**Physics 310**
**Lab 5 – Transistors**

**Equipment:** Little silver power-supply, little black multimeter, Decade Resistor Box, 1k, 2N3904, 470Ω, LED, 10k, pushbutton switch, 270Ω, 2.7k, function generator, o'scope, two 5.1k's, 47k, two 4.7k's, second 2N33904, two 10M's , two 15M's

**General Lab Notebook instructions (from syllabus)**
You should be sure to write down enough so that you can recall what you did several weeks later (it may come in handy when you're working on your final project.) The following information should be included:

1. Titles for labs and sections of labs.
2. Description of procedures followed (e.g. what was measured).
3. Well-labeled diagrams of circuits.
4. Record of observations and data (in tabular form when appropriate).
5. Analysis of data: computations and tables or graphs of results.
6. Comparison with theory: calculations and graphical or tabular comparison.
7. Answers to all questions.

**General Procedures:**
This lab will concentrate on properties and applications of NPN bipolar junction transistors.
- Be sure to measure the values of any DC voltages used in calculations because the power supplies do not provide exactly integer voltages.

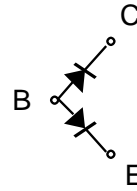**5-1. Transistor Basics**
**A. Testing Transistors**
1. The picture of the case of the 2N3904 transistor indicates which leads correspond to collector, base, and emitter. When the BC and BE junctions are tested <u>separately</u>, they should act like diodes with polarities indicated in the diagram on the right. That diagram is only for testing transistors and does <u>not</u> describe their operation when all three terminals are used!
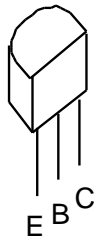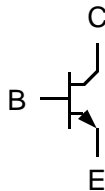


TO-92 Case          Circuit Symbol          Two-Terminal Behavior
                                            (For testing only!)

2. Try out the diode test function of the digital multimeter (DMM) on a 1N4004 diode. Select this mode by turning the dial of the DMM to the diode symbol. The meter will apply a small current from its positive ohmmeter terminal to its "COM" terminal, and displays the junction voltage. The voltage should read about "0.6" when a diode is forward biased and read about "1.0" when reverse biased, otherwise it is damaged.
3. Test that the BC and BE junctions of a 2N3904 transistor behave as described above. If a transistor doesn't pass this test, you should dispose of it and try another one.

## B. Current Amplification

**Pre-Lab**

1. In 5Spice build the circuit below. You can select the transistor icon from the menu represented by a diode; be careful to select the particular transistor icon shown in this schematic. To set the transistor type as 2N2222, right-click on the transistor icon, select "change parameter" and then you can search the list of component names.
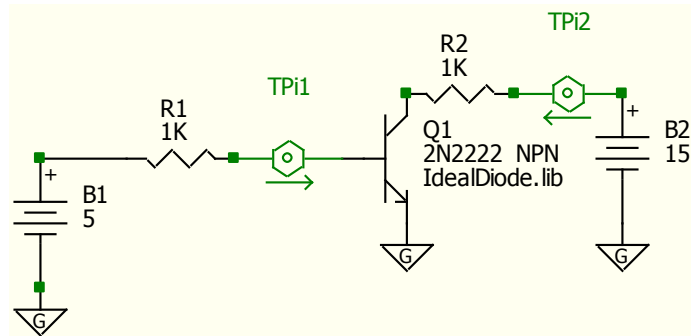


2. To get a sense of how the "current gain" ($I_{collector}/I_{base}$) varies with the base resistor, you'll (somewhat tediously) change the value of R1 from 1k to 2k, 5k, 10k, 20k, 50k, 100k, 200k, 500k, and finally 1000k; for each of these values, 'run' the circuit and read the currents passing through TPi1 and TPi2 (displayed on the "DC Bias" tab.) Record these resistance and current values in a spreadsheet and plot the current gain, i2/i1, as a function of the resistance, R1.

3. Print this plot and bring it to lab (so you can affix it in your notebook where appropriate.)

4. Construct the circuit below using a DMM as an ammeter. Never turn the resistance below 1 kΩ or the transistor will probably be damaged.
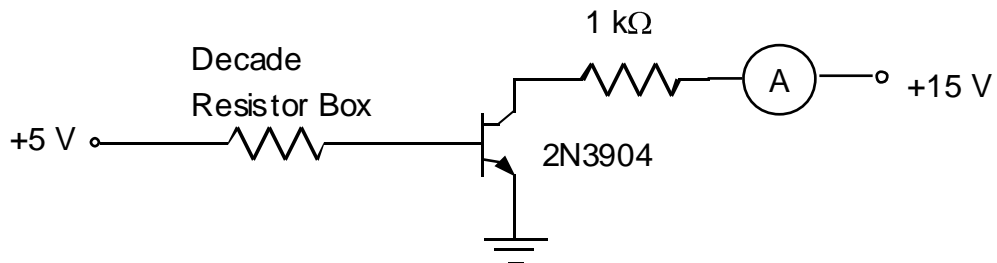


5. Measure the collector current ($I_C$) with the decade resistor box set to 1 kΩ, 5 kΩ, 10 kΩ, 50 kΩ, etc. up to 1 MΩ. Add 1-MΩ resistors to make measurements with total resistances of 2 MΩ and 4 MΩ.

6. Calculate the base current ($I_B$) and the current gain ($\beta = I_C / I_B$) for each resistance by assuming that ($V_B - V_E$) = 0.6 V.

**Questions:** Is the current gain constant over the whole range of base current tested? Why is there a limit to how large the collector current can get? (Hint: What is the approximate maximum voltage across the 1-kΩ resistor?)

**Question:** Compare the current gain in the range where it is approximately constant with that measured by other labs groups. Would it be a good idea to design a circuit that depends on *exact* value of a transistor's current gain? Explain.

## 5-2.    Current Source

**Pre-Lab**

1.  In 5Spice, construct the circuit shown below.
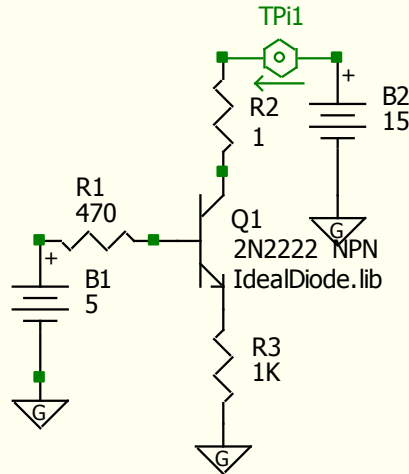


2.  This time you'll explore how the current drawn through the "load" resistor, R2, varies with its resistance. So, vary R1 from 1Ω, 2 Ω, 5 Ω, 10 Ω, 20 Ω, 50 Ω, 100 Ω, 1k, 2k, 5k, and finally 10k. For each resistance, record the current detected by TPi1, then plot that current vs. Log(R).

3.  Measure the resistances of the two fixed resistors to be used in the circuit below. Construct the circuit which is designed to keep a constant current through the load resistor (the decade resistor box) even if its resistance changes.
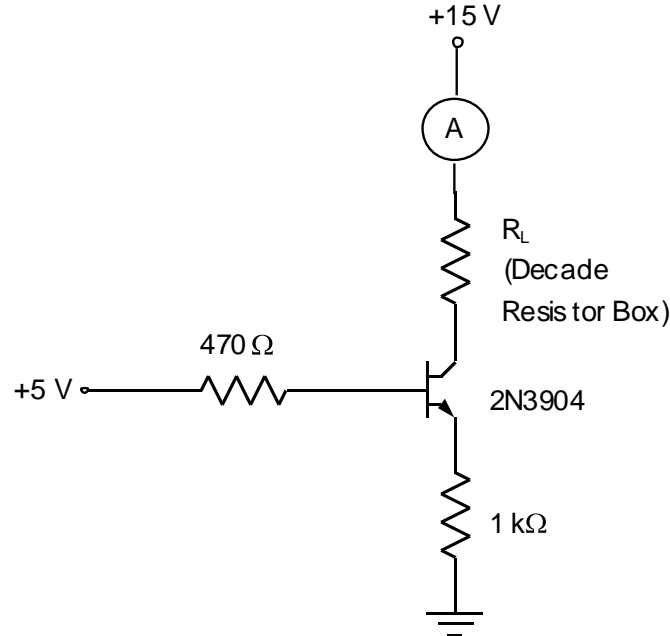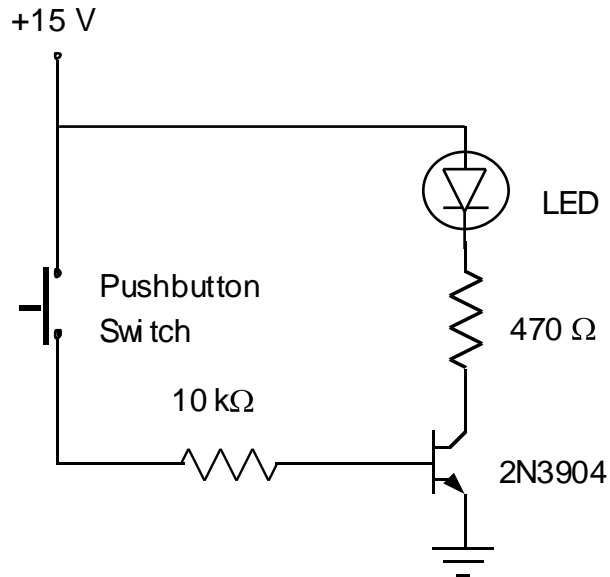


4.  Measure the current for several resistances from 1 Ω to 10 kΩ.

**Questions:** How do the measured currents compare to what is expected? (Again, assume that $V_B$ - $V_E$ = 0.6 V.) Does the circuit work best for low or high load resistance?

### 5-3. Transistor Switch

Construct and test the circuit below. Recall that the flat side of the LED corresponds to the stripe in the diagram.

+15 V



**Question:** How does the current through the switch compare to the current through the LED (measure them)?

**Challenge (optional):** Modify the transistor switch so that the LED is on when the switch is <u>not</u> pushed and turns off when it is pushed. Only a small amount of current should flow through the switch when it is closed.

### 5-4. Voltage Follower (Emitter Follower)

**Pre-Lab**

A. In 5Spice, construct the following circuit.
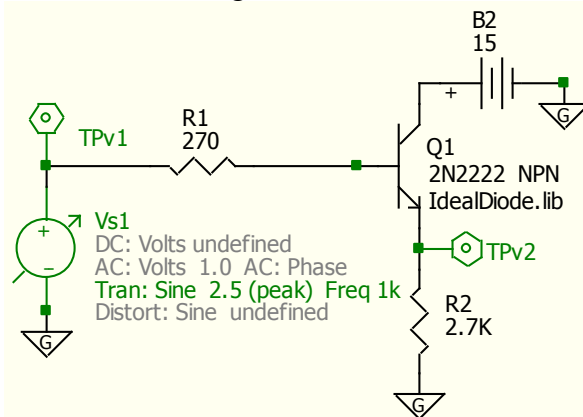


B. With the indicated supply voltage (1-kHz, 2.5-V amplitude), plot the input and output voltages (TPv1 and TPv2). To do that, Set up the analysis for a Transient-New, to run from 0 to 0.002 seconds, and use source Vs1; then set Graph/Table to plot both TPv1 and TPv2 using the Left axis.

C. Print the plot so you can tape it into your notebook where appropriate.

D.  Construct the following circuit.



+15 V

270 Ω

$V_{in}$

2N3904

$V_{out}$
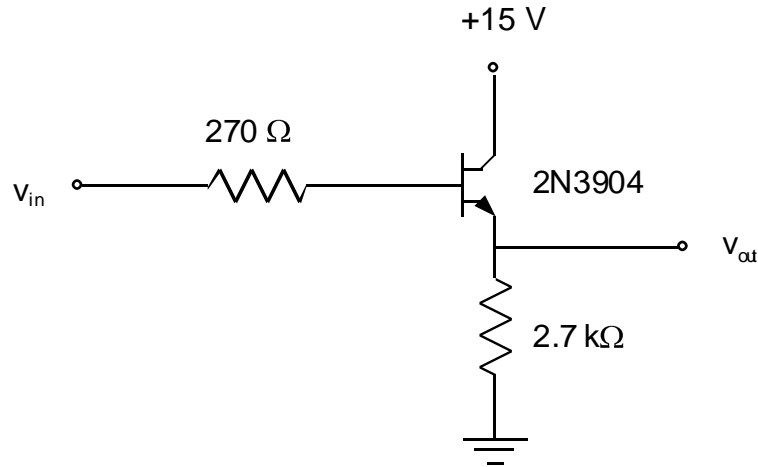
2.7 kΩ

E.  Input a 1-kHz sine wave with 5-V peak-to-peak. Carefully sketch the input and output voltages.

**Questions:** How does the output differ from the input?

F.  Replace the connection of the 2.7-kΩ resistor to ground with a connection to –15 V. Using the same input as before, sketch the input and output voltages again. Keep this circuit set up; you'll use it again shortly.

**Questions:** How does the modification improve the output? How does it still differ from the input?

G.   The voltage follower doesn't seem to do much, so this simple exercise will demonstrate one of its uses. Build the voltage divider shown below. Set the function generator to produce a 1-kHz sine wave with 10-V peak-to-peak. Measure the "unloaded" voltage between its output and ground. Attach a 2.7-kΩ resistor between the output of the voltage divider and ground, and measure the "loaded" voltage between output and ground. Finally, remove the 2.7-kΩ resistor and connect the output of the voltage divider to the input of the <u>original</u> emitter follower (with a connection to ground), and measure the voltage across its 2.7-kΩ resistor.



5.1 kΩ

Function
Generator

$V_{out}$

5.1 kΩ
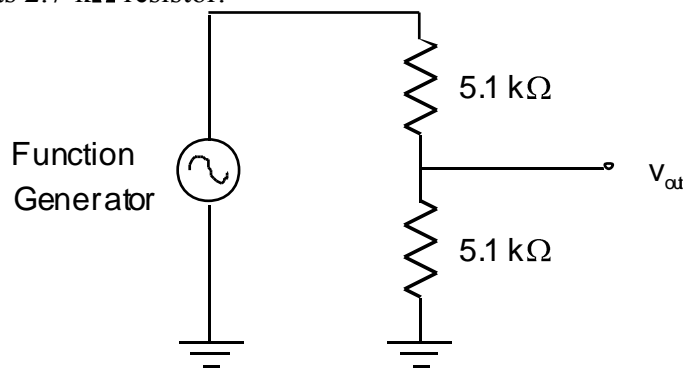
**Questions:** Why is the voltage across the 2.7-kΩ resistor closer to the voltage divider's unloaded output when the voltage follower is used? (Hint: Think about currents!) Explain why the voltage is still slightly different from the unloaded output of the voltage divider.

## 5-5.    Voltage Amplifier (Common-Emitter Amplifier)

**Pre-Lab**

A. In 5Spice, construct the circuit below.  Ideally, it should have an AC voltage gain of $V_2/V_1 = -R_C/R_E$.  Unlike filter circuits, the magnitude of this circuit's gain is larger than one!
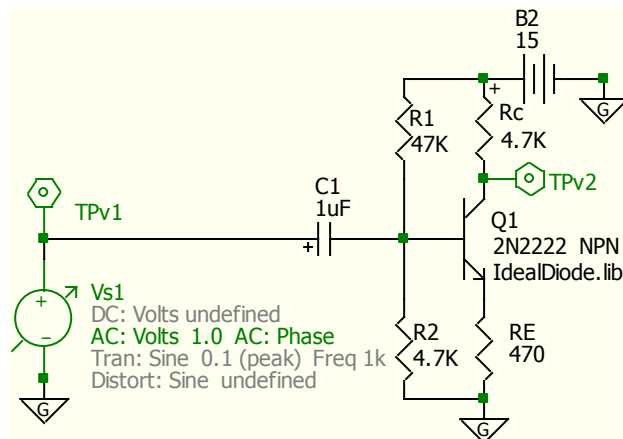


B. You'll investigate how this voltage gain actually depends upon the frequency of the input voltage by plotting the amplitudes V2 / V1.  To do that, set up the Analysis to be "AC-NEW", below that set the Frequency to vary From 10 to 1000k Hz in 10 steps/decade on a Linear scale, and select the source to be Vs1.  For the Graph/Table, simply set it to plot TPv2 against the Left axis.  Since Vs1 is set for an amplitude of 1V, a plot of TPv2 is equivalent to one of Tpv2/Tpv1.

C. Construct the following circuit that is designed to have an AC voltage gain of $(-R_C/R_E)$.
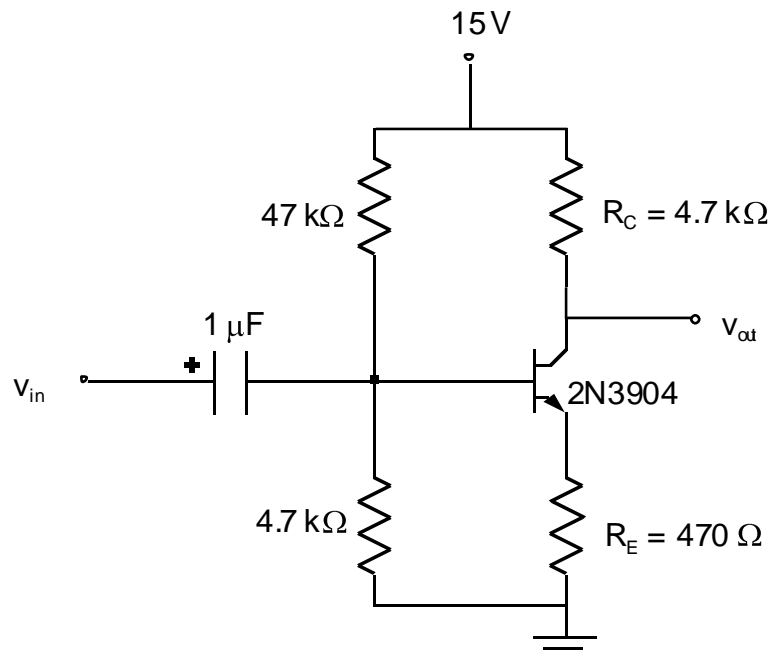


D. Input a sine wave with 0.2 V peak-to-peak. Vary the frequency in decade intervals from 10 Hz to 1 MHz. For each frequency, measure the output voltage (peak-to-peak) and calculate the AC voltage gain (A = $V_{OUT}/V_{IN}$ peak-to-peak).  Note: to disregard the output's DC offset, view it in AC mode.

**Question:** Does the voltage gain depend on the frequency?

To qualitatively understand this, recall that a p-n junction has a charge separation across it like a capacitor. Recall how the impedance of a capacitor depends on the frequency of the signal. At low enough frequencies, the junction's capacitive impedance is significant and affects both amplitude and phase of the output.

**Questions:** In the range where the measured voltage gain is constant, how does its size compare with what is expected (determine the expected value based on the *measured* resistances), what's the % difference? Is the output's phase shift what you expect?

**Questions:** What happens as the input voltage is increased to 2 V peak-to-peak? Why? (Hint: How large would the output voltage have to be if the circuit continued to work as before.)

E. Replace the transistor with a different one and measure the gain using a sine wave with 0.2 V peak-to-peak and 1-kHz frequency as the input.

**Question:** Does this circuit's behavior depend on the exact value of the transistor's current gain?


**5-6.    Darlington Configuration**

F. Construct the following circuit that combines two transistors in a Darlington configuration to give higher current gain. Use the following $R_{in}$ values: 30M, 25M, 20M, 15M, and 10M (we have 15M and 10M resistors, you can achieve the other values by putting some in series.)
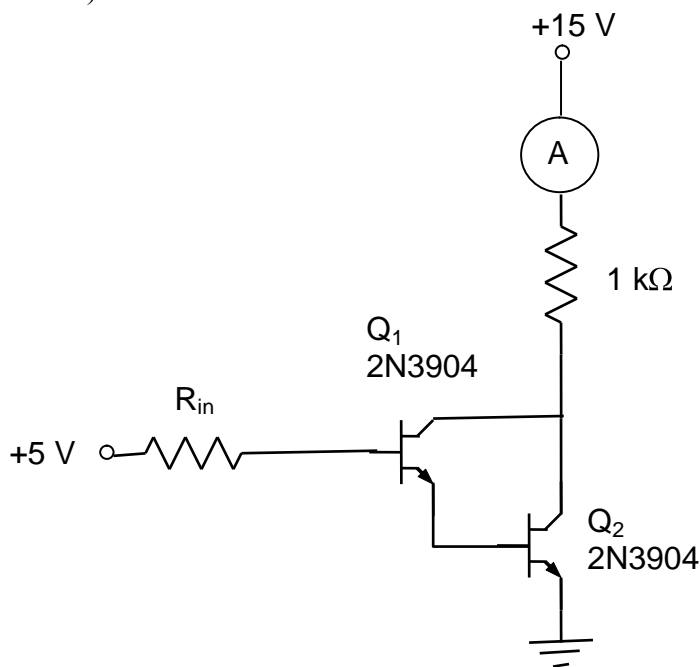


G. For these different input resistances, determine the current gain of the pair which is defined as the ratio of the collector current of $Q_2$ over the base current of $Q_1$. Note that there are two base to emitter voltage drops when calculating the base current of $Q_1$.

**Question:** How does the current gain compare to that of a single transistor?