Lab 8: Transistors I

Prelab

Read the following tutorial: https://learn.sparkfun.com/tutorials/transistors/operation-modes

In this lab you'll be using the transistor as a switch, that is, in either cut-off or saturation mode. What are the conditions for these two modes (give equations and a description)?

To get a feel for how to setup simple transistor circuits, watch this video. NOTE: HE DRAWS ELECTRON FLOW, NOT CONVENTIONAL CURRENT. https://www.youtube.com/watch?v=w9cd7B5QRRo

Why is beta a bad value to use in a design?

Part I: Background

1.1 Symbols and specifications

There are many types of transistors, but for now we'll only be dealing with Bipolar Junction Transistors (BJTs). The schematic symbol is shown in figure 1.

- The arrow indicates the forward bias direction of the Base/Emitter "diode" (PN junction). Thus it also indicates the direction of conventional current when in normal operation.
- The arrow is always[1] drawn on the emitter leg.
- The three lines exiting the circle correspond to the three "legs" of a transistor (as shown in figure 2. These three connections are also referred to as "pins", "terminals" and "leads".
- The circle is often left off the symbol but that difference has no meaning.

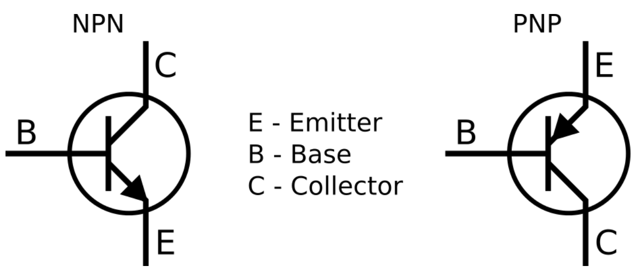

Figure 1: BJT (Bi-polar Junction Transistor) symbols.

Two very common general purpose[2] BJTs are the 2N3904 (NPN type) and 2N3906 (PNP type).

[1] To every symbol rule there exist exceptions.
[2] And quite old, first created in the 1960s.

Note the following conventions

- When voltages have single subscripts, they are referenced to ground, i.e. V_B is the voltage at the base relative to the ground node.
- When voltages have double subscripts with different letters they refer to the voltage difference between those nodes, i.e. V_{BE} is the voltage difference between the base and emitter which will only equal V_B if the emitter is connected to ground.
- When voltages have two identical subscripts they refer to power supply (power rail) voltages. V_{CC} is the supply voltage often connected to the collector, and V_{EE} the (negative) supply voltage often connected to the emitter.
- Voltage with three subscripts are mostly the same as the two letter ones. V_{CBO} refers to the collector-base voltage, but the 'O' indicates that the third terminal is "open" (no current).

Download the datasheets for the 2N3904 and the 2N3906 transistors and ***note down (in a well organized table) the following parameters which will help you keep the magic smoke inside.***

- V_{CBO} - The maximum amount the collector can be higher than the base.
- V_{CEO} - The maximum amount the collector can be higher than the emitter. (Most important when using as a switch.)
- V_{EBO} - The maximum amount the emitter can be higher than the base. (Shouldn't happen if properly biased.)
- I_C - The maximum collector current
- P_{tot} - The maximum power dissipation
- $V_{BE(sat)}$ - The voltage which must be applied to the base to saturate (fully turn on) the transistor
- $V_{CE(sat)}$ - The minimum voltage drop across the collector-emitter when saturated (fully on).

1.2 Pinout and avoiding breakage

Figure 2 shows which physical wires correspond to the emitter, base, and collector for the two transistors you will be using. ALWAYS CHECK THE DATASHEET FOR THE PHYSICAL PINOUT, MANY TRNSISTORS HAVE DIFFERENT PIN LAYOUTS.

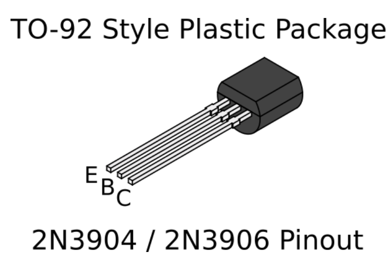

Figure 2: Pinouts for some of the most common through-hole transistors.

Bending the legs of the transistor to better match the breadboard hole spacing is very helpful, but be careful since the legs are prone to breaking off. Reference figure 3 for how to avoid breaking the transistor legs.

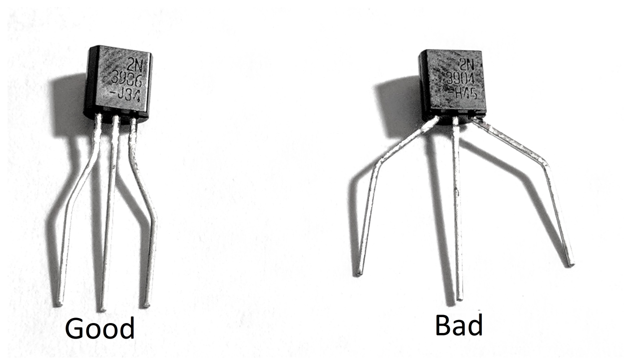

Figure 3: Proper leg bending

1.3 Basic Usage Rules

- NPN Transistors: Current goes from **collector to emitter** when the base is at least 0.6 volts **higher** than the emitter, assuming the collector is at least a few tenths of a volt **higher** than the emitter.
- PNP Transistors: Current goes from **emitter to collector** when the base is at least 0.6 volts **lower** than the emitter, assuming the collector is at least a few tenths of a volt **lower** than the emitter.

1.4 Diode model and testing

In some ways a transistor behaves like two diodes as shown in figure 4. ***Use your multimeter in diode test mode to measure the base-emitter and base-collector voltage drop for both the NPN 2N3904 and the PNP 2N3906 transistors. For each transistor, which voltage drop is larger, V_{BE} or V_{BC}?***

If you think a transistor has lost its magic smoke, use this test to check. If this test is passed then it is almost certain that the transistor is fine.

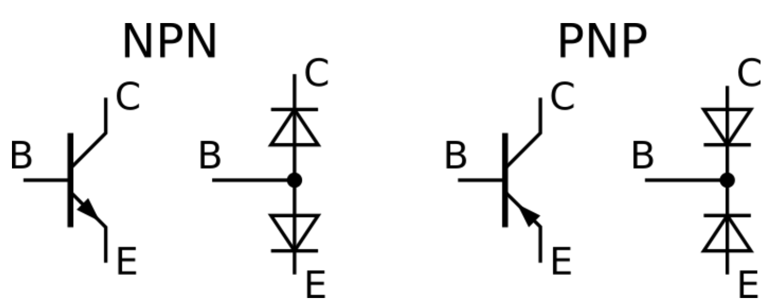

Figure 4: Diode model of a transistor

Part II: Transistor Characterization

2.1 NPN

To better understand the various aspects of transistor behavior you will slowly turn on a transistor while measuring the base current, the collector current, and the base-emitter voltage. The circuit is shown in figure 5.

1. V1 should be the HP/Agilent power supply with the current limit set to 100 mA.
2. Use the 5 volt rail on your breadboard for the 5 volt supply.
3. Using Ohm's law calculate the value for R1 to set the max collector-emitter current to 100 mA, assuming zero collector-emitter voltage drop. Check what power will be dissipated by a resistor of this value. Is the value less than or equal to 0.25 Watts? If not, use multiple higher value resistors in parallel such that no single resistor has to dissipate more than 0.25 Watts.
4. Set the base multimeter to microamp mode and the collector multimeter to milliamp mode.
5. Since you don't have a third multimeter, use your oscilloscope to measure the base-emitter voltage. Reset the scope with DEFAULT SETUP. Be sure your probe and scope are in 10X mode and display the mean value in the MEASURE menu. You may find that spontaneous oscillations in the signal will occur which you will be able to see on the scope as a large amount of noise. If this happens, connect a small capacitor (try .1 μF) in parallel with the collector and emitter.[3]
6. In a spreadsheet, record the base and collector currents for base-emitter voltages of approximately 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, and 0.9 volts. (Of course record the actual voltages at which you perform the measurements.) USE THE SCOPE, IGNORE THE POWER SUPPLY VOLTAGE READOUT.

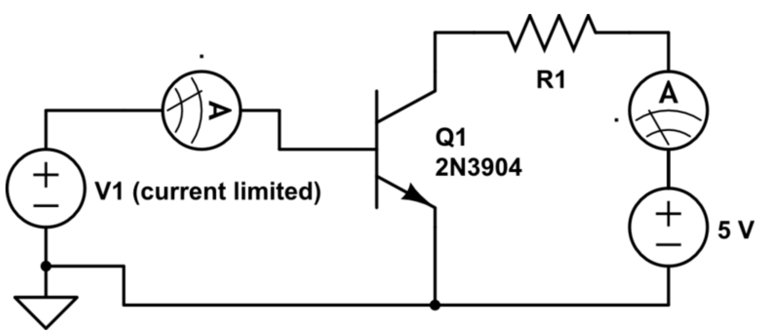

Figure 5: A 'low side' switch. When turned on, one side of the load is pulled to ground through the transistor.

- Create a plot of collector current as a function of base voltage. The is effectively the same plot as the one you made last week with a diode (also a forward biased PN junction). Explain the differences you see. Specifically, what value is this plot approaching and why?

[3]These oscillations are due to the stray inductance in the wires and the effective capacitance of the depletion region in the transistor forming an LC resonator.

- Create a plot of collector current as a function of base current and set the x-axis to be logarithmic.
- For each data point, calculate beta[4] ($\beta = I_c/I_B$). What range of values did you obtain (ignore the lowest two which were due to the current limiting of the resistor)? How does that range compare to the range of possible values indicated in the datasheet?

2.2 PNP

The setup for a PNP transistor is a bit different since the emitter is no longer connected to ground which makes it tricker to force a specific voltage across it. The load is now connected directly to ground and turning the transistor 'on' will connect the other side of the load to 5 volts. **You must use the HP/Agilent power supply in FLOATING mode, that is, DON'T connect 'common' to circuit ground.** Construct the circuit shown in figure 6 using the same current limit setting and the same current limiting resistors as in the previous section.

When V1 is set to 0 volts, the transistor should be off and the base will be at 5 volts. Increasing the voltage difference created by the power supply will pull the base lower than the emitter, turning the transistor on.

To measure the base-emitter voltage you will need to connect one scope probe to the base and a second probe to the emitter. Use the measure menu to display the mean value of each. The emitter voltage should stay very close to 5 volts, but there will be some minor variations. Once you have checked that your circuit works, start the base at about 4.5 volts (as read out on the scope) and decrease the voltage incrementally, taking similar data to the prior section. IGNORE THE VOLTAGE READOUT ON THE POWER SUPPLY, USE THE NUMBERS ON THE SCOPE.

Perform the same analysis as in the prior section (plots, calculations, etc...).

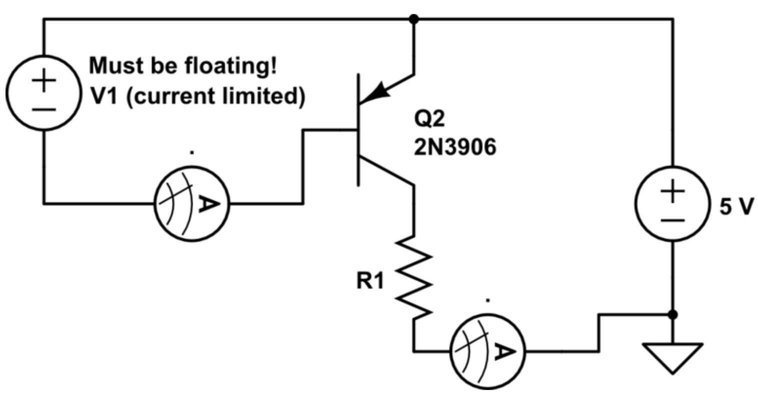

Figure 6: A 'high side' switch. When turned on, one side of the load is pulled to 5 volts through the transistor.

[4]Also called h_{fe}.

Part III: A Simple Night Light

In this section you will gain practice determining the appropriate values for the components in a circuit. Pay close attention to the steps and your circuit might even work on the first try. **All calculations and results must be shown in your report.**

The circuit shown in figure 8 behaves as an automatic night light, turning on as reduced light changes the resistance of the photoresistor, R2. You will need some supplies from the SparkFun Arduino Kits, MAKE SURE YOU RETURN THOSE PARTS TO THE KIT.

Obtain the following items from a SparkFun kit.

- LED (color of your choosing)
- photoresistor (check page 12 of the guide book for a photo)

3.1 LEDs

LEDs (Light Emitting Diodes) behave just like a 'normal' diode, except they emit light. Different color LEDs turn on at different voltages, varying from around 1.7 to 3.5 volts. The low voltage side can be identified by looking for the flat side as shown in figure 7 (think of the flat side like a minus sign). To work they must be connected in the proper orientation!

1. Most standard LEDs can handle a few tens of mA. Set your power supply current limit to 20 mA and connect to the LED.
2. Raise the voltage until reaching the full 20 mA and record this value as the LED voltage drop, V_{LED}.
3. Normally a resistor is used in series with an LED to limit the current. When the transistor is turned fully on, the 5 volt source will drop across R3, the LED and the collector-emitter junction. Find the voltage drop across the resistor by subtracting V_{LED} and $V_{CE(sat)}$ from the 5 volts. Call this V_{R3}.
4. Using the desired current value, and the voltage value you just found, calculate the appropriate resistor value. Choose the next highest real world value available to you.
5. The resistors you are using are quarter watt resistors. Using the values you have, check what the power dissipation will be in R3. If it is too high, use multiple larger value resistors in parallel.

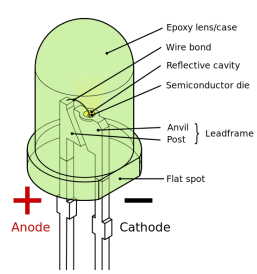

Figure 7: Anatomy of an LED

3.2 Voltage Divider

You will be using the voltage divider formed from R1 and R2 to set the base voltage. The resistance of R2 changes depending on the amount of light incident on it, thus changing the output voltage. Note that you can use the no load voltage divider formula as a good approximation since the transistor base will be drawing such a small amount of current.

1. Measure the resistance of the photoresistor when in normal lighting conditions and record this value as R2(light). Cover it with your the shadow from your hand and record the value as R2(dark). Is the resistance directly or inversely proportional to the light level?
2. When the room is light the transistor should prevent current flow to keep the LED off, which means the base voltage should be safely below 0.6 volts. But the voltage also shouldn't be too close to zero or else the transistor won't turn on very well. Aiming at 0.4 volts is a good compromise. Using the voltage divider equation, calculate the value of R1 using $V_{in} = 5V$, $V_{out} = 0.4V$, and the value for R2(light). Choose the closest real world value (higher or lower).
3. Now check that this will also work to turn the transistor on when the photoresistor is covered. Use the voltage divider equation to calculate the output voltage when R2 is equal to R2(dark). This should be above 1 volt to work well.

3.3 Putting it all together

Now that you have values for all the components. Build the circuit as shown in figure 8 check that it works. Take a moment to bask in the glory of your success. Try to control the brightness of the LED with the shadow of your hand.

- Measure the base-emitter voltage in the light (led off) and dark (led on) conditions. How do they compare to what you calculated as the output of the voltage divider in the prior section? Why aim for the "on" base voltage to be above 1 volt? Discuss and explain the result.
- Measure the collector-emitter voltage when the LED is on. Is the transistor in saturation? By covering the photoresistor even more, what is the smallest V_{CE} you are able to achieve?

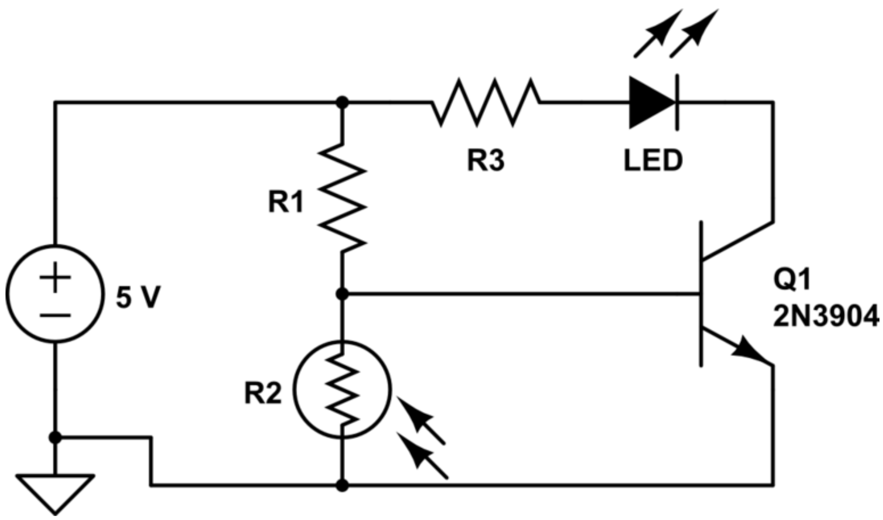

Figure 8: Automatic night light circuit