CircuitLab, Diodes, & Transistors

Introduction

In ECE 401, you can choose from a dozen different circuits to build. Regardless of which one you select, your overall design:

- Must operate at 5VDC
- Must have LEDs operating at 20mA +/- 5mA
- Must have one NPN and one PNP transistor (or more), capable of driving a 100mA load
- Must have at least one IC (PIC18F2620, MCP602 op-amp, 555 timer)

This lecture covers:

- Analysis and design of LED circuits,
- Analysis and design or NPN and PNP electronic switches,
- Analysis and design of a comparitor, and
- Analysis and design on 555 timers

CircuitLab

CircuitLab is a circuit simulator, which is very similar to SPICE or PSPICE, and has a graphical front end. The graphical front end makes CircuitLab very easy to use.

What CircuitLab does is it lets you check your design using a nonlinear circuit simulator. Typically, hand calculations make some approximations, such as diodes are ideal, op-amps are ideal, loading is insignificant, etc. With CircuitLab, you can test your design with a more accurate, more complex model. If you need to tweak your design slightly, it's really easy in CircuitLab.

Once you finalize your circuits, you can then build them on a breadboard to see if they really work in practice.

CircuitLab is capable of simulating

- Linear Circuits (Circuits II and II)
- Nonlinear Circuits (Electronics)
- Digital Circuits (Digital Systems)
- Dynamic Systems (Controls Systems)

Likewise, it's useful for many courses in ECE, including Senior Design.

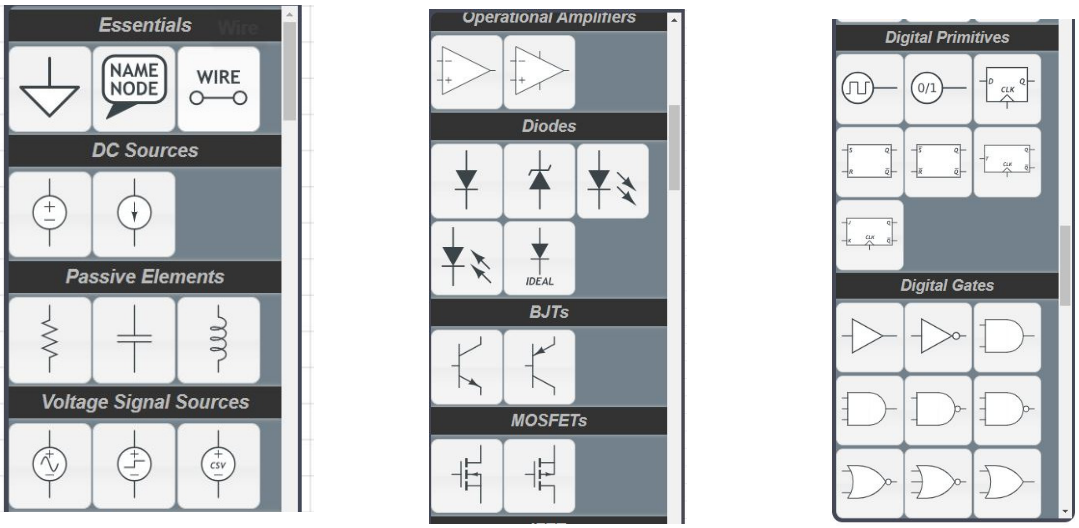
Signing Up for CircuitLab

There are several ways you can use CircuitLab:

- Trial Version: If you don't register or sign in, you're using the trial version. This limits you to 1/2 hour per session and you cannot save your work.
- Free Version: Register with CircuitLab using your NDSU email address (@ndsu.edu). The ECE department pays for a site license - so all NDSU students can use CircuitLab for free. There is no time limit and you can save your work.

- Personal Version: Sign up with your personal email account at a cost of $24/year. Again, there is no time limit and you can save your work. Plus, you still have your work after you graduate.

CircuitLab has components useful for linear circuits (left), nonlinear circuits (center), and digital circuits (right)



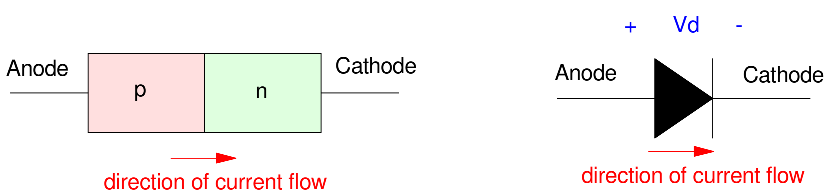
We'll cover some of the ways to use CircuitLab in upcoming examples...

Diodes

A diode is a semiconductor device made up of a pn junction (covered in ECE 320 Electronics I). Diodes act as valves:

- Current can flow from the anode to the cathode,
- Current is blocked if it tries to flow from the cathode to the anode.

Because of this, the symbol for a diode looks like an arrow: this arrow serves as a reminder for which way the current can flow.

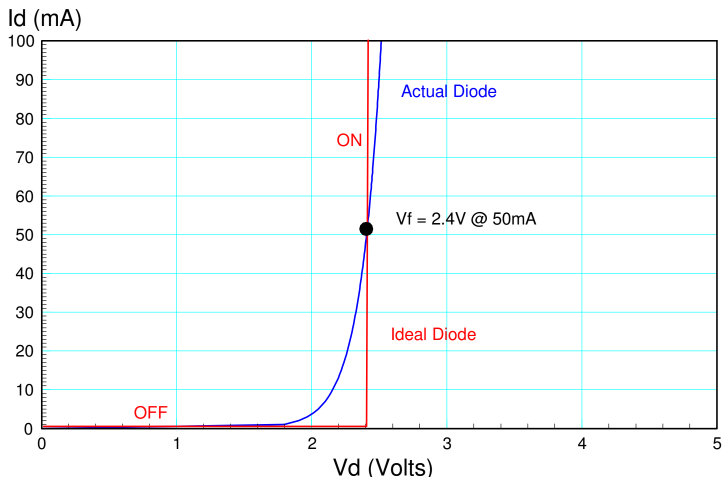


Symbold for a diode: Diodes only allow current to flow from the anode to the cathode

The VI characteristics of diodes are highly nonlinear. This makes analysis of diode circuits very difficult. To simplify circuit analysis. *ideal diode* models are usually used. This model approximates the nonlinear charaterictic with two linear models:

- Id = 0 when Vd < Vf
- Vd = Vf when Id > 0

While not perfect, the ideal diode model usually gives results which are close enough for most purposes. For more accurate results, nonlinear circuit simulators, such as CircuitLab, can be used.



To simplify circuit analysis, the nonlinear diode VI characteristics (blue) are replacd with an ideal diode model (red)

Vf acts like a turn-on voltage:

- If you try to apply more than Vf volts across the diode, it turns on.
- If you apply less than Vf volts across the diode, it turns off.

The value of Vf depends upon the diode. Some typical values are:

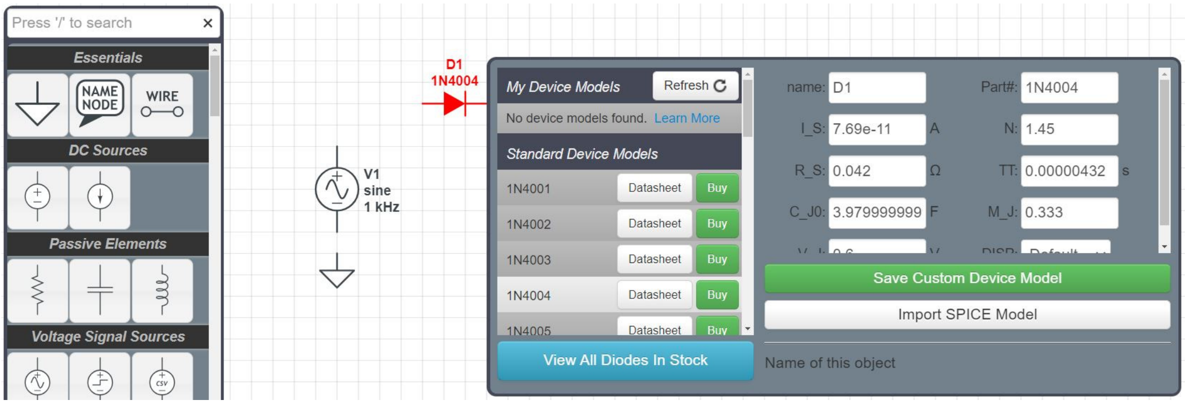
- Germanium Diode: Vf = 0.3V
- Silicon Diode: Vf = 0.7V
- Red LED: Vf = 1.9V
- Yellow LED: Vf = 2.0V
- Green LED: Vf = 2.0V

For example, take the following circuit: a source driving a 1k resistor through a diode.

In CircuitLab, you can build this circuit through drag and drop.

- R rotates the element
- Double Click to change values
- k = 1000
- M = million
- m = milli
- u = micro

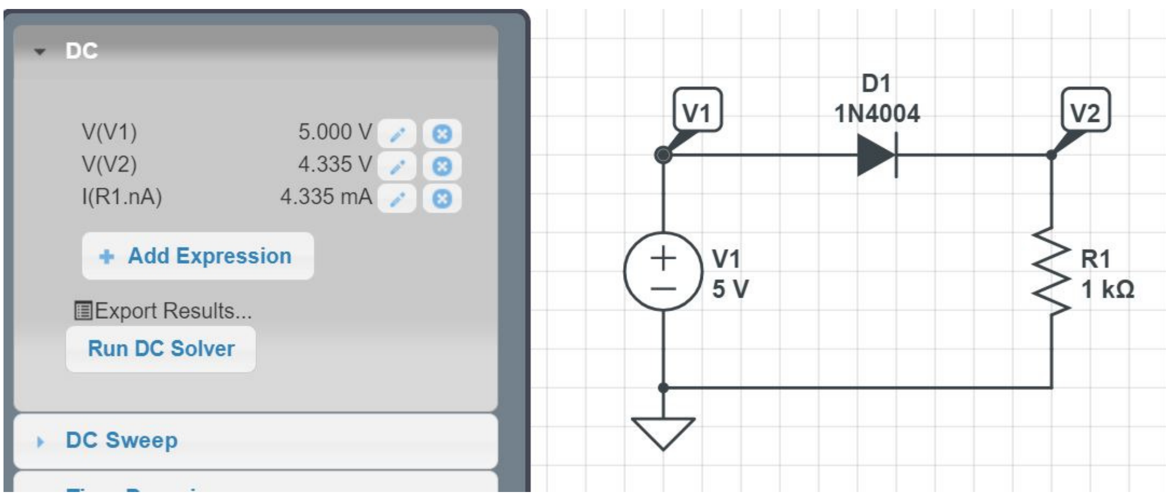
Make sure you have a ground (CircuitLab insists on this)



CircuitLab: Double Click to change a component

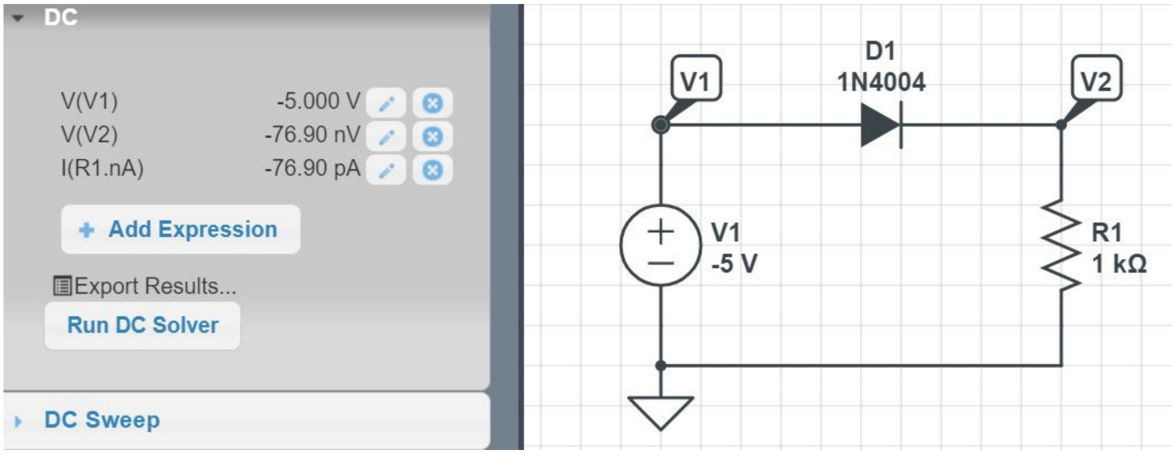
Once completed, you can determine the voltages and currents by

- Clicking on Add Expression and then click on the voltage node to see that voltage
- Click on one side of a resistor to see the current through that resistor:



DC Analysis in CircuitLab: Diode D1 turns on and has a 0.7V drop across it (roughly).

As expected, the diode is turned on with a 0.7V drop across it (approimately). If you apply -5V incread, the diode turns of and the current is approximately zero:



The diode turns off when you try to push current backwards through the diode

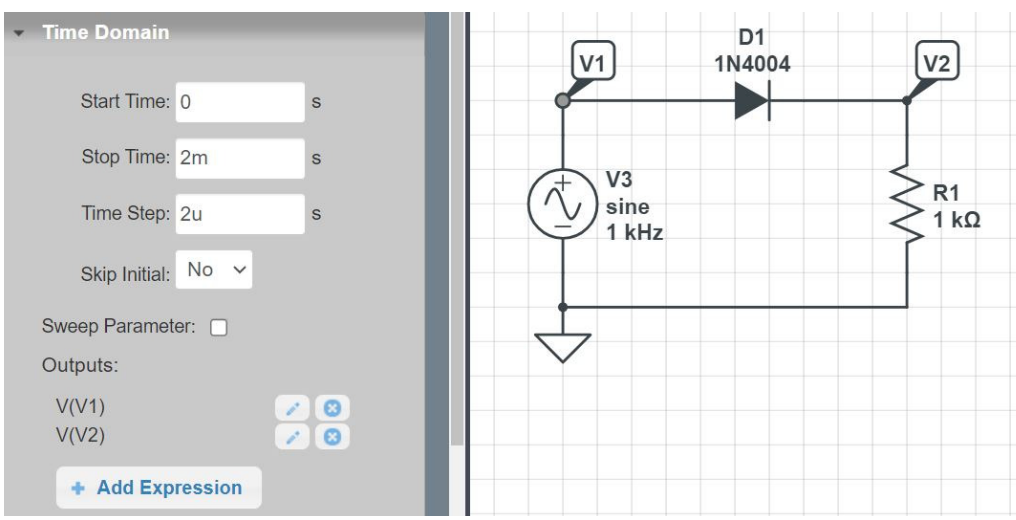
Note that when V1 is less than 0.7V,

- The diode turns off
- V2 = 0V (approximately), and
- I = 0 (approximately).

Diodes *do* allow some current when reverse biased, 76.9pA in this case. In this class were we deal with mA, that current is negligible.

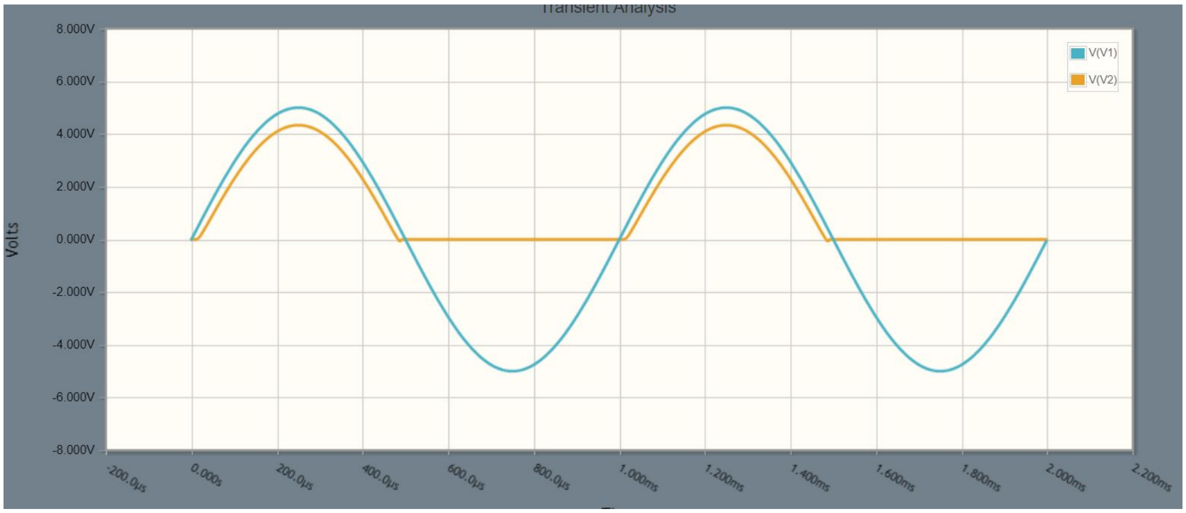
Another way to see diodes acting like a valve is to make V1 a 5Vp sine wave. In CircuitLab, if you run an AC transient simulation, you can see the voltage at V2 (similar to what you'd see on an oscilloscope). To do this

- Specify the start and stop time. For a 1kHz sine wave, 2ms cover two cycles
- Specify the time step. I usually make this 1000x smaller than the stop time, giving 1000 points



Time-Domain Simulation in CircuitLab

When you press Run Time-Domain Similation, a graph appears showing the voltages:



Result of a Time-Domain Simulation

Note:

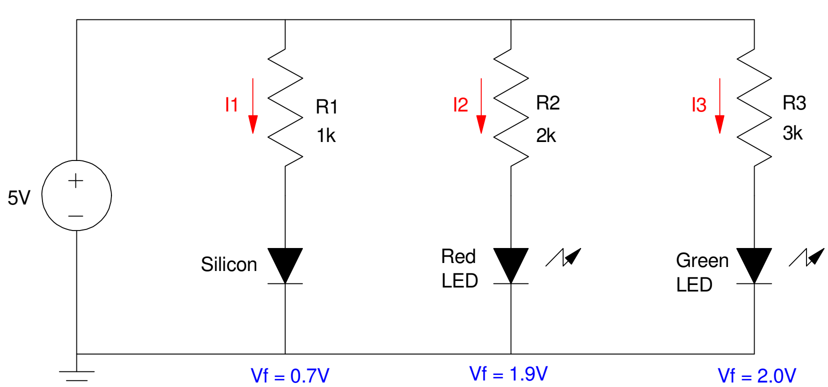
- There is a lot more information in a graph than a number (oscilloscopes tell you more than multimeters)
- When V1 > 0.7V (ish), the diode turns on and V2 = V1 - 0.7
- When V1 < 0.7V, the diode turns off and V2 = 0 (ish)

The diode is acting like a valve.

Diode Circuit Analysis: To analyze a circuit with a diode, you first have to determine whether the diode is on or off. This can be a bit of guesswork. If you guess correctly, the circuit will work, meaning

- Diodes which are on have Id > 0, and
- Diodes which are off have Vd < Vf

For example, determine the current through each diode for the following circuit:



Diode Circuit: Determine the current in each diode

In this case, the diodes have to be on since 5V > Vf for each diode. So, assume they are on.

The current can then be found as

$$I_1 = \left(\frac{5V - 0.7V}{1k}\right) = 4.3mA$$

$$I_2 = \left(\frac{5V - 1.9V}{2k}\right) = 1.55mA$$

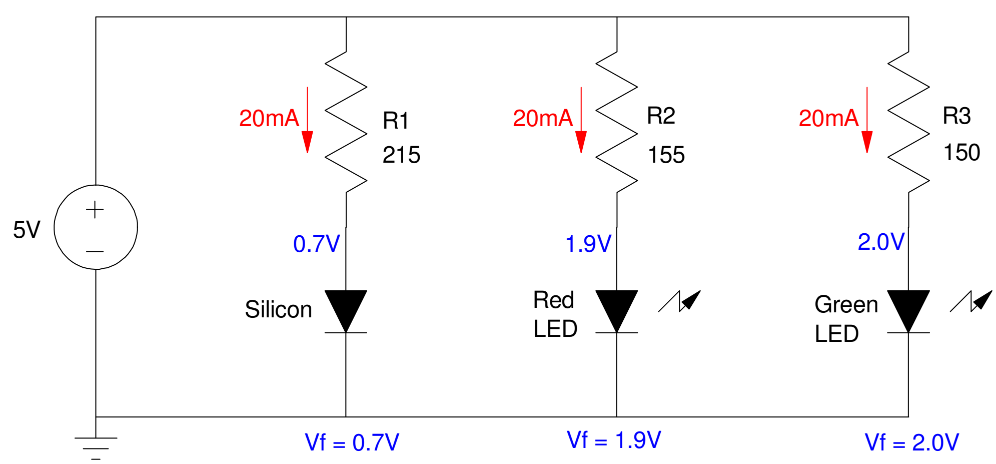
$$I_3 = \left(\frac{5V - 2.0V}{3k}\right) = 1.00mA$$

Diode Circuit Design: If you want to change the current through the diodes, change the resistor connected to it. For example, to set all three currents to 20mA

$$R_1 = \left(\frac{5V - 0.7V}{20mA}\right) = 215\Omega$$

$$R_2 = \left(\frac{5V - 1.9V}{20mA}\right) = 155\Omega$$

$$R_3 = \left(\frac{5V - 2.0V}{20mA}\right) = 150\Omega$$



Resistors adjusted so that 20mA flows through each diode

Light Emitting Diodes (LEDs)

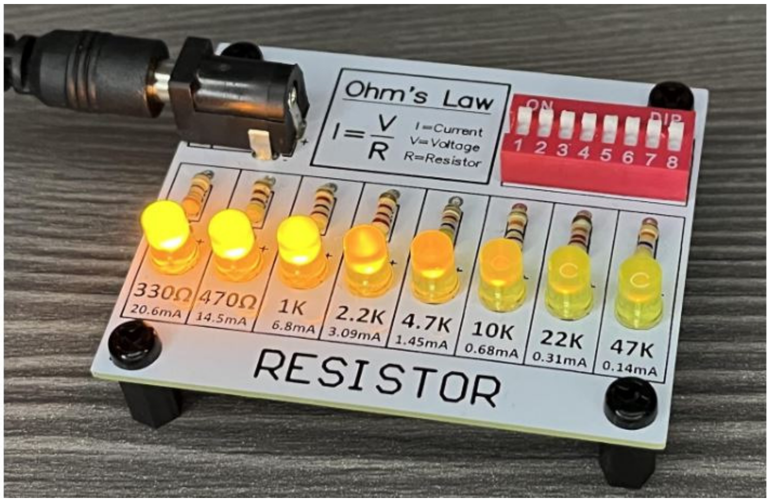
LEDs are nothing more than diodes - except that they produce light proportional to the current flowing through them. As diodes, they can be approximated with an ideal-diode model:

- Id = 0 if Vd < Vf
- Vd = Vf if Id > 0

The on-voltage (Vf) depends upon the diode and is usually specified in the diode's data sheets:

LED	Vf	mcd	Wavelength	Cost	Digikey PN
Red	1.9V @ 20mA	30mcd @ 20mA	645nm	$0.13	732-5016-ND
Yellow	2.0V @ 20mA	450mcd @ 20mA	592nm	$0.18	732-5018-ND
Green	2.1V @ 20mA	140mcd @ 20mA	572nm	$0.21	732-5017-ND

The brightness of an LED is proportional to the current flowing through the diode: if you halve the current, you halve the brightness. For example, the following solding kit from Amazon varies the current (and brightness) of each diode by varying the resistor connected to the diode



LED Soldering Kit from Amazon

Assuming a 9V source (the kit assume you're using a 9V battery). the current and brightness of the first diode (330 Ohms) is:

$$I = \left(\frac{9V - 2.0V}{330\Omega}\right) = 21.21mA$$

The brightness is then proportional to this current where 20mA = 450mcd:

$$\left(\frac{21.21mA}{20mA}\right) 450mcd = 477.2mcd$$

Diodes & Voltage Regulation

In ECE 401,

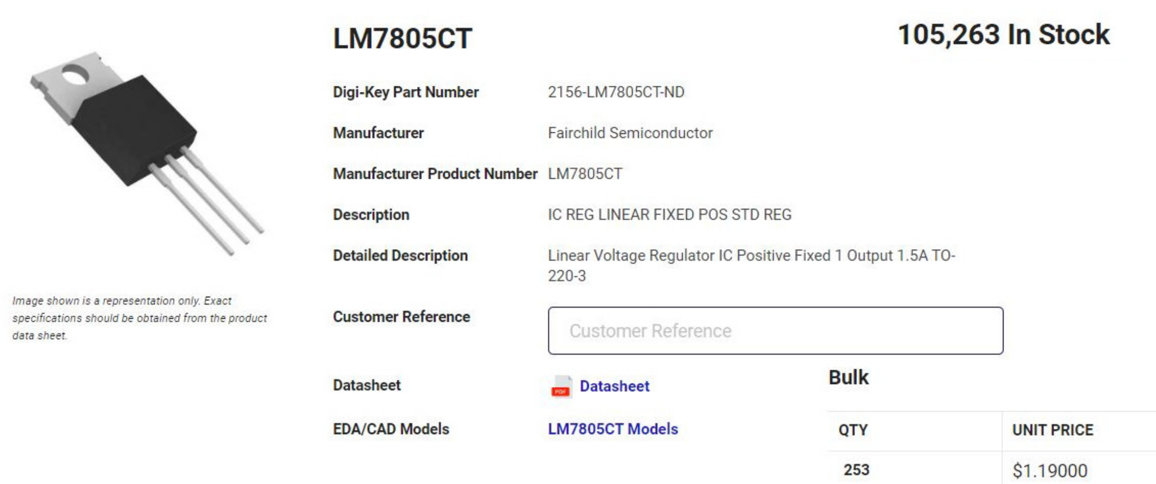
- Power to your PCB comes from a 9V battery, while
- Your components on your PCB operate off of 5VDC.

This creates a problem: how to generate 5VDC, capable of driving 100mA, using a 9V battery.

There are several ways to convert 9VDC to 5VDC. You could use

- A 7805SR Buck Converter: ($13, >90% efficient), or
- An LM7805 Voltage Regulator ($1.19, 55% efficient), or
- Many other IC's.

For ECE 401, we'll be using an LM7805 because they work, they're fairly inexpensive, and the power used in the circuits in this class are low enough that we don't worry too much about being only 55% efficient.



LM7805 Voltage Regulator from Digikey. These ICs are fairly inexpensive and available.

If you look at the data sheets for a LM7805, you can pull out the limits of this IC:

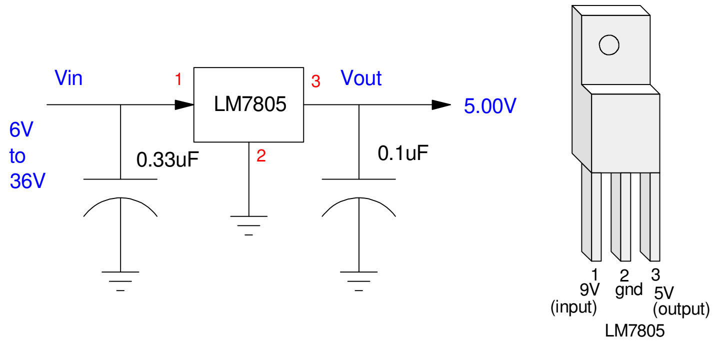
- Output Voltage: 4.80V to 5.20V with 1A load
- Peak Current: 2.2A
- Max continuous current: 1A
- Input voltage range: 7V to 36V
- Quiescent Current: < 8mA

What this tells you is

- The LM7805 will operate just fine with a 9V battery,

- It needs less than 8mA to operate, and
- It can drive a 5V load with up to 1A of current

The recommended configuration for a LM7805 is to connect a capacitor at the input (9V) and output (5V). Other than that, they're pretty easy to get to work.



Wiring for an LM7805 Voltage Regulator

For example, suppose you want to

- Convert 9V down to 5V, and
- Drive an LED at 10mA from the 5V source

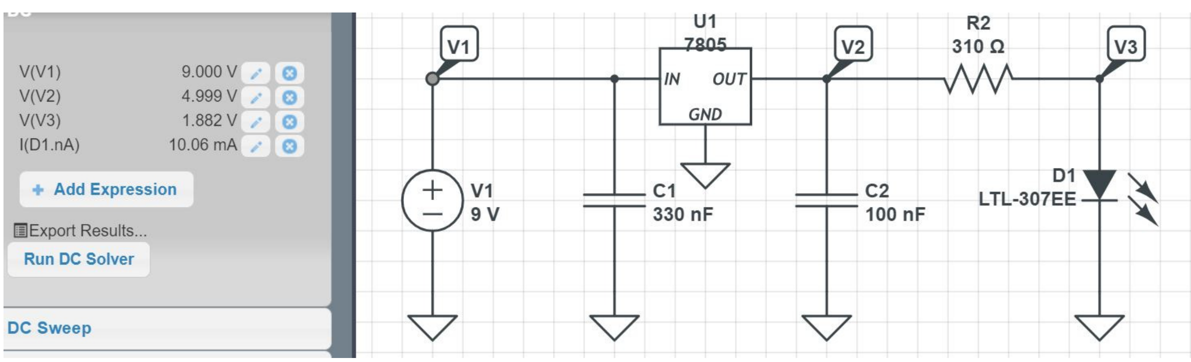
Assuming the LED has a 1.9V drop across it (ideal red LED), the resistor should be 310 Ohms

$$R = \left(\frac{5V - 1.9V}{10mA}\right) = 310\Omega$$

Checking in CircuitLab:

- V2 = 5V (close), meaning the 7805 is doing its job
- V3 = 1.9V (close), meaning the red LED is on, and
- I3 = 10mA (close), meaning R2 is correct

You could find tune R2 if you really want 10.00mA exactly.



Converting 9V to 5V using a LM7805 in CircuitLab

A limitation of the LM7805 is its efficiency

- The input current is the same as the output current, plus 8mA to operate the LM7805
- The way the LM7805 works is it dumps voltage. If the input is 9V, the 7805 will dump 4V to produce a 5V output.

This means, assuming the load draws 100mA

- The output power is 500mA (5V * 100mA)
- The input power is 900mW (9V * 100mA)

The efficiency is then

$$\eta = \left(\frac{\text{output power}}{\text{input power}}\right) = \left(\frac{500mW}{900mW}\right) = 55\%$$

It's actually a little less that this since the LM7805 draws some current for its own operation (less than 8mA).

You can buy voltage regulators with higher efficiencies, such as a 7805SR Buck Converter, but these are $13 each.

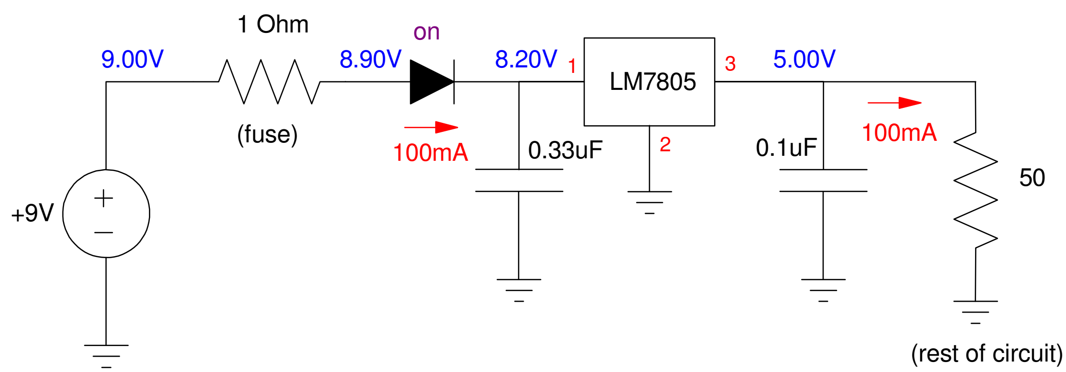
Reverse Polarity Protection & Overcurrent Protection

Another requirement for your PCB in ECE 401 is to add

- Reverse polarity protection (connecting 9V to your PCB backwards will not fry your PCB), and
- Overcurrent protection (if your circuit draws too much current, a fuse blows).

There are several ways to do this.

Method #1: Diode + Fuse. Diodes do not allow current to flow backwards. If you place a diode in series with your 9V battery, the diode will turn off if the 9V battery is inserted backwards.



One method of providing reverse polarity protection: add a diode in series with the 9V power supply.
note: The 50 Ohm resistor models the rest of your circuit - it isn't included in your actual design.

A disadvantage of this approach is you lose 0.7V through the diode. That's not a major issue here since you're going to dump 4V somewhere to bring 9V down to 5V. The diode just means the LM7805 now only has to dump 3.3V.

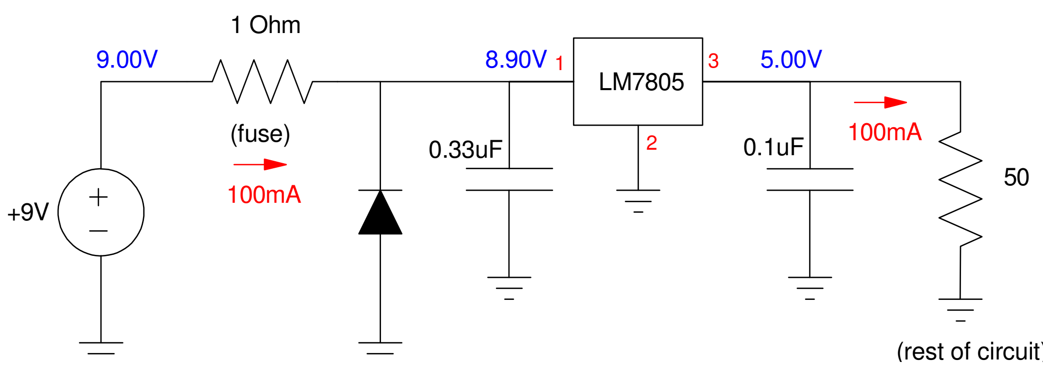
Adding a fuse in series with the 9V supply also protects your circuit from overcurrent: if your circuit tries to draw too much current, the fuse will blow.

In ECE 401, we use a 1 Ohm resistor instead of a fuse since they cost less than 2 cents each.

Method #2: Fuse + Diode.

A second approach is to use a fuse along with a diode.

- If the 9V battery is connected correctly, the diode remains off. The circuit operates as normal.
- If the 9V battery is reversed,
  - The diode turns on, limiting the voltage to the LM7805 to -0.7V,
  - The current through the fuse becomes large (9A), blowing the fuse.



A second method of providing reverse polarity protection and overcurrent protection.

Either circuit works for our application. In ECE 401, you can use either one.

note: The 50 Ohm resistor models the rest of your circuit in ECE 401, assuming your overall circuit draws 100mA. When you build your breadboard and PCB, replace the 50 Ohm resistor with your actual circuit.

BJT Transistors

Many of the electronic devices we use in ECE 401 have current outputs which are limited to 25mA. This includes

- PIC microcontrollers
- 555 timers
- MCP602 op-amps
- LM833 op-amps

What this means is

- If you are driving a load which needs less than 25mA, you can connect that load directly to these devices using a resistor.
- If, however, you need more than 25mA, you need to use a buffer circuit which amplifies the current. A BJT transistor is one way to do this.

BJT transistors act as

- Electronic switches (you can turn a device on and off using 0V & 5V),
- Which amplify current (1mA can turn on and off a device which draws 100mA)

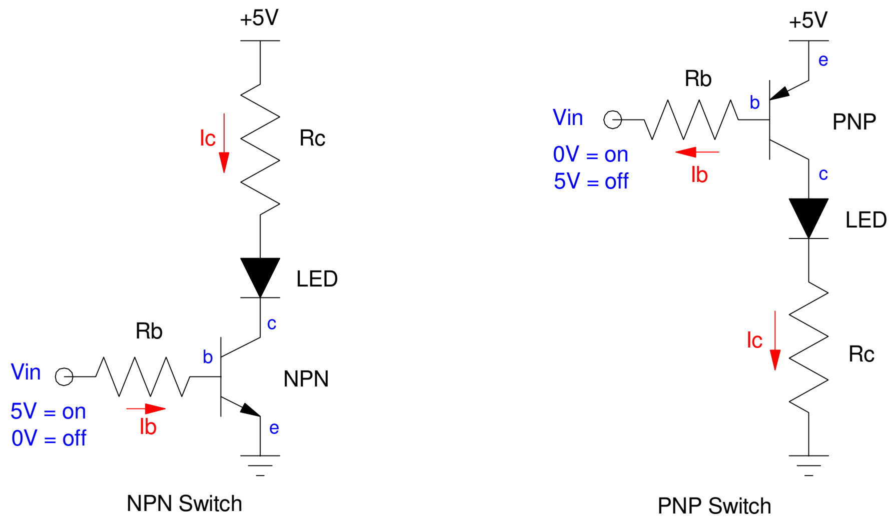
The current amplification and the maximum current a given BJT transistor can handle depends upon which transistor you're using. The specs for the ones used in ECE 401 are as follows:

Spec	3904 NPN	3906 PNP
Current Gain (min)	100	100
Max Current	200mA	200mA
|Vbe| (on)	0.7V	0.7V
|Vce| (sat)	0.2V	0.2V
Cost (ea)	$0.11	$0.11

Two types of BJT transistors exist:

- PNP: an electronic switch which connects your device to +5V, or
- NPN: an electronic switch which connects your device to ground.

The basic circuit for each of these are as follows:



BJT Switch: Either NPN or PNP transistors can be used.
NPN transistors act as a switch to ground, PNP transistors act as a switch to power

With the transistors, the arrow going between the base and the emitter is all important:

- The arrow represents a diode (a pn junction), telling you which way the current can flow
- The base current controls the current from the collector to the emitter.

Due to the way the transistor is made, the transistor tries to set Ic according to Ib by the current gain:

$$I_c = \beta I_b = 100 I_b$$

The transistor does this by dumping whatever voltage is necessary to set the current.

A good way to see how a transistor switch operates is to look at the load line for the transsitor. Assume that Rc is selected so that Ic = 20mA when Vce = 0V. Then, the load line will look like the following:

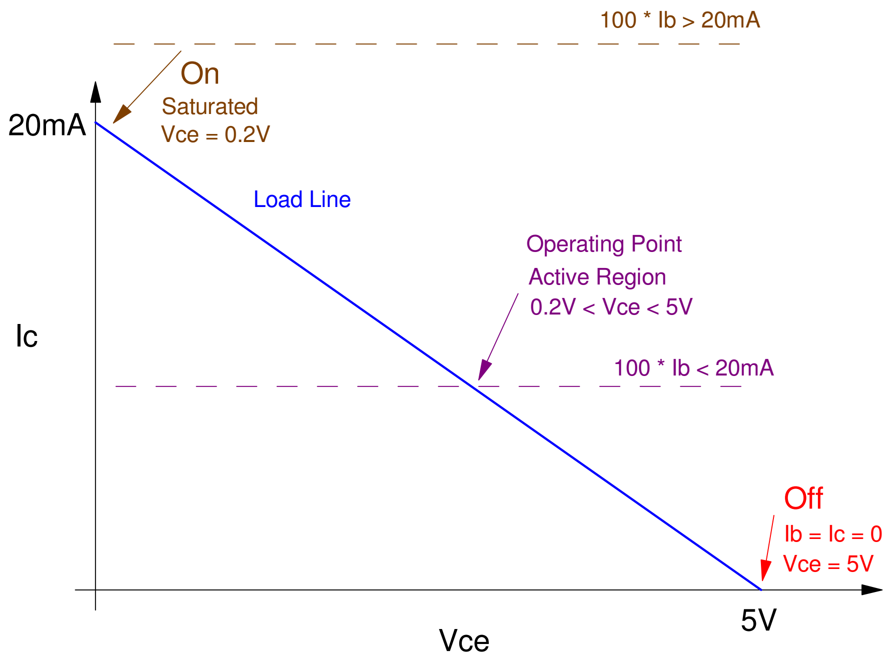
- When Ic = 0mA, Vce = 5V (the x-axis intercept)
- When Vce = 0V, Ic = 20mA (the y-axis intercept)
- The line connecting these two points is called *the load line.*

Any solution has to be on the load line somewhere.

When Ib = 0 (there is no current through the diode connecting the base and the emitter)

- Ic = 0
- Vce = 5V, and
- The transistor is off.

With no current flow, the diode is off.



Load Line for an NPN transistor switch
You want to operate either in the Off state or the On state (saturated)

As Ib increases,

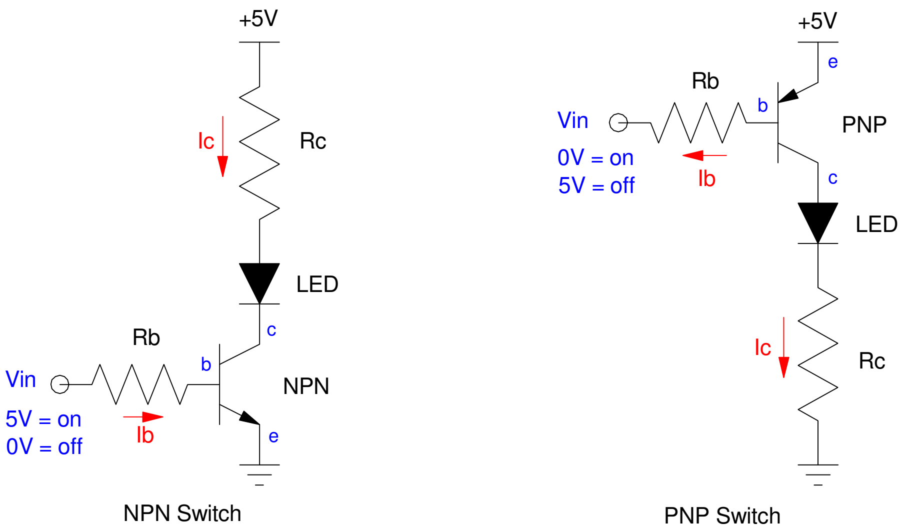
- Ic increases increases according to the current gain (Ic = 100 Ib),
- Vce drops from 5V down to 0.2V, and
- The transistor gets hot (P = V*I)

The way the transistor sets the current Ic is by dumping voltage (Vce). This places the transistor in the active region - and the transistor gets hot (P = V*I > 0). You want to avoid this when using a transistor as a switch.

If Ib is large enough that 100 Ib > 20mA, the transistor saturates:

- Vce saturates at its minimum value (0.2V), and
- Ic saturated at its maximum value (a little less than 20mA).
- The transistor is in the On state (saturated)

Analysis of Transistor Switches: In terms of analysis, the currents and voltages are as follows (same equations for both PNP and NPN):



Analysis: Find the voltages and currents

The off state is kind of a gimme: the currents are zero.

For the on-state, assume the transistor is saturated

$$V_{ce} = 200mV$$

$$I_c = \left(\frac{5V - V_f - V_{ce}}{R_c}\right)$$

$$I_b = \left(\frac{5V - 0.7V}{R_b}\right)$$

The check to see that the transistor is saturated is the current you allow (100 Ib) must be more than the current you need (Ic)

$$\beta I_b > I_c$$

$$I_b > \left(\frac{I_c}{100}\right)$$

Note that diodes and transistors are not ideal - meaning that the measured values will be slightly different from what you calculated. This show up in CircuitLab as well as in hardware.

For example, assume

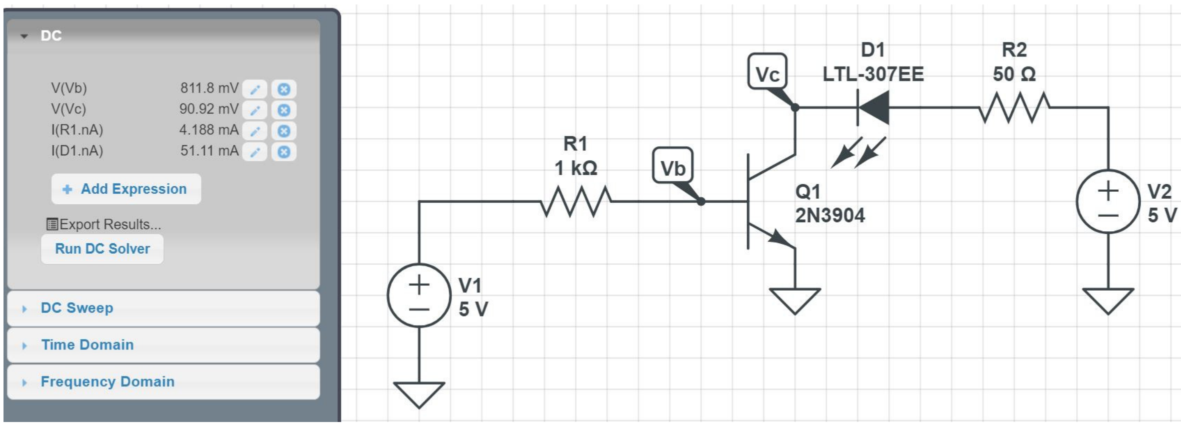
- Rc = 50 Ohms
- Rb = 1k Ohms
- Vf = 1.9V (red LED)
- 3904 NPN transistor with a current gain of 100

What you expect when Vin = 5V is

- Vb = 0.7V *the drop across a silicon diode*
- Vc = 0.2V *saturated*
- Ic = 58.0mA

$$I_c = \left(\frac{5V - 1.9V - 0.2V}{50\Omega}\right) = 58.0mA$$

In CircuitLab, what you get is close but slightly different:



NPN Switch Simulation in CircuitLab

What these numbers tell you is:

- Vb = 0.8118V: Q1 is a silicon transistor with Vf = 0.7V (ish)
- Vc = 0.0909V: Q1 is saturated with Vce = 0.2V (ish).
- I(D1) = 51.11mA: Close to 58.0mA but a little off due to the LED's voltage drop being a little different from 1.9V

Ideally, Vce = 0V when the switch is closed. NPN transisors are not ideal, however, so Vce will be close to zero but not quite zero. This switch should work as long as

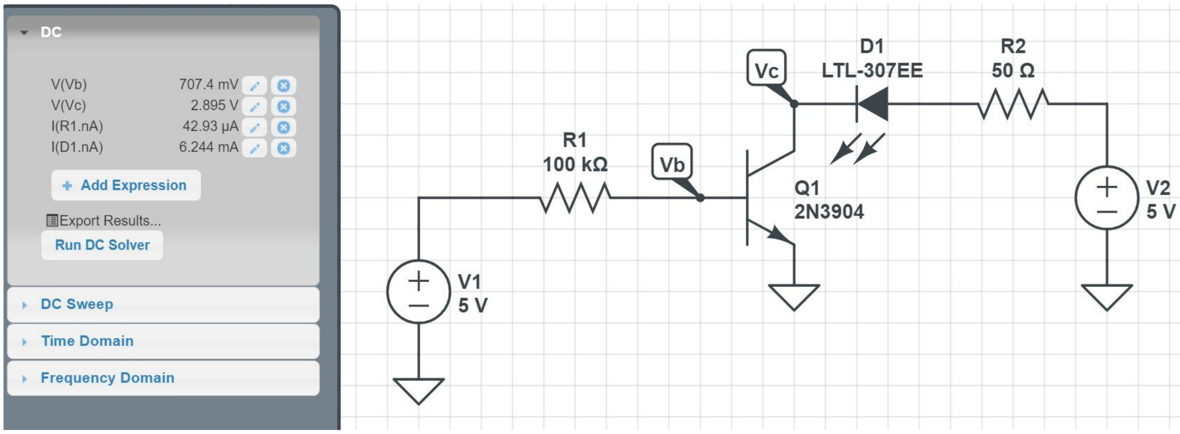
$$\beta I_b > I_c$$

$$100 \cdot 4.188mA > I_c$$

$$I_c < 418.8mA$$

As show, this switch should be able to turn on and off any load as long as it draws less than 418.8mA (ignoring the 200mA current limit of a 2N3904 transistor that is...)

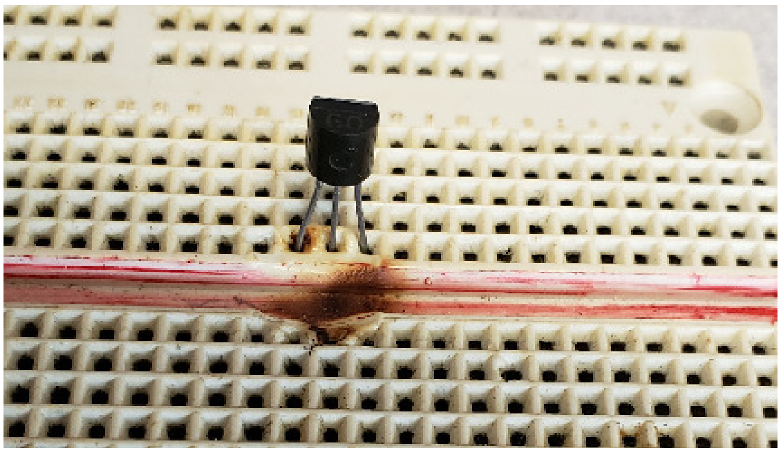
If R1 is increased to 100k, then this switch should work for Ic < 4.188mA. Since we're pushing more than that through the diode, the transistor leaves the saturated region and enters the active region. This shows up with Vce > 0.2V



If R1 is increased to 100k, the transistor is no longer saturated (Vce > 0.2V)

This is bad for several reasons:

- By placing the transistor in the active region, it starts to get hot (P = V*I).
- The current through the LED is no longer 58mA as calculated



If you operate a transistor in the active region, it will get hot (possibly melting your breadboard)

When designing a transistor switch, make sure that

$$\beta I_b > I_c$$

Design of Transistor Switches: In terms of design,

- Pick Rc to set the desired current
- Then pick Rb so that the transistor is saturated (Ib > Ic/100)

For example, design a circuit

- To turn on and off a red LED
- At 100mA when on,
- Using a 0V/5V input capable of driving at most 5mA.

Solution: First pick Rc to set the current to 100mA

$$R_c = \left(\frac{5V-1.9V-0.2V}{100mA}\right) = 29\Omega$$

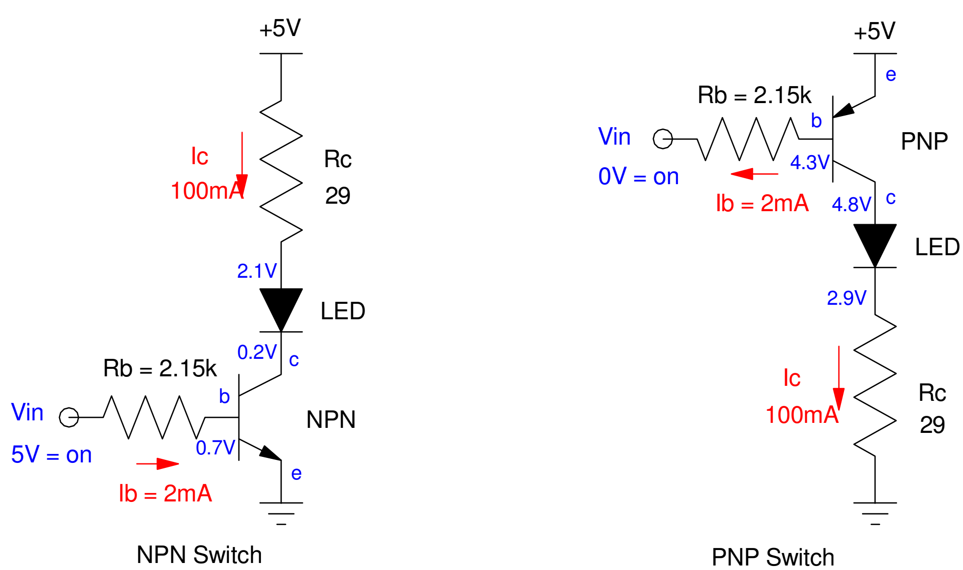
Next, pick Ib so that the transistor is saturated

$$I_b > \left(\frac{I_c}{100}\right) = 1mA$$

Let Ib = 2mA

$$R_c = \left(\frac{5V-0.7V}{2mA}\right) = 2.15k\Omega$$

Two versions of a BJT switch are then as follows.



Resulting Design for 2mA turning on and off 100mA through an LED

Note: If you want to reduce the current to the LED to 10mA (10x smaller), make Rc 10x larger (290 Ohms). Everything else can remain the same.