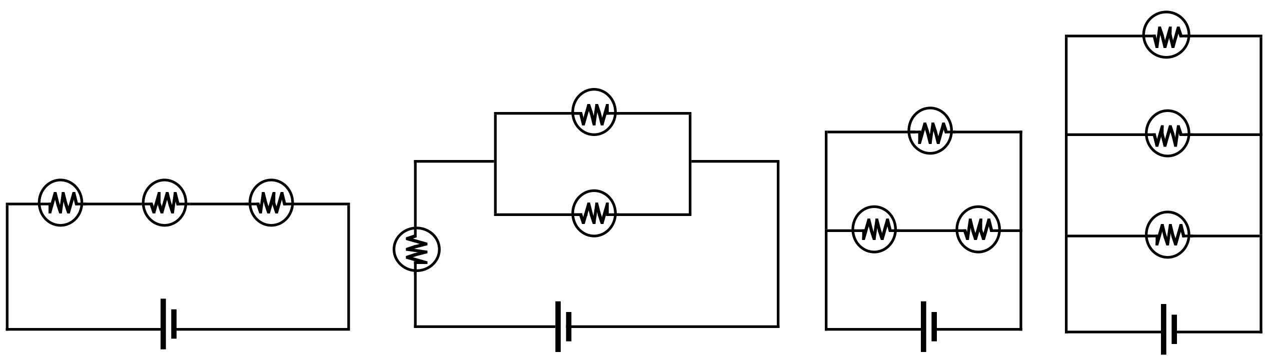
(B) Circuit 2

(C) Circuit 3

(D) Circuit 4

(E) None of the above





Circuit 1 Circuit 2 Circuit 3 Circuit 4

14) How does the resistance between the endpoints change when the switch is closed?

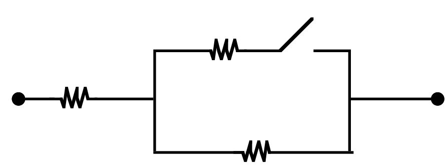
(A) Increases by R

(B) Increases by R/2

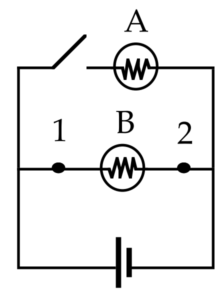
(C) Stays the same

(D) Decreases by R/2

(E) Decreases by R



15) What happens to the potential difference between points 1 and 2 when the switch is closed?



(A) Quadruples (4 times)

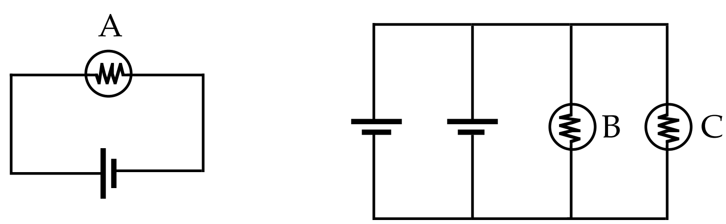
(B) Doubles

(C) Stays the same

(D) Reduces by half

(E) Reduces by one quarter (1/4)

16) Compare the brightness of bulb A with bulb B. Bulb A is _____ bright as Bulb B.



(A) Four times as

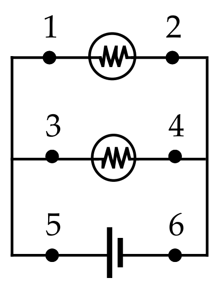
(B) Twice as

(C) Equally

(D) Half as

(E) One fourth (1/4) as

17) Rank the currents at points 1, 2, 3, 4, 5, and 6 from HIGHEST to LOWEST.



(A) 5, 3, 1, 2, 4, 6

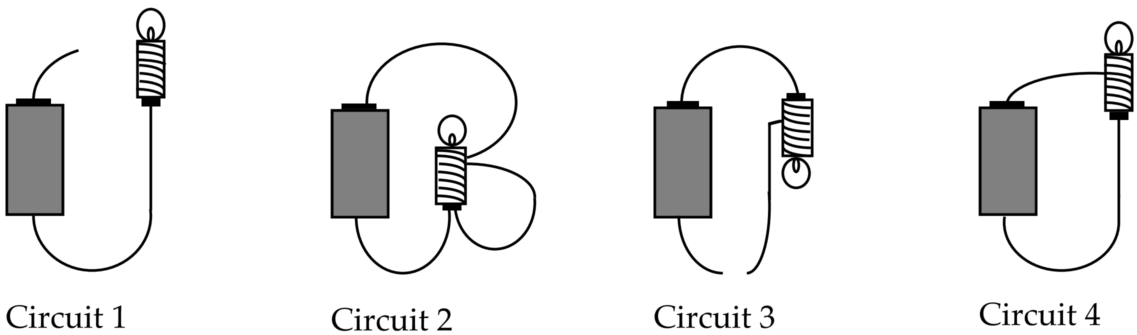
(B) 5, 3, 1, 4, 2, 6

(C) 5 =6, 3 = 4, 1 =2

(D) 5 = 6, 1 = 2 = 3 = 4

(E) 1 = 2 = 3 = 4 = 5 = 6

18) Which circuit(s) will light the bulb?



(A) Circuit 1

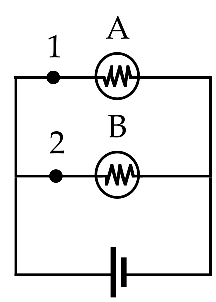
(B) Circuit 2

(C) Circuit 4

(D) Circuits 2 and 4

(E) Circuits 1 and 3

19) What happens to the brightness of bulbs A and B when a wire is connected between points 1 and 2?



(A) Both increase

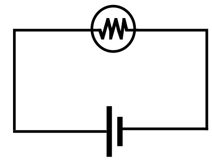
(B) Both decrease

(C) They stay the same

(D) A becomes brighter than B

(E) Neither bulb will light

20) Is the electric field zero or non-zero inside the bulb filament?



(A) Zero because the filament is a conductor.

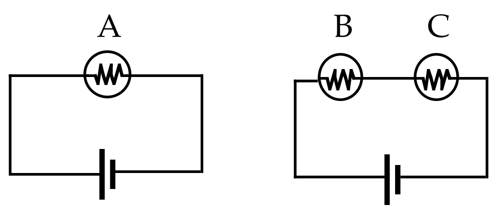
(B) Zero because a current is flowing.

(C) Zero because there are charges on the surface of the filament.

(D) Non-zero because a current is flowing which produces the field.

(E) Non-zero because there are charges on the surface of the filament which produce the field.

21) Compare the energy delivered per second to each light bulb shown below. Which bulb or bulbs have the LEAST energy delivered to them per second?



(A) A

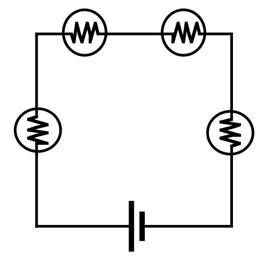
(B) B

(C) C

(D) B = C

(E) A = B = C

22) Which realistic circuit or circuits represent the schematic diagram shown below?



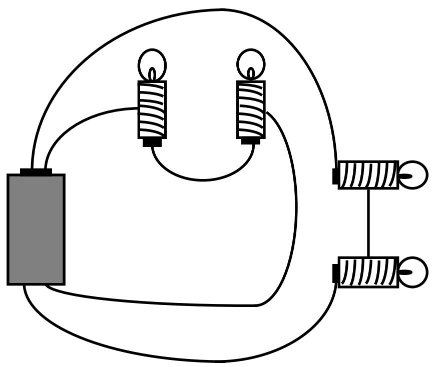
(A) Circuit 2

(B) Circuit 3

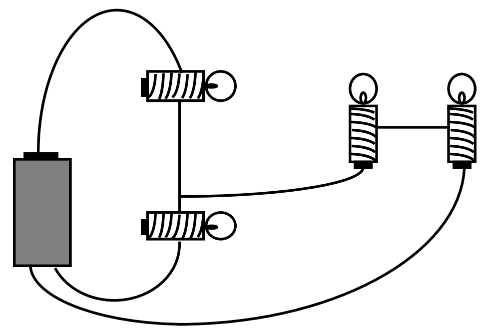
(C) Circuit 4

(D) Circuits 1 and 2

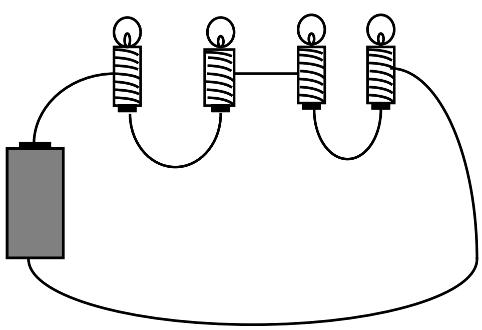
(E) Circuits 3 and 4



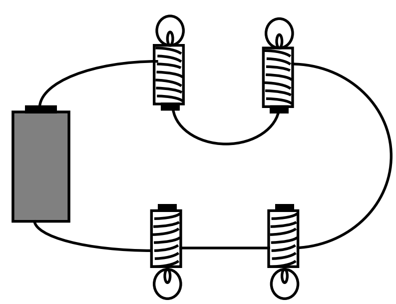
Circuit 1



Circuit 2

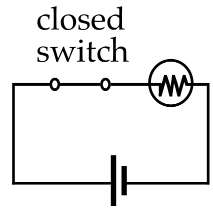


Circuit 3



Circuit 4

23) Immediately after the switch is opened, what happens to the resistance of the bulb?



(A) The resistance goes to infinity.

(B) The resistance increases.

(C) The resistance decreases.

(D) The resistance stays the same.

(E) The resistance goes to zero.

24) If you double the current through a battery, is the potential difference across a battery doubled?

(A) Yes, because Ohm's law says $V = IR$.

(B) Yes, because as you increase the resistance, you increase the potential difference.

(C) No, because as you double the current, you reduce the potential difference by half.

(D) No, because the potential difference is a property of the battery.

(E) No, because the potential difference is a property of everything in the circuit.

25) Compare the brightness of bulb A with bulb B. Bulb A is _____ bright as bulb B.

(A) Four times as

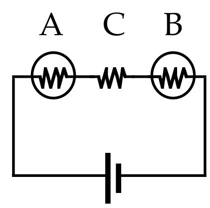
(B) Twice as

(C) Equally

(D) Half as

(E) One fourth (1/4) as

26) If you increase the resistance C, what happens to the brightness of bulbs A and B?



(A) A stays the same, B dims

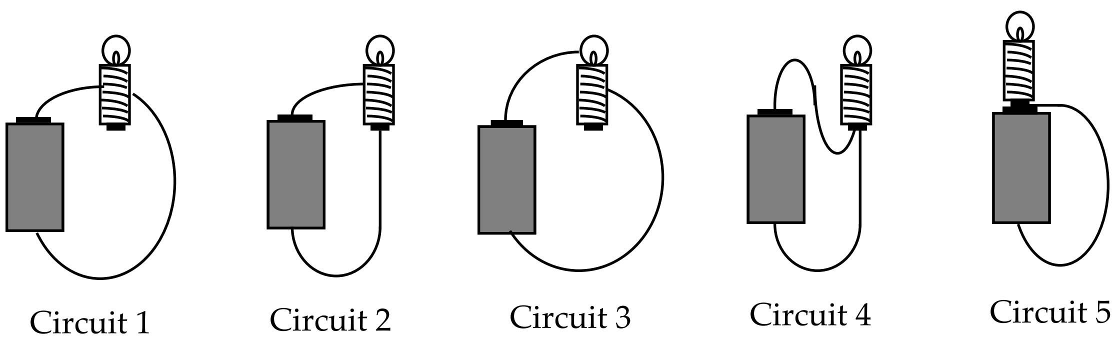
(B) A dims, B stays the same

(C) A and B increase

(D) A and B decrease

(E) A and B remain the same

27) Will all the bulbs be the same brightness?



(A) Yes, because they all have the same type of circuit wiring.

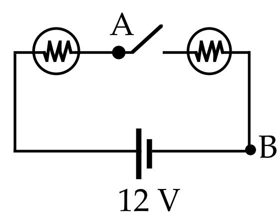
(B) No, because only Circuit 2 will light.

(C) No, because only Circuits 4 and 5 will light.

(D) No, because only Circuits 1 and 4 will light.

(E) No, Circuit 3 will not light but Circuits 1, 2, 4, and 5 will.

28) What is the potential difference between points A and B?



(A) 0 V

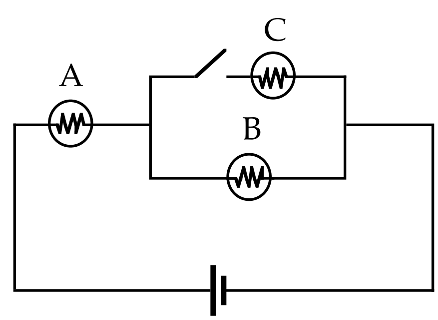
(B) 3 V

(C) 6 V

(D) 12 V

(E) None of the above

29) What happens to the brightness of bulbs A and B when the switch is closed?



(A) A stays the same, B dims

(B) A brighter, B dims

(C) A and B increase

(D) A and B decrease

(E) A and B remain the same