Diodes, & Transistors

ECE 401 Senior Design I

Week #5

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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 (Pi-Pico, MCP602 op-amp, 555 timer)

This lecture covers:

- Analysis and design of LED circuits,
- Analysis and design or NPN and PNP electronic switches,

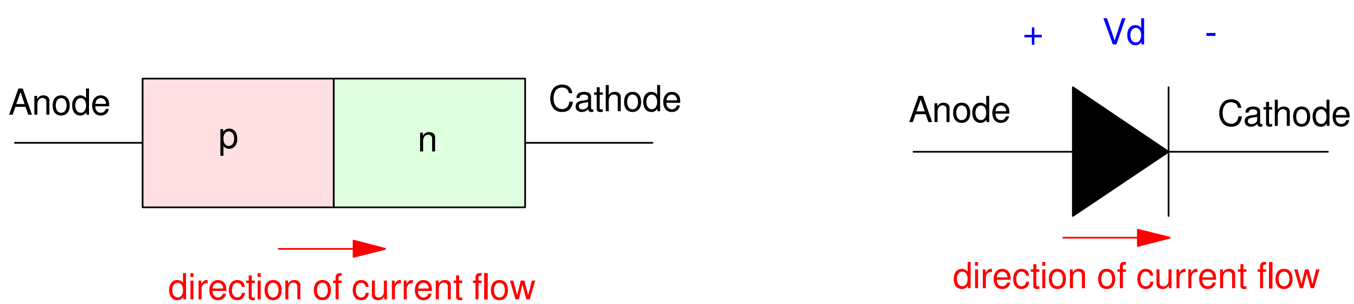
Diodes

- Covered in ECE 320 Electronics I.

Diodes act as valves:

- Current allow current to flow from the anode to the cathode,
- Current block current from flowing the other way.

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.



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

Diode VI Characteristics

Diodes are nonlinear devices

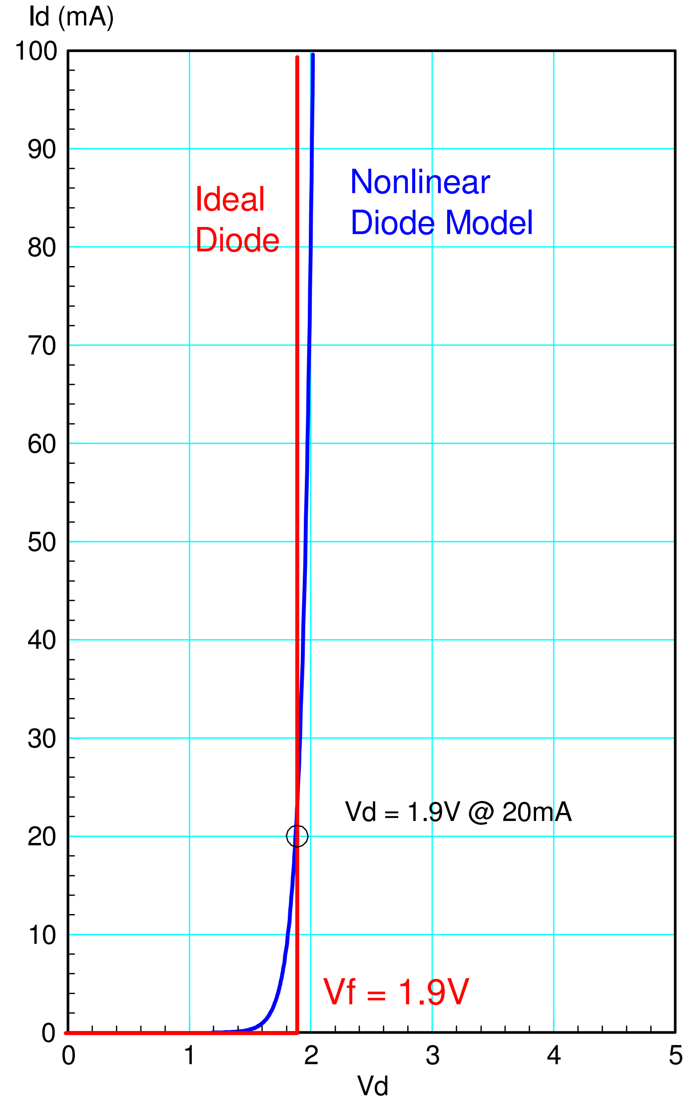
- This makes analysis of diode circuits difficult

Ideal Diode

- Simplified model of a diode
- Id = 0 when Vd < Vf
- Vd = Vf when Id > 0

Not perfect, but usually good enough

- Use CircuitLab to get better answers



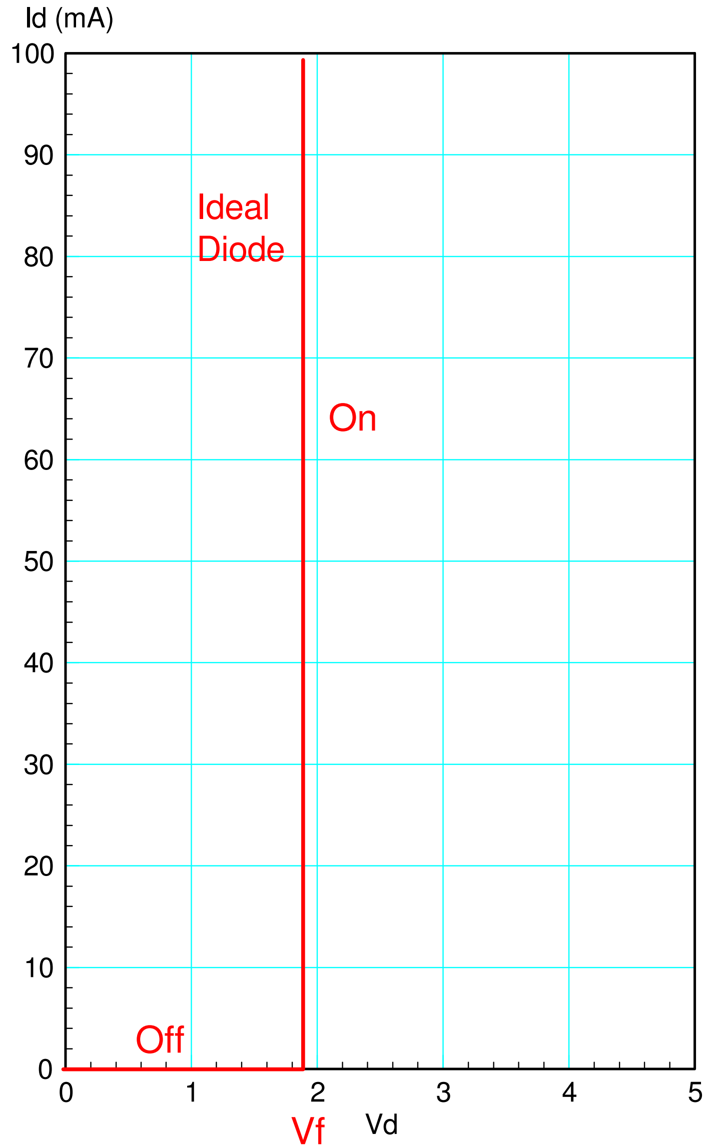
Ideal Diode Model

Vf acts like a turn-on voltage:

- Diode turns on if you apply more than Vf
- Diode turns off if you apply less than Vf

Vf depends upon the diode

- Germanium: Vf = 0.3V
- Silicon: Vf = 0.7V
- Red LED: Vf = 1.9V
- Yellow LED: Vf = 2.0V
- Green LED: Vf = 2.0V to 3.0V

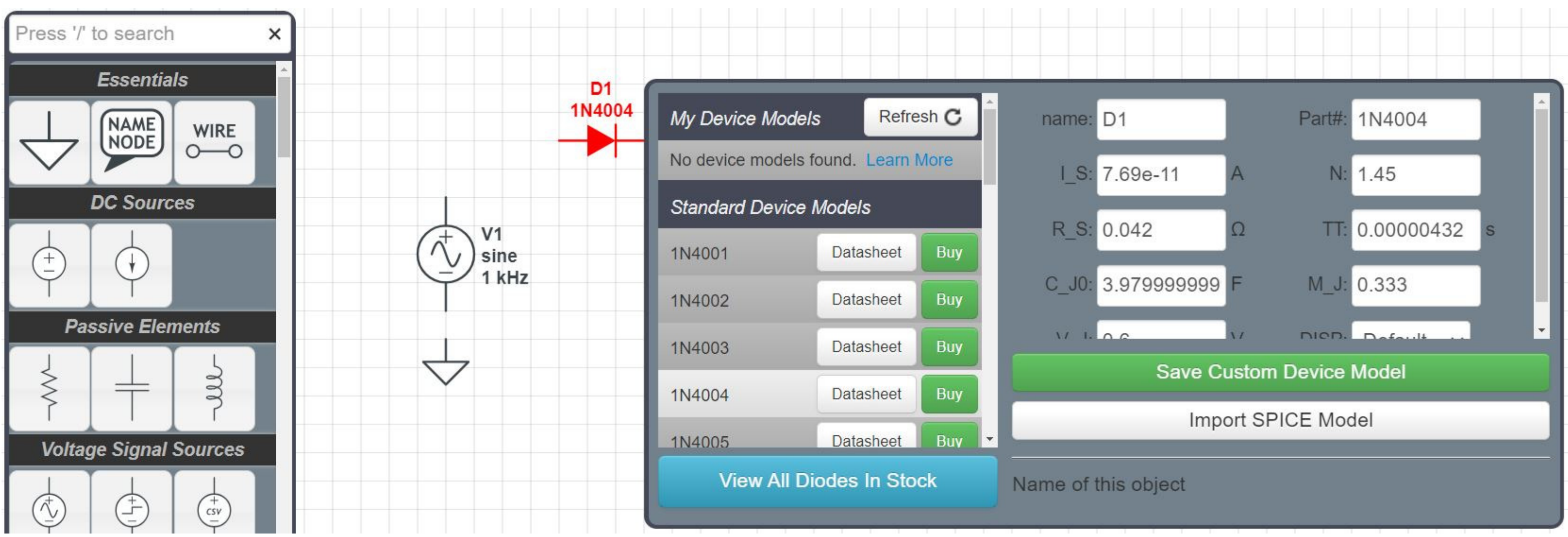


Diode Example (CircuitLab)

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

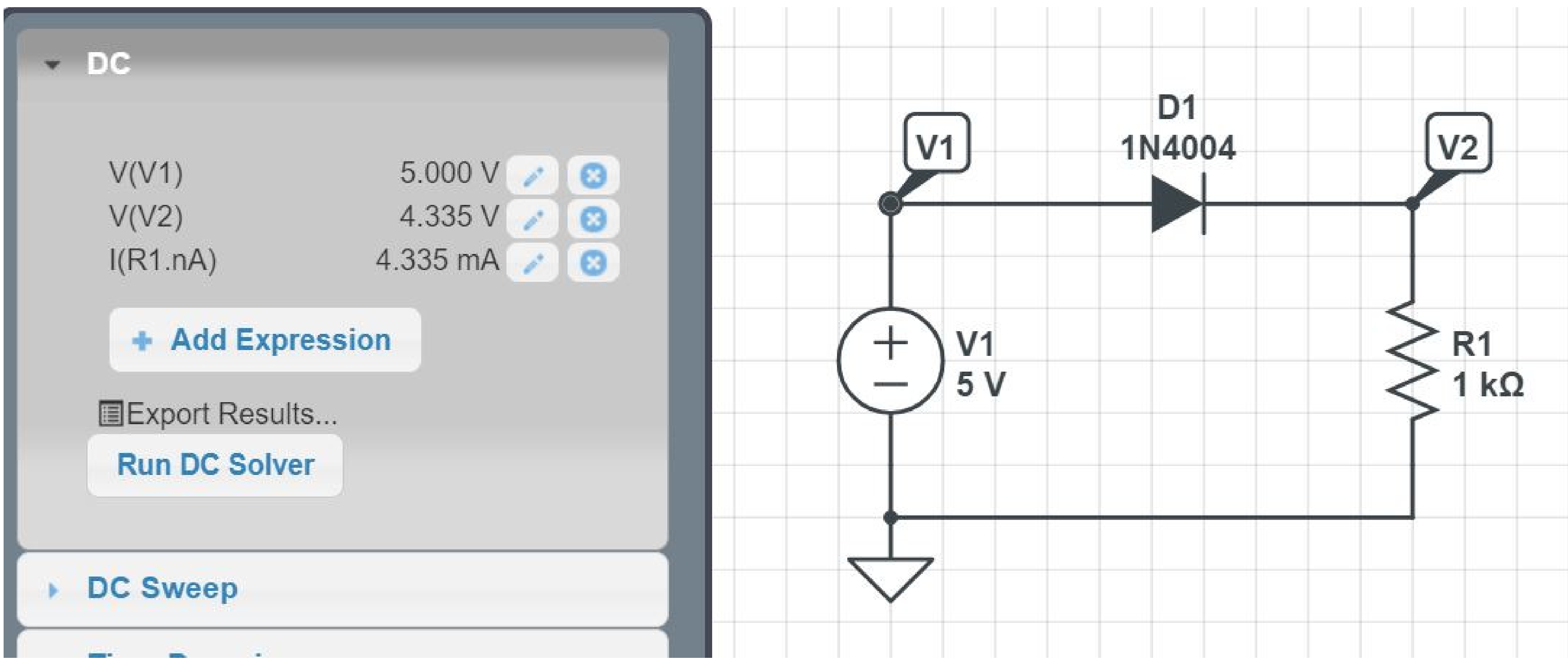
Make sure you have a ground (CircuitLab insists on this)



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

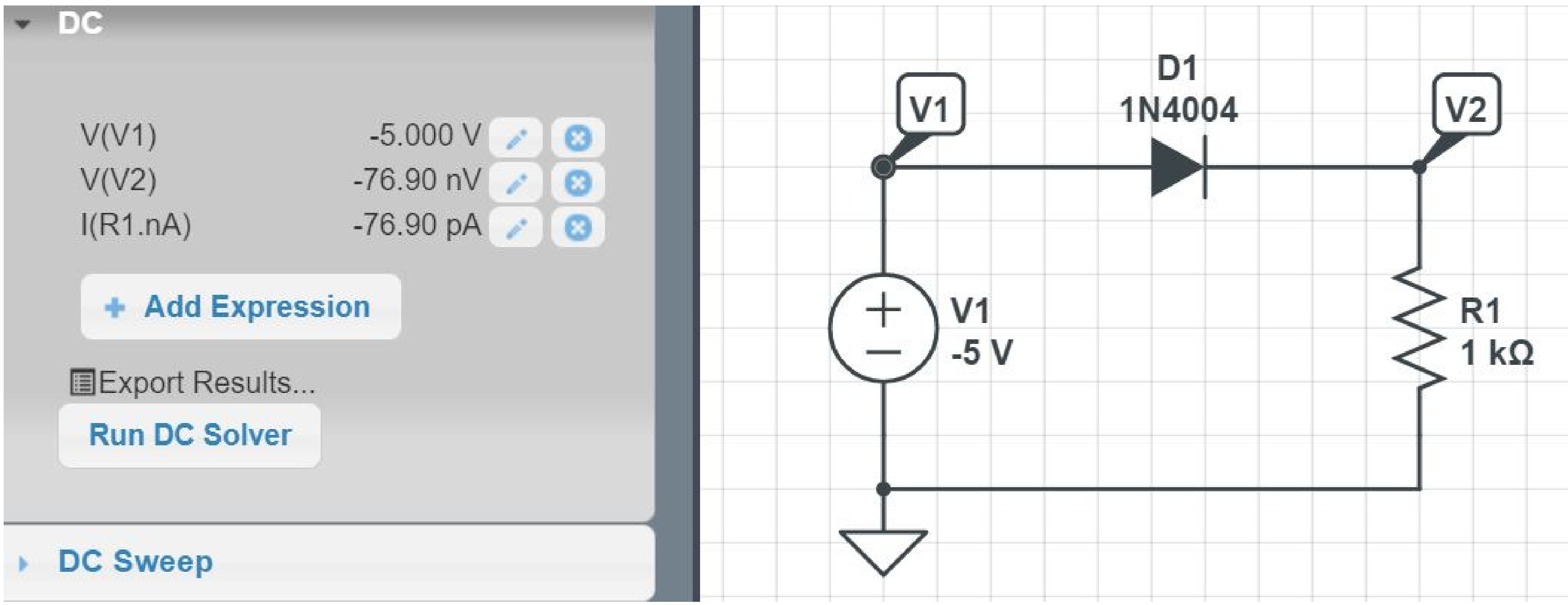
When the diode is turned on (Id > 0), the voltage drop is 0.7V (ish)



When you try to push current backwards, the diode turns off

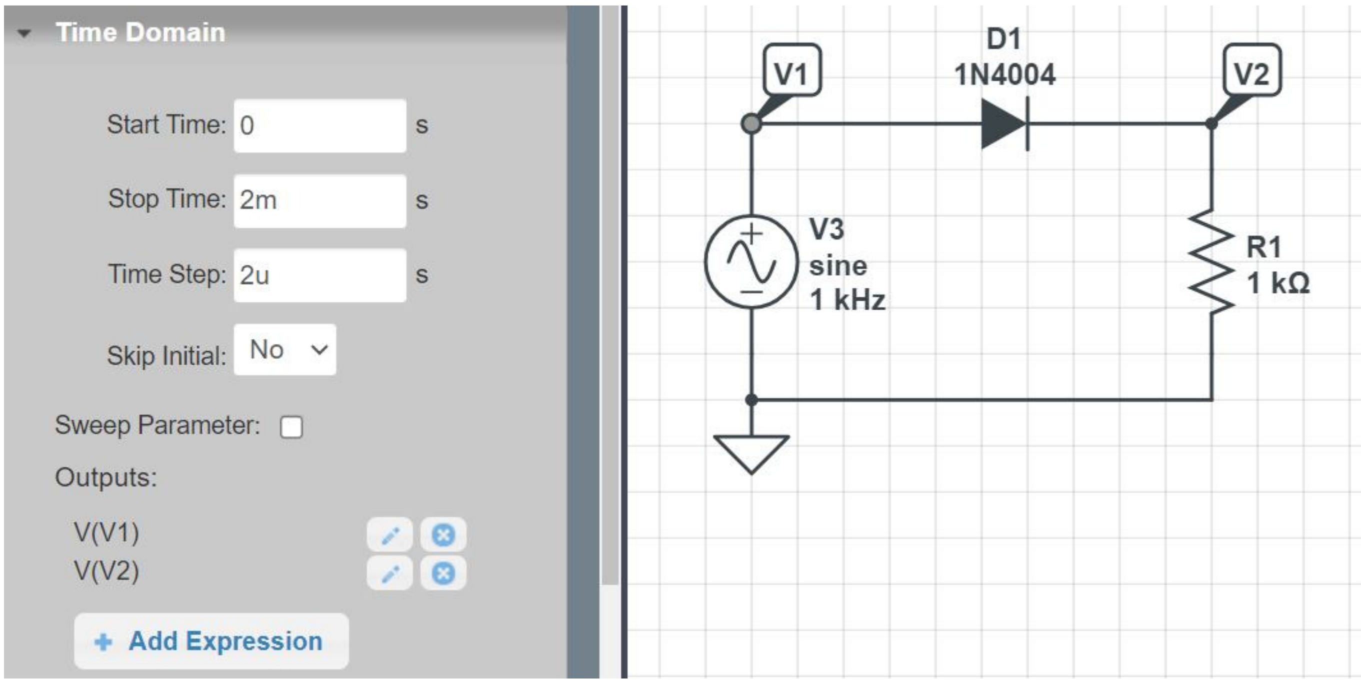
- Id = 0 (ideal diode)
- Id = -76.90pA (CircuitLab)

Diodes *do* conduct current when reverse biased, but it's really small



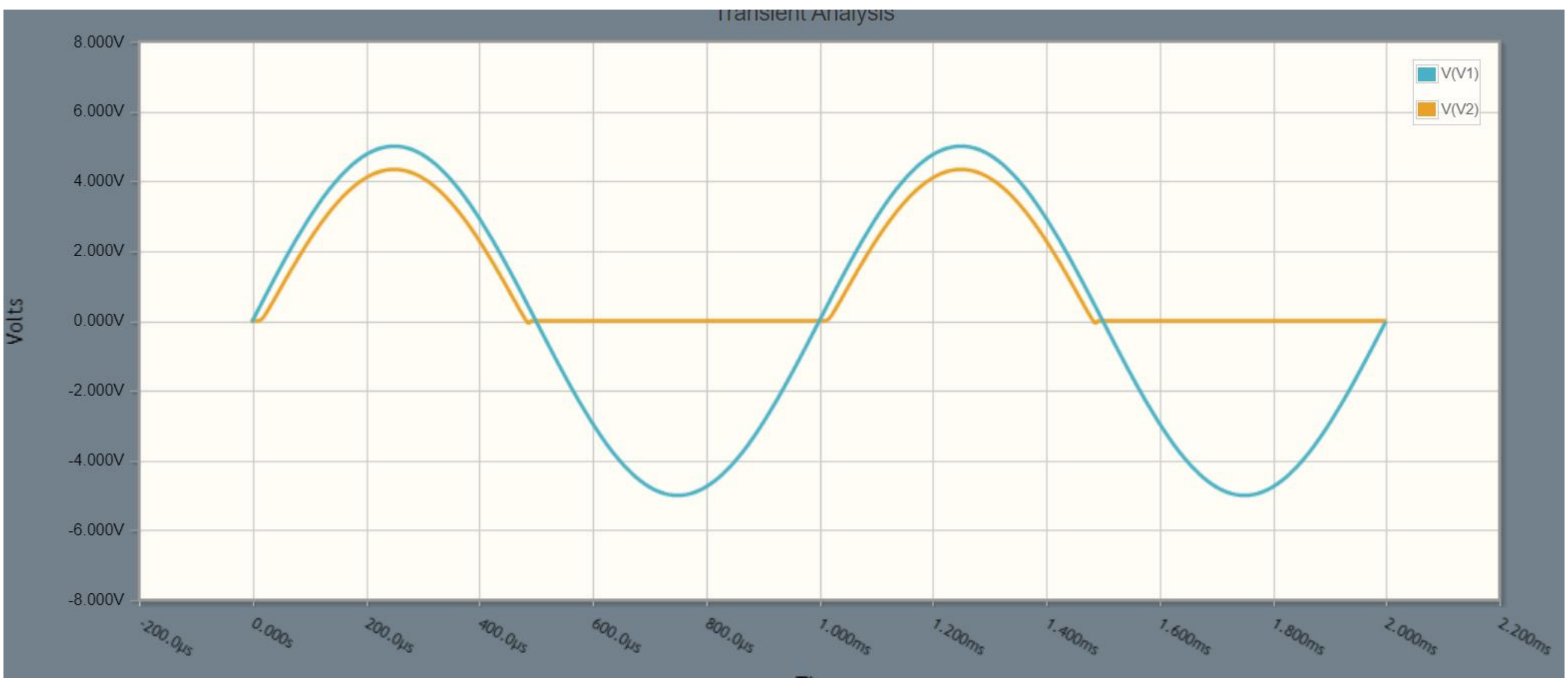
CircuitLab & Time Domain Simulations

- Similar to an oscilloscope
- Apply a sine wave for V3
- Run the simulation for 2-3 cycles
- Set the sampling rate 1000x smaller (gives 1000 points on the graph)



Resulting Waveform:

- When Vin > 0.7V, the diode turns on
  - Vout = Vin - 0.7V (ish)
- When Vin < 0.7V, the diode turns off
  - Vout = 0V



Diode Circuit Analysis:

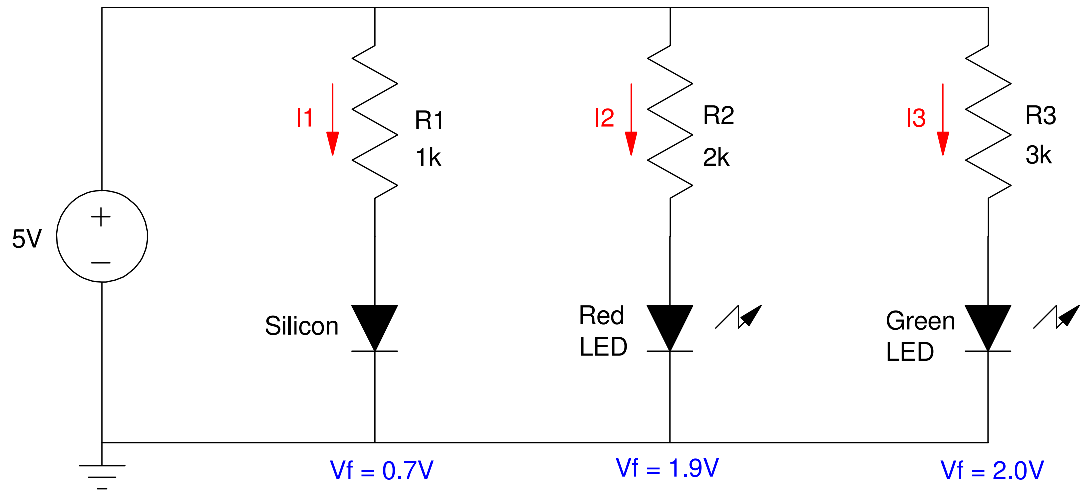
- Determine which diodes are on and off
  - Not always that easy
- Replace with the ideal diode model
- Determine voltages and currents

Calculations:

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

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

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



Diode Circuit Design:

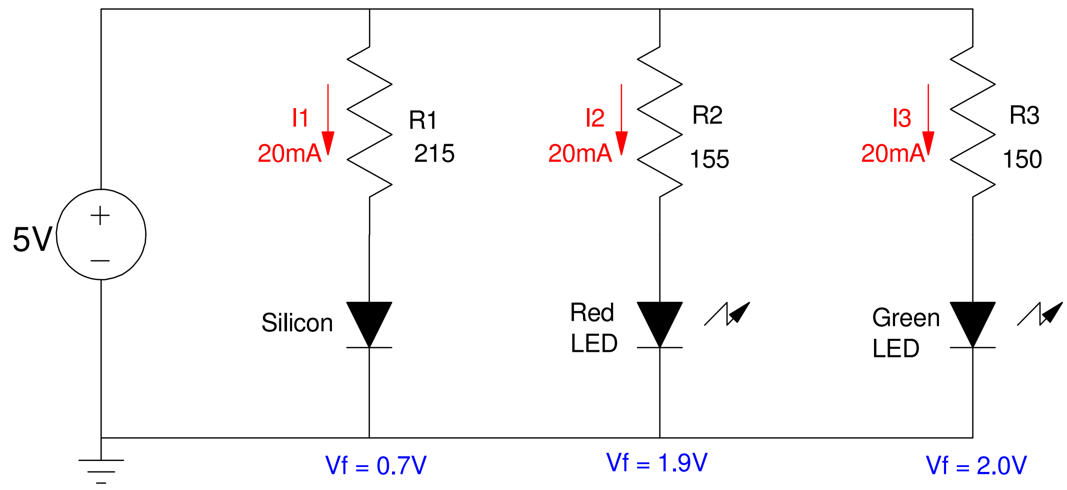
- Pick the current desired
  - Light is proportional to current
- Calculate the resistance needed

Example: Set Id = 20mA

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

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

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



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

With LEDs, brightness is proportional to current

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:

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

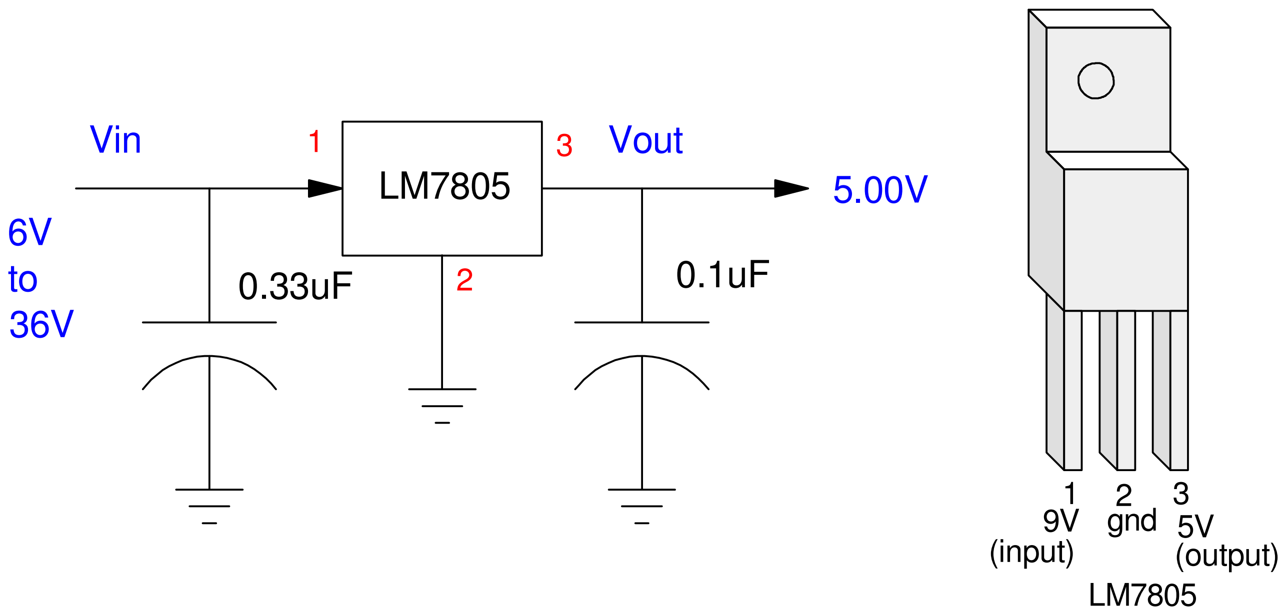
Voltage Regulation

In ECE 401,

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

Solution: Use a LM7805 regulator

- Pro: Simple circuit
- Con: Efficiency = 55% @ 9V

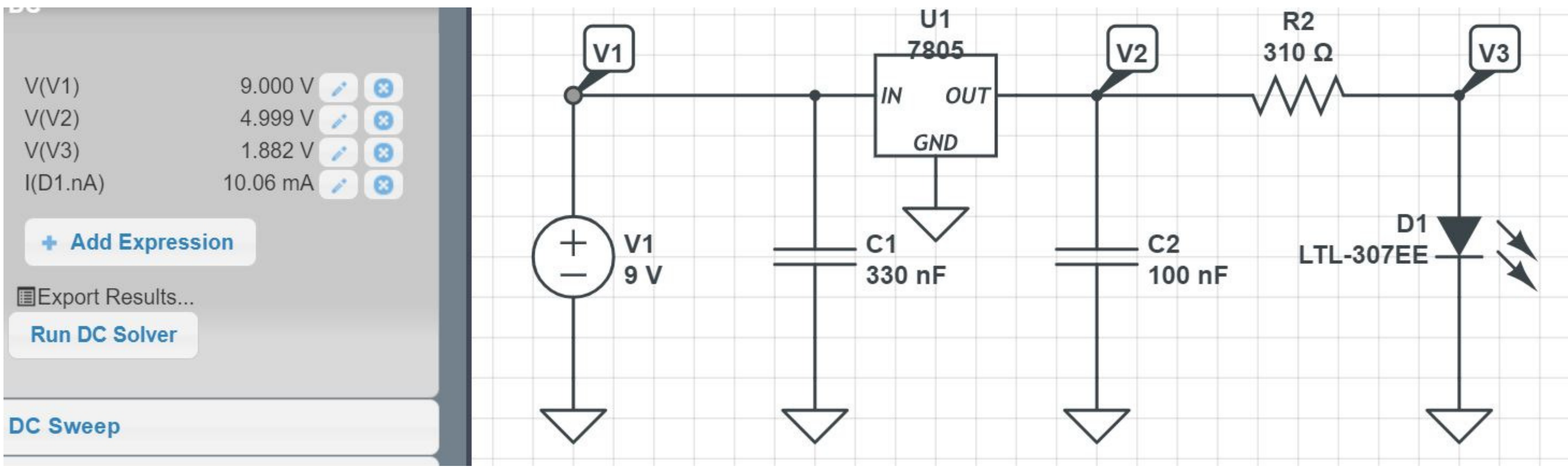


Example:

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

Assuming a red LED

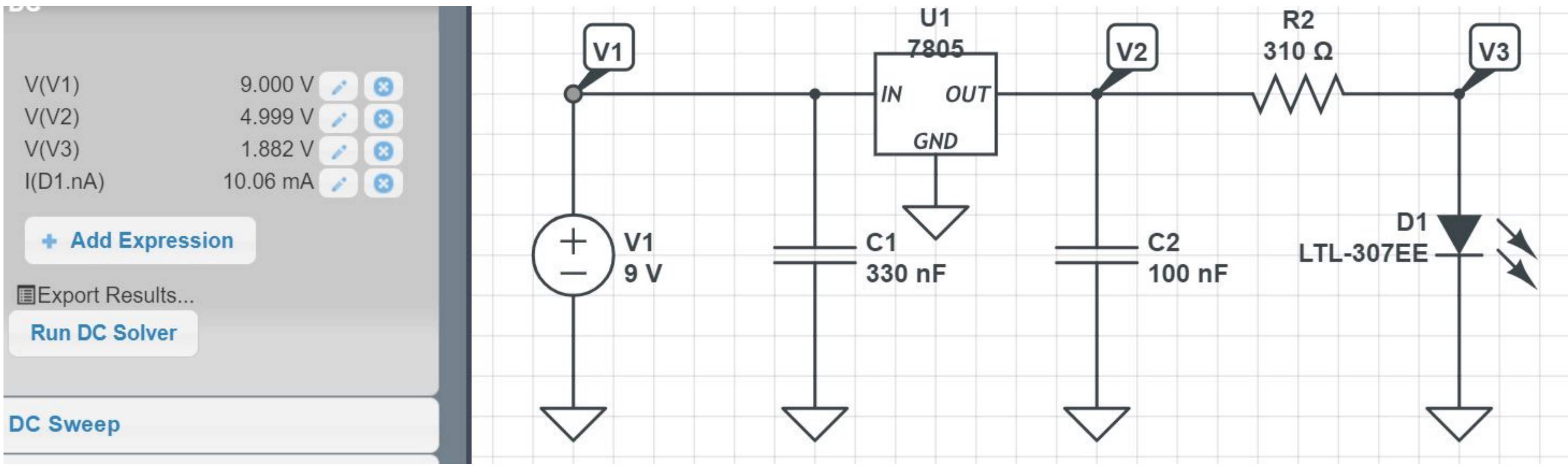
$$R = \left(\frac{5V - 1.9V}{10mA}\right) = 310\Omega$$



Interpreting the Results:

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

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



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
- Overcurrent protection
  - if your circuit draws too much current, a fuse blows.

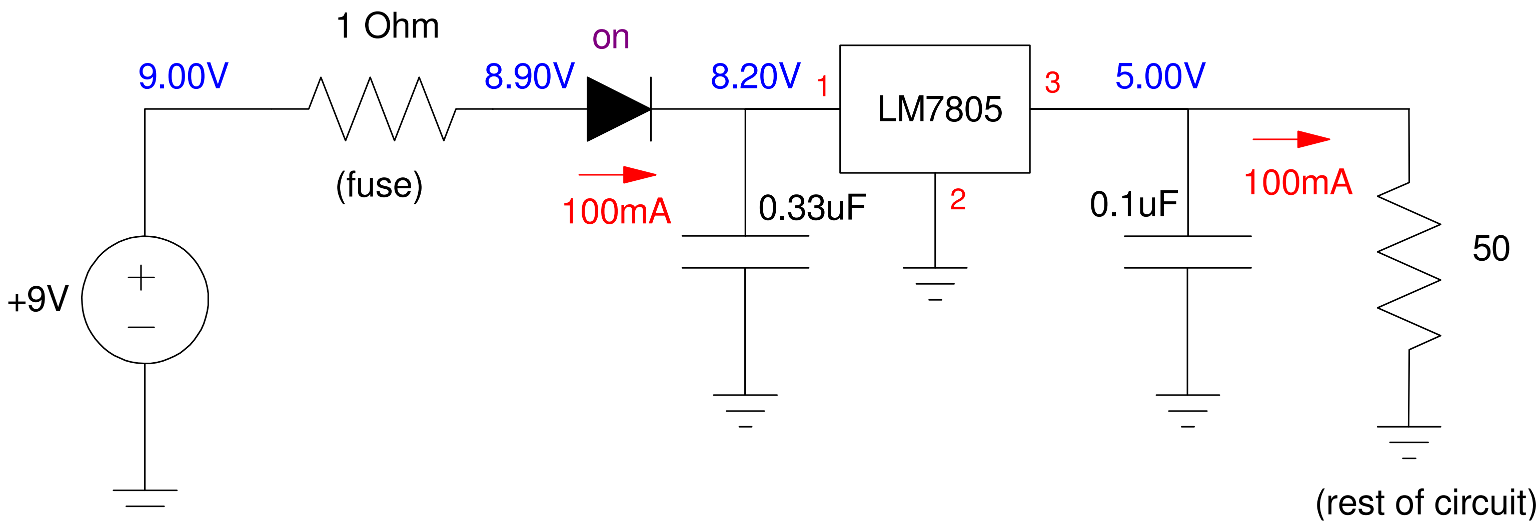
There are several ways to do this.

Method #1: Diode + Fuse.

- Diodes do not allow current to flow backwards
  - Blocks current if the 9V battery is inserted backwards
- Fuse blows if the load is too much
  - 1 Ohm resistor replaces the fuse for ECE 401 (2 cents)

Problem:

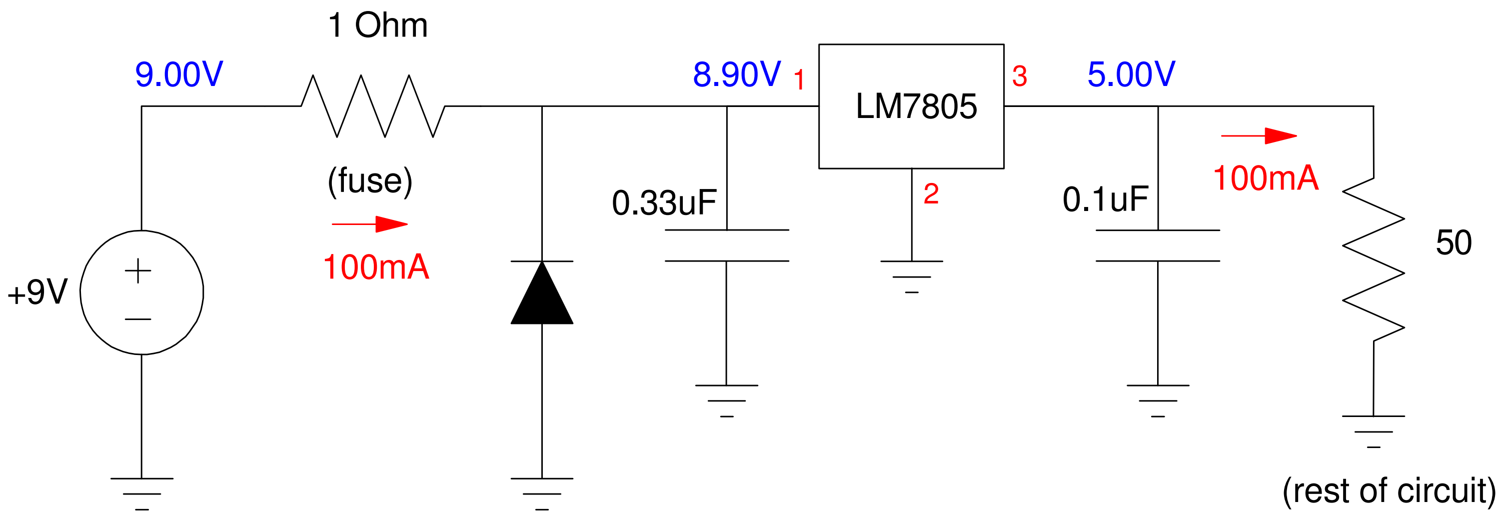
- Drops 0.7V through the diode



Method #2: Fuse + Diode.

Add a reverse biased diode to ground

- If the 9V battery is connected correctly, the diode remains off.
- 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.



BJT Transistors

Bipolar Junction Transistors

- 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.

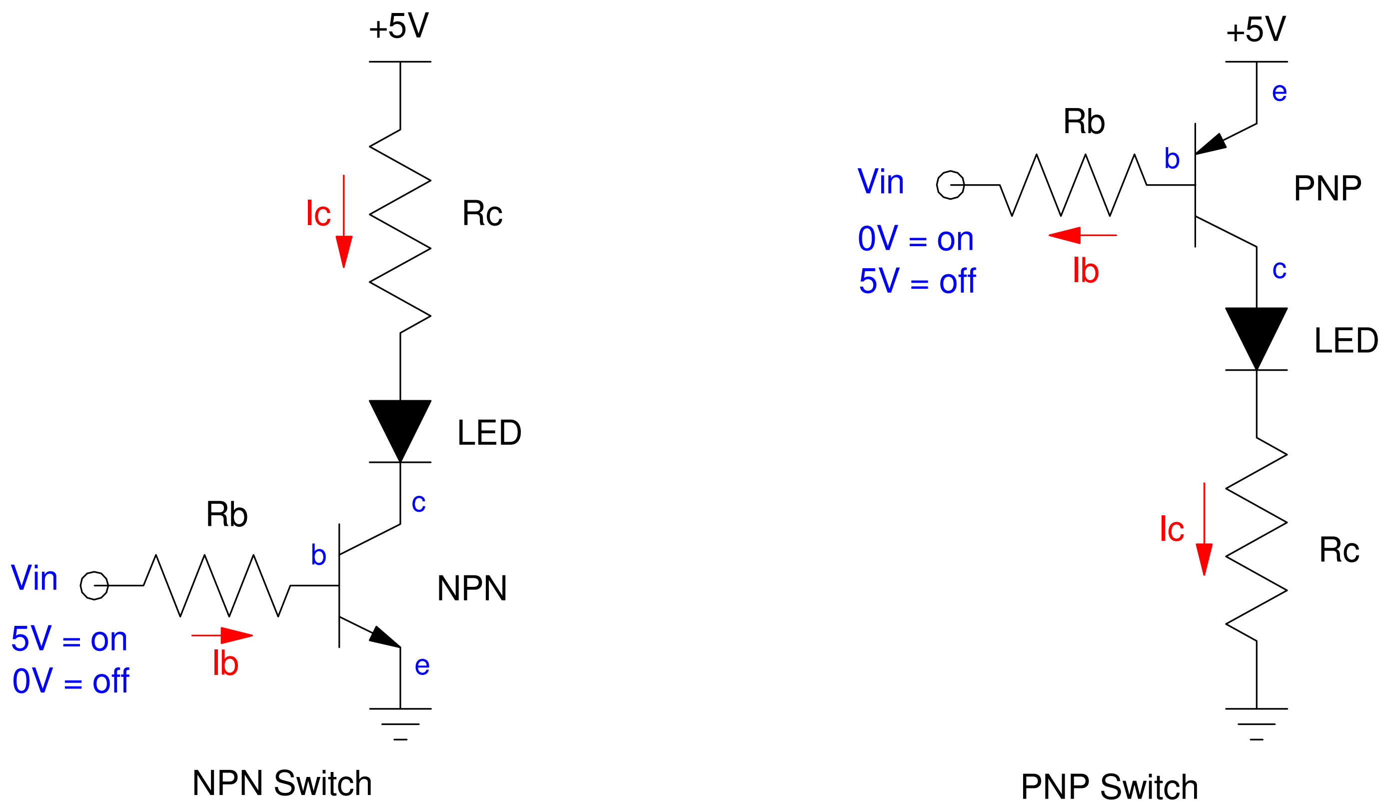
Spec	3904 NPN	3906 PNP
Current Gain (min)	100	100
Max Current	200mA	200mA
|Vbe| (on)	0.7V	0.7V
|Vce| (sat)	0.2V	0.2V
Cost (ea)	$0.11	$0.11

NPN and PNP Transistors

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:



Diode from Base to Emitter

The arrow going between the base and the emitter is all important:

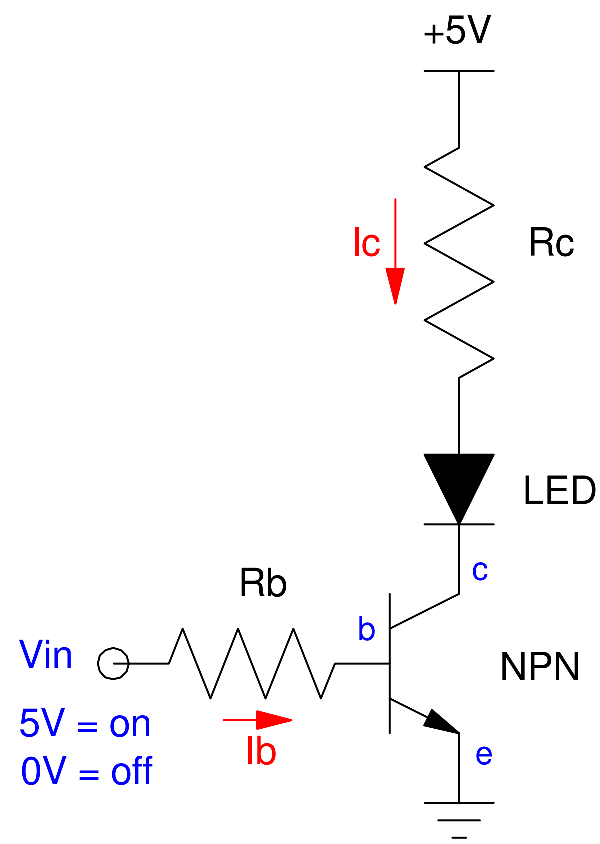
- It represents a diode (a pn junction)
- It tells you the direction current flows
- The base current controls the collector current

Ib limits the collector current

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

It does this by dumping voltage

- Whatever it takes to set Ic



NPN Switch

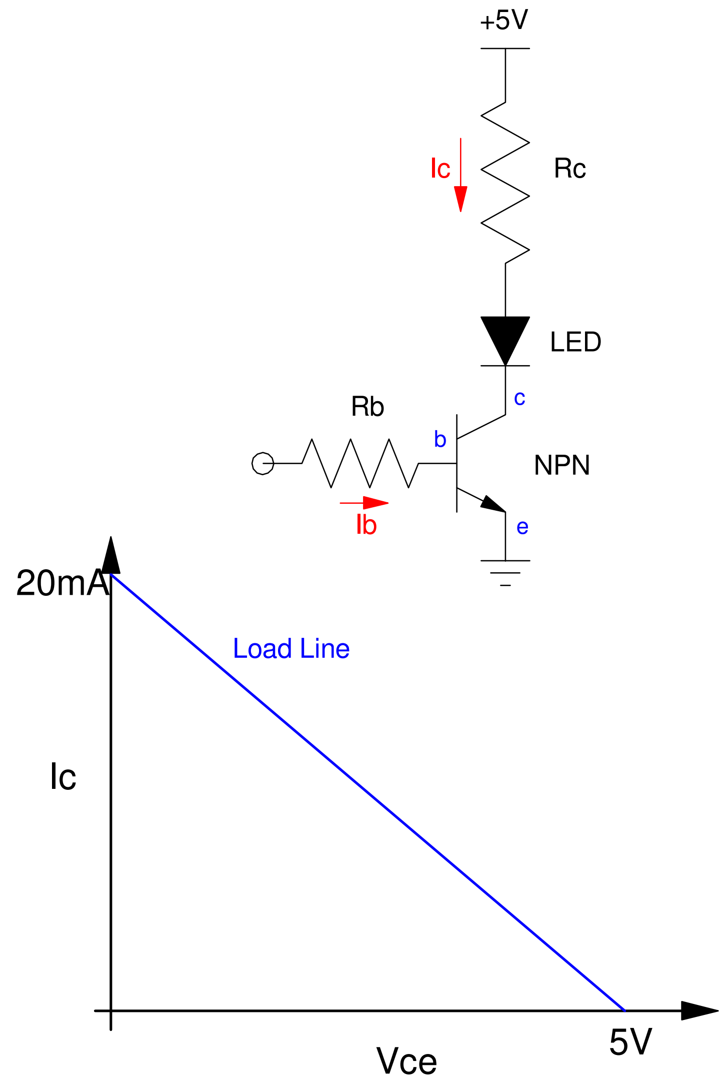
Load Lines

A good way to see how a transistor switch operates

- 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.



Off State:

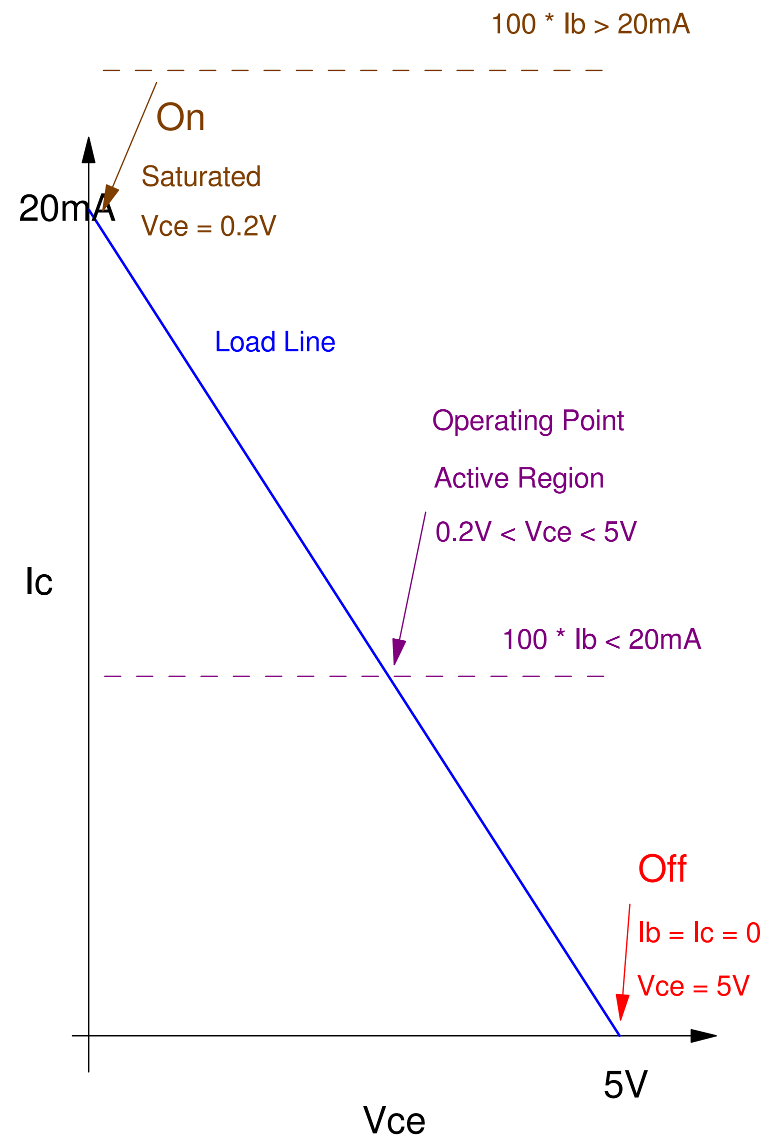
- Ib = 0
- Ic = 100*Ib = 0
- Vce = 5V

Active Region

- 0mA < Ib < 20mA
- 5V > Vce > 0.2V
- Ic = 100*Ib

On State

- Saturated Region
- 100*Ib > 20mA
- Vce = 0.2V



The Active Region is Bad

You want to operate in the ON and OFF state

Off State

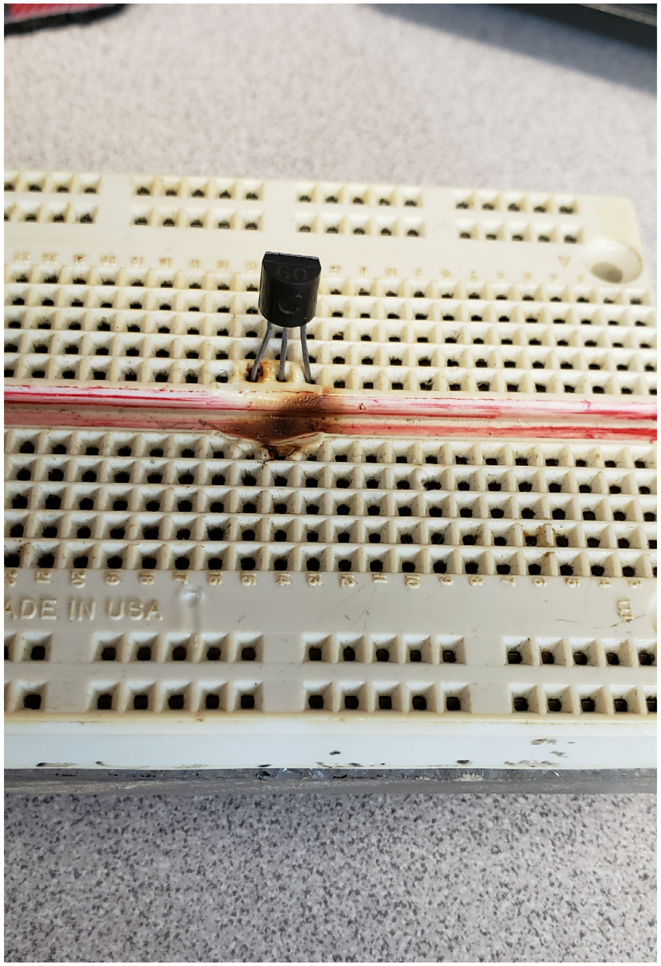
- I = 0
- P = V*I = 0

On State

- V = 0.2V (almost zero)
- I = 20mA
- P = 4mW (almost zero

Active Region

- P = V*I
- The transistor gets hot
- You start to melt your breadboard



Analysis of Transistor Switches:

- Same equations for PNP and NPN

Off State

- Easy: Ib = Ic = 0

On State:

$$V_{ce} = 200mV$$

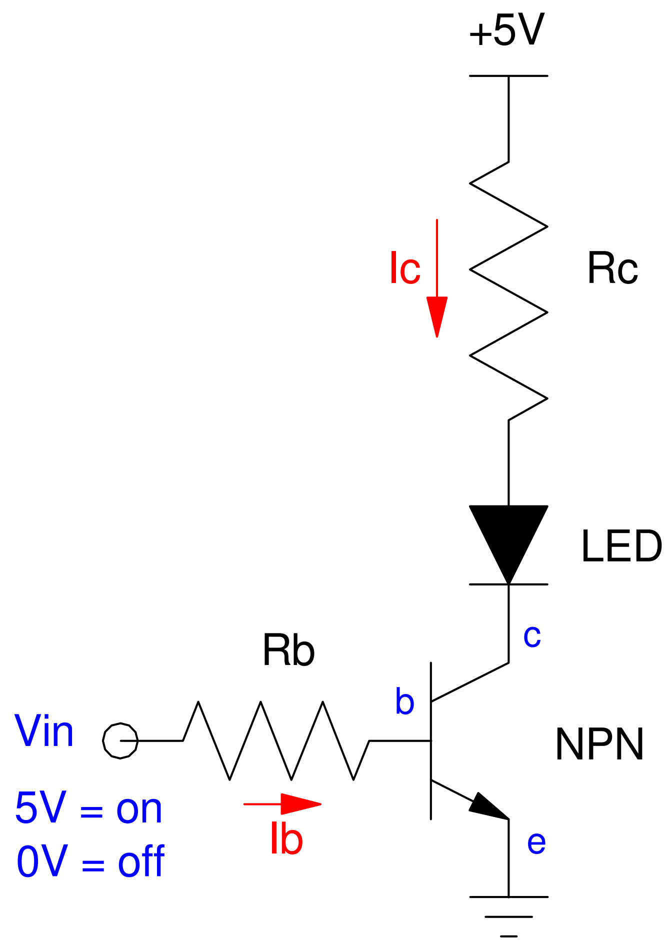
$$I_c = \left(\frac{5V - V_f - V_{ce}}{R_c}\right)$$

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

Check that you're saturated:

$$\beta I_b > I_c$$

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



NPN Switch

BJT Switch Example

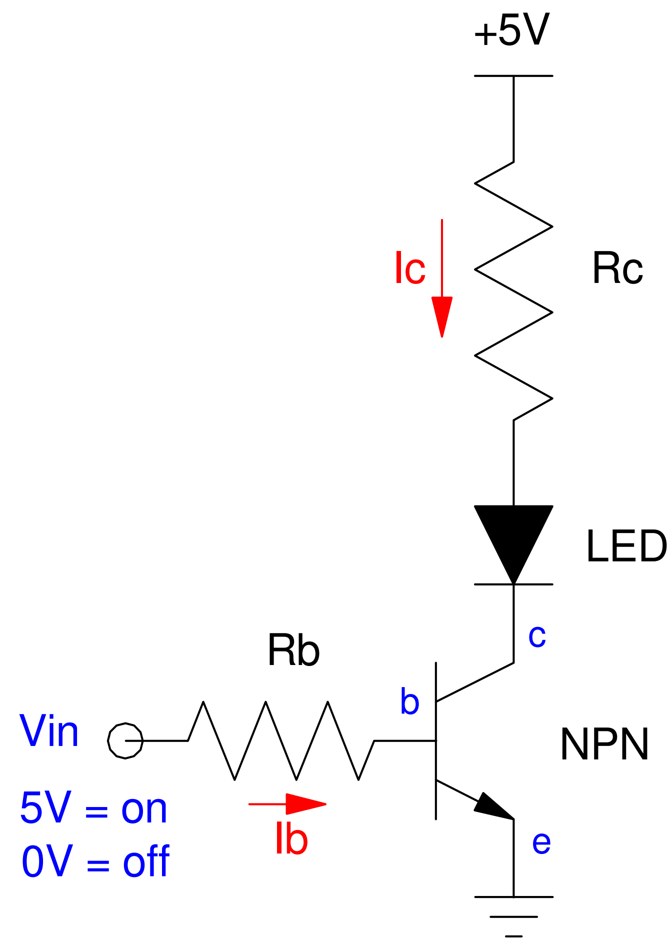
Assume

- 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

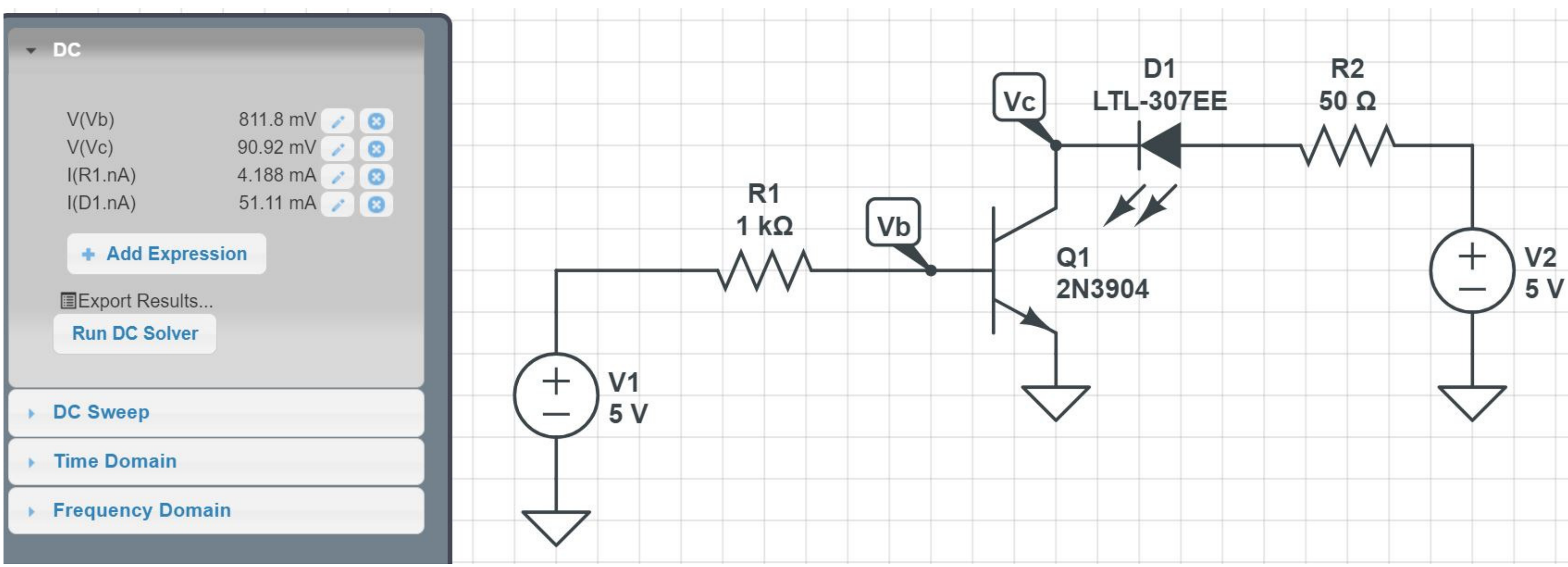
$$I_c = \left(\frac{5V - 1.9V - 0.2V}{50\Omega}\right) = 58.0mA$$



NPN Switch

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

- Vb = 0.8118V
  - calculated = 0.7V (ideal diode)
- Vc = 0.0909V
  - calculted = 0.2V
- I(D1) = 51.11mA
  - Close to 58.0mA

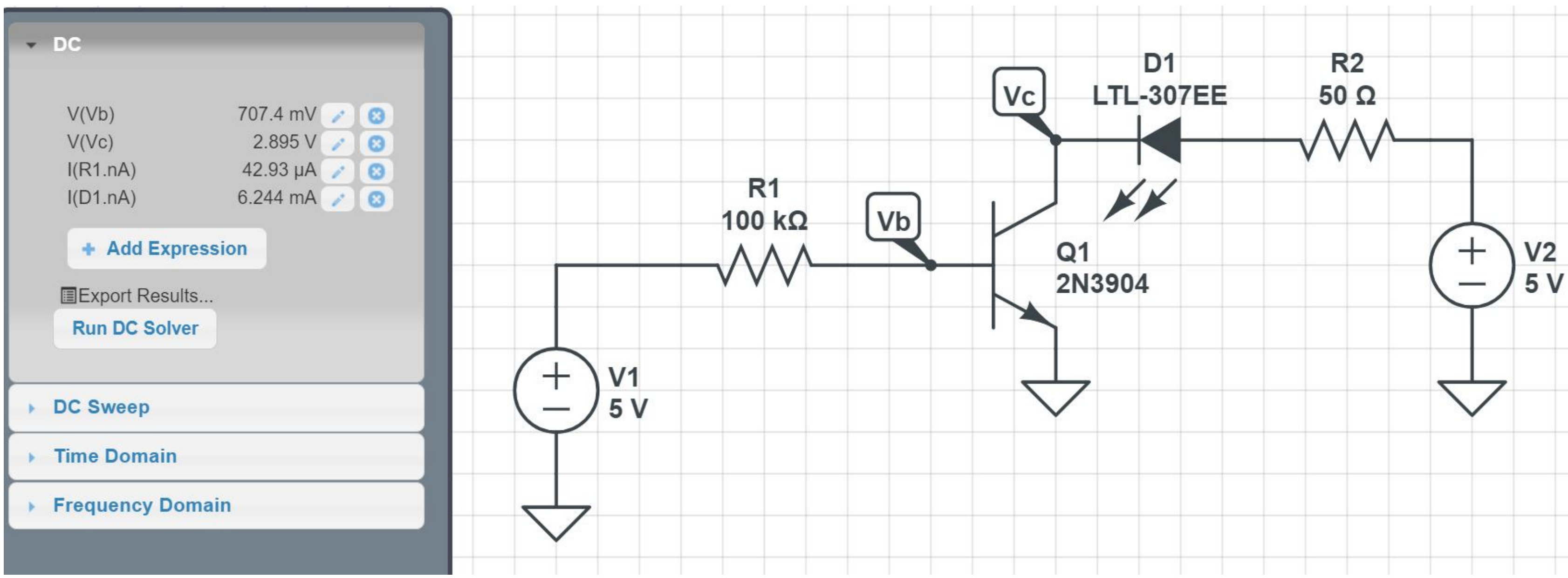


Operation in the Active Region

If Ib is too small, then the transistor enters the active region (bad)

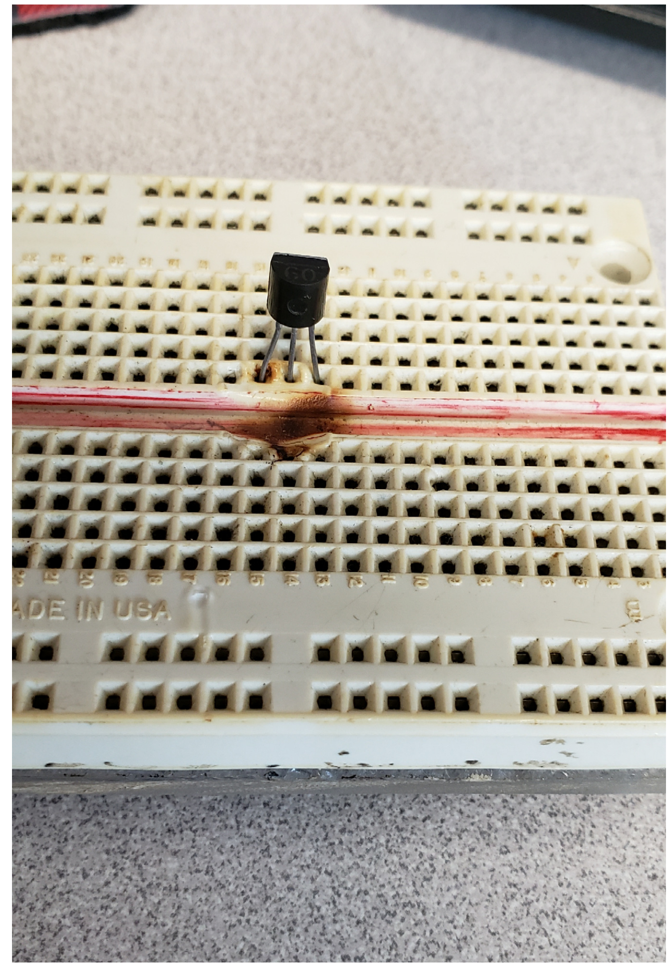
Example: Increase Rb to 100k

- Ib = 42.93uA
- Ic = min(βIb, max(Ic)) = 6.21mA
- Vce = 2.85V (active region)



What happens when you operate in the active region?

- Ic < 58mA
- The transitor gets hot
  - and can melt the breadboard



Avoid operating in the active region when using a transistor as a switch

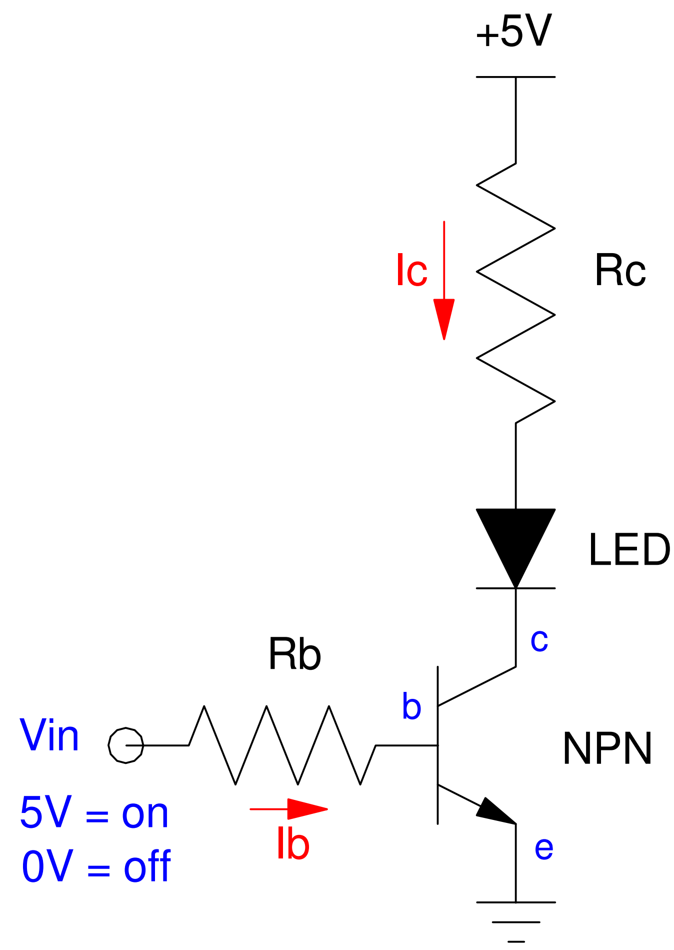
- Keep Vce = 0.2V (ish)

Design of Transistor Switches:

- Pick Rc to set the desired current
- Pick Rb to saturate the transistor
  - Ib > Ic/100

For example, design a circuit

- To turn on and off a red LED
- At 20mA when on,
- Using a 0V/5V input capable of driving at most 5mA.



NPN Switch

Solution:

First pick Rc to set the current to 20mA

$$R_c = \left(\frac{5V - 1.9V - 0.2V}{20mA}\right) = 145\Omega$$

Next, pick Ib so that the transistor is saturated

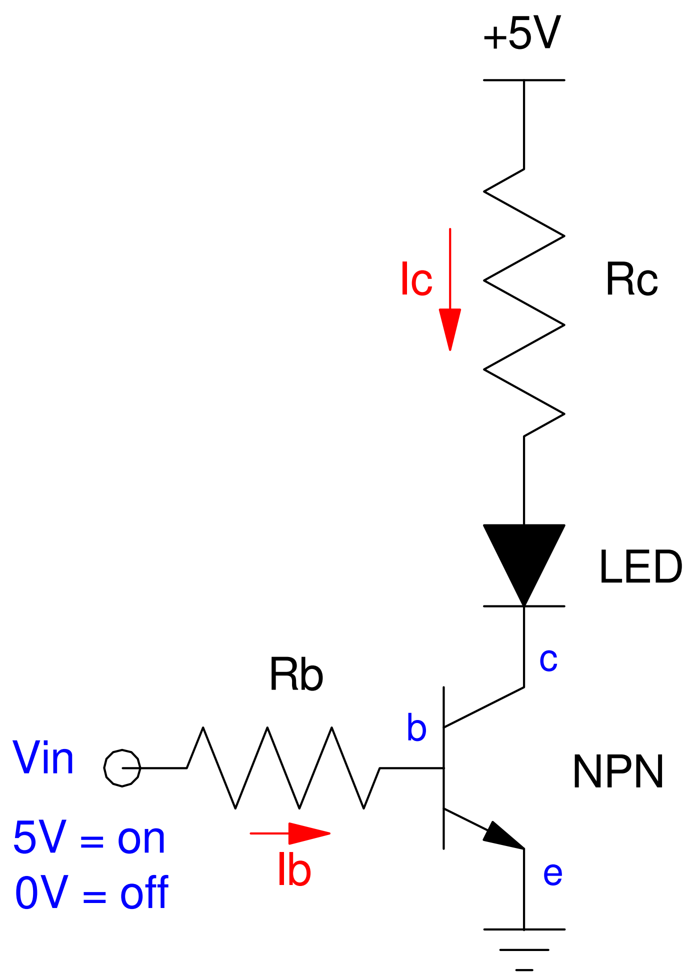
$$I_b > \left(\frac{I_c}{100}\right) = 0.2mA$$

Let Ib = 1mA

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

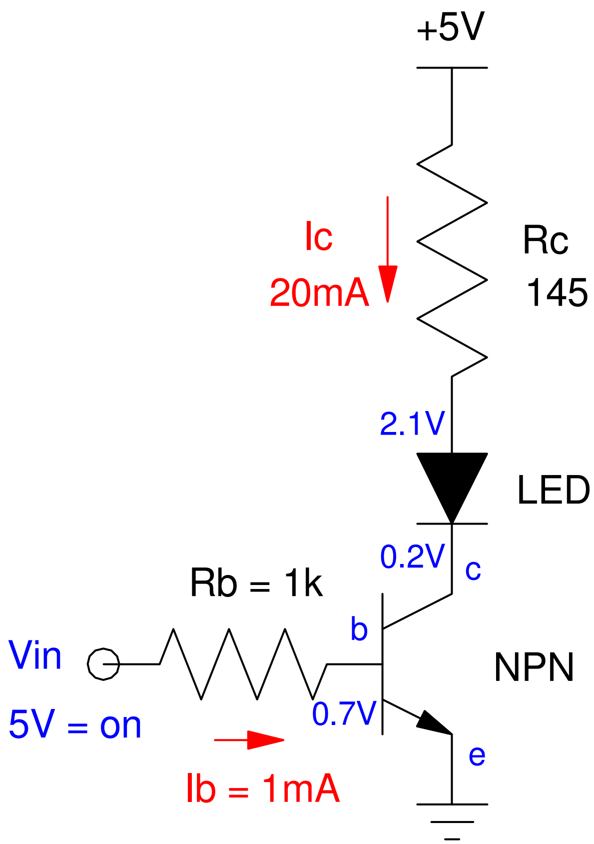
Same equations for a PNP switch

Resuting Circuit

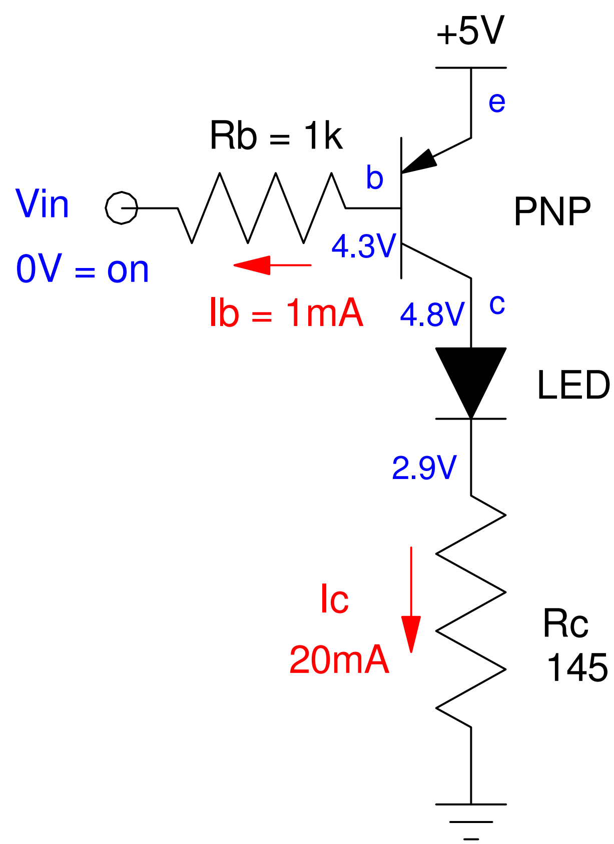


NPN Switch

NPN & PNP Switch



NPN Switch



PNP Switch

NPN Switch with a Pi-Pico

Have a Raspberry Pi-Pico turn on an off a red LED

- At 20mA
- Using an NPN transistor

Pick Rc to set the current

$$R_c = \left(\frac{5V - 1.9V - 0.2V}{20mA}\right)$$

$$R_c = 145\Omega$$

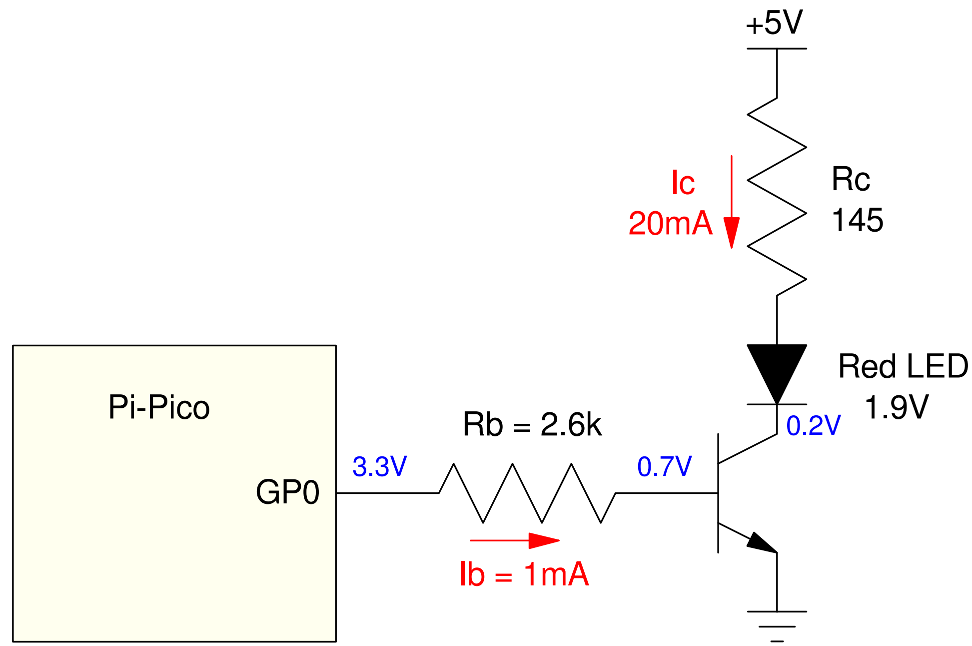
Pick Rb to set the voltage

- Saturate the transistor

$$\beta I_b > I_c = 20mA$$

Let Ib = 1mA

$$R_b = \left(\frac{3.3V - 0.7V}{1mA}\right) = 2.6k\Omega$$



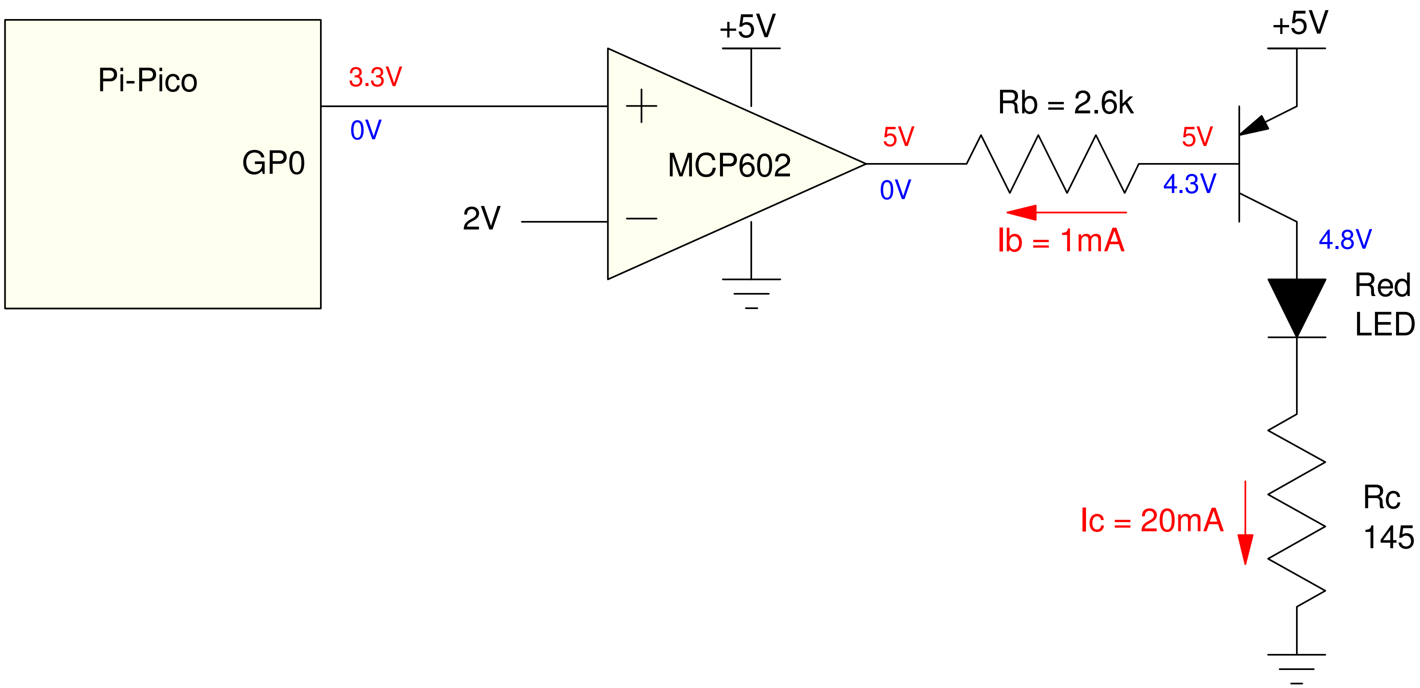
PNP Switch with a Pi-Pico

Have a Raspberry Pi-Pico turn on an off a red LED

- At 20mA
- Using a PNP transistor

Similar design but an op-amp

- Level shifter circuit (convert 3.3V to 5.0V)



Summary

Diodes can be used as electronic valves

- They let you control block reverse current.

BJT transistors can be used as electronic switches.

- They let you turn on and off devices
- They amplify current, allowing larger loads to be turned on and off

Homework #5:

- Due week #10

Reminder: ECE 401 Circuit Requirements

- Must operate off of 5VDC
- Must include at least one integrated circuit
- Must include at least one LED with Id = 20mA +/- 5mA
- Must include at least one NPN and one PNP transistor
  - Use a LM7805 regulator to drop 9V to 5V
- Must have a reverse-polarity protection diode
- Must have a 1/4 Watt 1-Ohm resistor in series with the power supply

1. Build your circuit on a breadboard
   - Power comes from a 9V battery
   - Include a photo in your OneNote document

Homework #5 (cont'd)

2. Take measurements to verify your circuit works
   - Include these measurements in your OneNote document
   - *Note where you these are recorded on your schematic*.
   - *These are the test points for your upcoming PCB)*

- DC Measurements (all cases)
  - Vbat (9V)
  - Vreg (5V)
  - Vbe for the NPN transistor when ON
  - Vce for the NPN transistor when OFF
  - Current through the LED when ON
  - Total current draw

- If using a 555 Timer, also provide waveforms (transient response: 2-3 cycles)
  - Waveform @ C1
  - Waveform @ Threshold
  - Waveform @ Discharge
  - Waveform @ Timer Out

Homework #5 (cont'd)

- If using an op-amp (MCP602), also provide the following DC measurements:
  - Voltge at inverting input when on and off
  - Voltage at non-inerting input when on and off
  - Voltage at Op-Amp output when on and off

- If using a microcontroller (Raspberry Pi Pico)
  - Voltage at uP output when on (5V) and off (0V)
  - DC voltage at the PNP transistor (Vb, Vc, Ve)

3) Parts List

- Parts used in your breadboard
- Vendor & Vendor number
- Description
- Price