Using a Transistor as a Switch

ECE 320 Electronics I

Jake Glower - Lecture #12

Please visit Bison Academy for corresponding
lecture notes, homework sets, and solutions

Using a Transistor as a Switch

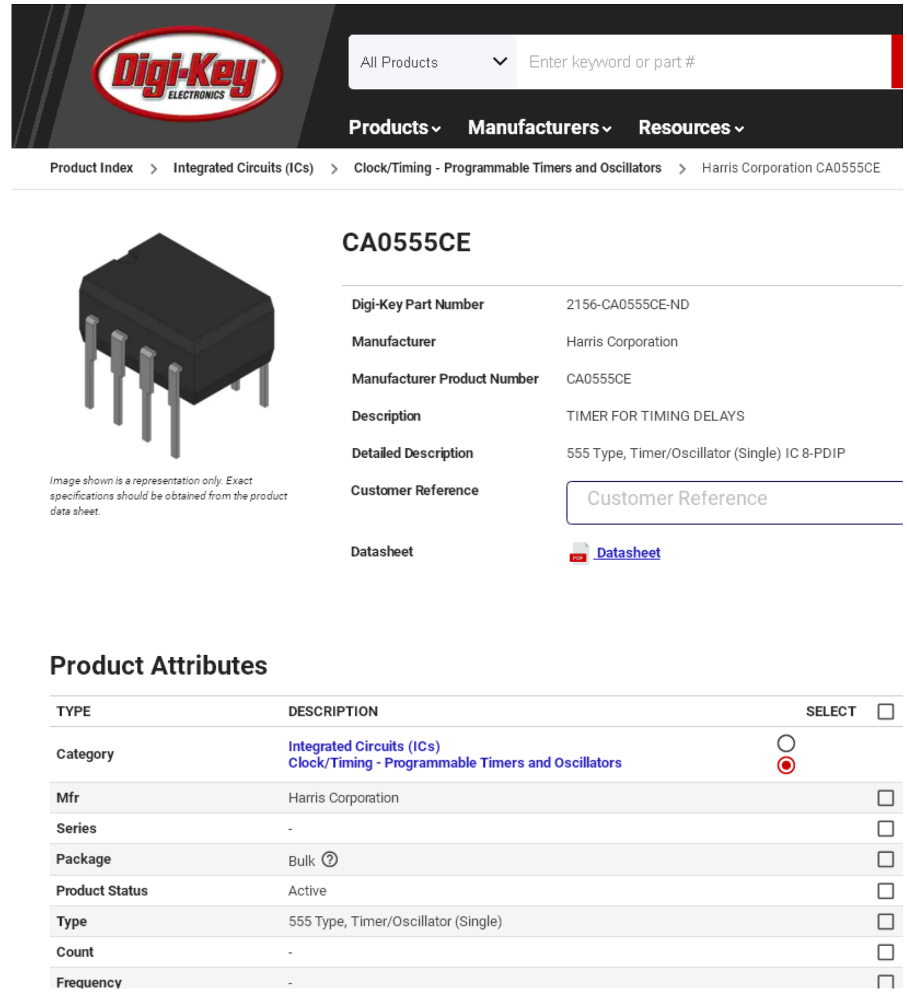
Microcontrollers and function generators (555 timers) have limited outputs

- 0V / 5V up to 20mA

Many loads need more:

- 200mW LED which draws 100mA @ 1.9V
- 8-Ohm speaker which draws 625mA @ 5V.
- Motor which draws 2A at 24V

A transistor can be used as a buffer between the two



On/Off Control with a SPST Switch

Connect your load to power and ground

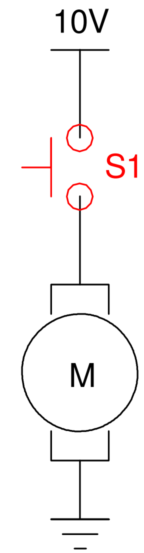
Add a switch,

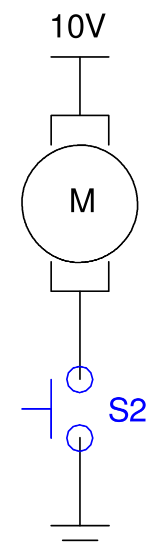
- At the power supply, or
- At the ground side

Either solution works

Works for any DC load

- Motor (on/off)
- LED (on/off)
- Speaker (push/off)
- etc.





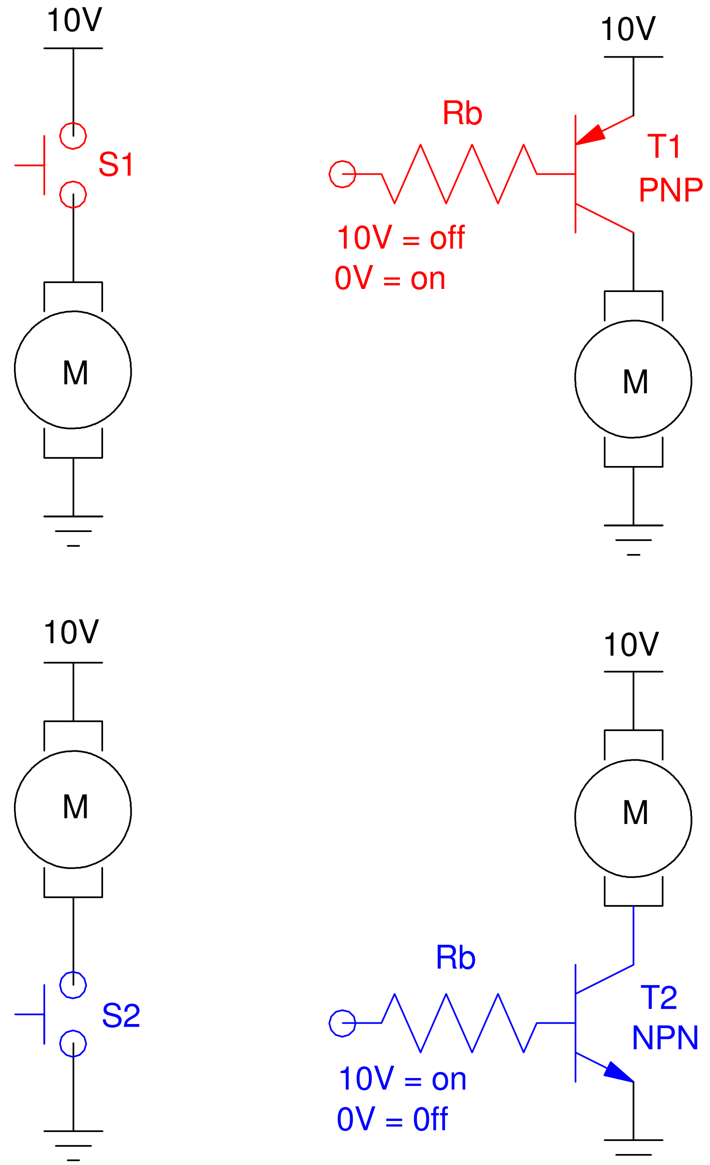
On/Off Control with a Transistor

Replace the switch with a transistor

- PNP on the high side
- NPN on the low side

Either solution works

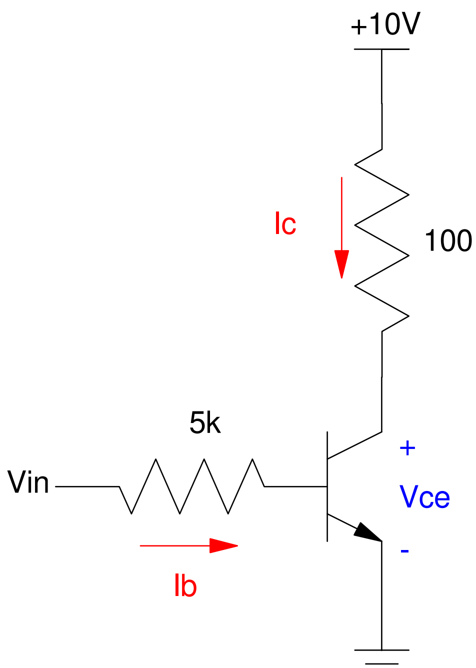
We'll be using the NPN transistor mostly in this class

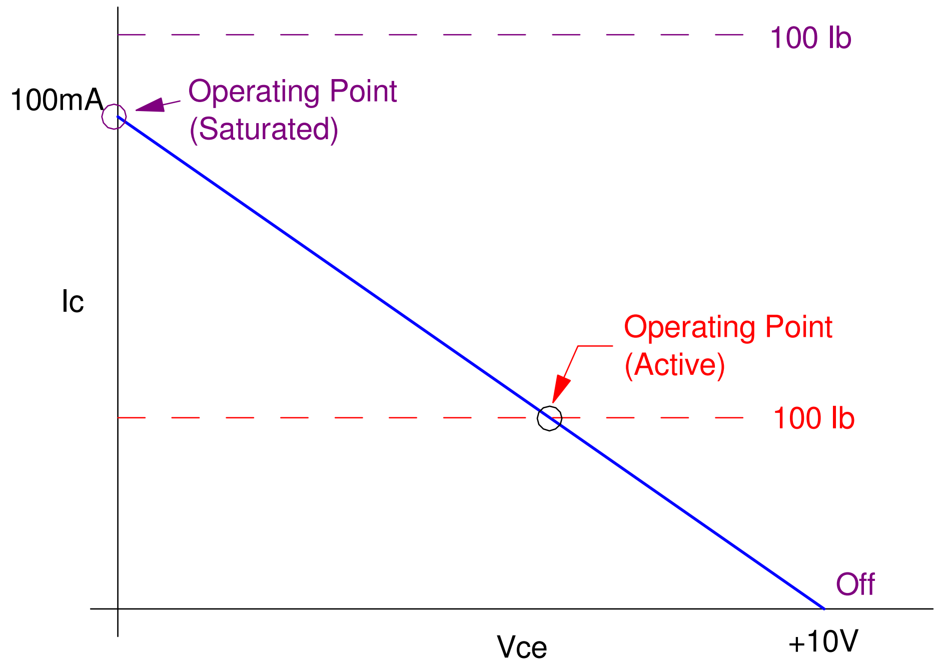


NPN Transistor Operation & Load Lines

Transistors are current limiters

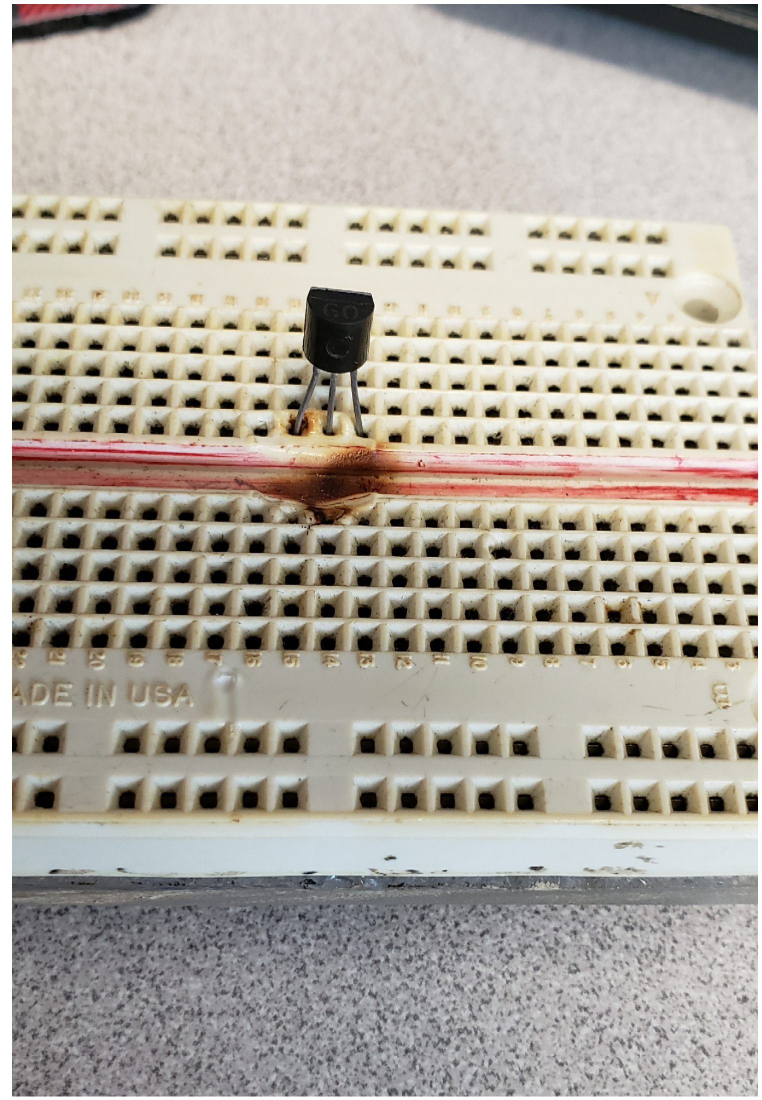
- $I_{c(\max)} = \left(\frac{10V - 0.2V}{100}\right) = 98mA$
- $I_c = \min(\beta I_b, I_{c(\max)})$





Goal when Using a Transistor as a Switch:

Operate Either Saturated (on) or Off (off)



- Saturated:
  - Power = 0
  - Good
- Off:
  - Power = 0
  - Good
- Active:
  - Power > 0
  - Bad

If you operate in the active region, the transistor will get hot (and may melt your breadboard)

Strategy:

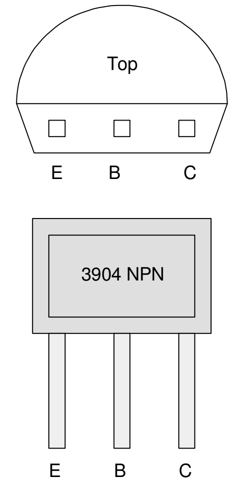
Determine how much current you need

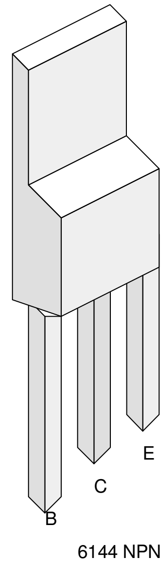
- What is Ic when the transistor is on?

Pick a transistor which can handle the current

Set Ib so that

$$\beta I_b > I_c$$





	2N3904 (NPN)	**6144** (NPN)
Ic max	200mA	13A (peak) 10A (continuous)
current gain (hfe = beta)	100 - 300	200 - 560
Vbe (on)	0.7V	0.7V
Vce (sat)	0.2V	0.18V
Cost	$0.04 ea	$0.62 ea

Example 1: Drive a 200mW LED

Input:

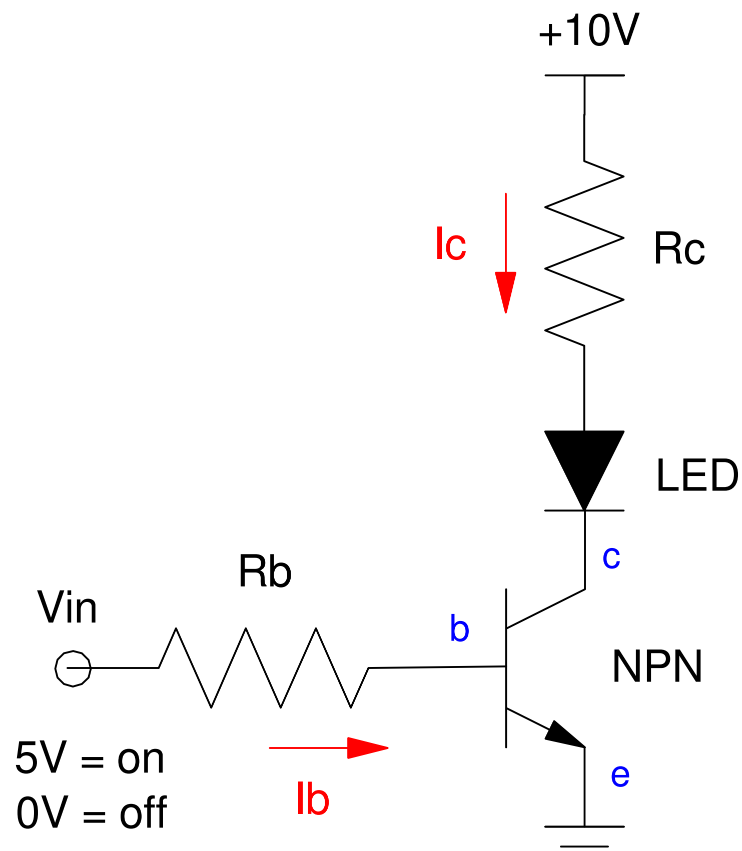
- 0V / 5V capable of 25mA

Output: LED

- Vf = 1.9V, 100mA (max)

Relationship:

- Vin = 0V: LED is off
- Vin = 5V: LED is on (100mA)



NPN Solution:

- Pick an NPN transistor that can handle the current.
  - 2N3904 works
- Pick Rc to set Ic = 100mA
  - The diode drops 1.9V (Vf)
  - The transistor drops 0.2V: (Vce(sat))

$$I_c = 100mA = \left(\frac{10V - 1.9V - 0.2V}{R_c}\right)$$

$$R_c = 79\Omega$$

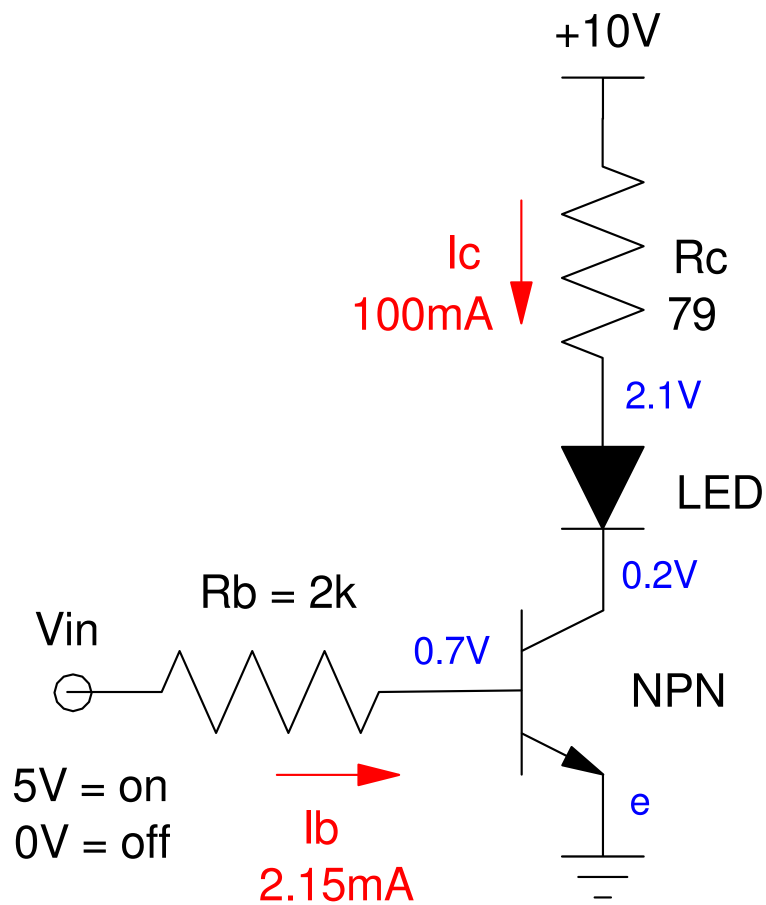
- Pick Rb so that the transistor saturates

$$\beta I_b > I_c$$

$$I_b > 1mA$$

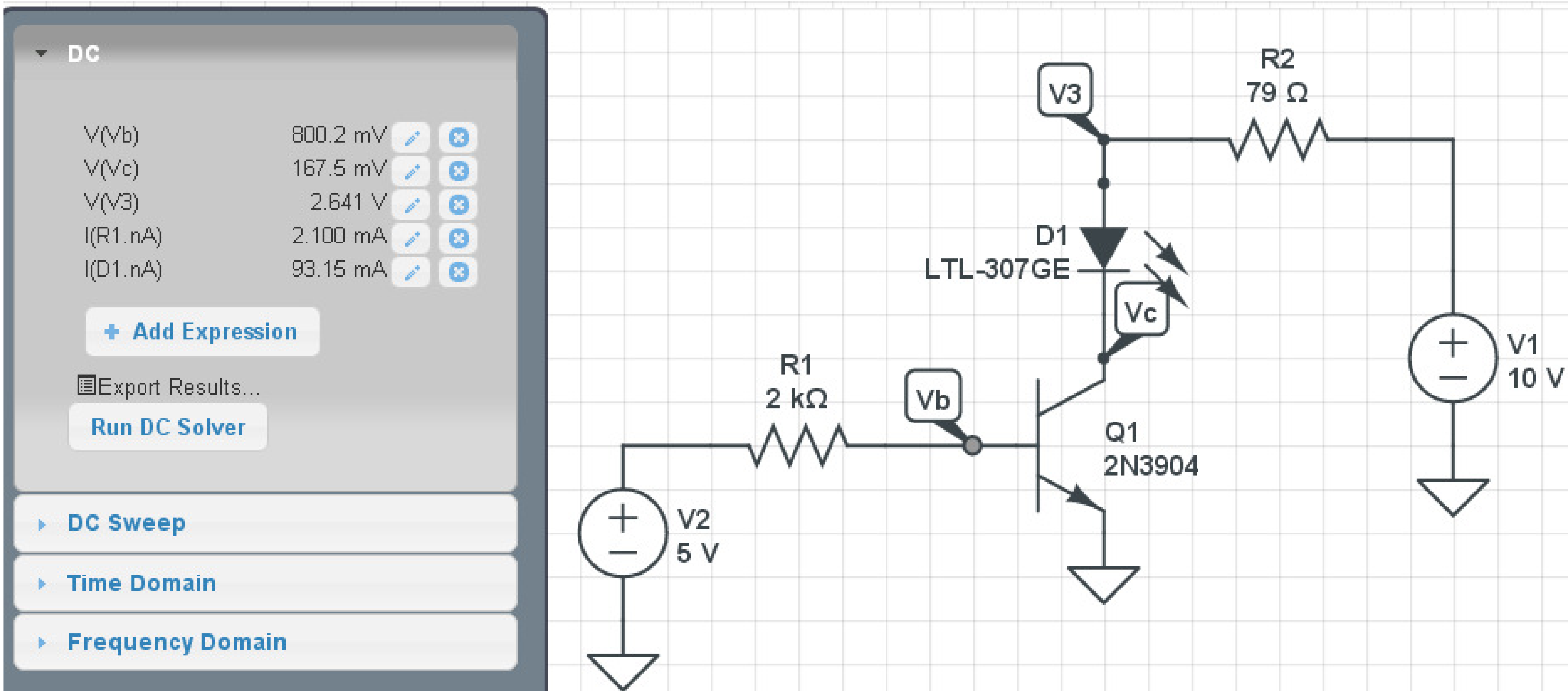
Let Ib = 2mA

$$R_b = \left(\frac{5V - 0.7V}{2mA}\right) = 2150\Omega \rightarrow 2k\Omega$$



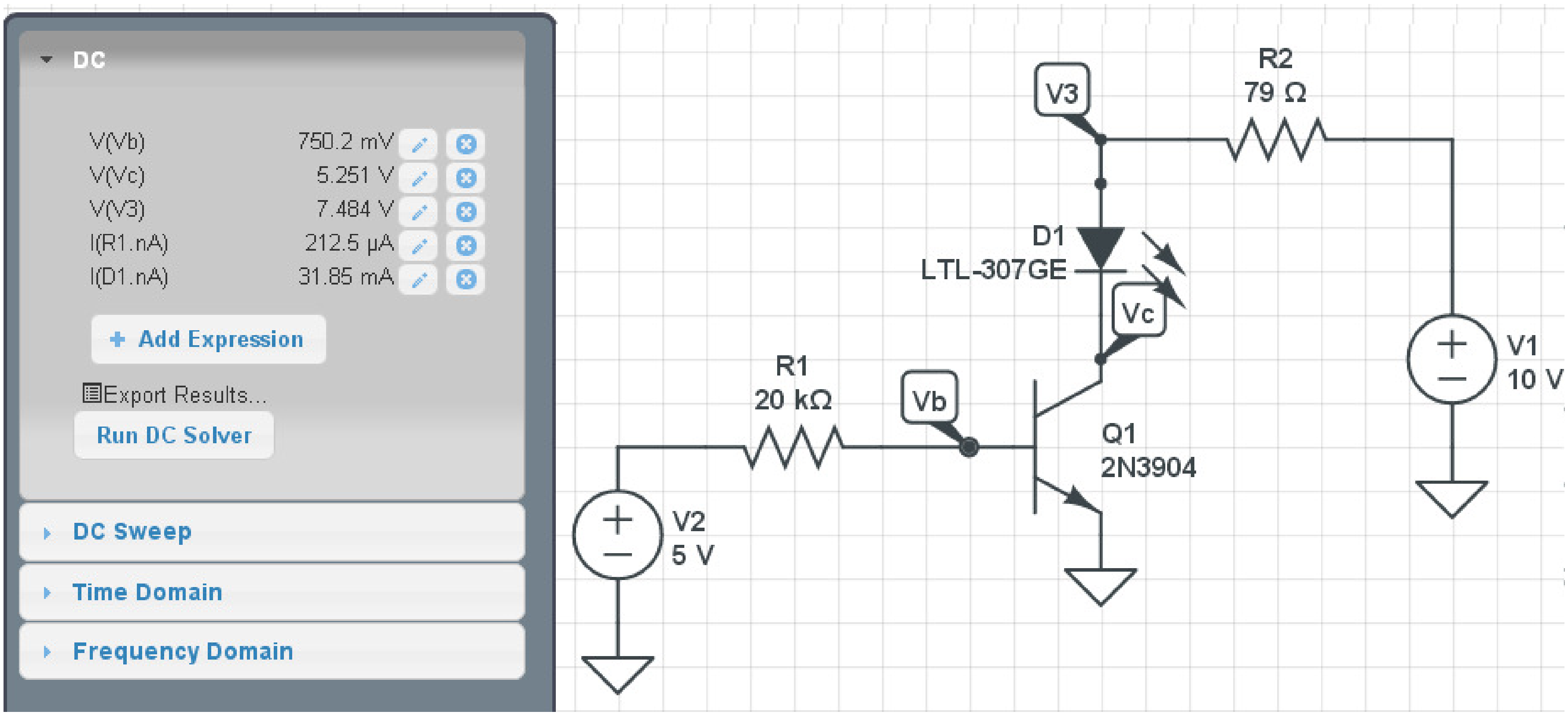
Checking in CircuitLab

- The voltage across the LED is 2.06V (had to modify part to get it to approx 1.9V)
- Vce = 167.5mV (vs. 200mV assumed for Vce(sat))
- Vb = 800.2mV (vs. 700mV assumed for a saturated silicon diode)
- Ic = 93.18mA (vs. 100mA target)



Note that Vce = 167mV tells you that the transistor is saturated:

- Vce = 200mV is a ballpark guess
  - Close to zero but not quite zero
- If Vce > 0.2V, you are operating in the active region
  - You need more base current (Rb is too large)



Checking in Hardware

Measure voltages

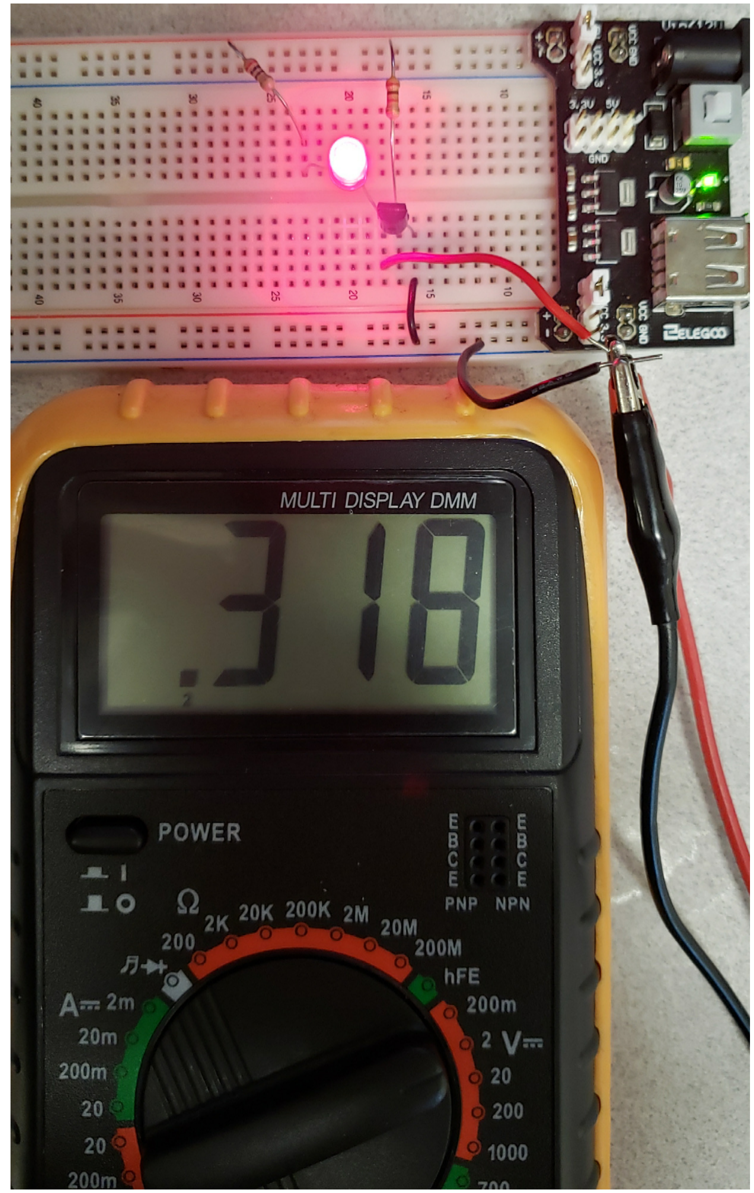
- Calculate currents from V = IR

Results are similar

- Calculated
- Simulated
- Measured

Vce = 0.2V (ish) meaning it's saturated

	Vbe	Vce	Ib	Ic
Calculated	0.7V	0.2V	2.15 mA	100mA
Simulated	0.800 V	0.167V	2.10 mA	93.15 mA
Hardware	0.867V	0.318V	2.07 mA	119.5mA



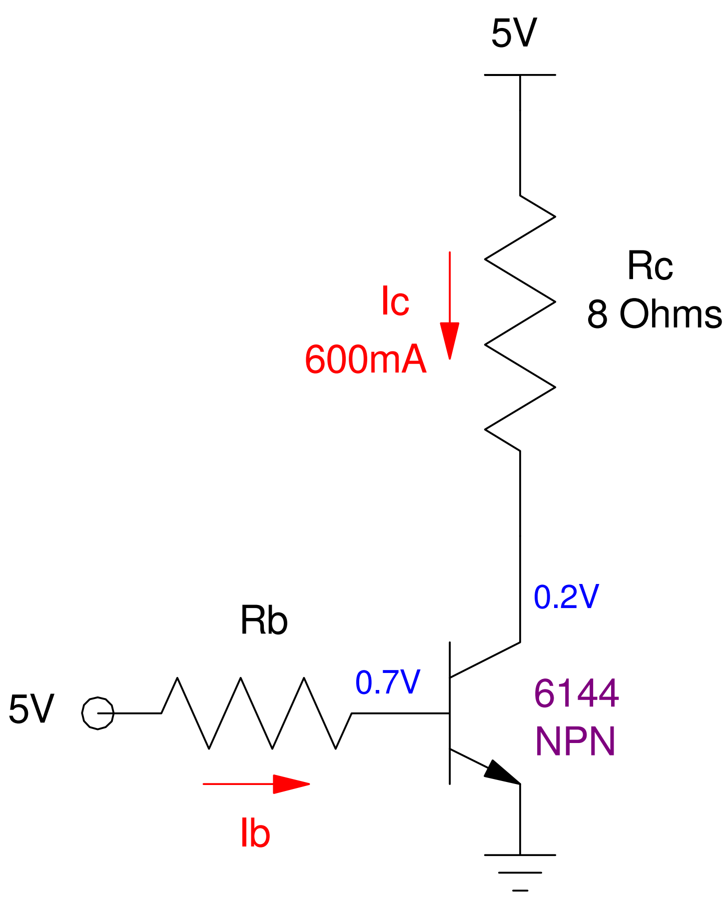
Example 2: Drive an 8-Ohm Speaker

Input: 0V / 5V square wave capable of 20mA

Output: 8 Ohm speaker

Relationship:

- When Vin = 0V, the speaker is off (0V and 0mA)
- When Vin = 5V, the speaker is on (4.8V, 600mA)



Step 1: Calculate the current you need:

$$I = \left(\frac{5V - 0.2v}{8\Omega}\right) = 600mA$$

Step 2: Pick a transistor that can handle the power

6144 NPN transistor

$$\max(I_c) = 10A$$

Step 3: Determine Ib (assume Ib < 25mA)

$$\beta I_b > I_c$$

$$25mA > I_b > \left(\frac{600mA}{200}\right) = 3mA$$

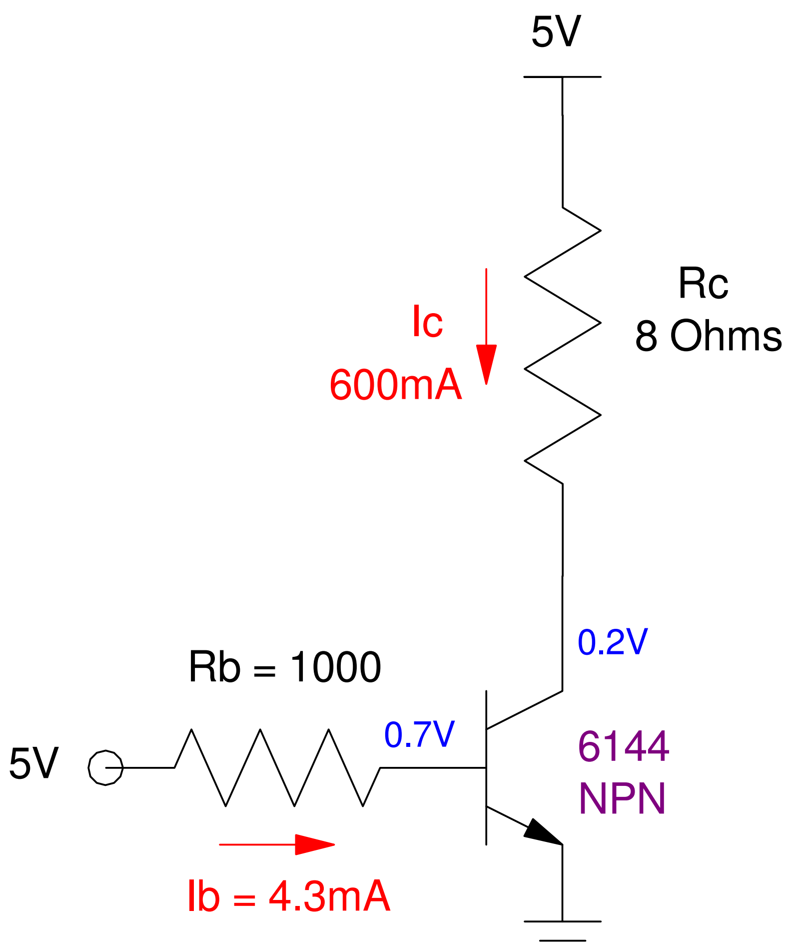
Let Ib = 4.3mA

Step 4: Determine Rb

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

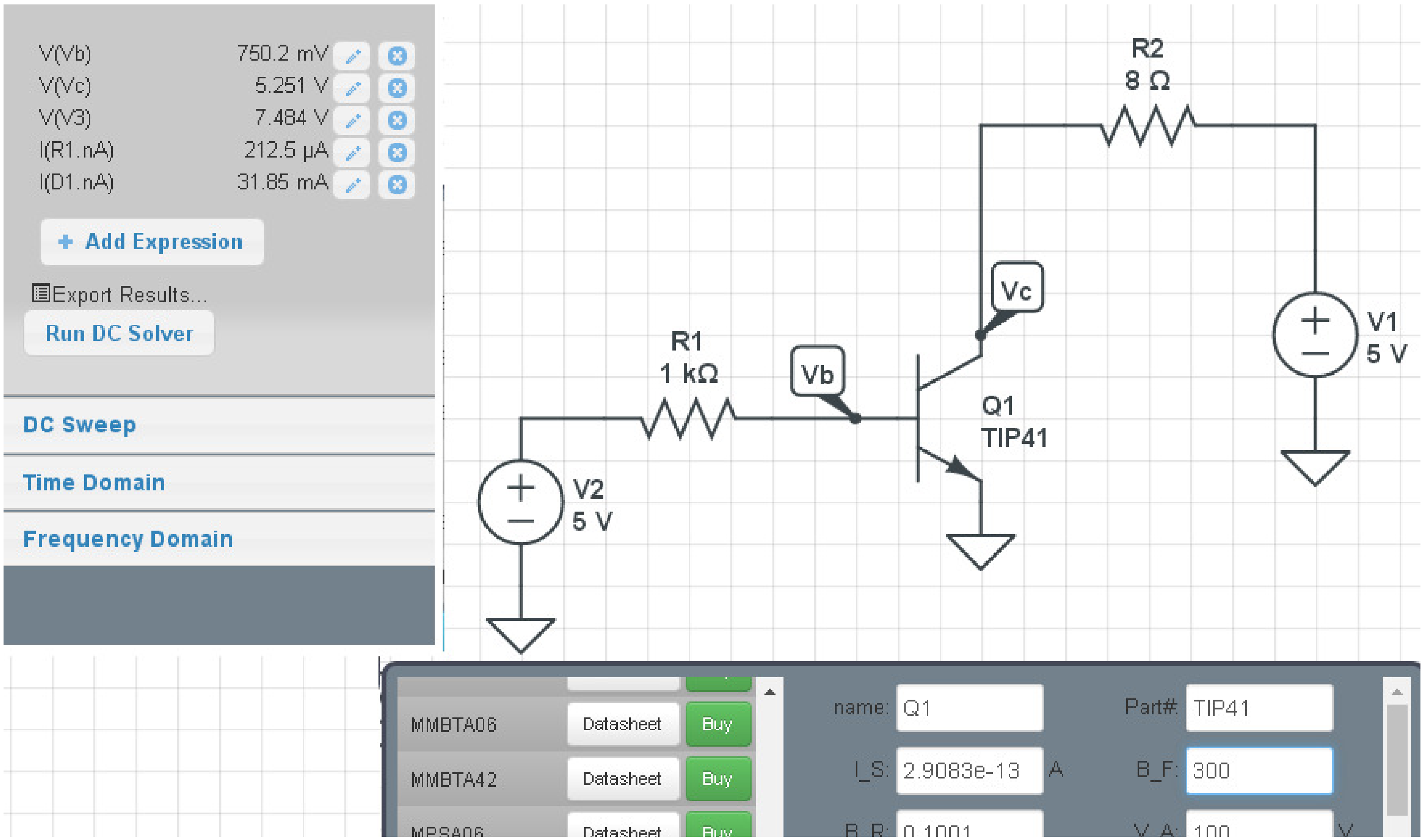
$$R_b = 1000\Omega$$

Anything in the range of 172 .. 1433 Ohms works



Checking in CircuitLab

- 6144 NPN transistor isn't an option, so pick one that's close
- Adjust gain to match a 6144 (B_F = 300)

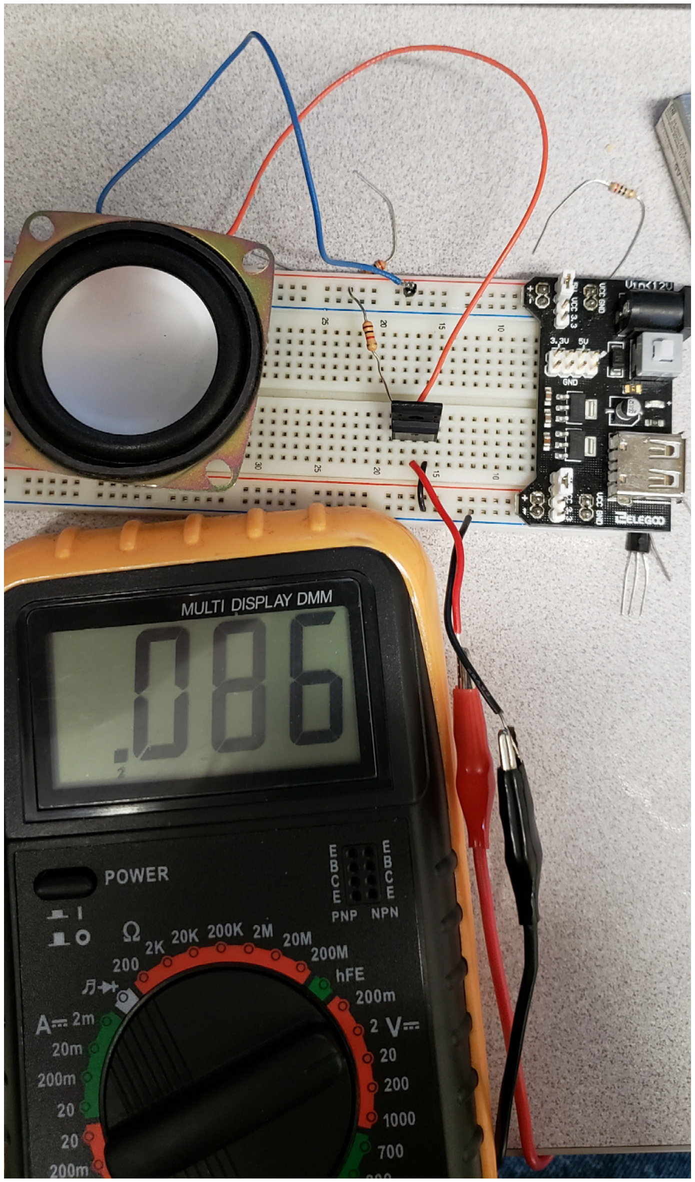


Checking in Hardware

Measure the voltages

- Calculate currents from V = IR
- Vce = 0.2V (ish) meaning it's saturated

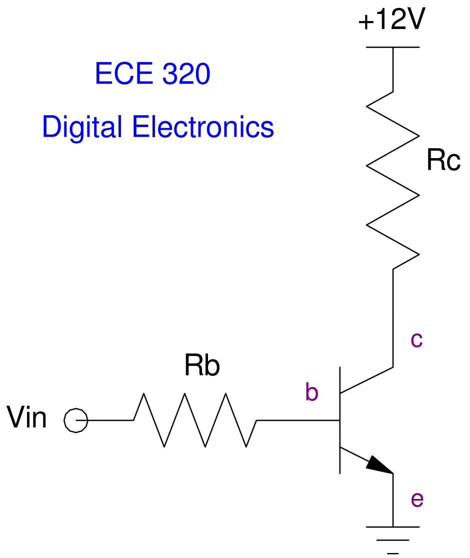
	Vbe	Vce	Ib	Ic
Calculated	0.7V	0.2V	4.30 mA	600.0 mA
Simulated	0.977V	0.088V	4.02 mA	614.0 mA
Hardware	0.670V	0.086V	4.33 mA	614.1mA



Note:

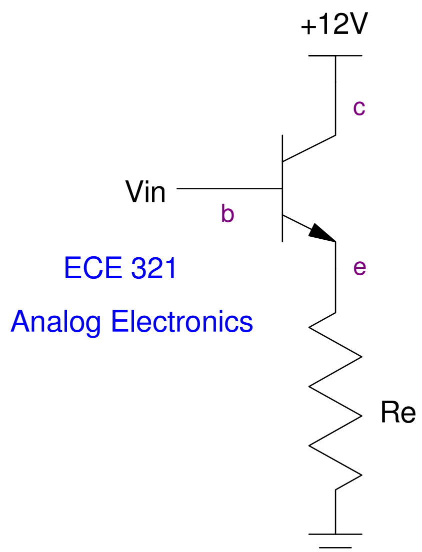
In Digital Electronics (ECE 320), the load connects to the collector

- This allows you to operate the transistor in the saturated (on) and off (off) regions
- The transistor acts as a switch



In Analog Electronics (ECE 321), the load connects to the emitter

- This places the transistor in the active region
- The transistor acts as an amplifier

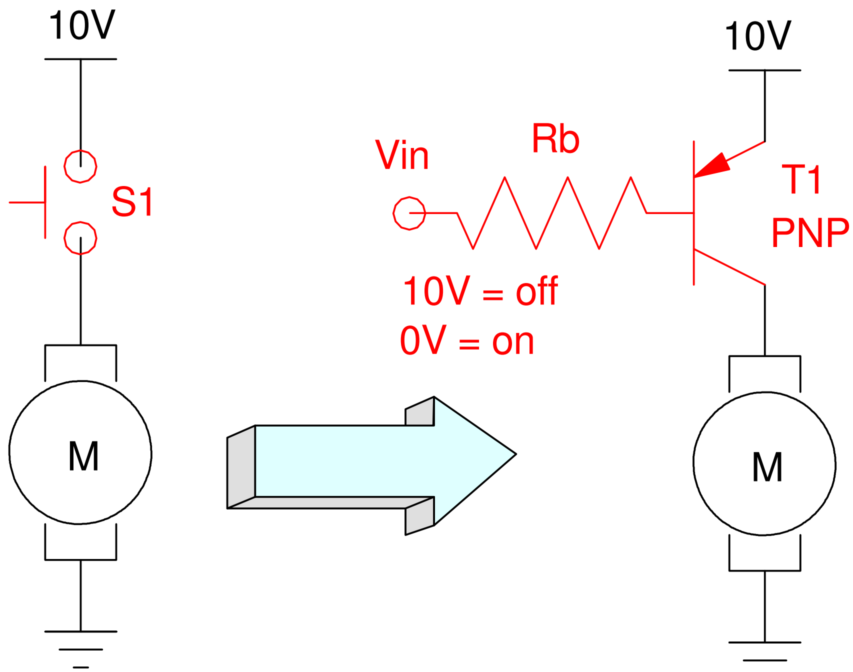


Electronic Switch with PNP Transistors

- Place the switch on the high side
- Use a PNP transistor as an electronic switch

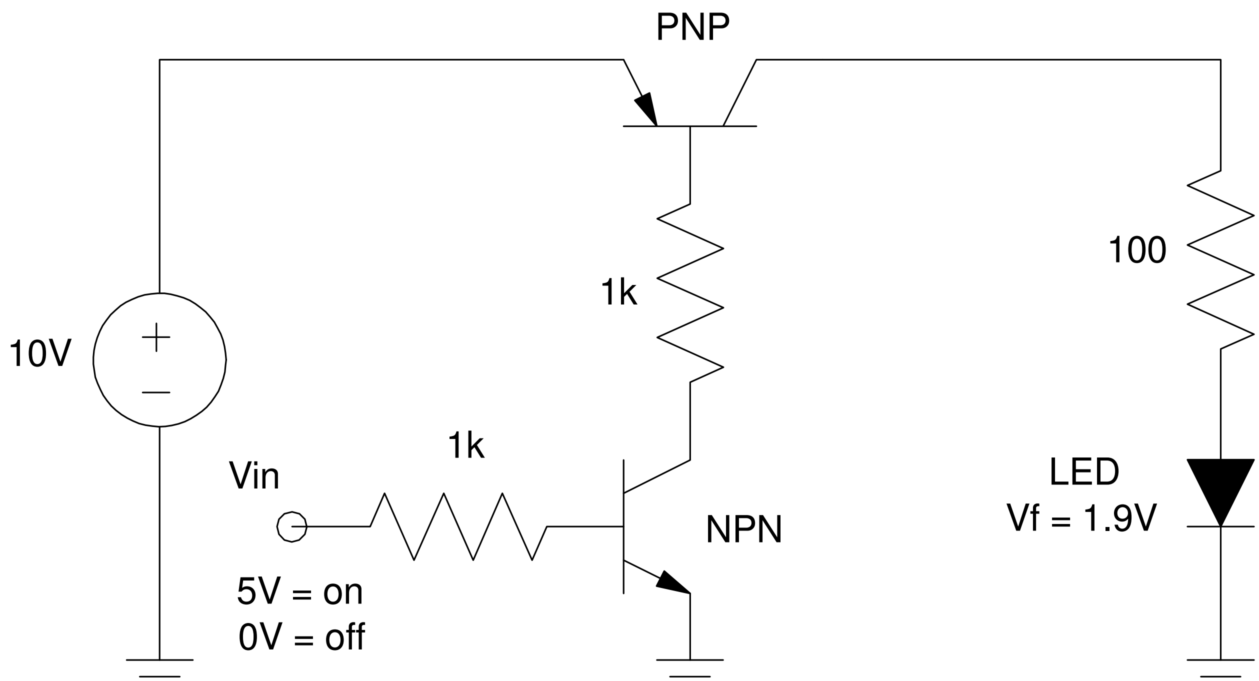
Note: TTL levels don't work

- Vin = 10V is off
- Vin = 0V is on

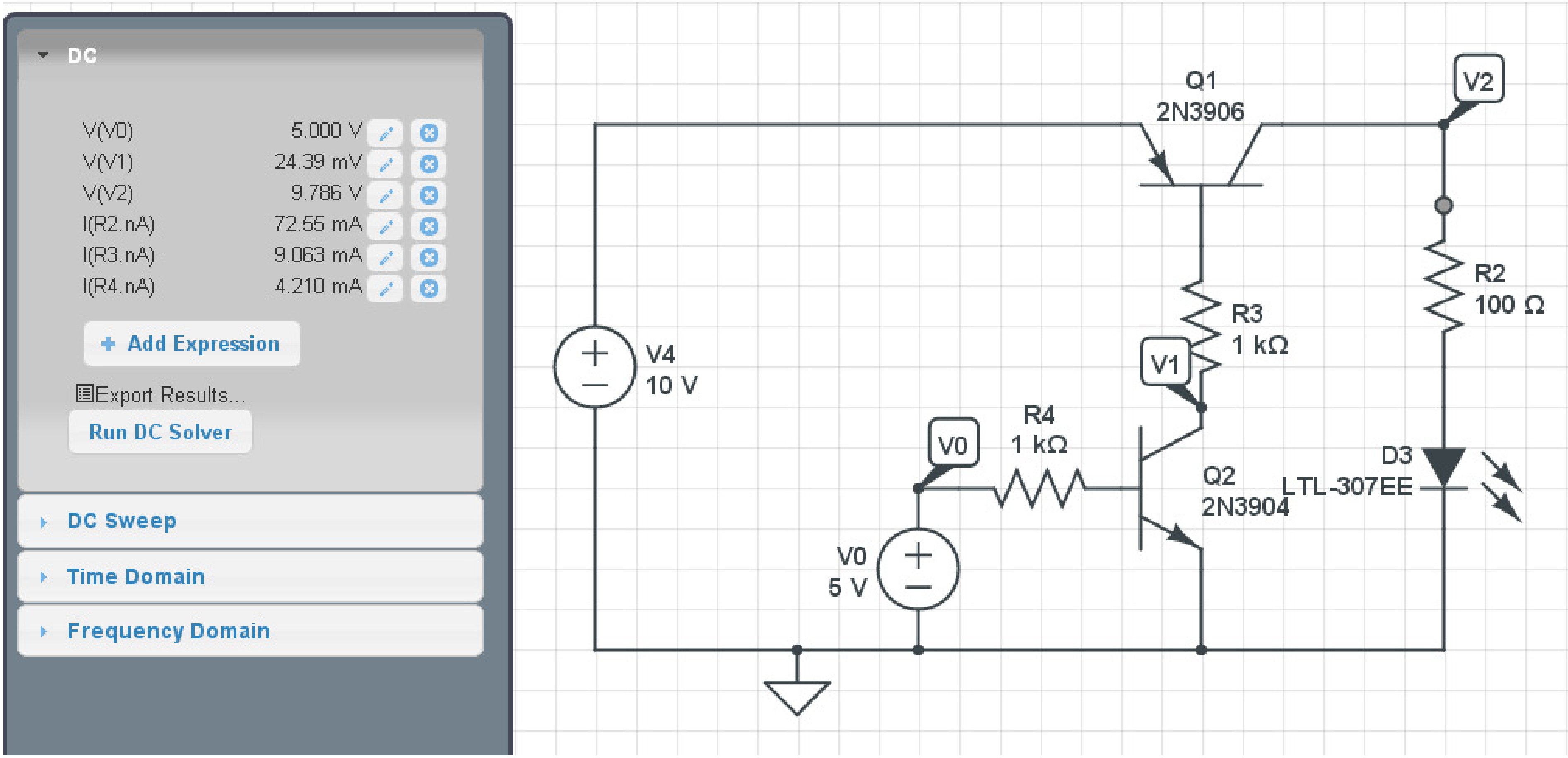


PNP Switch (version 2)

If you want to turn on and off the PNP with a 5V source, add an NPN transistor



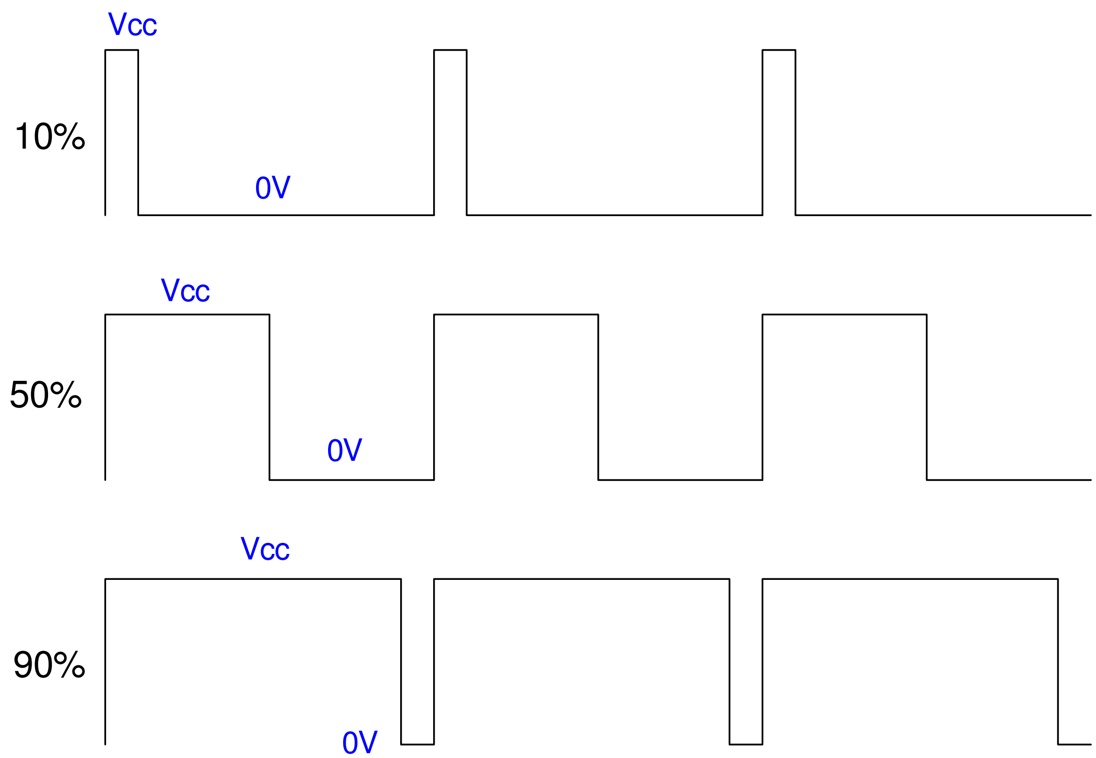
CircuitLab Simulation



Pulse Width Modulation (PWM)

You can 'fake' an analog voltage by varying the duty cycle

- Vin = 0V: off
- Vin = 5V: on
- Vin = X% X% on



Used in

- Tail-Lights
- RGB scoreboards
- Motor speed control
- etc.

PWM & LED Brightness Control

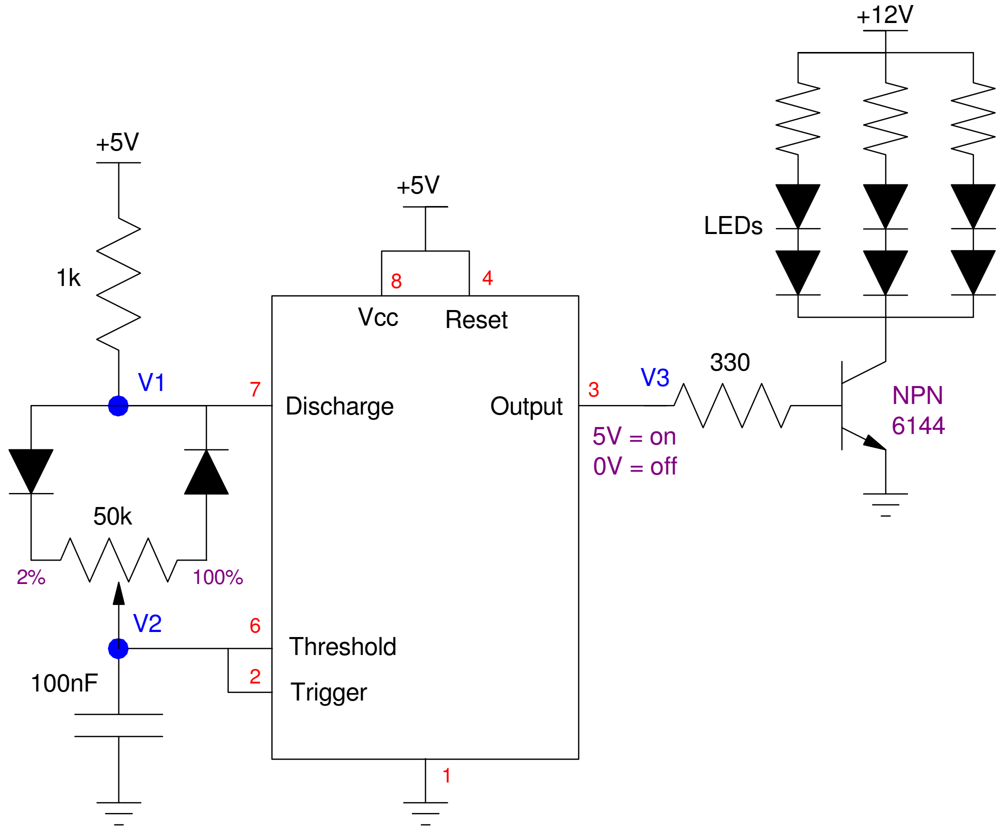
V3 = 5V

- $I_b = \left(\frac{5V - 0.7V}{330\Omega}\right) = 13.03mA$
- $I_c = 300 I_b = 3.9A$

This power a load up to 3.9A

Brightness is adjustable

- 2% with the pot all the way left
- 50% with the pot in the middle
- 100% with the pot all the way right



Darlington Pairs (TIP112)

A TIP112 transistor is actually a Darlington pair

- T1 provides gain
- T2 provides high current

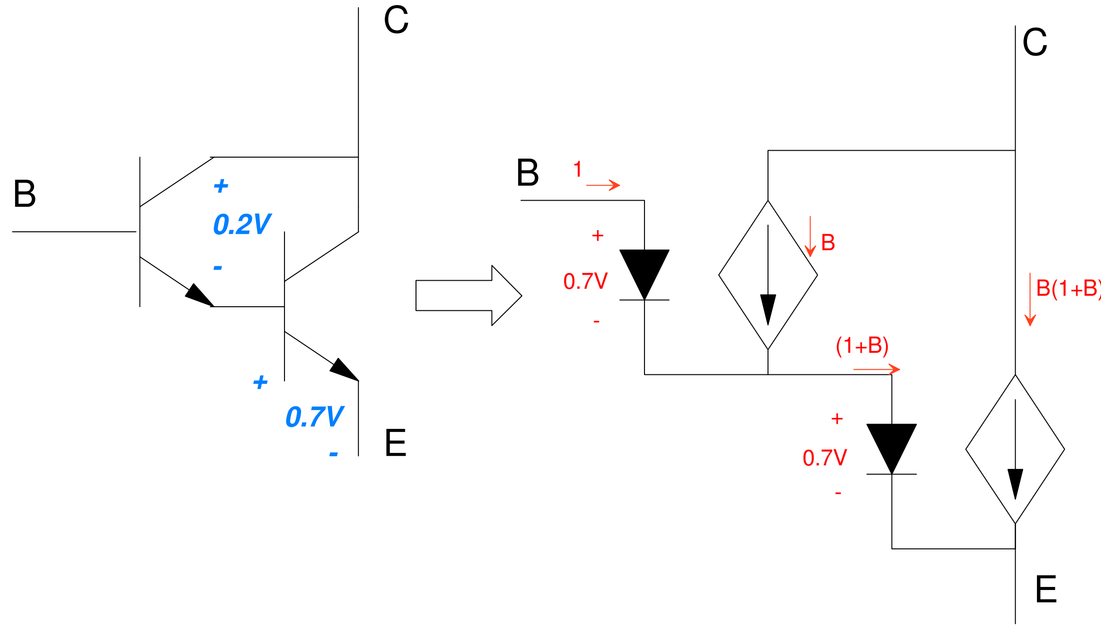
The net result looks like a big hogging transistor

$$V_{be} = 1.4V$$

$$\min V_{ce} = 0.9V$$

$$\beta = (1 + \beta_1)\beta_2 > 1000$$

$$\max(Ic) = 4A$$



Example 2: Drive an 8-Ohm speaker.

Input: 0V / 5V square wave capable of 20mA

Output: 8 Ohm speaker

Relationship:

- When Vin = 0V, the speaker is off (0V and 0mA)
- When Vin = 5V, the speaker is on (5V, 625mA)

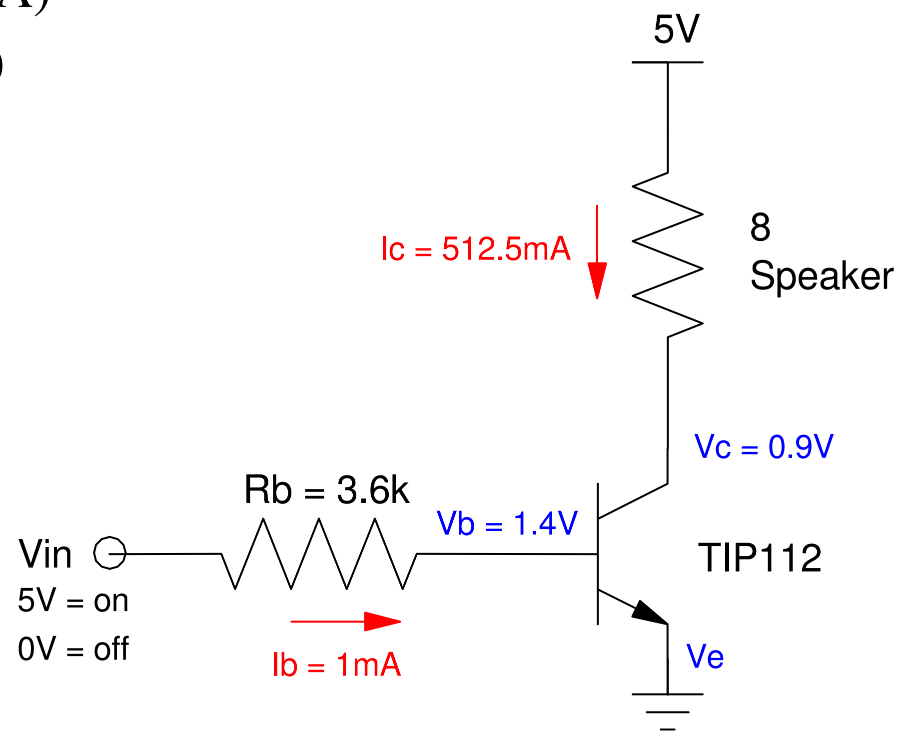
$$I_c = \left(\frac{5V - 0.9V}{8\Omega}\right) = 512.5mA$$

$$\beta I_b > I_c$$

$$I_b > 512.5\mu A$$

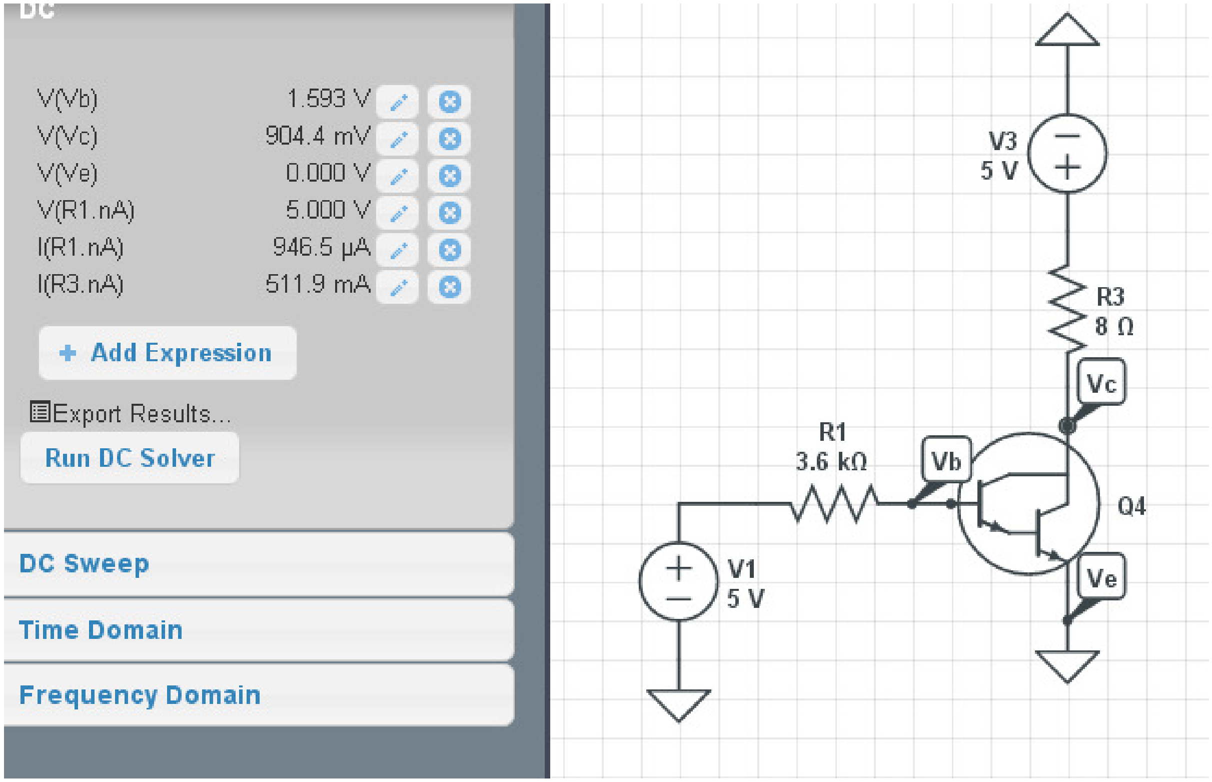
Let Ib = 1mA. Then

$$R_b = \left(\frac{5V - 1.4V}{1mA}\right) = 3.6k\Omega$$



CircuitLab Simulation

- Vb = 1.593V *1.4000V calculated*
- Vce = 904.4mV *900mV calculated*
- Ic = 511.9mA *512.5mA calculated*



Transistor Switch Demo

How to annoy your friends and neighbors

On/Off Control of a DC Motor

Problem:

- A DC motor only draws 30mA @ 24V when operating
- A 2904 transistor is used to turn it on and off, which is capable of 200mA
- The transistor *should* be able to handle the load

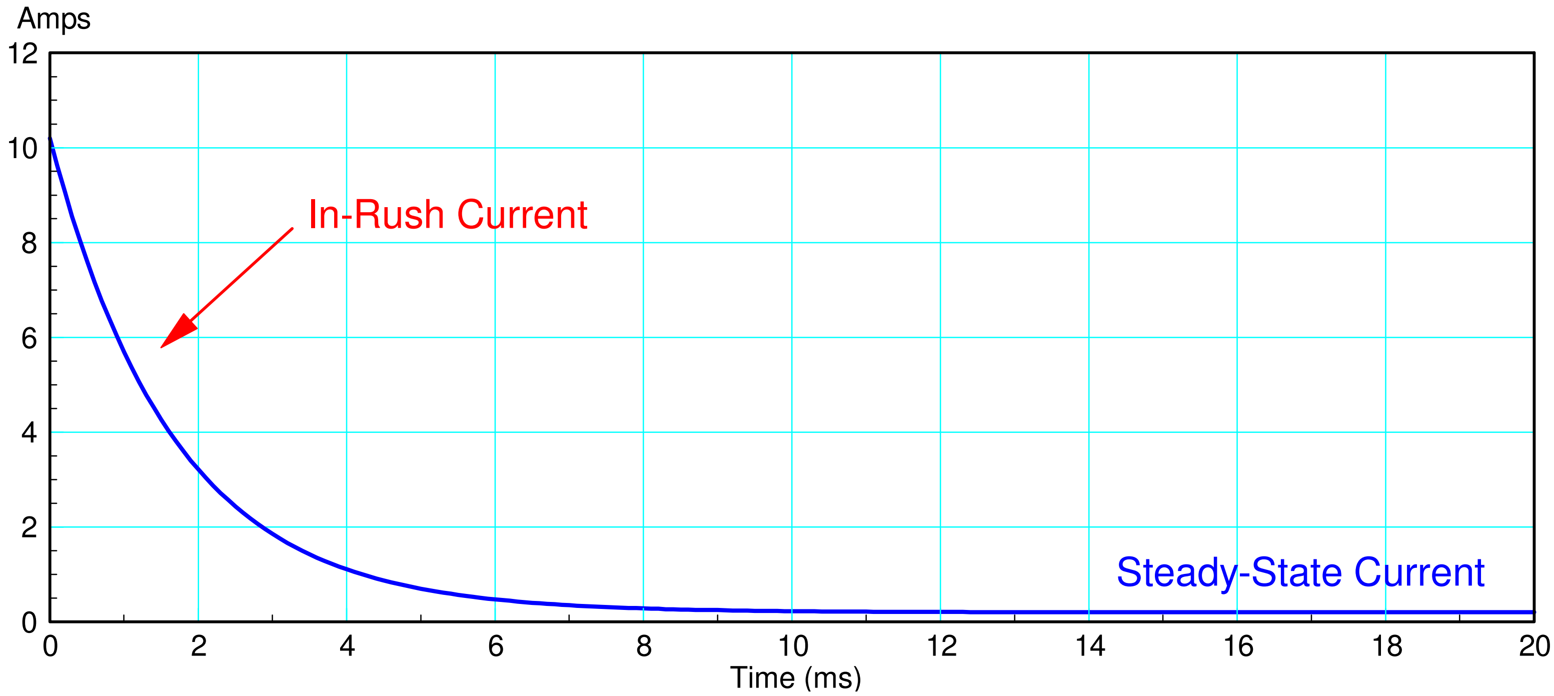
The transistor keeps getting fried.

Why?

Reason #1: In-Rush Current

The start-up current for a DC motor is much larger than the operating current

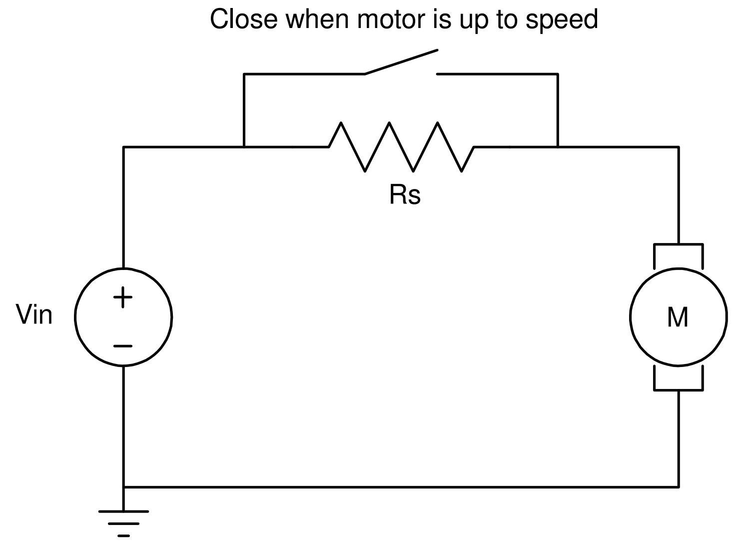
- When starting, a large amount of power is consumed. This power (VI) is stored in the motor's kinetic energy. (starting current is large)
- When starting, the back EMF is zero. This results in the current being limited by only the armature resistance. (starting current is large)



Ways to Limit In-Rush Current

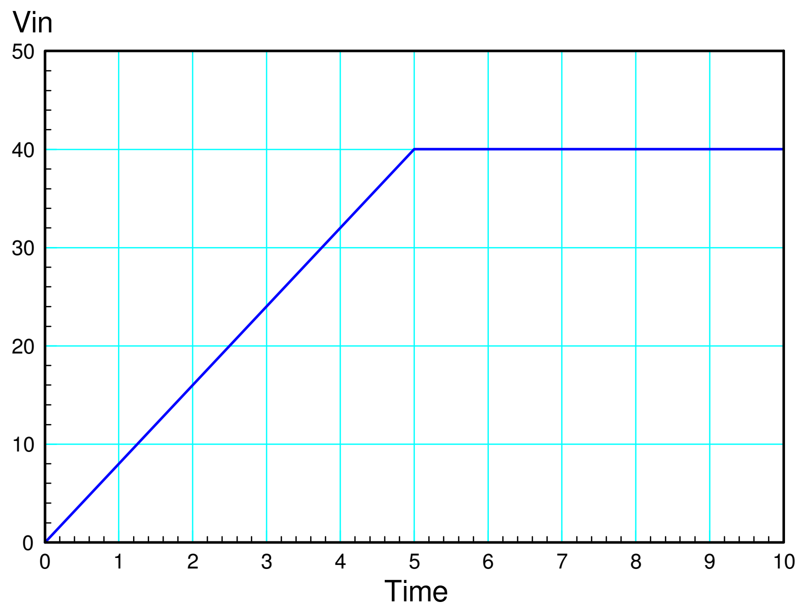
a) Add a resistor in series during startup

- The in-rush current will burn out the windings in large DC motors (covered in ECE 331)
- By adding a resistor in series, you limit the in-rush current.
- Once the motor gets up to speed, then remove the added resistance.



b) Ramp up the voltage

- Slowly bring the motor up to speed.



Reason #2: Motor Inductance

- Motors are inherently inductors.

The voltage across an inductor is

$$V = L \cdot \frac{dI}{dt}$$

Turning off the motor results in $\frac{dI}{dt} \to \infty$

- This fries the transistor

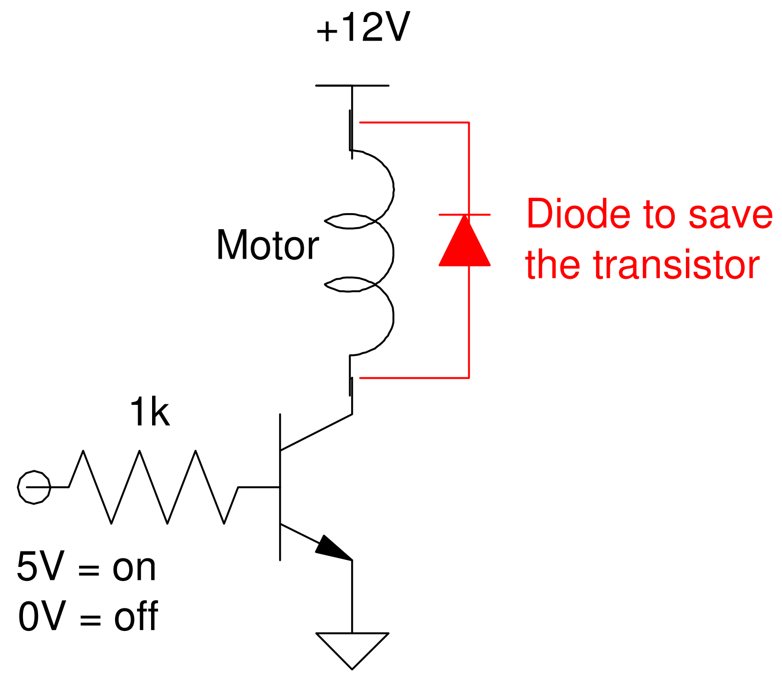
This is how spark plugs work

- Pass current through a large inductor (the car's alternator)
- This stores energy in a magnetic field ($E = \frac{1}{2}LI^2$)
- When the current goes to zero, the magnetic field collapses
- The energy stored is released by driving the current to infinity

Fix: Flyback Diodes

Flyback Diodes

- Provides a path for the current as the magnetic field collapses
- Clips the voltage at Vc to 12.7V



NPN Transistor Switch

Summary

Transistors can be used as an electronic switch

- Pick a transistor that can handle the load
- Place the load on the collector side
- Connect the emitter to ground
- Pick Rb so that

$$\beta I_b > I_c$$