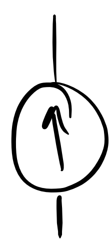
Constant-Current Sources and Sinks

- we have considered "perfect" voltage and current sources since our introduction to electricity!

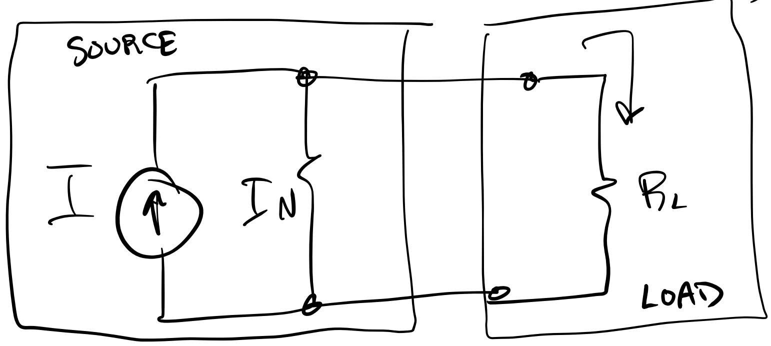
- voltage sources are comparatively easy to visualize
  - battery: pretty good approximation!
  - regulated power supplies: maintain constant voltage over required range of load current
  - but how do we do a current source?

I 

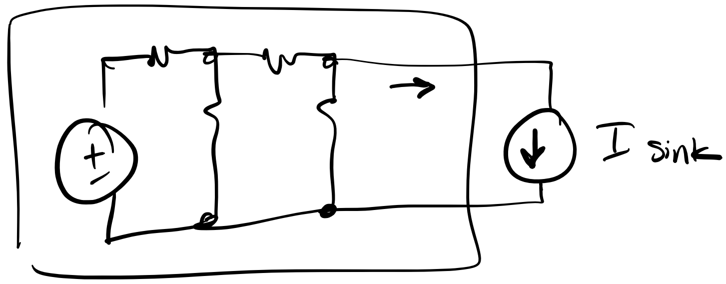
- *ideal* current source:
  - constant current at *any* voltage, AC or DC
  - can dissipate *any* power
  - *infinite* Norton equivalent impedance
- no simple battery-like device approximates this!
- but we can make them out of *transistors*.

Current Source vs. Current Sink

- current source supplies current; i.e., into a load, etc..

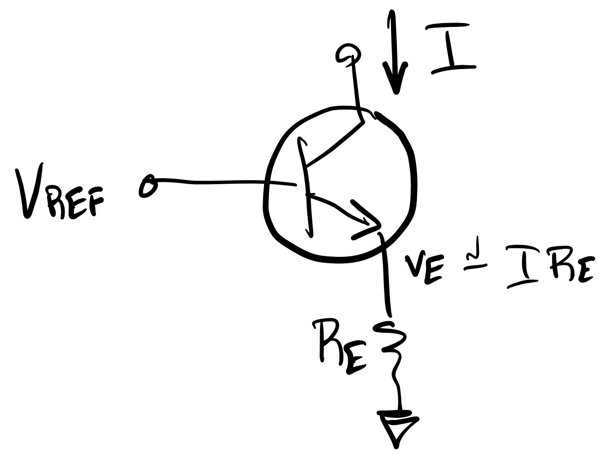


- current sink receives and maintains constant current, usually to ground (or $-V_{cc}$, etc.)



- we can design transistor circuits of either type
- main figure of merit for a current source/sink is its Norton or shunt impedance; we can also call this the output impedance or resistance

Basic BJT Current Sink



- since we know $V_{BE} \approx 0.7V$ for Si transistors, we can set V_{REF} to a known voltage;

then $V_E = V_{REF} - 0.7 \cong IR_E$

$$\boxed{R_E = \frac{V_{REF} - 0.7}{I}}$$

- ex: $V_{REF} = 5V$, need 2mA current sink

then $R_E = \frac{5 - 0.7}{2} = 2.15\,k\Omega$

-- Coincidentally, this is an E96 1% resistor value.

·· the output resistance of this current sink would ordinarily be $r_o = \frac{|V_A|}{I_C}$;

but in this case the unbypassed R_E, this increases to

$$r_{out} = \beta R_E + r_o$$

ex: $V_A = 100V$, $\beta = 200$

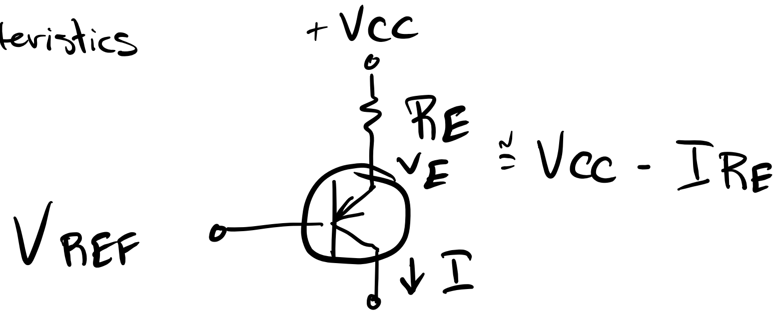
$$r_o = \frac{100}{2} = 50\ k\Omega$$

$$\beta R_E = 200 \cdot 2.150 = 430\ k\Omega$$

thus, $r_{out} = 480\ k\Omega$ [pretty good!]

Basic BJT Current Source

·· we can just as easily use a PNP transistor and R_E to make current source with similar characteristics



∴ since $V_{BE} \simeq -0.7$ for PNP Si,

$$V_E = V_{REF} + 0.7 \simeq V_{CC} - IR_E$$

$$\rightarrow \boxed{R_E = \frac{V_{CC} - (V_{REF} + 0.7)}{I}}$$

∴ ex: $V_{REF} = 5V$, $I = 2mA$, $V_{CC} = 12V$:

$$R_E = \frac{12 - (5 + 0.7)}{2} = 3.15\,k\Omega$$

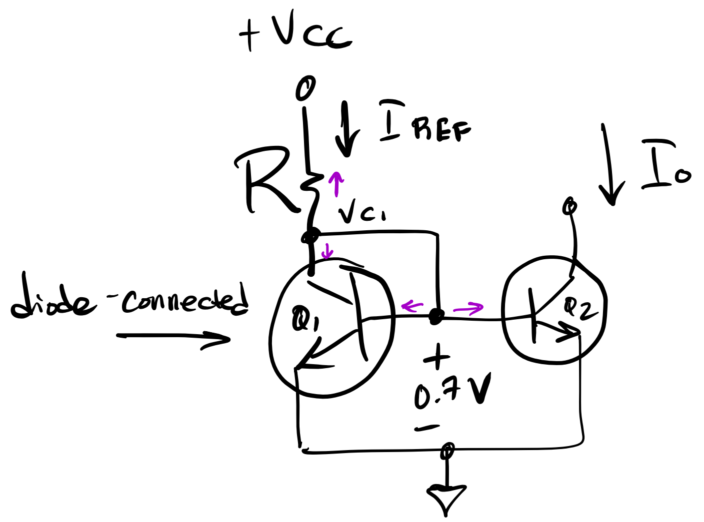
use $3.16\,k\Omega$ 1%

$$r_{out} = \beta R_E + r_o$$

$$= 200 \cdot 3.16 + 50k$$

$r_{out} = 682\,k\Omega$ (nice!)

Basic BJT Current Mirror



-- great importance in integrated circuit design!

-- we know $V_{BE} \sim 0.7V$; then with both emitters grounded,

$$V_{B_1} = V_{B_2} = V_{C_1} = 0.7$$

$$I_{REF} = \frac{V_{cc} - 0.7}{R}$$

-- to determine I_o, use KCL @ V_{C_1}

$$-I_{REF} + I_{C_1} + I_{B_1} + I_{B_2} = 0$$

-- assuming transistors are perfectly matched and operating at the same temperature, $I_{B_1} = I_{B_2} = I_B$

$I_{C_1} = I_{C_2} = I_C$

then $I_{REF} = I_C + 2 I_B$

$$= I_C + \frac{2 I_C}{\beta}$$

$$I_{REF} = I_C \left(1 + \frac{2}{\beta}\right)$$

$\therefore$ the output current I_o is then

$$I_o = I_{C_2} = I_C$$

$$\frac{I_o}{I_{REF}} = \frac{I_C}{I_C\left(1+\frac{2}{\beta}\right)} = \underbrace{\frac{1}{1+\frac{2}{\beta}}}$$

$\therefore$ if $\beta = 200$, then

$$\frac{I_o}{I_{REF}} = \frac{1}{1+\frac{2}{200}} = \underbrace{0.9901}$$

we don't like any dependence on β!

or $I_o = 0.9901\, I_{REF}$

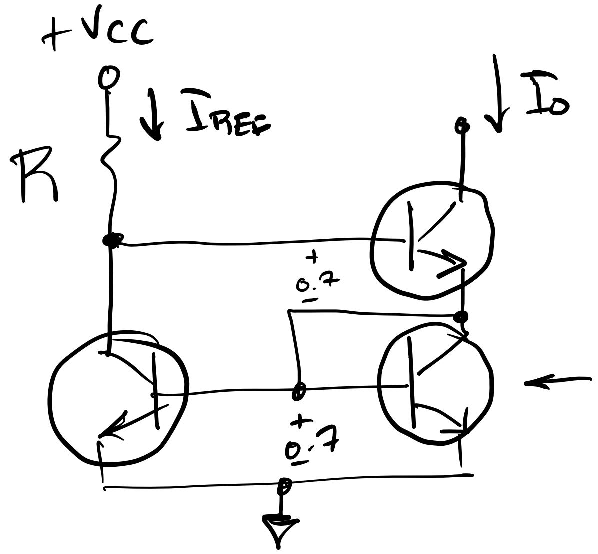
- output resistance of basic BJT current mirror is $\underbrace{r_o = \frac{|V_A|}{I_o}}$

if $V_A = 100V$, $I_o = 2mA$,

$r_o = \frac{100}{2} = 50 k\Omega$ (not great!)

Wilson Current Mirror

-- strives to solve both the $\frac{I_o}{I_{REF}}$ issue and poor r_{out} :



-- we now have two V_{BE} drops between ground and $V_{C_1} = V_{B_2}$; thus,

$$I_{REF} = \frac{V_{CC} - 2 \cdot 0.7}{R}$$

$$\rightarrow R = \frac{V_{CC} - 2 \cdot 0.7}{I_{REF}}$$

-- we can perform similar analysis as the basic BJT current mirror to show that

$$I_o = I_{REF} \left(\frac{1}{1 + \frac{2}{\beta^2}} \right)$$

and $r_{out} = \frac{\beta}{2} r_o$

- thus, if $\beta = 200$ and $r_o = 50k\Omega$,

$$I_o = I_{REF}\left(\frac{1}{1+\frac{2}{200^2}}\right) = .99995\ I_{REF}$$

$$r_{out} = \frac{\beta}{2}\cdot r_o$$

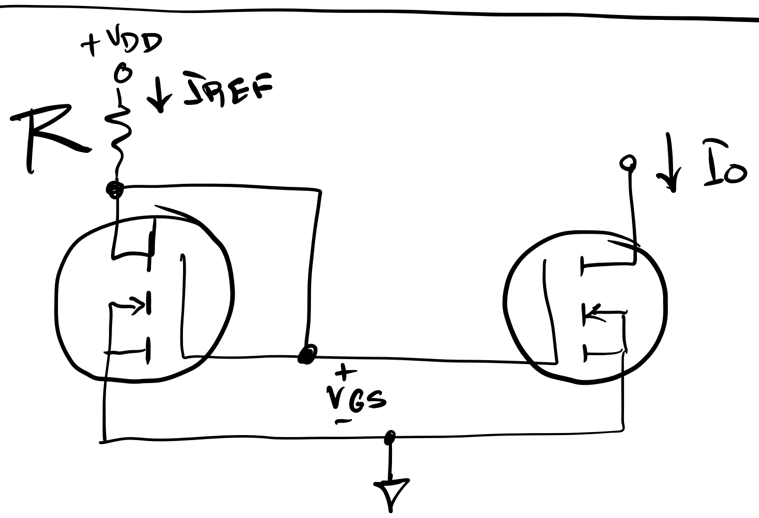
$$= \frac{200}{2}\cdot 50k = \underline{5M\Omega} \text{ (really good!)}$$

for $I_o = 2mA$ and $V_{CC} = +12V$,

$$R = \frac{12 - 2\cdot 0.7}{2} = 5.3\,k\Omega$$

use $5.36k$, 1%

MOSFET Current Mirror



$$I_o = I_{REF} = \frac{V_{DD} - V_{GS}}{R} \rightarrow R = \frac{V_{DD} - V_{GS}}{I_o}$$

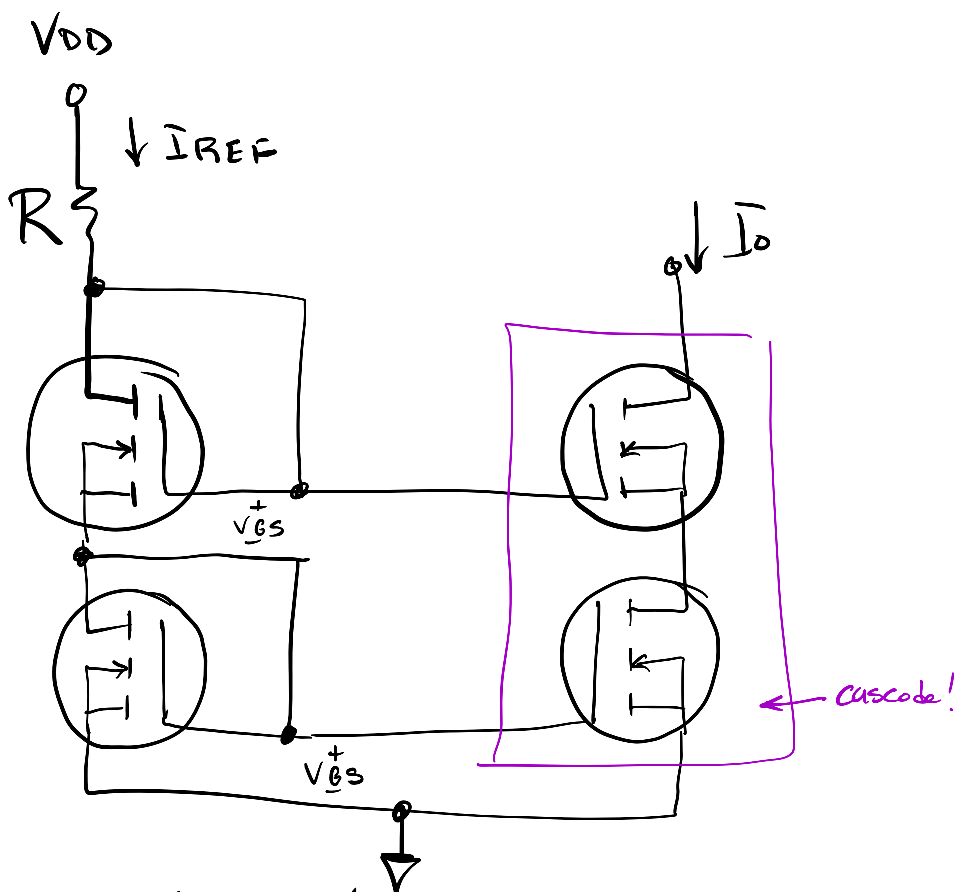
$r_{out} = r_o$ (not great)

- we can use $I_D = K(V_{GS} - V_t)^2$ to determine V_{GS} for desired I_o

- we need to improve that rout!

MOSFET Cascode Current Mirror

- even better than Wilson MOSFET Current Mirror!



$$I_o = I_{REF} = \frac{V_{DD} - 2V_{GS}}{I_o} \rightarrow R = \frac{V_{DD} - 2V_{GS}}{I_o}$$

.. recall that the basic BJT current sink had an unbypassed R_E, which increased rout by βR_E

.. now we have another MOSFET's r_o, which increases rout much more:

$$r_{out} = g_m r_o^2$$

ex: $V_{DD} = 24V$, $I_o = 2mA$, $r_o = 50k\Omega$

MOSFET: $K = 10\ mA/V^2$, $V_t = 1.2V$

$$I_D = k(V_{GS} - V_t)^2$$

$$\longrightarrow V_{GS} = \sqrt{\frac{I_D}{K}} + V_t$$

$$= \sqrt{\frac{2}{10}} + 1.2$$

$$V_{GS} = 1.647\ V$$

then $R = \dfrac{V_{DD} - 2V_{GS}}{I_o} = \dfrac{24 - 2 \cdot 1.647}{2}$

$R = 10.353k\Omega$, use 10.5k 1%

∴ to get r_{out}, need g_m :

$$g_m = 2\sqrt{K I_D}$$

$$= 2\sqrt{10 \cdot 2}$$

$$g_m = 8.944 \ mA/V$$

$$r_{out} = g_m r_o^2$$

just looking at multipliers!

$$= 8.944\cancel{m} \cdot 50k^{\cancel{2}}$$

$$= 22360k$$

or $r_{out} = 22.36 \ M\Omega$ ← get outta here!!!