

Experiments with
Electricity and Magnetism
for
Physics 336L

by

Richard Sonnenfeld
New Mexico Tech Physics Department

©2022 by New Mexico Tech

January 14, 2022

Contents

Course schedule	1
0 Introduction	2
0.1 Course Goals and Time Commitment	2
0.2 Honesty/Plagiarism	2
0.3 Safety	2
0.4 Laboratory Protocol	3
0.5 Required Supplies	3
0.6 Lab Reports	3
Lab Reports	3
0.7 Required report sections	4
0.8 Error Analysis	5
0.8.1 Random errors	5
0.8.2 Systematic errors	5
0.8.3 Handling Errors	6
0.9 Lab Grades	7
1 Circuits (n=1)	10
Understand DC series and parallel circuits and light-bulbs	10
1.1 Background theory	10
1.1.1 Multimeters	10
1.1.2 Circuits	10
1.2 Basic Formulae for DC Circuits	10
1.3 Series and Parallel Circuits with Resistors	11
1.4 Physics Puzzler [Answer two of these questions]	13
1.5 For Graduate Students	14
2 Complex Impedance (n=1)	15
Measure complex impedance of RLC circuit	15
2.1 Motivation for the experiment	15
2.2 Prelab	15
2.3 Background: Introduction to Complex Impedance	15
2.4 Requirements to use Complex Impedance	16
2.5 Why does it work?	16
2.6 Overall Approach for the experiment	17
2.7 Make Measurements for RLC Circuit	18
2.8 Compare theory and experiment	19
2.9 Physics Puzzler [Answer any two of these questions]	20
2.10 For Graduate Students	20
2.11 Equipment	20
2.12 Refresher on Complex Arithmetic	20

3	Magnetic Field, Inductance and Mutual Inductance (n=1)	21
	Exploring self-inductance, mutual inductance and transformer action	21
3.1	Introduction	21
3.2	Self Inductance	21
3.3	Magnetic Field Amplitude and Mutual Inductance	22
3.4	Transformer	23
3.5	Postlab: Calculations and analysis	23
4	Hysteresis (n=2)	25
	Measure hysteresis loop of a soft iron torus and learn how a transformer works	25
4.1	Prelab	25
4.2	Introduction	25
	4.2.1 Hysteresis defined	25
	4.2.2 B, H and M	25
	4.2.3 Ferromagnetic theory reviewed	25
4.3	Applying Maxwell's Equations	28
4.4	Laboratory Measurements	30
4.5	Calculations and Analysis	30
5	Operational Amplifiers (n=1)	32
	Learn basic op-amp theory then build an inverting and non-inverting op-amp	32
5.1	Uses of Operational Amplifiers	32
5.2	What Operational Amplifiers Do	32
5.3	The Golden Rules	33
5.4	A. Proper operation of an Op-Amp	33
5.5	B. <i>Clipping</i> of an Op-Amp	34
5.6	C. <i>Slew rate</i> of an Op-Amp	34
5.7	D. <i>Bandwidth</i> of an Op-Amp	35
5.8	E. Theoretical <i>Gain</i> of an Op-Amp	35
5.9	Analysis	36
5.10	For Graduate Students	36
6	Introduction to Arduino (n=2)	37
	We will learn how to use an Arduino uController and programmably change the bright- ness of an LED	37
A	Background:	37
	A.1 Introduction to the Arduino UNO Microcontroller Hardware:	38
	A.2 Introduction to the Arduino UNO Microcontroller Software:	39
B	Digital Output: Blinking LED	40
C	Digital Input: Switch	41
D	Analog Input: Potentiometers	42
E	Analog Output: Controlling LED Brightness	44
7	Digital to Analog Converters (n=2)	47
	Learn how to convert a digital number into an analog voltage	47
A	Saving your data and code	47
B	Motivation for the experiment	47
C	Overall Approach for the experiment	47

D	Build a 5-bit Ladder	47
D.1	Build a ladder using 16 identical resistors	48
E	Build a 5-bit binary counter with the Arduino	48
F	Build a 5-bit DAC	50
G	Build an 8-bit DAC using a ladder chip	50
8	Diodes (n=1)	51
	Characterize a diode, using Arduino as a data acquisition system	51
A	Measuring the Constitutive Relation of a Diode	51
9	Index of Refraction of Air (n=1)	53
	Compare optical path length in air to vacuum using an interferometer	53
10	Negative Resistance (n=1)	54
	Measure I-V curve of neon lamp. Use negative resistance to create an oscillator	54
11	Superconductivity (n=1)	55
	Understand Meissner effect with a High Tc superconductor	55
12	Serial Ports (n=1)	60
	Decode the signals that come out of a computer terminal.	60
13	Miscellaneous Experiments (n=various!)	63
	Develop an outlined experiment or create your own	63
A	Arduino Experiments	63
	The Arduino can measure or control a vast quantity of experiments and there is code for the taking out on the net.	63
B	Plasma Physics	63
	A table-top plasma apparatus allows you to manipulate and measure the plasma you have been learning about in Astrophysics courses.	63
C	The Radio Spectrum	64
	Use a spectrum analyzer to study the radio spectrum	64
D	Lightning Location	64
	Use the time of arrival technique to locate a spark	64
E	Lock-in Amplifiers	64
	Lock-in amplifiers allow you to see a tiny signal in the presence of substantial noise	64
F	TV remote control	64
	Detect and decode the infra-red control pulses sent by a TV remote	64
G	Dielectric Constant of Liquid Nitrogen	64
	Measure the dielectric constant of liquid nitrogen	64
H	Light-emitting diodes	64
	Use a light-emitting diode as a photodetector	64
I	Electric Motors	64
	Electric motors can be used in reverse as electric generators	64
J	Magnetic materials	65
	Measure magnetic properties of materials by incorporating them in an inductor.	65
K	Serial ports	65
	Decode the signals that come out of a computer terminal.	65
L	Build a Geiger Counter	65
	Build a Geiger Counter	65

M	Improve an electromagnetic can crusher	65
	A pulsed magnetic field can cause a coke-can to crush itself via eddy current	65
N	Solar Motor-driver	65
	Use Ultracapacitors in a circuit that extracts mechanical energy from the available sunlight	65
Appendices – Data Sheets		66

2022 Course schedule

Week of	Lab	Due
1/24	Circuits (1)	
1/31	Complex Imp. (2)	Circuits
2/07	BLM (3)	Complex Imp.
2/14	Hysteresis (4)	BLM
2/21	Hysteresis	—
2/28	OpAmps (5)	Hysteresis
3/07	Intro to Arduino (6)	OpAmps
3/14	Spring Vacation	
3/21	Digital to Analog Converters (7)	Intro to Arduino
3/28	Digital to Analog Converters (7)	
4/04	Diodes (8)	Digital to Analog Converters
4/11	Free Choice	
4/18	Free Choice	Diodes
4/25	Last week of lab	Free Choice
5/10	Last day to submit lab report (non Seniors)	

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 Commitment

There are four purposes for this course.

- To give practical examples of concepts learned in Phys333
- To give you practice thinking about sources of experimental errors.
- To let you experience some of the excitement (and confusion) of experimental physics.
- To encourage your creativity in the context of the complex and subtle world of measurement.
- 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 2.5 hours to get through and understand. The course grade is based on your accurate understanding of the labs and completion of the lab reports. 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 Honesty/Plagiarism

The Tech honor code is in effect in this class (as in all classes). More specifically, Lab reports using shared data or analysis, unless explicitly authorized and documented, will result in an automatic “F” for the report and a report to the Associate VP of Academic Affairs.

You can, of course, seek assistance in understanding from other students, the instructor, or online/library resources.

0.3 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. (Duct tape can be useful!)
- 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 disassemble, 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.

0.4 Laboratory Protocol

- The Laboratory hours are 2 PM to 4:30 PM. 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.
- Feel free to bring computing devices/smart phones to assist in data plotting/analysis or for web research related to your analysis.

0.5 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.

0.6 Lab Reports

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 L^AT_EX templates for a lab report on Canvas. I can give a short tutorial on L^AT_EX if 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:

0.7 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 in the report with A and B marked on it.

It is not unusual for raw data to be somewhat disorganized. For example, when measuring the current through a diode vs. applied voltage one may take a number of data points that are not interesting (because the diode has not yet turned on). 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. You may omit data that you later concluded is incorrect or uninteresting.¹

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 well-defined variables (described previously in discussion of tables).
4. **Answers to Numbered Questions** – For convenience in grading, please number your results/analysis with the numbers used 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

¹Sometimes incorrect data *is interesting* if it documents a malfunction or, at best, reveals some new physics or instrumental quirks. Feel free for extra credit to share “weird” results and your best explanation for their cause.

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. Derivations 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** – Because formal error analysis can be tedious and does not always contribute much to what you are learning, I generally do not require it. However some labs request it and I am also interested in your discussion of what part of the measurement or what piece of equipment is most likely to have contributed most to the error. If I do not request an error discussion or quantification, *it is unnecessary*. Even without formal error analysis, ALL measurements should be reported with an appropriate number of significant figures, as already stated in section 2.

0.8 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.

When I do request error quantification, measured quantities 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 and quantify experimental error.

0.8.1 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.

0.8.2 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 $1\ \Omega$ too high for all your resistance measurements (because of the resistance of the probe leads). Systematic errors cannot be reduced by averaging because all of the data is off in

the same direction (either too 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.

0.8.3 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 to what you compared your instruments to determine this inherent accuracy.²
 - 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, \dots, z . If the uncertainties $\delta x, \dots, \delta z$ are random, then the uncertainty in q is

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

- An alternate and sometimes easier error propagation technique than the method of partial derivatives just outlined is the method of *corner cases*. Given n -variables x_n that have values $x_n \pm \delta x$, you can calculate the final result q assuming all variables are $x_n + \delta x$ and again assuming all are $x_n - \delta x$. This tends to overestimate the error but is a quick way to get outer bounds.

²Our lab has voltage, resistance, inductance and capacitance standards available for your use.

0.9 Lab Grades

If you complete a lab and answer all the questions completely as discussed in section 0.6, you will get at least an “A-” for the lab. You can earn an “A” with exceptional clarity of presentation, insightful discussion of the “physics puzzler” questions, or other insights/connections that I did not think to ask about.

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-”.

Labs marked “n=2” are nominally two week labs and their grades count double.

Even if you lack confidence or facility at lab work, application of effort to this course should result in at least a grade in the “B” range.

Introductory discussion

We define basic terms in lab electricity

Ideal Components

Ideal Voltage Source A source that puts out the same voltage, (e.g. nine Volts) regardless of the circuit or load in which it participates.

Ideal Current Source A source that puts out the same current, regardless of its circuit.

Ideal Resistor Follows Ohm's law, regardless of voltage or current impressed.

These idealizations are useful, because though no real circuit completely match them, they do match them over certain ranges, and may usually be fairly accurately modeled as COMBINATIONS of ideal components.

Real Components

Battery or DC power supply A battery or power supply can generally be considered to be an ideal voltage source, V_B . It can be modeled in an almost completely realistic way as an ideal source V_B in series with an internal resistance, R_i .

Current source Using active components, there are many ways to design a near ideal current source. A passive approach to this is to have a very large ideal voltage in series with a large resistor. Then any load will not change the total load resistance, nor the circuit current.

Resistor Real resistors follow Ohm's law extraordinarily closely. However, they all have power ratings. Exceeding the power rating will cause the resistor to overheat and fail. Also, very high voltages can cause arcing, and failure. Real resistors may be designed for very high power or very high voltage, with an increase in size and cost.

More Vocabulary

Open circuit voltage The voltage of a battery with no load.

Short circuit current The current provided by a battery with its terminals shorted together ($I_{sc} = V_{oc}/R_i$).

Voltage divider A circuit consisting of two resistors in series with a battery. The voltage across the second resistor is always a defined fraction of the battery voltage.

Demonstration

A non-ideal battery is easy to demonstrate with a 9V battery, particularly a dead one. The battery is measured with a voltmeter. Then a human's fingers are put across the clips. The voltage will go down dramatically (if the battery is quite dead). One can record V_{oc} , V_h ("h" for human) and measure the resistance of the human and determine R_i . Along the way we see V_{oc} and R_i demonstrated, and also learn the formula for a voltage divider.

Multimeters

Analog Multimeters really only measured current that passed through them. However, by having a resistor placed between their + input and their current sensing element, they converted their current capability to a voltage measurement.

Today we use mostly digital multimeters, that in fact mostly measure voltage via an A/D circuit. However, they can measure current by having a resistor in parallel with the voltage sensor that joins the + and - inputs. Likewise, they can measure resistance by providing an ideal current source and measuring the voltage dropped across the resistor.

1 Circuits (n=1)

1.1 Background theory

1.1.1 Multimeters

A modern multimeter can measure Voltage, Current, Resistance and sometimes capacitance or other quantities. The electronics inside is fundamentally measuring voltage.

How then does it measure Resistance?

It supplies a small known current to the device under test and measures the voltage developed, then calculates the resistance. Thus, if you use it to measure an energized circuit with currents from a power supply or other sources flowing through it, the results will be misleading.

How does it measure current?

It puts an internal resistor in series with the circuit and measures the voltage developed across that resistor. *Note that this resistor becomes part of the circuit.*

1.1.2 Circuits

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

Kirchoff's famous laws for circuit analysis are stated in the caption of figure 1.

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 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. For a diode, $I = I_r(e^{eV/nk_B T} - 1)$, which as you can see is not Ohm's law at all!

1.2 Basic Formulae for DC Circuits

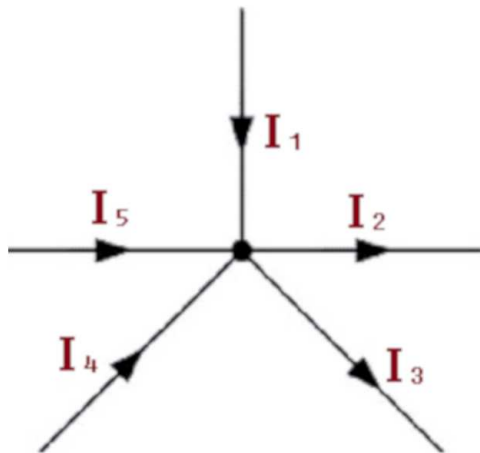
$$V = IR \tag{1}$$

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

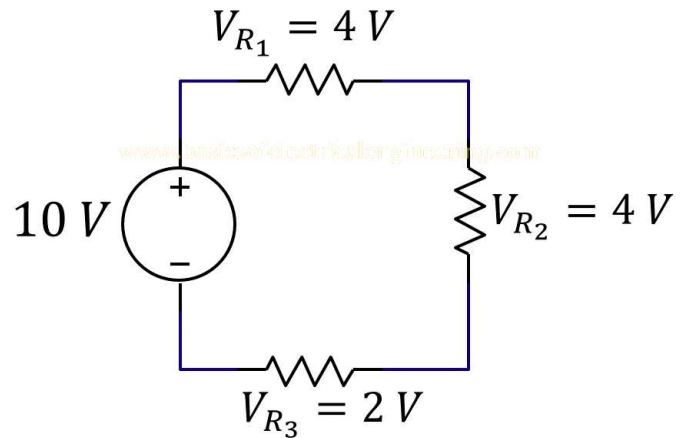
$$P = IV \tag{3}$$

$$R_{equivalent} = R_1 + R_2 + R_3 + \dots \tag{4}$$

$$1/R_{equivalent} = 1/R_1 + 1/R_2 + 1/R_3 + \dots \tag{5}$$



$$I_1 - I_2 - I_3 + I_4 + I_5 = 0$$



$$10\text{ V} = 4\text{ V} + 4\text{ V} + 2\text{ V}$$

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.

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

This lab should serve to remind you of things you may already know, and because it is relatively simple, you should be able to predict your results with three significant digits.

Use the power supply and several (nominally) identical resistors of value $R > 1\text{ k}\Omega$ to build and study circuits *i, ii, iii*.

- (1) Set the power supply to roughly six volts (Measure the actual value to 3 significant figures and record it). Before building circuit *i*, measure and record the resistor values you have selected (the three resistors will be slightly different even if nominally the same).
- (2) Now build circuit *i*, measure (and record) the voltage at point *A*, *B* and *C* (relative to point *D*).
- (3) Set the meter to its 10 Amp setting and measure and record the current at point *A*.³ Once you have verified that this works, switch to the *mA* and then the μA setting and record these values.
- (4) Measure and record the current at points *B*, *C*, and *D* using the 10 *A*, the *mA* and μA settings.

³IMPORTANT: A common beginner mistake can lead to currents in excess of an Ampere. If you obtain these large currents and then switch to the *mA* scale, you will immediately blow the fuse in your meter and will measure zero currents until you replace it.

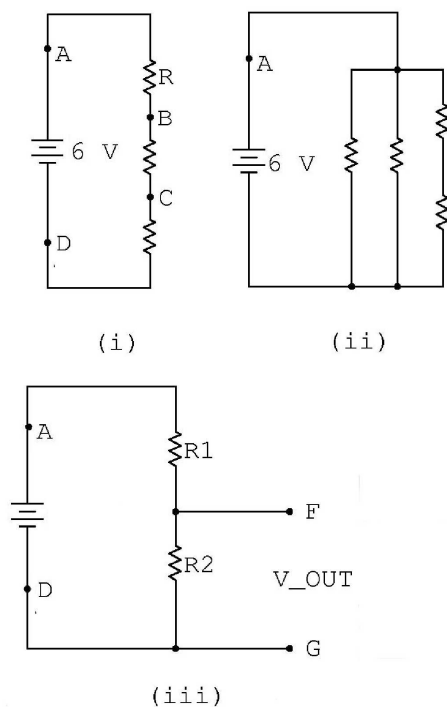


Figure 2: Circuit *i* is a simple series circuit. Circuit *ii* illustrates a combination of series and parallel circuits. Circuit *iii* is a very useful configuration called a “Voltage Divider”.

(5) Here are two hypotheses about how series circuits work.

Hypothesis A: Current gets divided as one proceeds through a series circuit Do your measurements support Hypothesis A? Explain.

Hypothesis B: Voltage gets divided as one proceeds through a series circuit Do your measurements support Hypothesis B? Explain.

(6) Having decided which hypothesis fits your measurements, predict the values of voltage and current at points *B*, *C*, and *D* based on your measurements of voltage and current at point *A* and the precise values R_1 , R_2 and R_3 you measured before assembling the circuit. Make a table which compares your measurements and your working theory.

(7) Build circuit *ii* and measure/record the current at point *A*. (It’s a good idea to remeasure/record the voltage on your power supply as they tend to drift at the third sig. fig.) Tabulate the values of the four resistors you are using and keep track of where they are in the circuit.

(8) Measure and record the current through the left branch, the middle branch, and the right branch of the circuit. (This requires some thought, you need to insert the meter into the correct circuit branch without disconnecting the other two branches.)

(9) Here are three hypotheses about how parallel circuits work.

Hypothesis A: Current follows the path of least resistance. So all the current flows through the smallest resistor and none through the others.

Hypothesis B: Current divides equally through each branch of the circuit

Hypothesis C: Current divides inversely proportional to the resistance of each branch

Explain which hypothesis your measurements support.

- (10) Once again, having selected a working theory you should be able to precisely compare your measurements of current through each branch to current through point *A* based on your measurements of R_1, R_2, R_3, R_4 . Make a table.
- (11) There is a useful trick in circuit analysis called "Thevenin equivalence". Any combination of resistors may be replaced by a single "equivalent" resistor such that the total current through the circuit (and power consumed) is the same as it was for the several actual resistors used. What is the Thevenin equivalent resistance for circuit *i*? For circuit *ii*?
- (12) – **EXTRA CREDIT** Circuit *iii* is called a "Voltage Divider". This is because $V_{OUT} = V_{FG}$ is always a fixed fraction of $V_{IN} = V_{AD}$. 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 significant digits based on the value of resistors you do find. Verify your prediction with three different values of V_{IN} (that is, not just 6 Volts).

Using resistance to measure temperature of a light-bulb

- (13) Get an Ecko #46 lightbulb out of the box and measure and record the resistance through it with your Ohmmeter.
- (14) Remove your meter and instead connect the lightbulb to the 6 V power supply. Measure the current through the bulb and the Voltage of the supply. Use this to calculate the resistance of the light-bulb.
- (15) The following formula allows you to calculate the resistance of tungsten wire as a function of temperature. Assuming that room temperature (T_{ref}) is 300 K, calculate the temperature of the light bulb filament in step 14.

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

- (16) The series and parallel circuit laws (eqn 4-5) come directly from Ohm's law and Kirchoff's laws. Derive equations 4 and 5 from Ohm's law, Kirchoff's laws and the definition of Thevenin equivalent resistance.

1.4 Physics Puzzler [Answer two of these questions]

Lightbulbs are resistors Discuss the truth/falsehood of this statement based on your measurements

Which is the more accurate measurement? In 3, 4, 5, and 6 you explicitly compared the measured currents with the calculated currents based on your resistor measurements. Assume your resistor measurements are "correct". Which if the current measurements is most accurate? WHY? Can you think of additional tests you might do to help figure this out?

Black body radiation The Planck black-body equation can be used to estimate the temperature of a body (e.g. a light-bulb) that appears to glow "white". Get the equation and see if you can use it to calculate the temperature of the filament just based on its color. Document your assumptions.

1.5 For Graduate Students

(18) Answer ALL the physics puzzles.

(19) Figure out the equivalent series resistance (ESR) for each of the three current scales on the device. Explain how you did it. Explain how it impacts the accuracy of your measurements and try to remove the systematic error from the measurements.

Equipment

- HP 6235A Triple output Power Supply
- Proto-board or Spring Board
- Your Personal Multimeter (Amprobe 35XP or AM-560)
- Resistors

2 Complex Impedance (n=1)

2.1 Motivation for the experiment

Complex Impedance is a wonderful “trick” that allows the analysis of complex AC circuit consisting of inductors, capacitors and resistors almost as easily as a DC circuit that contains only resistors. 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 Prelab

- (P1) If frequency $f = 10 \text{ kHz}$, what is angular frequency ω ?
- (P2) Given a circuit driven at $f = 10 \text{ kHz}$ with R and C in series $R = 10 \text{ k}\Omega$ and $C = 20 \text{ nF}$, express the total effective impedance Z_{eff} in cartesian form (the form $x + iy$).
- (P3) Given a circuit with previous values of f , R , C in series with an inductor $L = 5 \text{ }\mu\text{H}$, express Z_{eff} in cartesian form.
- (P4) Express the complex impedance from problem P3 in polar form ($Z = Z_0 e^{i\phi}$). [That means calculate Z_0 and ϕ for given conditions.]
- (P5) Given a R, L, C circuit driven with a 10 V sinewave that passes a maximum of one milliamp of current, what is Z_0 ?

2.3 Background: Introduction to Complex Impedance

Voltages in a series circuit add. Engineers call this “Kirchoff’s voltage law” (KVL). KVL 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.

$$R_{eff} = R_1 + R_2 + R_3 + \dots \quad (1)$$

$$1/R_{eff} = 1/R_1 + 1/R_2 + 1/R_3 + \dots \quad (2)$$

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

$$V_{source} = IR_{eff} \quad (3)$$

We can generalize the concept of effective (or Thevenin equivalent) resistance beyond purely resistive circuits to include circuits with resistors, capacitors and inductors. When applied to circuits with R’s, L’s and C’s, effective resistance (R_{eff}) becomes *effective impedance* (Z_{eff}) and we have the following formulae.

$$Z_{eff} = Z_1 + Z_2 + Z_3 + \dots \quad (4)$$

$$1/Z_{eff} = 1/Z_1 + 1/Z_2 + 1/Z_3 + \dots \quad (5)$$

$$V_{source} = IZ_{eff} \quad (6)$$

By analogy, you can see that these formulae apply to series and parallel combinations of R's, L's and C's.

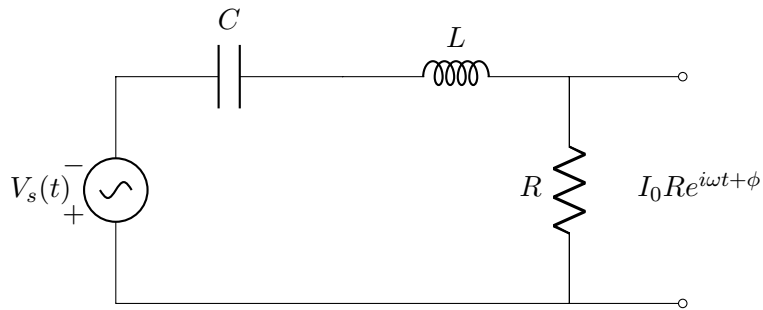
2.4 Requirements to use Complex Impedance

Here are the requirements to use complex effective impedance.

- The circuit must be driven by a sine or cosine voltage.
- The impedance must be manipulated as a complex number.
- $Z_R = R$, i.e., the impedance of a resistor is just its resistance.
- $Z_L = i\omega L$, i.e., the impedance of an inductor is proportional the angular frequency of the source, and is purely imaginary.
- $Z_C = \frac{1}{i\omega C} = \frac{-i}{\omega C}$, i.e., the impedance of a capacitor is inversely proportional to the angular frequency of the source and to the capacitance.

2.5 Why does it work?

The circuit below is what you will build in this experiment. The complex impedance may be used for ANY linear circuit, including ones with several parallel branches, but we will prove it for this particular series circuit for concreteness. The differential equation for this circuit, expressed in



terms of the charge on the capacitor is:

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

If we require that $V_s(t) = V_0 \cos(\omega t)$ then we expect $Q(t) = Q_0 \cos(\omega t + \phi) + Q_{transient}$. Why do we expect this? Driven oscillators must respond at the driving frequency, but they do not have to respond in phase. Furthermore $Q_{transient} \rightarrow 0$ over several cycles, and will henceforth be ignored⁴. Because of this property, we can rewrite

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

⁴I am assuming that you have solved enough similar equations to understand that this really is the characteristic of the solution.

$$Q(t) = \text{Real}[Q_0 e^{i\omega t + \phi}] \quad (9)$$

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.⁵

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

By assuming sinusoidal variation, a derivative becomes as simple as multiplying by $i\omega$. Furthermore, we can write

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

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

$$\frac{dQ}{dt} = I_0 e^{i\omega t + \phi} \quad (12)$$

$$\frac{d^2Q}{dt^2} = I_0 i\omega e^{i\omega t + \phi} \quad (13)$$

$$Q = \frac{I_0}{i\omega} e^{i\omega t + \phi} \quad (14)$$

Plugging the above three expressions into equation 7, we obtain

$$V_0 e^{i\omega t} = Li\omega I_0 e^{i\omega t + \phi} + RI_0 e^{i\omega t + \phi} + \frac{I_0}{i\omega C} e^{i\omega t + \phi} \quad (15)$$

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

$$V_0 = I_0 e^{i\phi} \left[Li\omega + R + \frac{1}{i\omega C} \right] \quad (16)$$

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

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

Voila! We have shown that Z_{eff} is just the sum of the individual Z 's provided we define complex impedance as in the list ending section 2.4 above.

2.6 Overall Approach for the experiment

You will build the circuit shown in figure 2 below consisting of a function generator, connected to a capacitor an inductor and a resistor. All measurements will be made by connecting appropriate cables to the circuit and an oscilloscope.

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:

$$V = IZ \quad (18)$$

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:

⁵From here on out I will no longer show the "Real" operator. It is assumed.

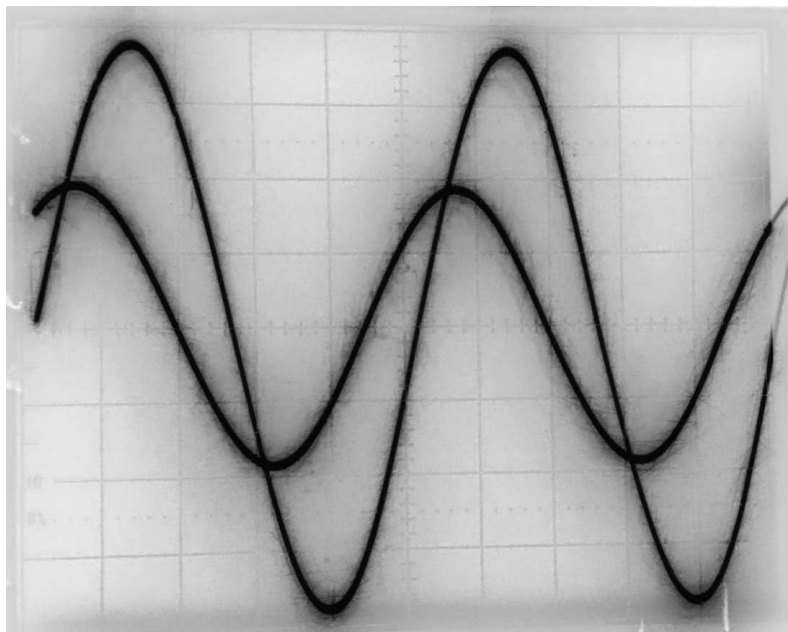


Figure 1: The larger signal is V_{FG} . The smaller signal shifted to the left is V_R .

$$V_{FG} = I_R Z_{eff} \quad (19)$$

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} . The procedure below guides you to that in more detail.

2.7 Make Measurements for RLC Circuit

- (1) **Measure components R and C** – Select a 400Ω resistor and a 22 nF capacitor. Use your multimeter to measure the actual resistance and capacitances that you picked.
- (2) **Measure component L** – Select a $L=4 \text{ mH}$ inductor. Use the HP4261 inductance meter in the lab. (It should be set to 1 V , Auto , 1 kHz and Series). The inductor *also* has some resistance, which you should measure with your multimeter. This resistance should be considered to be a built-in series resistance for the purposes of your analysis.
- (3) **Build RLC circuit** – Build circuit according to figure 2. Use a T-connector and two BNC cables to hook the function generator both to channel 1 of the oscilloscope and to V_{FG} on the circuit. Note that the black alligator clip must be connected to the circuit GND . Set the function generator to produce roughly 2 V amplitude at $f=10 \text{ kHz}$. Take a third BNC cable and connect the alligator clips to measure V_R . Connect V_R to channel 2 of the 'scope. If you did it correctly your 'scope should look something like figure 1 for the 'scope on the 500 mV/division setting.

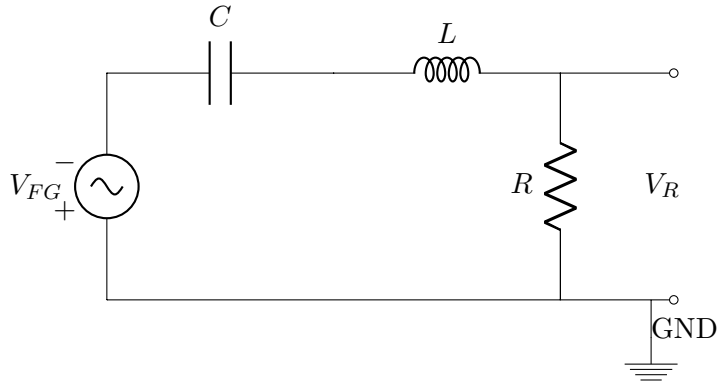


Figure 2: Channel 1 of 'scope should measure V_{FG} . Channel 2 should measure V_R .

- (4) **Record amplitude and error** – Read the actual amplitude of the function generator off the oscilloscope and record it (The oscilloscopes have voltage cursors). Estimate reading error in Volts (One way to do this is to measure it 5 times while covering the cursor readout with a sticky note).
- (5) **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 .
- (6) **Record amplitude and time shift of V_R** – Figure 1 shows that V_R hits its first peak *before* V_{FG} . This is considered a positive time shift. Record the amplitude of V_R and the time-shift Δt . (The oscilloscopes also have time cursors.) Estimate the error in amplitude in Volts and error in Δt in seconds. Calculate the phase (ϕ , in degrees) from the time delay Δt . (You know how to do this ... think about it.)
- (7) **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.
- (8) **Repeat at 25 kHz** Change the frequency to $f = 25\text{ kHz}$ and repeat steps 4–7. Watch the 'scope as you change the frequency.
- (9) **Measure the resonance frequency and amplitude** Hopefully you noticed in step 8 that the phase shift went from positive to negative as you increased the frequency. Find as closely as possible the frequency at which the phase shift is zero. Measure V_R at this point as well.

2.8 Compare theory and experiment

- (10) **Calculate Z_{eff}** – You have measured R , L , and C independently. Combine them properly to come up with Z_{eff} in cartesian form at 10 kHz and 25 kHz.
- (11) **Compare theory and experiment** – Convert Z_{eff} from step 10 to polar form for your theoretical values. In steps 4–8 you determined Z_0 and ϕ experimentally. Make a table comparing all these values.

2.9 Physics Puzzler [Answer any two of these questions]

Explain the sign problem – At 10 kHz the phase shift is positive. Shouldn't the phase shift of a capacitance dominated circuit be negative (per section 2.4)? Explain what is going on here.

Predicting resonance frequency – Determine what the resonance frequency should have been based on the measured values of your components. Show that the formula for complex impedance gives this frequency directly as the point of zero phase shift

Predicting amplitude at resonance – You might think V_R at resonance should have been equal to V_{FG} . Why wasn't it? Can you determine what it should have been and compare it to what you measured.

Properly propagating errors – You may assume that your component measurements were good to one percent, which makes them much better than your oscilloscope measurements. Assuming all your errors were with the oscilloscope revisit the table from step 11 and put error bounds on your experimental measurements. I recommend you use the “corner” method described in the error propagation section of the introduction, but feel free to use the partial derivative method.

2.10 For Graduate Students

(**12 – 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.

(**13 – Filters Experiment**) Build this filter and characterize it over the 10.0 Hz to 1.0 MHz frequency range ⁶. Overlay the theoretical and experimental curves.

2.11 Equipment

- Oscilloscope
- Function generator
- Multimeter
- $C=0.022\mu\text{F}$ Capacitor
- $R=400\ \Omega$ Resistor
- $L=4.7\ \text{mH}$ Inductor

2.12 Refresher on Complex Arithmetic

Recall that for *any* complex number Z :

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

where $Z_0 = \sqrt{x^2 + y^2}$ and $\phi = \text{atan}(y/x)$. 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 $Z^* = \frac{1}{a-ib}$

⁶You might want to refer to the write-up entitled “Low-Pass Filters” for guidance.

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

3.1 Introduction

In this laboratory exercise you will

- reinforce your understanding of complex impedance,
- learn how to measure mutual and self inductance,
- review how to calculate mutual and self inductance,
- learn how to measure the amplitude of an oscillating magnetic field, and
- demonstrate how a transformer works.

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

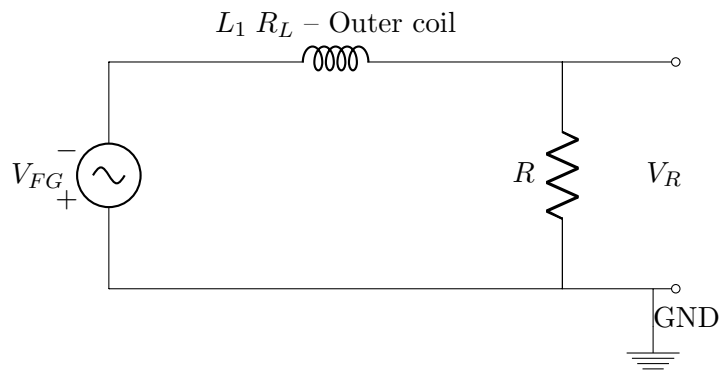


Figure 1: Circuit for measuring self-inductance

3.2 Self Inductance

In the last lab, we used the measured R , L , and C values to predict what experimental currents and phase shifts ought to be. In this lab, we will build an LR series circuit (see figure 1), then calculate the other direction and use those same currents/phase shifts to calculate L_1 , R_L , and R without the need to use separate inductance or resistance meters.⁷

- (1) **Choose components** – Look up the nominal inductance L_1 of the large coil.⁸ Choose a resistor with a comparable impedance to the coil at $f = 800 \text{ Hz}$. This will give the most accurate measurement. State what resistance you chose, then measure (with your multimeter) and record the resistance (R) of the resistor and the inductor (R_L).
- (2) **Record amplitude** – Record V_{FG} as measured on channel 1 of oscilloscope.
- (3) **Record period, frequency f , and ω** –

⁷Note: The setup and the first four measurements below are nearly identical to the Complex Impedance lab. Thus, some explanatory detail is omitted.

⁸The coil spec sheet is in the appendix at end of this manual.

- (4) Record amplitude, time delay, and phase of resistor voltage (V_R)– Give phase in degrees.
- (5) Calculate the magnitude $|Z_{eff}|$ – From your measurements calculate the amplitude of the current through the LR circuit. Using $|V_{FG}| = |I_R| |Z_{eff}|$, what is the magnitude of Z_{eff} ?
- (6) Write Z_{eff} in polar form –
- (7) Write Z_{eff} 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) Calculate effect of iron on inductance – Insert an iron rod fully into the coil. Repeat steps 2–8 and arrive at the inductance of the coil with the iron rod in it.
- (10) Calculate L_1 from geometry – Using the theory you learned in Physics 333, derive an expression for the self-inductance of the outer coil. Measure/look-up relevant quantities about the outer coil (e.g. length, area, windings) and plug these in to obtain a theoretical estimate of the self-inductance of the coil
- (11) Physics Puzzler (required question) The results you get from step 8 and step 10 probably do not agree very well. Discuss which one is more likely to be correct and also what you could do to get them to agree better. You probably want to work on this when you are still in the lab to see if you can get closer agreement between these quantities.

3.3 Magnetic Field Amplitude and Mutual Inductance

- (12) Measure induced voltage on a search coil Insert a search coil into the large coil and measure the waveform with the oscilloscope at $f = 800 \text{ Hz}$. You need V_R and V_2 per figure 2. (You already have the V_R measurement.)

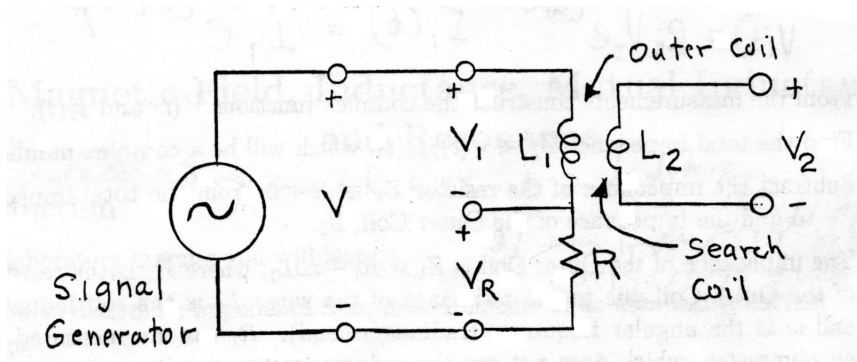


Figure 2: Circuit with Outer Coil and inner Search Coil. The Search Coil can be used to find the magnetic field from the Outer Coil. Also, there is a mutual inductance between the two coils. As a unit, the two coils form a transformer.

3.4 Transformer

The two coils together form 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). An ideal transformer is defined by the transformer equation (equation 22). Remove the resistor from the primary circuit so that the function generator is connected directly to the primary winding. Then do the following:

- (13) **Find the frequency range where the transformer equation will apply** – You should have noted that the transformer equation has no frequency dependence, but it is not valid at very low or very high frequencies. Find and note the range of frequencies for which V_2 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*.
- (14) **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 voltages V_1 and V_2 .

3.5 Postlab: Calculations and analysis

- (15) **Find an expression for 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 . The derivation should include a sketch of the paths of your line integrals. The quantities I_1 , N_1 , and ℓ_1 have subscript 1 to indicate that they are associated with the Outer Coil (transformer primary).
- (16) **Find a numerical value for B** – In step 4 and/or 12 you measured the current amplitude. What peak magnetic field does this correspond to?
- (17) **An alternate way to calculate B** – The search coil voltage V_2 can also be used to determine B . By Faraday's law, the search coil voltage is proportional to dB/dt , but it is easy to calculate B from dB/dt for a sinusoidal voltage. Measure what you need about the search coil and arrive at an alternative expression for B . Compare the numerical result to question 16.
- (18) **Experimental mutual inductance between the coils** – The definition of mutual inductance is $\Phi_2 = M_{12}I_1$. You know I_1 from measurements and B_2 , Φ_2 from steps 16/17. Calculate M_{12} .
- (19) **Theoretical mutual inductance** – Derive the following approximate equation for the mutual inductance between the Outer Coil and the Search Coil

$$M_{12} = \mu_0 N_1 N_2 A_2 / \ell_1. \quad (21)$$

- (20) **Plug and chug** – Compare your results from 18 and 19.
- (21) **Derive the transformer equation** – Derive the following expression for the ratio of voltages of a transformer:

$$\frac{V_2}{V_1} = \frac{N_2 A_2}{N_1 A_1}, \quad (22)$$

Compare your measured ratio (from step 14) with that predicted from the above expression.

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 – (you choose) Ω resistor
- Oscilloscope
- Function generator

4 Hysteresis (n=2)

4.1 Prelab

Note: If you read through the Introduction to this lab, you will get all the background you need to answer the questions below. (When added to what you learned in 333 and the earlier labs this term.)

- (P1) Given an air-core inductor of length 10 cm and diameter 1 cm with 1000 windings carrying a current of 2 Amperes calculate \mathbf{B} and \mathbf{H} inside the inductor.
- (P2) You are given an unknown paramagnetic material with $\chi_m=10000$. What is μ_r ?
- (P3) Imagine the air-core is replaced by the previously described paramagnetic material. What are \mathbf{H} and \mathbf{B} now? What is \mathbf{M} ?

4.2 Introduction

4.2.1 Hysteresis defined

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. [*hysteresis* comes from the Greek word for *lagging*, but it is probably a better mnemonic to think of it as “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 auxiliary magnetic field, \mathbf{H} . As \mathbf{H} increases, \mathbf{M} can be said to lag behind. This is clearer once when looks at a *hysteresis loop* (figure 4). In this experiment, we explore hysteresis by measuring both the magnetic field \mathbf{B} and the auxiliary field \mathbf{H} in an iron toroid. The variable \mathbf{M} can be deduced from \mathbf{H} and \mathbf{B} .

4.2.2 \mathbf{B} , \mathbf{H} and \mathbf{M}

It is important to define terms since the scientific literature is INCONSISTENT.⁹ In this lab \mathbf{B} is called “magnetic field”, though some literature calls it “magnetic flux density” or “magnetic induction”. \mathbf{H} will be referred to as “auxiliary field”, though some sources call it “magnetic intensity” and worse, others call it “magnetic field”. Recall that these quantities are useful because \mathbf{H} is created by a true external current (which you control in the experiment), while \mathbf{B} is the total field, but it includes the *bound currents* in the material which you have no direct control over as an experimentalist.

4.2.3 Ferromagnetic theory reviewed

The auxiliary field \mathbf{H} is *defined* by the equation

$$\mathbf{H} \equiv \frac{1}{\mu_0} \mathbf{B} - \mathbf{M} , \quad (23)$$

where \mathbf{B} is the magnetic field, 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

⁹Fortunately Maxwell’s equations ARE consistent. You will never see \mathbf{B} and \mathbf{H} used incorrectly in the math, but the English descriptions vary.

equation

$$\mathbf{M} = \lim_{\Delta V \rightarrow 0} \frac{1}{\Delta V} \sum_i \mathbf{m}_i . \quad (24)$$

\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

$$\mathbf{M} = \chi_m \mathbf{H} , \quad (25)$$

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

$$\mathbf{H} = \frac{1}{\mu_0} \mathbf{B} - \chi_m \mathbf{H} \quad (26)$$

$$\text{so that } \mu_0 \mathbf{H} = \mathbf{B} - \mu_0 \chi_m \mathbf{H} \quad (27)$$

$$\text{and } \mathbf{B} = \mu_0 (1 + \chi_m) \mathbf{H} . \quad (28)$$

By comparing this last equation with the free space equation,

$$\mathbf{B} = \mu_0 \mathbf{H} , \quad (29)$$

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

$$\mu = \mu_0 (1 + \chi_m) . \quad (30)$$

The relative permeability K_m is defined as

$$K_m = \frac{\mu}{\mu_0} \quad (31)$$

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

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

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

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

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

and

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

This behavior can be explained by examining the microscopic structure of a ferromagnetic material. The material actually is polycrystalline, 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 \mathbf{m} of the individual 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 field \mathbf{H} , 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.

If a weak external magnetic field is applied to a specimen 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} .

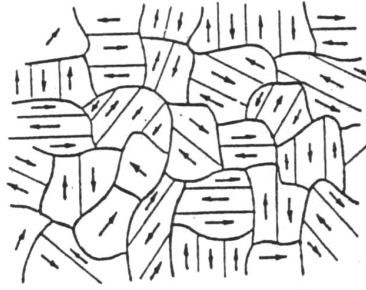


Figure 1: Magnetic domains in a ferromagnetic material when the applied field H is small.

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,

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

and

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

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*.

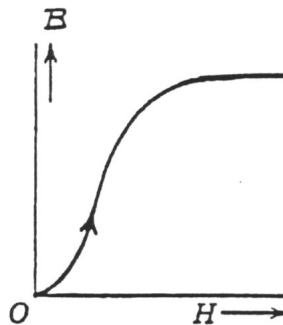


Figure 2: The normal magnetization curve of B versus H .

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

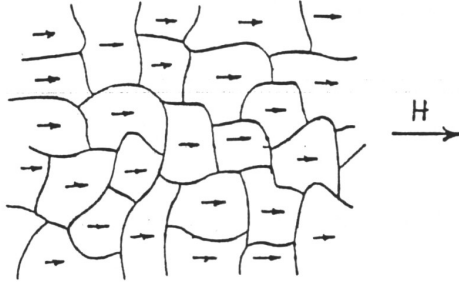


Figure 3: Ferromagnetic domains when the applied H is large.

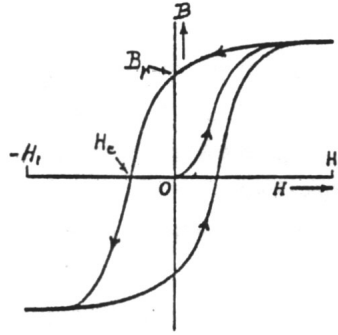


Figure 4: Magnetic hysteresis loop.

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.

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 *remanent magnetization* or *remanence*. Only when H reaches the value $-H_c$ does B become zero. This value H_c is called the *coercive field* or simply the *coercivity* of the material. 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):

$$W = \int_{\text{vol}} \oint_{\text{cycle}} H dB \, d\tau \quad . \quad (38)$$

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

4.3 Applying Maxwell’s Equations

Using the apparatus diagrammed in Figure 5, we can observe the hysteresis loop 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.

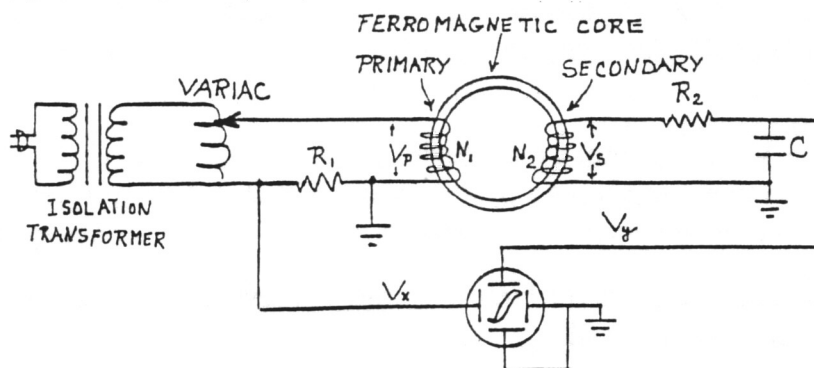


Figure 5: Schematic of apparatus to generate and display hysteresis loops.

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),

$$\int \mathbf{E} \cdot d\ell = -\frac{\partial}{\partial t} \int \mathbf{B} \cdot d\mathbf{A} \quad , \quad (39)$$

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

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

Integrating gives

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

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

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

Hence the potential difference across C at any instant is

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

so that the vertical deflection is proportional to B :

$$B = k_B V_y \quad . \quad (44)$$

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

$$\int \mathbf{H} \cdot d\ell = \int \mathbf{J} \cdot d\mathbf{A} + \frac{\partial}{\partial t} \int \mathbf{D} \cdot d\mathbf{A} \quad , \quad (45)$$

and yields

$$H = k_H V_x \quad (46)$$

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

4.4 Laboratory Measurements

- (1) **Set up apparatus** – Assemble the apparatus according to figure 5. The oscilloscope should be set to xy mode and display V_x on the x axis and V_y on the y axis. Be *sure* to include the isolation transformer. Use a 10Ω , 5W resistor for R_1 , a $500k\Omega$, 1/4W resistor for R_2 , and a $0.1\ \mu\text{F}$ capacitor for C . As usual, log their values in your notes.
- (2) **Measure hysteresis loops** – 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 onto clear acetate film, continuing until the material reaches saturation. You may be tempted to just take a digital photo of the curves, but you will need all the curves on the same piece of film for your analysis, so you are better off with the old technology of Sharpie® markers tracing on acetate. I recommend varying the Sharpie color so you can better distinguish adjacent curves. These measurements must be quantitative so you should include a scale marking for voltage. Try to set the 'scope channels so that the largest loop fills that display.
- (3) **Measure temperature rise** – Hysteresis loops dissipate energy, so the toroid will slowly warm. The key phrase is *slowly*. The maximum temperature rise you will see is a few degrees over 20 minutes. It requires some finesse to see this warming and to distinguish it from room temperature fluctuations. I recommend leaving the variac turned off and logging temperature every 30 seconds for 10 minutes to establish a baseline drift. Then crank the variac up to show the largest hysteresis loop and track progress for another 20 minutes. Hopefully your temperature vs. time plot will allow you to estimate a temperature rise rate.¹⁰

4.5 Calculations and Analysis

This is the single most difficult analysis of the term. I encourage you to work on it between the first and second lab period so that you can ask questions on your return.

- (4) **Analyze Transformer Secondary (derive k_B)** – Derive equation (44) in which the constant k_B is replaced by an expression containing other constants having to do with your experiment. This derivation is almost done for you in section 4.3, but the expression for k_B is never explicitly stated. State it. ALSO, for your derivation to be complete, it should include a large figure that shows the path for the line integral on the left side of equation 39 and the integration area implied by the right side of 39. Your figure should look as much as possible like the toroid that we are measuring.
- (5) **Get a numerical value for k_B** – Given your expression from above, plug in relevant constants to arrive at a numerical value for k_B specific to your apparatus. What are the units of k_B ?
- (6) **Analyze Transformer Primary (derive k_H)** – The derivation of k_B was a bit tricky, which is why I largely did it for you. The derivation of an expression for k_H is easier, but you have to do it yourself. Start with Ampere's Law (equation 45) and

¹⁰Some of the setups will not show a temperature rise. Report what you find even if it is a null result.

arrive at equation 46 where k_H is, as before, replaced with variables related to your apparatus. Ampere's law again has a line integral on the left and an area on the right. Complete your derivation by drawing the path that is integrated over as well as the area.

- (7) **Get a numerical value for k_H** – Plug in relevant constants and come up with a numerical value for k_H specific to your apparatus. What are the units for k_H ?
- (8) **Warburg's Law** – Choose one of your largest hysteresis loops (the one for which you took temperature data in step 3) 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. There are several pieces of cleverness here. First, what exactly does equation 38 mean? How do you do an integral when you have a graph, not a function? Do the units come out right? Finally, does your theory match experiment? (If your temperature measurements gave a null result, figure out what the error bars are ... what is the maximum temperature change it could have been?)
- (9) **Magnetization curve** – Plot the normal magnetization curve using the end points of the hysteresis loops on your acetate
- (10) **Saturation Magnetization and Coercivity** – Your magnetization curve gives you the saturation magnetization of iron and your B-H curves give you the Coercivity. Come up with numerical values for these.
- (11) **Relative permeability** – From the normal magnetization curve (B vs. H), plot the relative permeability μ/μ_0 of the material as a function of H .
- (12) **Physics Puzzler 1** – These are really applied physics – but then there are many industries based on magnetic materials. First, can you think of any applications wherein Warburg's law would matter? Why would it matter?
- (13) **Physics Puzzler 2** – Different materials have different coercivities. Some are much higher than others. Can you think of applications for low and high coercivity materials? Feel free to Google and give a couple sentences about each.

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 k Ω)
- Capacitor C (0.1 μ F)
- 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 $IN_+ - IN_-$ between its ‘+’ and ‘-’ inputs (see Figure 1). The output voltage is

$$OUT = A_{OL}(IN_+ - IN_-) , \quad (47)$$

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 $10\text{ M}\Omega$ for operational amplifiers which use bipolar junction transistors (BJT) amplifiers, and $10^{10}\ \Omega$ 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 $G \ll A_{OL}$, 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).

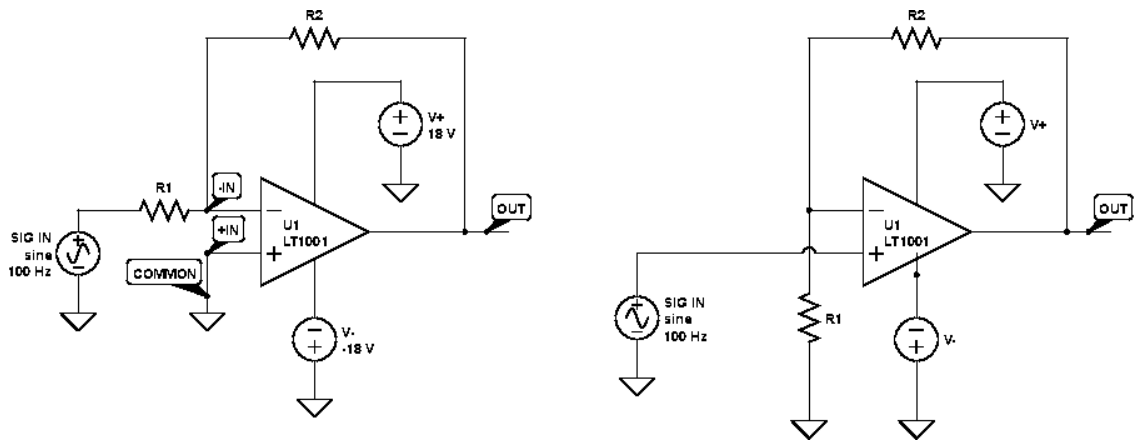


Figure 1: Inverting and non-inverting configurations.

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.

This lab calls for some sketching. Sketching by hand is still an important skill for a scientist. Where told to sketch, please do not use your cell-phone camera. Colored pencils/pens and 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 $1000 \Omega \leq R_1 \leq 100 \text{ k}\Omega$ 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”) $SIG\ IN$ and OUT . In Figure 1, $V_{PS} = \pm 18\text{ V}$. On your function generator, set the amplitude of $SIG\ IN$ to 1.5 V and the frequency to approximately $f = 100\text{ Hz}$.

- (1) **Determine approximate gain (G)** Apply sine wave and triangle waves at the inputs ($SIG\ IN$) 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} to $\pm 11\text{ V}$. 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 $V_{PS} = \pm 13\text{ V}$** 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.¹¹ Explain how your results fit the properties in the data sheet.

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 the square wave looks like a triangle wave.

- (6) **Compare the input to the output waveform .** Note the frequency at which the square wave looks like a triangle wave. Sketch (or photograph is OK here) the 'scope showing both the input square wave and the output triangle wave on the same display. Would you say that they are in phase? Explain.
- (7) **What's a slew rate?** Based on your observations, how would you define a slew rate? Look up the value of the slew rate in the data sheet.
- (8) **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).

¹¹Data sheets are in Appendix to this lab manual

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, therefore 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 $1/\sqrt{2}$. Therefore, 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 7.07.

One of the reasons you learned about slew-rate is, for larger amplitude 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 $SIG\ IN = 5\text{--}20\ mV_{pp}$.

- (9) **Measure the bandwidth of your op-amp** Once you have set $SIG\ IN$ properly, increase the frequency to measure the bandwidth using a sinewave.
- (10) **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.
- (11) **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 voltmeters.

- (12) **Precisely measure DC gain of Inverting Op-Amp** – Hook up the op-amp input ($SIG\ IN$) to the 6 V output of your power supply and vary ($SIG\ IN$) and measure OUT . Use two multimeters to get measurements of $SIG\ IN$ and OUT to three significant figures. Make a table of your results for $SIG\ IN$ and OUT and calculate the precise op-amp gain.
- (13) **Precisely measure DC gain of Non-inverting Op-Amp** – 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.
- (14) **Test your measurements against a hypothesis** – 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 a non-inverting amplifier is $G = R_2/R_1$.”

Based on the precision of the measurements you made, is the OP-AMP GAIN HYPOTHESIS correct? Discuss briefly.

5.9 Analysis

- (15) **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.
- (16) **Compare your new analysis with the measured gains from 13 and 14.**

5.10 For Graduate Students

- (17) Find out what the output impedance of an op-amp means.
- (18) Determine the output impedance of a particular op-amp circuit for two very different feedback resistors and test the theory that the output impedance of the OpAmp does not depend on the feedback resistor.

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
- HP6235A ± 18 volt power supply
- Resistors: R and 10R ($R > 2000\Omega$)
- Ohmmeter

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 Inventor's Guide. The SparkFun Inventor's 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.

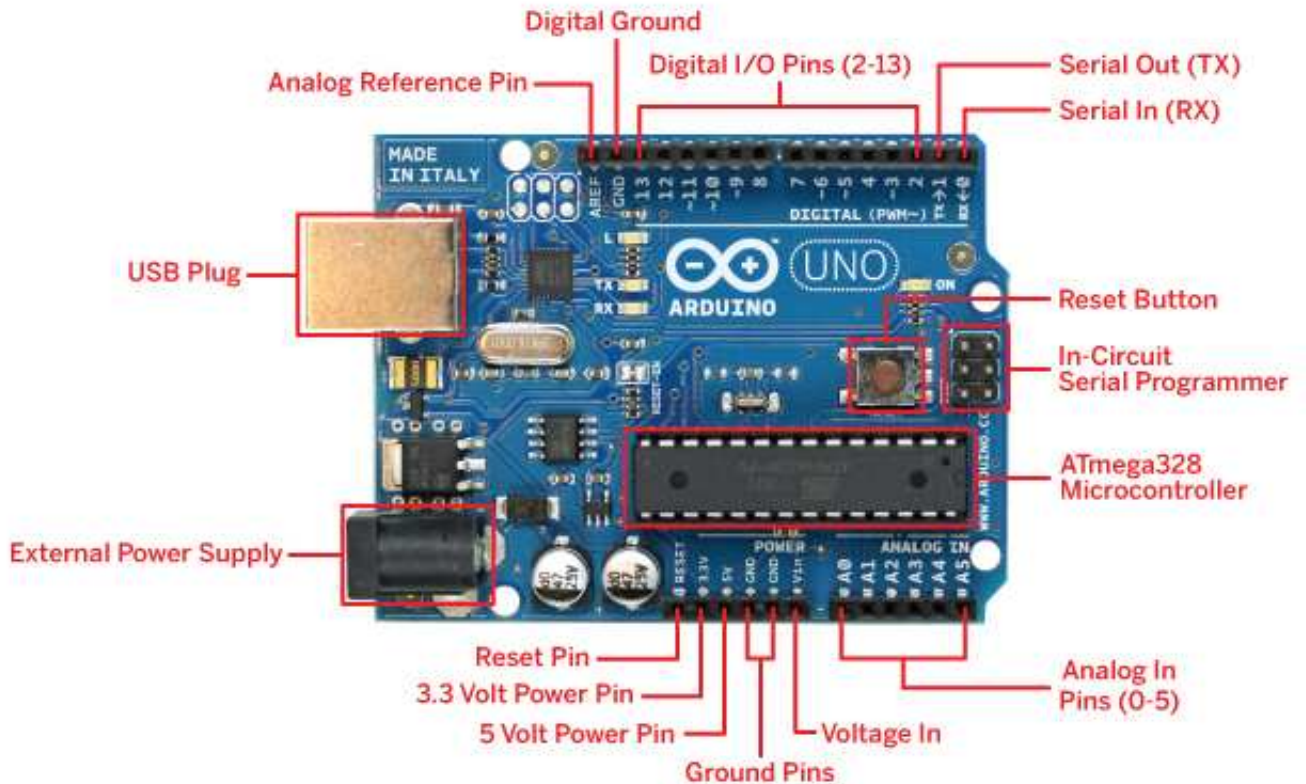


Figure 1: Arduino UNO microcontroller: Note the three LEDs to the left of the Arduino logo, they are labeled "TX", "RX", and "L".

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)	High (5 V)
	Low (0 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 Arduino’s 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 oscilloscope, 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 Arduino's 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.

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

- (10) **Discover why a *floating* input is problematic:** Connect the free end of the jumper wire to the Arduino's 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

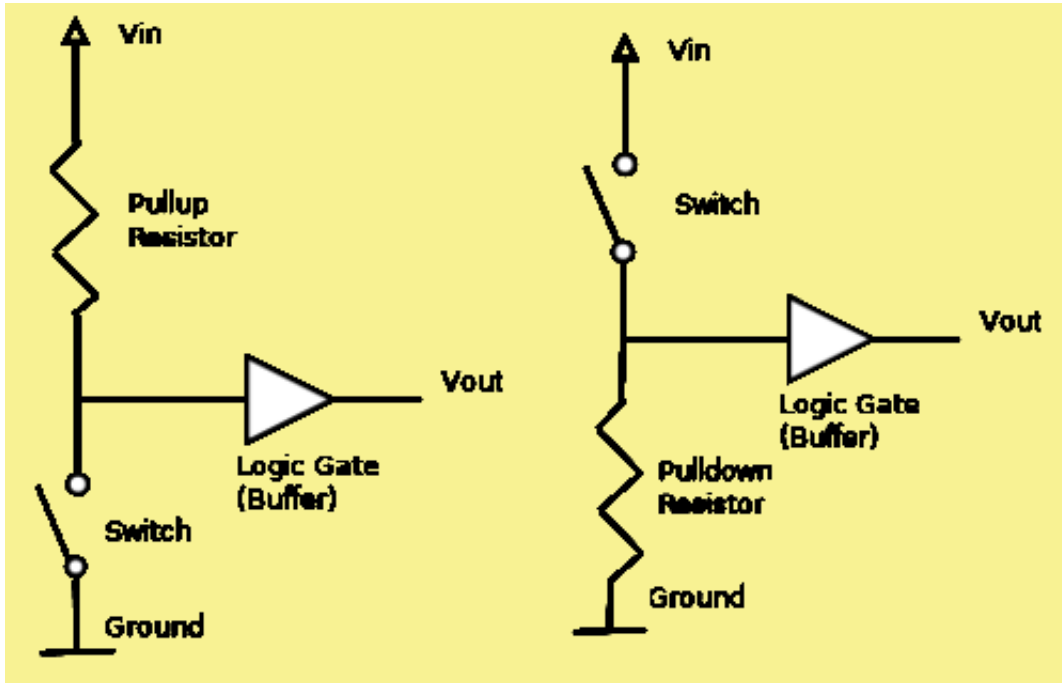


Figure 2: Pull-up resistor (left) and Pull-down (right).

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 $10\text{ k}\Omega$, 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 $12\text{ k}\Omega$ 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 step 13 above, 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 Arduino’s “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 knob?
- (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 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 USB-toTTL

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 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

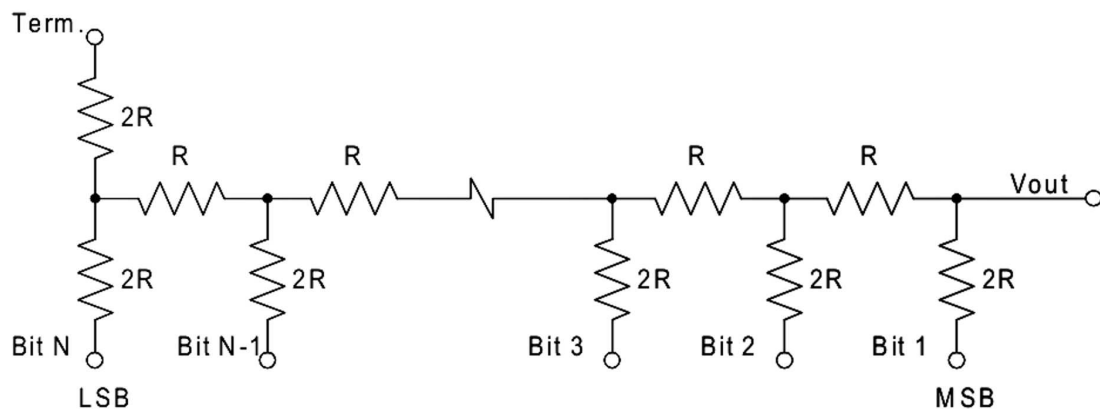


Figure 1: An R-2R, ladder network for N-bits.

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 significant 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 multi-meter 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 40–50 k Ω resistor as R 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 R in figure 1 to around 250 k Ω . 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 exact copy of the top half of the input waveform?

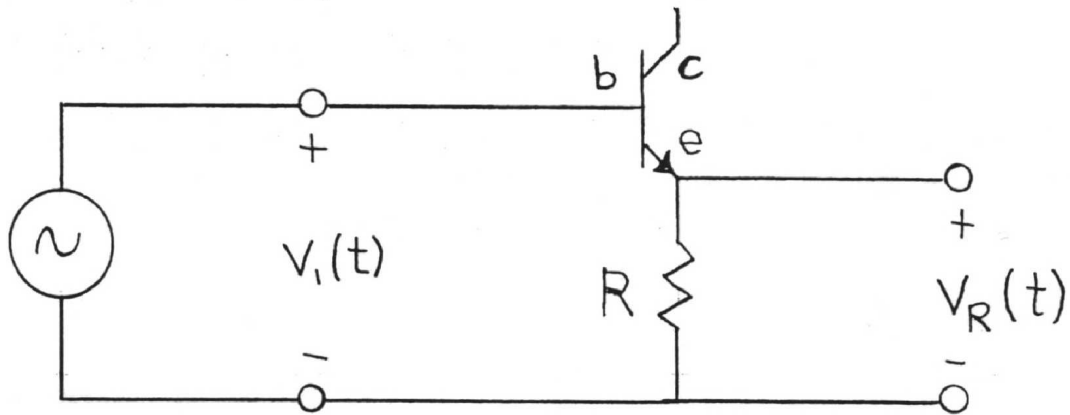


Figure 1: Circuit to rectify a voltage.

7. PHYSICS PUZZLER I: 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.
8. PHYSICS PUZZLER II: Did you notice that as the diode started to put out current the slope of the voltage vs. DAC curve changed. What is going on? Can you think of any tricks we used in previous labs to fix it?

Equipment list

- Function generator
- Arduino with DAC chip attached
- NPN Transistor: 2N4401 or MPSW01
- Oscilloscope
- 50 k Ω Resistor
- 250 k Ω Resistor

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.

Note: This experiment is very cool and requires you to use a Michelson Interferometer. Michelson Interferometers hate some people which means you can never get fringes in them. An instruction manual will be provided. It is a “good experience” to set up an interferometer, but I cannot help you, because interferometers hate me.

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° 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

10 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 measurements so 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

11 Superconductivity (n=1)

Introduction

The discovery of ceramic compounds that are superconductors when immersed in liquid nitrogen has made it possible to investigate some properties of superconductivity using very simple apparatus. In this lab we will use a commercial high-temperature-superconductivity experiment kit to study some of aspects of superconductors. The kit contains a disk of ceramic superconductor, a module consisting of a smaller ceramic superconductor disk with an attached thermocouple, and two very strong, small magnets.

A superconductor is a substance which acts like a perfect conductor when its temperature is below some critical value, the critical temperature T_c . Thus when $T < T_c$ a superconductor acts as if its resistance were zero, so that if a current were to be established in a ring of superconductor it would persist indefinitely.

In 1933, Meissner discovered that a magnet was repulsed by a superconductor, an effect now known by his name. The following are some considerations of how the Meissner effect might come about.

Suppose that a strong magnet is brought up to a superconductor so that the superconductor experiences a finite dB/dt . Then an emf would be induced in the superconductor such that a current would begin to flow. This induced current would continue to flow after the magnet stops moving ($dB/dt = 0$) because zero voltage will maintain a current when the resistance is zero. According to Lenz's law the induced current will be in a direction such that the B field due to it would be opposed to the B field of the magnet. Thus there would be a repulsive force between the small magnet and the superconductor. If the small magnet had a sufficiently strong field then the repulsion could result in the magnet being levitated above the superconductor.

However, if the magnet were placed on the superconductor while the superconductor was warmer than the critical temperature, and then the superconductor was cooled to below the critical temperature, the magnet would not be levitated since dB/dt would never have been different from zero. Nevertheless, if one were then to try to remove the magnet from the superconductor, there would be an attractive force between the two of them resisting the removal of the magnet due to the B field of the current induced in the superconductor as the magnet was moved. Since there is zero resistance in the superconductor we might expect that the induced current would be entirely on the surface and not in the interior of the superconductor.

Another way that a superconductor might repulse a magnet is if microscopic magnetic dipoles are induced in the superconductor which then oppose the applied field. Then, inside the superconductor there would be zero B field, and the external field of the dipoles induced in the superconductor would repel the source of the applied field, that is, the magnet. The superconductor would then be described as diamagnetic. This implies that the effect would be a volume, or bulk effect, becoming stronger when the volume of the superconductor is increased. In this case, if the magnet were placed on the superconductor before it was cooled, as the superconductor became superconducting it would exclude the magnetic field from its interior and the magnet would be levitated. Of course, this assumes that the strength of the magnet is sufficient to support its own weight.

This experiment is divided into two parts. In the first part you will study the Meissner Effect. In the second part you will determine the critical temperature of the ceramic superconductor.

Preparation Before Lab

Read the article on Superconductivity by Philip B. Allen in *Encyclopedia of Physics*, Second Edition, edited by Lerner and Trigg, VCH Publishers, New York, 1991, pages 1198–1203.

Safety Procedures

Liquid Nitrogen

Liquid nitrogen (LN₂) is COLD, it will kill skin cells by freezing them.

- Wear safety glasses when using LN₂.
- Do not allow any LN₂ to contact your body.
- Do not touch anything that has been immersed in LN₂ before it has warmed to room temperature. Use the plastic tweezers provided.
- Be very careful to avoid splashing of the LN₂.
- Avoid overfilling any vessel or spilling the LN₂.
- Do not put LN₂ in any vessel with a tight-fitting lid.
- The extreme cold of LN₂ will damage many surfaces, so do not pour LN₂ on or in anything not intended for LN₂ contact.
- Let the lab instructor dispose of any unused LN₂.

Ceramic Superconductor Handling Precautions

The ceramic superconducting material is made of oxides of various metals. The salts of these metals are toxic if ingested.

- Never handle the ceramic disks with your hands. Use tweezers provided.
- Do not under any circumstances ingest the materials.
- Do not expose the superconductor disk to water. After use in LN₂, carefully wipe the superconductor to remove water or frost. Then warm it under a lamp to completely dry it.
- The ceramic disks are brittle. Handle gently!
- Do not expose the ceramic disks to temperatures greater than 100° F.

Things to Do

Meissner Effect

The two possible causes of levitation (the Meissner effect) may be summarized as:

1. Induced currents (due to change of B with time, which by Lenz's law oppose the change in magnetic flux).
2. Diamagnetism (induced magnetic dipoles which *oppose* an applied B field).

Write clear and concise descriptions of your observations and answer the questions below.

1. Place the 1 inch diameter ceramic superconductor disk in an empty styrofoam cup. Place the cubic magnet on the uncooled superconductor, then cool to superconducting state with liquid nitrogen. If (1), then no levitation (no change in B with time). If (2), levitation.
2. If necessary, lift the magnet above the superconductor. If (1), a force will oppose removal of magnet (of about same magnitude as force which opposes moving magnet closer to superconductor). If (2), force always repulsive. Also, try to move the levitated magnet toward the edge of the superconductor disk. What happens?
3. Surface current vs. bulk effect. Repeat the previous two steps using two superconductor disks stacked one on top of the other. If (1), the current is only on surface, and there is no dependence on the thickness of the superconductor. If (2), double thickness of superconducting disk (two disks), increases height of levitation. Also, as superconductor warms up to non-superconducting state, the magnet will abruptly fall if (1), but gently descend if (2).

Magnetic Field studies

4. What is the orientation of the magnetic field of the suspended cube magnet? To test if there is a preferred orientation, cause the magnet to rotate by blowing on the cube's edge with a straw. Can you get it to rotate about another axis? From this you should be able to infer the axis of the magnet. (This also demonstrates the possibility of a frictionless magnetic bearing.)
5. Try to change the orientation of suspension by using a second magnet (whose poles can be determined using the compass provided) to attract the levitated magnet into an upright position (while spinning, say). Is the upright position stable? Why or why not?

Measuring Superconducting transition temperature

6. Measure the critical temperature T_c of the ceramic superconductor using the module provided consisting of encapsulated superconductor disk and attached thermocouple. The module has six wires. The red and blue wires are the thermocouple wires. Since the voltages produced by the thermocouple are just a few millivolts, you need to set your voltmeter to its most sensitive range. (Some meters have a special 300 mV setting, others just autorange.) In order to determine the temperature of the superconductor you need to know the relation between temperature and thermocouple voltage. See the table for the particular thermocouple you are using. The table below is appropriate for the type K thermocouple included in the Colorado Superconductor kits.

TABLE OBTAINED FROM <http://srdata.nist.gov/its90/download/all.tab>
May 2009

ITS-90 Table for type K thermocouple

C	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10
Thermoelectric Voltage in mV											
-270	-6.458										
-260	-6.441	-6.444	-6.446	-6.448	-6.450	-6.452	-6.453	-6.455	-6.456	-6.457	-6.458
-250	-6.404	-6.408	-6.413	-6.417	-6.421	-6.425	-6.429	-6.432	-6.435	-6.438	-6.441
-240	-6.344	-6.351	-6.358	-6.364	-6.370	-6.377	-6.382	-6.388	-6.393	-6.399	-6.404
-230	-6.262	-6.271	-6.280	-6.289	-6.297	-6.306	-6.314	-6.322	-6.329	-6.337	-6.344
-220	-6.158	-6.170	-6.181	-6.192	-6.202	-6.213	-6.223	-6.233	-6.243	-6.252	-6.262
-210	-6.035	-6.048	-6.061	-6.074	-6.087	-6.099	-6.111	-6.123	-6.135	-6.147	-6.158
-200	-5.891	-5.907	-5.922	-5.936	-5.951	-5.965	-5.980	-5.994	-6.007	-6.021	-6.035
-190	-5.730	-5.747	-5.763	-5.780	-5.797	-5.813	-5.829	-5.845	-5.861	-5.876	-5.891
-180	-5.550	-5.569	-5.588	-5.606	-5.624	-5.642	-5.660	-5.678	-5.695	-5.713	-5.730
-170	-5.354	-5.374	-5.395	-5.415	-5.435	-5.454	-5.474	-5.493	-5.512	-5.531	-5.550
-160	-5.141	-5.163	-5.185	-5.207	-5.228	-5.250	-5.271	-5.292	-5.313	-5.333	-5.354
-150	-4.913	-4.936	-4.960	-4.983	-5.006	-5.029	-5.052	-5.074	-5.097	-5.119	-5.141
-140	-4.669	-4.694	-4.719	-4.744	-4.768	-4.793	-4.817	-4.841	-4.865	-4.889	-4.913
-130	-4.411	-4.437	-4.463	-4.490	-4.516	-4.542	-4.567	-4.593	-4.618	-4.644	-4.669
-120	-4.138	-4.166	-4.194	-4.221	-4.249	-4.276	-4.303	-4.330	-4.357	-4.384	-4.411
-110	-3.852	-3.882	-3.911	-3.939	-3.968	-3.997	-4.025	-4.054	-4.082	-4.110	-4.138
-100	-3.554	-3.584	-3.614	-3.645	-3.675	-3.705	-3.734	-3.764	-3.794	-3.823	-3.852
degC	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10

77 Kelvin is -196 C Type K thermocouple should read -5.829 mv

7. After setting up your circuit cool the superconductor/thermocouple module with LN2. Once it has come to equilibrium at the temperature of LN2 (77 K) the thermocouple voltage should be 6.43 mV.
8. Remove the module from the LN2 and place it on an insulating surface (an empty styrofoam cup will do). Now balance the cylindrical Samarium magnet so that it is levitated over the center of the superconducting disk.
9. Observe the magnet carefully, measuring its levitation height, and simultaneously recording the thermocouple voltage every 10 s. If the levitation is due to a surface effect the levitation should cease abruptly, whereas if it is a bulk effect, the levitation should weaken over a finite time interval.
10. Redo this experiment by first placing the magnet on the encapsulated superconductor and *then* cooling it down to LN2 temperature, while observing the magnet and recording the thermocouple voltage.
11. Describe your observations and measurements.

Four point probes and resistance measurements

You will see text on the superconducting module that says "500 mA" maximum. Here's what it means. The module has two wires connected to a thermocouple. You have already used those. The other four wires comprise something called a four-point probe, a sketch of which is shown below. Four point probes are the established way to measure small resistances. You apply a current between the two out wires, and correct cause a small DV

Other questions

12. Why does the LN2 boil when you pour it into the "dish?" and when you put the superconductor disk into it?
13. When the LN2 has evaporated, the magnet stays levitated for many more minutes. Why is this so?
14. Describe the way in which the magnet falls as the superconductor warms to above the critical temperature and explain this behavior.
15. Under some circumstances, the magnet may suddenly scoot to one side of the brass cup as the assembly warms. Why is this?
16. Why does the assembly develop a layer of frost only after the LN2 has boiled away?
17. If the two different determinations of T_c yielded different values of T_c , explain why and determine which is the correct value.

Equipment list

- 1 inch diameter ceramic superconductor disk.
- Ceramic superconductor and thermocouple module ("device").
- Cubic neodymium rare-earth alloy magnet.
- Cylindrical samarium rare-earth alloy magnet.
- Plastic tweezers.
- Insulated dish (styrofoam cup).
- CSI Instruction Manual.
- Safety glasses.
- Liquid Nitrogen (LN2)
- Digital Multimeter.
- Magnetic Compass.
- Plastic straw.

12 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 of 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.

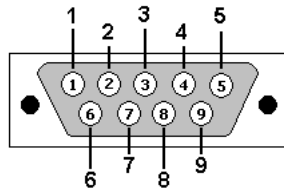
Connectors and pin definitions

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.

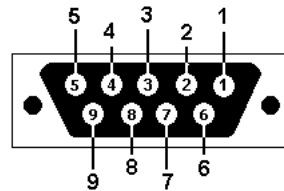
In this lab, you will be using only RX, TX and ground. The RS-232 specification says that pin 2 is RX (receive). Pin 2 is sometimes called RD (Receive data). Pin 3 is TX (transmit), also known as TD (Transmit data). Pin 5 is ground (by now you know that you always need a ground!). Looking at the diagram 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



DB9: View looking into male connector



DB9: View looking into female connector

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.

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.

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 understand 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

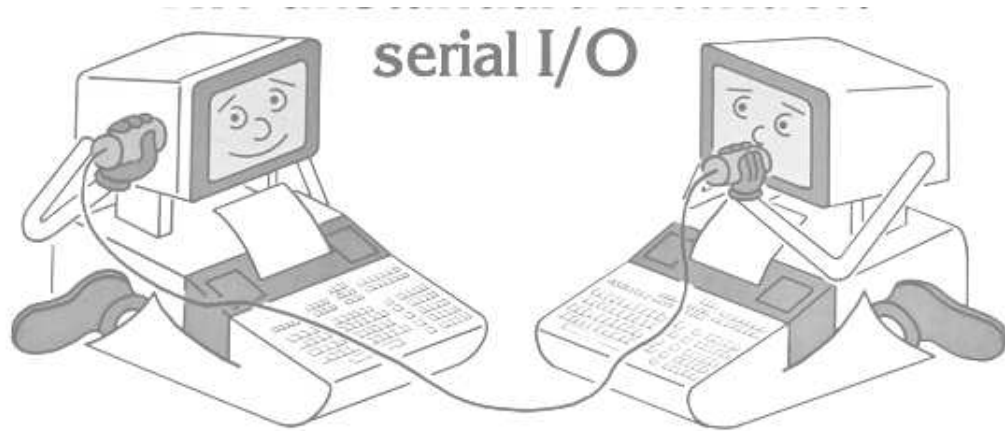


Figure 2: Why you need a crossover cable: The computer on the right is “talking” into its TX line. The computer in the left is “listening” to its RX line. If the left computer wants to “talk”, it wiggles it’s TX line, which must obviously be connected to the RX line of the computer on the right.

- Tektronix TDS-1002 Digital Oscilloscope
- Serial port cables

Equipment

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

Laboratory Time

Two hours

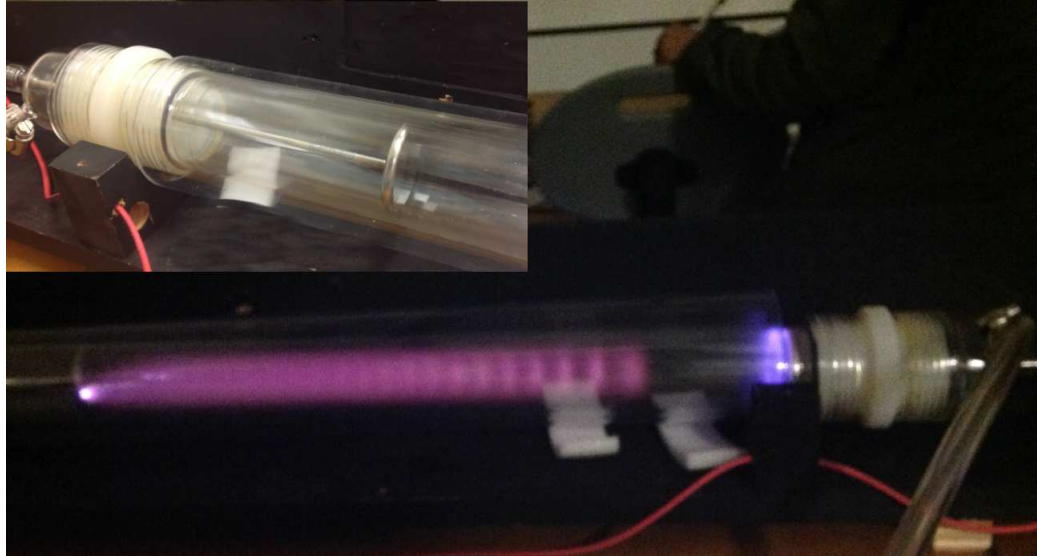


Figure 3: A glow discharge tube with a Nitrogen plasma.

13 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 assembling 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.

G Dielectric Constant of Liquid Nitrogen

Use a parallel-plate capacitor to measure the dielectric constant of liquid nitrogen. The experiment is pretty straightforward. The handling of the liquid nitrogen adds the challenge.

H Light-emitting diodes

Light-emitting diodes can also be used as light detectors. This effect and others are discussed in an article by David A. Johnson (Demonstrating the light-emitting diode, *American Journal of Physics*, 63(8), 761-762, 1995). The article describes simple circuits for seeing various effects.

I Electric Motors

Requires NO advance notice.

If you rotate a motor shaft (say, with another motor) it will generate a voltage. Connect the shaft of one motor to the shaft of another motor and make measurements to observe the generated voltage in both the driving motor and the driven motor.

J Magnetic materials

Requires one month advance notice to order the materials. It should be possible to study the magnetic properties of different types of materials by seeing how they affect the inductance of a coil in an oscillating circuit.

K Serial ports

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

L Improve an electromagnetic can crusher

Another good group project that is potentially fatal ... but not until energized. I can guide you through the steps needed to charge large capacitors and fire them safely. A small group of students built a crusher in 2014 that was both successful and safe. A new group may attempt to improve on their work. This is something that should be brought up in March.

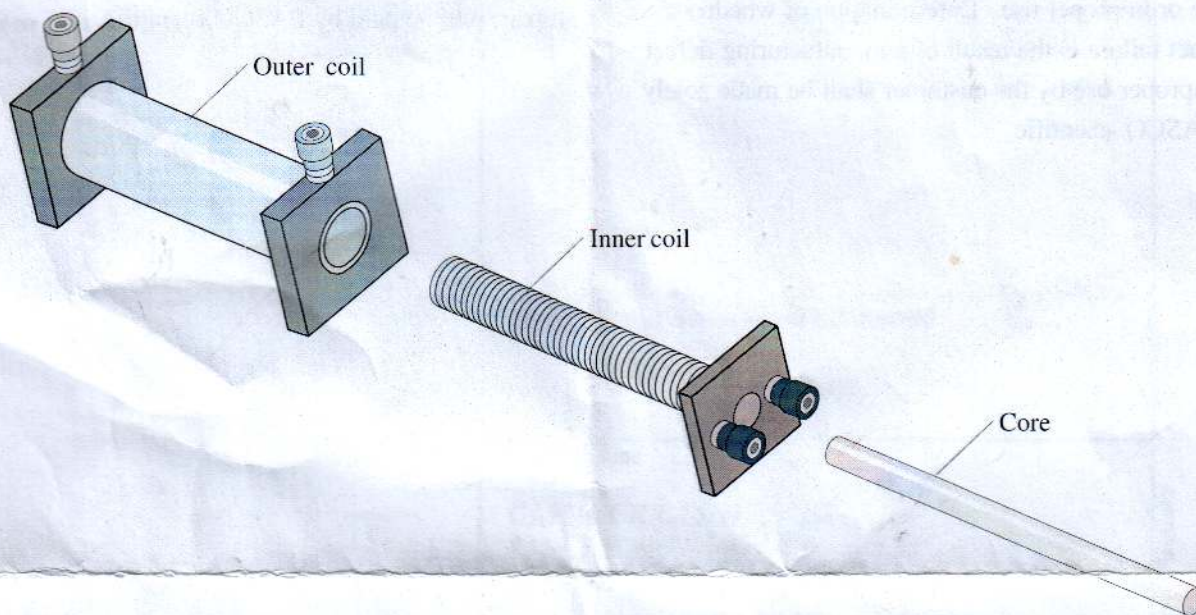
M Solar Motor-driver

There is no more important problem for society than energy that is renewable and does not contribute to global warming. Solar cells are an important part of the solution, but the current sourced by a solar cell depends directly on the amount of sunlight available. Electric DC motors typically have a minimum current required to make them turn at all. Can you overcome this limitation?

Appendix – Data Sheets

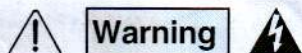


PRIMARY and SECONDARY COILS



Introduction

The PASCO Primary and Secondary Coils set consists of an outer coil, an inner coil, and a soft iron core. The coils and core may be used to investigate and perform experiments in electro-magnetism, inductive reactance, and transformer coupling. Two way binding posts are used in the coils for convenient connection.



Hazardous voltage and currents capable of producing injury can be produced by improper use of the Primary and Secondary Coil set. This apparatus should only be used under the supervision of experienced, trained personnel.

The Primary and Secondary Coils must never be used in a configuration which uses a voltage to be produced in excess of 30V r.m.s. 42.4V peak or 60V d.c. Never connect the Primary and Secondary Coils to the AC power mains.

Specifications

Inner Coil: 235 turns, #18 wire approx. 1mm, inductance: $78 \pm 22\mu\text{H}$, resistance: $0.4 \pm 0.1\Omega$, capacitance: $142 \pm 2\text{pF}$.

Dimensions: 12cm coil length X 1.7cm coil outside diameter.

Base: 5cm X 5cm.

Outer Coil: 2920 turns, #29 wire: approx. 0.29mm, inductance: $63 \pm 3\text{mH}$, resistance: $76 \pm 2\Omega$, capacitance: $124 \pm 2\text{pF}$.

Dimensions: 11 cm coil length X 3.5cm coil outside diameter.

Base: 5cm X 5cm.

Core: 16.5cm X 0.8cm.

Ratio of turns: 12.4:1.

Ratio of voltage: approximately 10:1.

FEATURES

- **Guaranteed Low Offset Voltage**

LT1001AM	15 μ V max
LT1001C	60 μ V max
- **Guaranteed Low Drift**

LT1001AM	0.6 μ V/ $^{\circ}$ C max
LT1001C	1.0 μ V/ $^{\circ}$ 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 0.3 μ V_{p-p}**

APPLICATIONS

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

DESCRIPTION

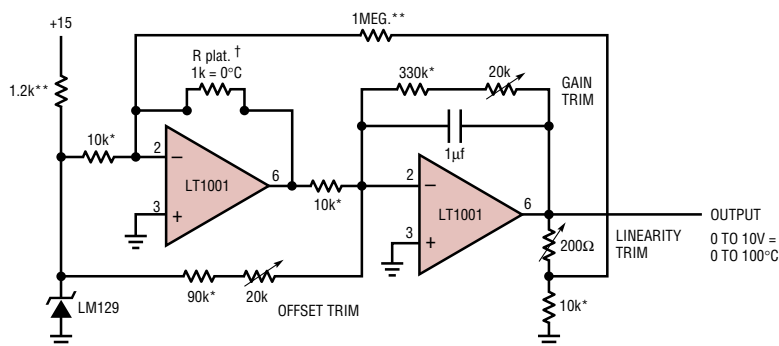
The LT[®]1001 significantly advances the state-of-the-art of precision operational amplifiers. In the design, processing, and testing of the device, particular attention has been paid to the optimization of the entire distribution of several key parameters. Consequently, the specifications of the lowest 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 50 μ V (see distribution plot below). This allows the LT1001AM/883 to be specified at 15 μ V. 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.

 LTC and LT are registered trademarks of Linear Technology Corporation.

TYPICAL APPLICATION

**Linearized Platinum Resistance Thermometer
with $\pm 0.025^{\circ}$ C Accuracy Over 0 to 100 $^{\circ}$ C**

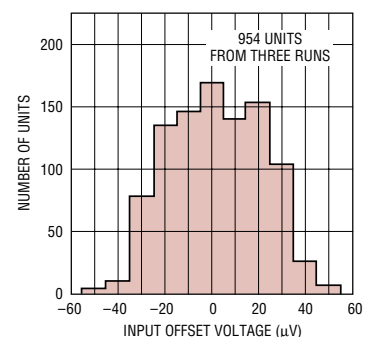


* ULTRONIX 105A WIREWOUND
 ** 1% FILM
 † PLATINUM RTD
 118MF (ROSEMOUNT, INC.)

‡ Trim sequence: trim offset (0 $^{\circ}$ C = 1000.0 Ω),
 trim linearity (35 $^{\circ}$ C = 1138.7 Ω), trim gain
 (100 $^{\circ}$ C = 1392.6 Ω). Repeat until all three
 points are fixed with $\pm 0.025^{\circ}$ C.

1001 TA01

**Typical Distribution
of Offset Voltage
 $V_S = \pm 15V, T_A = 25^{\circ}C$**



1001 TA02

LT1001

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

<p>OBSOLETE PACKAGE Consider the N8 and S8 Packages for Alternate Source</p>	<p>ORDER PART NUMBER</p> <p>LT1001AMH/883 LT1001MH LT1001ACH LT1001CH</p>	<p>OBSOLETE PACKAGE Consider the N8 and S8 Packages for Alternate Source</p>	<p>ORDER PART NUMBER</p> <p>LT1001ACN8 LT1001CN8 LT1001CS8</p>
		<p>S8 PART MARKING</p> <p>1001</p>	<p>ORDER PART NUMBER</p> <p>LT1001AMJ8/883 LT1001MJ8 LT1001ACJ8 LT1001CJ8</p>

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 $T_A = 25^\circ\text{C}$. $V_S = \pm 15\text{V}$, unless otherwise noted

SYMBOL	PARAMETER	CONDITIONS	LT1001AM/883 LT1001AC			LT1001M/LT1001C			UNITS		
			MIN	TYP	MAX	MIN	TYP	MAX			
V_{OS}	Input Offset Voltage	Note 2	LT1001AM/883		7	15	18		60	μV	
			LT1001AC		10	25					
$\frac{\Delta V_{OS}}{\Delta \text{Time}}$	Long Term Input Offset Voltage Stability	Notes 3 and 4			0.2	1.0	0.3	1.5		$\mu\text{V}/\text{month}$	
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	$f_0 = 10\text{Hz}$ (Note 6) $f_0 = 1000\text{Hz}$ (Note 3)			10.3	18.0	10.5	18.0		nV $\sqrt{\text{Hz}}$ nV $\sqrt{\text{Hz}}$	
A_{VOL}	Large Signal Voltage Gain	$R_L \geq 2\text{k}\Omega$, $V_0 = \pm 12\text{V}$ $R_L \geq 1\text{k}\Omega$, $V_0 = \pm 10\text{V}$	450	800	300	500	400	800	250	500	V/mV V/mV
CMRR	Common Mode Rejection Ratio	$V_{CM} = \pm 13\text{V}$	114	126	110	126				dB	
PSRR	Power Supply Rejection Ratio	$V_S = \pm 3\text{V}$ to $\pm 18\text{V}$	110	123	106	123				dB	
R_{in}	Input Resistance Differential Mode		30	100	15	80				M Ω	

1001fb

ELECTRICAL CHARACTERISTICS The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at $T_A = 25^\circ\text{C}$. $V_S = \pm 15\text{V}$, $T_A = 25^\circ\text{C}$, unless otherwise noted

SYMBOL	PARAMETER	CONDITIONS	LT1001AM/883			LT1001M/LT1001C			UNITS	
			MIN	TYP	MAX	MIN	TYP	MAX		
	Input Voltage Range		±13	±14		±13	±14		V	
V_{OUT}	Maximum Output Voltage Swing	$R_L \geq 2\text{k}\Omega$	±13	±14		±13	±14		V	
		$R_L \geq 1\text{k}\Omega$	±12	±13.5		±12	±13.5		V	
S_R	Slew Rate	$R_L \geq 2\text{k}\Omega$ (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		46	75		48	80		mW
		No load, $V_S = \pm 3\text{V}$		4	6		4	8		mW

$V_S = \pm 15\text{V}$, $-55^\circ\text{C} \leq T_A \leq 125^\circ\text{C}$, unless otherwise noted

SYMBOL	PARAMETER	CONDITIONS	LT1001AM/883			LT1001M			UNITS
			MIN	TYP	MAX	MIN	TYP	MAX	
V_{OS}	Input Offset Voltage		●	30	60		45	160	μV
$\frac{\Delta V_{OS}}{\Delta \text{Temp}}$	Average Offset Voltage Drift		●	0.2	0.6		0.3	1.0	$\mu\text{V}/^\circ\text{C}$
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	$R_L \geq 2\text{k}\Omega$, $V_O = \pm 10\text{V}$	●	300	700		200	700	V/mV
CMRR	Common Mode Rejection Ratio	$V_{CM} = \pm 13\text{V}$	●	110	122		106	120	dB
PSRR	Power Supply Rejection Ratio	$V_S = \pm 3$ to $\pm 18\text{V}$	●	104	117		100	117	dB
	Input Voltage Range		●	±13	±14		±13	±14	V
V_{OUT}	Output Voltage Swing	$R_L \geq 2\text{k}\Omega$	●	±12.5	±13.5		±12.0	±13.5	V
P_d	Power Dissipation	No load	●	55	90		60	100	mW

$V_S = \pm 15\text{V}$, $0^\circ\text{C} \leq T_A \leq 70^\circ\text{C}$, unless otherwise noted

SYMBOL	PARAMETER	CONDITIONS	LT1001AC			LT1001C			UNITS
			MIN	TYP	MAX	MIN	TYP	MAX	
V_{OS}	Input Offset Voltage		●	20	60		30	110	μV
$\frac{\Delta V_{OS}}{\Delta \text{Temp}}$	Average Offset Voltage Drift		●	0.2	0.6		0.3	1.0	$\mu\text{V}/^\circ\text{C}$
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	$R_L \geq 2\text{k}\Omega$, $V_O = \pm 10\text{V}$	●	350	750		250	750	V/mV
CMRR	Common Mode Rejection Ratio	$V_{CM} = \pm 13\text{V}$	●	110	124		106	123	dB
PSRR	Power Supply Rejection Ratio	$V_S = \pm 3\text{V}$ to $\pm 18\text{V}$	●	106	120		103	120	dB
	Input Voltage Range		●	±13	±14		±13	±14	V
V_{OUT}	Output Voltage Swing	$R_L \geq 2\text{k}\Omega$	●	±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.

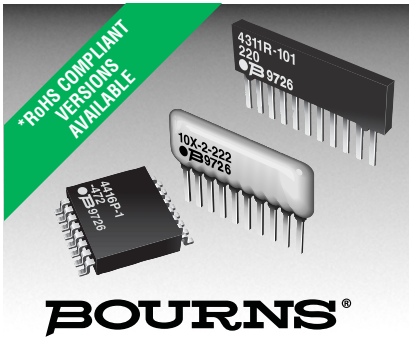
Note 2: Offset voltage for the LT1001AM/883 and LT1001AC are measured after power is applied and the device is fully warmed up. All other grades are measured with high speed test equipment, approximately 1 second after power is applied. The LT1001AM/883 receives 168 hr. burn-in at 125°C . or equivalent.

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 $2.5\mu\text{V}$.

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.



Features

- Resistance range: 100 ohms to 1 megohm
- SIP and DIP packages
- Surface mount and through-hole available
- RoHS compliant* (see How to Order "Termination" option)

For information on R/2R Thick Film Networks, download Bourns' R/2R Application Note.

R/2R Series Thick Film Networks

Product Characteristics

Resistance Range
 Models 4100, 4300, 4400 & 4800 100 ohms to 100K ohms
 Model 4600...100 ohms to 1 megohm
 Standard Tolerance $\pm 2\%$

See applicable model data sheet for complete list of product characteristics.

Environmental Characteristics

See applicable model data sheet for complete list of environmental characteristics.

Physical Characteristics

See applicable model data sheet for complete list of physical characteristics.

How To Order

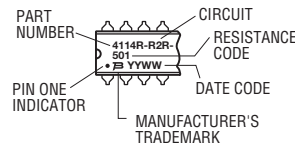
4116R - R2R - 501

- Model _____
 (See "Available Models")
- Electrical Configuration _____
 R2R = Standard R/2R**
 121 = Reversed R/2R***
- Resistance Code (for value of R) _____
 • First 2 digits are significant;
 third digit represents the
 number of zeros to follow.
- 2R is double the value of R in circuit.
- Terminations _____
 LF = Tin-coated (RoHS compliant version)
 (Model 4416P is ONLY available in the
 RoHS compliant version.)
- Blank = Tin/Lead
 (Model 4416P is not available with
 tin/lead terminations.)
- **Standard R2R Electrical Configuration not
 available for Model 4600H Series.
- ***Reversed R/2R Electrical Configuration not
 available for Model 4600H, 4600M or 4600X
 Series.

For Standard Values Used in
 Capacitors, Inductors, and Resistors,
[click here](#).

Typical Part Marking

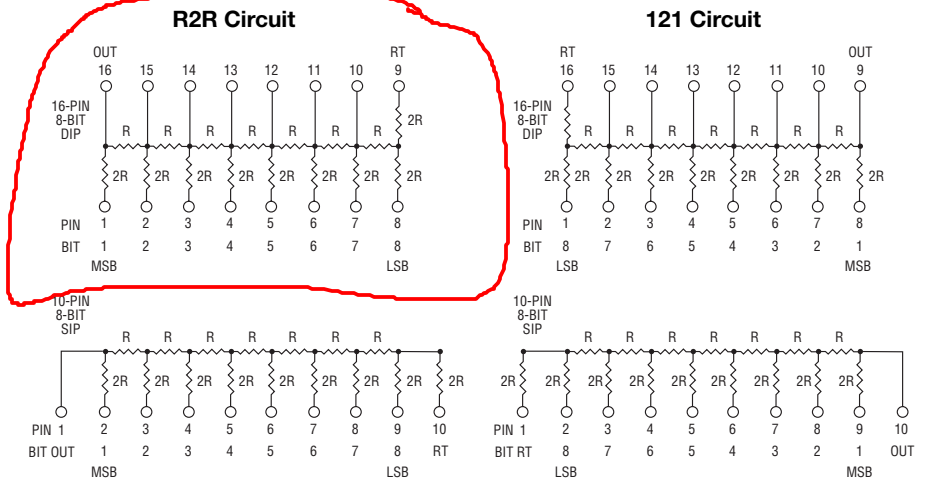
Represents total content. Layout may vary.



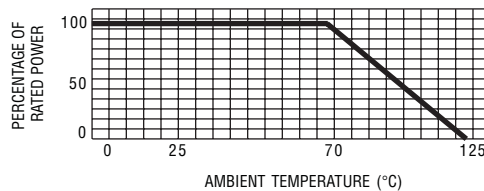
Product Dimensions

See applicable model data sheet for complete product dimensions.

Resistor Schematic



Power Derating Curve



Power Rating per Resistor

Model	Power per Resistor (Watts)
4100R, 4300R, 4400P, 4600X***, 4800P.....	0.125
4300M, 4600M***	0.170
4300H.....	0.200

*RoHS Directive 2002/95/EC Jan 27, 2003 including Annex. Specifications are subject to change without notice.

Customers should verify actual device performance in their specific applications.

One Watt High Current Transistors

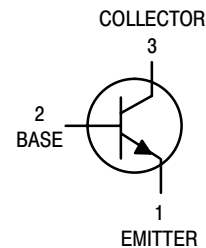
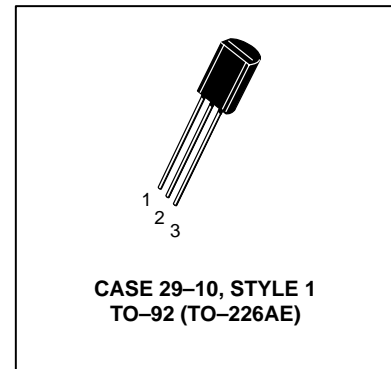
NPN Silicon

MPSW01 MPSW01A*

*ON Semiconductor Preferred Device

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 @ $T_A = 25^\circ\text{C}$ Derate above 25°C	P_D	1.0 8.0	Watts mW/ $^\circ\text{C}$
Total Device Dissipation @ $T_C = 25^\circ\text{C}$ Derate above 25°C	P_D	2.5 20	Watts mW/ $^\circ\text{C}$
Operating and Storage Junction Temperature Range	T_J, T_{stg}	-55 to +150	$^\circ\text{C}$



THERMAL CHARACTERISTICS

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

ELECTRICAL CHARACTERISTICS ($T_A = 25^\circ\text{C}$ unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
----------------	--------	-----	-----	------

OFF CHARACTERISTICS

Collector–Emitter Breakdown Voltage ⁽¹⁾ ($I_C = 10 \text{ mAdc}, I_E = 0$)	MPSW01 MPSW01A	$V_{(BR)CEO}$	30 40	—	Vdc
Collector–Base Breakdown Voltage ($I_C = 100 \mu\text{Adc}, I_E = 0$)	MPSW01 MPSW01A	$V_{(BR)CBO}$	40 50	—	Vdc
Emitter–Base Breakdown Voltage ($I_E = 100 \mu\text{Adc}, I_C = 0$)		$V_{(BR)EBO}$	5.0	—	Vdc
Collector Cutoff Current ($V_{CB} = 30 \text{ Vdc}, I_E = 0$) ($V_{CB} = 40 \text{ Vdc}, I_E = 0$)	MPSW01 MPSW01A	I_{CBO}	— —	0.1 0.1	μAdc
Emitter Cutoff Current ($V_{EB} = 3.0 \text{ Vdc}, I_C = 0$)		I_{EBO}	—	0.1	μAdc

1. Pulse Test: Pulse Width $\leq 300 \mu\text{s}$, Duty Cycle $\leq 2.0\%$.

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

MPSW01 MPSW01A

ELECTRICAL CHARACTERISTICS ($T_A = 25^\circ\text{C}$ unless otherwise noted) (Continued)

Characteristic	Symbol	Min	Max	Unit
ON CHARACTERISTICS⁽¹⁾				
DC Current Gain ($I_C = 10\text{ mAdc}$, $V_{CE} = 1.0\text{ Vdc}$) ($I_C = 100\text{ mAdc}$, $V_{CE} = 1.0\text{ Vdc}$) ($I_C = 1000\text{ mAdc}$, $V_{CE} = 1.0\text{ Vdc}$)	h_{FE}	55 60 50	— — —	—
Collector–Emitter Saturation Voltage ($I_C = 1000\text{ mAdc}$, $I_B = 100\text{ mAdc}$)	$V_{CE(sat)}$	—	0.5	Vdc
Base–Emitter On Voltage ($I_C = 1000\text{ mAdc}$, $V_{CE} = 1.0\text{ Vdc}$)	$V_{BE(on)}$	—	1.2	Vdc

SMALL–SIGNAL CHARACTERISTICS

Current–Gain — Bandwidth Product ($I_C = 50\text{ mAdc}$, $V_{CE} = 10\text{ Vdc}$, $f = 20\text{ MHz}$)	f_T	50	—	MHz
Output Capacitance ($V_{CB} = 10\text{ Vdc}$, $I_E = 0$, $f = 1.0\text{ MHz}$)	C_{obo}	—	20	pF

1. Pulse Test: Pulse Width $\leq 300\ \mu\text{s}$, Duty Cycle $\leq 2.0\%$.

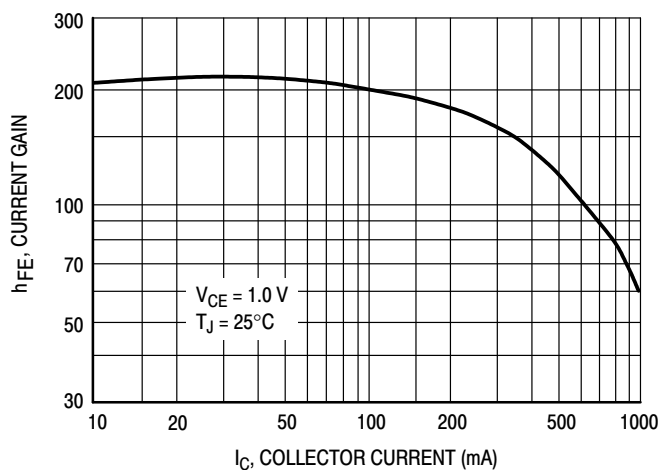


Figure 1. DC Current Gain

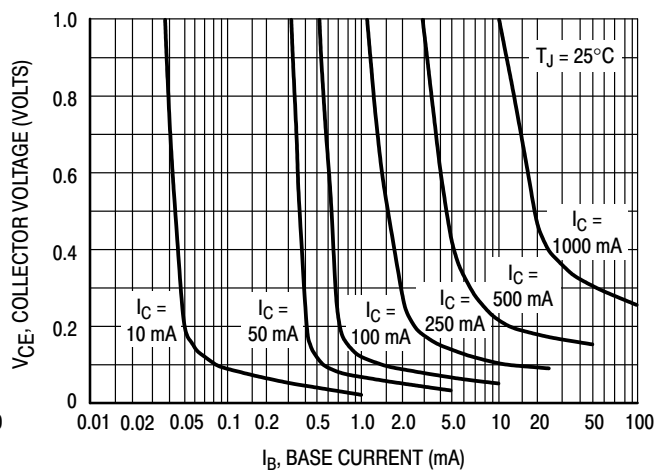


Figure 2. Collector Saturation Region

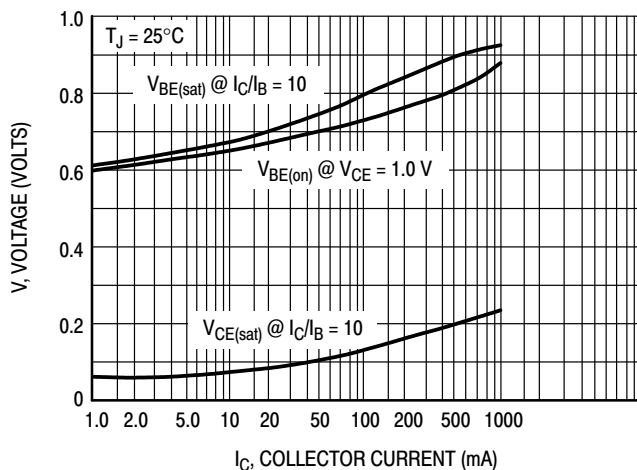


Figure 3. "ON" Voltages

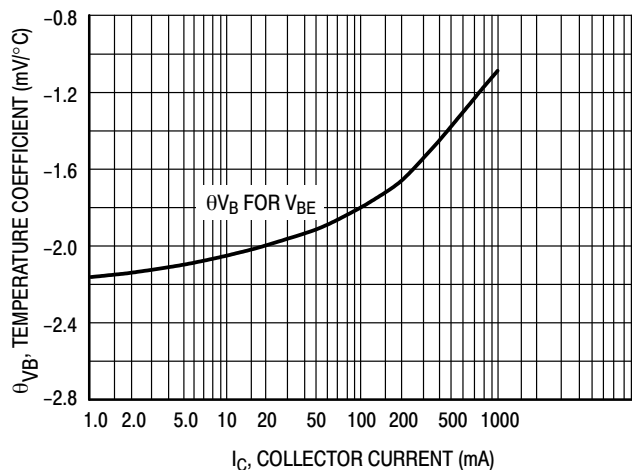


Figure 4. Temperature Coefficient