Current Mirrors

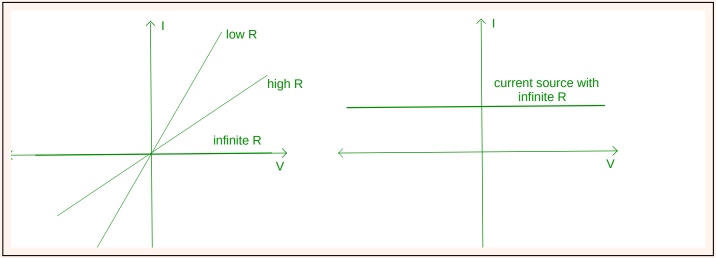
- Sometimes it's advantageous to have a current source in our circuits.
- A current source could be approximated with a high-value resistor and a high-voltage. But this is of limited usefulness as resistors consume a large area in ICs.
- Current sources can provide a high resistance load for an amplifier, increasing its gain dramatically.
- An ideal voltage source sources whatever current necessary to maintain a constant voltage across its terminals.
- A current source adjusts its terminal voltage to a value necessary to maintain a constant current through its terminals.

Ideal Voltage Source: Source/Sink current necessary to maintain the terminal voltage

Ideal Current Source: Raise/Lower terminal voltage to maintain the desired current

Current Mirrors

- Real BJTs can only approximate an ideal current source.
- Our circuits do not have infinite voltage supplies available.
- The limitation of BJT current sources to maintain a constant current due to limited supplies or circuit design is called its *compliance*.
- For example, a BJT current source operating from a single 5 volt supply cannot raise its voltage to more than 5V or lower than 0V.
- Another limitation of BJT current sources is output impedance. They can provide fairly high Z_{out} but not ∞.



Current Mirrors

- We looked at the traditional BJT model as a current controlled current source. The base current controlled a collector current. The defining equation of the CCCS is $I_c = \beta * I_b$.
- As we have seen, the more useful way to look at BJTs (and current sources) is to view it as a voltage controlled current source (VCCS). In this case the defining equation is the Ebers-Moll equation:

  $I_e = I_{es}(e^{\frac{V_{be}}{V_T}} - 1)$; where:

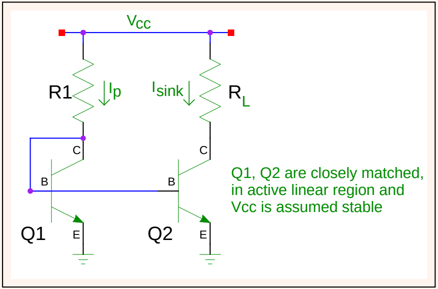
  I_e is the emitter current
  I_{es} is the B-E reverse saturation current (10^{-15} to 10^{-12} A)
  V_{be} is the base-emitter voltage
  $V_T = {}^{KT}/_{q} = 26mV$ at 300deg K
- The Ebers-Moll model is a large-signal model, but we can use its results in small-signal analysis though a constant current source is not necessarily operating in the small-signal region.

Current Mirrors

- The Ebers-Moll equation should look familiar to the Shockley (not Schottky) diode equation we saw earlier: $I_d = I_s(e^{\frac{V_D}{nV_T}} - 1)$. This makes sense since the B-E junction is a diode. They should look familiar!
- Remember that in the Ebers-Moll model, V_{be} *programs* the emitter current and that the emitter current is essentially the collector current plus the base current.
- The relationship between the emitter and collector currents is defined by α, where $\alpha = \frac{I_c}{I_e}$. Typical values of α are between 0.98 to 0.998. Again, the base current is treated as an annoyance.

Current Mirrors

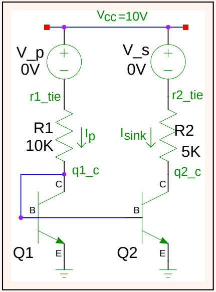
- Let's take advantage of our new knowledge and make a current sink.



- Q1 is *diode configured*. We will come back to why collector and base are connected.
- A current $\frac{V_{cc} - V_{be}}{R1}$ flows through R1.
- Thus, $V_{be}(Q1) = V_{be}(Q2)$; so $I_p = I_{sink}$
- But, if we change R_L, I_{sink} continues to be I_p! Q2 is *mirroring* the programming current through Q1 because Q2's V_{be} is the same as Q1. This circuit configuration is called a *current mirror*.

Current Mirrors

- Here is an example:.




```
.title mirror.sp
*Two NPN BJTs in a current mirror.

.include 2n4401.mod

Vcc   vcc      gnd            10v   ;supply voltage
*     coll.    base   emit.
Q1    q1_c     q1_c   gnd   2n4401 ;programming transistor
Q2    q2_c     q1_c   gnd   2n4401 ;sinking transistor
R1    r1_tie   q1_c             10K ;programming resistor
V_p   vcc      r1_tie            0V ;programming current sense
V_s   vcc      r2_tie            0V ;sinking current sense
R2    r2_tie   q2_c              5K ;load resistor

.control
  op                                ;find dc operating point
  print v(q1_c) v(q2_c) i(V_s) i(V_p); print nodes I and V
.endc
.end
```

- Currents and voltages are:

$$v(q1_c) = 0.628V$$

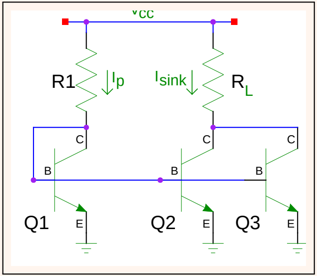
$$v(q2_c) = 5.165V$$

$$i(v_s) = 0.967mA$$

$$i(v_p) = 0.937mA$$

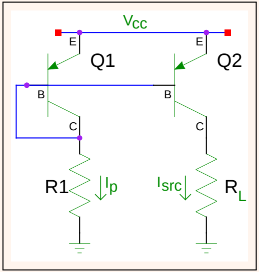
Current Mirrors

- We can double the current through the load resistor by doubling the emitter area of the sinking BJT or paralleling another identical BJT.
- In this case, $I_{sink} = 2I_p$.



Current Mirrors

- We can also make a current source with PNP BJTs:



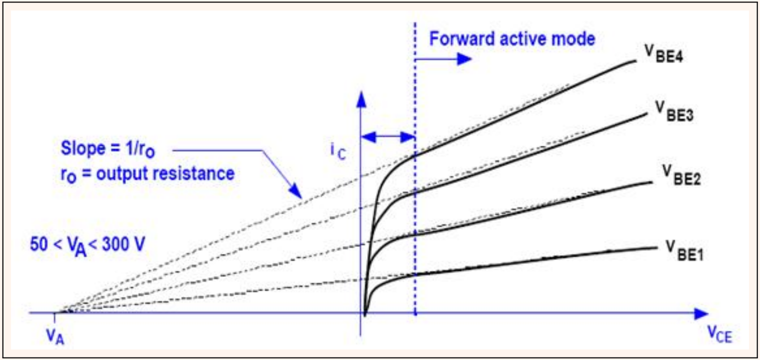
- We set a programming current with R1 and an identical current will be sourced by Q2.

Current Mirrors

- BJT current mirrors are not ideal. Two of the errors are: *Early voltage* and input current errors.
- Early Voltage: When V_{cb} increases, the C-B depletion region grows. This thins the base region further causing less recombination in the base region, which causes an increase in collector current.
- If I_c increases with V_{ce}, it means that the output impedance is behaving as a resistor. A flat I_c vs V_{ce} curve would indicate the ideal situation of an infinite Z_o. A tilted line, this indicates a decrease in the output impedance of the current source.
- Connecting base to collector reduces the Early Effect by keeping the CB voltage and thus the depletion layer constant. (differing only in V_{be}, and holding the emitter at ground)

Current Mirrors

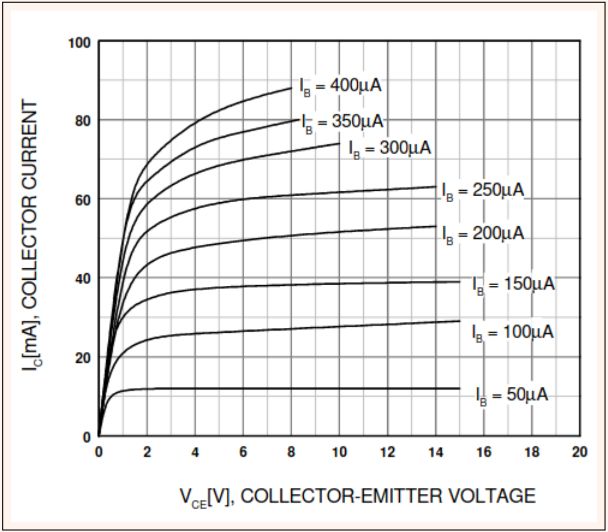
- Here's a graph showing the Early effect and its effect on output resistance.



Thanks Analog Devices!

Current Mirrors

- Here's a graph showing the Early effect on a BC546 NPN BJT.



Current Mirrors

- β error: In our current mirror (NPN version), each transistor (Q1 and Q2) draw a current I_b from the programming current I_p. Thus, the output current will be slightly different than the programming current.
  $I_p - (I_b(Q1) + I_b(Q2)) = I_{sink}$
- If the β were infinite, there would be no I_b, and no error.
- Temperature errors: As the Ebers-Moll equation indicates, V_{be} is dependent on temperature. As the temperature changes, a corresponding change in I_c will occur although all the currents derived from the programming current would track as long as they were identical.