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

<table>
<thead>
<tr>
<th></th>
<th>2N3904 (NPN)</th>
<th>TIP112 (NPN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ic max</td>
<td>200mA</td>
<td>4A (peak)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2A (continuous)</td>
</tr>
<tr>
<td>current gain (hfe = beta)</td>
<td>100 - 300</td>
<td>&gt; 1000</td>
</tr>
<tr>
<td>Vbe (on)</td>
<td>0.7V</td>
<td>1.4V</td>
</tr>
<tr>
<td>Vce (sat)</td>
<td>0.2V</td>
<td>0.9V</td>
</tr>
<tr>
<td>Cost</td>
<td>$0.04 ea</td>
<td>$0.34 ea</td>
</tr>
</tbody>
</table>

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 $R_c$ to set $I_c = 100\text{mA}$:
  - The diode drops 1.9V ($V_f$).
  - The transistor drops 0.2V: ($V_{ce(sat)}$).

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

$$R_c = 29\Omega$$

- Pick $R_b$ so that the transistor saturates

$$\beta I_b > I_c$$

$$I_b > 1\text{mA}$$

Let $I_b = 2\text{mA}$

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

The exact value of $R_b$ isn’t critical: anything that results in $I_b > 1\text{mA}$ works.

Checking in CircuitLab

- The voltage across the LED is 2.06V (had to modify part to get it to approx 1.9V).
- $V_{ce} = 167.5\text{mV}$ (vs. 200mV assumed for $V_{ce(sat)}$).
- $V_b = 800.2\text{mV}$ (vs. 700mV assumed for a saturated silicon diode).
- $I_c = 93.18\text{mA}$ (vs. 100mA target).
Note that $V_{ce} = 800\text{mV}$ tells you that the transistor is saturated:
- Ideally, $V_{ce} = 0\text{V}$ for an ideal switch.
- If $V_{ce}$ is close to zero, the switch is working

To illustrate this, increase $R_1$ ($R_b$) to 10k Ohms. This results in
- $V_{ce} = 1.187\text{V}$

The transistor now in the active region (and will get hot: $V_I > 0$). This tells you that you need more base current to saturate the transistor ($R_1$ is too large).

If $R_1$ ($R_b$) is too large, the transistor will no longer saturate. This show up with $V_{ce} > 0.2\text{V}$

### 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 $V_{in} = 0\text{V}$, the speaker is off ($0\text{V}$ and $0\text{mA}$)
- When $V_{in} = 5\text{V}$, the speaker is on ($5\text{V}$, 625mA)

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

A TIP112 transistor is actually a Darlington pair. This is a pair of transistors put back to back as follows:
Darlington pairs use two transistors:
- The first transistor in a Darlington pair provides a high gain (say, 100).
- The second transistor provides a high current capability (4A max with a gain of 10)

Together, you wind up with a transistor with
- A high overall gain \((10 \times 100 = 1000)\), 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
- \(V_{be(on)} = 1.4V\) \(\text{two diodes are in series from base to emitter}\)
- \(V_{ce(sat)} = 0.9V\) \(\text{Add 0.2V across transistor 1} \ (V_{ce}) \text{plus 0.7V for transistor 2} \ (V_{be})\)
- \(\beta = (1 + \beta_1)\beta_2\)

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 $I_b$ so that

$$\beta I_b > I_c$$

$$I_b > 512.5\,\mu A$$

Let $I_b = 1\,mA$. Then

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

Simulating this circuit in CircuitLab gives almost the same results

- $V_b = 1.593V$  
  \textit{1.4000V calculated}
- $V_{ce} = 904.4mV$  
  \textit{900mV calculated}
- $I_c = 511.9mA$  
  \textit{512.5mA calculated}
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 \( V = L \frac{dI}{dt} \) 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 \( V_c \) to 12.7V