Physics 117 Lab Handouts Compiled

March 21, 2017

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LABORATORY 1

PHYSICS 117, Fall 2017

Prof: Pietro Musumeci, TA: Albert Brown, ATA: Maxx Tepper

The lab write-ups are based on the laboratory manual by Hayes and Horowitz, but have been modernized and adjusted by the professor. If you find mistakes or unclear items, let the Prof. know so he can update these sheets.

Reading: S&M 2.1 to 2.19 (You know most of this, so esp. 2.19), 2.32

Beginning exercises:

a) Set your DC voltage to a nominal 5V. Use both the lab-bench voltmeter and a DVM, and compare to the power supply display. Compare the precisions. (Note: while the displayed voltages on these power supplies are pretty good, don't count on that in general.) Now use the oscilloscope to measure the voltage. (You can use either "force trigger" or use "auto" trigger. This is one of the very rare times when it makes sense to use auto trigger.)

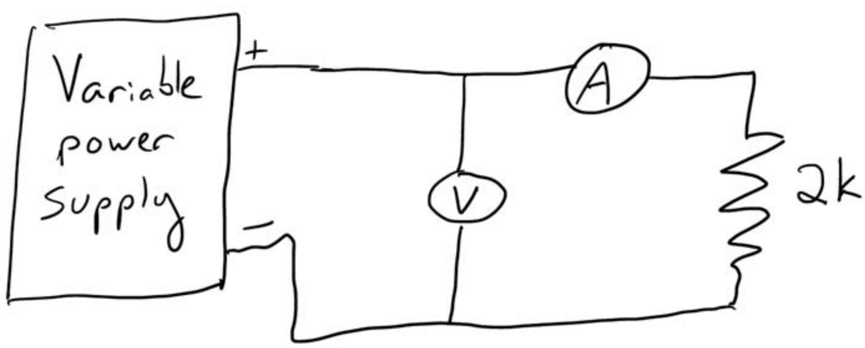
Never use the "Autoset" button on the scope. It is a bad habit that will come back to bite you. It could cost you hours of trouble at some point.

b) Explain to your TA, ATA or Prof why: (1) You cannot hook up the ammeter directly to the voltage source. (2) Explain why when the meter is set to Ohms, you cannot hook it up to anything that is powered. DO NOT CONTINUE UNTIL THEY SAY OKAY.

c) Get a breadboard from the back of the lab. Use your lab meter on Ohms mode to figure out the connectivity of your breadboard. Sketch the pieces of basic elements of the breadboard showing the connectivity of the "busbars" and other sections.

Ohm's Law

d) The figure below and the few that follow before part (k) will be about the only times we will draw a complete circuit in the course. As you encounter them, redraw using grounds following the convention of this course (and engineering).



Build the circuit above using your breadboard, not in the air. Amateurs suspend items such as resistors in the air using alligator clips. Instead bring in the power through the banana jacks and then bring the power to the breadboard using wires.

When using the figure above, use your lab-bench meter as the ammeter and the oscilloscope as the voltmeter. (Note that sometimes you will see the meters labeled as "VOM" instead of "DVM" or "DMM". That is an antiquated term for "Volt-Ohm Meter".) Verify Ohm's law by measuring a few points.

In general, get used to making your circuit as follows:

1. match the figures geometrically so it is easier to debug when they get more complicated. (This will not always be possible.) In general circuit diagrams will flow from inputs to outputs by going left-to-right top-to-bottom like reading a page.
2. Put your grounds and powers on a busbar so they are easy to connect to.
3. Use sensible color coding. Typically red is for one voltage being supplied and black is for the grounds. If you use other voltages, you can use other colors.

Now measure Ohm's law by measuring a few voltages and currents.

<u>Effects of instruments on your readings</u>
e) Use the DVM and procedures similar to the previous part to measure how non-ideal your lab-bench multi-meter is on the ammeter setting. Estimate its internal resistance on the ammeter setting. (Hint: you shouldn't just measure its resistance with an ohmmeter. Why not? (In this case it turns out you can, and it pretty much works, so do that as a check.))

<u>More Exercises</u>
f) Use your ohm-meter to measure the resistance of a 10 MΩ (or larger) resistor. Do it once in your breadboard and again using your fingers to hold the meter probes against the leads. Why is there a difference? Can you use your fingers to measure a 10kΩ resistor?

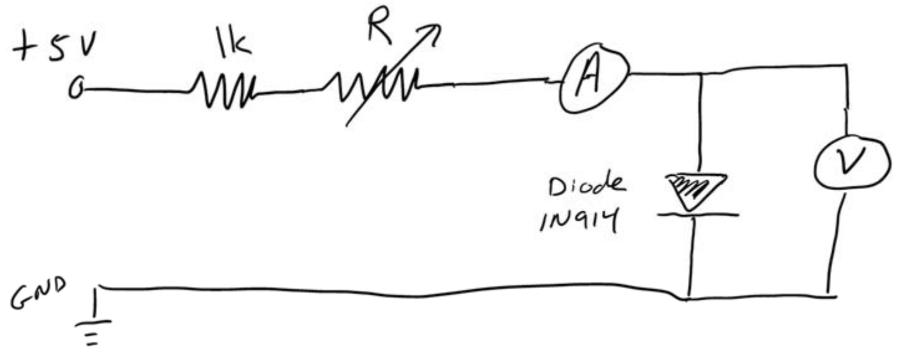
g) We have mostly 1/4 W resistors on the shelf. (That means you cannot use them to safely dissipate more than 1/4 W). Using the 5V setting but not exceeding the 1 Amp output of the power supply, what resistor value should you choose to dissipate several watts in a resistor that is only rated for 1/4 W and what happens? Try it. (Throw away the resistor when you are done.) We have some 2A power supplies in the lab if you want to get all dramatic about it.

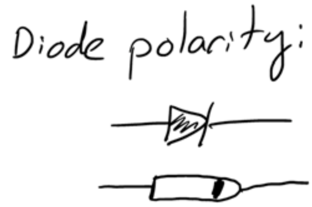
<u>Testing Ohm's law on Lamp</u>
h) Now perform the Ohm's Law test on one of the small lamps we have. Do not go far beyond the listed maximum ratings. You should take enough points to show the violation of Ohm's Law. Does it go the direction you would anticipate? (We have hot air guns you can use to see what they do to the circuit.) How would you report the "resistance" of the lamp?

(If you break a lamp in a base, throw away the bulb but not its base.)

<u>Testing Ohm's law with diode</u>

i) Another circuit element that does not obey Ohm's Law is the "diode". (We will explain how a diode works later this quarter, for now it is just an example of something that does not obey Ohm's "Law".) Follow the circuit below or similar:





Measure the diode's I vs. V (called an "I-V curve" with voltages ranging from at least 350mV to 750mV. You may need to adjust the voltage on your power supply as well. You can ask Excel plot both lin-lin and log-lin for this section.

You can vary R more easily if you use a "variable resistor" also known as a "potentiometer" (why?), which you can find in the lab drawers. Use the ohmmeter between 2 of the 3 leads to learn how it works. If you pick one up and want to know its maximum value to put back in a drawer, how would you determine that without having to turn the knob?

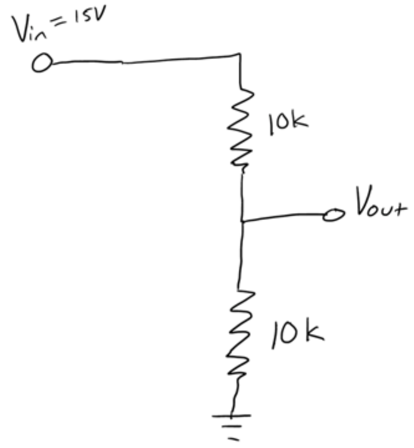
Typically diodes are used with a current rage from 10-100mA in our course. Is there a convenient "rule of thumb" you can say about voltage drops across diodes then?

j) When you are done, you can put the full 5V across the diode just to see what happens. DO NOT PUT BROKEN COMPONENTS BACK IN WITH THE GOOD DIODES. WE HAVE A TRAY FOR "BROKEN DIODES" FOR A FUTURE LAB. You can use the Fluke meter's diode setting (checking both polarities) to see if the diode still works. Look up the diode's "data sheet" and explain how what you did is consistent with the specs.

Note: in this lab room we also have "Zener Diodes". These look similar and are almost impossible to separate if you mix them in with the other diodes. "Just Say No!" to mixing up different types of diodes.

Voltage Divider and Thevenin Mode

k) Build the circuit below, now using our standard convention:



Apply V_{in}=15V. Measure the open-circuit output voltage (V_{OC}). Then attach a 10k "load" resistor between the output and ground and see what happens.

Remove the load and measure the short-circuit current (I_{SS}) from V_{out} to ground. (Why is it safe to "short circuit" V_{out} to ground in this case?) Using your measured I_{SS} and V_{OC}, draw the Thevenin equivalent circuit.

Now build the Thevenin equivalent circuit you drew. Verify that V_{OC} and I_{SS} stay the same. Now attach the 10k load resistor to your Thevenin equivalent circuit and see if the voltage droop at the point marked V_{out} stays the same as in the first circuit.

Function generator

l) Connect your function generator to the speaker and drive it with a sine wave you can hear. Use the "sweep" feature to make the Star Trek (TOS, of course) "Red Alert". Manuals (with an index) are on the shelf.

1-5 (Oscilloscope)

m) Get familiar with the scope and function generator. You gen generate various frequency sine waves (eg 1000 Hz or 1kHz, or old-school 1 kilocycles/sec) and other shapes which you should be able to see on the scope. There are a lot of knobs and such, but don't worry you will get used to them.

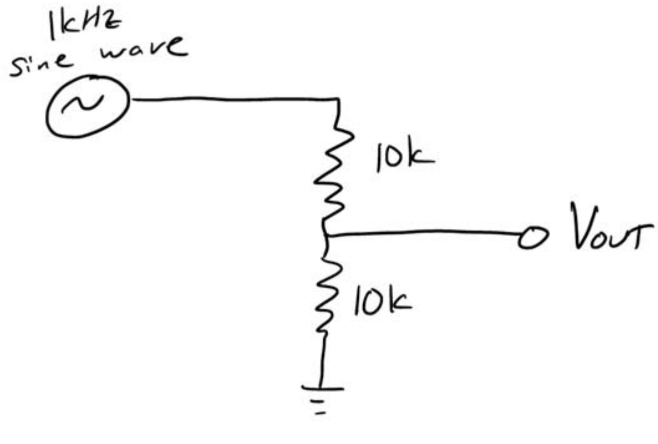
(For a very stupid reason your TA, ATA, or professor will explain, the display on the function generator for V-PP ("Voltage peak-to-peak") is off by a factor of two. They can show you how to fix it.)

Try the following with your function generator and scope:

---See what the volts/div knob does. Make sure you can read off the peak-to-peak voltage by eye from your scope without having to use any fancy scope features.

--Now use a fancy scope feature under the "measure" menu to measure the peak-to-peak voltage
--Similarly adjust the time/div knob. You should be able to read off the period by eye and calculate a frequency in your head reasonably well.
---Repeat using the "measure" feature to measure the frequency
---Use "normal" trigger and get a feeling for what the "level" adjustment does does. Change the slope of your trigger and see what happens and explain why. You should always try to use Normal trigger. Why did you have to use Auto trigger in part a of this lab?
---With the function generator on square waves look at a rising edge and use the "measure" tools to measure the risetime. You might think the risetime looks instantaneous. It is not. Adjust the scope so you can see that fact. Repeat for falltime. How are risetime and falltime precisely defined? Is that the same as the "time constants" you learned in Physics 1B and 1C?
--Use another channel to look at the SYNC output of your function generator while it is making a sine wave. Which is a better signal to trigger the scope with and why?
--Put an offset into your sine wave so that it moves up and down on the scope. If you change the scope to AC coupling that blocks the DC component. Try it and show that it works. What happens if you try to look at a slow signal 50 Hz square wave but are on AC coupling instead of DC coupling?

AC voltage divider
n) Take the voltage divider you built earlier and apply a 1kHz sine wave instead.



Does the analysis of its output voltage change now that you have a voltage that changes in time? (If you have a long answer, you either know too much or too little.) What happens to V_{out} as you change the frequency of the sine wave?

2 Lab 2

LABORATORY 2

PHYSICS 117, Winter 2017

Prof: Pietro Musumeci, TA: Albert Brown, ATA: Maxx Tepper

The lab write-ups are based on the laboratory manual by Hayes and Horowitz, but have been modernized and adjusted by the professor. If you find mistakes or unclear items, let the Prof. know so he can update these sheets.

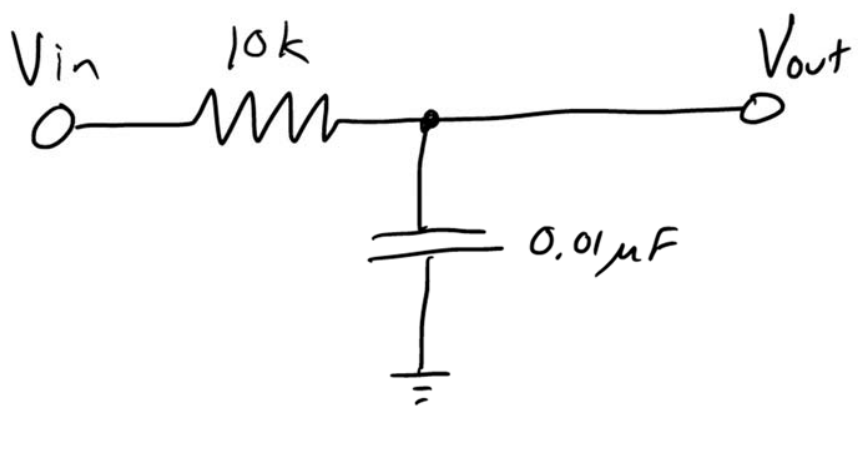
Reading: 2.23-2.29, 2.33

a) Use the LC-meter (or C-meter or DMM) in the lab to measure capacitance of two 0.01 μF capacitors in series and then in parallel. (The C and LC meters are old-school. You have to turn them off when you are done!)

See the note on how to read capacitors values on on the lab bulletin board. Further complicating things, note that the LC meter will display in nF even though we only ever label capacitors in the lab or on circuits as mF, μF or pF. Go to the drawers and check that you can measure a 0.15 μF capacitor correctly. Find the value printed on that capacitor and explain how to read it correctly.

** Now that you know how to read capacitors, please be sure to return your caps to the correct bin. The future hours of work you save may be your own **

b) Build the RC circuit below:

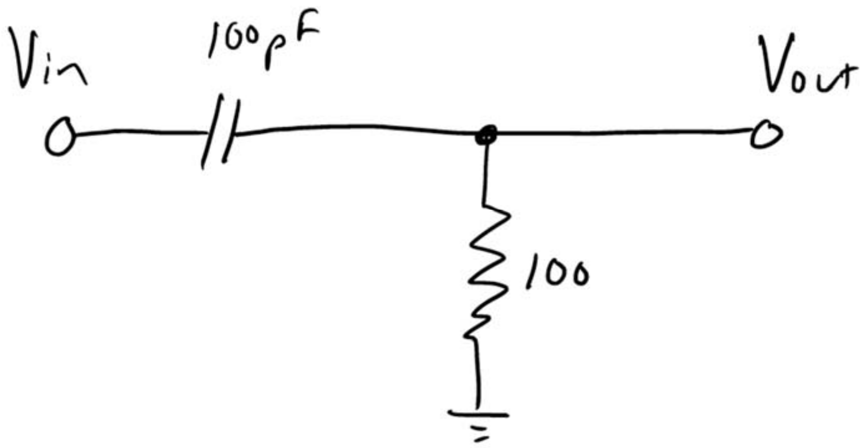


Explore and explain how this circuit works "in the time domain". You can do this by driving the circuit with a 500 Hz square wave and look at the signal output. (Hint: make sure your scope is on the "DC" setting. Why?) Measure the "time constant" of the circuit and show that it corresponds to the RC time constant. You may need to measure R and C rather than trusting their nominal values. Compare the rise time from 0% to 63% of the maximum to the fall time from 100% to 37% of the maximum. Why are these the same?

Now you can explore how this circuit works "in the frequency domain" by driving it with different frequency sine waves.

In general to "think like a physicist" about a circuit (or any other system, really), you should think about it concurrently both in the time and frequency domains. We will revisit this.

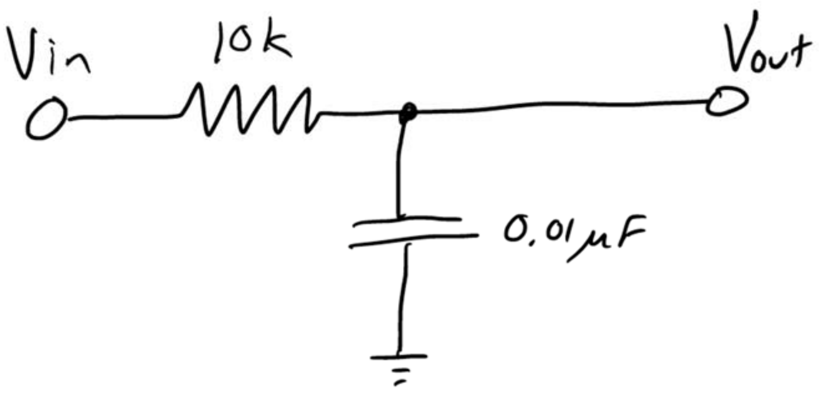
c) Circuits can do calculus! This RC circuit below is known as a "differentiator".



Drive it with a square wave, saw-tooth wave, triangle wave, and sine waves. Use two channels of your oscilloscope so you can look at the input and output signals at the same time. Does the output behave as a differential? Explain.

What is the input impedance of this circuit at 0 Hz? At infinite frequency?

d) Build the "integrator" below (note the same as an earlier circuit).



Drive it at 100 kHz with a (large amplitude) square wave. Try the other functions. Explain why it is working as an integrator. Look carefully at the integral of the triangle wave to see the output is not a sine wave although it looks close. What function is it? Are the conditions about RC vs. the time scales as discussed in class obeyed?

Show that the amplitude of the output of the sine wave is roughly what you expect.

We will build better integrators and differentiators when we learn about "operational amplifiers" (op-amps).

e) Now use integrator circuit you just built now as a low-pass filter. Again you should be looking at both the input and output simultaneously on your scope. Calculate and then measure ν_{3dB}. Drive the circuit with a sine wave of various frequencies, especially deep into the "stop band" (if you go too far though the components may stop working as advertised though). Compare the phase of the input to the output sine waves when you are deep into the stop band, deep into the pass band, and at the "3 dB point".

The low pass filter should attenuate at the famous "6 dB per octave". An octave is a factor of two in frequency. Show that it obeys this rule reasonably well.

Now use the 3rd channel of your scope to look at the SYNC output of your function generator at the same time. That output defines a t=0 with a fast rising edge. Watch what happens if you vary the trigger level while trigging on the input sine wave. Now watch what happens if you vary the trigger level on the sync pulse. Explain why it will often be best to trigger your scope on the SYNC output instead of your actual signals of interest.

f) Reverse the positions of the capacitor and resistor and show that it works as a high pass filter.

Put the SYNC output of your scope and trigger on it using a time base of 0.1 seconds per division. Let the function generator's sweep take 1 second to cover a range of interesting frequencies (chosen to be nice round values for easy computation.) You can now easily read off the "3 dB point" of your circuit this way. (Hint: you may find putting your scope on "peak detect" gives you a better image.)

g) Working with a transformer.

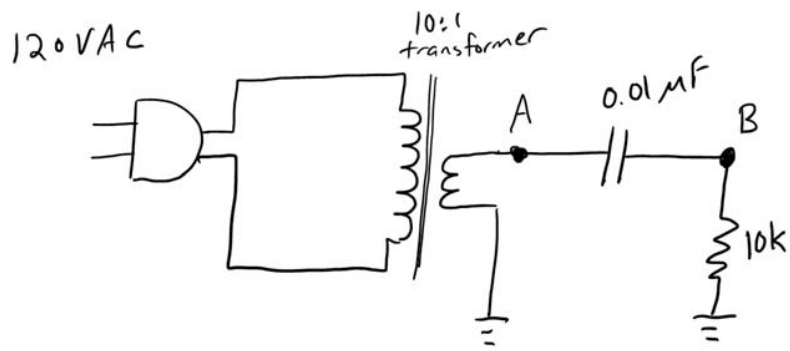
TRANSFORMER

Grab a small transformer from the shelf (marked “audio transformers”). Use the one marked “TM018” which has equal numbers of windings on the “primary” and “secondary”. Put a 1 kHz signal into the outer leads on one side and measure the signal between the outer leads on the other side. Show on your oscilloscope that the ratio of voltages is 1:1, but inverted. What is the frequency range over which the transformer works as expected? Now go back to 1 kHz and look at the output between an outer lead and the center-tap. Explain the voltage ratio.

OPTIONAL: You may find at some frequencies, the output voltage that is greater than the input voltage. What’s going on?

h) Now we can make a real application using a filter. Let’s measure the “garbage” on the physics building’s AC power lines. We have 12 Volt (“12 VAC”) step-down 11:1 transformers so that not too many of you accidently kill yourselves with the 120 Volts. Note that although these look like DC power supplies that you might use for your consumer electronics, these really are just a transformer. There is a disassembled one on the shelf you can look at, but should not use.

Build this circuit below. (Please be careful not to short the two output wires which can blow the fine wires inside transformer. I have put a 50 ohm resistor inside to reduce that possibility.)



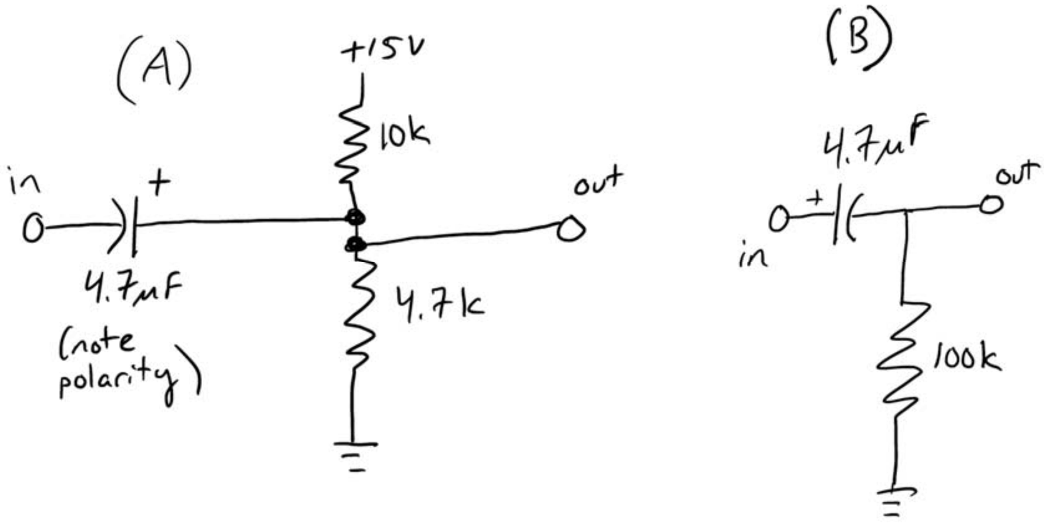
At point **A** you should see what looks like a reasonable sine wave at 60 Hz. Is the period correct? (You don’t get the world’s greatest sine wave from the power company.) Is the peak-to-peak voltage what you would expect? (Hint 120V is the “R.M.S.” voltage so there may be a sqrt(2) involved depending on what you are measuring.) Calculate the filter’s attenuation at 60 Hz. Now look at point **B** to see all the noise.

(Note that the transformer itself says its RMS output is 9V but they are being “conservative” and you should see more like 11V RMS.)

i) Note that electrolytic capacitors have an orientation. If you connect one to a power supply backwards it will fail dramatically. (I do not recommend doing this.) Why do electrolytic capacitors have a polarity? (You can use the web to find out.)

Capacitors are often used to “block” DC while coupling in an AC signal. The circuits below do this:

x



You can think of it as a high-pass filter with a really low 3dB point compared to all the signals that interest you. But it really is a different way of thinking about it. This blocking capacitor is really just there to block DC.

Build the circuit labeled A above. Drive it with the function generator and look at the output on the scope (remember to be DC coupled). The circuit lets the AC signal ride on top of +5V without exposing your function generator to +5V input to its output, which might damage it. Now add the circuit labeled B to the output of A. Notice the signal swings around ground again. What is the low frequency limit of this blocking circuit (circuit B)?

Circuit B is essentially what your scope does on “AC coupling” but with a 1 MΩ resistor. Try looking at the output of circuit A with that instead.

The two circuits above when put together seem pretty useless. But we will use each one individually as we go on.

3 Lab 3

LABORATORY 3

PHYSICS 117, Winter 2017

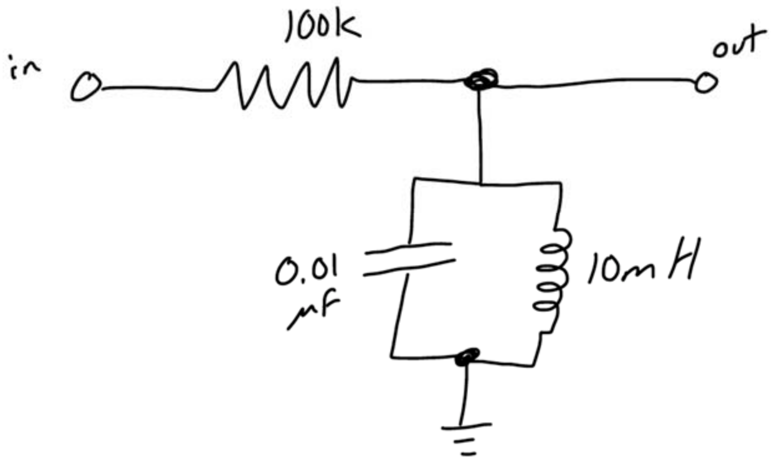
Prof: Pietro Musumeci, TA: Albert Brown, ATA: Maxx Tepper

The lab write-ups are based on the laboratory manual by Hayes and Horowitz, but have been modernized and adjusted by the professor. If you find mistakes or unclear items, let the Prof. know so he can update these sheets.

Reading: Section 4.2

a) Modern scopes such as yours have a "Fast Fourier Transform" (FFT) option in the math menu. Really this is the "Power Spectral Density" (PSD) but it is often just called the FFT. Find the "Fourier transform" (meaning PSD) of a 1 kHz sine wave. Repeat for a square wave. Describe what you see and explain why it behaves that way. (You may find this link helpful:
http://mathworld.wolfram.com/FourierSeriesSquareWave.html)

b) Build the LC resonant circuit below:



Drive it with a sine wave, varying the frequency using the knob on your signal generator over a range from below to above the resonant frequency which you calculate. (The peak pass band does not exactly match what you calculate due to some losses/damping—how far off is it?).

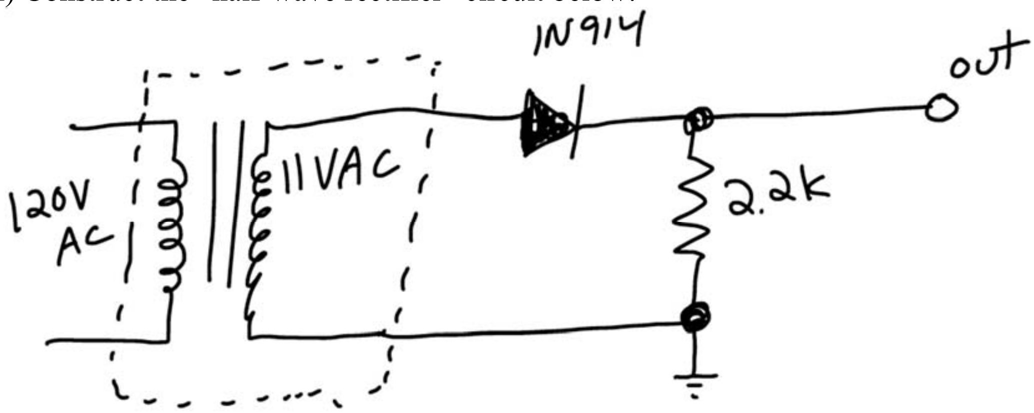
For the two parts below, the Wikipedia page on "Q factor" may help as a good reminder.

c) Repeat this using the "sweep" function of your function generator. Trigger the scope off of SYNC. Choose starting and stopping frequencies so you can easily read off the x-axis of your oscilloscope as if it were frequency instead of time. Explain what you did. Using the width of the distribution, calculate the resonant circuit's "Q factor". This is a measurement in the "frequency domain".

d) Drive it with a square wave of a fairly long period, but zoom in on the transition edge. You should see some resonance behavior after you "whack" the circuit with the sharp transition. Is the frequency what you expect? Calculate the "Q factor" using the energy lost per cycle. This is called a measurement in the "time domain". You should get about the same Q factor each way.

e) Now drive the circuit using a square wave, which you now know contains many frequencies. Set the frequency of the square wave to be at the resonant frequency. You should see the circuit "pick out" the principle component. Change the frequency of the square wave until you find its first harmonic. Is it the frequency you expect? Is it a lower amplitude. With some careful work, you should be able to locate 5 or so harmonics.

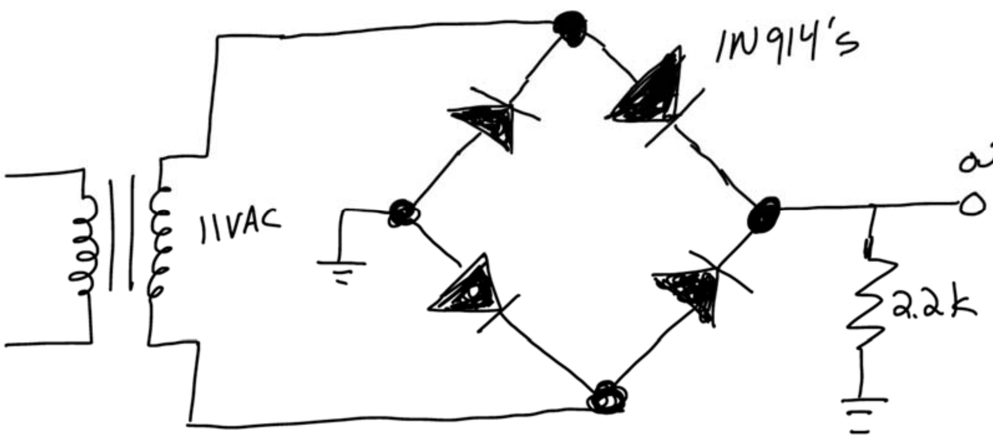
f) Construct the "half-wave rectifier" circuit below:



Use your 11V (RMS) output transformer that steps down from the AC "mains". (Note that diodes start with the prefix "1N" to denote that there is one "P-N" junction, which we will discuss more in class later.) Is the output what you expect?

Can you change the circuit to flip the polarity?

g) Construct the "full-wave rectifier" circuit below:



Be careful what you do with your scope. Note that the outer conductor of its BNC connector is connected to ground so you cannot stick it just anywhere, only where ground is already.

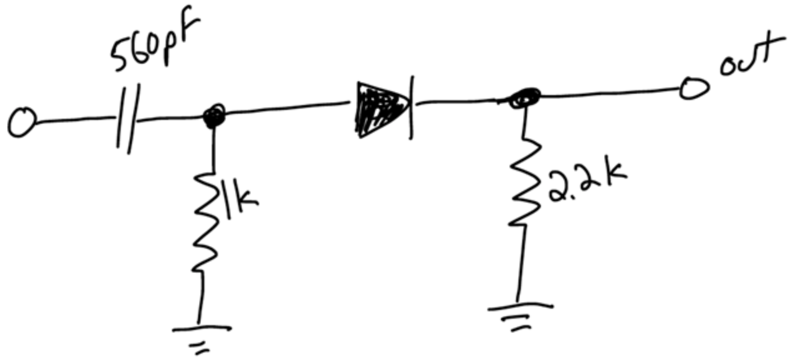
Here's how you can look at the output across the secondary windings of the transformer. Connect one channel of the scope (ie, connected to pin of BNC connector) to one side. Use another channel to look at the other. Both grounds should be connected to the ground on the circuit above. Then you use the "math" mode on your scope to subtract the two channels. Do you see the waveform you expect based on working with the transformer previously?

Look at the output near zero volts. Is there a deviation from a sine wave? Why?

h) Repeat this by replacing your diodes with LEDs and feeding the full wave rectifier with your signal generator on 0.5 Hz so you can see which diodes are active. NOTE: To do this you need to temporarily disconnect the ground of the signal generator from the world ground. Make sure no world grounds are connected to your signal generator.

i) Now put a 15 μF electrolytic capacitor from the output of your full wave rectifier to ground. (Hint: check the polarity first!) Does the new output make sense? The remaining wiggles are called "ripple". What happens if you use a larger capacitor? If you look inside various AC-powered lab equipment, you should see a circuit similar to what you just built.

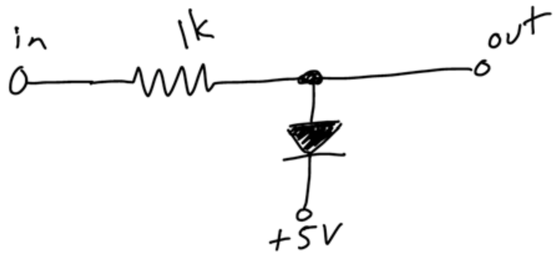
j) Use a diode to rectify the output of a differentiator as below:



Drive it with a square wave of 10 kHz at large amplitude.   Does the output make sense?

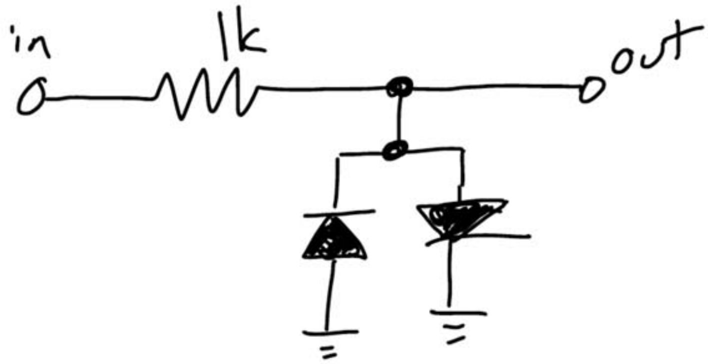
What does the 2.2 kΩ resistor do? (Try removing it.)   Hint: You should see RC discharge curves in both cases. Try looking at the data sheet of the diode for its capacitance.   Optional: does the 1N914 behave differently from the 1N4004?

k) Make the "diode clamp" circuit below:



Drive it with a sine wave of amplitude 2.0V, then 6.0V. Does the output make sense?

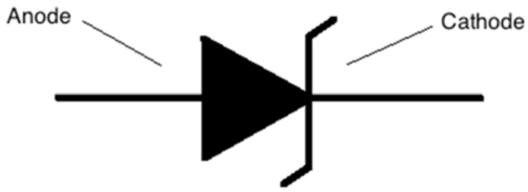
l) Build the "diode limiter" circuit below:



Drive it with various functions of amplitude 2.0V and explain the output. What use would this have?

m) We have "scope probes" on the wall. Use it on both the x1 and x10 settings and make sure you can get the same answer. (Hint: check the "attenuation setting" on your channel menu.). Using an Ohmmeter, measure the resistance of your scope probe on each setting when it is connected to the scope but not a circuit.

n) Zener diode challenge:



Design a set-up to test whether a diode is a regular diode or a Zener diode and determine the Zener breakdown voltage without having to make every individual voltage measurements by hand. Ie, you can plug in the diode into a circuit and just look at the scope. Try to do this without your TA telling you how.

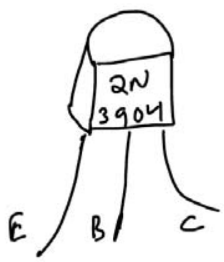
The TA will give you a secret diode and you will tell him which type it is using your apparatus. (This technique is useful if you had a lot of diodes to test.) Warning: Make sure your setup will not burn out the diode. (Test it on the regular diodes first which we have many more of than the Zeners.)

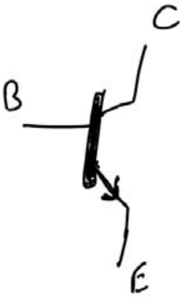
4 Lab 4

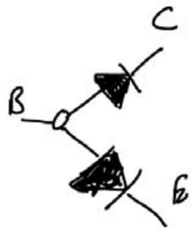
LABORATORY 4

PHYSICS 117 (Winter 2017)
Prof: Pietro Musumeci, TA: Albert Brown ATA: Maxx Tepper
Reading: Sherz & Monk: sections 4.3, 2.32

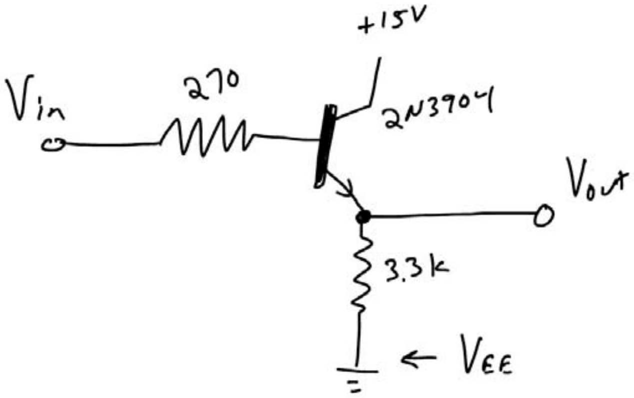
a) Transistor Junctions:
Use the DMM on the “diode test” function to measure the voltage drop across a diode for the test current (a few milliamps). A transistor is much more than two diodes stuck together, but that model is at least a useful way of checking if a transistor has been damaged. Using an NPN resistor (eg, 2N3904), measure the voltages across the BC and BE junctions using the DMM’s diode test function.







b) Emitter-follower:
Wire up an NPN transistor as an emitter-follower as below:



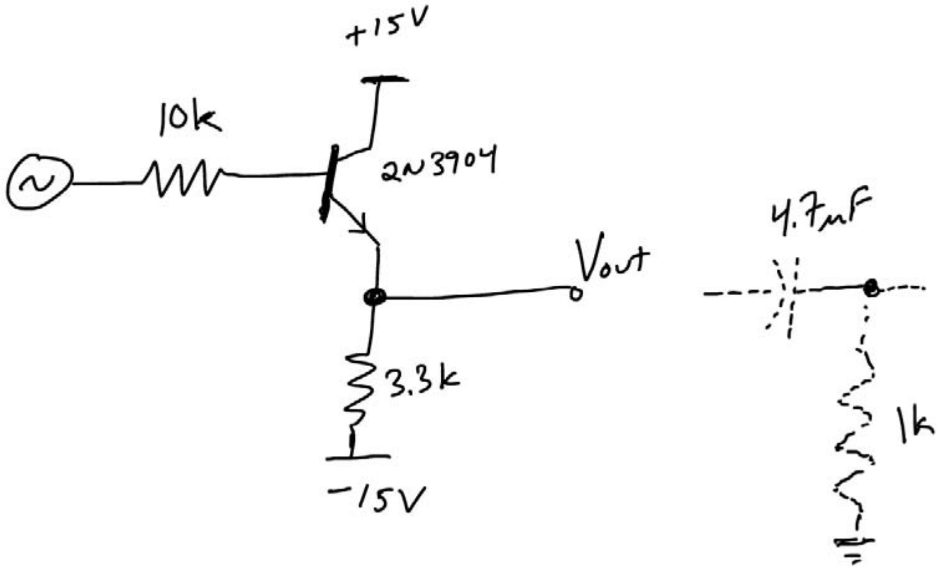
(If you find the output is noisy (due to high frequency oscillations) try a larger input resistor, e.g. 3kΩ.)

Drive the input with a sine wave with no DC offset and amplitude of a few volts. Look at the input and output simultaneously. Notice the poor replica that comes out. Turn up the waveform amplitude and you will see bumps that appear below ground. What is going on? (Hint check the data sheet for “breakdown” of the 2N3904).

Now change the voltage at V_{EE} to be -15V instead of ground. (Your power-supply knob does not go below zero. How will you make a negative voltage?) Do you see an improvement?

c) Measure V_{CE} with a DMM and explain why it is not just two diode drops (ie, not ~1.2V)

d) Drive the emitter-follower circuit below (part in solid lines) with a signal amplitude of a few volts.

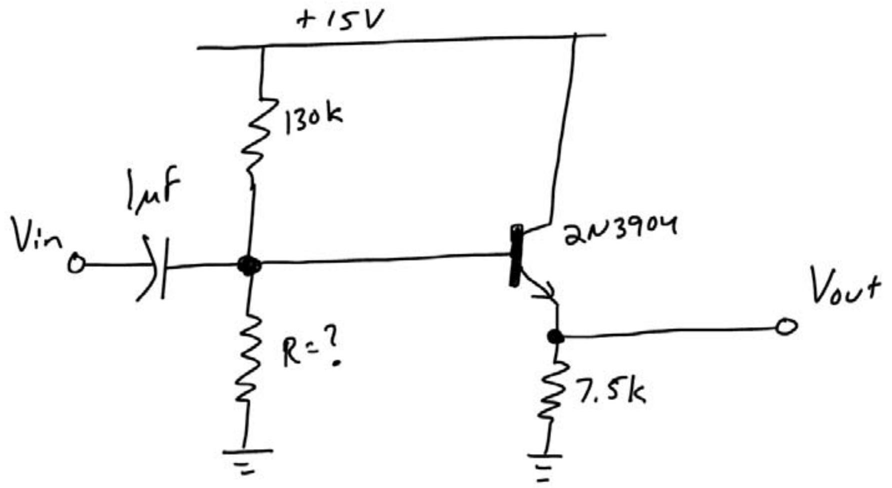


Measure Z_{in} and Z_{out} . Hint #1: to find Z_{out}, you can't just short the output to ground, but you can use a well-chosen resistor value to determine it. Hint #2: You will probably want to use a blocking capacitor on the output to remove the DC offset which can be confusing. The dashed lines show parts you will be adding to the circuit to make measurements.

Using Z_{in} and Z_{out}, calculate your transistor's β.
Measure V_{CE} again and notice it is large.

Hint: You can't measure I_{SS} or even go much lower than about 500Ω for the output load before drawing too much current from the circuit and causing it to go nuts. So you have to do it with a larger resistor, make a careful measurement, and calculate Z_{out}.

e) Single-supply emitter-follower:
The emitter follower can be made using one voltage supply, as long as you build in the voltage offset on the input, as shown below:



This input DC offset is called the "bias". The output voltage corresponding to this bias is the "quiescent point". Assuming V_{BE} is 0.6V, what value of *R* should you use so the output voltage has a quiescent point at 7.5V, thus giving you the most range before the signal hits the maximum allowed upper or lower voltage (beyond which, it suffers what is called "clipping")? Build the circuit above with your calculated *R*. (Note that it may not clip symmetrically, and rather the transistor pushes the average voltage lower.)

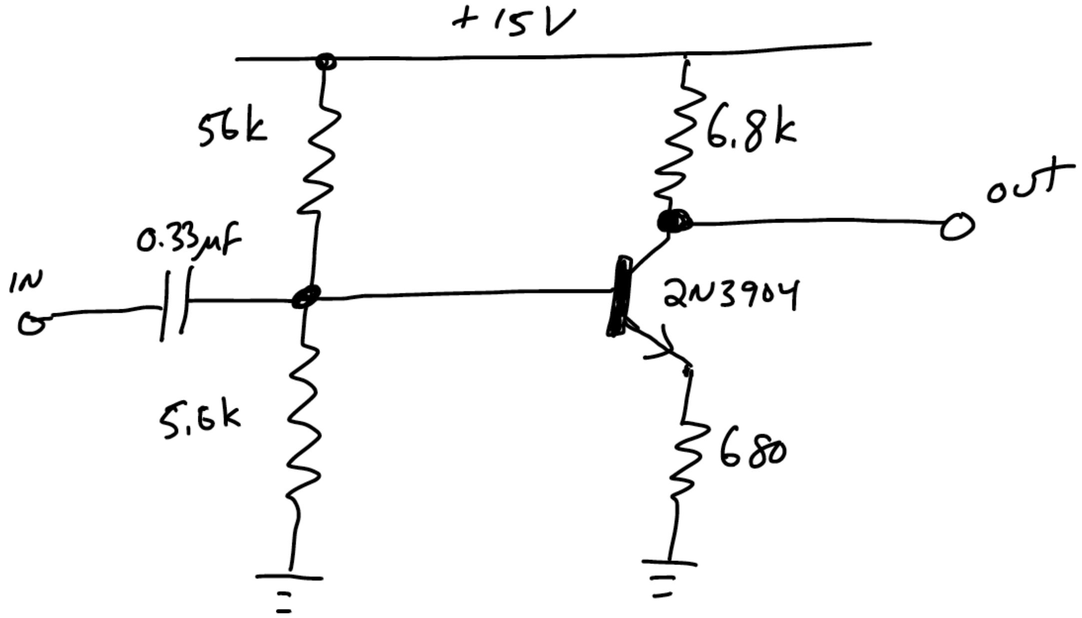
f) Drive the circuit at an easy-to-hear frequency and put its output into a 100Ω speaker. What happens to the tone once you start clipping? Why might this be bad for the speaker?

Measure V_{CE} again and observe that it is large.

g) Measuring β:
Build a circuit to measure the current gain (the ratio of I_C to I_B) of the 2N3904 while watching V_{CE}. You can use various currents from microamps to milliamps. Beyond a few milliamps, you should see the gain start to "saturate" and V_{CE} decrease. You might want to use the "1% tolerance" resistors we have in the lab to get nice event steps.

How could this circuit be used to provide a constant current source to a load? (Draw it.)

h) <u>Common-Emitter Amplifier</u>   Build this amplifier circuit:



Drive it with 5kHz sine wave.

What should its voltage gain be? Is it?

What is the purpose of the capacitor?

Explain why you needed to connect V_{OUT} to the collector instead of the emitter in to get voltage gain.

What happens to the phase of the output relative to the input?

What is the quiescent point of the output?

What should the output impedance be? Check it with a similar sized resistor.

i) Set the function generator to about 5 kHz. First, hook up one of the 100Ω speaker to the input of your circuit (the other side of the speaker should be connected to ground) to verify the speaker is working. Then, hook up the speaker to the output of the amplifier. Even though the voltage is amplified, you can barely hear it. Why?

Now, put an emitter follower between the output of the amplifier and the input of the speaker. You should hear the tone is louder even though that second stage has no voltage gain. Why did this work?

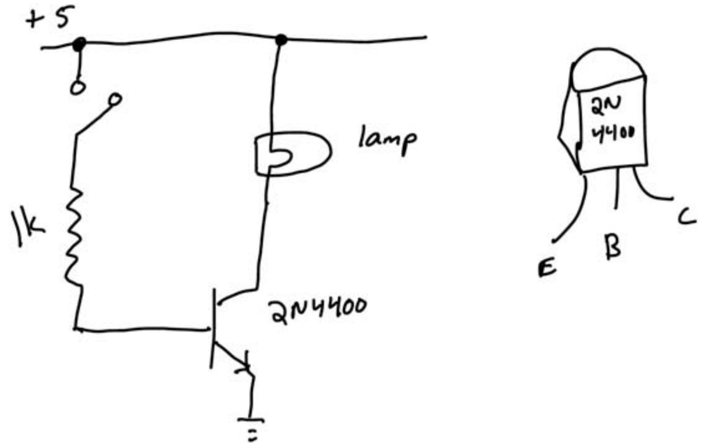
5 Lab 5

LABORATORY 5

PHYSICS 117 (Winter 2017)
Prof: Pietro Musumeci, TA: Albert Brown ATA: Maxx Tepper
Reading: Sherz & Monk: sections 4.3, 8.1-8.5, 8.8

a) Transistor Switch

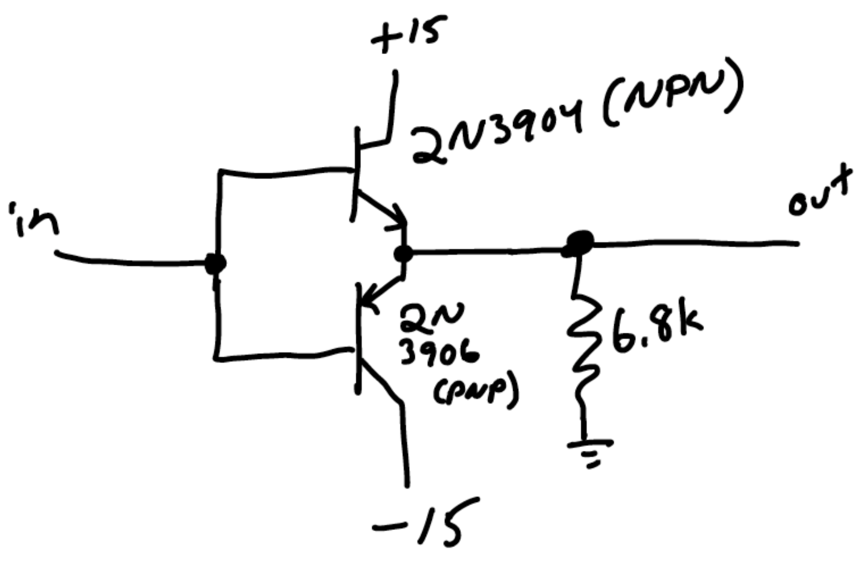
The circuit below uses the transistor in a mode called "saturation", where it provides as much current as it can so there is no longer a linear relationship between I_B and I_C. Or you can consider it as β dropping as I_C increases. We are using a 2N4400 now which is just like the 2N3904 but can drive more current and dissipate more pwer. Build the circuit below.



What is the minimum β that still lights the lamp? When the switch is "on" how much power does the transistor dissipate?

b) Push-Pull

Build this circuit:

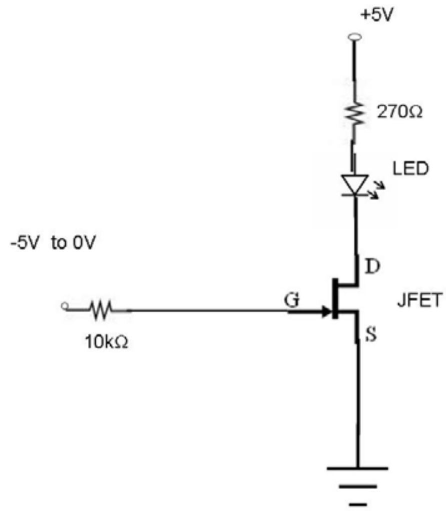


Drive it with a sine wave of a few volts amplitude. Note that the output does not look as good as the output of the single transistor circuit you built last week. Why not? (This is called a “Class B” amplifier and your amplifier last week was “Class A”. Do some research to find out the difference. What are the advantages and disadvantages of each?)

Try adjusting the DC offset of your signal generator and see what happens.

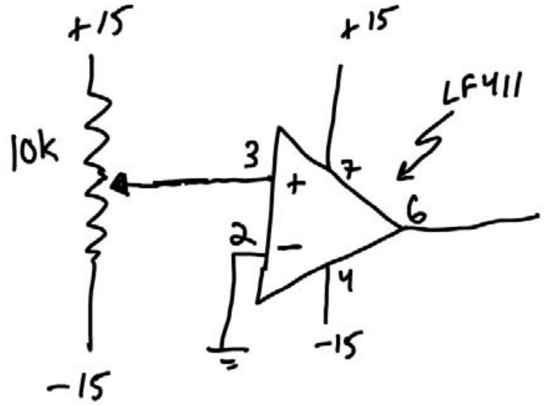
c) Field-Effect Transistors (FET)

Build a switch using a FET transistor (J309, J310 or 2N4392 in our lab, which are N-channel JFETs) transistor using the circuit below. (Look up the pin assignments!)



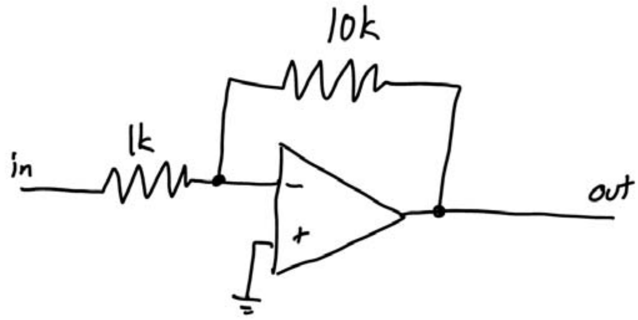
Connect the 10kΩ resistor to -5V versus 0V to show how the JFET works as a switch. Why do you need the 270Ω resistor? Now instead of connecting the 10kΩ resistor to -5V, instead touch one finger to your -5V supply a finger on the other hand to the gate. (Use only external unbroken skin.) What does this say about the input impedance of a FET? You can vary the gate voltage from -5 to 0 Volts and see when it switches. Try disconnecting the 10kΩ resistor from the power supply when the LED is on and watch the behavior of the circuit as you move your hands and dance around.

d) <u>"Open Loop" Op-Amp test</u>
Use a potentiometer as shown below to try to make the Op-Amp output a value somewhere between the two rail voltages:



Hint: You can monitor the input and output voltages on your scope using AUTO trigger.
Note: We have special "chip pullers" to remove your chip from the breadboard without breaking pins.

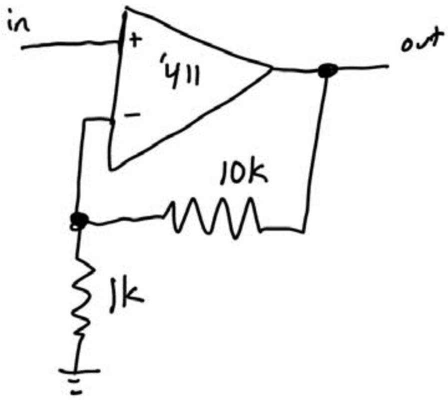
e) <u>Op-Amp amplifier</u>
Construct the inverting amplifier below with +5V and –5V rails.



Drive it with a 1 kHz sine wave and measure the gain. What is the maxiumum output voltage swing? How good is the linearity? (Hint: put in a triangle wave). Try sine waves of increasing frequencies. Note that at some fairly high frequency it starts to fail. Try a similar frequency square wave and see what happens. You are seeing the effect of "slewing" and you can measure the "slew rate" using the square wave input. (HINT: It helps if you use a fairly large amplitude to get a good measurement.)

Measure the input impedance of this circuit (including the resisitors) using another 1kΩ resistor. Try to measure the output impedance (but you will fail) as long as you are not drawing much current from the output (it maxes out at around 20 mA).

f) Non-inverting amplifier   Construct the circuit below. Don't forget the rails.



Confirm the voltage gain is what you expect.   Try to measure the input impedance (you will fail).   You might actually find some effect around 1MΩ but that is actually due to the capacitance of the input and your probe or wires.

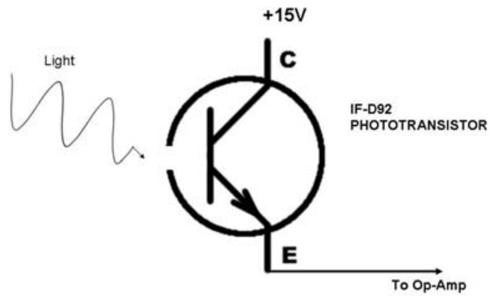
g) Bandwidth
Measure f_{3dB} of your amplifier (either one that you built). It is not caused by RC but the speed of the electronics inside the op-amp. The range of frequencies any device works for (in this case from 0 Hz to ν_{3dB}) is called the "bandwidth" of the amplifier.   Compare this bandwidth to an older model (but famous) op-amp we have in the drawers, the LM741.

6 Lab 6

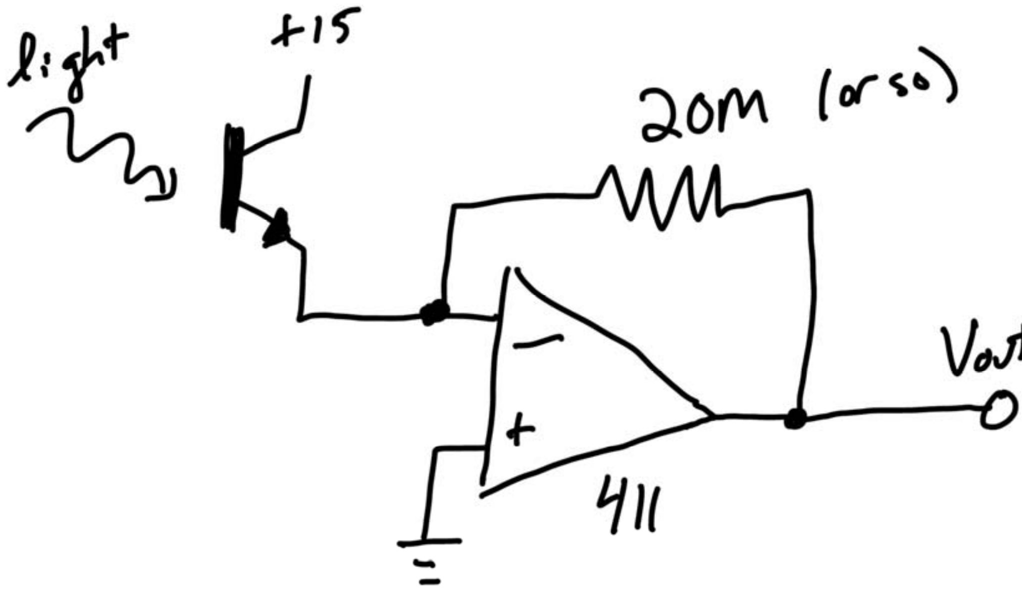
LABORATORY 6

PHYSICS 117 (Winter 2017)
Prof: Pietro Musumeci, TA: Albert Brown ATA: Maxx Tepper
Reading: Sherz & Monk: sections 8.1-8.5

a) Phototransistor:
The IF-92 phototransistor (Emitter is pin 1, with the white dot) turns the small electric current induced by light at the base into a current form C to E as shown:

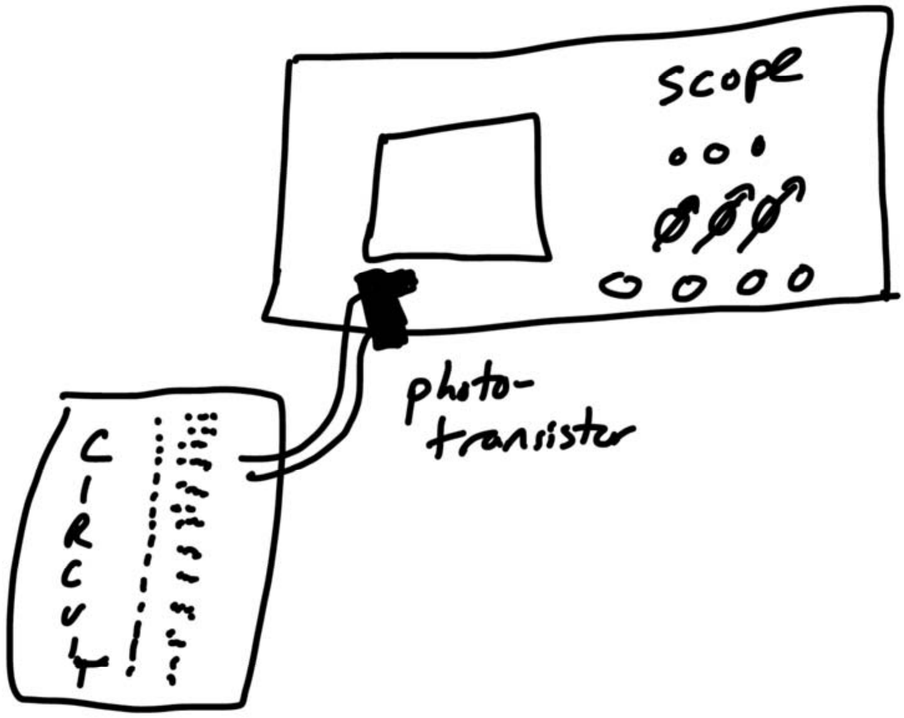


The current produced is very small but we can detect it with the op-amp circuit below:

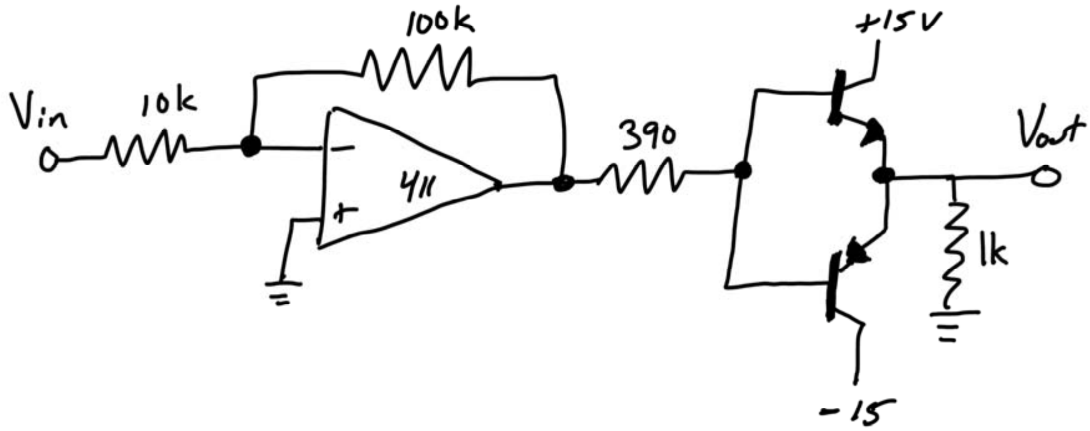


Measure the output voltage and use that to infer the current driven by the phototransistor at E. Assuming β=200, what is the current induced by the light at the base? (This is called the "photocurrent".)

b) Feedback loop
You can make the oscilloscope itself part of the feedback loop. Put the scope at around 250 msec/div and aim your phototransistor at the screen. HINT: For this lab use "auto" trigger mode on your scope since there is nothing to easily provide a trigger. You may need to turn out the lights and experiment with which color channel works the best. You should see the display becomes part of the circuit.

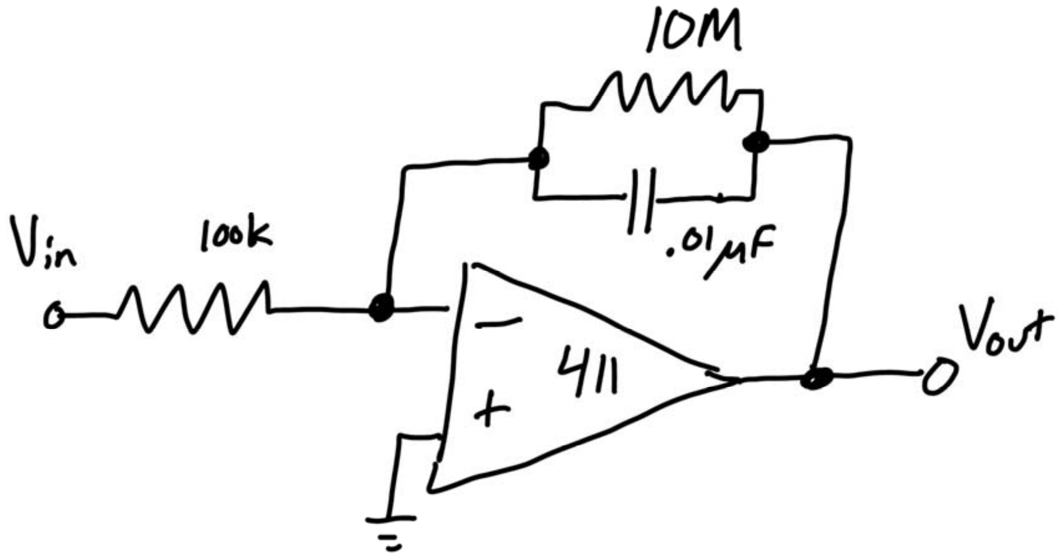


c) <u>Op-amp plus push-pull</u>
Connect an op-amp amplifier to a push-pull "buffer" as shown below. Why might you want a circuit like this? Drive it with a sine wave of a few kHz and amplitude a few volts and notice you still see the crossover distortion.



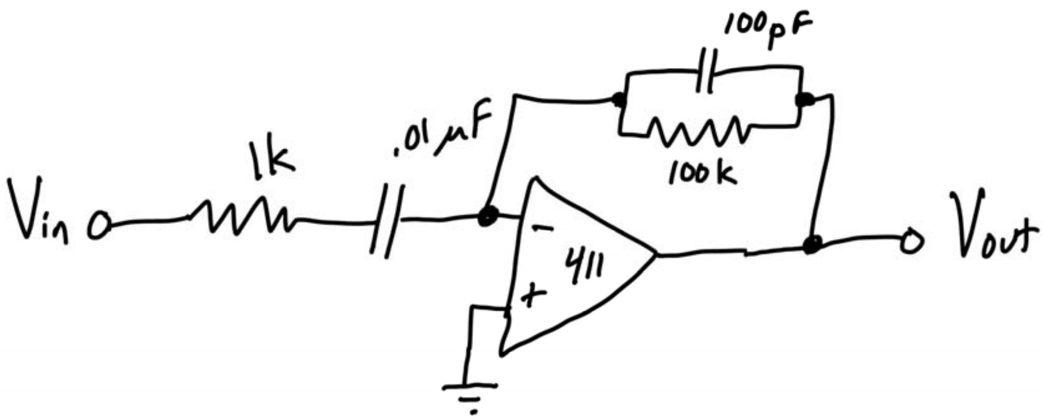
Now connect the feedback resisitor to the output of the push-pull instead of the output of the op-amp. Why does it get better? HINT: You can look at the output of the op-amp directly while you are doing this. Pretty clever! If you drive it fast enough, you should see it start to fail. Why?

d) <u>Integrator</u>. Build the circuit below:



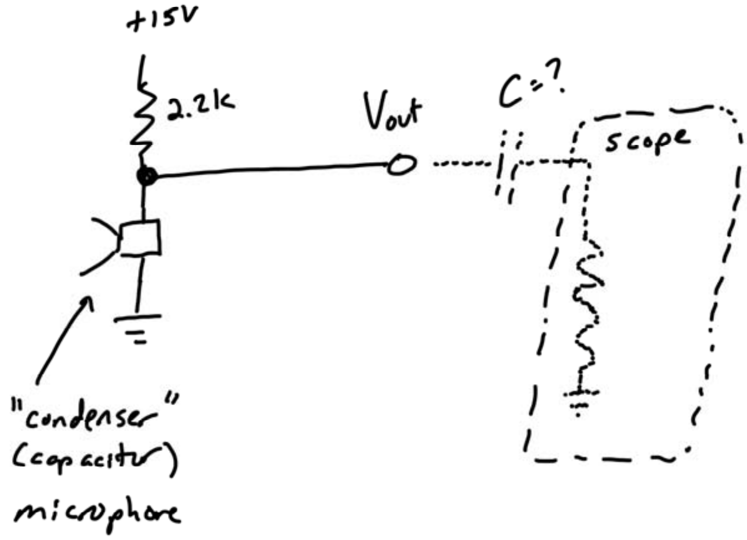
Drive it with a 1kHz square wave and then a triangle wave and predict the output shape and amplitude. What is the function of the 10M resistor? Try removing it.

e) Differentiator: Build the circuit below:



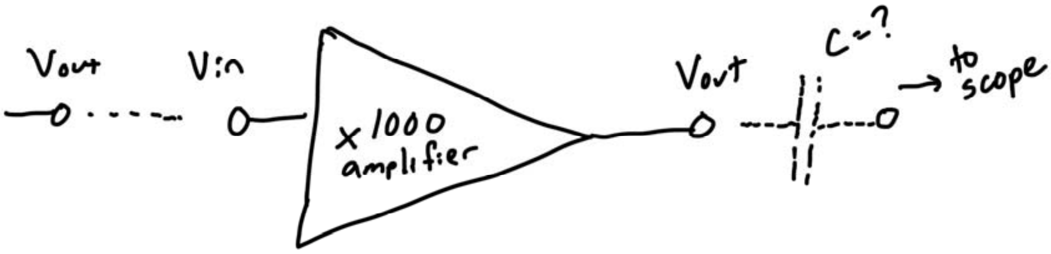
Try driving it with various shape waveforms and show it is a differentiator. Show that you can calculate the output shape and level of a sawtooth wave.

f) Audio Detector: You will build an audio amplifier to see your own speech. First note you can connect the microphone using the following circuit:



As the capacitor plates move, the voltage drop for the charge on the plates changes slightly. There is a large DC offset, so attach a high pass filter with f_{3dB} at about 100 Hz. If the resistor of your filter is your scope, what capacitor do you need? Why did we choose about 100 Hz?

You should see the signal (it helps to whistle and cup your hands around the mic) but it is low voltage and very noisy. Now pass your signal (after the capacitor, so you are not passing DC) through a x1000 amplifier you can build with your op-amp:



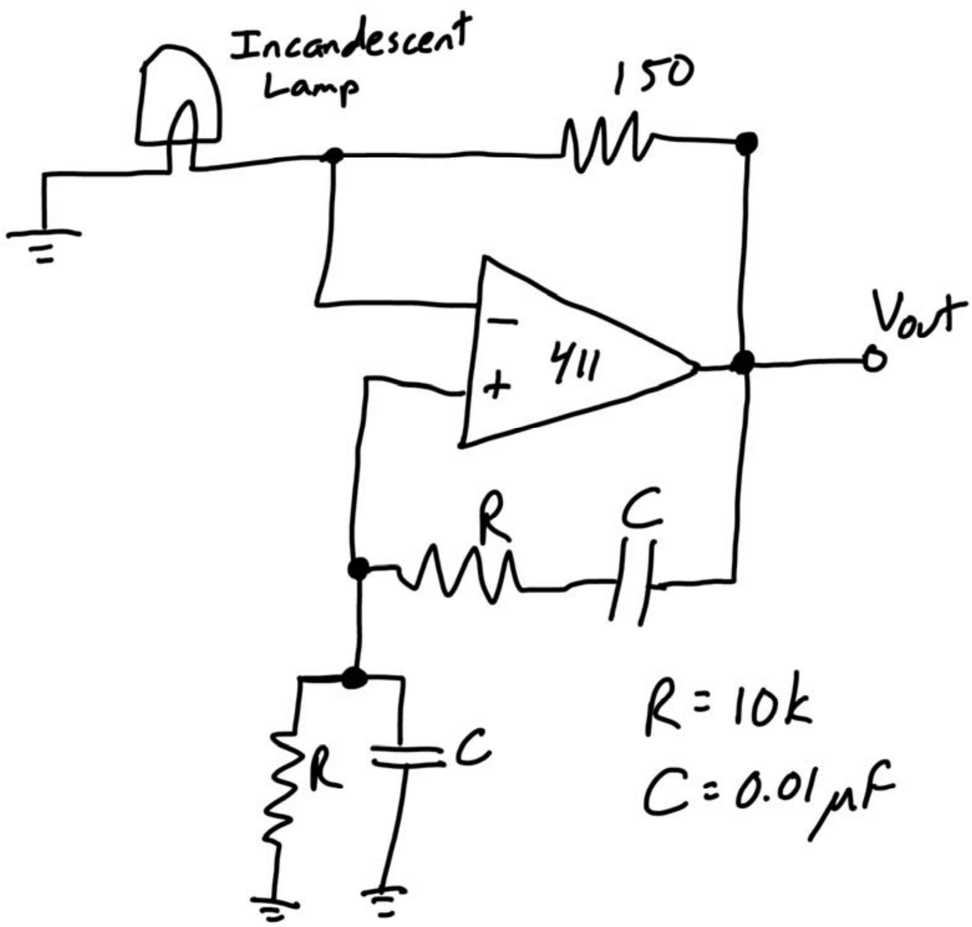
The output may have some DC on it, you can filter the op-amp output again as you did before. You should see a nice clear signal as you whistle and speak. Can you see your whistle on the fourier transform?

Now set the scale on the oscilloscope to 1.0 sec per division and talk into the microphone. You should see the visual voice recordings that FBI agents use in the movies. (Hint: this is a rare case where you need to "auto" trigger so the scope displays in real time, rather than waiting 10 seconds. This is known as "scan" mode, and is like an old-fashioned chart-recorder.)

OPTIONAL: I found that when I added the op-amp, it put a significant large DC signal on its input and output. Do you know why? (HINT: I don't know.)

g) Other feedback:
Build the now-familiar inverting amplifier with an op-amp. But replace the feedback resistor with a diode with a cathode connected to the output. Drive the circuit with a sawtooth wave that is offset so it is always positive. (You could have oriented the diode the other way as long as this signal was always negative.) Assuming a simple model for the I-V curve of your diode, does the shape of the output make sense? . Explain what function you see using the basic op-amp rules. HINTS: You should use two channels of the scope: one to look at the signal from the function generator and the other to be the output. Since the output of the circuit is "inverted", under the channel menu set your scope to "invert" so you may more readily recognize the function. Mathematically speaking, why did you need to make your signal always positive?

h) Positive feedback
Make the circuit below, which is William Hewlett's (of Hewlett-Packard fame) master's thesis from 1939:



You should see a sine wave at the frequency you can calculate. (If the negative feedback is not working, you will see a square wave that hits the rails.) This is an example of positive feedback put to good use. The lamp is providing negative feedback. (Hint take a look at page 216 in the Hayes & Horowitz old lab book or section 5.17 of the Horowitz and Hill hardcover). If you see noise, remember what we said to try with large capacitors on the power supplies. Now replace the lamp with an equivalent resistor---does it still work? What key property of the lamp is different than the resistor? HINT: I could only get this to work with the small-bulb lamp (P/N 7219) but you can try the larger bulb with a different feedback resisitor.

7 Lab 7

LABORATORY 7

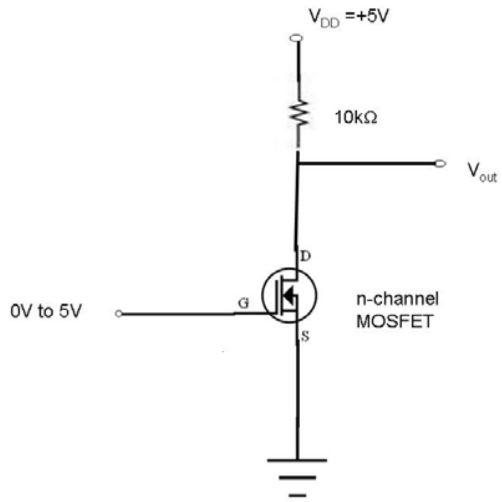
PHYSICS 117 Winter 2017

Prof: Pietro Musumeci, TA: Albert Brown, ATA: Maxx Tepper

HEADS-UP: In part (a) you will be using two positive voltages. Make sure you wire up your power supply correctly.

<u>MOSFET logic inverters</u>

a) MOSFET switches are the basis of the CMOS digital electronics we will be using. Build the logic inverter shown below. Because the circuit has an n-channel MOSFET (in our lab IRL-510), it is called an "NMOS" inverter. A common standard is that a +5V output level is called 1 (true) and and 0V output level is called 0 (false). Plot the input vs. output voltage. HINT: having two DVM's for this measurement will make it easier. Why couldn't you just hook the drain directly to the +5V?



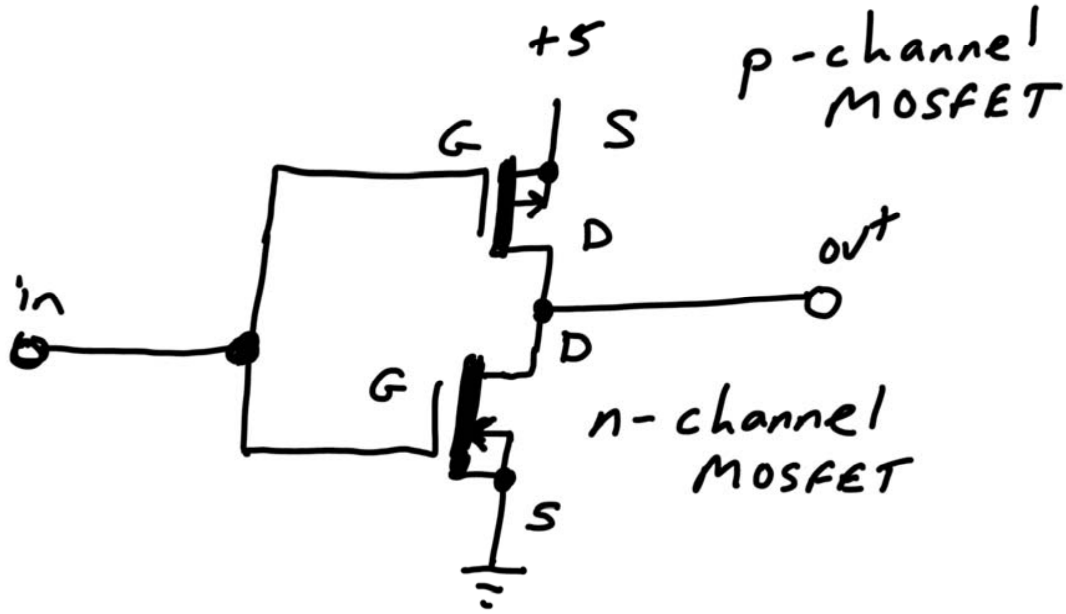
b) Without disassembling your NMOS inverter, build a PMOS inverter somewhere else on your breadboard using a p-channel MOSFET (in our lab IRF-9Z20PBF). Note you will have to rearrange this circuit. Hint: Remember the difference between V_{GS} and V_{SG} in class notes. Try to figure out the correct circuit without asking your TA.

c) Estimate and measure the output impedance of the NMOS inverter you built. Is it the same for 1 (true) and 0 (false)?

d) Set the amplitude and offset of your function generator to produce a square wave oscillating between 0 and 5V. (Remember the display will be wrong unless you set it to "high Z".) Now put this signal into the input of one of your inverters using the function generator starting at a low frequency, say 100Hz square wave and verify your circuit is inverting. How long (time) does it take your circuit to react (0 to 1? 1 to 0?) By watching the input and output on the scope, increase the frequency of the square wave to measure the highest “baud” (bitrate) at which this inverter circuit still works. Compare to the bitrate of what you expect goes on in your home modem, computer etc.

e) Measure the risetimes and falltimes (10-90%) for the NMOS and PMOS inverters. Explain why the risetimes and falltimes are different.

f) Homemade CMOS inverter
The high output impedance of the NMOS and PMOS inverters are a pain. As you saw, even if you are driving another MOSFET next in line, the high output impedances combined with stray capacitances reduce the maximum switching speed of your circuits (due to the RC time). Also one logic state is always drawing current which wastes power. This is solved by the CMOS circuit, where C stands for “**C**omplementary”. Build the CMOS-based inverter shown below:

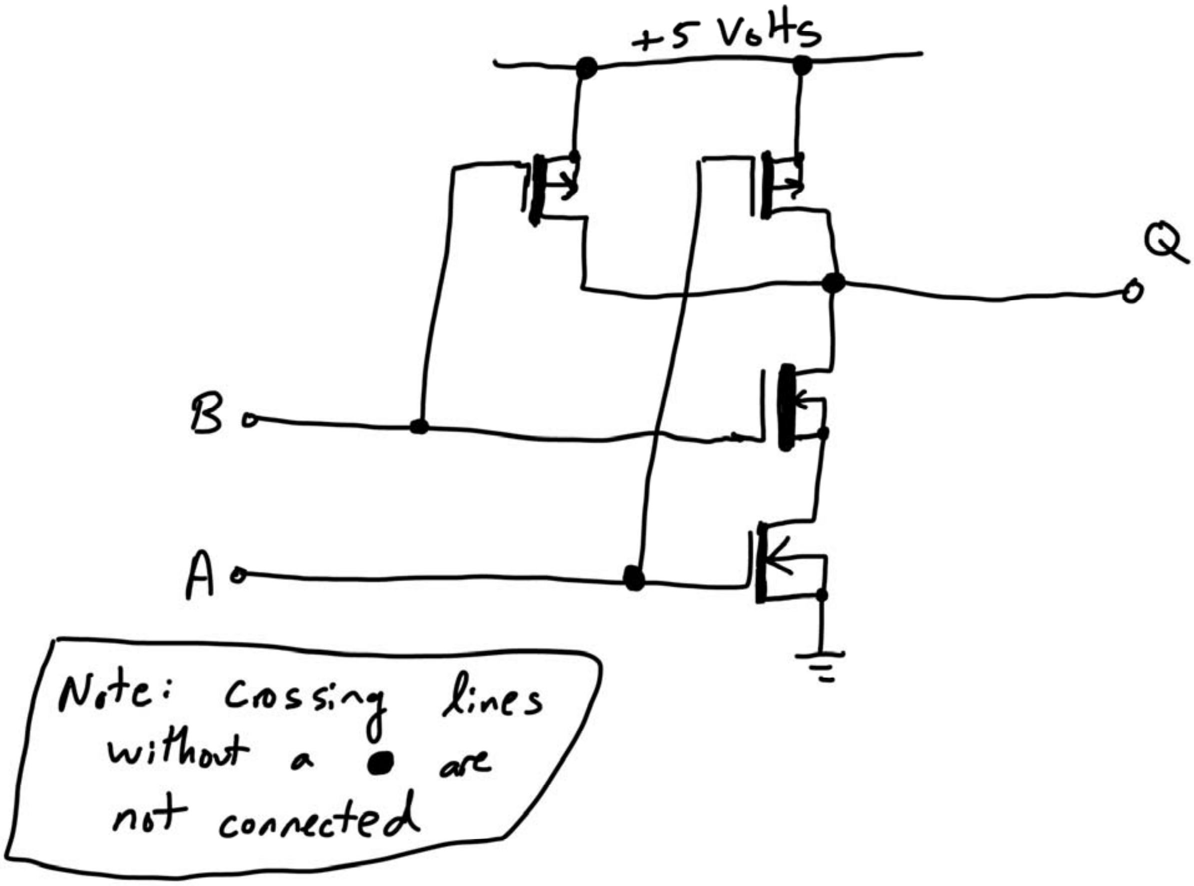


This is known as “active pull-up”.

Measure the risetime and falltime of the CMOS inverter output and compare to what you got for the NMOS and PMOS inverters. Can you find the highest frequency at which this circuit still works using an input square wave?

Off-the-shelf CMOS inverter
g) Now use one of the CMOS inverters on a chip (74HCT04) located in the lab and compare its behavior to the one you built. Remember to put the unused inputs at 0 or 5V. Remember the chip needs to be powered. Because CMOS historically followed TTL, “V_{DD}” is still called V_{CC}” as if it had bipolar transistors inside. Measure the range of input voltages that correspond to 0 and 1 logic levels. (Now that you have your scope hooked up looking at square waves it is probably faster and easier to do it with your current setup rather than going back to the two DVM method from before.)

homemade NAND
h) Build your own NAND gate using CMOS logic (combined NMOS and PMOS) as shown below:



Measure the "truth table" and confirm that is a NAND. Explain in words why this circuit behaves as a NAND.

i) Commercial NAND: Wire up a NAND on a chip (74HCT00) and show it works the same way. HINT: You will need to look up its datasheet. Does it work better (faster)?

j) DeMorgan's Theorem: Use a NAND gate and Inverters to make an OR gate. HINT: You should look up "DeMorgan's Theorem" (Amazingly this was proved in the 1800's.)

8 Lab 8

LABORATORY 8

PHYSICS 117, Winter 2017

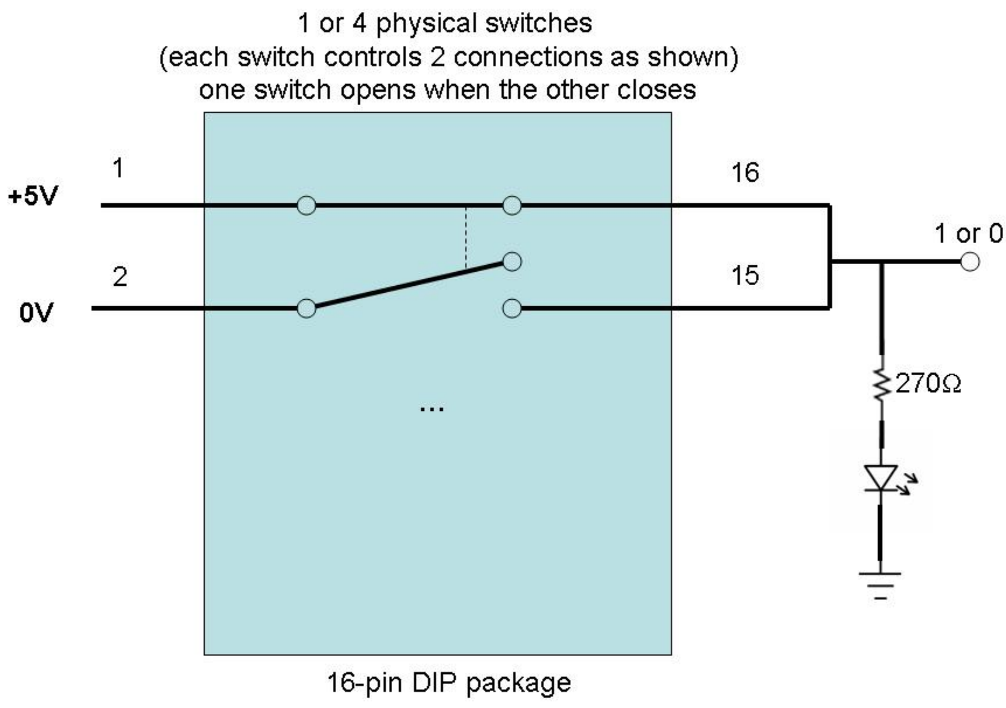
Prof: Pietro Musumeci, TA: Albert Brown, ATA: Maxx Tepper

<u>On/off logic switch with LED</u>

It is going to be helpful for you as we study more digital circuits to have switches that switch between +5V and 0V so you don't have to move wires--or forget to connect all CMOS inputs to 0 or 5V. Also an LED is handy to have to indicate the "on" at state (logic=1) (+5V).   We want to use an SPDT switch.

Nominally, the SPDT switch needs 3 connections to the outside world. However, the manufacturer has decided to give you more flexibility by having two switches with opposite on/off states as shown below in a DIP package. By connecting pins 15&16 (or 13&14, 11&12, 9&10) you turn each switch into a standard SPDT as shown below.

a) Set up two bits you can control with an SPDT switch. Each should have their own LED showing 1 (on) or 0 (off).   Do this on the side of your breadboard away from other work you will do later since you will use it multiple times.



This switch is the blue package. There is another in a red package that works differently but you can figure it out!

b) Using the scope trigger, try to catch the rattiness of the switch transition on its up and down transition.   You may find this is worse with the red package switch than the blue. Repeat this with a 1 and/or 15 uF capacitor on the "pole" side of the switch and see if it is better (It should be).   See which value works best.

NANDs--> other gates

c)

1) Use NAND gates to light an LED only when two inputs are high (i.e., make an "AND")

2) Use NAND gates to light an LED when either of two inputs are high (i.e., make an "OR")

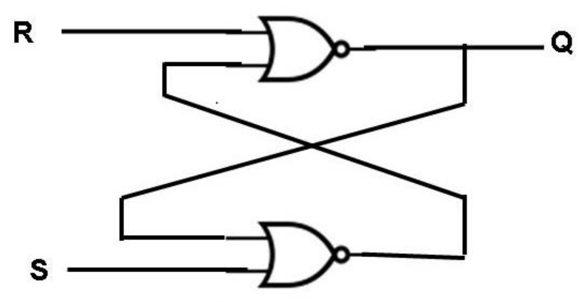
3) Use NAND gates to light an LED when either but not both of two inputs are high (i.e., make an "XOR"). This can easily be done with 5 gates and a challenge to do with 4.

Various off-the-shelf Gates

d) Find the CMOS-family XOR, and AND chip in the trays that do these logics directly. Confirm that they work as advertised by measuring their truth tables using your switches and putting an LED on the output.   (Remember to hook up unused inputs to 0 or +5V) Feel free to do others.

S-R Latch

e) Build this crazy-looking circuit below with the 74HCT02 (Dual NOR). The crossing lines are not a connection.



f) Experiment with the input states S and R using your switches with Q driving an LED. Why are called "S" and "R"?   Which input state is the "memory" state. (Hint: The S=1, R=1 state is unused and not important.)   This circuit is called an S-R Latch

D-type Flip-Flop

g) Take a 74HCT74 dual D-type flip-flop from the drawers for this section and look up its data sheet. Take control of one of the D (pin 2) and CLOCK (pin 3) with your two switches and have Q drive an LED   You can put "Reset*" (pin 1) and "Set*" (pin 4) to 1

(+5V) and ignore them for now. Remember that the four unused inputs on the chip should be set to 0 or +5V.

--Confirm that the flip-flop ignores changes at D if there is no clock transition.
--Confirm that the flip-flop moves D to Q if there is a rising edge of the clock

h) Confirm that your Flip-flop only changes Q when the clock is rising, not falling. You will likely find that it fails and reacts on a falling edge. That is due to “switch bounce”. Try instead using a 1 uF capacitor as you did in part b.

i) When Q is on, connect RESET* to 0V and see what happens. Try to make the output change by using D and CLOCK. When you see what RESET* does, play around with SET* as well to verify that it does what it sounds like.

<u>“Seven Segment” Display</u>
j) Take a seven-segment common-cathode numeric display (LDS-C514RI) from the drawer and look up its datasheet. Notice that it is just 7 diodes connected in parallel to a common cathode. Connect the common cathode to GROUND (but through a 270Ω resistor in series so you don’t blow it out!!) This current-limited power connects to pin 3 or 8. Light the various segments by connecting pins 1,2,4,5,6, or 7,9 or 10 to +5V either singly or in combination. (REITERATE: Do not hook directly to GROUND, have at least a 100Ω resistor in series.)

<u>Divide-by-10 and Counter</u>
k) Use the CD4026 decade counter as a divide-by-10. You need to hook up some extra pins that you can find on the data sheet. Fill in the pin numbers and for the enable/inhibit/reset pins figure out whether to hook up to +5 or 0 V.

Pin _____ = +5V power,
Pin _____= ground power,
Pin _____= clock input (square wave from your generator)
Pin _____= output (i.e., one pulse per 10 inputs)
Pin _____= ______ Volts in order to enable the display (for use below)
Pin _____ = ______ Volts “clock inhibit”
Pin _____ = ______ Volts “reset”

Use your square wave generator as the input clock. Remember to set the offset so it is changing between 0 and +5V. Use the scope to show it gives an output pulse for every 10 input pulses.

l) Hook up the CD4026 chip’s drivers to the 7-segment common-cathode LED numeric display (LDS-C514RI) and clock the chip at 1 Hz using your function generator. (Remember you need an offset to swing between 0 and 5V.) You should see the display count properly. You can also make it count faster than you can see it change, but catch it on your phone’s Slo-Mo mode if you have one.

9 Lab 9

LABORATORY 9&10

PHYSICS 117, Winter 2017

Prof: Pietro Musumeci, TA: Albert Brown, ATA: Maxx Tepper

Game Time!

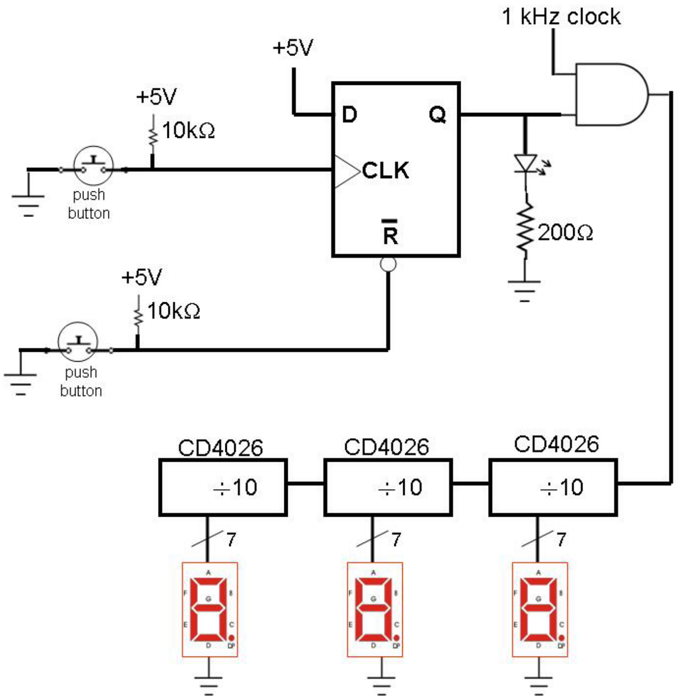
You are going to build a "reaction time" game. The game is that you hit a button that lights an LED, then your friend hits the second button as fast as possible. The display gives the result in milliseconds.

Week 1: You will build this on your usual (reusable) breadboard first. Your "lab report" is a 2-3 page summary of how this works: Make a full schematic *showing every pin number*. Keep a second printed copy for yourself: You will work from this for "week 2".

Week 2: When you have it all working, we can help you solder it to a solder-able breadboard and put it into a box you can keep. **VERY IMPORTANT** When you build with solder it is very hard to debug. So build it in stages, testing every step. Don't try to build it all at once and just turn it on, hoping for the best. For lab 10, instead of a writeup, send the prof. a video of your working game and photo of the board. I will put them on the web for everyone in the class to see.

Lab version

Build the circuit below using your external function generator as the 1kHz clock. This uses a flip-flop to start and stop the counters, which are displayed on the LED 7-segment displays. (Note the standard notation: / through a line with a 7 next to it means 7 wires in parallel.) Note that on the bottom the circuit goes from right-to-left which is usually frowned upon, but makes sense here because that is the order of the digits.



Note: You will also have to add a switch that will "reset" the counters between games. (There is a way to make it work with still only two pushbutton switches.)

*** NOW MAKE ONE TO TAKE HOME, USE THE FOLLOWING STEPS ***

Part 2: (Do this during week 9)

Replace the function generator with an "on board" 1kHz clock. You can build this out of the 555 timer in the lab. The "555 timer" is the most famous timer chip. Look up the datasheet on the web and make it count at 1 kHz and replace the external clock.

Part 3 (Do this during week 9)

Replace the 5V power supply with four 1.5V AA or AAA batteries. We have clips for the batteries. For your week-9 writeup: measure how much current your game draws and compare to the specs for the batteries.

Part 4:

Use a solder-based breadboard to wire it all up. We have been using "22 gauge" wire for our solderless breadboards. You will find it easier to use a smaller "24 gauge" or less, which we have in the lab.

Part 5:

Put connectors on a plastic project box for the pushbutton cables. Put your breadboard in the box and now you have your own game.

Part 6

Send prof. a link to a short video & photos of the board to establish credit for finishing and we'll share it with the rest of the class.