Using a Transistor as a Switch

Background:

Transistors can be used as a buffer between a microcontroller and another device. Microcontrollers typically output +5V and up to +20mA. With a transistor, this 0V/5V signal can turn on and off:

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

If you are driving something that requires more than +5V or more than 20mA, you need to use a buffer, such as a transistor.

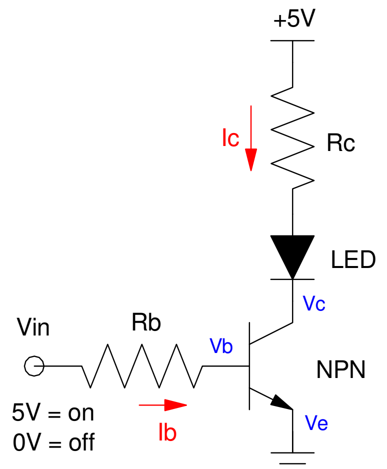
Note: For each of these, make sure that you are using a transistor which can handle the current. As a reminder, the ones we use are

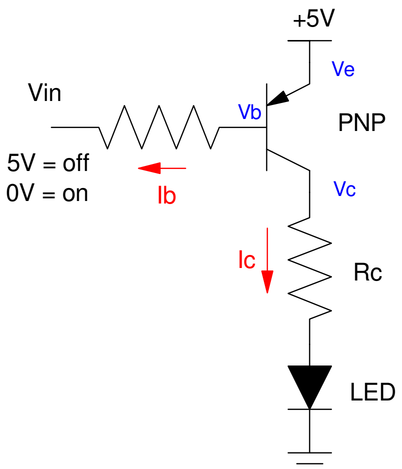
	2N3904 (NPN)	TIP112 (NPN)
Ic max	200mA	4A (peak) 2A (continuous)
current gain (hfe = beta)	100 - 300	> 1000
Vbe (on)	0.7V	1.4V
Vce (sat)	0.2V	0.9V
Cost	$0.04 ea	$0.34 ea

Example 1: Use a 0V/5V TTL signal to turn on and off a 200mW LED at 100mA. Assume

- The 5V source can output only 20mA (or less),
- The LED drops 1.9V when on.

Solution: There are actually two solutions depending on whether you prefer NPN or PNP transistors.





NPN Solution:

- Pick an NPN transistor that can handle the current. A 2n3904 works
- Use the circuit above. Place the transistor between the LED and ground.
- Pick Rc to set Ic = 100mA
    - The diode drops 1.9V (Vf)
    - The transistor drops 0.2V: (Vce(sat))

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

$$R_c = 29\Omega$$

- Pick Rb so that the transistor saturates

$$\beta I_b > I_c$$

$$I_b > 1mA$$

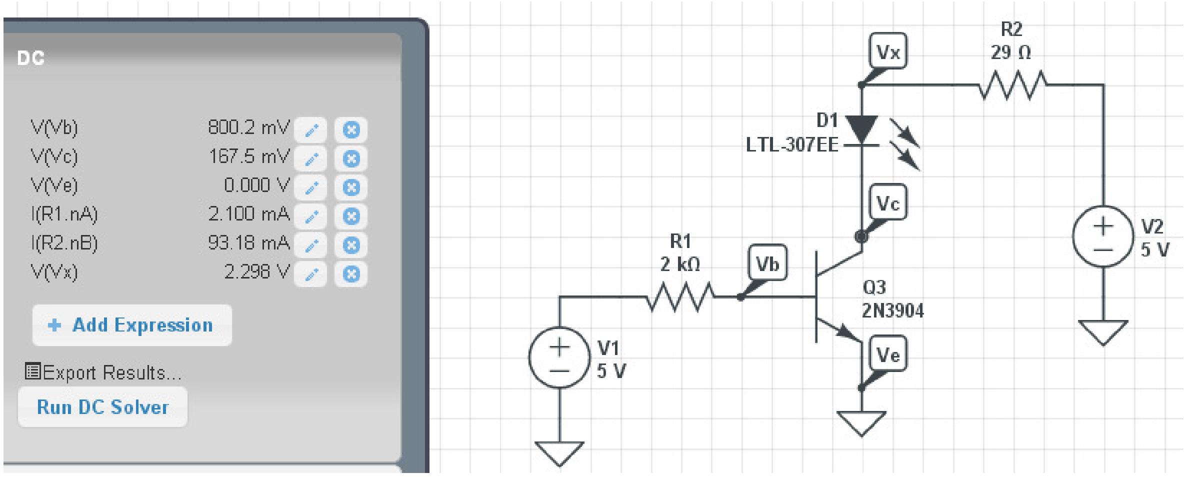
Let Ib = 2mA

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

The exact value of Rb isn't critical: anything that results in Ib > 1mA works.

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)



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DC

V(Vb)        800.2 mV
V(Vc)        167.5 mV
V(Ve)        0.000 V
I(R1.nA)     2.100 mA
I(R2.nB)     93.18 mA
V(Vx)        2.298 V
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Simulation of a transistor switch in CircuitLab. When V1 = 0V, the transistor is off and all currents are zero. (not shown)

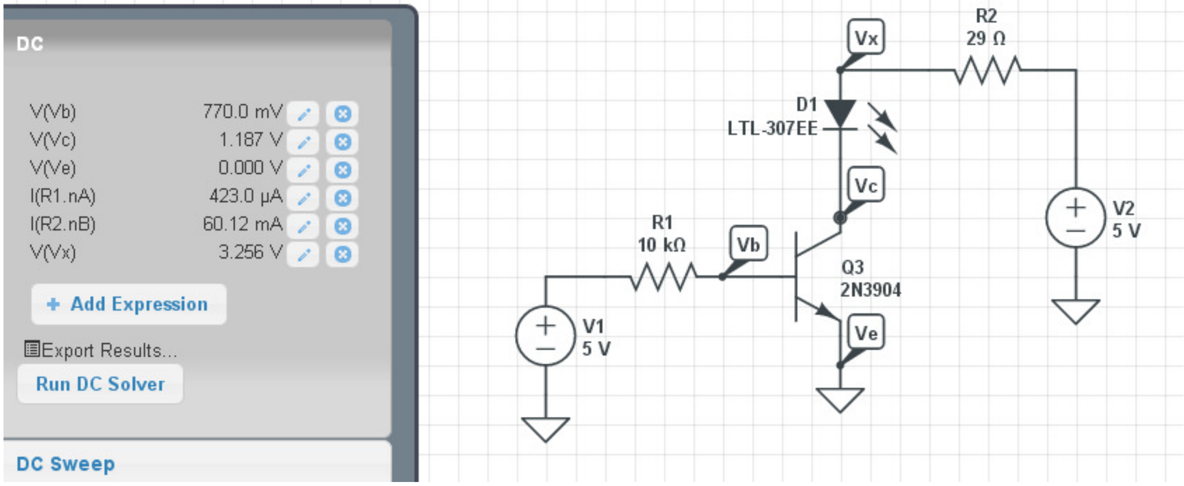
Note that Vce = 800mV tells you that the transistor is saturated:

- Ideally, Vce = 0V for an ideal switch.
- If Vce is close to zero, the switch is working

To illustrate this, increase R1 (Rb) to 10k Ohms. This results in

- Vce = 1.187V

The transistor now in the active region (and will get hot: VI > 0). This tells you that you need more base current to satuate the transistor (R1 is too large).



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V(Vb)     770.0 mV
V(Vc)      1.187 V
V(Ve)      0.000 V
I(R1.nA)  423.0 µA
I(R2.nB)  60.12 mA
V(Vx)      3.256 V
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If R1 (Rb) is too large, the transistor will no longer saturate. This show up with Vce > 0.2V

Darlington Pairs

Example 2: Design a circuit to allow a function generator to drive an 8-Ohm speaker.

Input: 0V / 5V square wave capable of 20mA (i.e. a function generator, PIC board, etc)

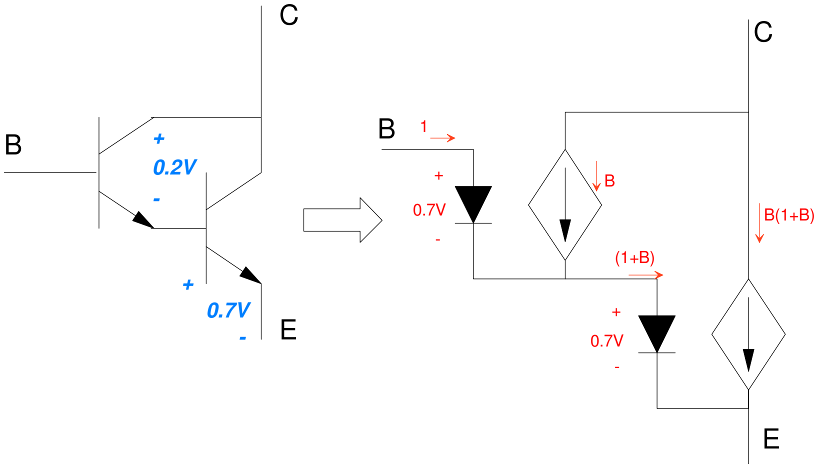
Output: 8 Ohm spekaer

Relationship:

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

Solution: In this case, the 3904 transistors will not work: they can't take the current. Instead, use a TIP112 transtor.

A TIP112 tansistor is actually a Darlington pair. This is a pair of transistors put back to back as follows:



Darlington Pair: Two transisors put back to back

Darlington pairs use two transistors:

- The first transistor in a Darlington pair provides a high gain (say, 100).
- The second transistor provides a high currcent capability (4A max with a gain of 10)

Together, you wind up with a transistor with

- A high overall gain (10 x 100 = 1000), and
- A high current capability (4A)

The reason to use a Darlington pair is to obtain both

- High current capacity, and
- High gain

By combining two transistors, you wind up with what looks like a single transistor with

- Vbe(on) = 1.4V *two diodes are in series from base to emitter*
- Vce(sat) = 0.9V *Add 0.2V across transistor 1 (Vce) plus 0.7V for transistor 2 (Vbe)*
- $\beta = (1+\beta_1)\beta_2$

For the transistors we have in lab (2n3904 and TIP112), the latter is a Darlington pair with $\beta > 1000$.

Going back to example #2 (drive an 8-Ohms speaker at 5V), you wind up with

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

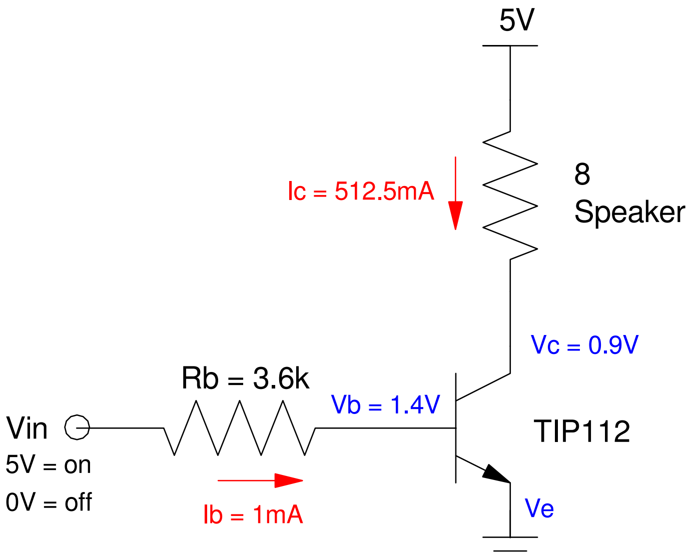
To saturate the transistor, pick Ib so that

$$\beta I_b > I_c$$

$$I_b > 512.5\mu A$$

Let Ib = 1mA. Then

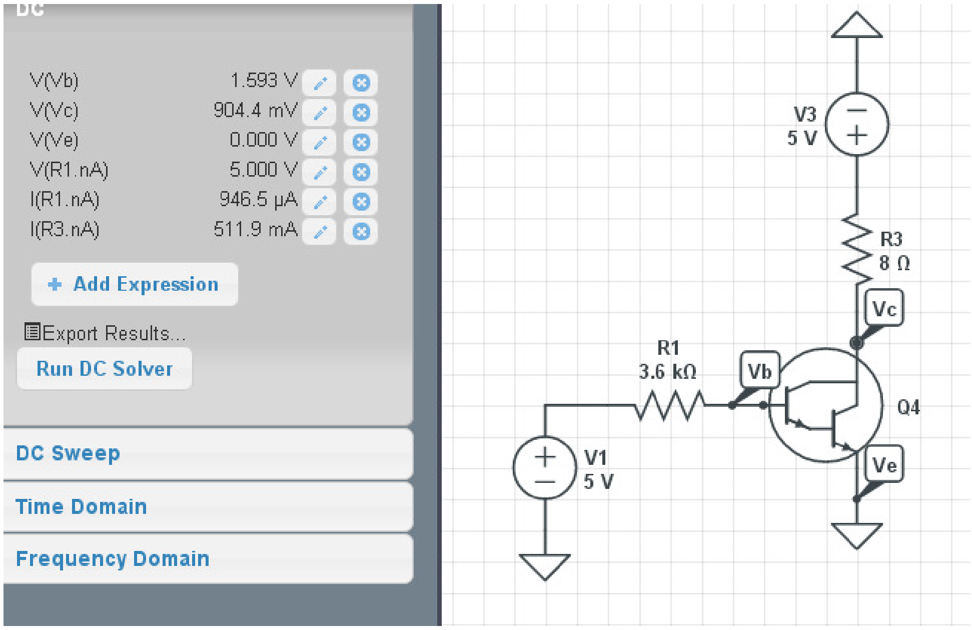
$$R_b = \left(\frac{5V - 1.4V}{1mA}\right) = 3.6k\Omega$$



Using a TIP112 transistor to drive an 8-Ohm speaker.

Simulating this circuit in CircuitLab gives almost the same results

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



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V(Vb)        1.593 V
V(Vc)        904.4 mV
V(Ve)        0.000 V
V(R1.nA)     5.000 V
I(R1.nA)     946.5 µA
I(R3.nA)     511.9 mA
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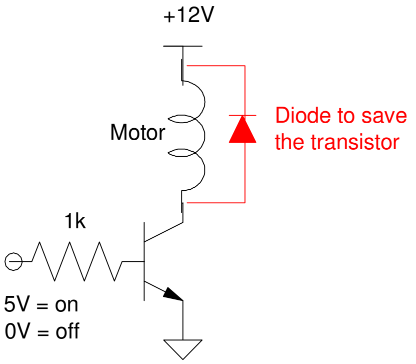
Example 3: Drive a 12V, 1A DC motor

Motors are inductive in nature. This causes a problem when turning them on and off

- When on, energy is stored in the magnetic field as $E = \frac{1}{2}LI^2$
- This collapse creates large voltages $\left(V = L\frac{dI}{dt}\right)$ as the energy in the magnetic field *has* to go somewhere
- These large voltages can fry your transistor.

In order to save the transistor, a flyback diode is needed. This diode

- Provides a path for the current to follow, and
- Clips the voltage at Vc to 12.7V



NPN Transistor Switch