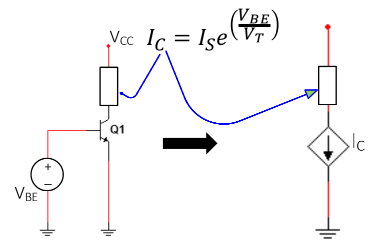
IC Biasing

- Integrated Circuits (ICs) have millions or billions of transistors in it
- How can we bias them in a single piece of circuit?

How to bias multiple transistors using a single circuit?

- Higher fabrication area is expensive in terms of area
- Fabricating resistors and capacitors are expensive, but transistors are relatively cheaper.

$I_C = I_S e^{\left(\frac{V_{BE}}{V_T}\right)}$



- We have already learned that a transistor is a voltage controlled current source.
- How can we use transistors to get a constant current source.

1

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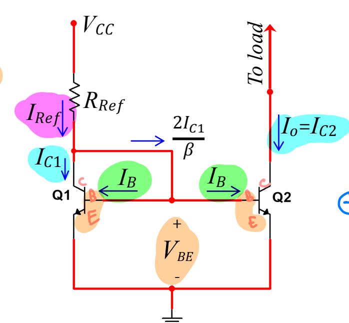
Two-Transistor Current Source (Current Mirror)

- The two transistors are identical
- $V_{BE1} = V_{BE2} = V_{BE(on)}$ (Same nodes)
- $I_{B1} = I_{B2} = I_B$
- $I_{C1} = I_{C2} = I_o$
- Strictly considering, $I_{Ref} \neq I_{C1}$
- However, for large β values,

$$\boxed{I_{Ref} \approx I_{C1} = I_o}$$

This is a mirror circuit where the reference current is mirrored to the load.



current mirror is when 2 identical transistors are connected in this configuration

- B and C are shorted
- there is R_{Ref} connected to C

Notice that

$$\boxed{I_{Ref} \approx I_o = \frac{V_{CC} - V_{BE(on)}}{R_{Ref}}}$$

using KVL:

$V_{CC} - V_{BE(on)} - I_o R_{Ref} = 0$

2

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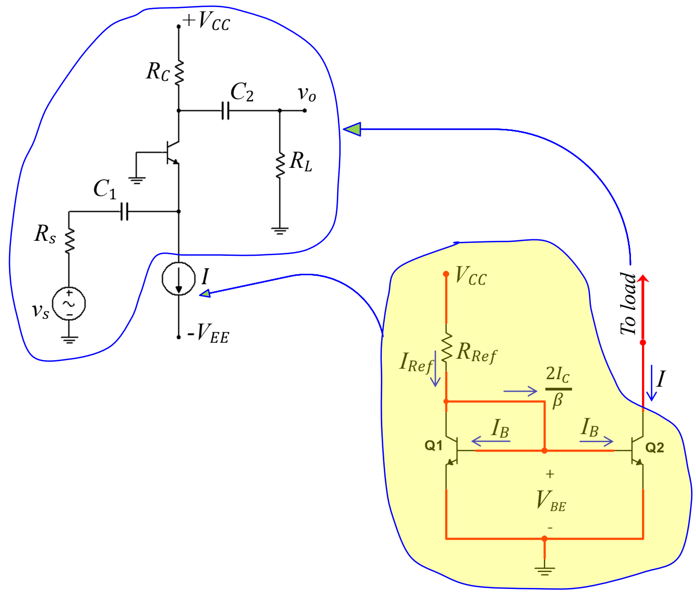
Current Source in a Practical Circuit



this is how to connect a current source to Load

current mirror circuit

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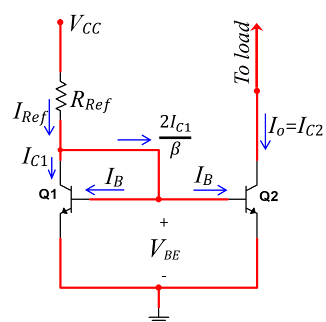
Current Mirror: Effect of β

- β values are not always very large
- What is the effect of β?
- Assume that β of Q1 and Q2 are finite, and the base currents cannot be ignored



$$I_{Ref} = I_{C1} + 2I_B = I_{C1} + \frac{2I_{C1}}{\beta}$$

or, $$I_{Ref} = I_{C1}\left(1 + \frac{2}{\beta}\right)$$

or, $$\boxed{\frac{I_o}{I_{Ref}} = \frac{1}{1 + \frac{2}{\beta}}}$$ [since $I_{C1} = I_o$]

If $\beta = 60$,

$$\frac{I_o}{I_{Ref}} = \frac{1}{1 + \frac{2}{60}} = 0.968$$ 3.2% error

If $\beta = 160$,

$$\frac{I_o}{I_{Ref}} = \frac{1}{1 + \frac{2}{160}} = 0.988$$ 1.2% error

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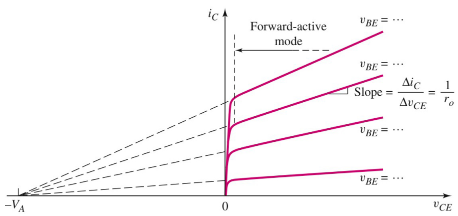
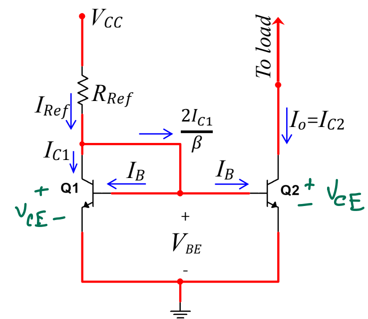
Current Mirror: Effect of V_A





- Recall Early voltage effect
- For lower V_A values, I_C doesn't remain constant with V_{CE}
- For the current mirror, V_{CE1} and V_{CE2} are NOT guaranteed to be the same

Thus, even with $\beta = \infty$, the two collector currents can be different depending on their V_A value.

what determines V_A value

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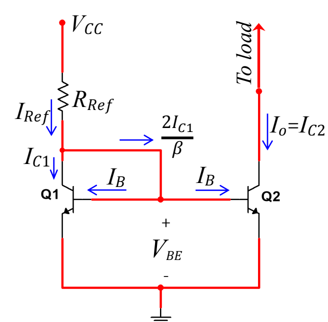
Current Mirror: Effect of V_A When $\beta = \infty$

- Recall Early voltage effect
- For lower V_A values, I_C doesn't remain constant with V_{CE}



Assume V_A is finite, but $\beta = \infty$. We can write,

$I_{Ref} = I_{C1}$ and

$$I_{C1} = I_s e^{\left(\frac{V_{BE}}{V_T}\right)} \left(1 + \frac{V_{CE1}}{V_A}\right)$$

$$I_{C2} = I_s e^{\left(\frac{V_{BE}}{V_T}\right)} \left(1 + \frac{V_{CE2}}{V_A}\right)$$

shockley's

or, $$\boxed{\frac{I_{C2}}{I_{C1}} = \frac{I_o}{I_{Ref}} = \frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{V_{CE1}}{V_A}}}$$

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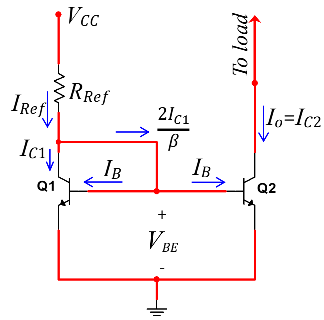
Current Mirror: $\beta \neq \infty$ and $V_A \neq \infty$



When β and V_A both are finite, we can write

$$\frac{I_o}{I_{Ref}} = \left[\frac{1}{1+\frac{2}{\beta}}\right] \times \left[\frac{1+\frac{V_{CE2}}{V_A}}{1+\frac{V_{CE1}}{V_A}}\right]$$

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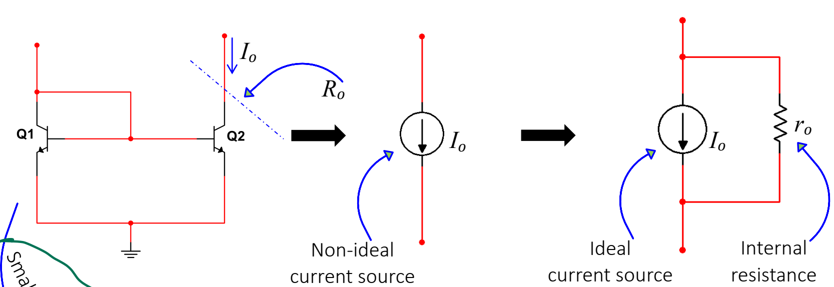
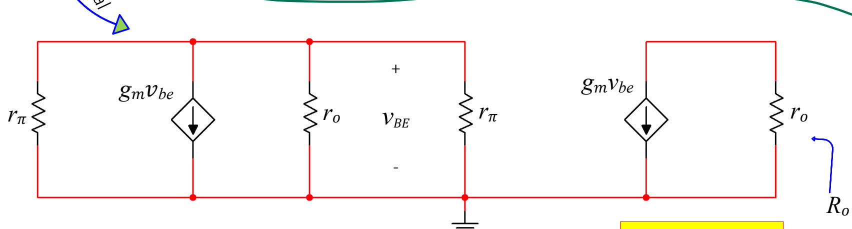
Current Mirror: Output Resistance



-simply says that a current mirror can be represented by ideal current source and internal resistance



$R_o = r_{o2} = r_o$

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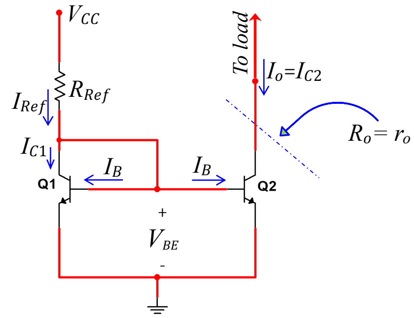
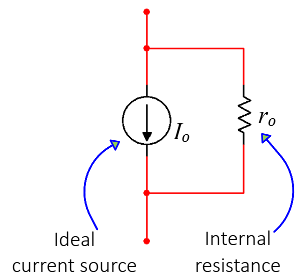
* Parameters
g_m
r_π
$r_o = r_{o2} = R_o$
given in formula sheet

Ideal Current Source





For an ideal (good quality) current source, we need to ensure the following two important things

- The output current I_o must be equal to the desired current. For a two-transistor current mirror, I_o must be equal to I_{Ref}, i.e., $I_o = I_{Ref}$
- The output resistance r_o must be infinite. In practice, as high as possible.

Two-transistor current mirror

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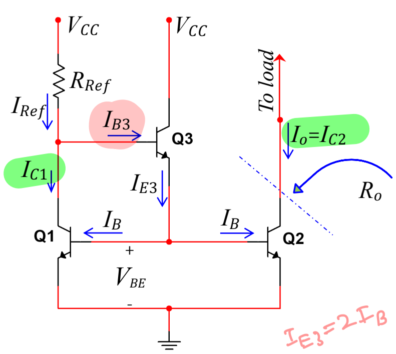
Current Mirror With Current Compensation



- All transistors are identical
- $I_{C1} = I_{C2} = I_C$
- $\beta_1 = \beta_2 = \beta_3 = \beta$

$I_{E3} = 2I_B$

Here, $I_{B3} = \dfrac{I_{E3}}{\beta + 1} = \dfrac{2I_B}{\beta + 1}$

Or, $I_{B3} = \dfrac{2I_C}{\beta(\beta + 1)}$ $\qquad I_B = \dfrac{I_C}{\beta}$

[Since $I_C = \beta\, I_B$]

We have,

$$I_{Ref} = I_C + I_{B3} = I_C + \frac{2I_C}{\beta(\beta+1)}$$

Or, $I_{Ref} = I_C\left[1 + \dfrac{2}{\beta(\beta + 1)}\right]$

Or, $\dfrac{I_o}{I_{Ref}} = \dfrac{1}{1 + \dfrac{2}{\beta(\beta + 1)}}$

Or, $\boxed{\dfrac{I_o}{I_{Ref}} \approx \dfrac{1}{1 + \dfrac{2}{\beta^2}}}$

$R_o = r_{o2}$

$R_o = r_o$

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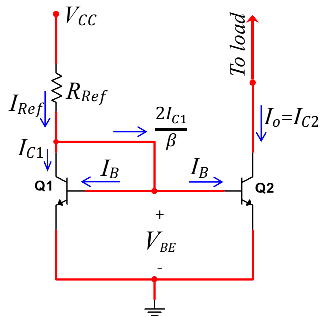
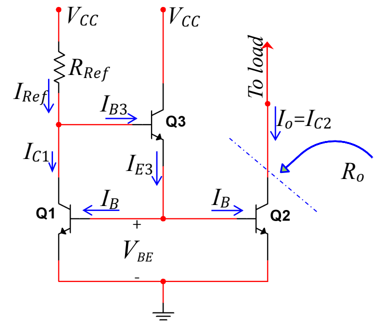
Current Mirror With Current Compensation: Example





* The only diff is β^2

$$\frac{I_o}{I_{Ref}} \approx \frac{1}{1+\frac{2}{\beta^2}}$$

Recall that for two-transistor current mirror,

$$\frac{I_o}{I_{Ref}} = \frac{1}{1+\frac{2}{\beta}}$$

For $\beta = 60$, we had 3.2% error

$$\frac{1}{1+\frac{2}{60}} =$$

For $\beta = 160$, we had 1.2% error

$$\frac{1}{1+\frac{2}{160}}$$

For current mirror with current compensation

If $\beta = 60$,

$$\frac{I_o}{I_{Ref}} = 1/\left(1+\frac{2}{60^2}\right) = 0.999$$ 0.1% error

If $\beta = 160$,

$$\frac{I_o}{I_{Ref}} = 1/\left(1+\frac{2}{160^2}\right) = 0.9999$$ 0.01% error

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Clearly there is much less error with current compensation

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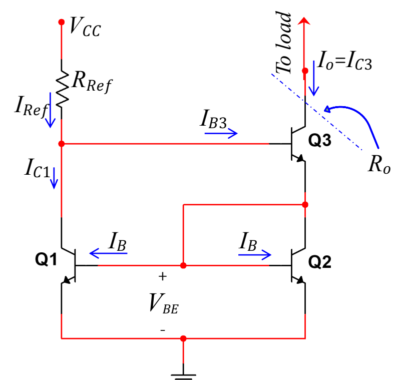
Wilson Current Mirror

- Wilson current mirror also uses current compensation with a slight difference for increasing the output resistance.
- All transistors are identical

the second quality to have an ideal current source



- B and C shorted for Q_2
- E of Q_3 feeds C of Q_2

It can be shown that

$$\frac{I_o}{I_{Ref}} = \frac{1}{1+\frac{2}{\beta^2}}$$

$$R_o = \beta\frac{r_o}{2}$$

If
$I_o = 4$ mA
$V_A = 100$ V
$\beta = 140$

For a two-transistor current mirror,

$$R_o = r_o = \frac{V_A}{I_C} = \frac{100}{4\times10^{-3}} = 25\ k\Omega$$

For Wilson current mirror,

$$R_o = \frac{\beta r_o}{2} = \frac{140\times100}{2\times4\times10^{-3}} = 1.75\ M\Omega$$

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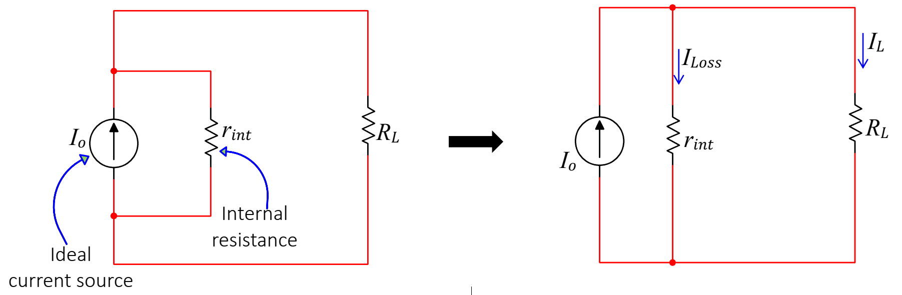
much greater output resistance

12

Effect of Current Source Internal Resistance



For, $r_{int} = 25\ k\Omega$

If $R_L = 10\ k\Omega$,

I_L = 71% of I_o and I_{Loss} = 29% of I_o

If $R_L = 100\ k\Omega$,

I_L = 20% of I_o and I_{Loss} = 80% of I_o

For, $r_{int} = 1.75\ M\Omega$ (Wilson mirror)

If $R_L = 10\ k\Omega$,

I_L = 99.4% of I_o and I_{Loss} = 0.6% of I_o

If $R_L = 100\ k\Omega$,

I_L = 94.6% of I_o and I_{Loss} = 5.4% of I_o

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- most of the current goes to load and there is barely any I_o

as $R_L \uparrow$ it becomes worse

Mon Oct 23rd

Wilson vs Widlar

$I_{Ref} = \frac{V_{CC} - V_{BE1}}{R_{Ref}}$

$V_{BE1} = 0.7$

Widlar Current Source

- The two transistors are identical
- $\boxed{V_{BE1} \neq V_{BE2},\ I_{B1} \neq I_{B2},\ \text{and } I_{C1} \neq I_{C2}}$

We can write for Q1 and Q2

based on assumption that β is large

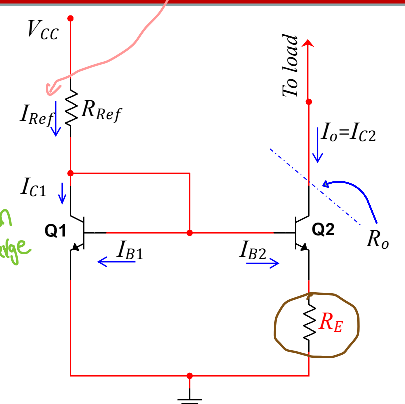
$$V_{BE1} = V_T \ln\left(\frac{I_{Ref}}{I_S}\right)$$

and, $$V_{BE2} = V_T \ln\left(\frac{I_o}{I_S}\right)$$

Subtracting the two equations,

$$V_{BE1} - V_{BE2} = V_T \ln\left(\frac{I_{Ref}}{I_o}\right)$$

Or, $$I_o R_E = V_T \ln\left(\frac{I_{Ref}}{I_o}\right)$$



One can also show that

$$R_o = [1 + g_m(R_E\ //\ r_{\pi 2})]r_{o2}$$

input resistance

(no need to know derivation)

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• for all previous:

$I_{C1} = I_{C2}$

$V_{BE1} = V_{BE2}$

• not case here due to resistor in emitter of Q_2

if $\alpha \approx 1$

$I_{C_2} = I_{E_2} = I_o$

$= \frac{V_T}{R_E} \ln\left(\frac{I_{Ref}}{I_o}\right)$

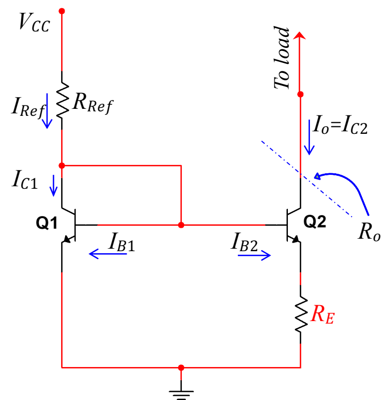
Widlar Current Source (Continued ...)

- Both transistors must operate in active region
- The reference current is still

$$\boxed{I_{Ref} = \frac{V_{CC} - V_{BE1}}{R_{Ref}}}$$

last slide

- The output current cannot be higher than the reference current I_{ref}
- The output current can be set to any fraction by changing R_E
- The output resistance is very high, particularly for low output currents



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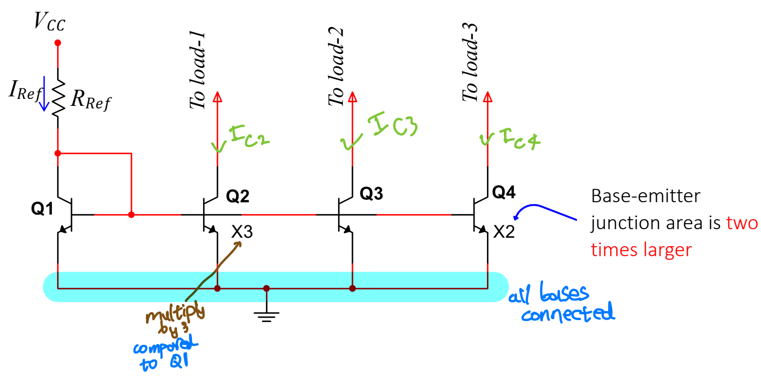
Current Steering



Assume β and V_A are infinite

- $I_{C3} = I_{Ref}$
- $I_{C2} = 3I_{Ref}$
- $I_{C4} = 2I_{Ref}$

Thus,

$$\boxed{I_{Ref} = \frac{I_{C2}}{3} = I_{C3} = \frac{I_{C4}}{2}}$$

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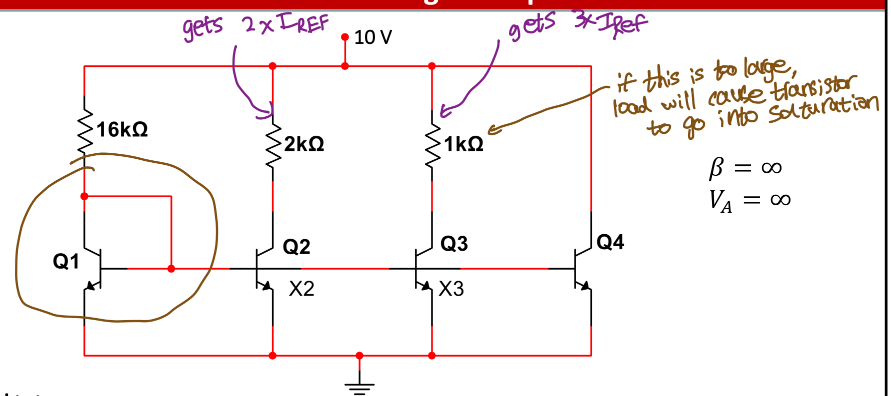
hardest part:
-identify reference transistor

find all currents

$I_{Ref}, I_{C2}, I_{C3}, I_{C4}$

Current Steering: Example-1



will be one where B and C are shorted

$\beta = \infty$

$V_A = \infty$

Here,

$$I_{Ref} = \frac{V_{CC} - V_{BE1}}{R_{Ref}} = \frac{10 - 0.7}{16\times10^3}$$

$I_{Ref} = 0.581\ mA$

$I_{C2} = 2\times I_{Ref} = 1.162\ mA$

$I_{C3} = 3\times I_{Ref} = 1.743\ mA$

$I_{C4} = I_{Ref} = 0.581\ mA$

17

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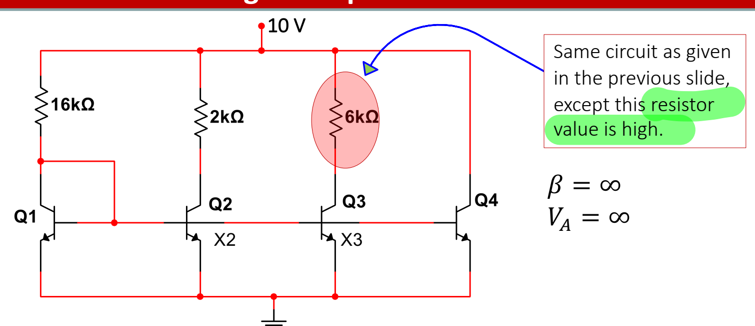
one of resistor values too high, so that transistor doesn't act as current mirror

Current Steering: Example with Saturation



Same circuit as given in the previous slide, except this resistor value is high.

$\beta = \infty$

$V_A = \infty$

The currents are exactly same as before, i.e.,

$$I_{Ref} = \frac{10 - 0.7}{16\times10^3} = 0.581\ mA$$

$I_{C2} = 2\times I_{Ref} = 1.162\ mA$

$I_{C3} = 3\times I_{Ref} = 1.743\ mA$

$I_{C4} = I_{Ref} = 0.581\ mA$

Notice that

$$I_{C3(max)} = \frac{(10 - 0.2)}{6\times10^3} = \cancel{0.490\ mA}\ \ 1.633\ mA$$

$$I_{C3(max)} = \frac{V_{CC} - V_{SAT}}{R_3}$$

- Thus, Q3 is in saturation
- I_{C3} will be $I_{C3} = I_{C3(max)} = \cancel{0.490\ mA}$ 1.633mA
- Q_3 doesn't work as a current mirror

the rest of transistors work fine

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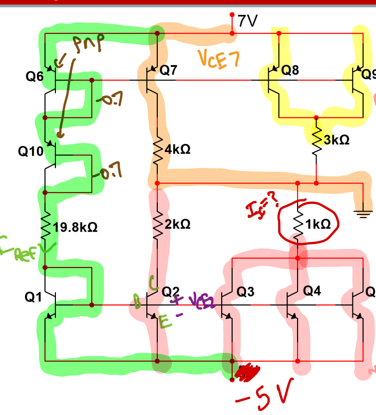
* Q_1 is reference, can write clear KVL

* There must be clear current that doesn't depend on other parameters in circuit

Current Steering: Example-2

Example: Consider the given current steering circuit where β and V_A are infinite. Determine:
a) I_C of all transistors and
b) $|V_{CE}|$ of all transistors



7−(3×0.5)−0
=
** they are connected
7−(3×1)−0=
=4V

=(1.5mA×1kΩ)−(−5)
=3.5V

$$I_{Ref} = \frac{\overset{Q6}{7-0.7}\overset{Q10}{-0.7}\overset{Q1}{-0.7}-(-5)}{19.8\times10^3} = 0.5\ mA$$

Here, all transistor have equal collector current which is 0.5 mA

DC analysis

$V_{CE3} = V_{CE4} = V_{CE5} = -1\times1.5+5 = 3.5\ V$

$V_{CE1} = |V_{CE10}| = |V_{CE6}| = 0.7\ V$

$V_{CE7} = 7-4\times0.5 = 5\ V$

$V_{CE2} = 0-2\times0.5-(-5) = 4\ V$

$V_{CE8} = V_{CE9} = 7-3\times1 = 4\ V$

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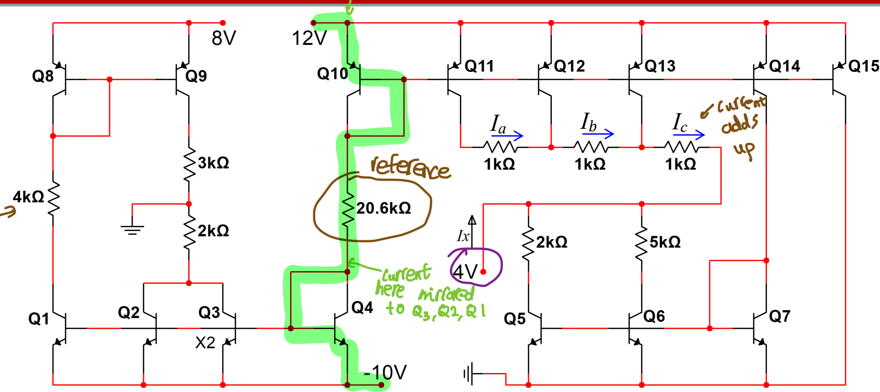
*
*
2 criteria to identify reference:
① B and C are shorted
② can write KVL with no unknowns, i.e. independent of other components

$I_{REF} = \frac{12-0.7-0.7-(-10)}{20.6\times10^3}$
$= 1mA$

Current Steering: Example-3

not reference cuz voltage across Q_1 is unknown



$I_{C5}+I_{C6} = I_c+I_x$

$I_x = I_{C5}+I_{C6}-I_c$

Determine the power in 4V source

$I_{Ref} = I_{C4} = I_{C10} = 1\ mA$

$I_a = I_{C11} = 1\ mA$

$I_b = I_{C11}+I_{C12} = 2\ mA$

$I_c = I_b+I_{C13} = 3\ mA$

By KCL,

$I_{c5}+I_{c6}-I_c-I_x = 0$

Why?

$I_x = 1+0.76-3 = -1.24\ mA$

Q6 is saturated

The power in 4V source is,

$P_{4V} = 4\times(-I_x) = 4.96W\ (absorbed)$

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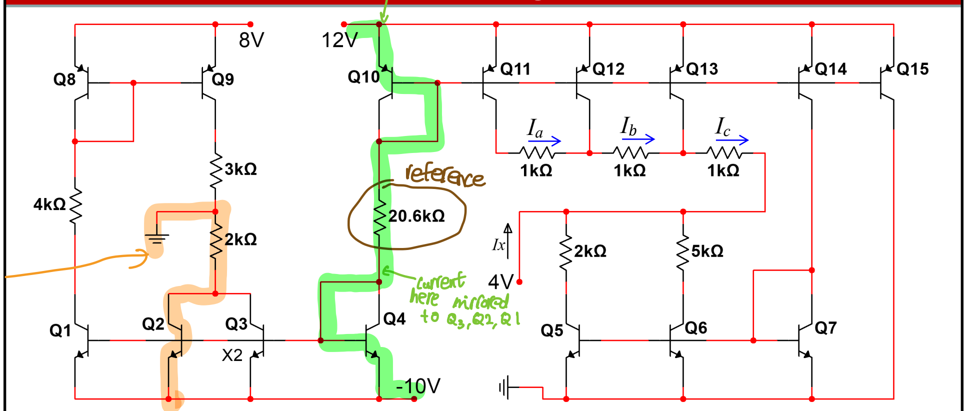
$I_{REF} = \frac{12-0.7-0.7-(-10)}{20.6\times10^3}$

$\simeq 1mA$

Same as ex 3

Current Steering Circuit



$V_{CE2} = V_{CE3} = 0$ -

$I_{C6(max)} = \frac{4-0.2}{5\times10^3}$

$= 0.76mA$

Gain a Deeper Understanding (GADU)

- Determine $|V_{CE}|$ and I_C of all 15 transistors
- There is one transistor that is not in active region; find it ↙ Q6
- What are the effects of increasing or decreasing the 4V source?
- Are there any limits on increasing or decreasing the resistor values?

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$I_{REF} = I_{C4} = I_{C10} = 1mA$

$=$ all others except I_{C3} and I_{C6}

$I_{C3} = 2mA$

$I_{C6} = 0.76mA$