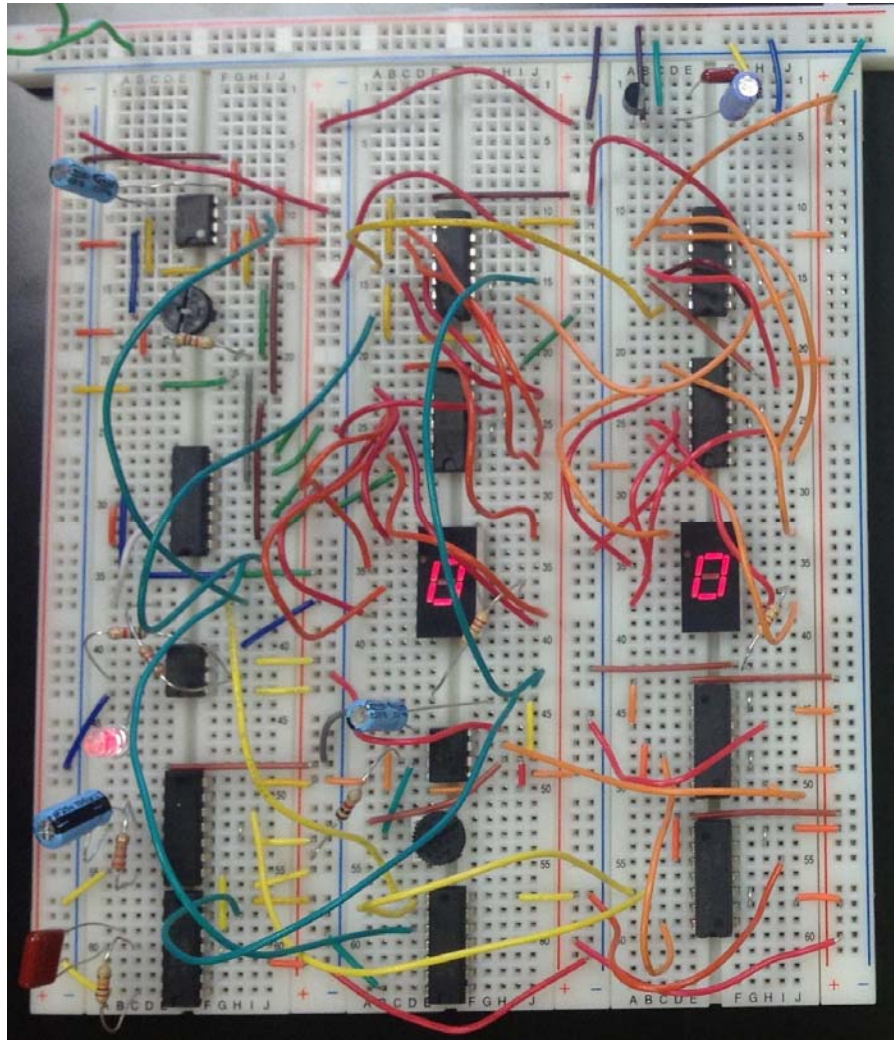


# **PHYS:3850 Electronics**

## **Laboratory Manual**



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**Updated for Spring 2015**

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4. Junction Transistor, Part I	1.2
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\* An average student will require approximately 3 hours to complete a lab that is indicated as 1 week. Some students will require more than 3 hours. Lab grades will be weighted by the number of weeks shown, when computing the lab component of the course grade.

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# **PREFACE**

## **GOAL**

The purpose of the experiments described here is to acquaint the student with:

- (1) analog & digital devices
- (2) design of circuits
- (3) instruments & procedures for electronic test & measurement.

The aim is to teach a practical skill that the student can use in the course of his or her own experimental research projects in physics, astronomy, or another science.

At the end of this course, the student should be able to:

- (1) design and build simple circuits of his or her own design.
- (2) use electronic test & measurement instruments such as oscilloscopes, timers, function generators, etc. in experimental research.

## **REFERENCE**

This manual is coordinated with the following textbook.

Horowitz and Hill  
The Art of Electronics  
2nd Edition, 1989/1990  
Cambridge University Press

A copy of this book is in the lab.

## **DATA SHEETS**

Data sheets for integrated circuits can be found online by searching for the part number. They can also be found in books, such as the Texas Instruments or National Instruments references for TTL, CMOS and LINEAR circuits. These books are on a shelf in the lab.

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## LAB NOTEBOOKS

As a part of training to be a scientist, students should maintain a personal notebook just as a research scientist does. This lab notebook will not be graded, but the student must have one and use it. It must be bound, with no loose pages.

Here is a guideline for lab notebooks: a notebook should contain sufficient detail so that a year later the experiment could be duplicated exactly.

In the notebook, the student should:

draw a schematic diagram for every circuit that is built

- ❑ label this diagram with
  - part numbers
  - pin designations
  - output/input designations
- ❑ show the major connections to external power supplies, etc.

list the instruments used by type and model

- ❑ include in this list: oscilloscope, multimeters, function generators, etc.

record a table of all measurements

- ❑ include units (e.g. mV) for inputs and outputs
- ❑ record the scale (e.g. 200 mV) of the meter or oscilloscope
- ❑ for digital circuits, this table may be in the form of a truth table

record error values for measurements that have an uncertainty:

- ❑ list more than one measurement as an error check
- ❑ estimate the error bar



A spiral notebook is ok for this course.



Researchers use notebooks with sewn-in pages

## PRELAB

In each lab, you are given prelab questions. These are intended to help you prepare for the lab. You should write your response in this manual. These questions are not handed in, and they are not graded. If you do not understand a prelab question, be sure to ask your TA.

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# LAB REPORTS

For each Lab, students will individually prepare a lab report for grading. This report is distinct from the notebook; the notebook is not a substitute.

Reports should be organized as a brief introduction, and then an experimental section that is organized according to the section number.

*Preface:* brief introductory paragraph,  $\approx 30$  words, describing the report's theme

*Experiments*

*REPEAT THE FOLLOWING FOR EACH SECTION*

*Apparatus*

schematic diagram, labeled with:

part numbers (e.g. 1N914 diode)

pin designations (on ICs)

output / input terminals

list of instruments used (e.g., Tektronix 2235 oscilloscope)

*Procedure*

A maximum of three sentences to explain:

what was measured (e.g., amplifier gain)

what was varied (e.g., oscillator frequency)

how errors were estimated\*

*Results*

– indicates a response is required

where it is appropriate, response should include:

table and/or graph of results

label each curve

draw smooth curves through data points

label axes and indicate units (e.g., Hz, mV)

\*estimate of errors, for analog measurements

as a column in a table

or as a representative error bar on a graph

sketch or print of the oscilloscope display, if one was used,

and discuss briefly in a few sentences the features

of the waveform to demonstrate that you understand

the significance of the waveform.

timing diagram or truth table, for digital circuits

explanation of any problems you encountered

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Handwritten lab reports are adequate. Typewritten reports are unnecessary. Be brief, but write in complete sentences. For graphs, you may use “Graphical Analysis”<sup>†</sup> or other software. If preparing your report consumes significantly more than two hours, talk to your TA to ask if you are doing something that is unnecessarily time consuming. Example lab reports are provided in the lab room for you to inspect.

\* Some instructors may not want error analysis included in the report. Ask to be sure.

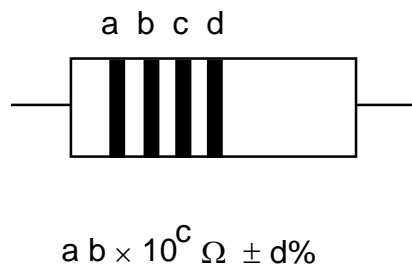
## SYMBOLS USED IN THIS MANUAL

- } For your information
- \* Instructions for you to follow
- Requires an answer or comment in your lab report

## RESISTOR COLOR CODE

### *MULTIPLIERS TOLERANCES*

Silver	-2		
Gold	-1		
Black	0	none	20%
Brown	1	silver	10%
Red	2	gold	5%
Orange	3		
Yellow	4		
Green	5		
Blue	6		
Violet	7		
Gray	8		
White	9		



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<sup>†</sup> as of 2001, Graphical Analysis was installed on PCs at this location:  
Start\Programs\Vernier Software\GA

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# TREATMENT OF EXPERIMENTAL ERRORS

“Error” does not mean a mistake. It means an uncertainty.

In measuring any value, the result is not just one number, such as 5.3 Volts. It is two numbers,  $5.3 \pm 0.1$  Volts. The second number is the experimental uncertainty, or error bar. It usually represents one standard deviation (one sigma) from the first value.

In making an analog measurement with a meter or an oscilloscope, you should record not just the first number, but the error as well.

To decide what value to assign to the error, you must use some judgment. Here are some tips:

## Multimeters:

The manufacturer gives specifications for the precision for the multimeter.

The precision of a **BK model 388-HD hand-held multimeter** is:

DCV	0.50 % rdg + 1 LSD
ACV	1.25 % rdg + 4 LSD
F	2.00 % rdg + 4 LSD
ACA	1.50 % rdg + 3 LSD
DCA	1.00 % rdg + 1 LSD
$\Omega$	0.75 % rdg + 1 LSD
Hz	1.00 % rdg + 3 LSD

where rdg is the reading on the display, and LSD is the least significant digit

## Example:

1. You measure a DC voltage and get 5.30 Volt.
2. The uncertainty is given as 0.5 % of the reading, or  $0.005 \times 5.30$ , plus  $1 \times$  LSD, where the LSD is 0.01 here.
3. So the uncertainty is  $\pm (0.005 \times 5.30 + 1 \times 0.01) = \pm 0.0365$  Volt.
4. Rounding to  $\pm 0.04$ , your result is  $5.30 \pm 0.04$  Volt.

## Agilent 34410A Multimeter:

### Accuracy Specifications $\pm$ (% of reading + % of range)<sup>1</sup>

Function	Range <sup>3</sup>	Frequency, Test Current or Burden Voltage	24 Hour <sup>2</sup> Tcal $\pm 1^\circ\text{C}$
DC Voltage	100.0000 mV 1.000000 V <b>10.00000 V</b> 100.0000 V 1000.000 V <sup>4</sup>		0.0030 + 0.0030 0.0020 + 0.0006 <b>0.0015 + 0.0004</b> 0.0020 + 0.0006 0.0020 + 0.0006
True RMS AC Voltage <sup>5</sup>	100.0000 mV to 750.000 V	3 Hz – 5 Hz 5 Hz – 10 Hz <b>10 Hz – 20 kHz</b> 20 kHz – 50 kHz 50 kHz – 100 kHz 100 kHz – 300 kHz	0.50 + 0.02 0.10 + 0.02 <b>0.02 + 0.02</b> 0.05 + 0.04 0.20 + 0.08 1.00 + 0.50
Resistance <sup>6</sup>	100.0000 $\Omega$ 1.000000 k $\Omega$ <b>10.00000 k<math>\Omega</math></b> 100.0000 k $\Omega$ 1.000000 M $\Omega$ 10.00000 M $\Omega$ 100.0000 M $\Omega$ 1.000000 G $\Omega$	1 mA 1 mA <b>100 <math>\mu\text{A}</math></b> 10 $\mu\text{A}$ 5 $\mu\text{A}$ 500 nA 500 nA    10 M $\Omega$ 500 nA    10 M $\Omega$	0.0030 + 0.0030 0.0020 + 0.0005 <b>0.0020 + 0.0005</b> 0.0020 + 0.0005 0.0020 + 0.0010 0.0100 + 0.0010 0.200 + 0.001 2.000 + 0.001
DC Current	100.0000 $\mu\text{A}$ <b>1.000000 mA</b> 10.00000 mA 100.0000 mA 1.000000 A 3.000000 A	< 0.03 V <b>&lt; 0.3 V</b> < 0.03 V < 0.3 V < 0.8 V < 2.0 V	0.010 + 0.020 <b>0.007 + 0.006</b> 0.007 + 0.020 0.010 + 0.004 0.050 + 0.006 0.100 + 0.020
True RMS AC Current <sup>7</sup>	100.0000 $\mu\text{A}$ to 3.00000 A	<b>3 Hz – 5 kHz</b> 5 kHz – 10 kHz	<b>0.10 + 0.04</b> 0.20 + 0.04
Frequency or Period	100 mV to 750 V	3 Hz – 5 Hz 5 Hz – 10 Hz 10 Hz – 40 Hz <b>40 Hz – 300 kHz</b>	0.070 + 0.000 0.040 + 0.000 0.020 + 0.000 <b>0.005 + 0.000</b>
Capacitance <sup>8</sup>	1.0000 nF 10.000 nF 100.00 nF 1.0000 $\mu\text{F}$ 10.000 $\mu\text{F}$	500 nA 1 $\mu\text{A}$ 10 $\mu\text{A}$ 10 $\mu\text{A}$ 100 $\mu\text{A}$	0.50 + 0.50 0.40 + 0.10 0.40 + 0.10 0.40 + 0.10 0.40 + 0.10



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**Analog oscilloscope:**

The display has about 8 boxes (divisions) in the vertical direction and 10 boxes horizontally. It also has 5 small tick marks within each division.

You can usually measure a value to about  $\pm 0.25$  of a tick mark, i.e.  $\pm 0.05$  divisions.

Example: You use the oscilloscope on the 2 Volt/div scale, and your result is 5.3 Volt. The error bar is  $\pm 0.05$  divisions, so your final result is  $5.3 \pm 0.1$  Volt.

**Propagation of Errors:**

When two or more experimental measurements are combined into one by some mathematical operation (such as a product  $P = I V$ ), the two errors add in a non-trivial way.

Example:

You measure  $I = 1.2 \pm 0.1$  mA and  $V = 2.5 \pm 0.3$  V. The error of  $P$  is computed using partial derivatives, as:

$$\begin{aligned} dP &= [ (\partial P / \partial I)^2 dI^2 + (\partial P / \partial V)^2 dV^2 ]^{1/2} \\ &= [ V^2 dI^2 + I^2 dV^2 ]^{1/2} \\ &= [ 2.5^2 0.1^2 + 1.2^2 0.3^2 ]^{1/2} \\ &= 0.44 \text{ mW} \end{aligned}$$

so the result you report for the measurement is  $P = 3.00 \pm 0.44$  mW.

In general:

For  $F = F(A, B, C, \dots)$ , the uncertainty  $\delta F$  in terms of the uncertainties  $dA, dB$  etc. is given by:

$$dF^2 = \Sigma [ (\partial F / \partial A)^2 dA^2 + (\partial F / \partial B)^2 dB^2 + \dots ].$$

Note that errors add through their *squares*.

In this lab course, you are asked to use propagation of errors only twice, both times in Lab 1, in order to develop this skill. These two instances are indicated in Lab 1 with a footnote. Otherwise, to save time, do not perform propagation of errors analysis.

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# TO THE INSTRUCTOR

## HOW ONE CAN USE THIS MANUAL

This manual is intended for a one-semester course. The instructor probably will skip some experiments or parts of experiments due to lack of time.

The first few experiments, analog circuits, will challenge the student the most.

One option is to skip some of the Labs and then finish with a project. This project is a circuit invented by the student; it requires about four weeks. The student must begin planning a project several weeks before this four-week period begins.

## TO THE TA:

Before the students do their experiments, you must:

- do the experiment yourself
- inventory parts to be sure they are all available
- set up each lab table
- before the first lab, check batteries (including those in multimeters)

If enough parts are available, leave your setup in working order for students to examine when they have difficulty.

You will need to schedule additional time in the lab to accommodate students who are unable to complete their work in 3 hours.

Students need their graded lab reports within a week of handing them to you. If you take longer to grade them, students will not know whether they were writing their report as expected, or whether they are omitting required information or spending too much time on unnecessary efforts in writing the report.

Mark your copy of the lab manual with the word “EDIT” to indicate changes that need to be made for next year.

# Lab 1

## DC Measurements

**REFERENCE:** Horowitz and Hill: Sections 1.01 - 1.05  
Appendix C (Resistor color code)  
Appendix E (How to draw schematic diagrams)

### INTRODUCTION

} This experiment has the following objectives:

*Become familiar with:*

- multimeter
- prototyping board
- resistor color code
- reading a schematic diagram
- wiring a circuit

*Study a current source.*

A *voltage source* (Figure 1-1) such as a battery or power supply is inherently a device with a low internal resistance. It should provide a *constant voltage* for a wide range of currents.

A *current source* (Figure 1-2) on the other hand should provide a *constant current* to a wide range of load resistances.

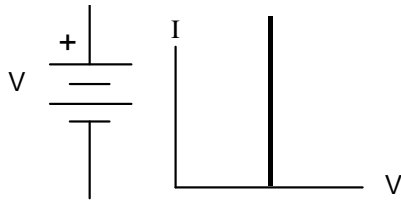


Figure 1-1  
Voltage source

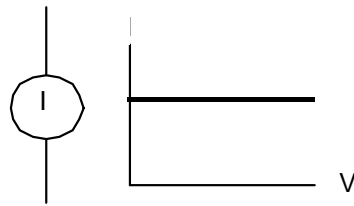
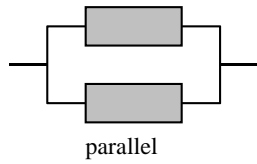
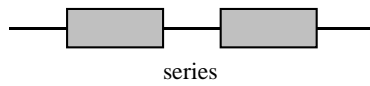


Figure 1-2  
Current source

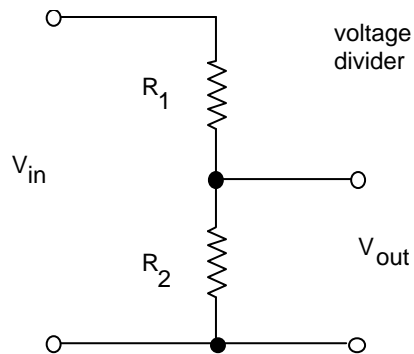


$$R_{\text{series}} = R_1 + R_2$$

Series and parallel circuits.

### *Study a voltage divider*

A *voltage divider* is two resistors connected in series.



$$V_{\text{out}} / V_{\text{in}} = R_2 / (R_1 + R_2)$$

## EQUIPMENT

### Lab supplies:

Digital multimeter (BK Model 388-HD)

Battery 1.5 V (2)

DC power supply

Box of assorted of resistors

Switches (with wires soldered on): SPST, SPDT

Potentiometer (with wires soldered on, preferably > 1k)

Resistor substitution box (with 1000  $\Omega$ /decade or higher for top decade)

~8 V transformer

Prototyping board

Two short solid-core wires (to stick into prototyping board)

Alligator clips for multimeter test leads

Board with three terminals

2 A fuses, may be needed by TA

### Student kits:

Wire kit

Resistors

100, 560, 1 k, 1.8 k, 3.3 k, 50k

TA note:

Check batteries and fuses  
in all multimeters before use. Check  
prototyping boards to verify that their  
power supplies work.

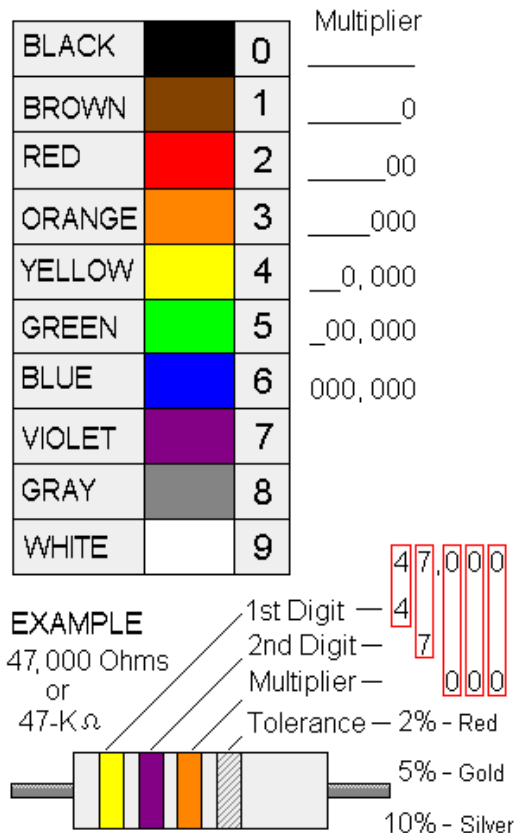


Multimeter

## PRELAB

**Note: this page is best viewed in color.**

1. Identify all the formulas you will need in this Lab.
2. Describe one mistake that can damage a multimeter for each of the following measurements:
  - A. voltage
  - B. resistance
  - C. current
3. State whether propagation of errors can be used to find the uncertainty of:
  - A. a quantity measured directly using a multimeter
  - B. a calculated quantity based on more than one measurement
  - C. both of the above
4. Use the resistor color code chart to determine the value of a four-band resistor with the colors brown, black, brown, gold.



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## PROCEDURE

### Familiarization with equipment

#### } The digital multimeter

The hand-held digital multimeter is used widely to make electrical measurements of

Voltage dc & ac  
current dc & ac  
resistance  
continuity  
other quantities, such as frequency, depending on your meter's features

#### *Input impedance:*

In the voltage mode, the input impedance of a digital multimeter is usually high enough (several  $M\Omega$ ) that it has negligible effect on the circuit being measured.

#### *Continuity check:*

Many models allow you to check continuity, emitting an audible beep so that you don't need to look at the meter while making the test.

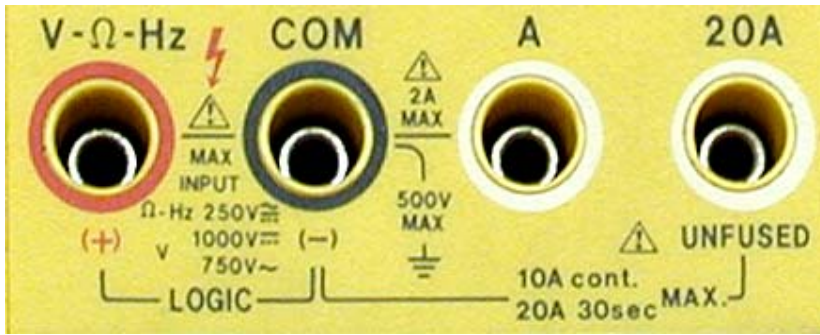


#### *Hooking up the meter:*

Note that the meter is connected:

- in *parallel* to measure voltage or resistance
- in *series* to measure current.

See the figures to see how this is done.



Input jacks on a multimeter



(a) Voltage  $V$



(b) Resistance  $\Omega$



(c) Current  $A$

Multimeters. The meter can measure voltage, resistance and current. Note two things:

- which connectors at the bottom are used
- where the dial points (your dial might look different from the one shown here, but somewhere it will have  $V$ ,  $\Omega$ , and  $A$  for measuring voltage, resistance, and current).

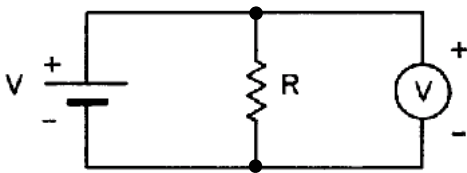


Figure 1-4. Using a multimeter (shown by the circle with a  $V$ ) to measure *voltage*.

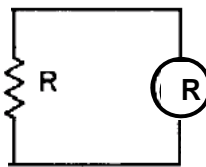


Figure 1-3. Using a multimeter (shown by the circle with a  $R$ ) to measure *resistance*.

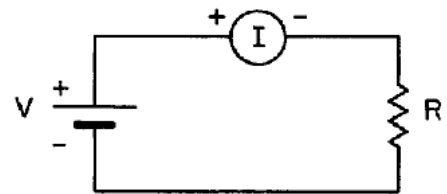


Figure 1-5. Using a multimeter (shown by the circle with an  $I$ ) to measure *current*.



## 1. DC voltage

- \* Set the function switch of the multimeter to DC volts, with a scale commensurate with the voltages expected in the circuit.

- \* To protect the meter from damage:

ALWAYS SELECT THE MAXIMUM VOLTAGE SCALE TO START WITH.  
Then adjust the scale downward until a meaningful reading is obtained.

### (a) Batteries in series

- \* – Measure the individual voltages  $V_1$  and  $V_2$  of two 1.5 V batteries.

- \* – Then connect the batteries in series, with forward polarity, as shown in Fig. 1-7 and measure the total voltage  $V_{\text{meas}}^f$ . Provide an uncertainty for this measurement based on the multimeter's specifications.



Figure 1-6.  
Board with two batteries.

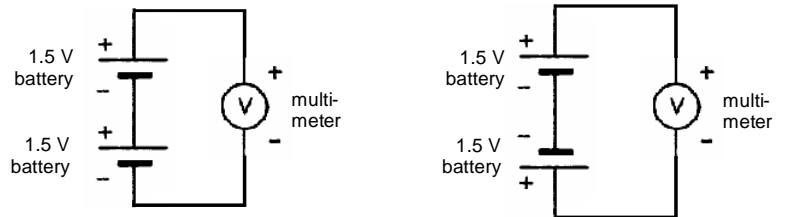


Figure 1-7.  
Two batteries connected in series, with forward polarity (left) and reverse (right).

- \* – Reverse the polarity of one of the batteries and measure the total voltage  $V_{\text{meas}}^r$ . Provide an uncertainty for this measurement based on the multimeter's specifications.

- \* – Calculate the expected results  $V_{\text{calc}}^f = V_1 + V_2$  and  $V_{\text{calc}}^r = V_1 - V_2$  for forward and reverse polarity of the two batteries. Note that these are calculated quantities, not measured quantities, so that their uncertainty must be calculated using propagation of errors. Perform this uncertainty calculation, yielding  $\delta V_{\text{calc}}^f$  and  $\delta V_{\text{calc}}^r$

- Compare these expected results  $V_{\text{calc}}^f \pm \delta V_{\text{calc}}^f$  and  $V_{\text{calc}}^r \pm \delta V_{\text{calc}}^r$  to the corresponding measured values  $V_{\text{meas}}^f \pm \delta V_{\text{meas}}^f$  and  $V_{\text{meas}}^r \pm \delta V_{\text{meas}}^r$

- \* – In both your notebook and lab report, you must always draw a schematic of whatever you connect, including components and any external instruments. For this step, the schematics should look like Fig. 1-7. (As you gain experience, you will learn how to draw schematics without being shown an example to copy.)

## (b) Power supply

} A power supply is a voltage source powered by 110VAC. You will use a “bench” power supply, which has supplies an adjustable voltage.

} A benchtop power supply typically has two knobs: voltage and current. The way it works is that only one knob will have an effect, depending on two things: the setting of the other knob and the load resistance. For example, if you turn the current knob up to its maximum value and if you use a large resistance for a load across the power supply outputs, the voltage knob will be the one that has an effect, while the current knob merely provides an “upper limit” to how high the current is allowed to go. This will be how you will usually operate the power supply in this course.

} An analog meter, with a needle, will have a measurement error due to your ability to read it. Use your own judgment of what you think is a reasonable value for the error, based on factors such as the width of the needle, the spacing between tick marks, and parallax due to viewing the meter with your head positioned at various angles.

\* – Set the power supply to two different voltages and measure each of these.

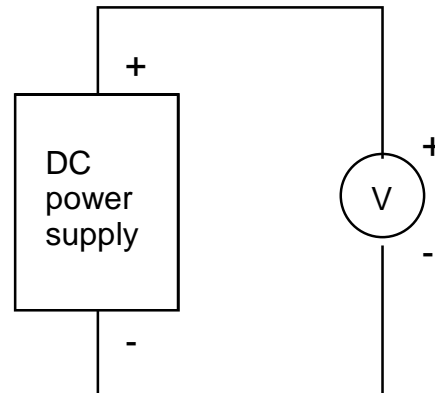
– Does the value on the power supply's meter agree with the value measured on the multimeter, within the error bars for the two measurements?

} As a rule, remember that meters on a power supply are usually less reliable than multimeters. Always make measurements of voltage and current with an external meter.

\* – As always, in both your notebook and report, draw the schematic for whatever you connect, including external instruments. For this measurement, it looks like the example below.



Power supply



Schematic

---

## 2. AC voltage and frequency

} No error measurements are required for this section.

\* Set the AC/DC switch of the multimeter to AC and reset the scale to maximum voltage.

\* – Plug the primary of the transformer (it is labeled 8 Vrms, but you will measure this yourself) into the AC outlet and measure the AC voltage of the transformer secondary.

} The wiring in a building in the USA is nominally rated at 110 V rms, but will vary from this value. Since this is connected to the primary of the transformer, and the voltage on the secondary is a fixed fraction of the primary voltage, you may find that your output voltage is not exactly the level printed on the transformer.

} The electrical generators used by utility companies produce a 60 Hz voltage

\* – If your multimeter has a frequency (Hz) feature, use it to measure the frequency of the transformer output.

\* Return the multimeter's ac/dc switch, if there is one, to dc.



Transformer

## 3. Resistance<sup>‡</sup>

\* Set the function switch to Ohms.

\* Check the meter by shorting the test leads. The meter should read zero ohms.

(a) Tolerances -- note: if you are color blind, skip this step and inform the TA.

\* For this step only, use the box of assorted resistors. Measure the resistance of four of your resistors. (Use only resistors with four bands; resistors with five bands are uncommon – sometimes the fifth band is used to indicate temperature sensitivity or to provide an additional significant digit for the resistance value.)

\* Determine the fractional error from the nominal value (from the color code).

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<sup>‡</sup> If you are *color blind*, you will be unable to identify the colors on the resistors. Inform the TA so that you can be excused from this step. Otherwise in this course, you will need to rely on your multimeter to determine your resistor values, if you are unable to read the color code.

– Make a table with seven columns: color code, nominal value, tolerance, measured value, multimeter scale, multimeter error, multimeter error as a fraction of measured value. How many of the values fall within the specified tolerance?

\* – As always, draw the schematic. For this measurement, see Fig. 1-3.

(b) Series & parallel

\* Choose two resistors that are within a factor of ten of the same value. Wire them up in series and then in parallel, using the board with three terminals. Measure the series and parallel resistances.

\* – Calculate the expected resistances (use measured values from part a) and compare with your measurements, including error values calculated using propagation of errors.<sup>§</sup>

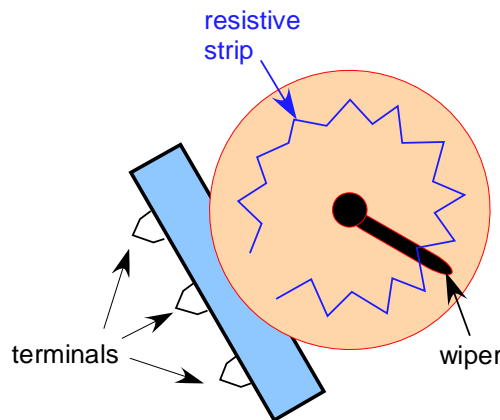
4. Potentiometer [no response needed for lab report]

\* The potentiometer has three terminals: two are the ends of a fixed resistor, and one is the “wiper.” Using the two leads of the multimeter to test different pairs of the potentiometer terminals, and by turning the potentiometer while observing the resistance: (a) determine which terminal is the wiper, and (b) verify that the resistance between the other two terminals does not vary as the potentiometer is turned.

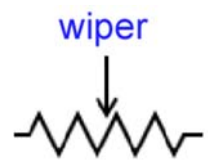
\* Determine which pair of terminals has a resistance that increases when you turn the potentiometer clockwise, as viewed from the top.



rotary




What's inside



Schematic symbol

<sup>§</sup> This is one of two instances in this lab where you are asked to use propagation of errors.

## 5. Continuity [no response needed for lab report]

- \* With the function switch set to Ohms, touch the two test leads together while watching the display.
- \* Now set the function switch to continuity. Depending on your multimeter, this might be indicated with a symbol like this: . Touch the two test leads together and listen for the beep.

### } **Caution:**

Avoid damaging your multimeter:

In the *current* function:

Never connect a *current* meter directly to a voltage source like 110 VAC or a battery. Without a resistor to limit the current, this would destroy the meter, or at least blow a fuse inside the meter.

In the *resistance* function:

Never connect the multimeter to a resistor that is part of a circuit. Use it only to measure the value of a loose resistor.

## 6. Current

### (a) Measured values

- \* – Measure the actual value of the resistor shown in Fig. 1-8. (Throughout this course, always measure your resistor values before assembling the circuit.)

### (b) Comparison to predicted values

- \* Wire up the circuit in Figure 1-8. Set the function switch to the maximum current scale (2 A) and connect the meter into the circuit.

} Note that for current measurements the meter is in series with the other elements of the circuit. This is different from voltage measurements, where it is in parallel.

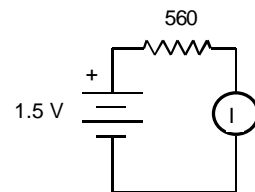


Figure 1-8.

- \* – Compare the measured value with the value of current you would calculate using the measured values of voltage and resistance. Do they agree within the error value range? Explain any discrepancy.

## 7. Current Source

- \* Connect a 1.5 V battery and a large-valued resistor (3.3 kΩ or higher) to make a current source. For a load resistor, use the resistor substitution box (choosing values ranging from 0.1 to 2.0 times the value of the large resistor), as shown in Figure 1-9.

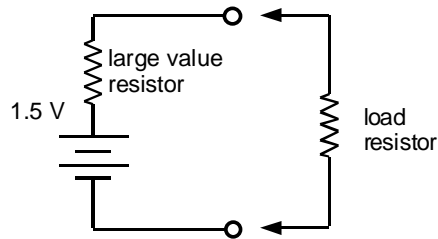


Figure 1-9  
Testing a current  
source

} This combination of a battery in series with a large resistor will act as a current source, provided the load resistance connected to the terminals is small. The current is:

$$\begin{aligned} I &= V / (R_1 + R_L) \\ &= (V / R_1) / (1 + R_L / R_1) \\ &\approx V / R_1 \text{ for } R_L \ll R_1. \end{aligned}$$

This is a crude current source, because the current depends on the load resistance, especially when  $R_L$  is not much less than  $R_1$ . You will build a better current source using a transistor in Lab 4.

- \* – Connect three different load resistances across the terminals and measure the current through the load resistor and the voltage across it in each case.
- (a) What is the most accurate way for you to use a multimeter to measure current: passing the current directly through the meter, or using the meter to measure the voltage drop across a known resistance and computing the current from Ohm's Law?

(b) Make a table and/or graph of current vs. load resistance.

(c) Compliance: Determine the range of load resistance over which the current remains constant to 10%.

*[Note: In Lab 4 (Junction Transistors) you will need this result again; record it so that you can find it then..]*

---

## 8. Voltage Divider - note: no error measurements required for this part

} A voltage divider reduces a voltage to a desired level.

- \* Measure the values of the resistors shown in Figure 1-10, then wire up the circuit. Use the prototyping board. Use the 5-Volt power supply built into the prototyping board to supply  $V_{in}$ .

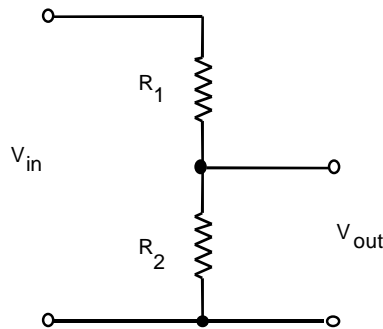


Figure 1-10  
Voltage Divider

### (a) without load

- \* – Measure  $V_{in}$  and  $V_{out}$  for  $R_1 = 3.3\text{ k}$  and  $R_2 = 1.6\text{ k}$ . Then repeat, with  $R_1 = 1.6\text{ k}$  and  $R_2 = 3.3\text{ k}$ . Compare  $V_{out} / V_{in}$  to the predicted values.

### (b) with load

- \* – Connect a  $1\text{ k}\Omega$  load resistor across the output. Determine how much  $V_{out}$  is reduced (loaded), reporting the reduction of  $V_{out}$  as % of the unloaded measurement of  $V_{out}$ . Using the rules for parallel resistances, compare to theory.

} Note that while a voltage divider is easy to build, it is a poor voltage source. Its output is not “stiff.” It is easily “loaded.”

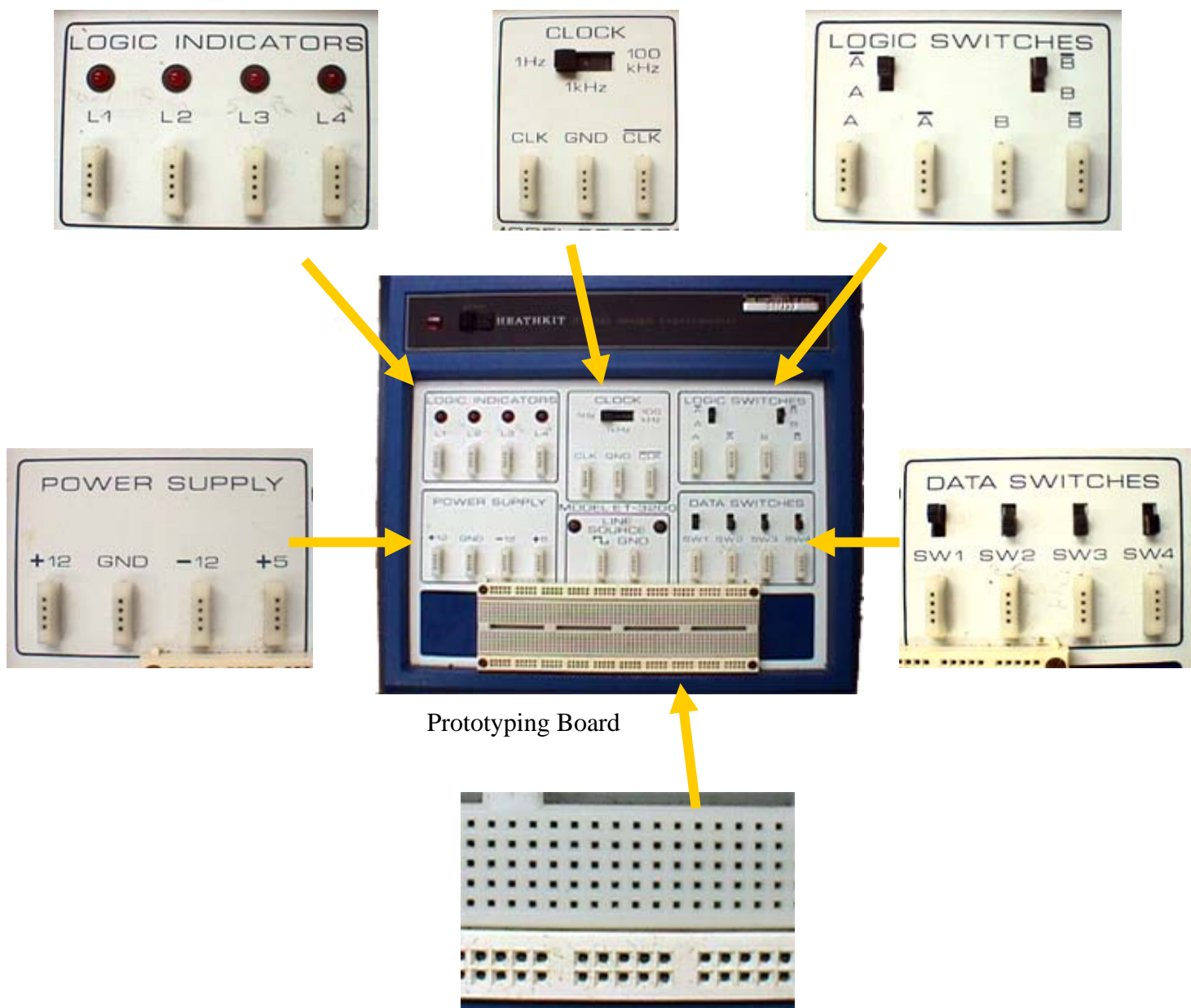
## 9. Learn how to use the prototyping board [no response needed for lab report]

### } The prototyping board

Prototyping boards are rows of connectors wired together behind a plastic face.

Things you can stick into the little holes of prototyping boards include:

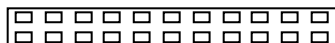
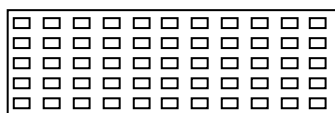
- wire (22 gauge solid-core is typical)
- resistor leads (1/4 or 1/8 Watt is typical)
- leads for transistors, capacitors, diodes, etc.



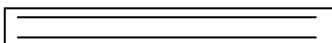
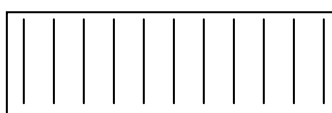
ICs (the hole spacing is made for DIP [dual-inline package] chips)

- \* Put an alligator clip connector on each test lead of the multimeter.
- \* Insert two wires into various holes in the prototyping board. Checking for continuity, convince yourself that the board is connected as shown below.

what it looks like from outside



connections under the surface





---

10. Potentiometer as a Voltage Divider [no response needed for lab report]

\* Examining Figure 1-9, use the potentiometer, instead of fixed resistors, to hook up the circuit. Be sure that you apply the *input* voltage across the two terminals that have a *fixed* resistance. The *wiper* of the potentiometer should be the output terminal in the middle-right of Figure 1-8. Observe the output voltage while turning the potentiometer. If the output voltage increases as you turn the knob clockwise, you are done; otherwise change one of the *output* connections.

11. Familiarity with switches [no response needed for lab report]

\* An SPST switch has two terminals, while an SPDT switch has three. Use a multimeter's continuity-check function to test these two switches. Become familiar with which terminals become connected or disconnected when the switch is in a certain position.



SPST



SPDT

# Lab 2

## AC Measurements

**REFERENCE:** Horowitz and Hill      Sections 1.13, 1.18, 1.19  
Appendix A (Oscilloscope)

### INTRODUCTION

} The object of this lab is to learn measurement skills. You will become familiar with the oscilloscope, function generator, and pulse generator, in measuring time-varying electrical signals. You will measure:

- DC and AC voltages
- Frequency
- Phase
- Time constant of an RC circuit
- Amplitude and phase-shift responses of low-pass and high-pass RC filters.

### EQUIPMENT

#### Lab supplies:

Analog Oscilloscope	(Tektronix 2235 or equivalent)
Function generator	(BK 4017)
Pulse generator	(HP 8013B)
DC power supply	
Multimeter – handheld	
Multimeter – Agilent 34410A	
~8 V transformer	
BNC cables	
BNC TEE	
BNC-banana adapter	
wooden board with binding posts	
use computer to plot graphs	
print graph paper at end of this manual	
to draw waveforms	

#### Student kits:

Resistors	5 k
Capacitors	0.003 $\mu$ F



## ABOUT ANALOG OSCILLOSCOPES

} The heart of an analog oscilloscope is its cathode ray tube (see Figure 2-1a). An electron gun produces a beam of electrons that strikes the screen, making a visible spot. The beam is deflected by two pairs of deflection plates. A sawtooth time-base voltage is supplied internally to the horizontal deflection plates to sweep the beam linearly with time across the screen horizontally. The voltage to be observed is supplied to the vertical deflection plates. The result is a picture of the signal voltage versus time.

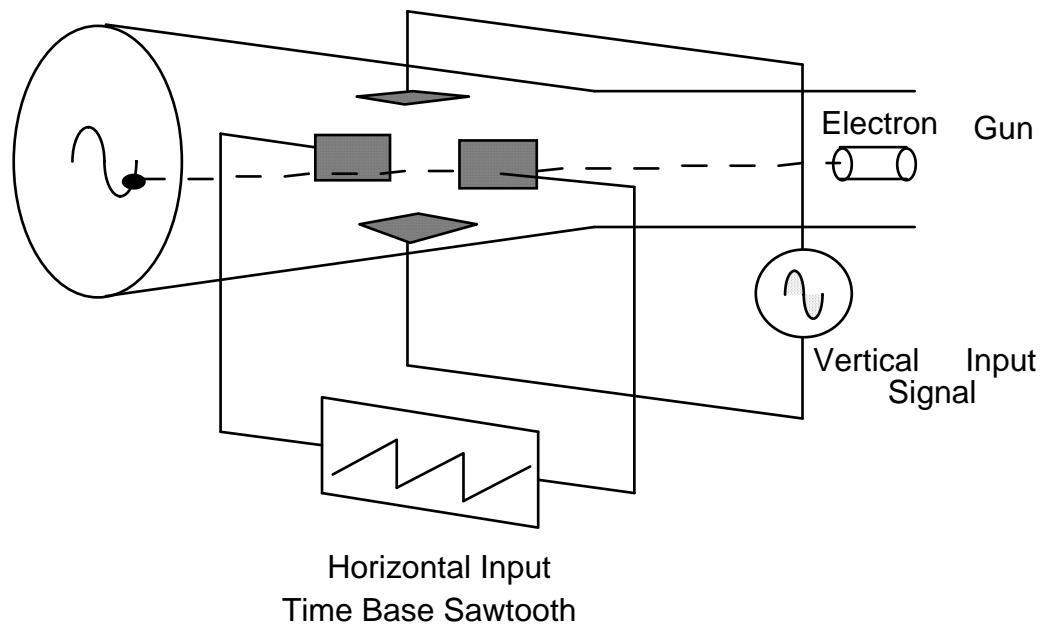


Figure 2-1

---

## ABOUT TRIGGERING

Triggering of an oscilloscope is often confusing for beginners. A trigger is an event that starts the horizontal sweep or trace (see Figure 2-1b). This trigger event is defined by comparing two voltages: the moment when the “trigger source” voltage exceeds the “trigger level” voltage is the trigger event.

The “trigger source” can be:

- an external voltage EXT that you connect to the oscilloscope,
- or it can be one of the vertical inputs, CH1 or CH2.

Usually you must choose between AUTO and NORM triggering:

- NORM triggering will allow a trigger only if there is a trigger event.
- AUTO triggering will cause a trigger even if there is never a trigger event (the beginner will usually use this setting since it always yields a display).

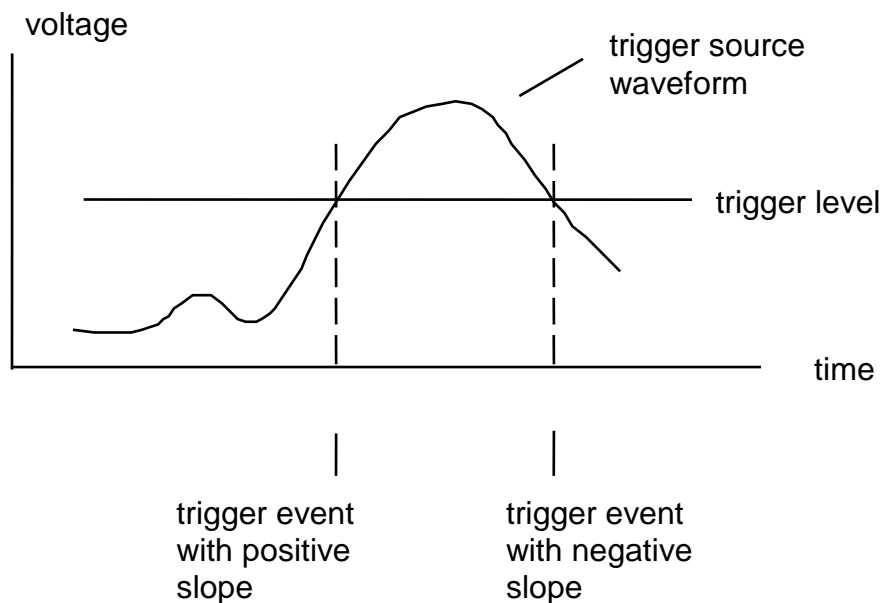


Figure 2-1 b Oscilloscope triggering

2235

100 MHz OSCILLOSCOPE

INTENSITY  
A — B



TRACE ROTATION



BEAM FIND



PROBE ADJUST



≈ 500mV P-P  
≈ 1kHz

FOCUS



POWER



ON OFF



VERTICAL MODE



CH1 VOLTS/DIV

10X PROBE



CH1 OR



1MΩ 20pF ≤ 400V pk

CH2 VOLTS/DIV

10X PROBE



CH2 OR



1MΩ 20pF ≤ 400V pk

HORIZONTAL MODE



A AND B SEC/DIV

ms μs



B DELAY TIME POSITION



VAR HOLDOFF



B TRIGGER



A TRIGGER



A SOURCE



A EXT COUPLING



EXT INPUT



≈ 100mV/DIV

1MΩ 20pF ≤ 400V pk

SERIAL  
B017034

} One use of the oscilloscope is to measure relative phases between two waveforms. This is done by adjusting both waveforms so that they are symmetric about the horizontal line in the middle of the screen. Then note the time delay  $\Delta t$  between the zero crossings, as shown in Figure 2-2. This corresponds to the phase shift, which is  $\phi = 360^\circ \Delta t / T$ .

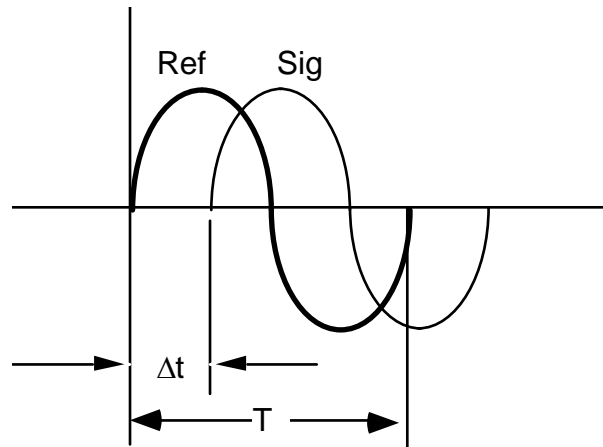


Figure 2-2

Tip: Sometimes it is hard to get *anything* to show on the scope. In that case, follow this procedure:

- set trigger to: AUTO, DC COUPLING, CH1
- set horizontal mode to: A
- set vertical mode to: BOTH
- set sweep speed to: 1 ms/div, CAL, MAGNIFIER OFF
- set vertical coupling to: ground
- turn up intensity
- wiggle vertical position until a horizontal line appears
- set vertical coupling to: AC or DC









---

## TA Instructions:

Before the students begin this lab, demonstrate the following tricks for using an analog oscilloscope:

### Checking trace rotation:

- Adjust the intensity as low as practical so that the trace is a thin curve
- Use GND coupling to produce what should be a horizontal line.
- Use the vertical position to move the curve to the middle of the display
- Verify that the trace is aligned with a horizontal gridline that is shown permanently on the display
- If not aligned, the scope requires using a small screwdriver to adjust the trace rotation; this is required for approximately one out of ten oscilloscopes each year.

### Measuring amplitude:

- Adjust the intensity as low as practical so that the trace is a thin curve
- Adjust the vertical scale so that the waveform fills *most* of the display area
- Use the GND coupling to adjust the zero, then the AC or DC coupling to make the measurement.
- Adjust the horizontal position so that the peak or trough of the waveform coincides with the vertical line that has fine tick marks
- Adjust the time scale so that the peak has an appropriate width, so that you can accurately find its maximum; typically this will require that you see about *two* complete oscillations in the horizontal direction.
- Use the second trace (other input channel) with a GND input to make a cursor, as an optional aide in measuring the waveform's height.

### Measuring time:

- Adjust the vertical scale to *overflow* it by a *significant* amount, so that the waveform looks like almost straight vertical lines; then look for zero crossings
- Use the lowest practical intensity.
- Adjust the horizontal position so that one of the zero crossings occurs on a major division of the horizontal scale.
- Choose an appropriate time scale for best resolution in measuring the time; typically about 1.5 or 2 complete oscillations displayed

---

## PRELAB

1. Recall the relationship of angular frequency  $\omega$  (units  $\text{s}^{-1}$ ) and the usual frequency  $f$  (Hz).
2. Calculate the roll-off frequency (in Hz)  $1 / (2\pi RC)$  that you expect for the low pass & high pass filters, using the nominal values for  $R$  and  $C$  as specified in the schematic diagrams.
3. Calculate the charging time  $RC$  (in msec) that you expect for the low-pass filter circuit.
4. Find the formula for the frequency response curve for a *high-pass* filter. This formula will be an expression with the ratio  $V_{out} / V_{in}$  on the left-hand side of the equation, and the right-hand side will depend on  $f$ ,  $R$ , and  $C$ . Find or make a graph of this function.
5. Find the formula for the frequency response curve for a *low-pass* filter. Find or make a graph of this function.

---

## PROCEDURE

- \* Read Appendix A in Horowitz and Hill 2<sup>nd</sup> Ed. You will need to know oscilloscope terminology before you begin.
- \* In this lab you will record a lot of data. It is recommended that you record it in columns in your lab notebook, with separate columns for:
  - the reading (e.g. in mV)
  - the scale on the oscilloscope (e.g. 100 mV per division)
  - the estimated error for each measurement.

### 1. Measurement of Voltages


#### (a) DC Voltages

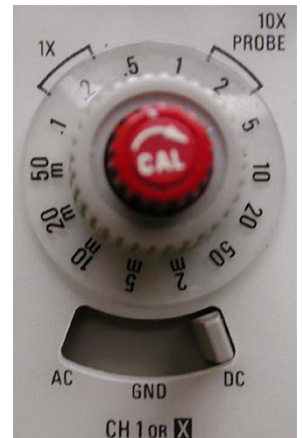
- \* To start, adjust the oscilloscope settings to the following:\*\*

#### vertical mode CH1

CH1	Volts/Div	1 Volt (use 1x indicator on dial)
	input coupling	GND
	CAL knob	fully clockwise to click
CH2	same as CH1	
	set INVERT switch	to the out position

#### horizontal mode A

time base	A sec/div	1 ms
	CAL knob	fully clockwise to click
var holdoff	NORM	
A trigger	P-P AUTO	
level	turn to middle of knob's range	
slope	rising slope	
A & B INT	CH1	
A source	INT	
A ext coupling	DC	



---

\*\* These instructions are for Tektronix 2235; other analog oscilloscopes are similar.

- 
- \* Once you have found a trace that looks like a horizontal line, use the vertical position knob on CH1 to position the trace in the center of the display. Then change the CH1 coupling to DC.
  - \* Connect the output of an adjustable power supply to the oscilloscope input CH1. You should see a trace at a non-zero voltage. Change the CH1 coupling back and forth, from GND to DC, to see the difference.
  - \* – Set your power supply to three different DC voltages and measure each voltage with both the oscilloscope and the digital multimeter.
  - \* Adjust the display intensity as low as practical so that the trace is a thin line.
  - Compare the DC voltage measurements of the oscilloscope and the digital multimeter. Report the measurement uncertainty (error) values, based on the specifications for the multimeter and the oscilloscope, and your impression of how precisely you can read the oscilloscope display. Which is more precise, the meter or the oscilloscope?

(b) AC Voltages

- \* Connect the function generator to signal input CH1 of the oscilloscope.
- \* Set the function generator to produce a sine wave of about 1 to 2 Volt amplitude, a frequency of about 100 Hz, and no DC offset. Verify that the sweep INT/EXT switch is in the EXT position, to disable the “sweep” feature of this instrument.
- \* Set a multimeter to the AC voltage function. Connect it to the function generator’s output.
- \* Adjust the display intensity as low as practical so that the trace is a thin line.
- \* – Measure the peak-to-peak AC voltage using the oscilloscope. Calculate the RMS value of the voltage.
- Compare the AC voltage oscilloscope measurements to those on the digital multimeter. Report the measurement uncertainty (error) values. Which is more precise, the meter or the oscilloscope?

(c) Sweeping the frequency [no response necessary for lab report]

- \* Learn to use the frequency sweep feature of your function generator. “Sweeping” means that the frequency is ramped up with time in a way that repeats itself. Observe this by depressing the INT button to enable the sweep.

---

Observe the waveform. Try different adjustments of the TIME and WIDTH knobs for sweep to see their effect.

\* When you are done, return the generator to its normal (non-sweep) operation by pressing the INT button so that it is out (not in).

(d) AC and DC coupling

\* Make sure the oscilloscope coupling is set to DC.

\* Set the function generator frequency to about 10 kHz.

\* Turn on the offset voltage on the function generator, and twiddle the offset up and down. You should see a vertical deflection of the trace.

\* Now change the oscilloscope coupling to AC and twiddle the offset voltage slowly. You should see no change.

– Explain the difference between AC and DC coupling. Through what additional component inside the oscilloscope does the signal pass when using AC coupling?

## 2. Measurement of Frequency

\* Use the same set-up as above. Use a digital multimeter to measure the frequency, connecting the multimeter to the function generator's SYNC output (which might be labeled TTL, depending on the model of the function generator). Determine the frequency from the measured time per cycle. Repeat for five frequencies in total, over the entire range of the function generator.



Sync output of  
function  
generator

– Make a table to compare the frequency measurements made with the oscilloscope to those with the digital multimeter. Include columns for the measurement uncertainty (error) values. Which is more accurate, the meter or the oscilloscope?

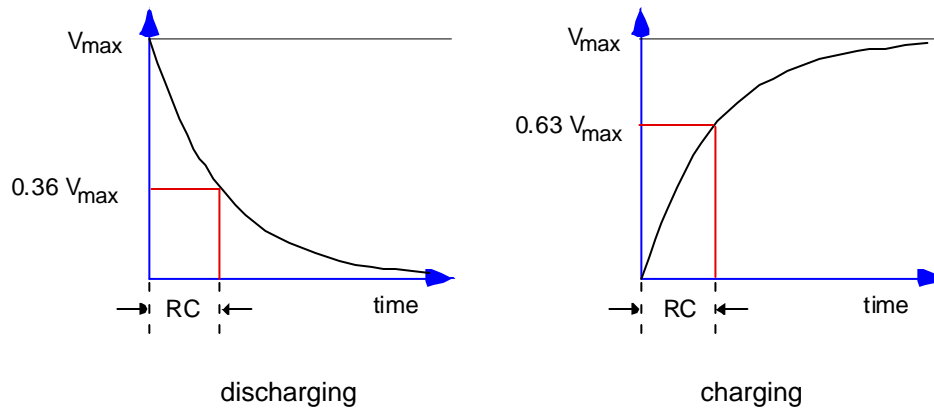
} As a practice, never trust the frequency and voltage readings shown on a function generator. Always make external measurements of the frequency and voltage.

\* For the remainder of this experiment, use the multimeter for your frequency measurements.

### 3. Time Constant of an R-C Circuit

} The output voltage of an RC filter is

$$\begin{array}{ll} V(t) = V_{max} [1 - \exp (-t/RC)] & \text{for charging} \\ V(t) = V_{max} \exp (-t/RC) & \text{for discharging} \end{array}$$



Rules of thumb:

$RC$  The product  $RC$  is called the “RC time constant” or simply the “RC time”.

When the input voltage of an R-C circuit changes from one level to another, the output voltage will approach its final value asymptotically.  $RC$  is the time required for the output to swing by 63% toward its final value. [Because  $1 - \exp (-1) = 0.63$ .]

$5RC$  is the time required to swing within 1 % of the final value. [Because  $\exp (-5) = 0.007 \pm 1\%$  ]

- 
- \* – Measure the actual values of a 5 k resistor and an 0.003  $\mu\text{F}$  capacitor.
  - \* Connect the series  $R$ - $C$  circuit to a function generator and an oscilloscope, as shown in Figure 2-3 a and 2-3 b. (This circuit is shown two ways to help you figure out how to wire it up.) Use a wooden board with binding posts.
  - \* Connect a multimeter to a function generator to measure its frequency.
  - \* Set the oscilloscope for external triggering (EXT), and connect the trigger input to the SYNC output of the function generator (BNC connector labeled TTL/CMOS, see photo).



Sync output  
of function  
generator

- \* Set the function generator to produce square waves with a peak-to-peak amplitude of about 5 Volts. Set the frequency so that it is appropriate for measuring the time response of the  $R$ - $C$  circuit -- the period  $\tau = 1/f$  should be  $\geq 10 RC$ .
- \* Set the oscilloscope vertical voltage scales to be the same, choosing a scale so that the trace fills a large portion of the screen. (If it fills only a small portion of the screen, your measurements will not be very precise.) Use GND input coupling to find where zero volts is, and use the vertical position to locate this on a gridline.
- \* If your function generator has a DC offset, adjust it so that the bottom of the waveform is at zero volts. Draw the oscilloscope display for the square wave, and indicate the voltage at both the bottom and top of the waveform.
- \* Adjust the oscilloscope horizontal time base so that the discharge time takes a considerable portion of the display. Use the horizontal position to locate the waveform so that the triggering time is at a convenient gridline.

(Your display should look like the figure above, labeled “charging.” Change the oscilloscope trigger slope between + and - to see the difference it makes.)

(a) Charging

- \* – Determine the charging time constant from the oscilloscope display. Estimate your errors. Calculate the ratio of your charging time to  $RC$ .

(b) Discharging

- \* Change the scope triggering slope to see the discharge portion of the trace. (Your display should look like the figure above, labeled “discharging.”)
- Determine the discharging time constant from the oscilloscope display. Estimate your errors. Calculate the ratio of your discharging time to  $RC$ .

Figure 2-3 a

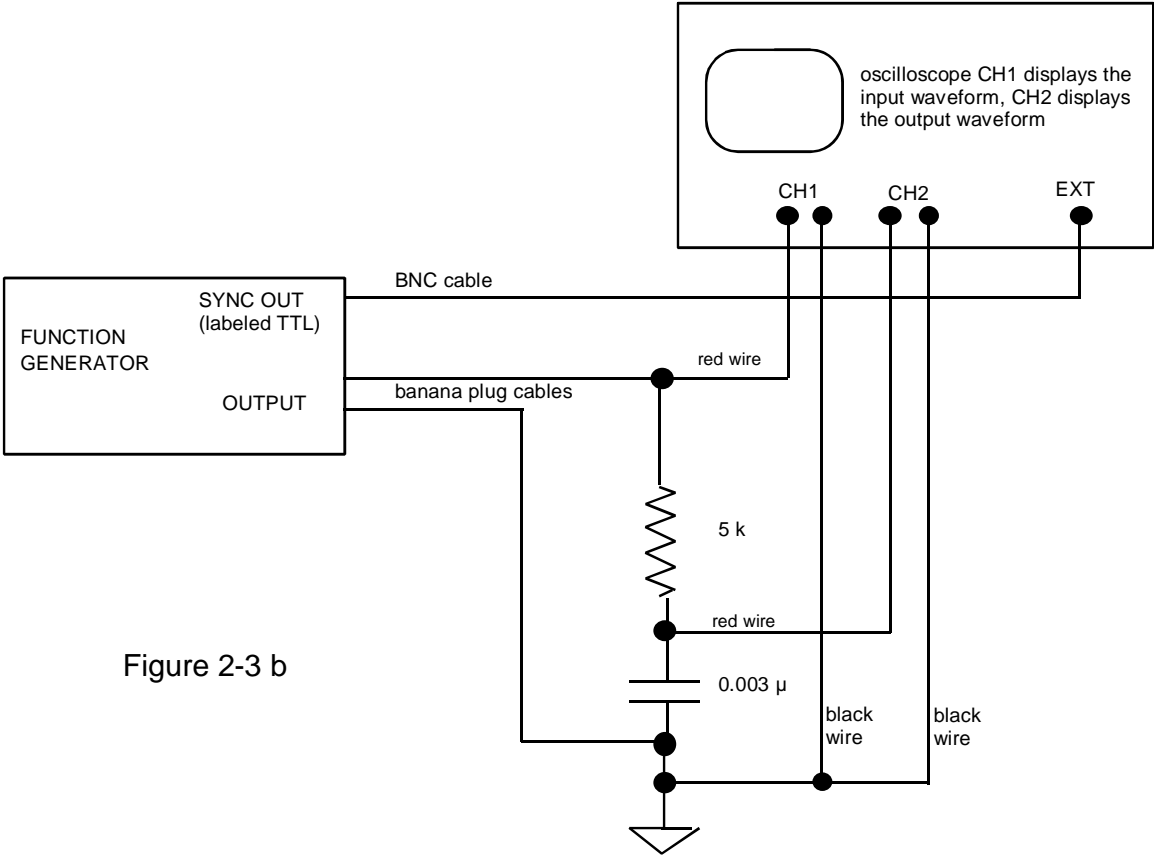
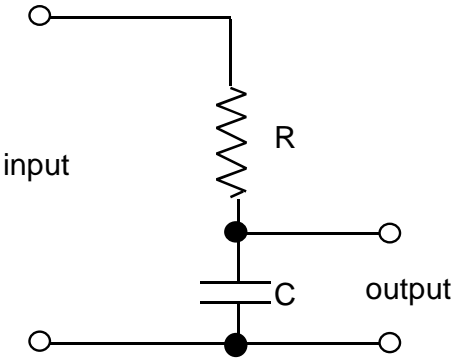


Figure 2-3 b



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#### 4. R-C Low-Pass Filter

##### (a) Amplitude Response

- \* Use the same circuit as above, in Figure 2-3 b.
- \* Set the function generator to produce a sinusoidal output with an amplitude of about 4 or 5 V peak-to-peak. Use a 1, 2, 5 frequency sequence from 500 Hz to  $10^5$  Hz (i.e., 500, 1000, 2000, 5000 Hz, ...)††. Also include a frequency of  $f = 1 / (2\pi RC)$  in this sequence, as calculated from measured values of  $R$  and  $C$ .
- \* – (i) Record a table of your data with columns for:
  - $f$  (Hz), error bar for  $f$
  - $V_{in}$ , oscilloscope scale for  $V_{in}$ , error bar for  $V_{in}$
  - $V_{out}$ , oscilloscope scale for  $V_{out}$ , error bar for  $V_{out}$ .
  - $V_{out} / V_{in}$
- (ii) Plot the voltage ratio  $V_{out} / V_{in}$  with log-log axes, with frequency on the horizontal scale. Make a theoretical plot of  $V_{out} / V_{in}$  on the same graph. You may use Graphical Analysis or other software to create the graph using the instructions below.

– At a frequency of  $f = 1 / (2\pi RC)$ , compare the ratio of the output and input voltages to the predicted ratio  $V_{out} / V_{in} = 0.707$ .

##### (b) Phase Response

- \* Use the same circuit as above.
- \* Measure the phase shift of the voltage across the capacitor relative to the input voltage from the oscillator, for the same frequency sequence as for the amplitude response above.
- (i) Record your data with columns for:
  - $f$  (Hz), error bar for  $f$
  - delay in msec, error bar for delay in msec\*
  - phase in degrees, error bar for phase in degrees.

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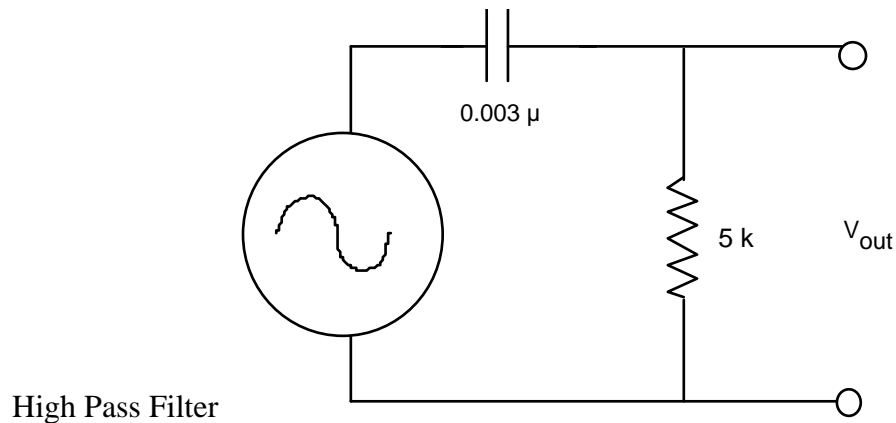
†† Tip to save time: it's quicker to do both the *amplitude* and *phase* measurements for a frequency before changing the frequency

- \* Indicate whether the output is delayed compared to the input or vice versa
- (ii) Plot the phase curve on a graph with a semi-log scale ( $\theta$  linear,  $f$  log). Compare with a theoretical plot of the phase shift on the same graph.

(iii) What is the phase angle, measured and theoretical, at  $f=1/(2\pi RC)$ ?

### 5. R-C High-Pass Filter

- \* Use the same 5 k $\Omega$  resistor and 0.003  $\mu$ F capacitor as in the R-C low-pass filter, above, but swap them to make a high-pass filter.



- \* Instead of the analog oscilloscope, use the Agilent 34410A multimeter to measure the input voltage (rms) and output voltage (rms).
- \* – Make the amplitude response measurements and plots (omit the error values). Use the following frequencies: 100 kHz, 50, 20, 10, 3, 1, 0.3, 0.1 kHz; also include a frequency of  $f=1/(2\pi RC)$  in this sequence, as calculated from measured values of  $R$  and  $C$ .

### 6. Measurement skills [no response necessary for lab report]

Use your remaining time in the lab session to familiarize yourself with the oscilloscope and pulse generator.

- \* Connect the function generator to the oscilloscope as shown.

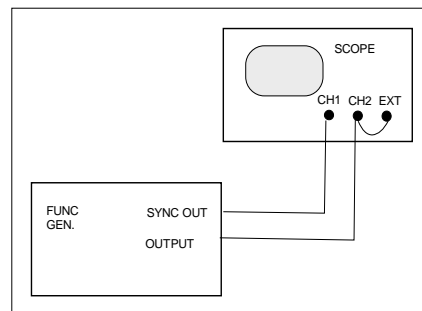


Fig. 2-

- \* Adjust the oscilloscope settings to the following settings (hereafter referred to as the *original settings*).

<u>Vertical mode</u>	BOTH and ALT
CH1	Volts/Div 1 Volt (use 1X indicator on dial)
input coupling	DC
CH2	same as CH1
INVERT switch	set to the out position

<u>horizontal mode</u>	A
time base A sec/div	0.2 ms
VAR HOLDOFF	NORM
A TRIGGER	P-P AUTO
LEVEL	turn to about the middle
SLOPE	out
A & B INT	CH1
A SOURCE	EXT
A EXT COUPLING	DC

- \* Adjust the function generator settings to produce a sine wave with a frequency of about 100 Hz, with DC offset turned OFF.
- \* Learn the various vertical modes

Try various settings of the vertical mode switches and see the display.

Use the “BOTH” mode on the vertical mode. Compare ALT and CHOP. (You may need to adjust the beam intensity on the scope.)

Change time base to 5  $\mu$ s, observing the display. Again compare ALT and CHOP. You may be able to see the chopping of the signals in the chop mode.

Do you understand the difference between ALT and CHOP?

- \* Learn how to use X-Y mode.

First return the oscilloscope to the original settings.

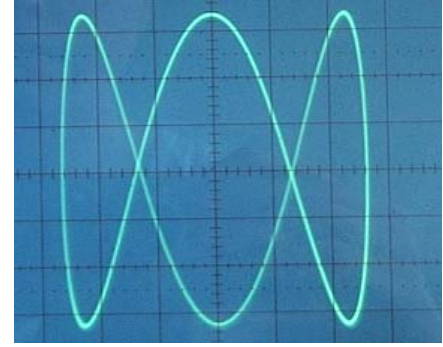
Then set the time base to X-Y.

---

Vary the CH1 and CH2 volts/div and see how the display changes.

Make a Lissajous figure. Connect a ~8 V transformer to CH1 and a sine wave from the function generator to CH2. Adjust the frequency to multiples of 60 Hz while watching the display.

Don't worry if you are unable to make the figure stationary. – it is hard to make two independent oscillators operate synchronously



Lissajous figure

\* Learn about trigger levels

First return the oscilloscope to the original settings, and set the time scale to 0.2 ms.

Change the cables to the function generator as shown in Figure 2-4. Adjust the function generator to produce a sine wave of about 1 kHz.

Vary the trigger level and the trigger slope. Observe the results. Do you understand why the display depends as it does on these settings?

Change the trigger mode from AUTO to NORM. Adjust the trigger level and/or the function generator amplitude until you see that the oscilloscope no longer triggers. Then adjust them back so that they do trigger. Do you understand why the display depends on these parameters in the NORM trigger mode?

Return the oscilloscope triggering to AUTO before proceeding.

\* Learn to use the pulse generator

Repeat the steps above, using the delayed sweep, but this time use the Pulse Generator instead of the Function Generator. The purpose of this exercise is to learn about pulse generators, and to further develop oscilloscope skills.

For the output, use the pulse generator's right-most BNC connector.



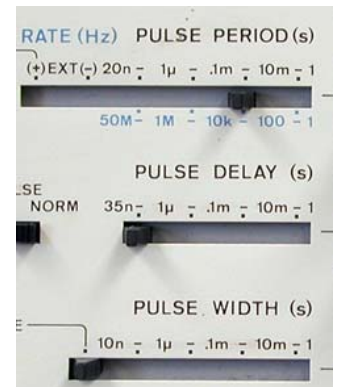
Adjust the HP pulse generator so that it has the following settings:

Sliding switches:

Pulse period: 20 ns - 1  $\mu$ s  
Pulse delay: adjust to minimum  
Pulse width: 10 ns - 1  $\mu$ s  
Amplitude: adjust to maximum

Other switches:

Pulse: Norm  
Offset Off  
Output Norm  
Int Load IN



Verniers:

Pulse period 3 O'Clock position  
Pulse width 12 O'Clock position  
Amplitude 12 O'Clock position



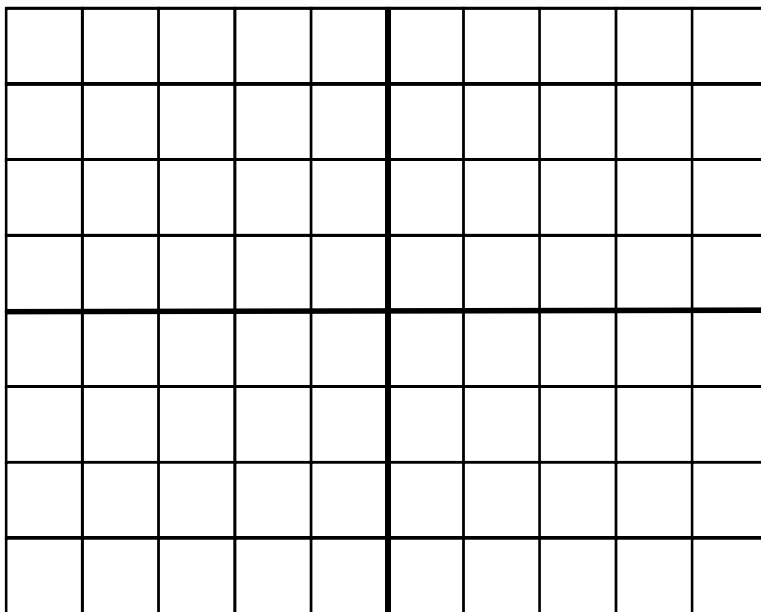
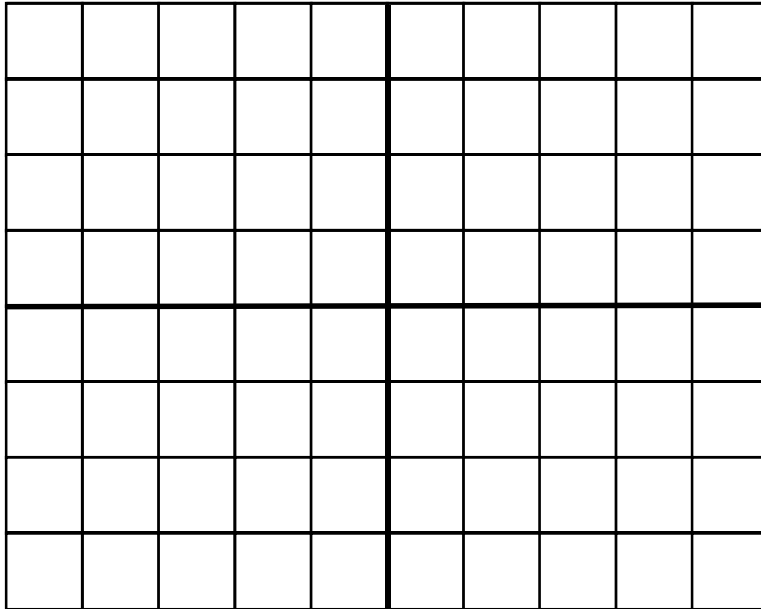
When examining the delayed traces, notice whether the pulse generator produces a more ideal square pulse than the square wave from the function generator. Look for "ringing", i.e., unwanted oscillations.

After you've finished with the delayed trace:

- Set the scope to Horizontal Mode A, so that you are no longer viewing the delayed sweep.
- Pull the time base knob out so that the mark on the inner knob is aligned with the two black marks on the clear outer knob; now they will move together when you adjust them. Be sure that the vertical coupling of CH1 is set to be DC.
- On the pulse generator, vary the following, and observe how the waveform changes:
  - Vary the vernier for pulse period.
  - Vary the vernier for the pulse width (up to a maximum of 50% of the pulse period).
  - Switch between NORM and COMPL output.

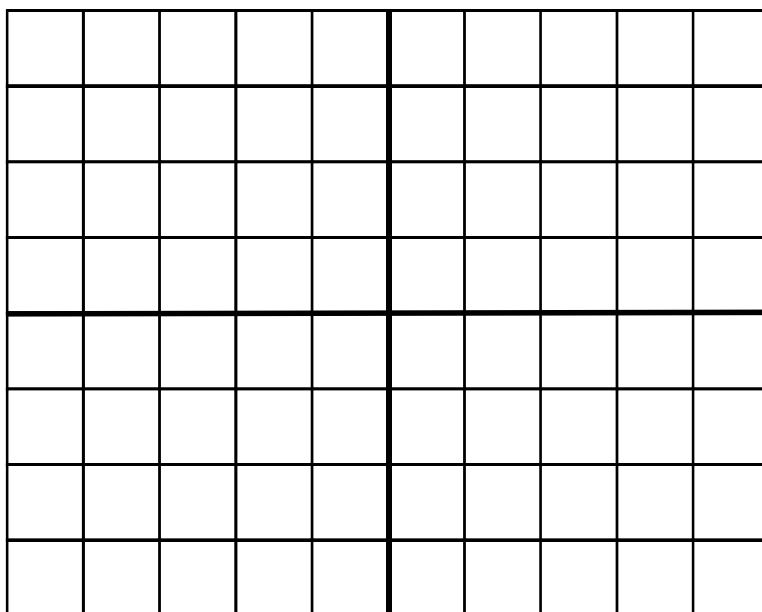
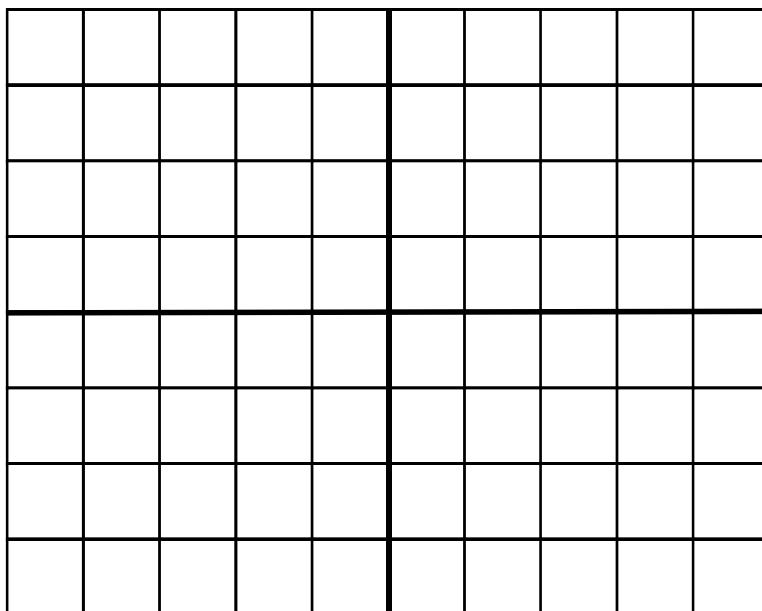
---

Print these blank “oscilloscope screens” and use them to sketch waveforms shown on an analog scope.



---

Print these blank “oscilloscope screens” and use them to sketch waveforms shown on an analog scope.





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## Lab 3

### Diodes, Power Supplies, Zeners, and SCRs

<b>REFERENCE</b>	Horowitz and Hill	Sections 1.25- 1.30.	rectification filtering, regulation
		Sections 6.11 - 6.14	power supply parts
		Sections 6.16	3-terminal regulator

### INTRODUCTION

In this lab we examine the properties of diodes and their applications for power supplies and signals:

- Diode rectification in half-wave and full-wave bridge circuits
- Filtering in power-supply circuits
- 3-terminal voltage regulator
- Zener diode and its use as a voltage regulator
- Diode clamp circuit
- Silicon controlled rectifier (SCR)

Note: the instructor probably will choose not to do all of the above. Professor Goree usually skips the SCR.

We will also build our measurement skills, learning to use a digital oscilloscope.

---

## EQUIPMENT

### Lab supplies:

Digital Oscilloscope

Function generator

Multimeter (handheld model only; to protect the more expensive Agilent 34410A, do not use it for this lab.)

Prototyping board

Transformer, center tapped ~8 V

Variac

[for 3-term.regulator]

Resistor substitution box

Potentiometer 50 k

[for SCR circuit]

SCR

[for SCR circuit]

0 - 30 V dc power supply

6 V lamp

[for SCR circuit]

Test leads

Scope probe

BNC-banana plug adapter

### Student kits:

Wire kit

Power diodes (4 & spares)

Signal diodes (2) 1N914 (or similar)

Zener diode (1 & spares) 5 V or 10 V

Resistors 91 (2 W), 1 k

56 k, 110 k

[for SCR circuit]

Capacitors

0.47  $\mu$ F, 100  $\mu$ F (2),

1000  $\mu$ F

[for SCR circuit]

0.01  $\mu$ F, 4.7  $\mu$ F

[for 3-term. regulator]

3-terminal regulator

78L05 in TO-92 package

[for 3-term. regulator]



1N914 signal diode



Power diode



TO-92 package

---


## **PRELAB**

1. Identify all the formulas you will need in this Lab.
2. Identify a type of connector you should not connect to a power diode, to avoid melting it.
3. What will happen if you connect a diode directly across the two terminals of a power supply, without a series resistor?
4. For the measurement of current, how must a multimeter be connected differently as compared to the measurement of voltage?

---

## PROCEDURE

### 0.0 Ohmmeter Check of Diode

- } You will need a multimeter to confirm the polarity of a diode. You don't need to report your results here in your lab report.
- } Use a magnifying glass to read the part numbers of your diodes, and to distinguish the signal, zener and power diodes.
- \* Look at your multimeter to see what special features it has. It might have a diode-check feature, as shown by the symbol . If it has one, depending on the model, the display might indicate the diode-drop *voltage* if the diode is not damaged.
- \* Confirm the PN polarity of a signal diode (these are smaller than the power diodes). Look at the markings on the diode to see how they show the polarity.
- \* Repeat the diode tests above, using a power diode.
- } Note that for a multimeter check to work, the multimeter must apply a voltage of at least 0.5 Volt between its two leads to bring the “diode” into conduction when it is forward biased.
- } If you suspect that you burned up a diode, check its diode drop using a multimeter to see if it is still good.

#### CAUTION:

In this lab it is possible to burn up components if you are not careful to make sure everything is correct before turning on the power.

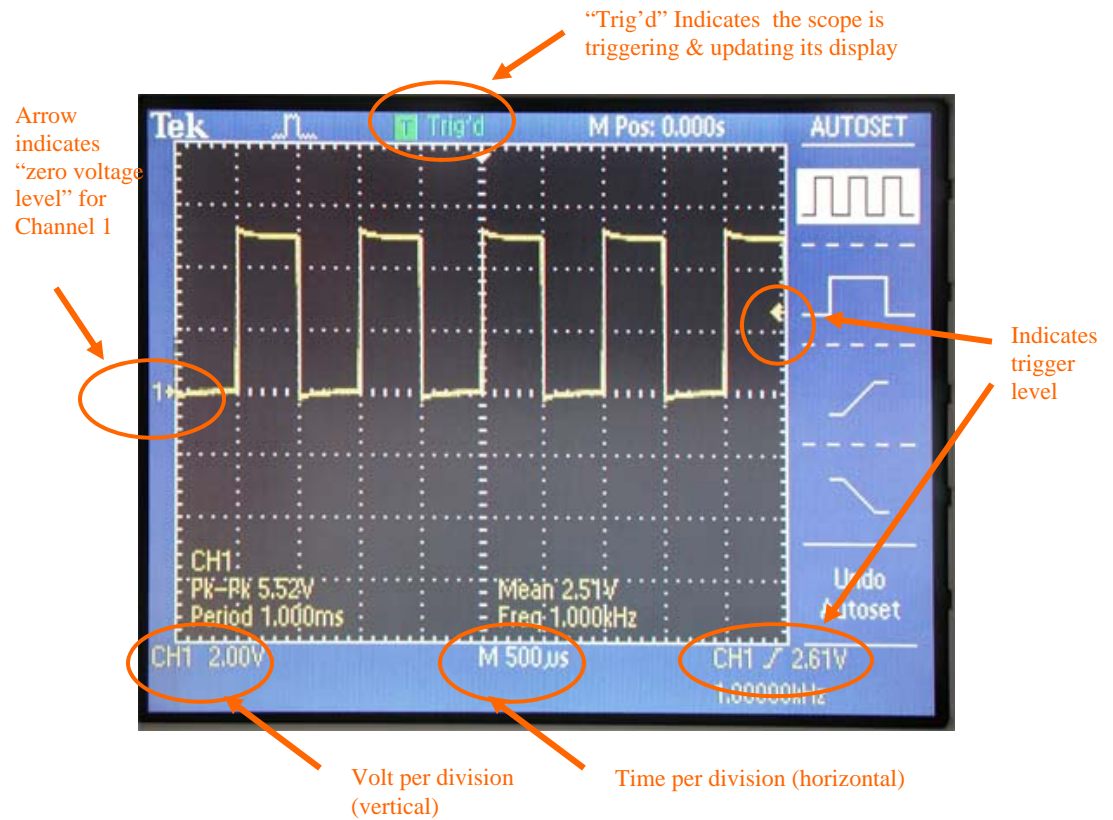
- Please note all caution statements in these instructions.
- Double-check before turning power on!
- When using the decade box, do not set the load resistance below 50  $\Omega$ .

- 
- \* Learn to use the digital oscilloscope & a scope probe – no written response required

Connect a scope probe to the digital oscilloscope as shown in the photos below.

A scope probe has two settings: 1X and 10X (photo shows 10X setting). This notation might be confusing: the 10X setting has the effect of dividing, not multiplying, the signal by a factor of ten. An advantage of a 10X probe is that it has a higher frequency response, so that if you need to view signals  $> 1\text{MHz}$ , you should use a 10X probe. In most of this course you will view slower signals, and a 1X probe is adequate.





Press the AUTOSET button to see the display of a square wave

Push the CH2 MENU button twice, to see how this turns the display for that channel off and on. The two channels are distinguished by their color.

To see their effect, adjust these knobs: VOLTS/DIV, SEC/DIV, VERTICAL POSITION, HORIZONTAL POSITION. Look for the arrow at the top that indicates the trigger time, and the arrow at the right that indicates zero voltage.

Push the CH1 MENU button to see the display. Toggle the “Probe” setting so that it indicates the same setting as on your probe (1X, not 10X or 100X). You must always check this, before using the scope, to avoid X10 errors in your voltage measurements.

Push the TRIG MENU button and view the menu. Sometimes in this course you will be asked to use EXT TRIG, which you can accomplish with the digital oscilloscope by toggling “Source” to the “Ext” setting. At other times, you might wish to use CH1 as the “Source.”



Build your triggering skills:

First, choose “AUTO” trigger, with the source specified as the same channel (1 or 2) as your probe. While viewing the square wave from the probe, adjust the trigger level knob up and down while watching the display. Observe that when the trigger level is adjusted too high or too low, there is a loss of triggering, and this can casuse the displayed waveform to be unstable in the horizontal direction.

Next, repeat with “NORM” rather than “AUTO” trigger. In this mode the scope will not update the display unless there is a valid trigger event, unlike the “AUTO” mode which will trigger occasionally even when there’s no valid trigger event, just so that you can see at least something on the display.

Push the MEASURE button and view the menu. Toggle the “Type” setting to measure the peak-to-peak voltage and the frequency of the waveform. Then adjust the TIME/DIV knob so that less than one full oscillation is shown, and notice how the scope is unable to measure frequency.

---

## 0.5 Digital Oscilloscope Skills

- \* – Use the function generator to apply a sine wave of approximately 1.2 – 1.8 volts amplitude and approximately 1 kHz frequency to one of the oscilloscope inputs. Using the MEASURE button, measure the amplitude and period of the waveform.
  
- \* – Compute the uncertainty of the amplitude, and the uncertainty of the period.
  - Do this using specifications from the oscilloscope manufacturer's user manual. For the TDS 1000 or 2000 series oscilloscope, see pp. 155-156.
  - To compute the uncertainty of the period, you will require the sample interval, which is the reciprocal of the samples per sec; this parameter depends on the tim/div setting – see the table on pp. 22-23.
  - Note: this exercise is intended to train you to look up manufacturer's specifications for an instrument, which is a routine all physics experimenters should follow in their research.



---

## 1. Diode Limiter

} Diode limiters can be used at the inputs of small-signal instruments to protect against accidental application of large input signals.

} This is a low-current application, so you use signal diodes, not power diodes.

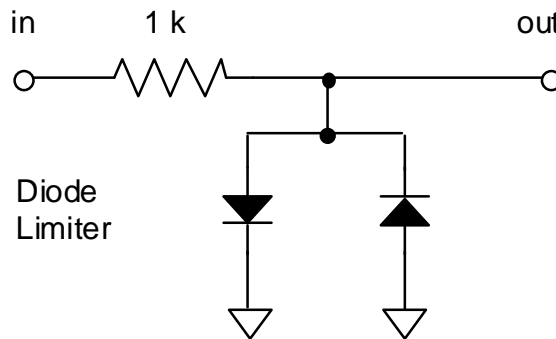
} Like most diode circuits, this has a *resistor* in series with the diode. Without this resistor the diode would burn up when it conducts.

\* Using (small) signal diodes, connect the input of the circuit shown below to the function generator, set to about 1 kHz. Check that the –20 dB attenuator switch on the function generator is activated. Try sine, triangle, and square waves of various amplitudes. Try a low amplitude for the oscillation, and adjust the function generator's dc offset to observe the effect of clipping.

\* – Print the output of the clamp circuit for sine wave inputs two ways:

- With an output waveform that is severely clipped.
- With an output waveform that is only slightly clipped.

– Comment quantitatively on the output amplitude where clipping is strongly observed and identify the diode's parameter that determines this amplitude.



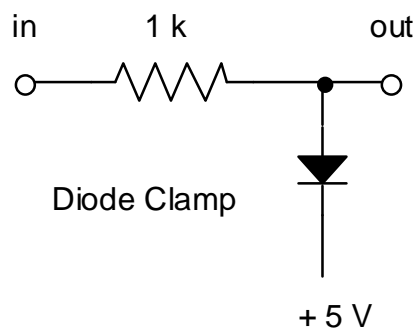
## 2. Diode Clamp

\* Connect the clamp circuit in the figure. Use the +5V power supply built into your prototyping board.

} This is a low-current application, so you use signal diodes, not current diodes.

\* Connect the input of this circuit to the function generator with a sine wave at 10 kHz. Check that the –20 dB attenuator switch on the function generator is not activated.

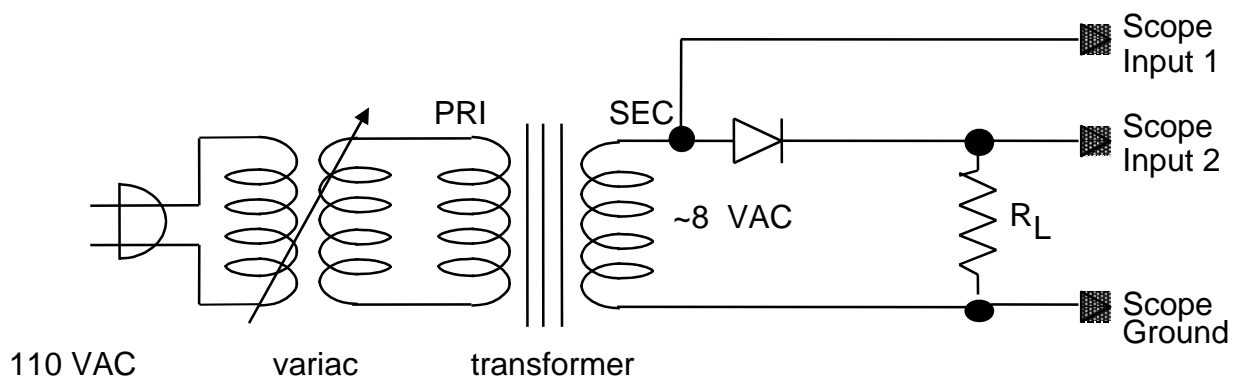
- \* Set up the oscilloscope to show the input and output waveforms. Use DC input coupling on the oscilloscope,
  - \* Connect three grounds together: the ground of the 5 V power supply, the ground of the function generator, and the ground of the oscilloscope.
  - \* Adjust the sine wave amplitude so that you can see a “clamped” output.
- Print the waveforms for the input and output of the clamp circuit. (If you can see that the clamped voltage is not quite flat, then you can see the effect of the diode’s non-zero impedance in conduction.) From your observation explain in one or two sentences what the clamp circuit is useful for.



### 3. Power Supply Rectifying Circuits

#### (a) Half Wave Rectification

- \* Set up the circuit as sketched here. (For this part, ignore the center-tap (CT) terminal on the transformer, if any.) You are building a power supply, so use power diodes rated at 1 W, not the little signal diodes. For the load, use a 1 kΩ resistor (or a resistor substitution box set for 1k).



\* **Caution:** do **not** use the insulated “mini grabber” connectors to connect the transformer to power diodes; they can melt and they are costly. Instead, use alligator clips



Mini-grabber connector

\* **Caution:** take care in arranging components on your prototyping board to avoid shorting the alligator clips:

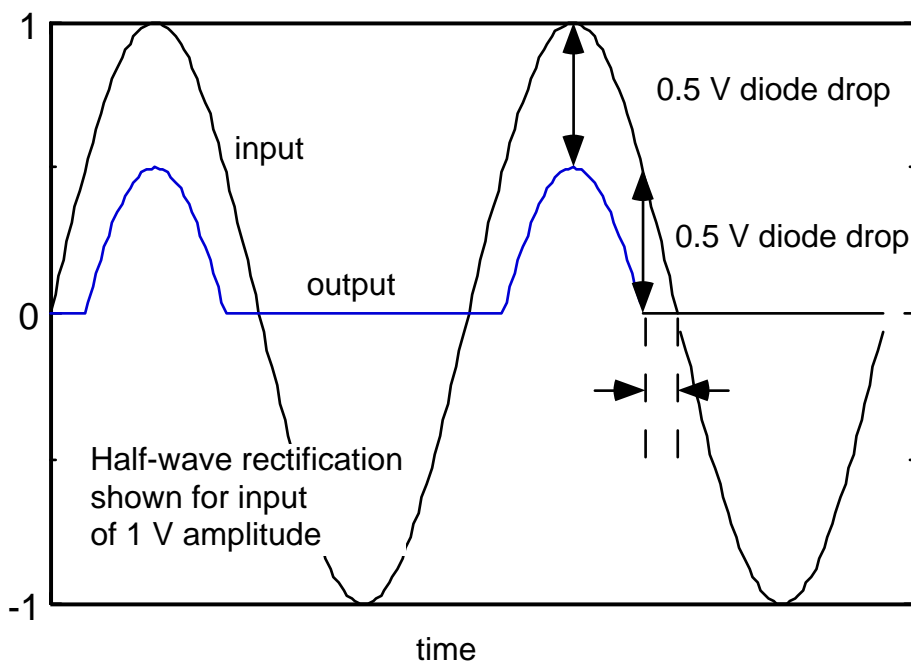
- Keep the two alligator clips >2 inches apart so that they can't touch one another.
- Don't let the alligator clip touch ANY undesired conductor, as that can also cause a short.

\* If using an analog scope, set the oscilloscope as follows:

**input coupling** DC (CH1 and CH2)

**vertical mode** BOTH and either ALT or CHOP (this is the dual trace feature)

} In the figure below, the waveforms are shown as they would look if the input voltage had a 1 V amplitude. Notice the 0.5 V diode drop. Also notice the time interval shown between the dashed lines, when the input voltage is positive but not large enough for the diode to conduct.



\* Adjust the variac to indicate 10 VAC output.

- \* — Measure the P-P amplitude of:
  - the input voltage  $V_i$  from the transformer

- 
- the rectified sine wave output voltage  $V_o$  across the  $1\text{ k}\Omega$  "load resistor"  $R_L$ .

- Print the input and output waveforms and compare the peak output voltage with half of the PP input voltage. Explain the difference.

- \* – Repeat without the variac, i.e., with the transformer powered directly from a 110 VAC outlet, so that the waveform from the transformer has a larger output.

(b) Full Wave Rectification

- \* **CAUTION:** In this part, carefully *check the polarity of your diodes* before turning on the 110 VAC power-- otherwise you will burn up the diodes.

- \* – Measure the output waveform of the full-wave *bridge circuit* in Figure 3-3. Do not attempt to measure the input waveform. Use a  $1\text{ k}\Omega$  load resistor.
- Print the output waveform. Compare to the half-wave rectifier.

#### 4. Power Supply Filtering

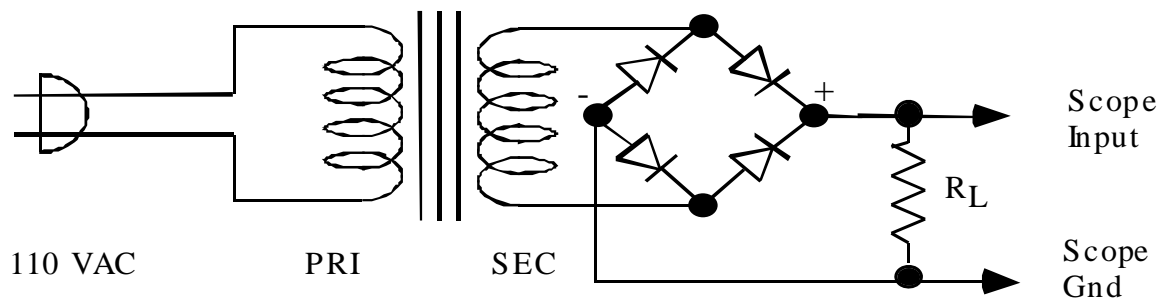


Figure 3.3. Full-wave rectifier bridge circuit. The input is 110 VAC line voltage.

\* **CAUTION:** In this part, carefully *check the polarity of your capacitor* before turning on the 110 VAC power.

\* Starting with the full wave rectifier circuits in Figure 3-3, add a capacitor  $C = 100\ \mu\text{F}$  across the load resistor as shown in Figure 3-4. Note that capacitors of such a large value are polarized: one of the capacitor's two leads is marked – or +.

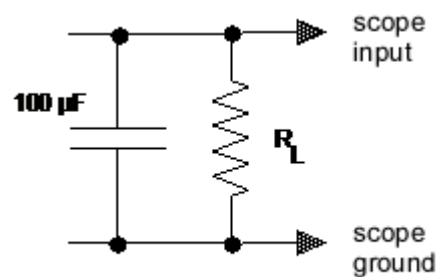


Figure 3-4 Filter Capacitor

\* Measure the DC output voltage.

\* – Measure the PP AC ripple using the oscilloscope.

[Try this two ways:

- first with DC input coupling
- repeat with AC input coupling.

You should find that AC coupling allows you to use a smaller scale in Volts/div and thereby make a more accurate measurement.]

– Print the output waveform. Discuss in one sentence how the filter capacitor improves the performance of a power supply.

\* Repeat with a capacitance of  $1000\ \mu\text{F}$ .

\* Using the capacitance of  $100\ \mu\text{F}$ , try a smaller load resistance (**CAUTION:** do not set the load resistance below  $50\ \Omega$ ).

– List your results. Compare with the calculated values of the DC output and ripple voltages. (See Horowitz & Hill 2<sup>nd</sup> Ed. p. 46.)

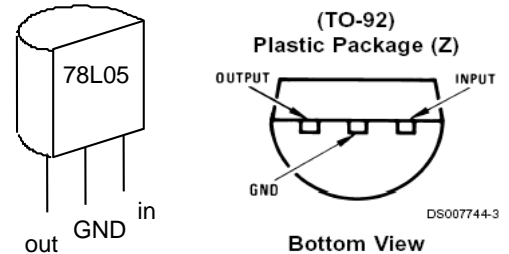
– Discuss (in two or three sentences) two factors that cause ripple to become worse.  
} Note that in a power supply, a bigger capacitance gives better filtering, but with the tradeoff that the component is costlier, larger and heavier.

} Note that the smaller the load resistance, i.e. the larger the current that the power supply must deliver, the worse the ripple.

\* Do not disassemble the full-wave rectifier yet.

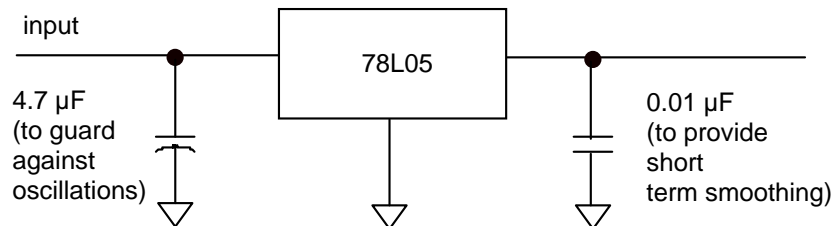
## 5. Voltage regulation with 3-terminal regulator

} 3-terminal voltage regulators are easy to use. From the outside it looks like a transistor, but on the inside there is a good regulator that makes use of negative feedback. It features thermal protection so that it is hard to burn up.



### (a) Simple test

\* Connect the 78L05 regulator on your prototyping board, as shown below. For an input, use the +12 Volt power supply that is built into your prototyping board, or an external power supply set to about +10 V.

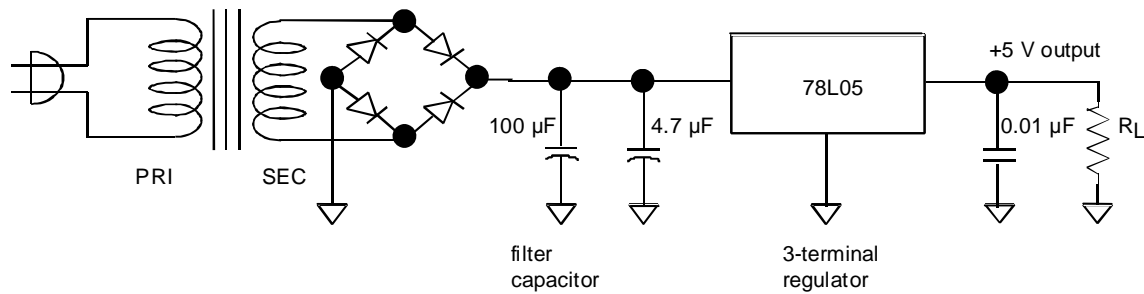


\* – Confirm that the output is nearly +5 Volts.

} An ideal voltage regulator supplies the same output voltage,  
• regardless of the input voltage, as in test (c), below  
• regardless of the output load, as in test (d), below

### (b) Use as a power supply regulator

\* Now connect the input of the 78L05 regulator, as shown below, to the output of the power supply you built in step 3. Include a 1 kΩ load resistor.



- \* Turn on the power supply, and observe the output voltage.
- \* – Compare to the filtered output without regulation, as measured in step 2.

(c) Regulation as the input voltage is varied

\* Now plug the transformer of your power supply into a variac instead of into 110 VAC. Connect a multimeter to measure the Volts ac from the transformer's output, when it is connected to the variac.

\* Set  $R_L$  to 1 k $\Omega$ .

\* Adjust the variac output voltage, beginning at 110 VAC and going downward, using the printed scale on the top of the variac. (**Caution:** Do not operate the variac at voltages above 110 V)



Variac

\* – Confirm that the regulator maintains the same +5 Volt output over a wide range of AC voltage (typically from 80 to 110 VAC).

(d) Regulation as the load is varied

\* Disconnect the variac. Connect your multimeter to measure current through the load. Notes:

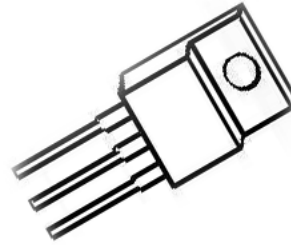
- Recall that a current meter should be in series, not in parallel as it is for voltage.
- If your multimeter appears to indicate zero current, it may have a blown fuse.

**CAUTION:** In this step, to protect the resistor substitution box, always keep 50 or 100  $\Omega$  switched in while you adjust the other scales. This precaution will keep you from accidentally setting the resistor substitution box to zero resistance.

**CAUTION:** As always, measure current beginning with the meter set to the highest scale.



TO-92 package



TO-220 package

- \* Set  $R_L$  to about 10 k $\Omega$ , and vary it downward.
- \* – Note the load resistance at which ripple begins to appear. What current value does this correspond to? (This is the maximum regulated current.)

(e) Thermal protection

- \* – Continue to decrease the load resistance. Does the output of the regulator shut down when the current exceeds a certain threshold? This is the current limit of your regulator.

[To work, this shut-down test requires using a regulator in the TO-92 package; don't use a larger package like TO-220 (LM78M05CT) for this lab -- it won't shut down under these conditions.]

} An advantage of these three-terminal regulators is the shutdown feature. Another alternative for voltage regulation is the zener diode in the next experiment, but zeners do not have thermal protection, so you must be careful to select the right one and use it within its design parameters.

## 6. Voltage Regulation with Zener Diodes

*[TA note: Some TAs omit the SCR circuit to save time. If it is necessary to reduce the time further, this zener diode section is the next choice for omission.]*

} Zener diodes can be used as a simple voltage regulator to establish a reference voltage source for non-critical applications.

### **CAUTION:**

Zener diodes are very easy to burn up if you make a goof in wiring them up.

- \* Remove the 3-terminal regulator and its accompanying two capacitors.



\* Verify that your Zener diode has a zener voltage that is appropriate for your transformer (e.g., 6.3 V zener for an 8 V transformer). Assume the Zener has a power rating of 0.4 W in either case.

\* Add a Zener diode across the output of the PI filtered power supply you built in part 3b, as shown in Figure 3-6.

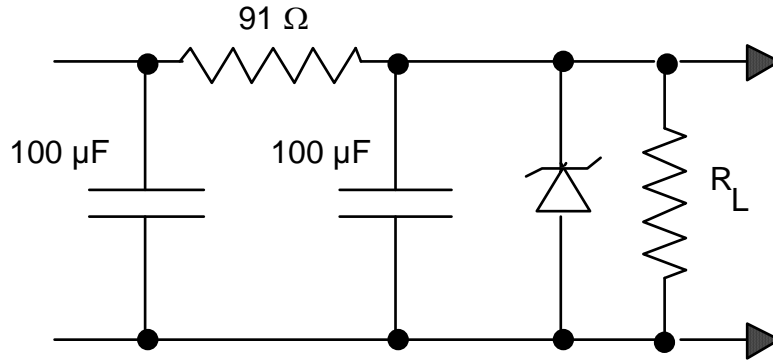


Figure 3-6 Pi filter with Zener diode voltage regulator

(a) Calculations

\* – Before you power up your circuit, do the following:

- (i) Determine the maximum Zener current  $I_{Z\max}$  from the power rating.
- (ii) Determine the total current through the 91  $\Omega$  resistor:

$$I_{tot} = (V_{in} - V_Z) / 91.0 \Omega$$

This current is the sum of the Zener current  $I_Z$  and the load current  $I_L$ . Check whether it exceeds  $I_{Z\max}$  because there must then be a minimum load current to prevent overloading the Zener. This will imply a maximum load resistance.

(b) Measurements

- (i) Output voltage

\* Power up your circuit.

\* – Measure the voltage across the load resistance.

**CAUTION:** in the next step, to protect the resistor substitution box, always keep 100  $\Omega$  switched in while you adjust the other scales. This precaution will keep you from accidentally setting the resistor substitution box to zero resistance.

(ii) Regulation

\* Vary  $R_L$  beginning at 10.1 k $\Omega$  and stepping downward to 500  $\Omega$ .

\* – Note the load resistance above which the voltage stays approximately constant. To what current does this correspond?

7. SCR Circuits [optional depending on whether TA finds there is enough time – in most years this part is skipped]

(a) DC Control – RC Timer

} The circuit in Figure 3-8 switches on a voltage across the load after a delay. The SCR switches on when the gate voltage (G) exceeds the cathode voltage (C). The gate voltage is developed across the capacitor  $C_1$  by the R-C combination.

\* Short  $C_1$  to remove all charge.

(i) Switching time

\* – Turn on the supply and determine the time for the voltage to be switched across the load.

(ii) Gate voltage

\* Short  $C_1$  again and repeat with each of the resistors in the time constant portion of the circuit.

\* – Determine the gate voltage necessary for firing.

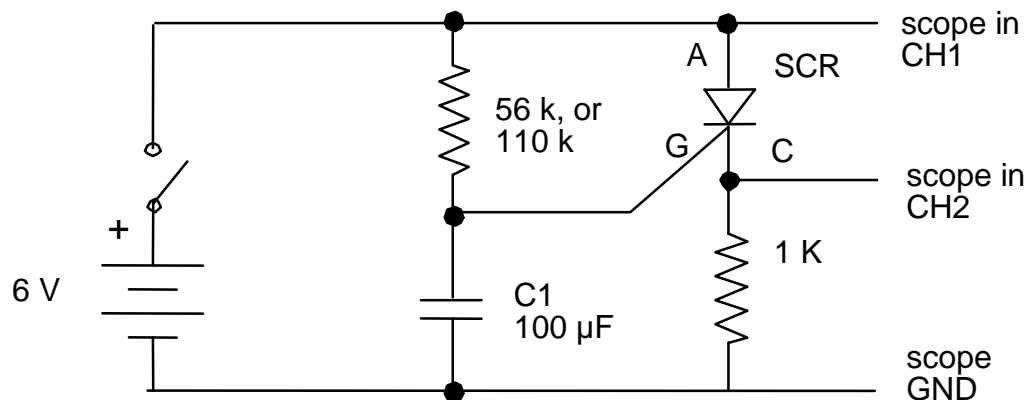


Figure 3-8 RC Timer

(b) AC Control -- Lamp Dimmer

} In the circuit in Figure 3-9, the  $R$ - $C$  combination acts as a phase shifter for the 60 Hz AC voltage. As  $R$  is increased, the phase is shifted from  $0^\circ$  to  $-90^\circ$ . With this circuit it is possible to control the output half wave from completely on to completely off.

\* Use the input from the transformer secondary as a reference signal for the oscilloscope.

\* — Observe the phase shifted wave across  $C$  and the output wave across  $R_L$ .  
Explain why the lamp dims.

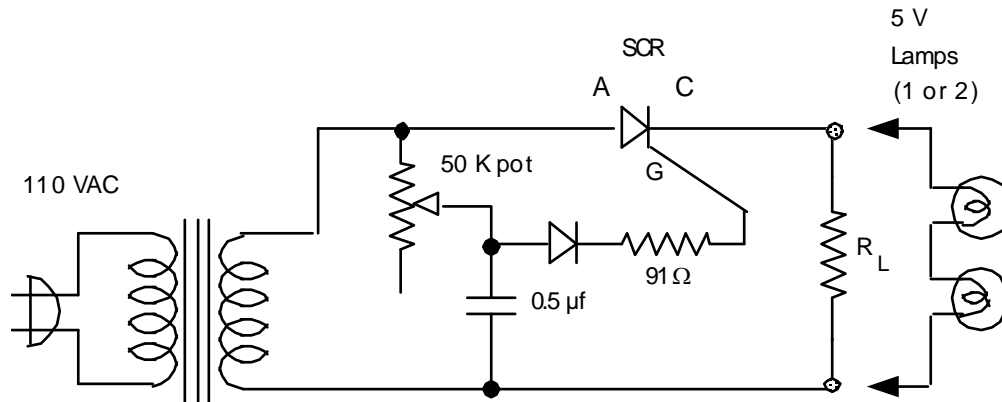


Figure 3-9

# Lab 4

## Junction Transistor, Part I

**REFERENCE:** Horowitz and Hill      Section 2.01 - 2.12  
Appendix G  
Appendix K data sheet for 2N4400

### INTRODUCTION

} Junction transistors are either NPN or PNP, with the symbols in Figure 4-1.

Small signal-type transistors come in various pin configurations. An NPN in a TO-92 package is shown in Figure 4-2.

In the junction transistor, a small base current ( $\approx$  few  $\mu\text{A}$ ) controls a much larger Emitter-Collector current ( $\approx$  1.0 mA).

You will demonstrate the transistor in three common applications:

- Emitter Follower      (Common Collector Amplifier)
- Transistor Switch
- Current Source      (Better performing than the one in Lab 1)

This experiment will also improve your skills at wiring circuits and using test & measurement instruments.

---

## EQUIPMENT

### Lab supplies:

Prototyping board

Digital Oscilloscope

Function Generator - Agilent 33220A

Pulse Generator - HP 8013B

Digital Multimeter - Agilent 34410A

Light bulb (typically # 47, 0.15 A @ 6.3 V, with wires)

SPST switch

Resistor substitution box

### Student kits:

Wire kit

NPN Silicon Transistor 2N4400 (or 2N2222 as a substitute) for *switching*  
2N3904 for *amplification*

Resistors 1 k $\Omega$ , 3.3 k $\Omega$ , 10k $\Omega$ , 22 k $\Omega$ , 33 k $\Omega$ , 1 M $\Omega$

Capacitors 0.1  $\mu$ F

# Amplifier Transistors

## NPN Silicon

**P2N2222A**

### MAXIMUM RATINGS

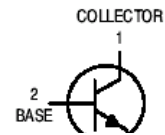
Rating	Symbol	Value	Unit
Collector-Emitter Voltage	$V_{CEO}$	40	Vdc
Collector-Base Voltage	$V_{CBO}$	75	Vdc
Emitter-Base Voltage	$V_{EBO}$	6.0	Vdc
Collector Current — Continuous	$I_C$	600	mA dc
Total Device Dissipation @ $T_A = 25^\circ\text{C}$ Derate above $25^\circ\text{C}$	$P_D$	625 5.0	mW mW/ $^\circ\text{C}$
Total Device Dissipation @ $T_C = 25^\circ\text{C}$ Derate above $25^\circ\text{C}$	$P_D$	1.5 12	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	$R_{\theta JA}$	200	$^\circ\text{C}/\text{W}$
Thermal Resistance, Junction to Case	$R_{\theta JC}$	83.3	$^\circ\text{C}/\text{W}$



CASE 29-11, STYLE 17  
TO-92 (TO-226AA)



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

Characteristic	Symbol	Min	Max	Unit
<b>OFF CHARACTERISTICS</b>				
Collector-Emitter Breakdown Voltage ( $I_C = 10 \text{ mA dc}, I_E = 0$ )	$V_{(BR)CEO}$	40	—	Vdc
Collector-Base Breakdown Voltage ( $I_C = 10 \text{ } \mu\text{A dc}, I_E = 0$ )	$V_{(BR)CBO}$	75	—	Vdc
Emitter-Base Breakdown Voltage ( $I_E = 10 \text{ } \mu\text{A dc}, I_C = 0$ )	$V_{(BR)EBO}$	6.0	—	Vdc
Collector Cutoff Current ( $V_{CE} = 60 \text{ Vdc}, V_{EB(off)} = 3.0 \text{ Vdc}$ )	$I_{CEX}$	—	10	nA dc
Collector Cutoff Current ( $V_{CB} = 60 \text{ Vdc}, I_E = 0$ ) ( $V_{CB} = 60 \text{ Vdc}, I_E = 0, T_A = 150^\circ\text{C}$ )	$I_{CBO}$	— —	0.01 10	$\mu\text{A dc}$
Emitter Cutoff Current ( $V_{EB} = 3.0 \text{ Vdc}, I_C = 0$ )	$I_{EBO}$	—	10	nA dc
Collector Cutoff Current ( $V_{CE} = 10 \text{ V}$ )	$I_{CEO}$	—	10	nA dc
Base Cutoff Current ( $V_{CE} = 60 \text{ Vdc}, V_{EB(off)} = 3.0 \text{ Vdc}$ )	$I_{BEX}$	—	20	nA dc

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

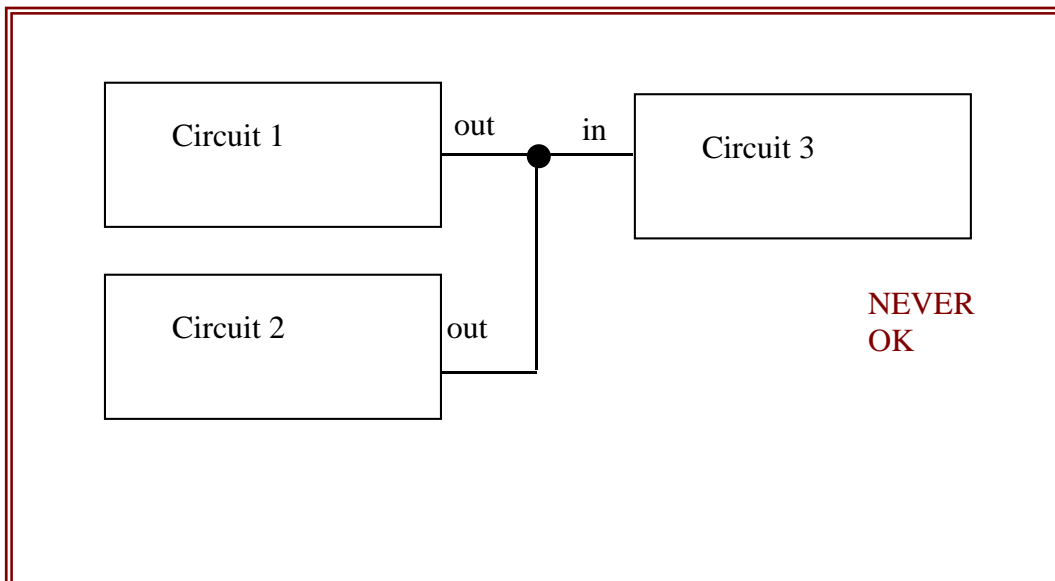
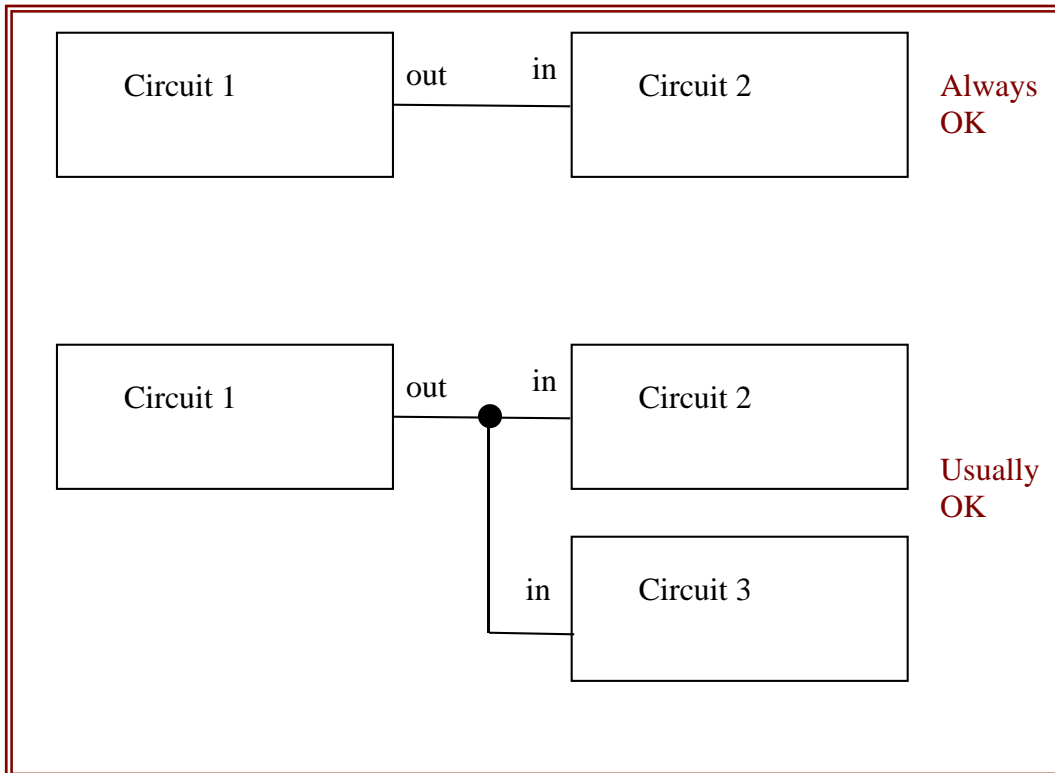
Characteristic	Symbol	Min	Max	Unit
<b>ON CHARACTERISTICS</b>				
DC Current Gain ( $I_C = 0.1 \text{ mA dc}, V_{CE} = 10 \text{ Vdc}$ ) ( $I_C = 1.0 \text{ mA dc}, V_{CE} = 10 \text{ Vdc}$ ) ( $I_C = 10 \text{ mA dc}, V_{CE} = 10 \text{ Vdc}$ ) ( $I_C = 10 \text{ mA dc}, V_{CE} = 10 \text{ Vdc}, T_A = -55^\circ\text{C}$ ) ( $I_C = 150 \text{ mA dc}, V_{CE} = 10 \text{ Vdc}$ ) <sup>(1)</sup> ( $I_C = 150 \text{ mA dc}, V_{CE} = 1.0 \text{ Vdc}$ ) <sup>(1)</sup> ( $I_C = 500 \text{ mA dc}, V_{CE} = 10 \text{ Vdc}$ ) <sup>(1)</sup>	$h_{FE}$	35 50 75 35 100 50 40	— — — — 300 — —	—
Collector-Emitter Saturation Voltage <sup>(1)</sup> ( $I_C = 150 \text{ mA dc}, I_B = 15 \text{ mA dc}$ ) ( $I_C = 500 \text{ mA dc}, I_B = 50 \text{ mA dc}$ )	$V_{CE(sat)}$	— —	0.3 1.0	Vdc
Base-Emitter Saturation Voltage <sup>(1)</sup> ( $I_C = 150 \text{ mA dc}, I_B = 15 \text{ mA dc}$ ) ( $I_C = 500 \text{ mA dc}, I_B = 50 \text{ mA dc}$ )	$V_{BE(sat)}$	0.6 —	1.2 2.0	Vdc

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## A BASIC FACT TO KNOW

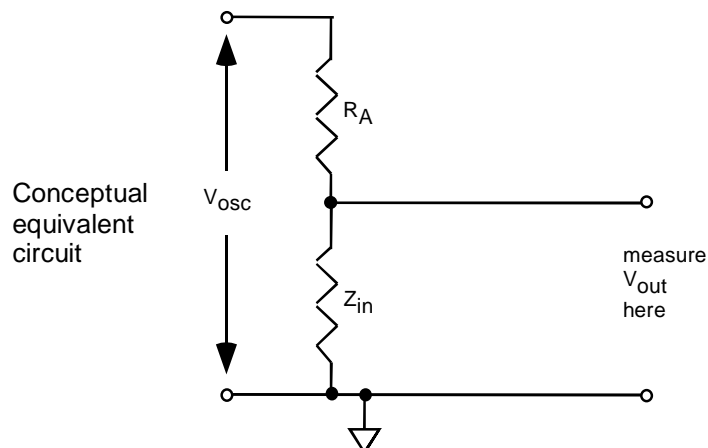
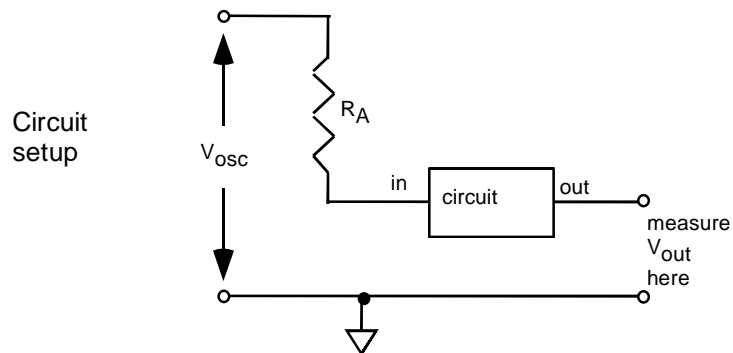
In electronics:

- It is **USUALLY OK** to connect an output of a circuit to the inputs of two circuits.
- It is **NEVER OK** to connect two outputs together



## PRELAB

1. Identify all the formulas you will need in this Lab.
2. In this lab we will use a method of measuring the input impedance  $Z_{in}$  of a circuit. This impedance will be purely resistive because the circuit will have no significant capacitance or inductance. The scheme is to connect a large input resistor  $R_A$  in series with the circuit's input, and measure the resulting decrease in the circuit's output. You can think of  $R_A$  and the circuit's input impedance as being like two resistors in series, i.e., a voltage divider. See the diagram below; the circuit, which has a gain  $A_v$ , is shown as a box with an input and an output.
  - (a) Derive a formula for  $Z_{in}$  as a function of  $R_A$ ,  $V_{osc}$ ,  $V_{out}$  and the gain  $A_v$
  - (b) Write a simplified version of this formula valid for  $A_v = 1$
  - (c) Write an even more simplified version valid if  $A_v = 1$  and  $V_{out} = V_{osc} / 2$ .





## PROCEDURE

Figure 4-1

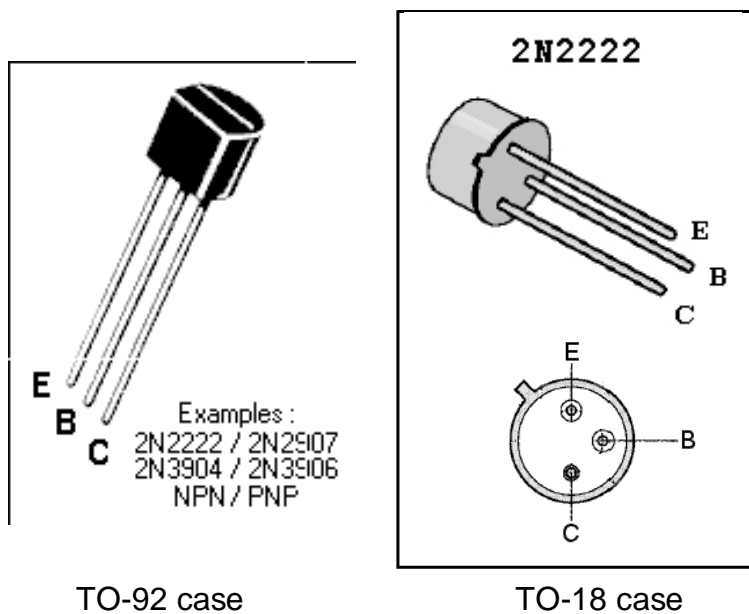
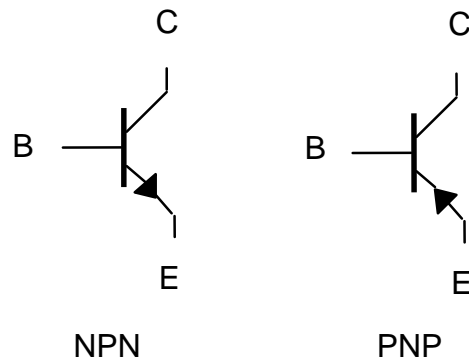


Figure 4-2:  
NPN Transistor pinouts

} The 2N3904 and 2N4400 are similar, except that:

- 2N4400 withstands a higher collector current, and is therefore better suited for switching circuits (you may you may substitute 2N2222 for 2N4400).
- 2N3904 is better suited for signal amplifier circuits.

### 1. Multimeter Check of Transistor

This test is similar to the one you did in Lab 3 with the diode. If you are unsure of how to do this test, first go back to Lab 3 and repeat the diode test with a diode.

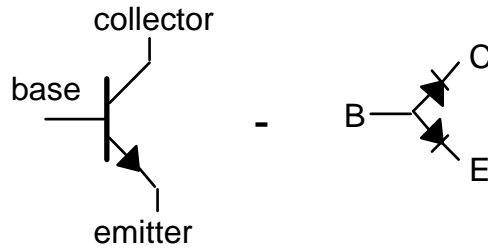


Figure 4-3

(a) Diode equivalent

\* – Use your multimeter’s diode-check feature. It will display the forward bias voltage. Verify that the transistor looks like two diodes, as shown in Figure 4-3.

(b) Beta measurement

\* – If your multimeter has special connectors labeled C B E, then it has a transistor check function. For some multimeters, this will display the beta, or  $h_{FE}$ . Try it. For the 2N3904, beta is typically  $h_{FE} \approx 210$ .

## 2. Emitter Follower

(a) Emitter-Follower Operation

\* Using the  $\pm 12$  Volt power supply that is built into your prototyping board, wire up an NPN transistor as an emitter follower, as shown in Figure 4-4.

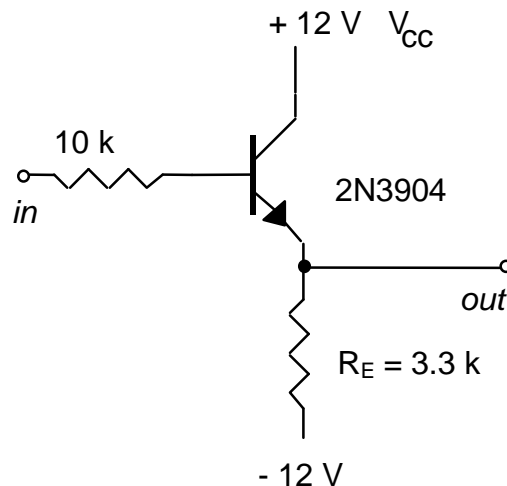


Figure 4-4

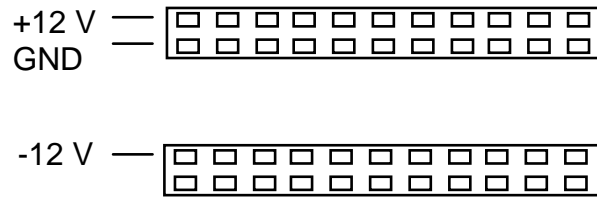


Figure 4-5. Power supply on prototyping board (left). Connect these using wires to the strips sketched on the right for convenient use. Note: some boards have only one strip per side, not two as shown here.

\* Hint: On your prototyping board, use wires to connect the outputs of the  $\pm 12$  V power supply and ground (three wires in all) as shown in the left of Figure 4-5 to a couple of strips that look like those shown on the right of Figure 4-5:

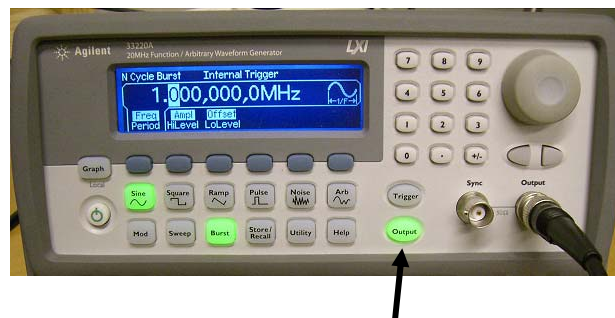
\* Set up the Agilent 33220A function generator to produce a sine wave that is symmetric about zero volts (turn off the “offset”). Initially, adjust it for  $f \approx 1$  kHz and P-P amplitude  $\approx 2$  V. (Do not use the “Burst” or “Sweep” modes here.)

\* Set up the oscilloscope to show a dual-trace, using DC input coupling, with one channel showing *in*, and the other showing *out*.

\* Be sure the grounds of the oscilloscope, function generator, and prototyping board are connected.

#### (i) input and output waveforms

\* — Print the oscilloscope display, and number your printout so that you can identify it in your report. Repeat for an input amplitude that is much larger and much smaller. Comment on any significant differences.



If output button is not lit, there will be no waveform applied to the instrument's output.

Agilent 33220A Function Generator

\* — Now connect the emitter return (the resistor on the bottom of the figure) to ground instead of - 12 V. Observe the display for several amplitudes of input. Explain how the circuit functions more poorly.

(iii) breakdown

\* – Look for bumps appearing at reverse bias. This is called breakdown. Measure the breakdown voltage, i.e., the voltage at which breakdown first occurs. Compare your result to the specification in a data sheet for the transistor. [Note, the breakdown voltage specifications for the 2N3904 and the 2N4400 are identical, so for this purpose you may use either data sheet.]

(iv) voltage gain

\* Connect the emitter return back to -12 V. Add a blocking capacitor to the output as shown in Figure 4-6.

} Why don't we use a blocking capacitor on the input? It's not necessary. When the function generator feeds the base directly, the DC bias of the base is held to that of the function generator, which is near the middle of the transistor's operating region. That's where we want it.

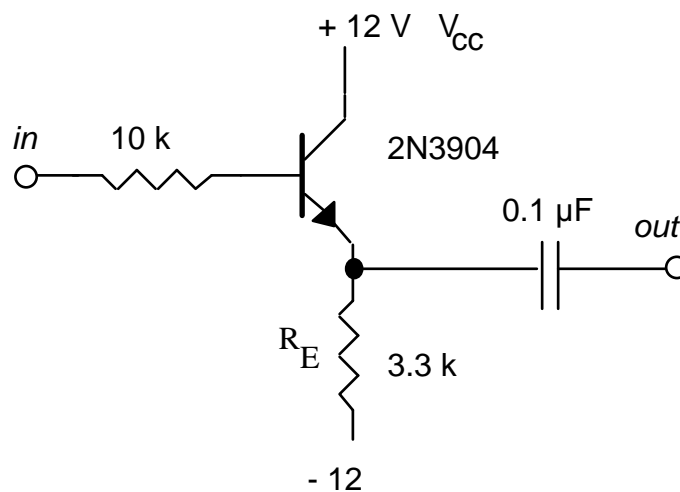


Figure 4-6

\* – Adjust the input amplitude of the sine wave from the function generator so that the output looks like a good sine wave. Measure the ac voltage gain.

(v) blocking capacitor test

\* – Use your oscilloscope with dc coupling to measure the dc bias of the output on each side of the output capacitor. Confirm that the output capacitor is blocking a dc bias.

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} *Note: the following procedures for measuring input and output impedances will be used again in later experiments.*

(b) Input Impedance

} You will measure the input impedance  $Z_{in}$ . Because there is no significant capacitance or inductance at the input of this circuit, we can write that  $Z_{in} = R_{in}$ . See the discussion and diagram in the PRELAB.

\* Insert a large-value resistor  $R_A$  (typically  $1\text{ M}\Omega$ ) in series with the function generator on the input of the amplifier, as shown in Figure 4-7.

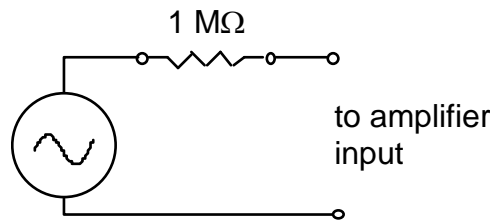


Figure 4-7

\* – Use the oscilloscope with AC input coupling to measure the output signal with and without the large input resistor  $R_A$ .

– Calculate the input impedance  $R_{in}$ . If you measured  $h_{fe}$  earlier, compare your result for  $R_{in}$  to the formula given in Horowitz & Hill 2<sup>nd</sup> Ed. p. 66:  $R_{in} = (h_{fe} + 1) R_E$ .

(c) Output Impedance

} To measure an amplifier's output impedance, you will connect a load resistor across the output. Recall that when two resistances  $R_1$   $R_2$  are connected in parallel, the parallel resistance is  $R_{eff} = R_1 R_2 / (R_1 + R_2)$ . When the two resistances are identical,  $R_1 = R_2 = R$ , then  $R_{eff} = R/2$ . Now consider that a load resistance connected across the output of an amplifier is effectively a resistance in parallel with the output impedance of the amplifier. If a *fixed* current  $i$  passes through the effective resistance, the voltage drop across it as given by  $v = i R$  will be reduced by half, if  $R$  is reduced by half.

\* Set the resistor substitution box resistance ( $R_L$ ) to the largest possible value. Then connect the resistor substitution box across the output of the amplifier, to serve as a load resistance, as shown in Figure 4-8.

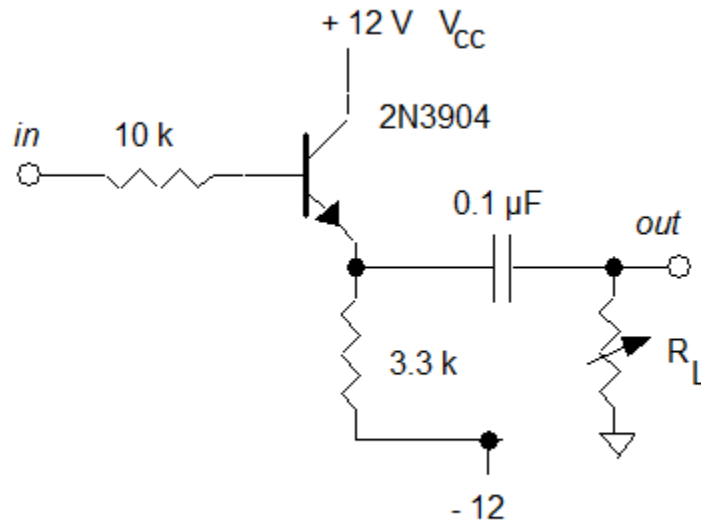


Figure 4-8

\* – Adjust the input signal to obtain a good sine wave on the output. Then reduce  $R_L$  until the peak-to-peak output signal falls by  $\frac{1}{2}$ . Then,  $R_L$  equals the output impedance of the circuit.

(d) Comparison

– Compare the measured input and output impedances by calculating their ratio  $R_{out} / R_{in}$ . Usually it is desirable for an amplifier to have a *high input impedance* and a *low output impedance*. To what extent is that true here?

### 3. Transistor switch

} Transistors are used often as switches. One application is “cold switching”, where a remotely located mechanical switch, which carries little current, controls a larger current someplace else.

} A transistor switch operates in the *saturated* mode when the switch is “on”, and in the *cutoff* mode when the switch is “off”. It should not be operated in the *normal* or

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*linear* mode, where  $I_C = h_{fe} I_B$ . See Appendix G in Horowitz & Hill 2<sup>nd</sup> Ed. for more on saturation.

- \* Use a wire on your prototyping board instead of a mechanical switch.
- \* Using the + 5 Volt power supply that is built into your prototyping board, wire up an NPN transistor as a “cold switch”, as shown in Figure 4-9. The lamp is the “load” here. (The 10 k resistor is not essential-- it makes sure that the base is near ground potential when the switch is open.)

(a) Cold switching

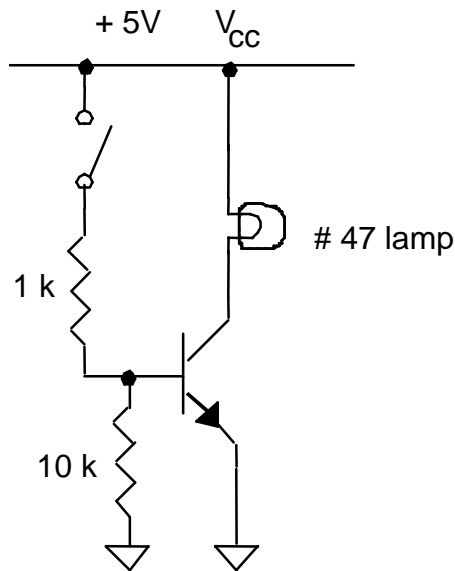


Figure 4-9. Cold switching

- \* – Verify that the lamp is turned on as you close the mechanical switch and off as you open it.

(b) Current through the switch

- \* – Setting your multimeter to operate in its highest current range to begin with, use it to measure the current flowing through the lamp.
- \* – Setting your multimeter to measure voltage, measure the voltage-drop across each of the two resistors. Compute the current flowing into the base.

- Comparing these two currents, is it true that the “cold switch” allows you to switch a larger current through the load (lamp) than passes through the actual switch?

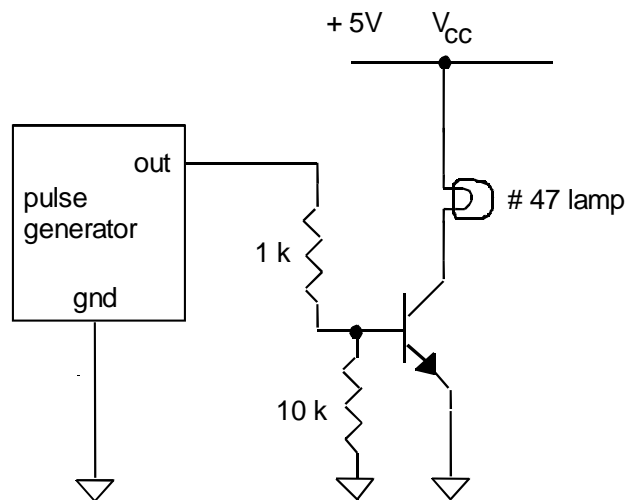
(c) Saturation mode

- \* – With the switch closed, use your multimeter to measure the DC voltage drops  $V_{CE}$  and  $V_{BE}$ .

- Is  $V_C < V_B$  as expected for saturation?

(d) Cold switching from a pulse generator's output

- \* Replace the manual switch with the pulse generator's output, as shown in the diagram, so that a high output from the pulse generator will cause the lamp to light.



Adjust the pulse generator to produce its maximum output voltage and maximum period, choosing a square-wave output (with a long period of 1s or more, so that you can observe both the lamp and waveform simultaneously). Observe the collector voltage waveform on an oscilloscope, with DC input coupling and the time/division adjusted to a long time.

- \* – Verify that the lamp is turned on and off periodically. Print the oscilloscope display, and mark the waveform indicating when the lamp is on and off. Measure the period using the oscilloscope.



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(a) Calculation

- \* – Measure the component values. Then calculate:
  - the bias on the base.
  - the potential at the emitter (assuming an 0.6 V B-E drop).

(b) Experiment

**CAUTION:**

In using the current measurement function of the multimeter, start at the highest possible range.

- \* Using the +12 V power supply built into your prototyping board, connect the circuit shown in Figure 4-10. For the load resistor, use a resistor substitution box, set to 2 k $\Omega$  to begin.

(i) comparison to calculated values

- \* – Measure and compare to the values calculated above:
  - the bias on the base.
  - the potential at the emitter.

(ii) current vs. load resistance

- \* Vary  $R_L$  from 100  $\Omega$  to 2 k $\Omega$ , in 100  $\Omega$  increments.

- Make a table of current vs. load resistance.

(iii) compliance

- Determine the range of load over which the current remains constant to 10%. Compare this result to your result in Lab 1 with the crude current source.

# Lab 5

## Junction Transistor, Part II

**REFERENCE:** Horowitz and Hill Sections 2.07, 2.12 (common-emitter amp)

### INTRODUCTION

We continue the bipolar transistor experiments begun in the preceding experiment.

In the common emitter amplifier experiment, you will learn techniques and terminology that are valuable not only in building circuits, but also in the use of commercially-made amplifiers.

### EQUIPMENT

#### Lab supplies:

Prototyping board

Oscilloscope

Function generator - Agilent 33220A

Digital multimeter - Agilent 34410A

Resistor substitution box

#### Student kits:

Wire kit

NPN Silicon Transistor (1) 2N3904

Resistors 220, 1 k, 6.8 k, 12k, 82 k [for CE amp]

Capacitors 0.1  $\mu$ F, 10  $\mu$ F electrolytic [for CE amp]

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## PRELAB

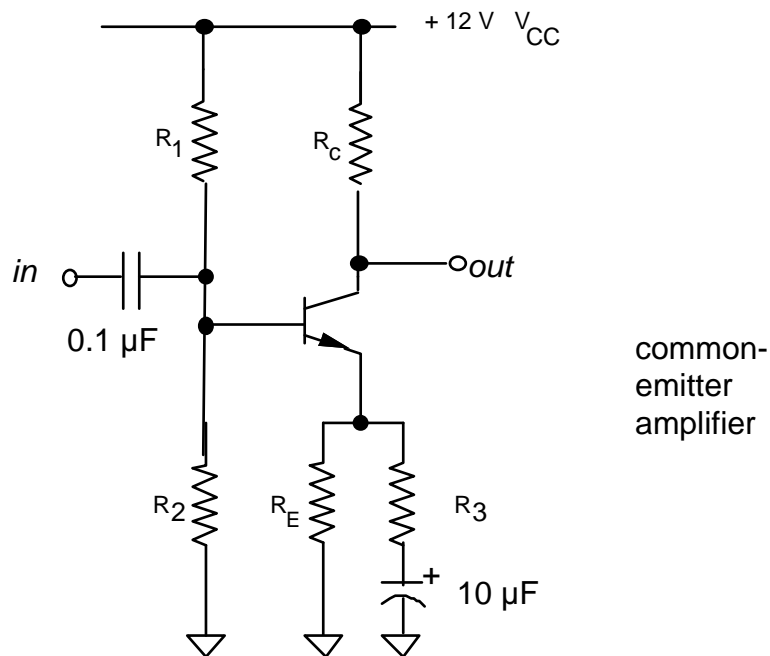
1. Identify all the formulas you will need in this Lab.
2. Compute the intrinsic emitter resistance  $r_e$  for a transistor with a collector current of  $I_c = 2 \text{ mA}$ . Your answer should have units of Ohms.
3. Referring to your text or lecture notes, describe the undesirable circuit behavior that can result if the dc bias of the common-emitter amplifier's output is not centered between the two power supply voltages.

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## PROCEDURE

### 1. Common Emitter Amplifier

} The common-emitter amplifier shown below is based on Figure 2.37 in Horowitz & Hill 2<sup>nd</sup> Ed. , with changes to accommodate  $V_{CC} = 12\text{ V}$  instead of 15 V in the power supply. The purpose of resistor  $R_3$  is to reduce the gain to avoid excessive high frequency noise.



Use the following resistor values:

$R_1$	$= 82\text{ k}$	$R_C$	$= 6.8\text{ k}$
$R_2$	$= 12\text{ k}$	$R_E$	$= 1\text{ k}$
$R_3$	$= 220\text{ }\Omega$		

#### (a) Calculations

\* – Measure your component values. If your multimeter has a beta-measurement feature, use it to measure  $h_{fe}$ .

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\* – Compute the following quantities:

- (i) Predicted value of the dc base bias and the emitter potential, assuming an 0.6V B–E drop.
- (ii) Predicted value of the dc collector current and the dc bias on the output.
- (ii) Compare the predicted value of the dc bias calculated in (ii) to  $0.5 V_{CC}$ . Explain, in terms of an undesirable circuit phenomenon that you wish to avoid, why the value of the dc bias you predicted is desirable.
- (iii) the impedance  $Z_{eb}$  of the emitter bypass, i.e., the parallel sub-circuit consisting of the emitter resistor  $R_e$  & the capacitor in series with resistor  $R_3$ , for the following frequencies:  
0, 100 Hz, 5 kHz,  $\infty$ .

} Recall that:

- a resistor  $R_3$  and capacitor  $C$  that are connected in series have a combined impedance  $Z_{series} = R_3 + Z_C$  where  $Z_C = j / \omega C$  is the impedance of a capacitor at frequency  $\omega = 2\pi f$
  - a resistor  $R_e$  in parallel with impedance  $Z_{series}$  has a total impedance  $1 / Z_{eb} = 1 / R_e + 1 / Z_{series}$
  - Also recall that the magnitude of the resulting impedance is computed from its complex value as  $|Z| = [Z Z^*]^{1/2}$ .
- (iv) the input impedance at 5 kHz (if you didn't measure  $h_{fe}$ , assume it is 100). Note that resistors  $R_1$  and  $R_2$  appear to be in parallel with  $h_{fe}$  times the emitter bypass. Use the 5 kHz result (see above) for the emitter bypass impedance.
  - (v) the theoretical gain  $A_v = - R_C / (r_e + Z_{eb})$  at  $f = 5$  kHz, assuming  $r_e = 25 / I_C$  (mA).

(b) Operating point

\* Connect the circuit shown above using a prototyping board. In wiring it up, it may be easiest if you use three of the long thin rails on the prototyping board for +12 V, GND, and -12 V.

- 
- \* – Measure and compare to the calculations above:
    - (i) the dc base bias and the emitter potential.
    - (ii) the collector current (use Ohm's Law and a measurement of the potential across the collector resistor to determine this).



Sync output of  
function  
generator

(c) Voltage gain

(i) with emitter bypass capacitor

- \* Set up the function generator to produce a 5 kHz sine wave with a low output amplitude. Set up the oscilloscope to make a dual-trace measurement of the input and output of the amplifier.
- \* Connect the SYNC output of the function generator to the EXT TRIGGER input on the scope, and use external triggering. Make sure that the grounds of the oscilloscope, the prototyping board, and the function generator are all somehow connected.
- \* Adjust the function generator amplitude to produce a good sine wave on the output of your amplifier. If the output waveform is saturated or clipped, reduce the input amplitude from your function generator. If it is necessary to reduce the input amplitude further, wire up a 1 k potentiometer as an adjustable voltage divider and connect it between the output of the function generator and the input of the amplifier.
- \* – Measure the input and output amplitudes using the oscilloscope.
- \* – Compute the gain, and compare to the theoretical value, using measured component values, from above. Is this an inverting amplifier?

(ii) without emitter bypass capacitor

- \*– Repeat these steps with the bypass capacitor disconnected. (Note: if clipping occurs, check that you have not shorted the emitter  $C_E$ ).

(d) Input impedance

- \* – Measure the ac input impedance of the circuit with the emitter bypass. Use the procedure from Lab 4. Compare to the theoretical value from above.

(e) Output impedance

- \* – Measure the ac output impedance using the procedure from Lab 4.

# Lab 6

## Optoelectronics

**REFERENCE:** Horowitz and Hill: rise time: p. 268; optoelectronics: pp. 590 - 598

### INTRODUCTION

} The term “optoelectronics” refers to semiconductor light sources and light sensors.

Light sources include light-emitting diodes (LED) and laser diodes. In this lab, you will use a visible LED. LEDs are cheaper, and are usually used as visual indicators rather than for high-speed communication. Laser diodes are more expensive, and are used for high-speed fiber-optic communication. In addition to their high speed in turning on and off, laser diodes have the advantage of producing a narrower spectrum of wavelengths helps overcome the dispersive effects of glass, where different wavelengths travel at different speeds

There are many kinds of light sensors. In this lab, you will test a photo transistor.

Other light sensors include:

- photodiodes (faster time response but less sensitive),
- photo-darlington (these are like a phototransistor but include an additional transistor to provide additional gain at the expense of a slower time response)
- photomultiplier tubes (a vacuum tube with a very fast time response).

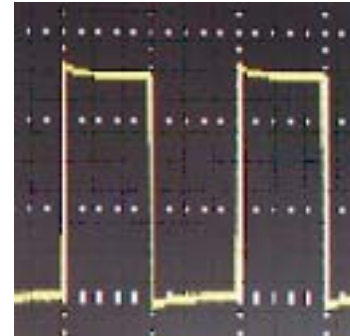
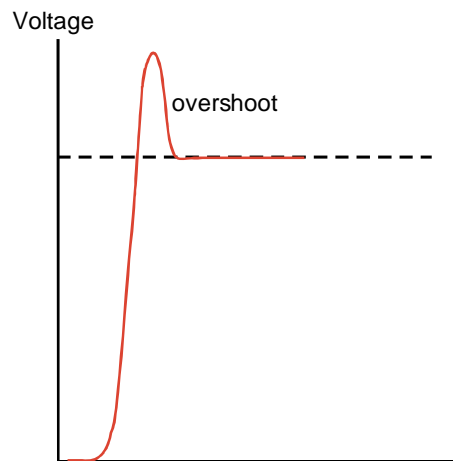
Measurement skills you will learn in this lab include:

- using a digital oscilloscope to measure a high-speed pulse.
- using a 10X probe, which is useful because it has a higher bandwidth (and faster time response) than a 1X probe.

### } Overshoot

A pulsed waveform does not transition instantly between two levels. Instead, it follows a curve, which asymptotically approaches the final level.

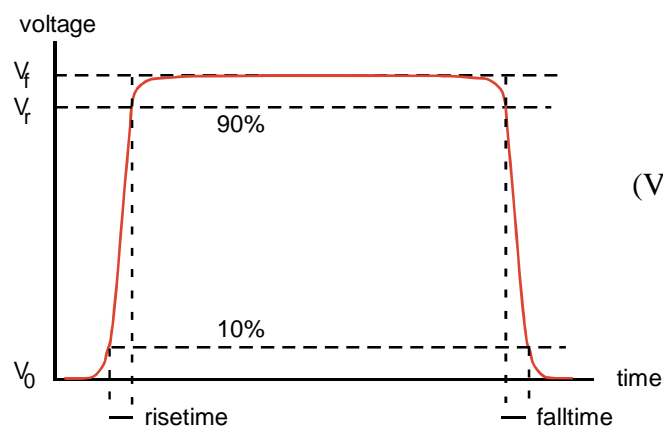
In some cases, a waveform will overshoot” the final level.



Square wave with overshoot

### } Rise time and fall time

The speed of switching between the two levels is characterized by a “rise time” and “fall time.” These are often measured as the time interval between the 10% and 90% voltage levels, as shown below. (Sometimes, however, a criterion different from the 10% - 90% rule might be adopted.)



$$(V_r - V_0) / (V_f - V_0) = 90\%$$



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## EQUIPMENT

### Lab supplies:

Digital Oscilloscope

Pulse generator - HP8013B

DC power supply

Prototyping board

10X probes (2) - and a manual for this probe model

Small screwdriver to adjust the 10X probe.

### Student kits:

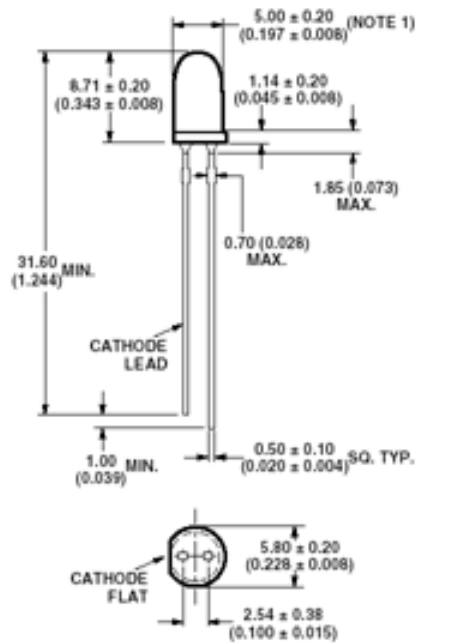
Wire kit

Resistors 270, 1k

Light emitting diodes:

- HLMP-C115 (obsolescent -- this LED chosen for its 30 nsec response)
- Red diffused LED

NPN Phototransistor: Panasonic PNA 1801L



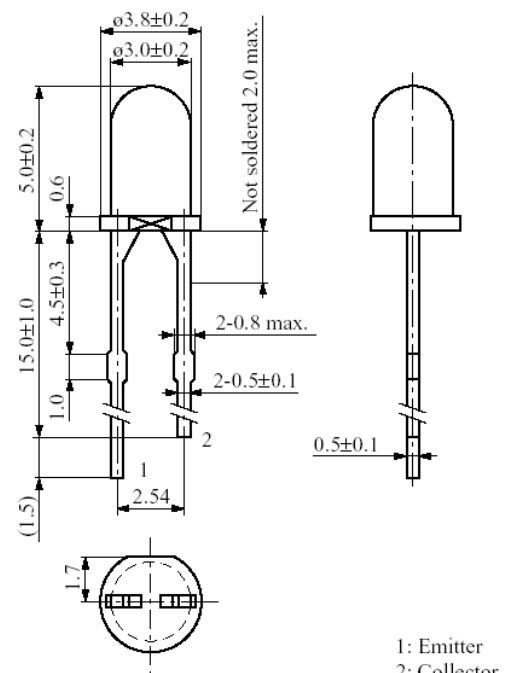
NOTES:

1. ALL DIMENSIONS ARE IN MILLIMETERS (INCHES).
2. LEADS ARE MILD STEEL, SOLDER DIPPED.
3. AN EPOXY MENISCUS MAY EXTEND ABOUT 0.5 mm (0.020 in.) DOWN THE LEADS.

**HLMP-Cx15 and HLMP-Cx23**

**LED HLMP-C115**

Note: the flat edge of rim indicates cathode



1: Emitter  
2: Collector

**NPN Phototransistor PNA1801L**

Note: emitter pin is longer

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## **PRELAB**

1. Identify all the formulas you will need in this Lab.
2. If a waveform ramps up gradually from a starting voltage to an ending voltage, what percentage of its change is used when measuring the “rise time”?

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## PROCEDURE

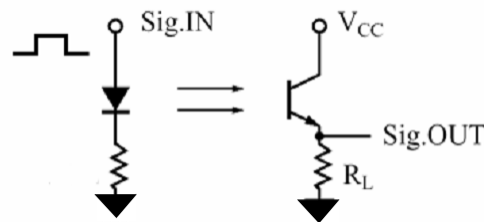
### 1. Adjust 10X probe compensation

- } As you previously learned in Lab 3, a 10X passive probe attenuates a voltage by a factor of 10, so that an oscilloscope measures one-tenth the original voltage. It is preferred over a 1X probe for high frequencies ( $>1$  MHz) and therefore it is used whenever one needs to measure fast rise times ( $<$  a few microseconds).
- } Due to variations in oscilloscope input capacitances it is necessary to adjust a compensation “trimmer” on a 210X probe after moving it from one oscilloscope to another.
- \* Adjust the compensation on both of your 10X probes. This requires a small screwdriver. Verify that the probe’s switch is in the 10X position. Follow the steps of the 10X probe manual (p. 3 of the manual for the P2200 200 MHz Tektronix probe). This procedure requires a square-wave input; use the two metal loop connectors labeled “Probe Comp” on the oscilloscope. One connector is for the probe tip and the other for the probe’s ground connector.

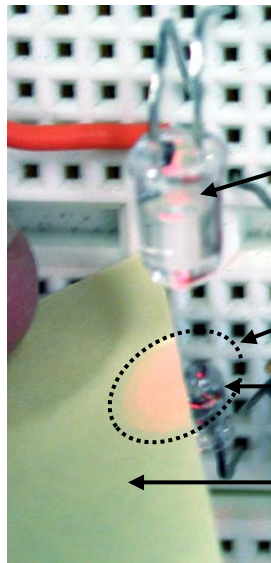


- \* Set up the digital oscilloscope so that both the CH1 and CH2 menus are set for:
  - Probe 10X
  - DC coupling
  - BW Limit off
  - Invert off.

- \* Identify the phototransistor and LED (they look alike but the LED is much larger and the bumps on its leads are nearer its lens.). Identify the two leads of the phototransistor (collector and emitter) and the LED (cathode and anode).
- \* – Discuss in one or two sentences why the phototransistor has no base lead.
- \* Set up the pulser as shown in the photo, except that you should use the following switch settings: OUTPUT: norm, INT LOAD: out, PULSES DELAY: doesn't matter, PULSE: norm. Produce a square wave with an amplitude in the range 5.0 – 5.5 V peak-to-peak, and a period of about 1 – 3 sec (slow enough that you can see the LED blink, when it is connected later). Set Apply the TRIGGER OUTPUT of the pulser to the external trigger input of the scope. Use the scope's trigger menu to choose "normal" and "external" triggering. Apply the OUTPUT (+) across the LED and ground, as indicated by "Sig.IN" in the diagram:



- \* Hook up the circuit shown in the diagram:
  - Use a 270 Ohm resistor in series with the LED.
  - Use an emitter resistor  $R_L = 1k$  on the phototransistor.
  - Use the bench power supply to provide +5 VDC for  $V_{CC}$ .
  - Connect the CH1 10X probe to the output of the pulser, and the CH2 10X probe to the emitter of the phototransistor to observe its output.
- \* Align the optical parts on your prototyping board so that the lens of the LED faces directly toward the lens of the phototransistor, with a separation of < 1 cm. The phototransistor's lens is highly directional, so make an effort to point the LED exactly on-axis with the phototransistor.
- \* Perform the following test to verify that the beam of light from the LED is pointed at the phototransistor. Hold a piece of paper immediately in front of the phototransistor so that it blocks half the phototransistor's lens, as shown in the photo (which is best seen in color). If the LED is aligned properly, you will see half of a big red dot on the paper, with the center of the red dot located at the center of the phototransistor's lens.



LED, facing the phototransistor at a distance of about 1 cm

LED illuminates a spot of this size on the paper, shown here with dashed lines

Phototransistor, facing the LED

Paper, blocking half the phototransistor's lens, so that you can see where the light is

- \* Obtain an oscilloscope display similar to what is shown in the screenshot, adjusting the horizontal position as necessary.
- \* Check that the signal disappears when you insert a piece of paper between the LED and the phototransistor to fully block the light. (Note: The photo shown here is best viewed in color to see the light from the LED.)
- \* Press the “measure” button on the scope and set it to measure Peak-Peak and rise time, as shown in the screen shot below.
- \* Without disturbing the LED or phototransistor, determine the criterion used by the oscilloscope to measure the rise time. Do this by measuring the waveform yourself. Measure three voltages:  $V_0$  before the rise,  $V_f$  after the rise is complete, and  $V_r$  at the time indicated by the scope as the measured rise time.
- \* Hint: Remember the skills you learned when using the analog scope: manual measurements are easiest if you make use of the major division lines on the scope display. Adjust the horizontal position or trigger delay so that the pulse begins on a major division on the time scale. Adjust the vertical position so that the baseline for the pulse is similarly on a major division line. Adjust the pulse amplitude so that the phototransistor output varies an integer number of divisions. Choose appropriate scales for the vertical and horizontal axes so that the interesting part of the waveform fills a large fraction of the display.
- \* — Print out your oscilloscope display, resembling the screenshot shown here.
- \* — Record the value of rise time indicated by the oscilloscope.

- 
- \* – Compute the ratio  $(V_r - V_0) / (V_f - V_0)$ , expressing your answer as a percentage (i.e., XX%). (This result should be the same regardless of the amplitude of the waveform or the student performing the test; it is a criterion determined by the oscilloscope's manufacturer.)

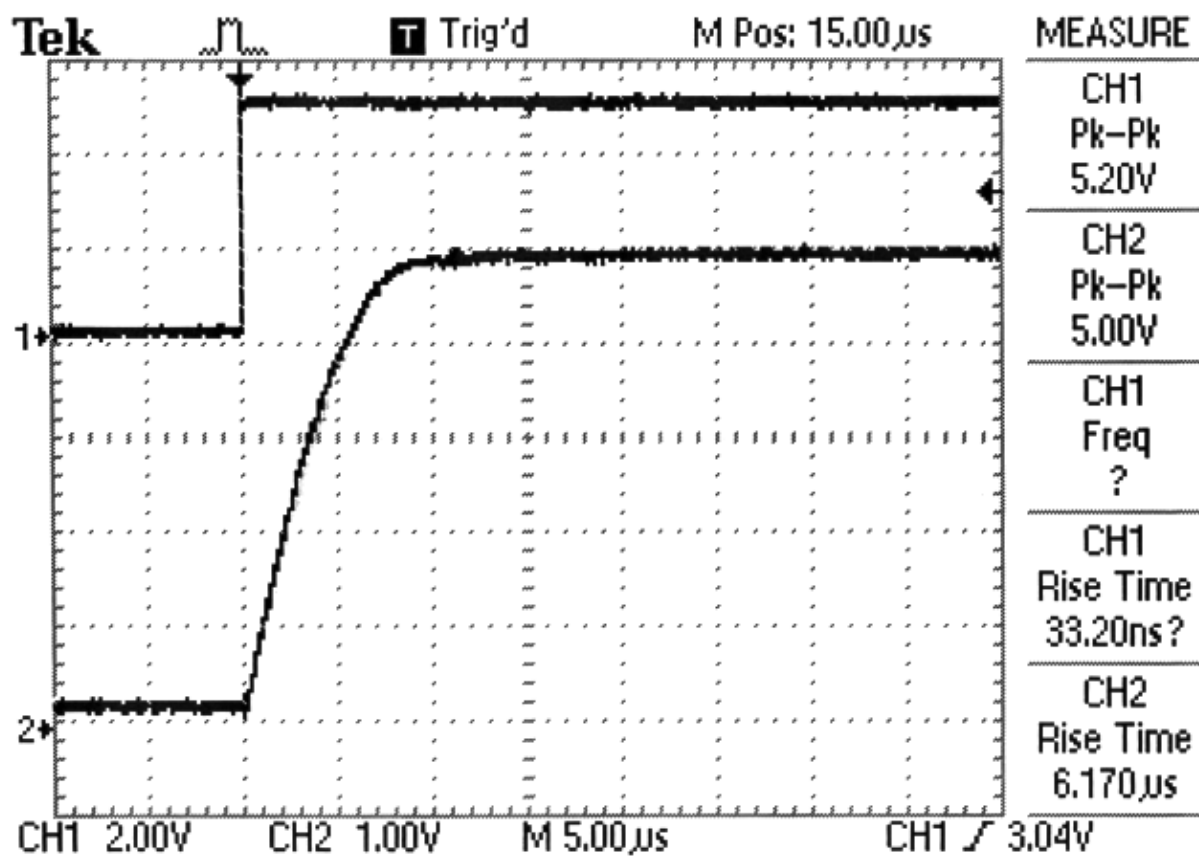
} Things to know about measuring speed:

The rise time that you measure for the output of the phototransistor is tens of microsec. This is the result of the rise times of several components and instruments:

- Oscilloscope: The oscilloscope has a bandwidth that is probably printed on top of its front panel. If it has a bandwidth of 100 MHz, for example, it will have a rise time of about  $0.35 / 100 \text{ MHz} = 3.5 \text{ nsec}$ . Faster oscilloscopes cost more.
  - Probe: The 10X probe also has a bandwidth that limits how fast the measurement of the waveform can be made; look in the manufacturer's manual for the 10X probe to find the specification for its rise time.
    - Record the value of this specification.
  - Pulse generator: The rise time for the pulse generator is finite, but it is much better than for an inexpensive function generator. Pulse generators are optimized to produce excellent pulses with fast rise times; function generators are not.
  - The phototransistor and LED have finite response times; here are the data from the manufacturer's specifications:
    - PNA1801L phototransistor, 4  $\mu\text{sec}$ , typical<sup>††</sup>
    - HLMP-C115 LED: 30 nsec, typical
  - The HLMP-C115 LED, (cost ~ \$0.60), is one of the fastest visible LEDs that I was able to find. Usually, in applications where the response time of a light source is important, you would not choose an LED; instead you would choose a laser diode, which is much faster (cost ~ \$10).
- \* – Replace the HLMP-C115 with any common LED (for example a red diffused LED like the one used in Experiment 8) and repeat the measurements of the time response for that LED.
  - \* – For both measurements (HLMP-C115 and the other LED), identify the component or instrument you believe is most responsible for the finite rise time that you measured, and discuss briefly how you came to that conclusion.
  - \* When finished, reset the CH1 and CH2 menus so that it has Probe 1X, not Probe 10X, so that this does not confuse measurements made with this scope in following labs.

---

<sup>††</sup> Note: manufacturer's specification is for parameters  $V_{cc} = 10 \text{ V}$ ,  $I_{CE} = 1 \text{ mA}$ ,  $R_L = 100$ . Your result might be slower at parameters different from these.





---

**REFERENCE:**            Horowitz and Hill                            Sections 4.01-4.09,4.11  
Appendix K: `411 datasheet

## INTRODUCTION

- } The operational amplifier (op amp):
  - is an integrated circuit, i.e., “chip.”
  - is a multistage transistor amplifier with a differential input.
  - has a high input impedance ( $10^{12} \Omega$  for J-FET input op-amps).
  - is usually used with an external feedback network.
  - can amplify or perform mathematical and logical operations.
  - can operate from DC to MHz frequencies, depending on the op-amp model.
  - requires bi-polar power supply, typically  $\pm 15 \text{ V}$ .
  
- } The comparator is similar to an op-amp, but it is used for a different application: its output swings from one rail to the other, depending on which of the two inputs is more positive.
  
- } Note: The student will need software to make graphs

## EQUIPMENT

### Lab supplies:

Prototyping board	
Digital Oscilloscope	
Function generator	
Digital Multimeter	
Resistor substitution box	
Photocell	NSL-4522 (from cabinet; not included in parts kit)

### Lab supplies:

Wire kit	
Op-amp (2)	LF411CN (or equivalent 8-pin DIP)
Comparator	LM311N
Resistors	1 k (2), 4.7 k, 10 k (4), 22 k, 100 k, 5 M
Capacitor	0.01 $\mu\text{F}$ , 50 pF
Potentiometer	approx. 50 k (okay to re-use part from Lab 3 kit)

---

## PRELAB

1. Identify all the formulas you will need in this Lab.
2. In this lab you will use “decibels”, or dB. This is a dimensionless ratio, in logarithmic form.
  - The formula is  $X_{\text{dB}} = 20 \log_{10} (|X|)$ , where  $X$  is the dimensionless ratio of two amplitudes. For example,  $X$  might be the gain  $A$  of an amplifier, which is the ratio of the output and input amplitudes. If the gain  $A$  of an amplifier is 100, you can also say that the amplifier has a gain of 40 dB.
  - Note that negative values correspond to a ratio of less than unity, for example an amplifier with a gain of 0.01 has a gain of -40 dB.
  - You can compute a voltage ratio by taking the exponent of 10, for example the voltage ratio corresponding to a gain of 15 dB is  $10^{(15/20)} = 5.623$ .
  - As your prelab exercise, calculate the following:
    - The gain in dB of an amplifier with a gain of 10,000.
    - The gain in dB of an amplifier with a gain of 0.1
    - The voltage ratio that corresponds to - 3 dB.

---

## PROCEDURE

### 0. Things to know

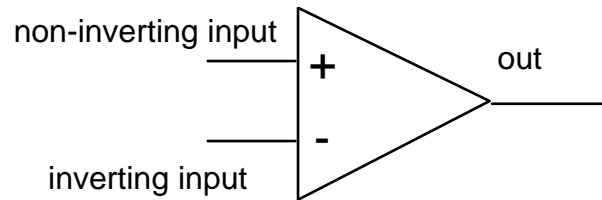


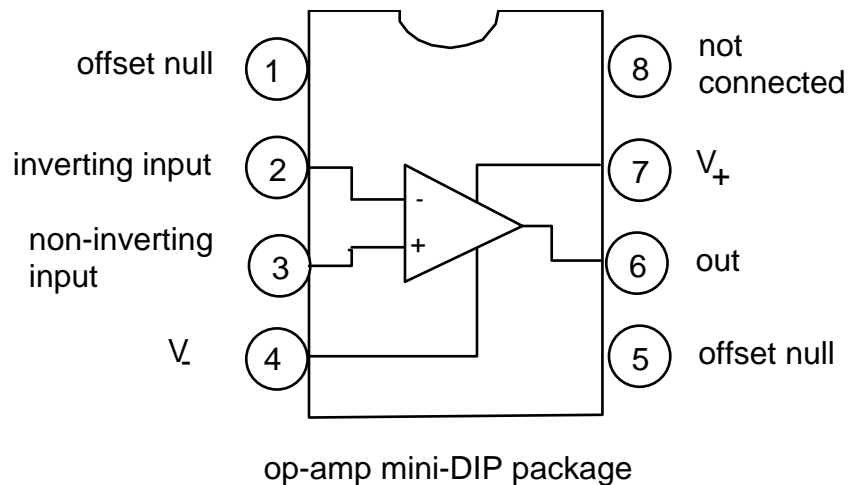
Figure 7-1 Symbolic representation of an operational amplifier

} An op-amp ideally obeys the rules:

- (1) The output voltage does whatever necessary to make the two inputs at the same voltage.
- (2) The current drawn by the two inputs is zero.

Also, an external feedback network must be provided that connects the output to the inverting input; this provides negative feedback.

The pin configuration for an 8-pin DIP op-amp is shown in Figure 7-2, as viewed from the top.



*in most applications,  
the offset null is not connected*

Figure 7.2 Op-amp pin configuration

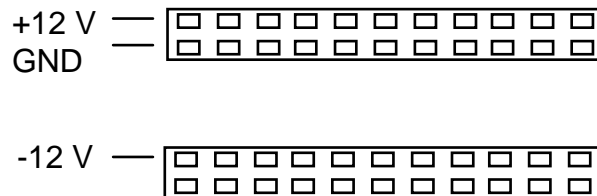
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} Note that an op-amp is an active component that must be powered to work. Most models need a bi-polar power supply. On a schematic diagram, the power-supply connections to an op-amp are often not shown.

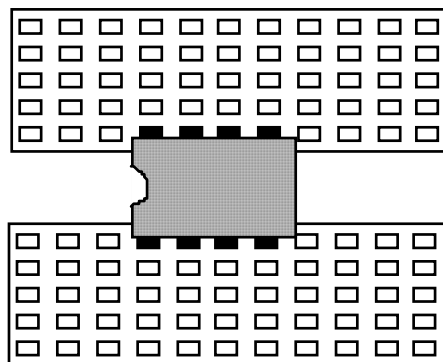
Connect the two terminals  $V_+$  and  $V_-$  to a  $\pm 15$  V power supply (or  $\pm 12$  V on your prototyping board).

### The prototyping board

A prototyping board is made especially for DIP (dual-inline package) ICs. Many models have built in power supplies that you may use. Use wires to connect the outputs of the  $\pm 12$  V power supply and ground (three wires in all) to a couple of narrow strips that look like this (note: some boards have only two strips, not four as shown here)



Insert the ICs (carefully to avoid bending their leads) into the wider strips, like this:



### 1. Inverting amplifier

} To measure the amplitude of a sine wave, measure peak-to-peak and divide by two.

\* Set up the oscilloscope to show a dual trace, one for the input of the op-amp and one for the output. Use DC input coupling. Set up the function generator to produce

a sine wave with an amplitude  $\approx 0.2$  V and frequency 1 kHz. (Use the  $-20$  dB button on your function generator, if necessary, to reduce your function generator output to such a low amplitude.) Make sure that the grounds of the function generator, oscilloscope, and prototyping board are somehow connected.

\* Measure the values of your resistors, then using the prototyping board, wire up the inverting amplifier shown in Figure 7-3.

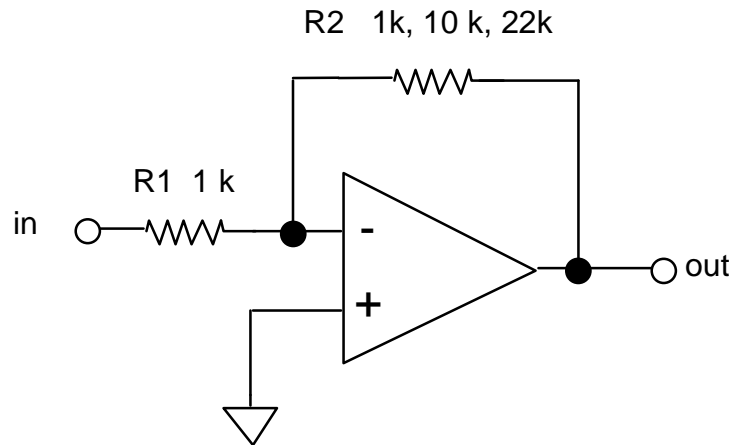


Figure 7-3 Inverting amplifier

(a) Gain

- \* – (i) Measure the gain  $A_V$  for  $R_2 = 1$  k, 10 k, and 22 k.
- (ii) Using measured values of  $R_2$  and  $R_1$ , compare to  $A_V = -R_2 / R_1$ .
- (iii) Verify that the amplifier inverts.

(b) Saturation

- \* For the circuit with  $R_2 = 22$  k, increase the input signal amplitude to observe clipping.
- \* Calculate the ratio  $V_{out} / V_{in}$  that corresponds to a  $-3$  dB drop in gain.
- \* – Measure the input amplitude that results in clipping with a 3 dB reduction of the output as compared to the ideal output amplitude. What is the output amplitude as a ratio of  $V_{CC}$ , when clipping occurs at this level?

---

(c) Frequency response

(i) roll-off frequency

\* – For the circuit with  $R_2 = 22\text{ k}$ , vary the frequency from a low value ( $\approx 100\text{ Hz}$ ) upward to find  $f_{3\text{dB}}$ , the frequency at which the gain drops by 3 dB. Compare to the value given by Figure 4.31 in Horowitz & Hill 2<sup>nd</sup> Edition.

(ii) graph of frequency response

\* – For the circuit with  $R_2 = 100\text{ k}$ , measure the gain  $A_V$  at the logarithmically-spaced frequencies of 100 Hz, 300 Hz, 1 KHz, 3 kHz,..., 1 MHz, 3 MHz. Repeat for  $R_2 = 10\text{ k}$ .

\* – Plot your results on a log-log graph. Also show on this graph the theoretical gain  $|A_V| = R_2 / R_1$ .

} Note that high gain is achieved at the expense of frequency bandwidth.

2. Voltage Follower (Unity Gain Non-Inverting Amp)

} The circuit in Figure 7-4 has a voltage gain of unity but a very high current gain.

(a) Input impedance

\* – Use a  $5\text{ M}\Omega$  resistor in series with the function generator at the input to measure the input impedance. If it is too high to measure, report it as  $Z_{in} \gg 5\text{ M}\Omega$ .

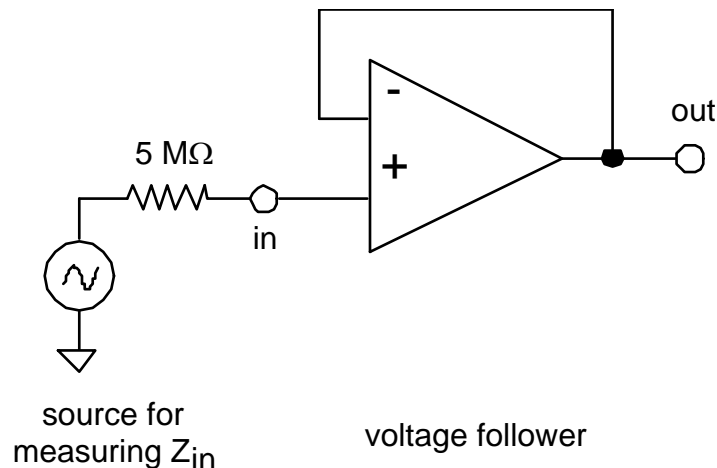


Figure 7-4 Unity gain non-inverting amplifier (Voltage Follower)

### 3. Summing Amp

Note: This circuit is similar to one in a homework problem

\* Build the circuit shown in Figure 7-5. Choose  $R_1 = 10\text{ k}$ .

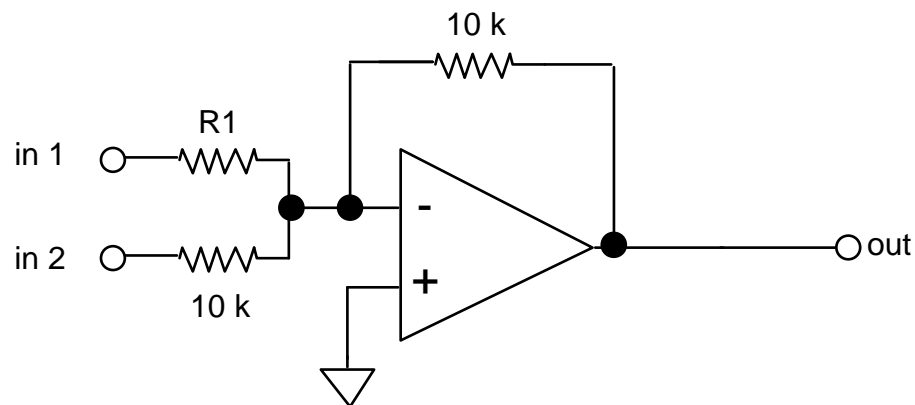


Figure 7-5 Summing Amplifier

\* Use a 4 Volt P-P sine wave for input 1. Use a + 5 V dc voltage from a power supply (your prototyping board is ok) for input 2. Connect the oscilloscope, using DC input coupling, to monitor input 1 and the output.

\* – Confirm that the output is (minus) the sum of the inputs. Sketch or print the waveforms, and mark values at the following phases of the sine wave: peak, trough and zero. Also present calculations showing that the output is approximately equal to the expected value of the sum of the inputs; do this for three cases, corresponding to the three phases: peak, trough and zero.

### 4. Difference Amp

} The circuit in Figure 7-6 is a differential amplifier.

} Recall that the common mode rejection ratio is defined as:

CMRR = differential mode gain / common mode gain, i.e.,

$$\text{CMRR} = A_D / A_C$$

} Using Op-amp rules 1 and 2 as described in Horowitz & Hill 2<sup>nd</sup> Ed., one can derive that:

$$V_{out} = -\frac{R_2}{R_1} V_{in1} + V_{in2} \frac{R_4}{R_1} \left( \frac{R_1+R_2}{R_3+R_4} \right) \quad (4.1)$$

Note that if  $R_1 = R_2 = R_3 = R_4$ , then the output is a simple difference

$$V_{out} = V_{in2} - V_{in1}. \quad (4.2)$$

More generally, we can find expressions that are valid even if the resistor values are not all exactly identical, which of course they won't be in practice, due to resistor tolerances. Substituting  $V_{in1} = -V_{in2}$ , we find that the "differential mode gain" is

$$A_D = -R_2 / R_1 \quad (4.3)$$

Substituting  $V_{in1} = V_{in2}$ , we find that the "common mode gain" is

$$A_C = -\frac{R_2}{R_1} + \frac{R_4}{R_1} \left( \frac{R_1+R_2}{R_3+R_4} \right) \quad (4.4)$$

which is zero if  $R_3 = R_1$  and  $R_4 = R_2$ . So, the CMRR =  $A_D / A_C$  is perfect (infinity) if  $R_3 = R_1$  and  $R_4 = R_2$ . However, resistors actually have a tolerance of typically 5%, and therefore the common mode gain will not actually be zero, and the CMRR will not be infinity.

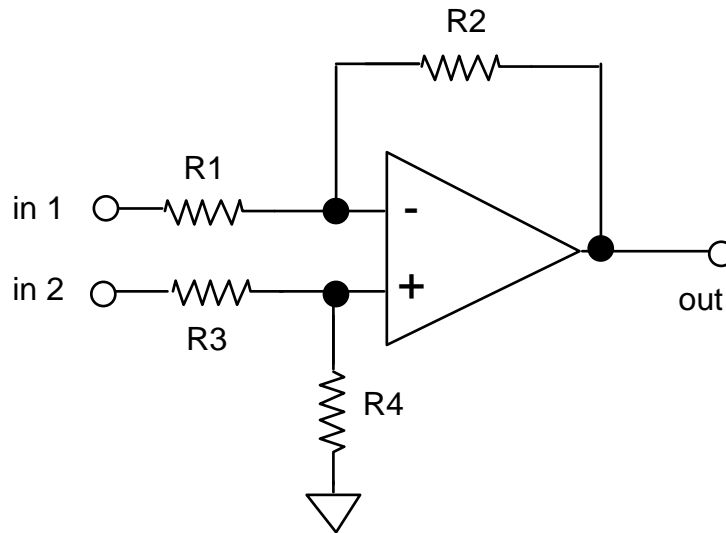


Figure 7-6 Differential Amplifier

- \* Connect the circuit in Figure 7-6, using resistor values  
 $R_1 = R_2 = R_3 = R_4 = 10 \text{ k}.$



---

(a) Differencing

\* – Use the setup with a sine wave and a dc signal set-up that you used for the summing amp. Verify that the output is the difference of the two inputs, as predicted by Eq. (4.2), by marking values at particularly significant times on the printout of the scope display.

(b) Differential mode gain

\* – Apply the sine wave to input 1 and connect input 2 to ground. Measure  $A_D = V_{out} / V_{in1}$ . Compare to the value predicted by Eq. (4.3), using actual measured values for the resistors.

(c) Common-mode gain

\* – Connect both inputs to the sine wave. Measure  $A_C = V_{out} / V_{in}$ . Compare to the value predicted by Eq. (4.4), using actual measured values for the resistors.

(d) CMRR

- Compute  $CMRR = A_D / A_C$ .

5. Integrator (low-pass filter)

} The circuit in Figure 7-7 is an integrator, which is also a low-pass filter with a time constant  $= R_1 C$ . Resistor  $R_2$  provides DC feedback for stable biasing, since without it there would be feedback through the capacitor only, and that would not provide any DC feedback. Note: if you observe a severe dc offset on the output of the circuit, you may replace  $R_2$  with a 100k resistor.

The output is  $V_{out} = -\frac{1}{R_1 C} \int V_{in} dt + \text{const}$

\* Adjust your function generator to produce a square wave, which will be applied to the integrator circuit's input.

(a) Integration

\* – Print waveforms for  $V_{in}$  and  $V_{out}$  at 1 kHz.

(b) DC stability

\* – Remove the resistor R2, and see if anything unfortunate happens to the output waveform (the effect might not occur, or it might not be extreme). Be sure to use DC coupling on your oscilloscope input.

(c) Frequency response

\* – Vary the frequency while observing the input and output waveforms on the oscilloscope. It is not necessary to record data for this step. Discuss in one sentence how your observations are consistent with the description “low-pass filter.”

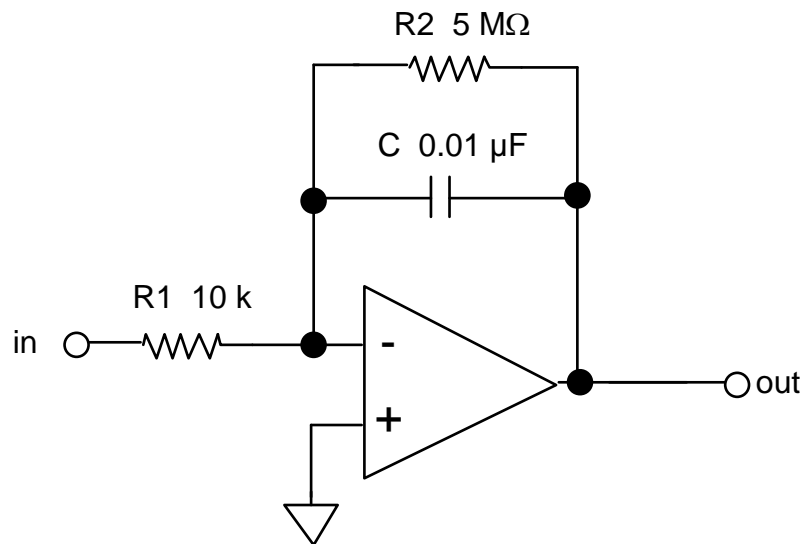


Figure 7-7 Op-Amp Integrator

6. Differentiator (high-pass filter)

TA Note: If necessary, this circuit can be deleted so that students have time for the comparator.

} The configuration in Figure 7-8, with the main components C<sub>1</sub> and R<sub>2</sub>, is a differentiator. Differentiators always have difficulty with high frequency noise, so a low-pass filter combination C<sub>2</sub> and R<sub>1</sub> is added to reduce the noise.

\* Connect the circuit shown in Figure 7-8, and apply a sine wave to the input. If the output of the circuit exhibits clipping, reduce the input amplitude; if turning the function generator's amplitude knob isn't sufficient, see if your function generator has an attenuation button, which might be labeled -20 dB for example.

(a) Differentiation

- \* – Print the outputs of the differentiator circuit for a sine wave and a ramp wave inputs at a frequency 100 Hz. Explain how your waveforms are consistent with the circuit taking the “derivative” of the input.

(b) Frequency response

- \* – For a sine wave input, vary the frequency while observing the input and output waveforms on the oscilloscope. It is not necessary to record data for this step. Discuss in one sentence how your observations are consistent with the description “high-pass filter.”

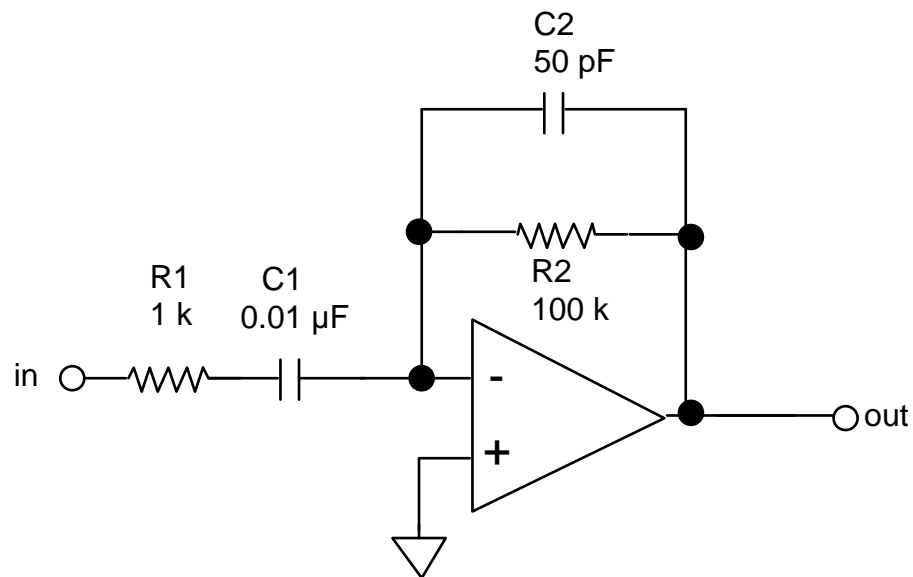


Figure 7-8 Op-Amp Differentiator

## 7. Comparator

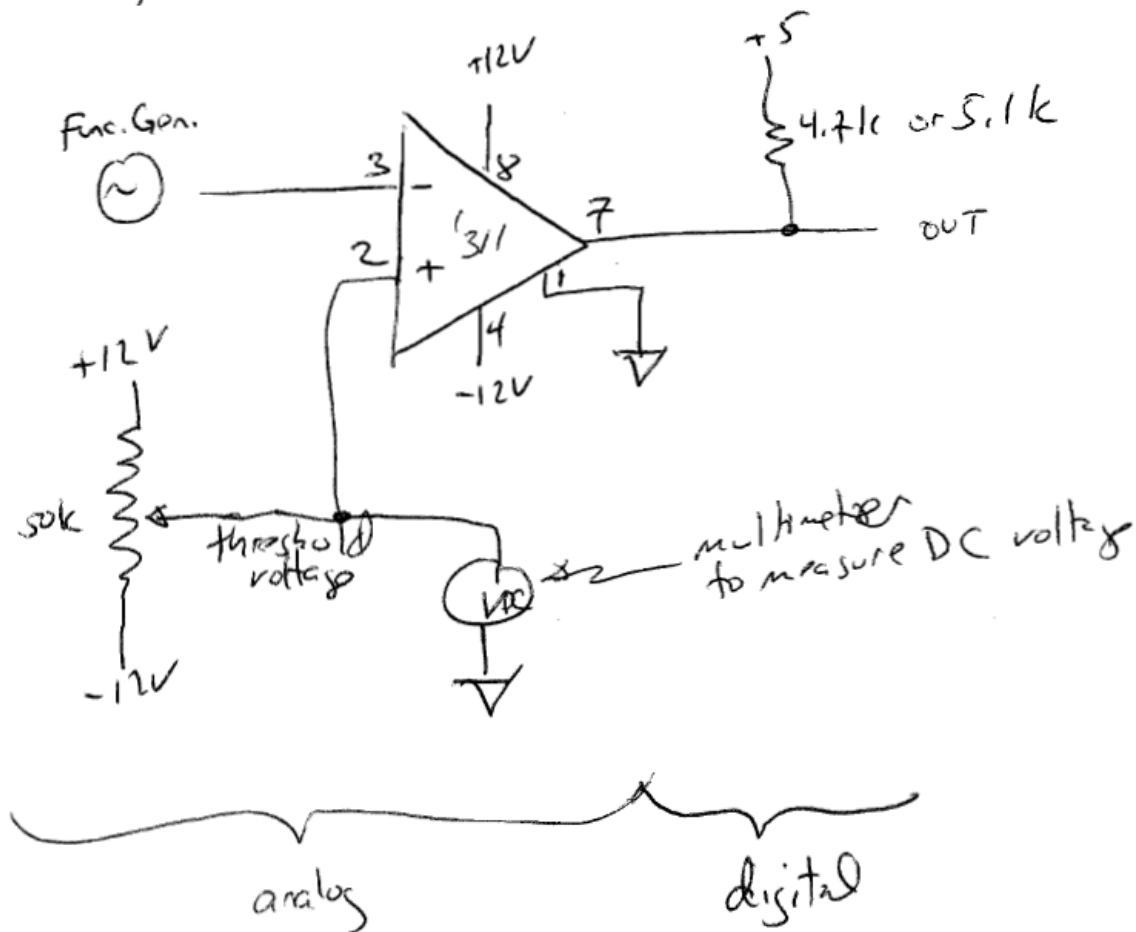
} You will observe how a comparator will output a (relatively) clean **digital** output (+5V or 0V) depending on whether an **analog** input voltage is  $>$  or  $<$  a threshold voltage. You will establish the threshold voltage using a potentiometer.

} You will also observe an undesired oscillation in the comparator's output, and you will diminish this oscillation by adding positive feedback to the comparator.

\* Connect the comparator chip, as shown below (pin-out is shown for '311; the '411 is different). Use the power supplies of the prototyping board:

+/- 12 V power supply for **analog**

+5 V power supply for **digital**.



\* Adjust the function generator to provide an 8 V peak-peak sine wave at 1.5 kHz.

\* Observe the (digital) output of the comparator on CH1 of your oscilloscope, and the sine wave (analog) input on CH2. Trigger the scope on CH1 using the falling edge, with 100  $\mu$ s / division for the horizontal scale.

- 
- \* – Record the oscilloscope display when the threshold is set to the following two values:
    - (i) + 3 V
    - (ii) 0 V.
  - Discuss qualitatively how the output waveform “changes states” in response to:
    - Up-going analog input voltage
    - Down-going analog input voltage.
  - \* Now zoom in to the down-going change in digital output voltage using a 250 nsec/div on the oscilloscope’s horizontal scale.
  - \* – Record the oscilloscope display showing the “ringing” or “oscillations” present in the digital output (with a typical characteristic time of ~ 200 nsec).
  - \* Now connect a 100k resistor between output pin 7 and the non-inverting input pin 2 of the comparator. This provides positive feedback.
  - \* – Record the waveform. Discuss whether the undesired oscillations are diminished by using positive feedback, and if so, whether the effect is a strong one.

## 8. Using sensors

} There are several ways to detect light:

- Here you will use a *photocell*, which is a simple two-terminal sensor that acts like a resistor, with a resistance that diminishes as the light level is increased. It is *not a linear* sensor, so its use is often limited to “electric eye” applications that require detecting whether conditions are dark, for example to turn street lights on and off.
- If you needed to measure light intensity over a continuous scale, you would choose a different sensor with a linear response to light intensity, such as a photodiode or photomultiplier tube.

NSL-4522 CdS Photocell specifications (from Silonex datasheet):

$R_{\text{dark}}$ (min)	1 M (minimum)
R @ 1 foot-candle	18.6 k (+/- 40%)
R @ 100 foot-candle	400 (typical)

---

\* – Design a simple voltage divider to replace the function generator in the comparator circuit above, so that the comparator circuit's output voltage will change when you cover the sensor with your hand to block the room lights.

- The voltage divider should consist of the photocell and a suitable fixed resistor, and it should be connected to a suitable power supply.
- It may be helpful to know that indoor room lighting is typically in the range of 10 – 100 foot candles. Whether this circuit works will depend on your choice for the voltage divider resistance, power supply, and threshold voltage for the comparator. (You must decide on your own what values to use for the resistance, and what to use for the voltage-divider's power supply.)
- After designing the circuit:
  - \* – Verify that the output of the comparator changes when you block/unblock room lights from hitting the photocell.
  - Report the values you chose for the resistor and the power supply voltage for the voltage divider.

# Lab 8

## Digital Gates

**REFERENCE:** Horowitz and Hill Sections 8.01 - 8.13

### INTRODUCTION

} Digital devices are basically electronic switches that use two states, or logic levels.

TTL and CMOS are two families of digital circuits. Most commonly, they are powered by a +5 V power supply, although CMOS is sometimes used with +12 V.

These are integrated circuits, i.e., ICs, or “chips.”

A digital signal is either ON or OFF:

state	other names for the state	TTL	CMOS
ON	(HI, "1", TRUE)	3.0 - 5.5 V	3.5 - 5.5 V or 8.5 - 12.5 V
OFF	(LO, "0", FALSE)	-0.5 - 1.5 V	-0.5 - 1.5 V

Digital ICs called “gates” perform arithmetic and logical operations:

one input: NOT (inverter)

two or more inputs: OR, AND, NOR, NAND, XOR (Exclusive OR).

On 14-pin logic chips, usually pin 14 is  $V_{CC} = +5V$ , and pin 7 is ground.

We will try out these devices and their truth tables, then combine them to perform more complicated logical operations. We will also test a half adder, which perform the arithmetic operation of addition, and a multiplexer.

---

## EQUIPMENT

### Lab supplies:

Prototyping board  
Power supply  
Digital multimeter

### Student kits:

Wire kits

Resistors: 220  $\Omega$  (1)

LEDs (4)

Digital ICs:

74HC00 and 74LS00

74LS02 (or 74HC02)

74LS04 (or 74HC04)

74LS86 (or 75HC86)

74LS151

Quad NAND

Quad NOR

Hex inverter

XOR

8 Input Multiplexer

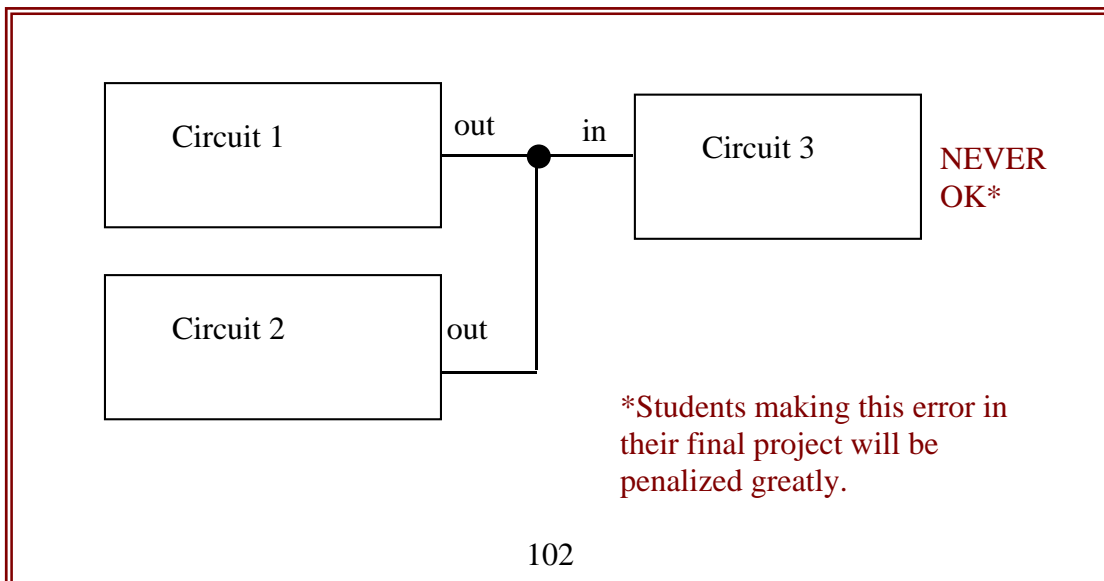
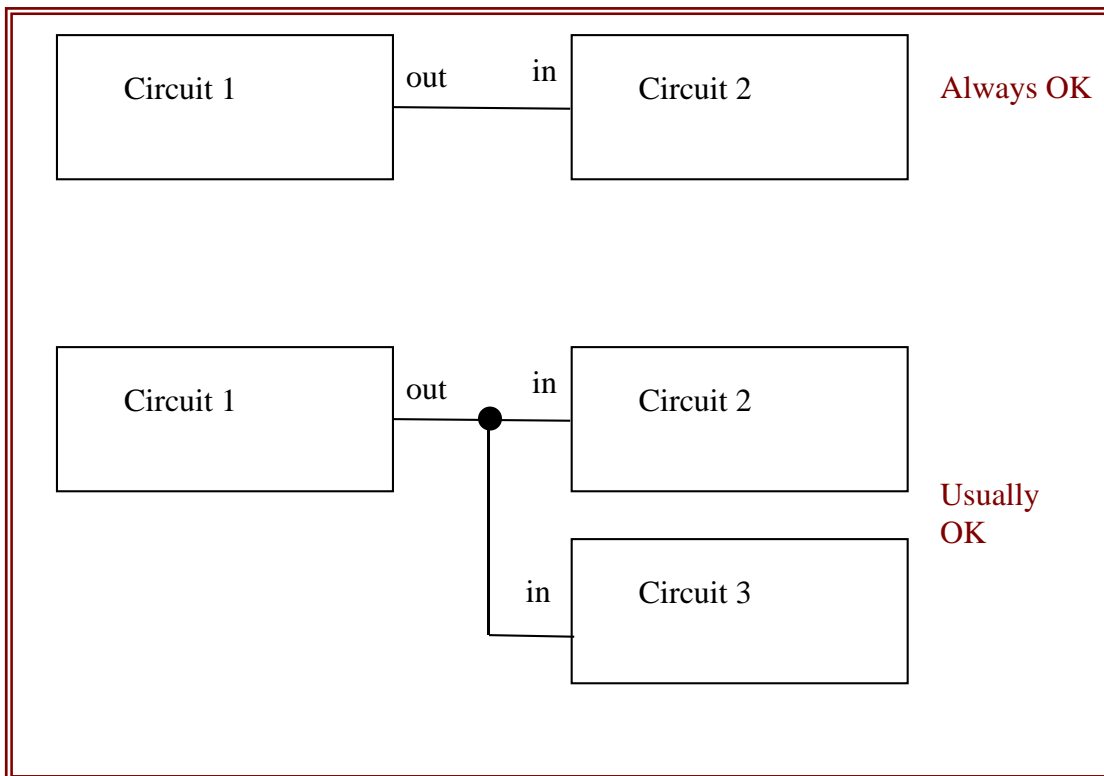


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## A BASIC FACT TO KNOW

In electronics:

- It is **USUALLY OK** to connect an output of a circuit to the inputs of two circuits.
  - It is **NEVER OK** to connect two outputs together.
- (A circuit's output attempts to establish the voltage on its wire. A wire can have only one voltage. If you connect two outputs to the same wire, the voltage on that wire will be unpredictable.)



---

## PRELAB

1. Look at all the diagrams in this lab, and verify that you are never asked to connect two outputs together, although you are often asked to connect an output to multiple inputs.
2. The two-input exclusive or (XOR) truth table (with inputs A and B) is

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0



Using the truth table for a NAND gate, verify that the circuit in Fig. 8-3 should have a truth table that is the same as XOR.

3. Refer to a textbook (e.g. Horowitz & Hill 2<sup>nd</sup> Ed. p. 495) for a description of a multiplexer. Learn how the address bits are used to select which of several inputs is sent to the multiplexer's output.
4. Why is it not okay to connect the outputs of two chips together?

---

## PROCEDURE

### 0. Things to know

#### } About digital inputs

In making tests, you will need to connect some inputs to your digital circuits.

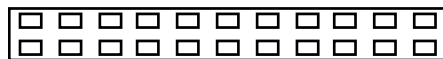
For a LO input, use a wire between the digital input and ground.

For a HI input, use a 1 k resistor between a digital input and +5 V.

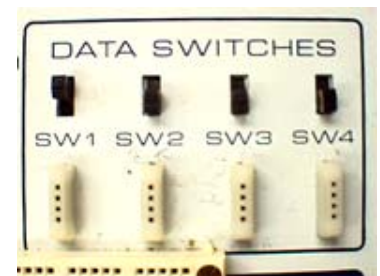
An alternative method (more convenient than using resistors as described above) requires using a prototyping board that has built-in switches for logical HI and LO inputs. These provide suitable inputs for logic circuits and don't require resistors.

#### } On your prototyping board:

Use two wires to connect the +5 V and GND outputs of the power supply to a strip that looks like:



Your prototyping board has built-in LED “Logic Indicators” that you can use for displaying a signal. As an alternative, you may use a discrete LED as an indicator, but be sure to use a series resistor, as described below.



#### } How to read part numbers:

The part number consists of numbers and letters.

Example: SM74LS00 -- the SM indicates that the manufacturer is Motorola (and this is not important), 7400 indicates that the chip is a quad 2-input NAND, and the LS indicates that it is a variety of TTL that is “low-power Schottky-input.” Other chips that perform the same logical function are 7400 (plain old-fashioned TTL) and 74HC00 (“High-speed” variety of CMOS). All of these chips are logically identical, and their pin configurations are the same.

---

} About CMOS:

CMOS is more common than TTL because it has a lower power dissipation. Nevertheless, your instructor may prefer TTL for this course because TTL chips, unlike CMOS, are immune to damage by static electricity.

Static electricity can destroy CMOS chips. To avoid damage:

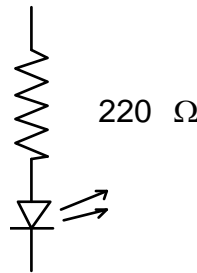
- store unused chips properly, in special plastic tubes or special plastic bags.
- before handling a CMOS chip, ground yourself by touching a ground, such as the metal cover plate on an electrical power outlet on wall.

} About the light-emitting diode (LED)

In building digital circuits, you will often use an LED as an indicator of the state, HI or LO.

Series resistors:

- ALWAYS USE A RESISTOR IN SERIES WITH THE LED.
- Typically  $220\ \Omega$
- The series resistor is needed to avoid destroying the LED. The LED is a diode, and when it is on, it has very little resistance. If you connected an LED directly between a source and either ground or  $V_{CC}$ , it would try to pass an infinite amount of current, which will burn up the LED.



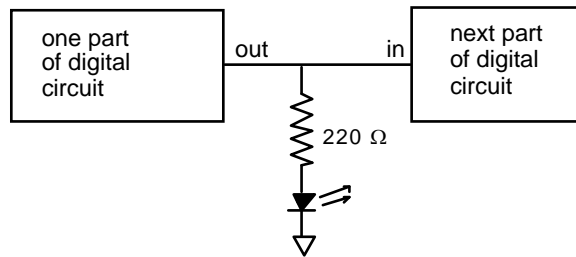
## } About buffers for the LED

A buffer is often needed to drive an LED. The outputs of many gates and circuits cannot source enough current to drive an LED directly; this is when you must provide a “buffer”. The buffer is a digital version of a follower; its output is at the same voltage as the input, but is capable of driving more current while sinking very little at its input.

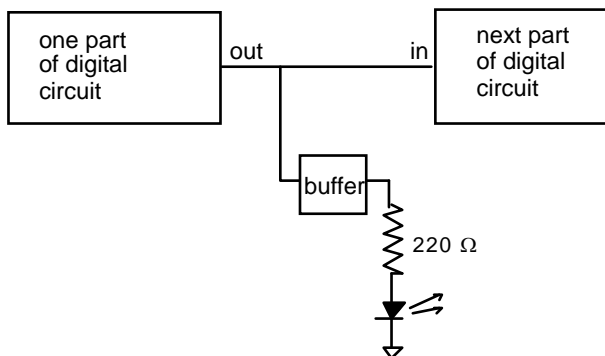
Your prototyping board has LEDs that are already wired so that you can use them as digital indicators.



without a buffer



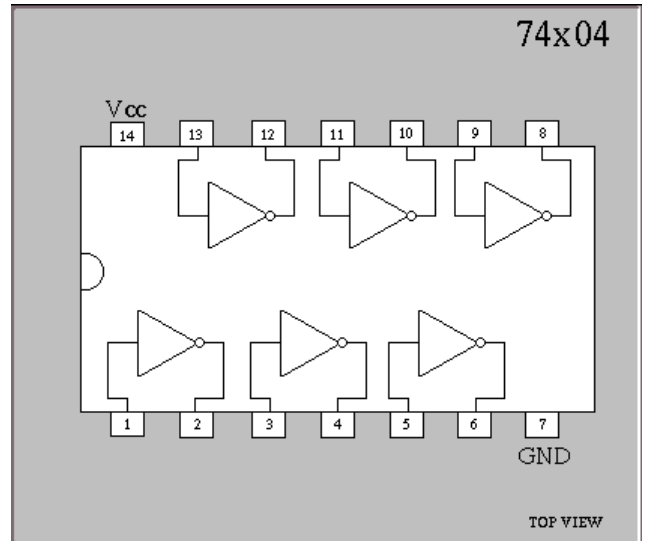
with a buffer



## 1. The '04 Hex inverter

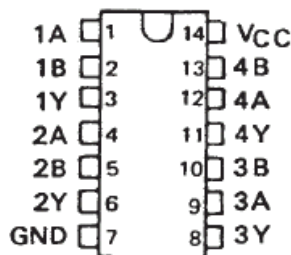
Use the 5V power supply for  $V_{cc}$ .

- \* Install the '04 hex inverter on the prototyping board. Examining the pin diagram, choose any of the six inverters. Connect its input to a “data switch” and its output to a Logic Indicator LED.
- \* – Verify that a HIGH on the input will cause the corresponding LED to be dark (LOW).
- \* – Verify that a LOW on the input will cause the corresponding LED to be bright (HIGH).
- Write the truth table (i.e., function table) for the inverter.
- \* Try using an LED in series with a 220  $\Omega$  resistor (instead of the LED built into the prototyping board) to display the state of the gate's output.



## 2. Quad 2-input NAND 74HC00 [CMOS] and 74LS00 [TTL]

SN7400 . . . N PACKAGE  
SN74LS00, SN74S00 . . . D OR N PACKAGE  
(TOP VIEW)



FUNCTION TABLE (each gate)

INPUTS		OUTPUT Y
A	B	
H	H	L
L	X	H
X	L	H

\* This chip has four NAND gates, each with two inputs (hence the name Quad 2-input NAND). Look up the pin configuration in a data sheet.<sup>§§</sup> The output pins are 3, 6, 8, and 11. Connect  $V_{CC}$  to + 5 V. If you are using a prototyping board with built-in input-switches use these for the inputs, and use the built-in LEDs to display the outputs. At first use the CMOS chip.

- (a) NAND (Figure 8-1a)
- (b) Inverter with NAND (Figure 8-1b)
- (c) AND (Figure 8-1c)
- (d) OR (Figure 8-1d)
- (e) NOR (Figure 8-1e)
- (f) Mystery NAND circuit (Figure 8-1f)

\* See the pin diagram, above.

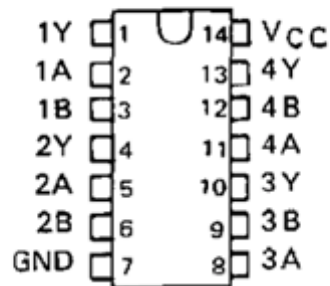
\* – Write down a Truth Table for each configuration listed above, and check off every state as you test it. Draw the gates.

\* – Finally, replace the CMOS chip with the TTL chip, and verify that the chip works the same, i.e., that the truth table for (a) is the same as for the CMOS chip.

} For the remaining exercises, you may use either TTL or CMOS.

### 3. Quad 2-Input NOR (74LS02 or 74HC02)

SN7402 . . . N PACKAGE  
SN74LS02, SN74S02 . . . D OR N PACKAGE  
(TOP VIEW)



FUNCTION TABLE (each gate)

INPUTS		OUTPUT
A	B	Y
H	X	L
X	H	L
L	L	H

<sup>§§</sup> It is a useful exercise to look up the pin diagram in the data sheet which can be found either in a Data Book, or on a manufacturer's website. This skill is necessary when you design a circuit yourself.

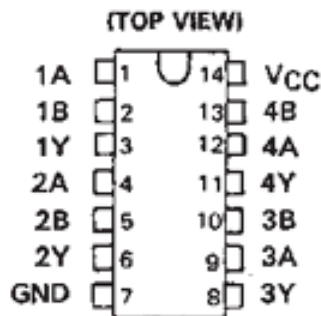
- (a) NOR (Figure 8-2a)  
 (b) Inverter with NOR (Figure 8-2b)  
 (c) OR (Figure 8-2c)  
 (d) AND (Figure 8-2d)

\* See the pin diagram, above.

\* – Write down a Truth Table and check off every state as you test it. Draw the gates.

4. XOR (74LS86 or 74HC86)

**SN7486 . . . N PACKAGE**  
**SN74LS86A, SN74S86 . . . D OR N PACKAGE**



**FUNCTION TABLE**

INPUTS		OUTPUT
A	B	Y
L	L	L
L	H	H
H	L	H
H	H	L

H = high level, L = low level

- (a) XOR from 7486 (Figure 8-3a)  
 (b) XOR using NAND only (Figure 8-3b)

\* See the pin diagram, above.

\* – Write down a Truth Table and check off every state as you test it. Draw the gates.

5. Half Adder

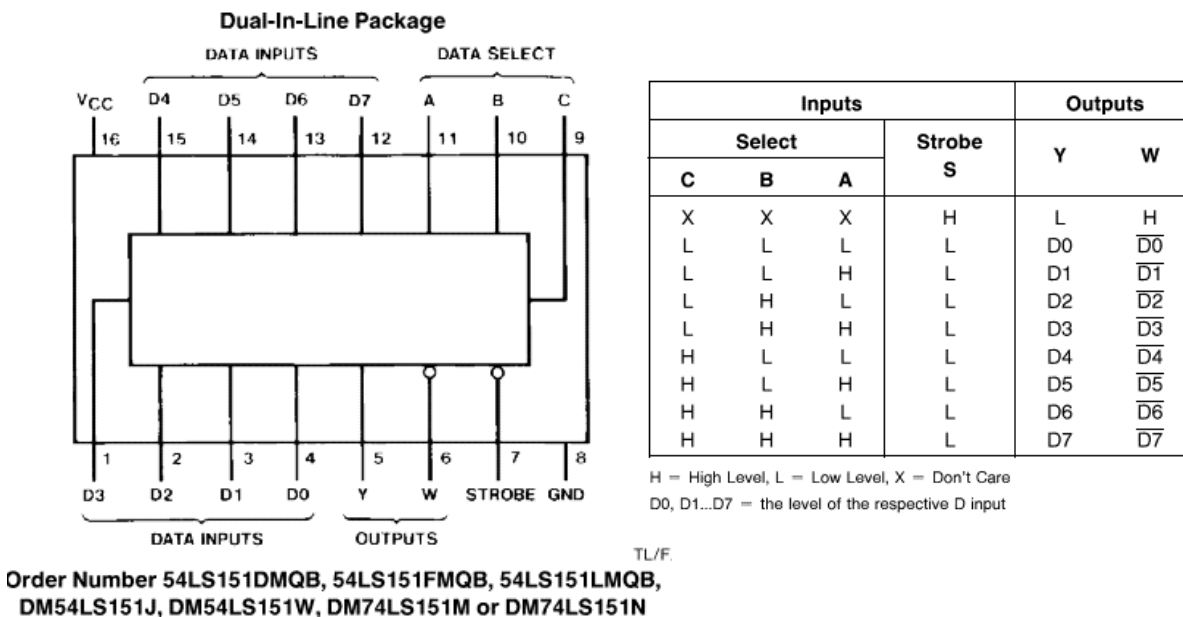
\* See Figure 8-4. Connect this circuit.

\* – Write down a Truth Table and check off every state as you test it. Draw the gates.



## 6. 74LS151 Multiplexer

} A multiplexer is a switch. It has multiple inputs and a single output. The purpose of the multiplexer is to allow the user to determine which of the inputs should be connected to the output.



\* Connect the 74LS151 as shown below.

	DATA SELECTS			OUTPUT
binary	$2^2$	$2^1$	$2^0$	
state	C	B	A	Y
IC pin	9	10	11	5
board	SW1	SW2	SW3	LED1

\* Set the following pins on the 74LS151 to LO:

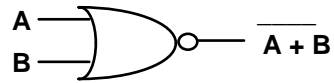
Strobe (pin 7)  
All data inputs except D1

Multiplexing:

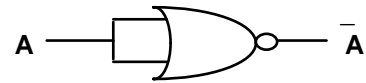
\* — Predict, by examining the truth table, which combination of input states A B and C will result in an output Y that is HI or LO if D1 is HI. Write your predictions in the form of a table with four columns: C B A and Y. Repeat for D1 LO.

\* – Operating the circuit, with D1 high and then D1 low, verify the two truth tables you predicted above (you can indicate a successful test with a checkmark to the right of a row).

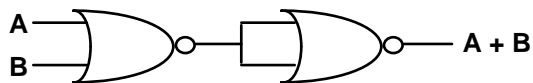
f



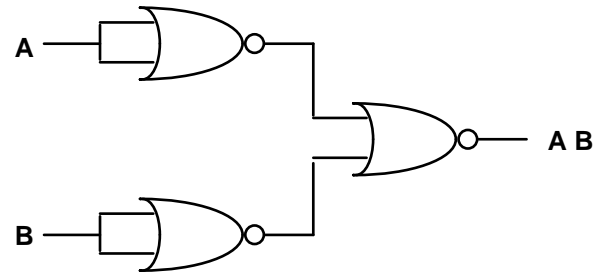
a.



b.



c.



d.

Figure 8-2 Circuits using NOR gates

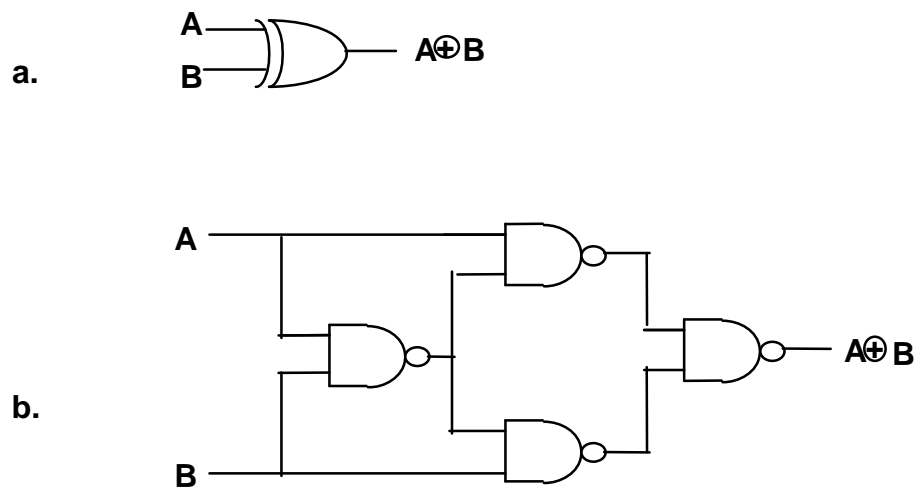


Figure 8-3 Different realizations of XOR

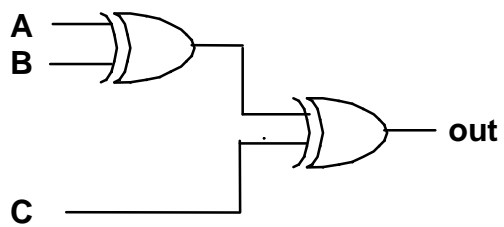


Figure 8-4 Half adder

# Flip-Flops, Shift Registers, Counters, Decoders, 7-Segment Display

# INTRODUCTION

## EQUIPMENT

- Prototyping board
- Digital Oscilloscope
- Pulse Generator
- Digital Multimeter
- Switch SPDT (momentary contact) with wires attached [for de-bounce]

Wire kit	
Digital ICs:	[TTL (LS) or CMOS (HC)]
	7400 Quad NAND
	7442 BCD to Decimal Decoder
	7447 BCD to 7-segment decoder driver (common anode)
	7490 decade counter
	74112 JK flip-flop
	74175 D flip-flop
	74161 4-Bit Synchronous Binary Counter
	74195 4-Bit Shift Register
Capacitors	0.1 $\mu$ F
Resistors	150 $\Omega$ , 10 k (2)
Seven-Segment LED (common anode)	LSD322X-XX <i>or</i> LN513RA

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## PRELAB

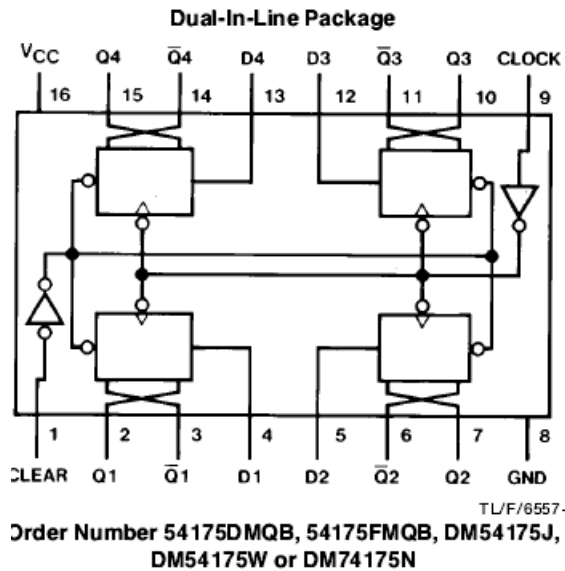
1. Explain the difference between parallel and serial:
  - what is meant by “parallel input”?
  - what is meant by “serial shift”?
2. What is the difference between common cathode and common anode, for a seven-segment display?
3. Look up the pin diagram for the ‘142 BCD-to-decimal decoder chip. To do this, just do an internet search for the generic part number to find a datasheet. You’ll need to include a prefix of 74, 74LS, or 74HC – they all have the same pin configuration.

# PROCEDURE

## 1. D Flip-Flop (74HC175 or 74LS175)

} The D Flip-Flop is the simplest but most important Flip-Flop. It simply saves at its output, Q, what it saw at its input, D, just before the most recent clocking edge.

The chip used below, the `175, has four flip flops, and they respond to a rising edge on the clock input.



**Function Table** (Each Flip-Flop)

Inputs			Outputs	
Clear	Clock	D	Q	$\bar{Q}^\dagger$
L	X	X	L	H
H	$\uparrow$	H	H	L
H	$\uparrow$	L	L	H
H	L	X	$Q_0$	$\bar{Q}_0$

H = High Level (steady state)

L = Low Level (steady state)

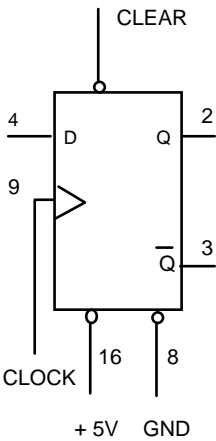
X = Don't Care

$\uparrow$  = Transition from low to high level

$Q_0$  = The level of Q before the indicated steady-state input conditions were established.

$^\dagger$  = 175 only

'151 Flip-Flop



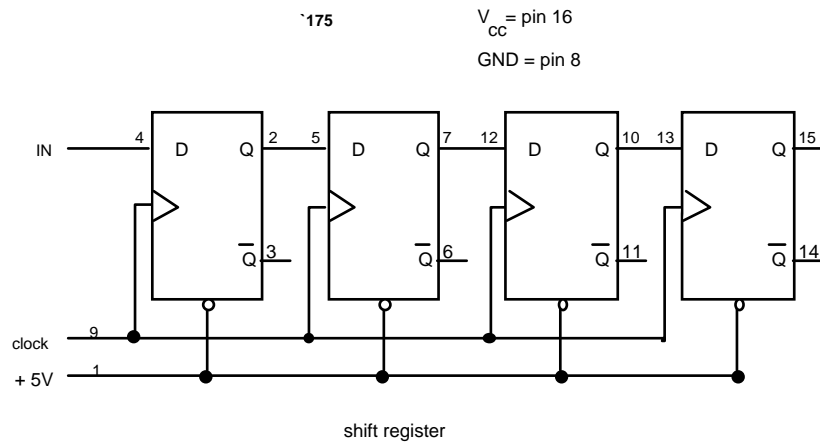
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(a) Basic operation

- \* Use  $V_{cc} = +5\text{ V}$  and GND to power this chip.
- \* Connect CLR (pin 1) to a breadboard switch, set to HI.
- \* Provide data to the D1 input (pin 4) from a prototyping board switch, by setting the D1 input to HIGH.
- \* Clock the flop (pin 9) with a momentary-contact switch (for example, “logic switch A on the prototyping board).
- \* Set up LED indicators of: the input D1 output Q1 (pin 2) and its complement  $\bar{Q}_1$  (pin 3).
- \* —
  - (i) Verify that the D flop ignores information presented to its input before a rising edge on the clock, and that it then shifts that value to the output. Draw a timing diagram, showing CLK, D1, and Q1.
  - (ii) Verify the Truth Table in the data sheet by copying the truth table (the figure labeled “Function Table” above) by placing a check-mark by each entry that you test and verify. Label the state on the timing diagram that corresponds to each entry in the truth table.

(b) Shift Register

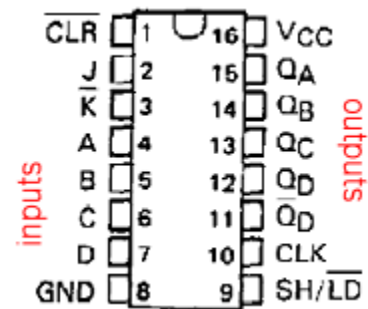
- \* Leaving the first flip-flop set up as it is, apply its output Q1 to the D2 input of another flip flop, and so on, for four flip-flops total, as shown below.
- \* Connect the four outputs Q1, through Q4 to LED indicators.
- \* Set CLR to HI using a switch on the prototyping board.
- \* Use a clock frequency of about 1 to 10 Hz, or use a momentary switch (for example, “Logic Switch A” on the prototyping board) as a manually-operated clock.



\* – Watch all the states. Observe that the input is shifted to the right once each clock cycle. Draw a timing diagram showing the four D inputs, the final output, and the clock.

## 2. The `195 4-Bit Shift Register

} Shift Registers use a series of D flip-flops, with the output of one flip-flop connected to the input of the next. It accepts both series and parallel inputs and produces both series and parallel outputs. Thus, the `195 can be used to convert series input to parallel output and *vice versa*.



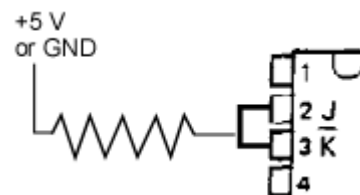


- 
- \* Connect the 74LS195 to data Switches (for inputs A B C D), Logic Switches (for inputs SH/LD' and CLK) and LEDs (to indicate outputs QA QB QC QD):

INPUTS							OUTPUTS (see note)			
<i>state</i>	IN <sub>D</sub>	IN <sub>C</sub>	IN <sub>B</sub>	IN <sub>A</sub>	CLK	SH	Q <sub>D</sub>	Q <sub>C</sub>	Q <sub>B</sub>	Q <sub>A</sub>
<i>IC pin</i>	7	6	5	4	10	9	12	13	14	15
<i>board</i>	SW1	SW2	SW3	SW4	A	B	LED1	LED2	LED3	LED4

You will also use inputs J and K', which you will connect as shown, with a wire to short the two inputs and a ~ 150 or 200  $\Omega$  resistor to connect to either +5V or GND.

TA note 2015: the above instruction has changed – please test the instruction and report to Prof. Goree



(a) Clearing

A shift register is a memory device, with a state (output values QA through QD) that depends on previous history. However, when it is first turned on the state of its memory is unpredictable.

- \* – Turn on the power. You will now cause the outputs to go to a desired known condition by “clearing” the shift register. Record the values when you turned it on. Then Connect the CLR (pin 1) to LO by connecting a wire directly to GND. (The other chip inputs don't matter, when you are clearing.) Verify that momentarily bringing CLR' to LO causes all outputs QA through QD to be set to LO, if they weren't already so.

- \* Now set CLR' to HI by connecting it to +5V through a current-limiting resistor (10k is typical). This will prevent CLR' from changing the values of the outputs during the remainder of the experiment.

(b) Serial shift sequence

*'195 Truth table for serial shift*

<u>INPUTS</u> at $t_N$		<u>OUTPUTS</u> at $t_{N+1}$			
J	K'	<b>QA</b>	QB	QC	QD
L	L	<b>L</b>	QAN	QBN	QCN
H	H	<b>H</b>	QAN	QBN	QCN
L	H	<b>QAN</b>	QAN	QBN	QCN
H	L	<b>QAN'</b>	QAN	QBN	QCN

\* Now set SH/LD' to HI to allow *serial shifting*. You should have the serial inputs J and K' connected together.

First, set J and K' to LO by connecting their external input resistor to GND. Now clock the register several times by pressing the data switch for CLK. Determine whether any outputs change their state.

Second, set J and K' to HI by connecting their external input resistor to +5V. Now clock the register once. Determine whether QA changes state, and if so, whether it did this on a *rising* or *trailing* clock edge.

Third, set J and K' back to LO. Then clock the register several times. Observe whether any data move from QA to QB etc., and if so, whether the move takes place on a *rising* or *trailing* clock edge.

(c) parallel load sequence

\* Choose the input number "1010" by setting the data switch A to 1, data switch B to 0, etc.

\* Load the input data by momentarily making SH/LD' LO. Then clock the CLK input *once*. Determine whether the input data for A is loaded to output QA etc. on a *rising* or *trailing* clock edge.

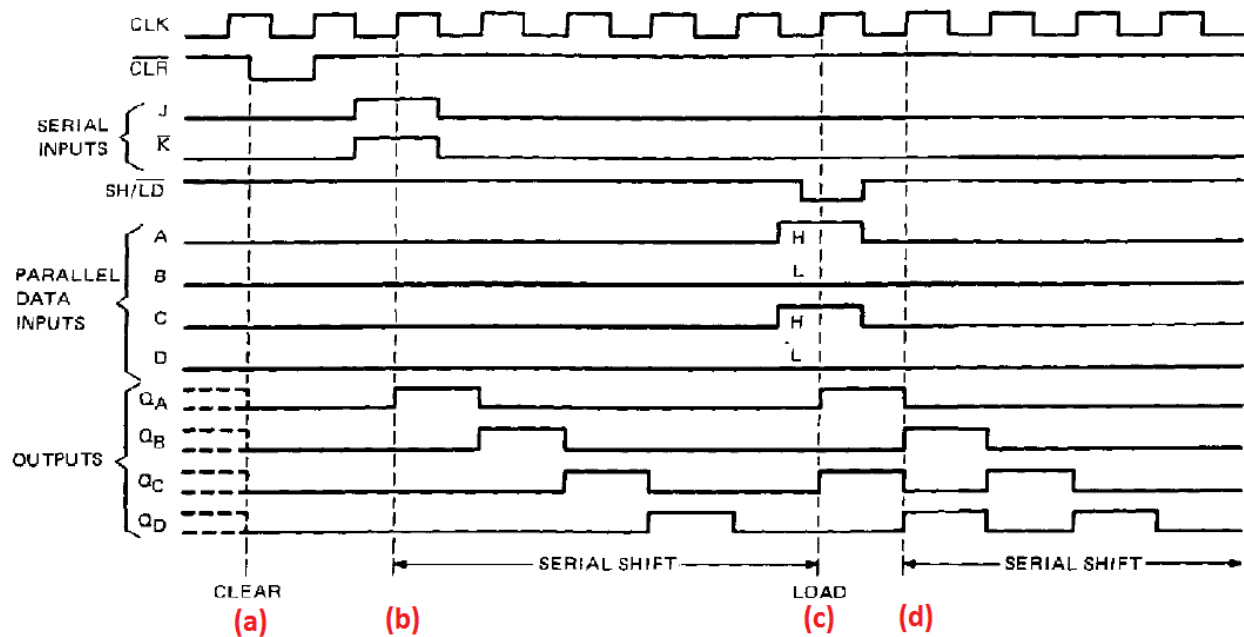
(d) Serial shift sequence

\* Do another serial shift sequence, and watch the data you previously loaded in parallel shift serially. Determine whether the outputs QA etc. change state on a rising or trailing clock edge.

– All of your results for steps (a) through (d) above should be presented in a timing diagram like the example shown here. Pay careful attention to lining things up vertically in your diagram. Use a full page if needed.

### Example Timing Diagram for '195 shift register

This is an example. You should draw your own diagram, showing your own results:



### 3. The '161 Synchronous Binary Counter

TA Note: This circuit can be deleted if necessary.

} This is a 4-bit binary counter with data inputs that can be preset, i.e., programmed, so that it begins counting from a desired number. Binary counters contain JK flip-flops.

\* Connect  $V_{CC}$  to pin 16 and GND to pin 8. Connect the inputs of the 74LS161 to switches on the prototyping board, and the outputs to LEDs, as follows:

INPUTS						OUTPUTS			
binary	$2^3$	$2^2$	$2^1$	$2^0$		$2^3$	$2^2$	$2^1$	$2^0$
state	IND	INC	INB	INA	LOAD	QD	QC	QB	QA
IC pin	6	5	4	3	9	11	12	13	14
board	SW1	SW2	SW3	SW4	SWA	LED1	LED2	LED3	LED4

\* Connect pin 2 (CLK) to a 1 Hz clock on your prototyping board.

\* Set the following pins on the 74LS161 to HI (you may use data input switch on your prototyping board to accomplish this).

Enable P (pin 7)  
 Enable T (pin 10)  
 Clear (pin 1)

} When LOAD' (pin 9) is LO, the counter can be loaded with a binary number on data inputs IND, INC, INB, INA. When it is HI, clock signals are counted.

\* Before using the circuit, convert the decimal number "12" to binary.

\* Program the counter so that it will count from 12. Do this as follows: With LOAD' LO, input the decimal number "12" on the input switches. Then set LOAD' to HI.

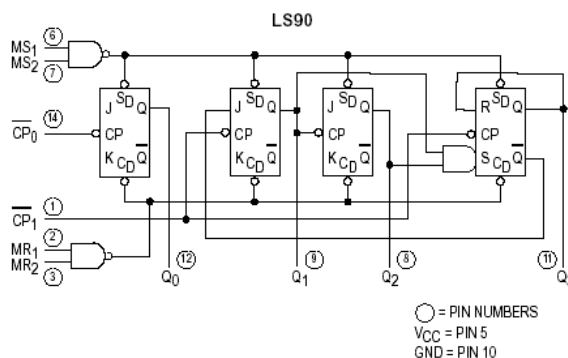
\* Now clock the CLK input and watch the chip count in binary from 0 to 15. Note that it will start at the value 12 that you programmed, then count up to 15, then start over at 0.

– Draw a timing diagram for the counting, showing CLK and outputs QA, QB, QC, QD.

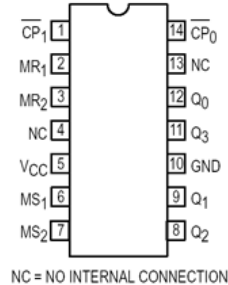
#### 4. Decade Counter (7490)

} Referring to the diagrams below from the data sheet, we see that the '90 has four internal Flip-Flops. The first one is not internally connected to the others while the other three are cascaded to form a divide-by-5 synchronous counter.

LOGIC DIAGRAM



CONNECTION DIAGRAM  
 DIP (TOP VIEW)



LS90  
 MODE SELECTION

RESET/SET INPUTS				OUTPUTS			
MR <sub>1</sub>	MR <sub>2</sub>	MS <sub>1</sub>	MS <sub>2</sub>	Q <sub>0</sub>	Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>3</sub>
H	H	L	X	L	L	L	L
H	H	X	L	L	L	L	L
X	X	H	H	H	L	L	H
L	X	L	X	Count			
X	L	X	L	Count			
L	X	X	L	Count			
X	L	L	X	Count			

H = HIGH Voltage Level  
 L = LOW Voltage Level  
 X = Don't Care

---

\* Connect the `90 as follows (note the unusual power supply pin assignments):

1.  $\div 5, \div 10$  input
2. GND
3. GND
4. NC
5. +5 V
6. GND
7. GND
8. QC
9. QB
10. GND
11. QD,  $\div 5$  output
12. QA,  $\div 2$  output
13. NC
14.  $\div 2$  input

\* For an input in parts (a) to (c), use the pulse generator to produce square pulses, between 0 and 5 V, at 5 kHz. (If you have difficulties below in getting a desirable signal from the outputs of the chip, check the input waveform: it sometimes helps to set the pulse generator's INT LOAD switch to the "in" position., or reduce the pulse height below 5 V.)

\* Set up a scope for dual-trace operation to show the pulse input from the pulse generator and an output (either pin 11 or 12 depending on what you are measuring) of the `90. Trigger the scope internally, using as the trigger source the scope channel CH1 or CH2 that you have connected to the counter's output.

\* For the '90 chip, to achieve the desired output waveform it may be necessary to use a pull-up resistor on the output pin 7. To do this, select a resistor with a value between 2 k $\Omega$  and 100 k $\Omega$  (it's not a critical value) , and use it to connect the output pin to +5V. **TA note 2015: the above instruction has changed – please test it and report to Prof. Goree.**

\* – Use the `90 to perform the following operations:

(a) Divide by 2

\* Connect the pulse input to the  $\div 2$  input.

\* – Print the waveforms. Discuss briefly the meaning of the phrase "divided by two" as it is shown by your waveforms, identifying which parameter is divided.

(b) Divide by 5

\* Connect the pulse input to the  $\div 5$  input.

---

\* – Print the waveforms. Explain how the waveform is “divided by five.” Note the asymmetry of the output waveform.

(c) Divide by 10

\* Connect the  $\div 5$  output to the  $\div 2$  input. Use the scope to observe the  $\div 2$  output.

\* – Print the waveform. Discuss briefly the meaning of the phrase “divided by ten” as it is shown by your waveforms, identifying which parameter is divided.

(d) BCD Counting

} Binary coded decimal (BCD) is the same as binary for numbers 0 to 9. For larger numbers it is different: BCD is composed of groups of four binary digits, where each group represents one digit in base 10.

*Example*

314 =	decimal	3	1	4
	BCD	0011	0001	0100
	binary	100111010		

For this chip, outputs QA, QB, QC, and QD are the four-bit BCD outputs.

\* Disconnect the pulse generator.

\* Use a switch on your prototyping board (SWA) to apply a pulse input on pin 14.

\* Connect QA (pin 12) to the  $\div 5$  input (pin 1) for BCD counting. (It may already be connected this way from part c above.)

\* By means of LED indicator lights (you may use those built into the prototyping board), test the levels of the D, C, B, and A outputs (pins 11, 8, 9, 12 respectively) after each pulse.

(i) counting

\* – Write a copy of Table 9-1, and check off each state 0 through 9 to confirm that the outputs D C B and A of the counter accumulate in a BCD counting cycle. (Note: the output may at first indicate an invalid number, such as 1011, when you first turn on the power. If this happens, just apply several pulse inputs until a new cycle begins.)

---

(ii) resetting

\* – Verify (by copying the first two rows from the “Mode selection” table above and placing check marks by the entries as you test and verify them) that setting both the reset inputs, MR1 and MR2, to HI will zero the outputs at D, C, B, and A of the decade counter.

\* To avoid wasting time, do not take this circuit apart yet. Leave this circuit wired up for use with the 7-segment display in the next part.

Table 9-1

<u>decimal</u>	<u>BCD</u>			
	D	C	B	A
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1
0	0	0	0	0
	etc.			

5. Decoder-Driver and 7-Segment LED Display (7447)

[Forewarning: this circuit is not hard, but it requires hooking up more wires than most; thus it might take more time.]

} Displays are popular output devices. LEDs are brighter, while LCDs consume far less power. Both types of displays require a decoder-driver to convert (decode) from BCD input and to drive the display.

} LED displays have 8 leads for the 7 LEDs. The displays and their corresponding driver IC's come in two varieties, common anode and common cathode.

} Ordinarily, when using LEDs, one uses a series resistor of about  $150\ \Omega$  to limit the current.

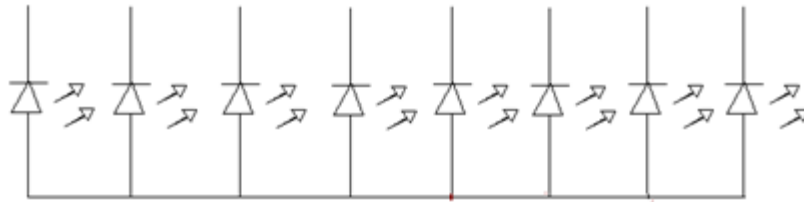
\* Leave the BCD counter hooked up as it was at the end of part 4, above, with a switch for the input and the 4 BCD outputs indicated by 4 LEDs.

---

\* If the part number is visible on the 7-segment display, check to see if it differs from the LSD322X-XX, specified here. In that case you will need to check the pin diagram for your display; this can be done by searching the internet for the part number, and looking for a data sheet.

\* Connect the BCD outputs of the BCD counter to the BCD inputs of the 7447. Connect the 7447 to the 7-segment LED display as shown.

- Note 1: pin configurations for LED displays is not standardized. Pins are shown here for the SENIOR SEA3210; your display might have a different model number but the same pins. This display has an additional LED for a decimal, which we will not use.
- Note 2: the LED display is “common anode”. This means that all the anodes of the seven LEDs are connected together, like this:



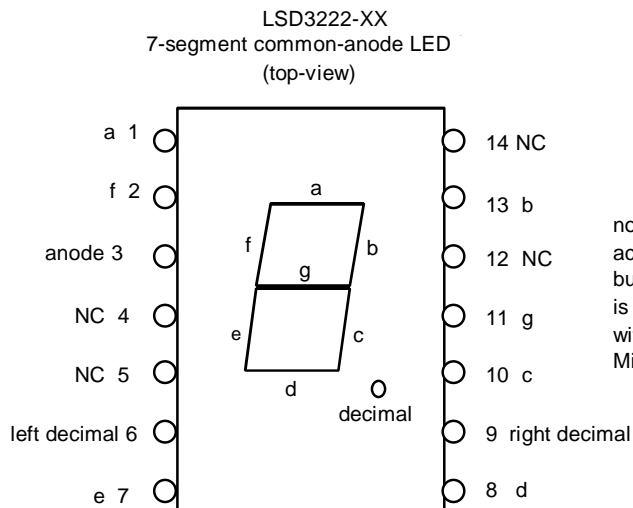
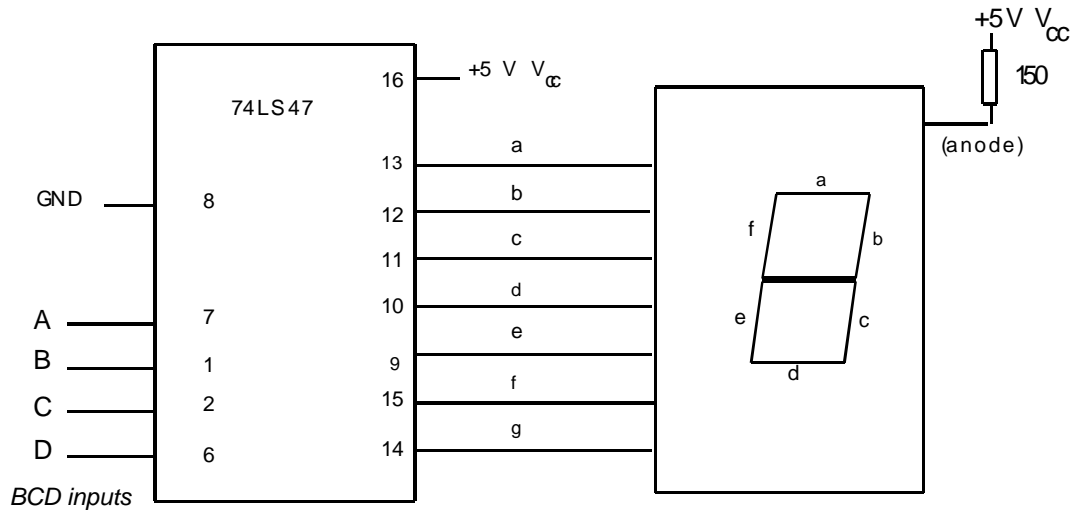
(a) Counting

\* – Write a copy of Table 9-1. Check off each state 0 through 9 to confirm that the LED outputs D C B & A of the counter are properly indicated by the display.



(b) Current consumption

\* – Use your multimeter in the dc-current mode to measure the current from the common anode to the + 5 V  $V_{CC}$ . How much current is consumed by the LED display when the display reads “1” and when it reads “8”? [Note that LED displays are power-hungry devices.]



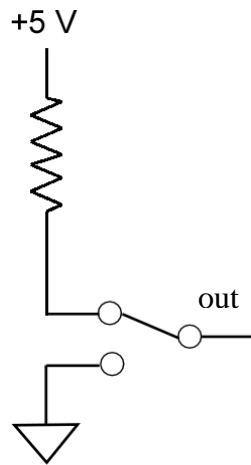
note: this LED display does not actually have 14 leads, but the package is shaped like a 14-pin DIP, with some leads missing. Missing leads are indicated here as NC

## 6. Latch Used for Switch De-Bouncing

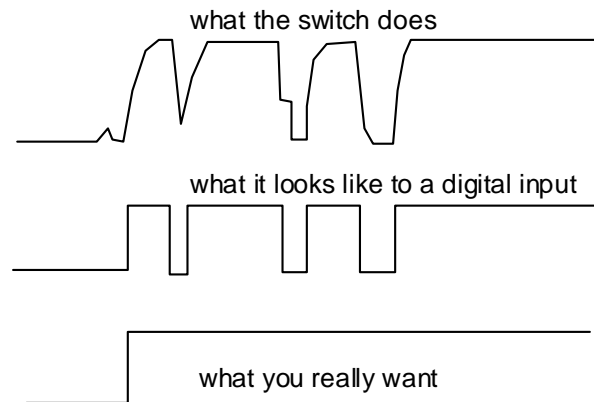
} Note to instructor: this circuit must be used with one of the counter circuits above. It is possible to use either the binary counter or the decade counter.

} An ordinary mechanical switch “bounces” several times when it opens or closes. This means that it opens and closes several times, on a time scale of about  $100\ \mu\text{s}$ , before reaching its final state. When using a switch to input data to a logic circuit, bounce is unfortunate because it looks like real data that is changing several times.

circuit intended to provide an  
input to a digital circuit



output waveforms (voltage vs.  
time) from switch

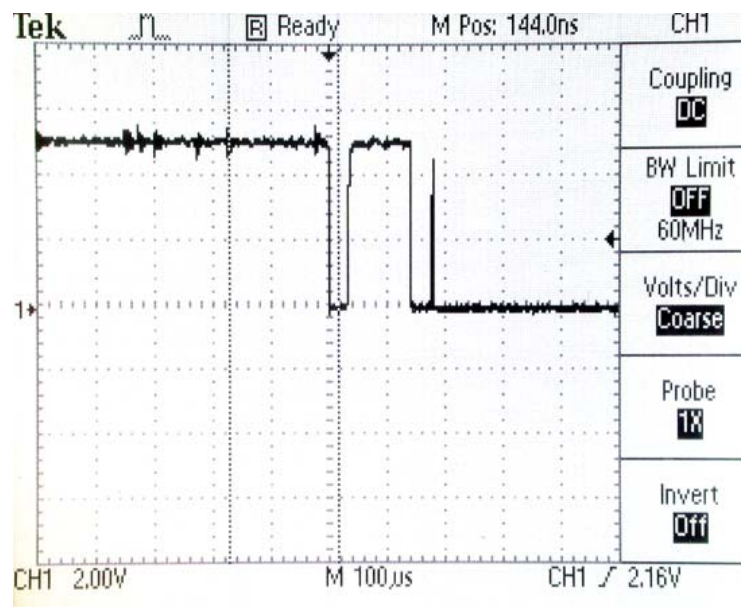
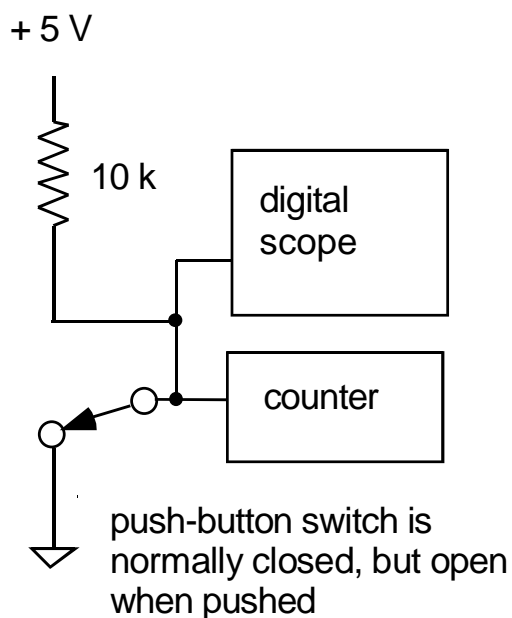


### (a) Bouncy switch

- \* Use a momentary-contact switch (not the switch built into your prototyping board; it is already de-bounced). Use the multimeter to check continuity, to see which two terminals to use on the switch so that it is normally open, and closed only when you push.
- \* Connect the simple SPDT input data switch shown below, so that the switch is normally connected to LO. This SPDT switch may be either push-button as shown, or toggle.



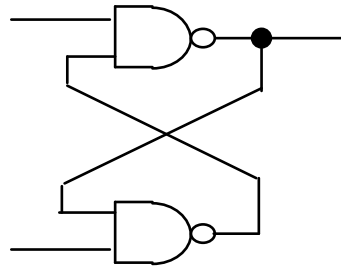
- \* Adjust a digital oscilloscope with DC coupling and approximately 100 or 250 usec / div. Observe the waveform of the output of the switch, adjusting the trigger and timebase so that you can see any bounce, as in the photo below.
- \* Apply the output to the clock input of a counter circuit (you may use any of the counter circuits you built above.
- \* — Press the switch, and watch an LED indicator of the counter output. Does the counter count more than one clock, due to bounce?
- \* — Observe and print the waveform produced by the switch. Use a digital storage oscilloscope.



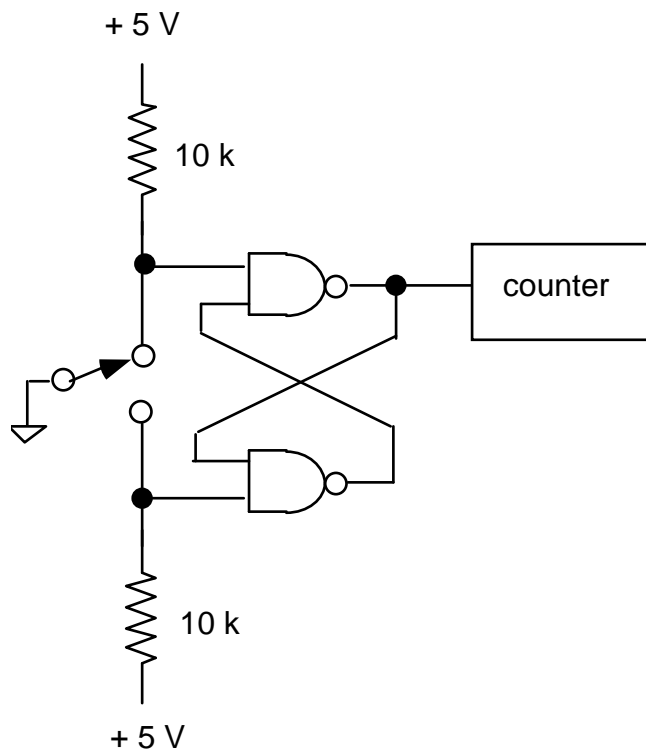
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(b) De-bounced switch

\* The circuit shown below is called an “SR flip flop” or a “cross-coupled NAND latch.” Wire it up using a 7400 quad NAND gate chip.



Now add a switch with pull-up resistors to make a data input, as shown below. Press the switch, and observe that the counter counts only one clock, because the switch is now de-bounced.



---

## 7. The `042 BCD to Decimal Decoder Chip

- \* Before wiring the circuit, convert the following decimal numbers to BCD:  
0, 1, 8.
- \* Wire the decoder chip with four inputs for BCD input. Use the switches on your prototyping board to provide input, as shown below:

### BCD INPUTS

binary		$2^3$	$2^2$	$2^1$	$2^0$
state	D	C	B	A	
IC pin	12	13	14	15	
board	SW1SW2	SW3		SW4	

- \* – Apply the BCD input corresponding to “0”. Touch a wire connected to an LED indicator to test the states of the 10 output pins. Verify that the output pin corresponding to “0” is LO and the other outputs are HI. Repeat with data inputs “1” and “8”.

## Lab 10

### Digital Meets Analog

**REFERENCE:** Horowitz and Hill    Sections 8.20 [one-shot]  
   Section 5.14 [555 timer]  
   Section 9.15-9.16, 9-20 [DAC& ADC]

#### INTRODUCTION

} In this lab we will test ICs used to interface digital and analog circuits. The first is a popular chip for making oscillators, the 555. Next is the monostable multivibrator (One-Shot) which can produce a jitter-free trigger signal from a rising or falling analog input. Finally we will set up an digital-to-analog converter (DAC) and an analog-to-digital converter (ADC).

#### EQUIPMENT

##### Lab supplies:

Digital Oscilloscope  
Function generator  
Agilent Digital Multimeter  
Pulse generator  
DC power supply  
Prototyping board  
Temperature sensor  
LM35DZ (TA: stored in cabinet)

##### Student kits:

Wire kit  
Capacitors                      0.1  $\mu$ F (3), 0.01  $\mu$ F, 0.001  $\mu$ F  
Resistor                        3k (2), 5.1k (2), 10k (4)  
Integrated circuits:  
74121                            one shot  
LM555 or 7555                timer  
DAC0808                      8-Bit Digital-to-Analog Converter  
ADC0804                      8-Bit Analog-to-Digital Converter

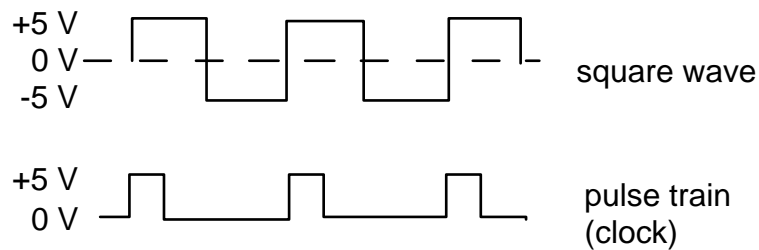
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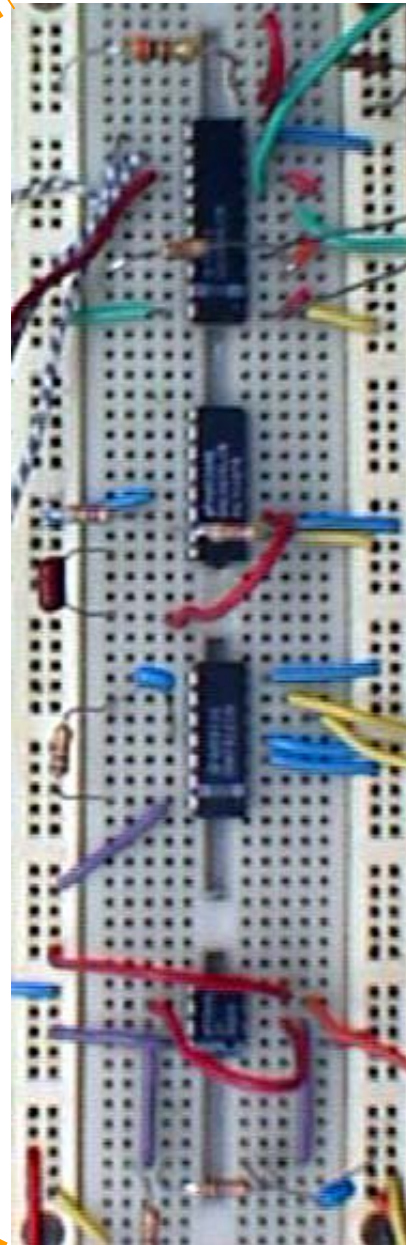
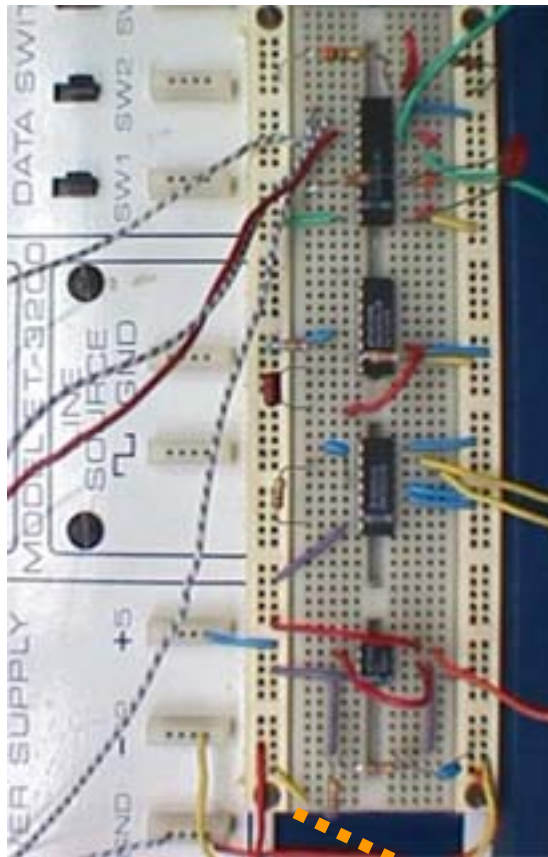
} The terms “pulse generator” and “square wave generator” refer to different things.

A “square wave generator” is usually a bipolar oscillator. The waveform swings from positive to negative voltages. Sometimes it has a feature to add an arbitrary DC offset to the output.

A “pulse generator” is usually not bipolar, and there is usually no DC offset adjustment. A pulse swings between zero and either a positive voltage (as in the case of logic circuits) or a negative voltage.

Pulse generators are used to clock digital circuits.





Lab 10 circuit, as wired on the prototyping board at the end of the Lab.



---

## **PRELAB**

1. Identify all formulas used in this lab.
2. While an analog voltage can have an unlimited number of values, a digital signal has a limited number of discrete values. How many discrete values can be represented by 8 bits of data?
3. What is the sensitivity (mV per degree C) of the temperature sensor you will use?

---

## PROCEDURE

### 1. 555 Timer, used as an oscillator

} Timer circuits are common in many of the instruments that are “home-built” in research laboratories. A favorite and easy-to-use chip is the 555 timer, or a modernized version such as the 7555. With this chip, you can easily build a simple oscillator or other waveform generator.

\* Using the prototyping board, build the circuit shown in the figure. Use +5 V from your prototyping board for  $V_{CC}$ . ( $V_{CC} = +15$  V should work too.)

\* As with many circuits, this one can benefit from adding a filter capacitor across the power supply leads to reduce problems arising from voltage drops appearing on the power supply. It is recommended to add a 10  $\mu$ F capacitor across the power supply pins 8 and 1; position this capacitor within a few millimeters of the 555 chip. Note the polarity of the leads of the electrolytic capacitor.

(a) \* Use the oscilloscope to observe the waveforms at the output and at pin TH.

\* – Measure the duty cycle of the output waveform.

Duty cycle  $\equiv$  fraction of time the output voltage is “high”

Specify your answer in percent, e.g. 37.5%  $\pm$  5%.

(b) \* – Measure the frequency two ways\*\*\*  
• Using the digital oscilloscope’s “measure” function  
• Agilent multimeter

Compare to the predicted value:

$$f_{osc} = 1 / [ 0.7 ( R_A + 2 R_B ) C ] .$$

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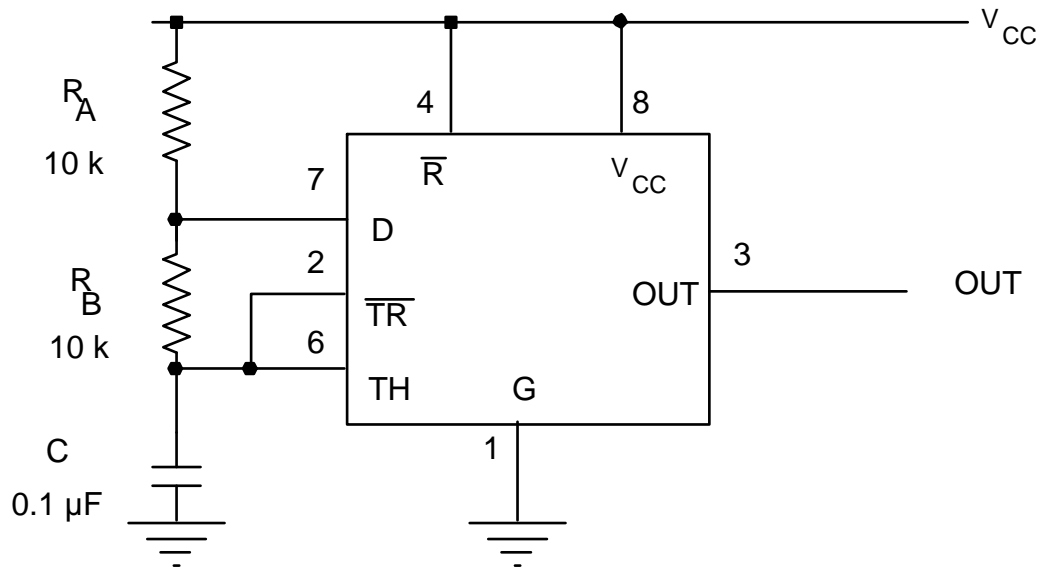
\*\*\* In a research lab, and in the Project at the end of this course, when you make a measurement, it is best to choose an instrument that yields a known error. For the measurement of frequency, the Agilent multimeter has the advantage that you can easily determine the error by referring to the manufacturer’s specifications. The Tektronix scope has manufacturer’s specifications also, but for frequency they are not easy to understand.

(c) \* – Replace  $R_B$  with a short circuit.

Describe the resulting waveform.

Explain your observation.

\* Leave this circuit hooked up. You will use it with the one-shot in the next part.

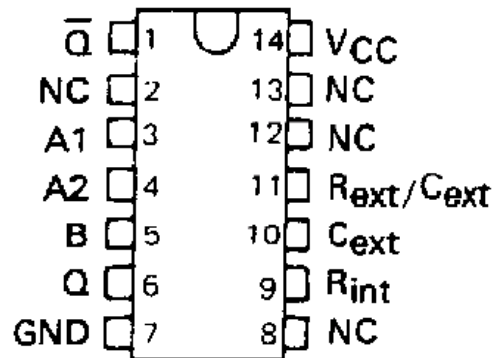


555 Timer square-wave oscillator

## 2. Monostable Multivibrator One Shot (74121)

} The output of a one-shot is a digital pulse triggered by an analog waveform at its input. Even if the input is noisy, the one-shot will produce a clean pulse. The pulse has a width determined by an  $RC$  time, and the pulse height is determined by the input voltage. The pulse begins when the input voltage exceeds a threshold voltage.

# SN74121 . . . N PACKAGE (TOP VIEW)



## FUNCTION TABLE

INPUTS			OUTPUTS	
A1	A2	B	Q	Q̄
L	X	H	L	H
X	L	H	L↑	H↑
X	X	L	L↑	H↑
H	H	X	L↑	H↑
H	↓	H	⌈	⌋
↓	H	H	⌈	⌋
↓	↓	H	⌈	⌋
L	X	↑	⌈	⌋
X	L	↑	⌈	⌋

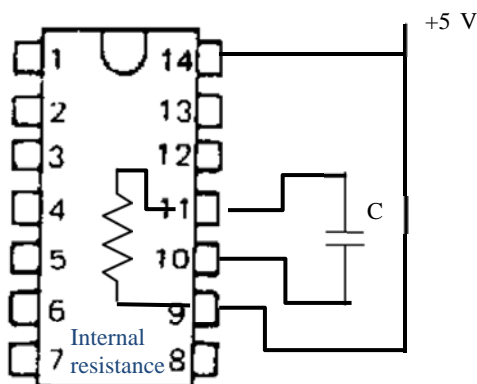
- } The One-Shot you will use has a Schmitt-trigger input (for the B input). Schmitt trigger inputs fire when the input exceeds an upper threshold, and reset when the input voltage drops below a lower threshold. This helps to produce a jitter-free pulse from a noisy input signal.

Setup for parts using [internal](#) resistance, parts (a) and (b):

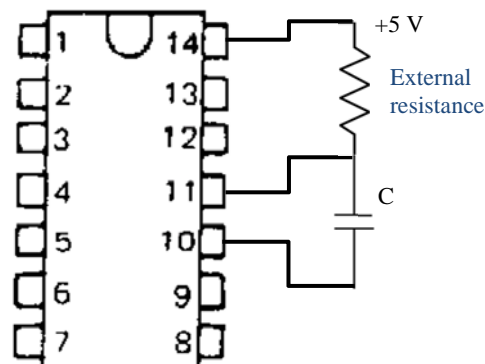
\* Referring to the specification sheet, connect the '121 on the prototyping board as follows. Connect an 0.1 μF capacitor between pins 10 and 11.

- |                   |   |
|-------------------|---|
| 1. Q̄ output      | 8. NC   |
| 2. NC             | 9. Connect to Pin 14 (to use internal resistor) |
| 3. input A1 = GND | 10. External capacitor +                        |
| 4. input A2 = GND | 11. External capacitor -                        |
| 5. input B        | 12. NC  |
| 6. Q output       | 13. NC  |
| 7. GND            | 14. +5 V  |

For using [INTERNAL](#) resistance



For using [EXTERNAL](#)



---

(a) For using **internal** resistance.

- \* Set up the pulse generator to apply a square wave, with  $\approx 7$  V peak, to the input of the one-shot. Use a frequency  $f \approx 1$  kHz.

- \* – By varying the input amplitude downward until no output pulse is generated, measure the trigger voltage.

- \* – Measure the output pulse width. Compare to  $R_{int} C \ln 2$ , assuming the manufacturer's nominal value  $R_{int} = 2k$ .

(b) \* – Reduce the input pulse width and verify that the output pulse width, at the output of the one-shot, is unaffected by the pulse width at its input.

Setup for using **external** resistance, parts (c ) and (d):

} We will now use an *external* resistor for timing. The RC time determines the pulse width. The one-shot has an internal timing resistor with a nominal value of  $R_{int} = 2\text{ k}\Omega$  (refer to the data sheet to confirm this value). You could use that internal resistor to time the pulse, but you will instead use an external 10k resistor.

(c) \* – Replace the shorting wire between pin 9 (the internal resistor) and pin 14 with a 10 k external resistor. Measure the pulse width, and compare the theoretical value  $R_{ext} C \ln 2$ .

(d) \* – At the input, replace the signal from pulse generator with the square wave signal from the 555 timer that you built in part 1. Verify that this combination works as a pulse generator.

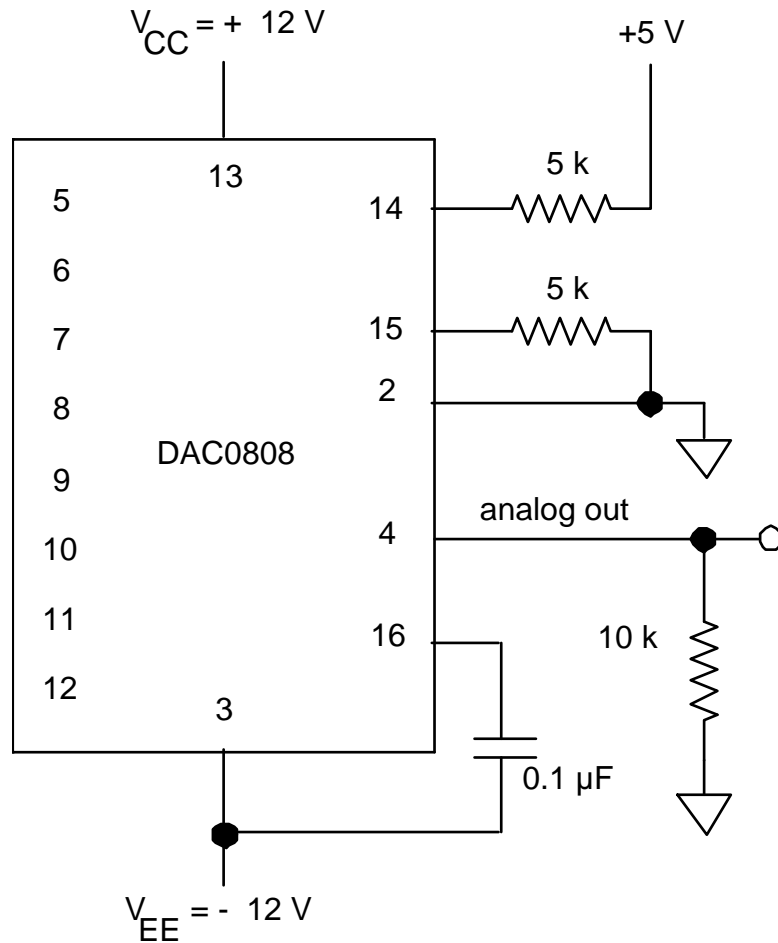
### 3. Digital to Analog Conversion (DAC0808LCN or equivalent)

} The DAC0808 is an easy-to-use 8-bit D to A converter (DAC).

- \* Wire up the DAC as shown in the figure. Use wires to connect the inputs of the three most-significant bits (MSBs) on pins 5, 6, and 7 to the input switches on your prototyping board. Connect the other five

inputs to LO by connecting pins 8 through 12 with wires directly to ground. Connect a multimeter to the analog output, pin 4.

\* – Make a table showing all eight possible combinations of the digital input states on the three most-significant bits. Then measure the analog output  $V_{out}$  for all of these states.



---

#### 4. Analog-to-Digital Converter

[Note: This circuit requires  $\approx 23$  wires to hook it up on your prototyping board.]

} An ADC is often used to interface digital circuits or computers to the real world, especially to acquire data. Your digital multimeter, for example, has an ADC. Among other things, an ADC contains comparators and voltage reference levels. The incoming analog signal is compared to the voltage reference levels to determine which is closest. A corresponding digital output bit is then set to TRUE.

} An ADC is rated by the number of bits and the maximum clock speed.

} We will use the ADC 0804, an inexpensive ADC that is contained on one chip. It digitizes eight bits at a clock speed up to 1.4 MHz. It can be clocked by an external pulse source, or by connecting a resistor and capacitor to make a simple relaxation oscillator (analogous to the way the 555 works); we will do the latter here.

} The ADC 0804 has two analog inputs for differential voltage measurement. For convenience in testing this ADC, we will ground one of the differential inputs (pin 7) and to the other one (pin 6) we shall apply a simple dc voltage. One way of doing this is to use a voltage divider as a voltage source, with an op-amp voltage follower to assure a low output impedance. The op-amp follower is not critical here if you use a voltage source with a low output impedance to drive it.

\* Connect the ADC0804 as shown. Use LEDs on your prototyping board to indicate the three most significant bits (pins 11 to 13).

} Pay careful attention to the grounds when using circuits with both analog and digital parts. Although in this lab you may be asked to connect them together, in general the analog ground and digital ground are different, and some circuits might not work if you connect them together.

\* Use a bench power supply (see photo) as an adjustable voltage source. Be sure its negative terminal is connected to its ground, and connect that ground to your circuit's ground



---

(a) Clock

\* – Using an oscilloscope, look at the waveform on pin 19, and print it. Confirm that there is a 5 V, 100 kHz clock signal present. [This frequency is determined by R and C, as it was in the 555 timer.]

(b) A to D Conversion

\* Connect a DMM to measure dc voltage across the differential input to the ADC (i.e., between pin 6 and ground).

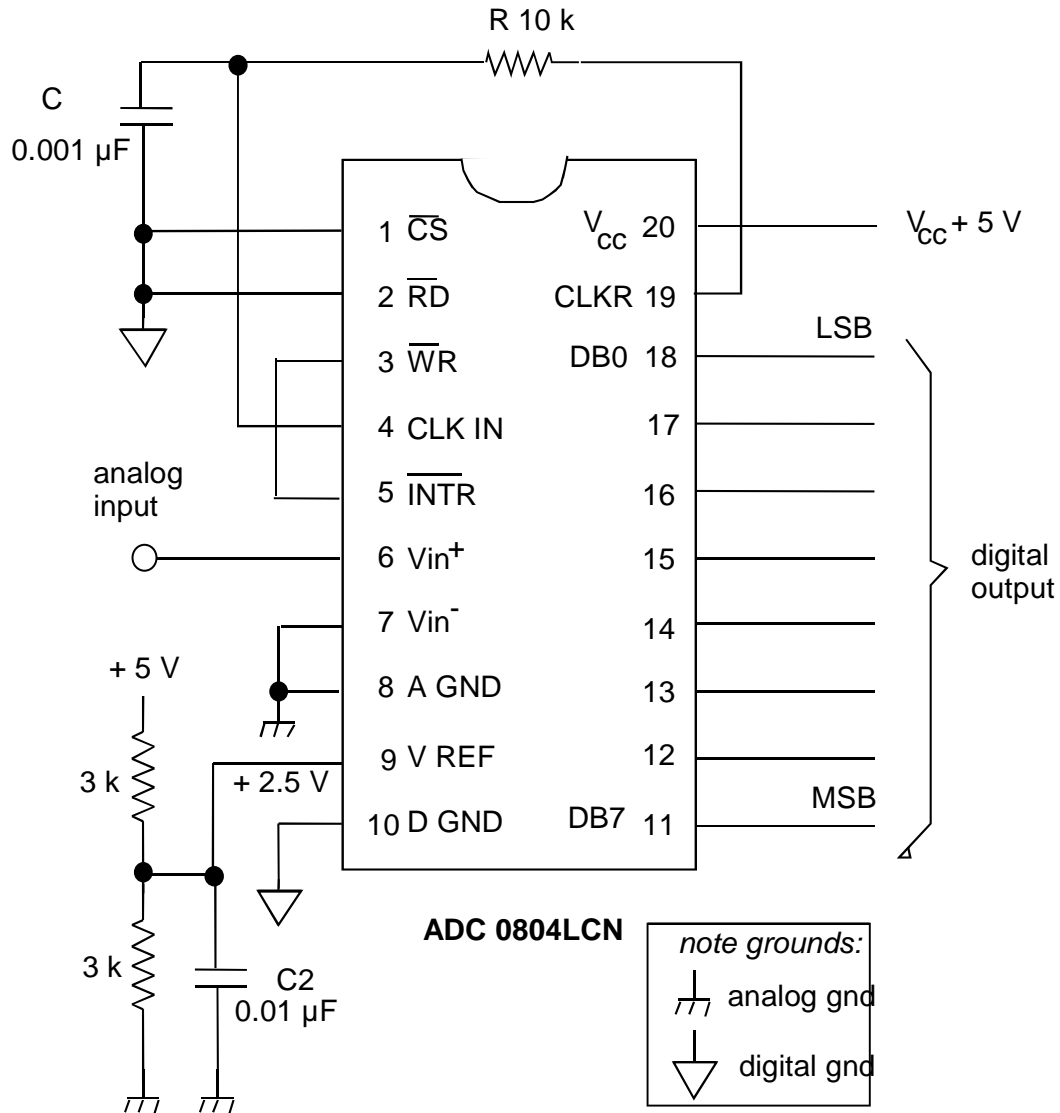
\* If it looks like too many LEDs are lighting up, the input voltage may be jittering near the borderline between digital levels, causing a fast alternation between one digital level and another, and because of the fast clock speed, it looks like all the LEDs are lit. Try adjusting the input voltage slightly up or down.

\* **Caution:** in the next step, try not to exceed 5.0 V input voltage; the chip will be destroyed if you exceed its maximum input voltage rating, which is about 15 V.

\* – Vary the input voltage from 0 V to 5 V, and record  $V_{in}$  (at the 8 levels) where the three most significant bits of digital output change from LO to HI. Present your results in the form of a table.

\* Using the function generator, produce a triangle wave (or sine wave) varying from 0 V to 5 V at approximately 0.1 Hz, and apply this signal to the input. Watch the LEDs as they change, and be sure that you understand why they change as they do.





Test circuit for the ADC 0804 analog-to-digital converter.

Use the GND on your prototyping board as both the analog and digital grounds. (The manufacturer designed the chip so that it can be used with two separate grounds, if desired, to reduce noise. Here we will not use this feature.)

The purpose of C2 is merely to reduce noise in the voltage divider's output; it is not a critical component.

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## 5. Using sensors

} There are several ways to detect temperature. As is often the case, a specialized integrated circuit is a good solution. Here you will test the LM35DZ.

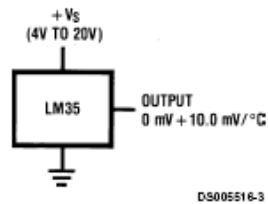
### Features

- Calibrated directly in ° Celsius (Centigrade)
- Output is linear + 10.0 mV/°C scale factor
- 0.5°C accuracy (at +25° C)

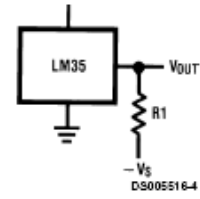
### General Description (from the National Semiconductor datasheet):

- The LM35 series are precision integrated-circuit temperature sensors, whose output voltage is linearly proportional to the Celsius (Centigrade) temperature. The LM35 thus has an advantage over linear temperature sensors calibrated in °Kelvin, as the user is not required to subtract a large constant voltage from its output to obtain convenient Centigrade scaling.
- The LM35 does not require any external calibration or trimming to provide typical accuracies of  $\pm 1/4^{\circ}\text{C}$  at room temperature and  $\pm 3/4^{\circ}\text{C}$  over a full  $-55$  to  $+150^{\circ}\text{C}$  temperature range.
- Low cost is assured by trimming and calibration at the wafer level.
- The LM35's low output impedance, linear output, and precise inherent calibration make interfacing to readout or control circuitry especially easy.
- It can be used with single power supplies, or with plus and minus supplies. As it draws only 60  $\mu\text{A}$  from its supply, it has very low self-heating, less than  $0.1^{\circ}\text{C}$  in still air.

- \* – Use the LM35 Precision Centigrade Temperature Sensor chip, which has a sensitivity 10 mV per degree C. The diagrams below are from the datasheet for the LM35DZ. Use a power supply voltage of  $V_s = +5\text{V}$ .  
**Caution: before turning power on, check polarity of the LM35 pins; otherwise you will burn it up.** Connect the sensor output to a digital multimeter, and touch your finger to the sensor and observe the change in the output voltage. Describe your observations.
- Discuss how you could use the ADC circuit to make a digital thermometer.



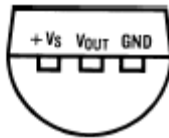
**FIGURE 1. Basic Centigrade Temperature Sensor**  
(+2°C to +150°C)



Choose  $R_1 = -V_S/50 \mu\text{A}$   
 $V_{OUT} = +1,500 \text{ mV at } +150^\circ\text{C}$   
 $= +250 \text{ mV at } +25^\circ\text{C}$   
 $= -550 \text{ mV at } -55^\circ\text{C}$

**FIGURE 2. Full-Range Centigrade Temperature Sensor**

**TO-92  
Plastic Package**



**BOTTOM VIEW**

**LM35CZ,  
LM35CAZ or LM35DZ**

# PROJECT

Toward the end of the semester, you will design and build a circuit of your own, to meet whatever purpose you like.

Project planning: This project is not like an ordinary lab assignment. It is more like a part of a thesis project. To be successful, you must do project planning.

Project planning entails:

- making a schedule for yourself
- allowing time to receive purchased supplies
- allowing time to assemble, test, and debug your experiment, and finish it on time
- budgeting for costs.

An original idea: The circuit you design may be analog, digital, or both. The circuit could arise from your thesis project, or it could complement an existing instrument, for example your guitar or stereo. You could make a game, a circuit that demonstrates some mathematical or scientific concept, or something for a hobby. It is up to your imagination.

## **Academic Dishonesty & the required “disclosure”:**

- Your design must be your own.
- At the beginning of your grading, you will present a **disclosure**, stating which portions of your circuit are your ideas, and which portions are copied from another source (such as this lab manual, the textbook, a specific internet page, etc.).
- It is plagiarism to fail to omit anything from your **disclosure**.
- It is plagiarism to copy entire designs (from books, the internet, or someone they know); students who do this are detected because they are unable to answer questions about their project at the time it is graded.

Requirements: Your circuit must include a minimum number of electronic components that will be agreed upon when you discuss your ideas with the instructor.

---

Money: Purchase your own components from vendors such as the following:

- UI Engineering Electronics Shop 2018 Seamans Center  
<http://www.engineering.uiowa.edu/~eshop/>
- DigiKey (tel 1-800-DIGIKEY), <http://www.digikey.com> Two ways to build:

You must choose either:

- to build it on a prototype board (recommended)
- to build it hardwired in a box with a battery or power supply. If your final project is built on a prototype board, it must be more ambitious. If it is hardwired in a box, it must meet good standards for safety and quality of construction. (This is not recommended unless you already have the required skills and tools.)

Hardwired projects:

- Safety:            use a grounded box  
                     use grommets & strain relief for power cord  
                     cover all 110 VAC so that it is unreachable when the box is closed
- Connectors:      use a terminal strip with crimp-on lugs for 110 VAC
- Holes:            de-burr holes after drilling sheet metal
- Wires to front panel:  
                     bundle them with tie-wraps for neatness
- Circuit boards:  
                     line up ICs and other parts in neat rows  
                     don't cross wires over chips  
                     use sockets for chips
- Testing:          test your ideas on prototype boards first  
                     show the instructor that your prototype-board version works  
                     (for partial credit, in case your final circuit doesn't work)

Project Tips:

*Planning*

As with all research projects:

- Plan ahead.
- Procrastinators will learn a hard lesson.
- Expect your project to require 3× as long as you expect.
- Expect things to go wrong.

---

### *Designing*

- A simple idea that works is better than a grand idea that fails.
- Avoid designing circuits with high speed, high frequency, high voltage, or high current.
- Design a circuit mainly or entirely based on components that you already understand, like op-amps and digital gates.
- Many successful projects begin with a fairly simple idea, then add “bells and whistles.” After your basic circuit is tested successfully, extra features such as displays or adjustable settings can be added. Do this if your basic circuit idea does not have enough components.

### *Purchasing*

- Buy from local sources wherever possible.
- Plan well ahead if you buy by mail.
- Buy several spares for every semiconductor, chip, or high-power item.
- Obtain data sheets for all semiconductors and chips.
- If you need a microphone, choose an “electret” model.

### *Testing tips:*

- Begin by testing your circuit, one section at a time, on a prototype board. Don’t assemble a big circuit all at once and expect it to work. You will have bugs to work out, and this is easiest to do if you assemble it in stages, one section at a time.
- For analog circuits, use an oscilloscope to observe AC signals.
- Buy a small prototyping board of your own so that you can keep your project assembled as you work on it. Otherwise you will have to disassemble it so that other students can use your board. A single strip or two may be enough.
- If your circuit’s inputs are to come from a transient source, such as pushbuttons or random pulses, test your circuit with a repetitive waveform from a function generator.
- A few students choose to test their design on a computer, using Spice-based circuit simulation software (such as Multisym) before building it.

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*Power supply tips:*

- Many students have problems because their circuit draws too much current for their power supply. Give some thought to choosing which power supply you use. If your circuit consumes more than 100 mA from a 5 VDC power supply, use a bench power supply (HP or Lambda, for example), not the prototyping board. Otherwise your circuit will stop working due to loading the power supply.
- Some circuits that involve large currents that are not DC currents, for example an LED display or a 555 timer with a large capacitor, will cause the power supply voltage to droop momentarily, and this can cause errors in logic chips elsewhere in the circuit. To avoid this, place an electrolytic capacitor (a few microfarads) across the power supply leads on your prototyping board, and locate this capacitor physically near the subcircuit (e.g., the 555 timer or LED display) that demands a large current.
- If you use a 9-Volt battery, you can reduce the voltage to 5 VDC using the 3-pin voltage regulator from one of the labs in this manual.

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### Checklist for Project Grading:

At the end of your project, you will:

- Present a schematic diagram
  - label every part (part number, and function if it is a chip)
  - identify function of switches, LED indicators, etc.
    - (e.g. reset, power)
- Present a list of specifications
  - at least 3 numbers
  - example:
    - frequency bandwidth [Hz @ 3 dB flatness]
    - max input voltage [V]
    - input impedance [ $\Omega$ ]
  - identify whether measured or computed
    - measured is better
  - include error estimate<sup>†††</sup> and units
- Demonstrate how your circuit works
  - plan how to show it in 5 minutes
  - start by showing the schematic diagram, and **disclosing** which features are not your own design
  - in case it doesn't entirely work:
    - demonstrate that part of it works
    - hope for partial credit for the part that does work
  - explain how you arrived at your error estimates

### Grading scheme:

<u>grading factor</u>	<u>prototype</u>	<u>hardwired</u>
design	80 %	60 %
cleverness of idea		
how well it works		
how ambitious it is		
schematic diagram	10	10
specifications	10	10
quality of construction	-	15
safety	-	5

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<sup>†††</sup> Error estimates require values from the manufacturer's specifications for the instrument. For the multimeter, parameters are reproduced in the preface to this manual; for other instruments (including digital oscilloscope) you should refer to the actual manufacturer's User Manual. *Qualitative user judgments of how well you can read a display, or jitter in the display, are not good error measurements.*