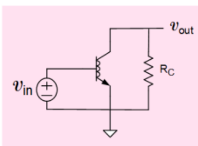
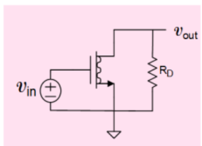
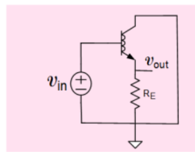
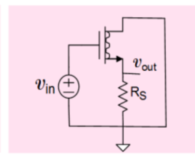
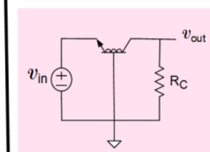
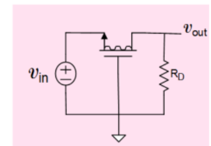
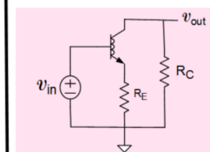
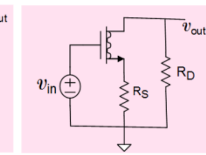
EE 330
Lecture 33

- High Gain Amplifiers
- Current Source Biasing
- Current Sources and Mirrors

Basic Amplifier Gain Table

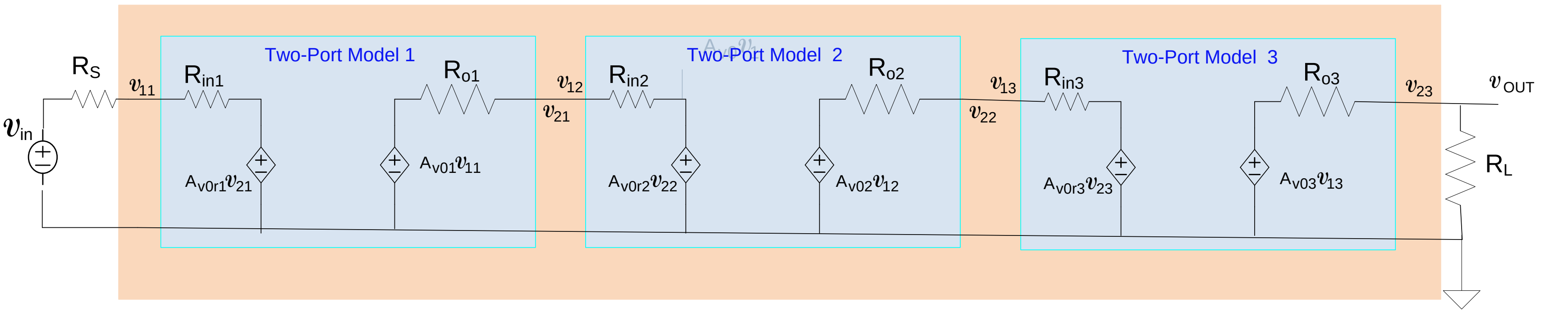
	CE/CS		CC/CD		CB/CG		CEwRE/CSwRS	
	BJT	MOS	BJT	MOS	BJT	MOS	BJT	MOS
								
A_V	$-g_m R_C$		$\frac{g_m}{g_m + g_E}$		$g_m R_C$		$-\frac{R_C}{R_E}$	
	$-\frac{I_{CQ}R_C}{V_t}$	$-\frac{2I_{DQ}R_D}{V_{EB}}$	$\frac{I_{CQ}R_E}{I_{CQ}R_E + V_t}$	$\frac{2I_{DQ}R_E}{2I_{DQ}R_E + V_{EB}}$	$\frac{I_{CQ}R_C}{V_t}$	$\frac{2I_{DQ}R_C}{V_{EB}}$		
R_{in}	r_π		$r_\pi + \beta R_E$		g_m^{-1}		$r_\pi + \beta R_E$	
	$\frac{\beta V_t}{I_{CQ}}$	∞	$\beta\left(\frac{V_t}{I_{CQ}} + R_E\right)$	∞	$\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$	$\beta\left(\frac{V_t}{I_{CQ}} + R_E\right)$	∞
R_{out}	R_C		g_m^{-1}		R_C		R_C	
			$\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$				

Can use these equations only when small signal circuit is EXACTLY like that shown !!

Cascaded Amplifier Analysis and Operation

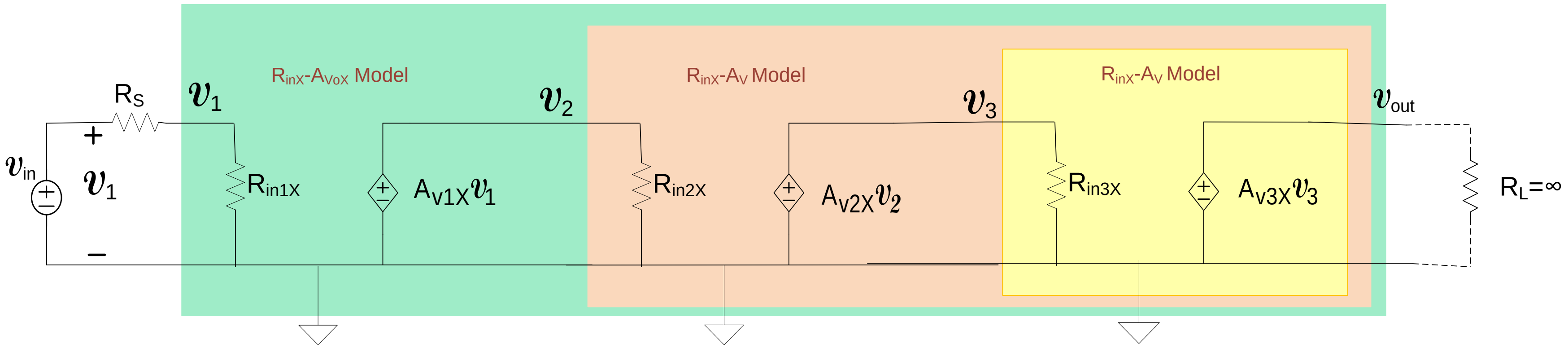
Case 2: One or more stages are not unilateral

- Standard two-port cascade



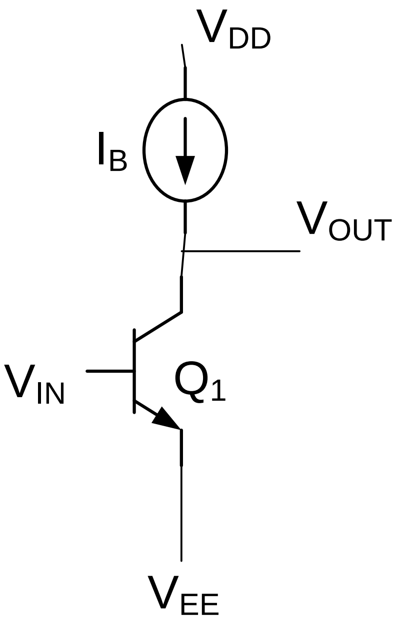
Analysis by creating new two-port of entire amplifier quite tedious because of the reverse-gain elements

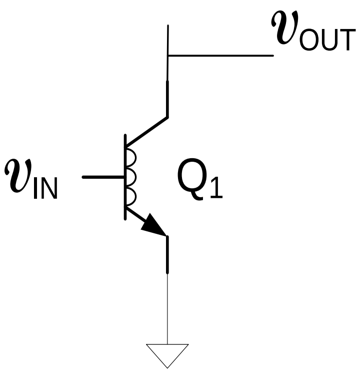
- Right-to-left nested R_{inx},A_{vX} approach

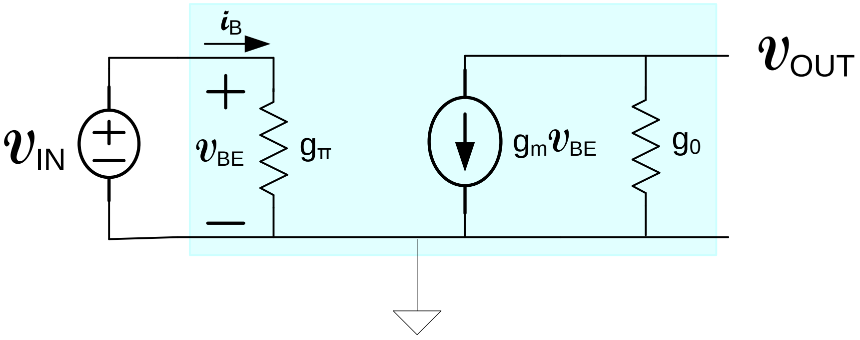


- R_{inx} includes effects of all loading
- AV_X is the voltage ratio from input to output of a stage
- AV_X's include all loading
- <u>Can not change any loading without recalculating everthing!</u>

High-gain amplifier







$$A_V = \frac{-g_m}{g_0}$$

$$A_V = \frac{-I_{CQ}}{V_t I_{CQ}/V_{AF}} = -\frac{V_{AF}}{V_t}$$

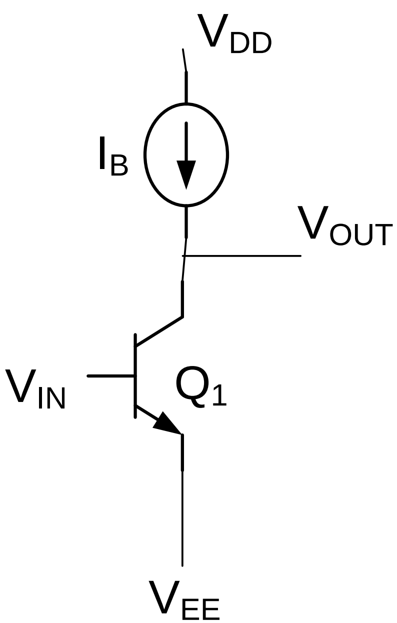
$$A_V = -\frac{V_{AF}}{V_t} \cong \frac{200\text{V}}{25\text{mV}} = -8000$$

This gain is very large (but realistic) !

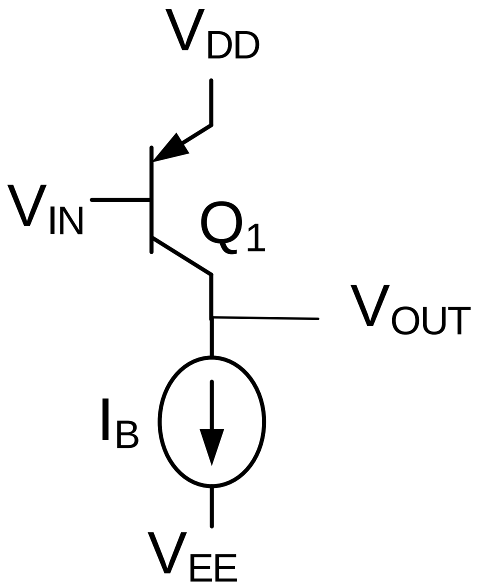
And no design parameters affect the gain

But how can we make a current source?

High-gain amplifier



$$A_V \cong -8000$$



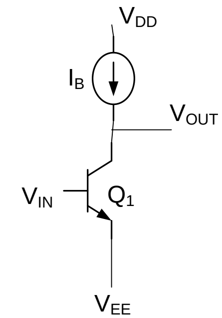
Same gain with both npn and pnp transistors

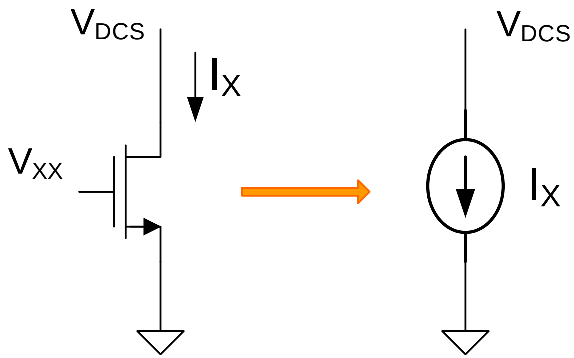
How can we build the ideal current source?

What is the small-signal model of an actual current source?

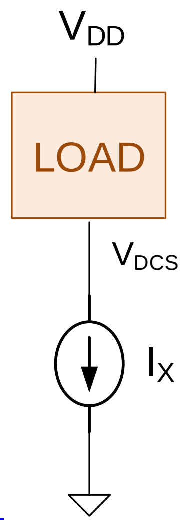
Simple Current Sources

a “sinking” current source





$$I_X = \frac{\mu C_{OX} W}{2L} \left(V_{XX} - V_T\right)^2$$



Since I_X is independent of V_{DCS}, acts as an ideal current source (with this model)

Termed a “sinking” current source since current is pulled out of the load

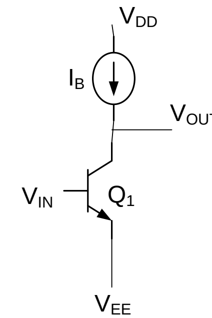
If V_{XX} is available, each dc current source requires only one additional transistor !

Have several methods for generating V_{XX} from V_{DD} (see HW problems)

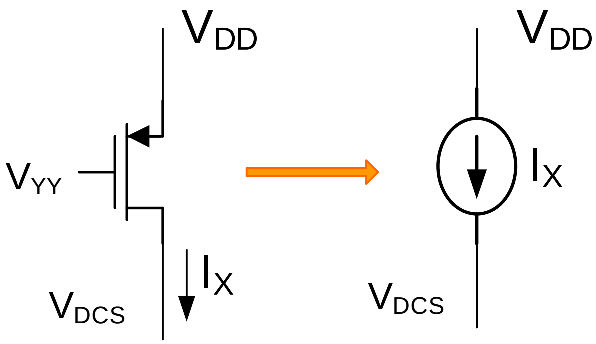
But for the npn high-gain amplifier considered need a sourcing current

But how good is this current “sink”?

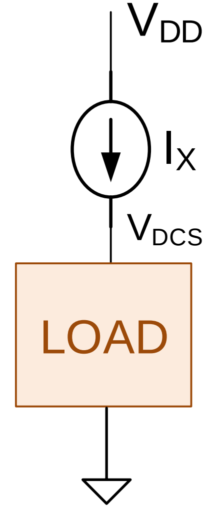
Simple Current Sources



a “sourcing” current source



$$I_X = \frac{\mu C_{OX} W}{2L}\left(V_{DD} - V_{YY} + V_{Tp}\right)^2$$



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Termed a “sourcing” current source since pushed into the load

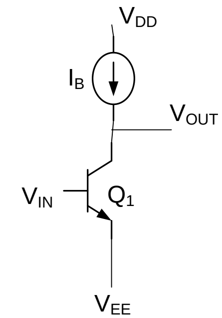
If V_{XX} is available, each dc current source requires only one additional transistor !

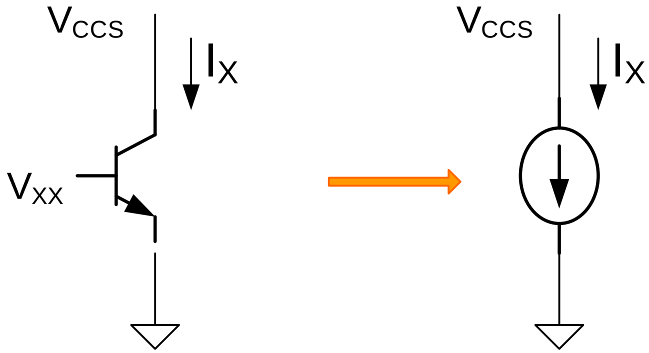
Have several methods for generating V_{XX} from V_{DD} (see HW problems)

But how good is this current “source”?

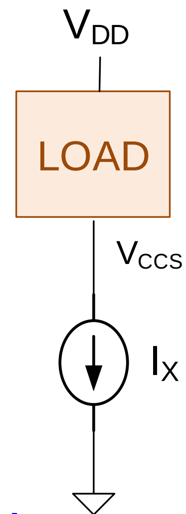
Simple Current Sources

a "sinking" current source





$$I_X = J_S A_E e^{\frac{V_{XX}}{V_t}}$$



Since I_X is independent of V_{CCS}, acts as an ideal current source (with this model)

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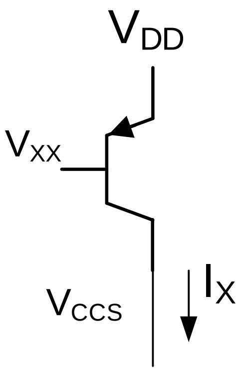
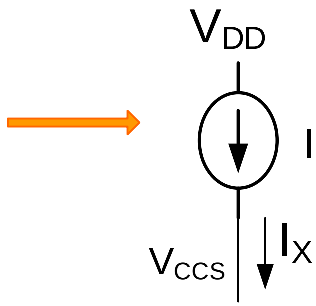
But how good is this current "sink"?

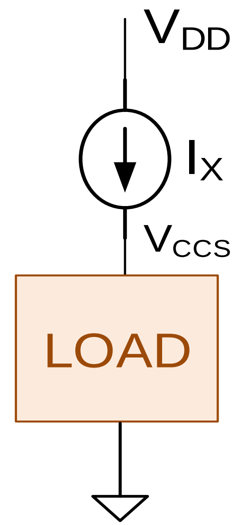
Simple Current Sources

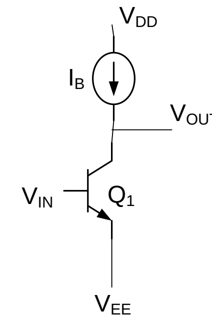
a "sourcing" current source





$$I_X = J_S A_E e^{\frac{V_{DD}-V_{XX}}{V_t}}$$





Since I_X is independent of V_{CCS}, acts as an ideal current source (with this model)

Termed a "sourcing" current source since pushed into the load

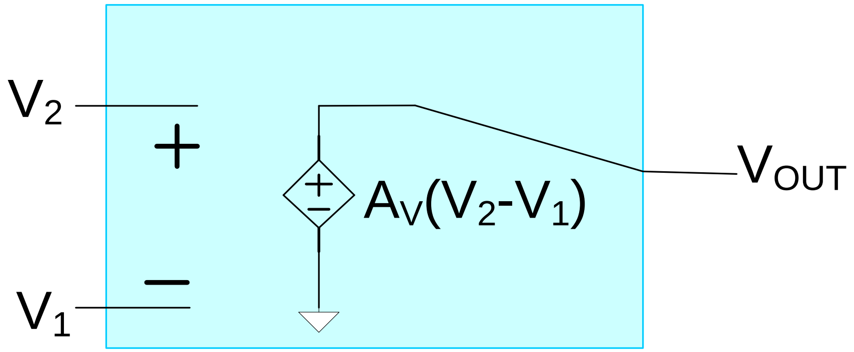
If V_{XX} is available, each dc current source requires only one additional transistor !

Have several methods for generating V_{XX} from V_{DD} (see HW problems)

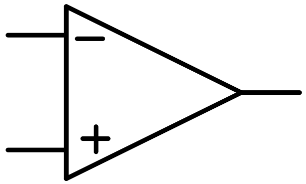
But how good is this current "source"?

Before addressing the issue of how a current source is designed, will consider another circuit that uses current source biasing

The Basic Differential Amplifier

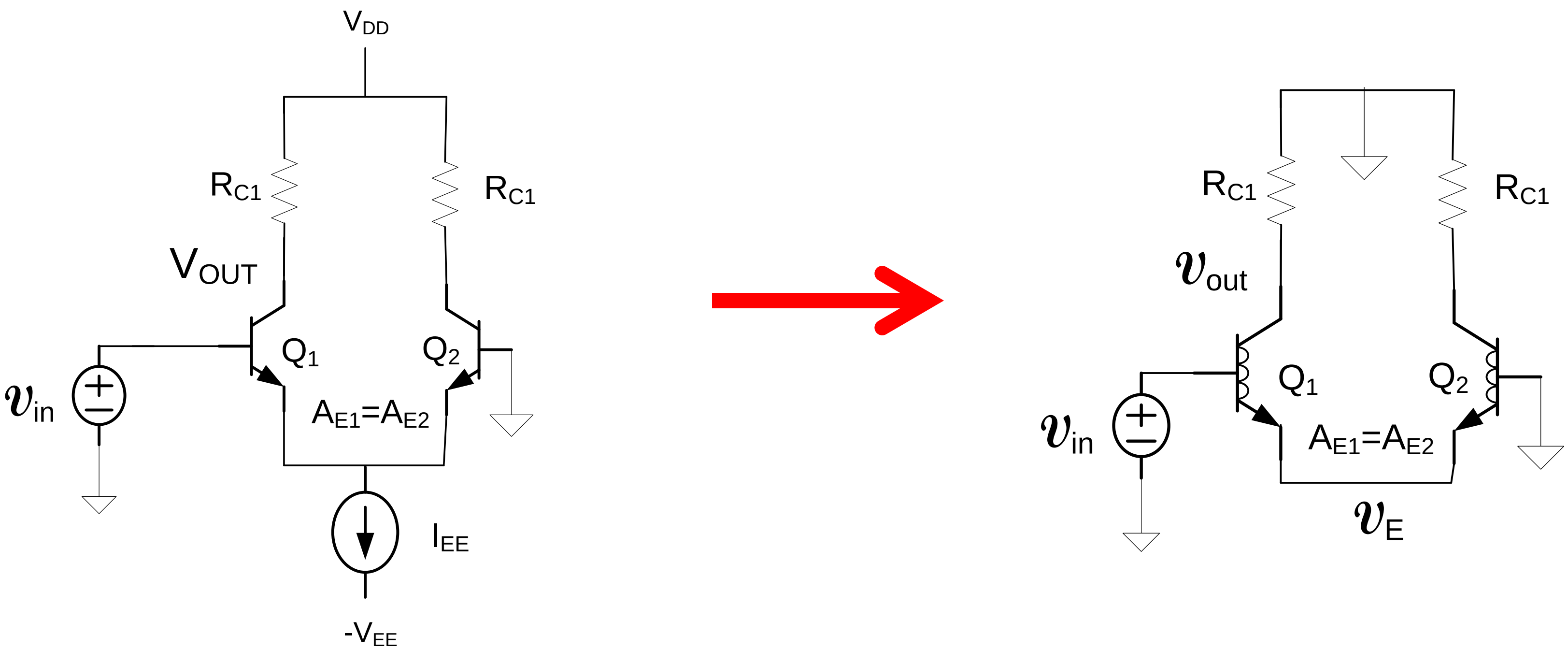


If A_V is large



Operational Amplifier (Op Amp)

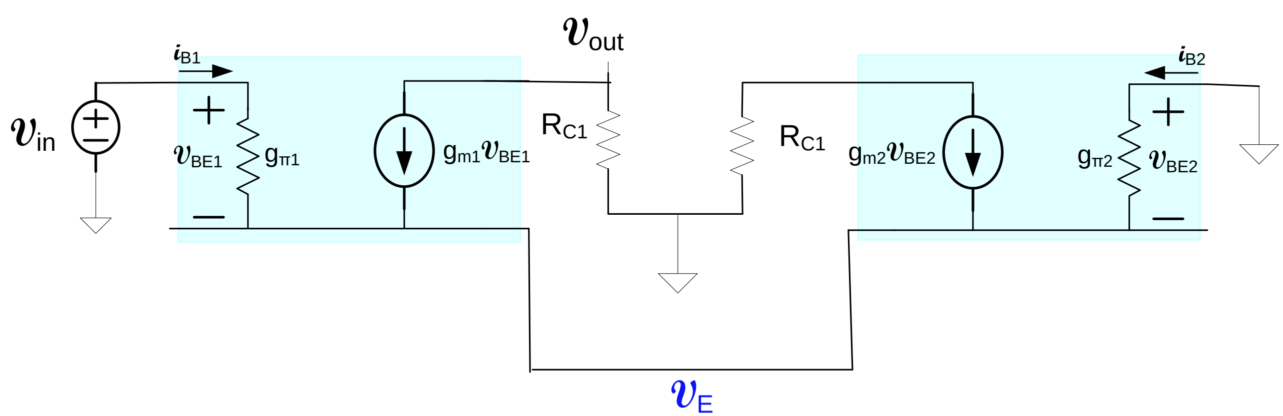
Example: Determine the voltage gain of the following circuit



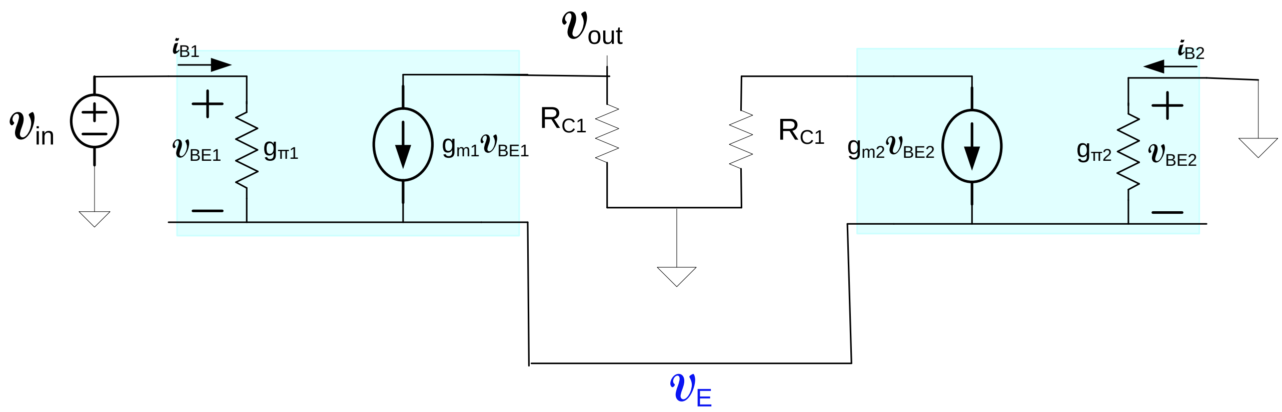
Since symmetric when v_{IN}=0

$$I_{C1} = I_{C2} = \frac{I_{EE}}{2}$$

$$g_{m1} = g_{m2} = \frac{I_{EE}}{2V_t}$$



Example: Determine the voltage gain of the following circuit



$$
\left.
\begin{aligned}
&v_E\left(g_{\pi1}+g_{\pi1}\right)=g_{\pi1}v_{IN}+g_{m1}\left(v_{IN}-v_E\right)+g_{m2}\left(-v_E\right)\\
&v_{OUT}=-R_{C1}g_{m1}\left(v_{IN}-v_E\right)
\end{aligned}
\right\}
$$

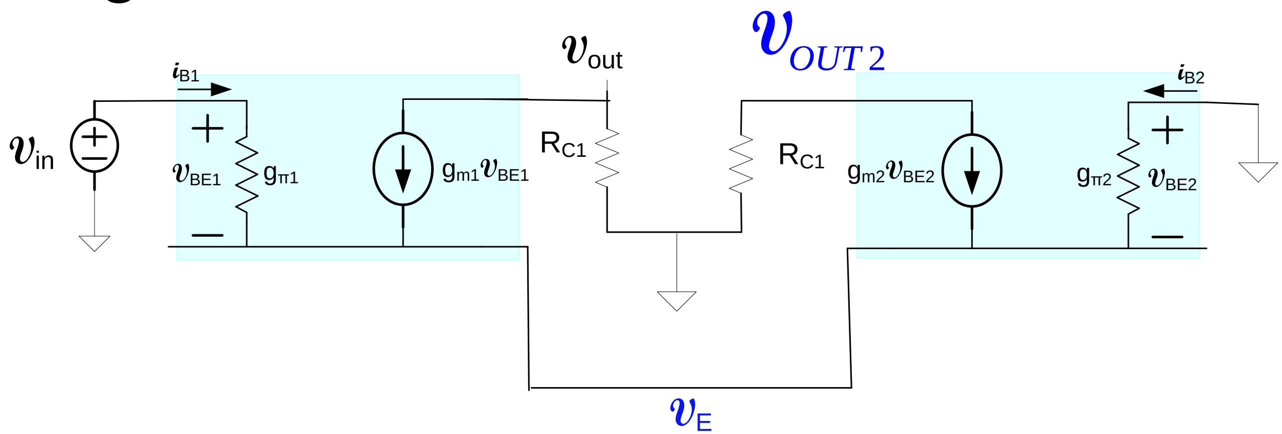
$$v_E\left(g_{\pi1}+g_{\pi2}+g_{m1}+g_{m2}\right)=v_{IN}\left(g_{m1}+g_{\pi1}\right)$$

$$v_E=\frac{\left(g_{m1}+g_{\pi1}\right)}{\left(g_{\pi1}+g_{\pi2}+g_{m1}+g_{m2}\right)}v_{IN}$$

$$v_{OUT}=-R_{C1}g_{m1}v_{IN}\left[1-\frac{\left(g_{m1}+g_{\pi1}\right)}{\left(g_{\pi1}+g_{\pi2}+g_{m1}+g_{m2}\right)}\right]$$

$$v_{OUT}=-R_{C1}g_{m1}v_{IN}\left[\frac{g_{\pi1}+g_{\pi2}+g_{m1}+g_{m2}-\left(g_{m1}+g_{\pi1}\right)}{\left(g_{\pi1}+g_{\pi2}+g_{m1}+g_{m2}\right)}\right]$$

Example: Determine the voltage gain of the following circuit



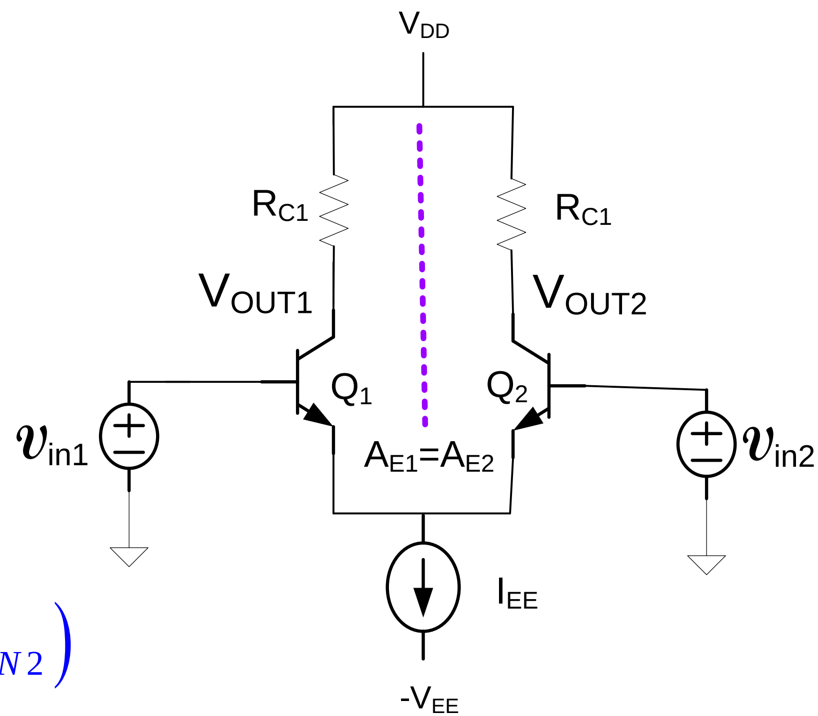
$$v_{OUT} = -R_{C1}g_{m1}v_{IN}\left[\frac{g_{\pi 1}+g_{\pi 2}+g_{m1}+g_{m2}-(g_{m1}+g_{\pi 1})}{(g_{\pi 1}+g_{\pi 2}+g_{m1}+g_{m2})}\right]$$

$$v_{OUT} \cong -R_{C1}g_{m1}v_{IN}\left[\frac{g_{m2}}{(g_{m1}+g_{m2})}\right]$$

$$v_{OUT} \cong \left[\frac{-R_{C1}g_{m1}}{2}\right]v_{IN}$$

$$v_{OUT2} \cong \left[\frac{R_{C1}g_{m1}}{2}\right]v_{IN}$$

Differential amplifier

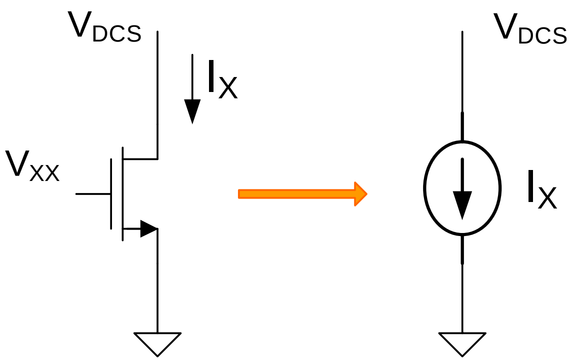


$$v_{OUT1} \cong -\left[\frac{R_{C1}g_{m1}}{2}\right]\left(v_{IN1} - v_{IN2}\right)$$

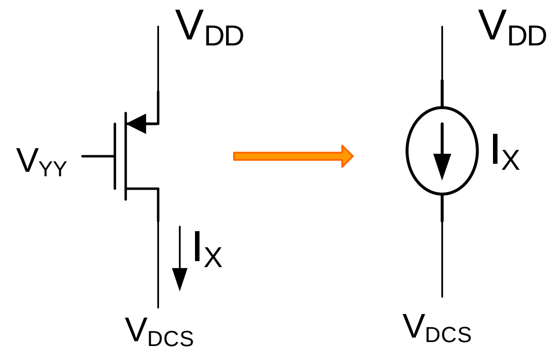
$$v_{OUT2} \cong \left[\frac{R_{C1}g_{m1}}{2}\right]\left(v_{IN1} - v_{IN2}\right)$$

- Very useful circuit
- This is a basic Op Amp
- Uses a current source and V_{DD} for biasing (no biasing resistors or caps!)
- But – needs a dc current source !!!!

Simple Current Sources



$$I_X=\frac{\mu C_{OX}W}{2L}\left(V_{XX}-V_T\right)^2$$

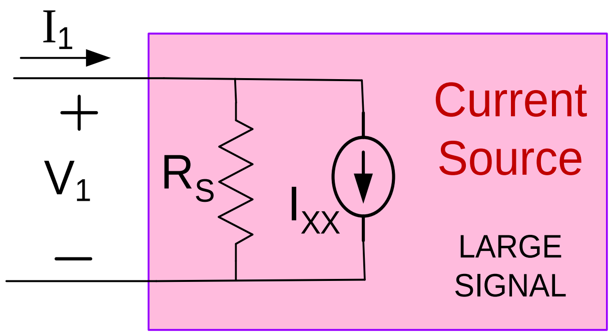


$$I_X=\frac{\mu C_{OX}W}{2L}\left(V_{DD}-V_{YY}+V_{Tp}\right)^2$$

But how good are these current sources?

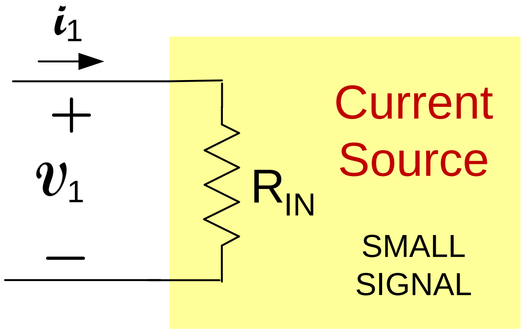
Model of dc Current Source

"Reasonable dc Current Source"



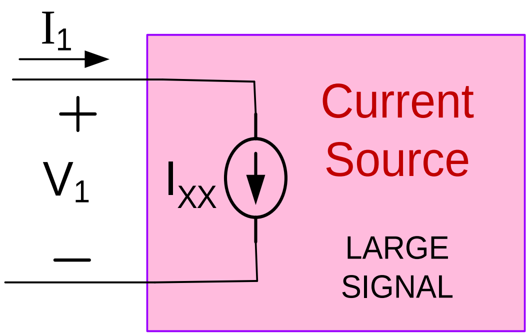
I_{XX} independent of V_1 and t , R_S large

Small-signal model of dc current source (since one-port)

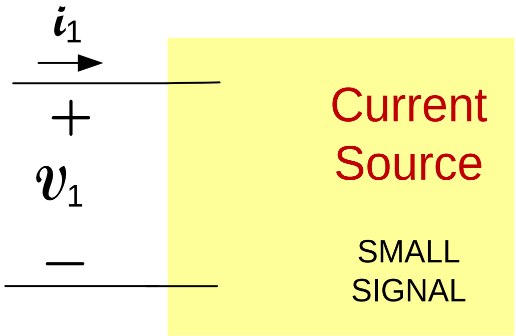


want R_{IN} large

Ideal dc Current Source



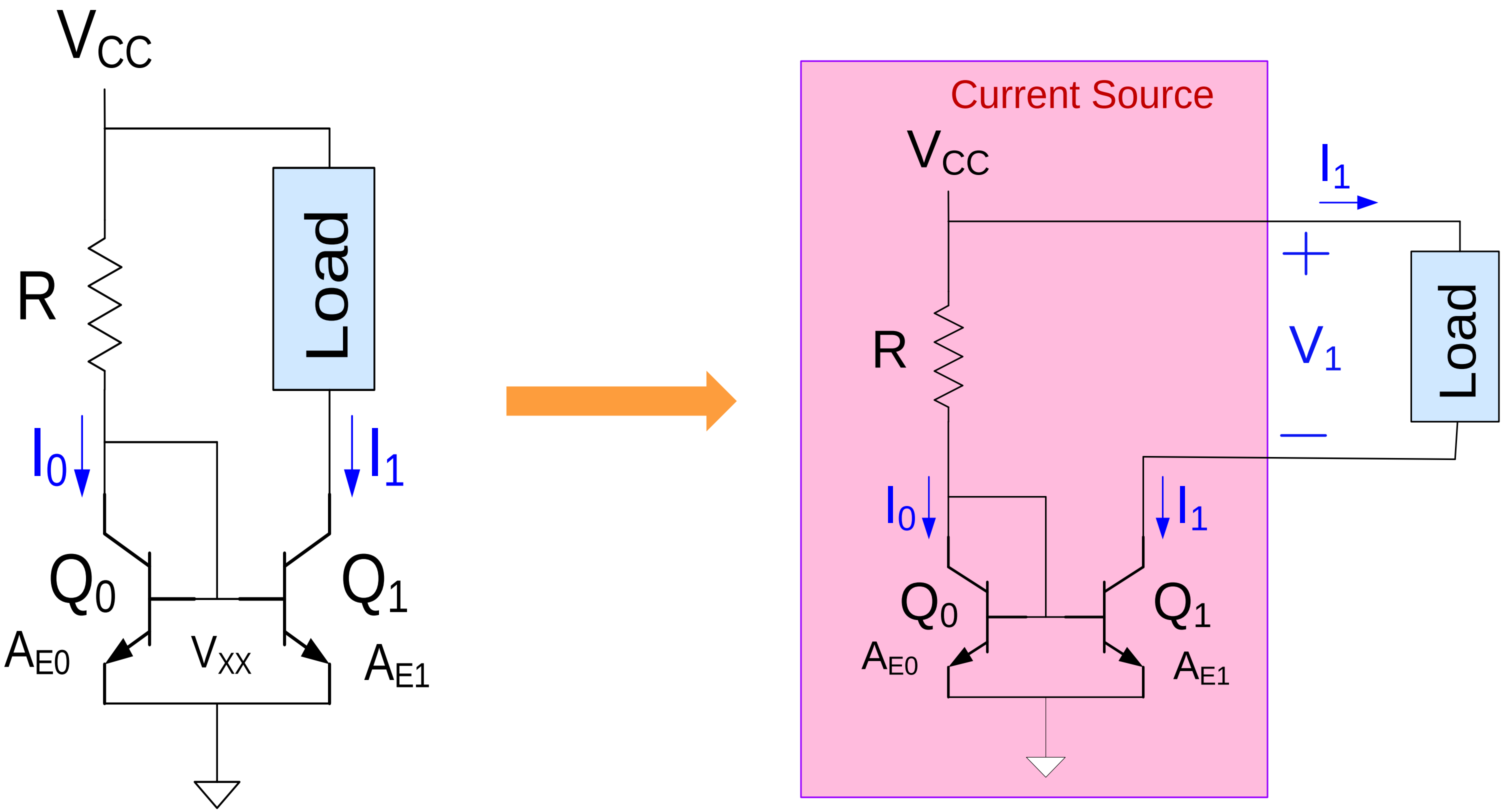
I_{XX} independent of V_1 and t



$R_{IN}=\infty$

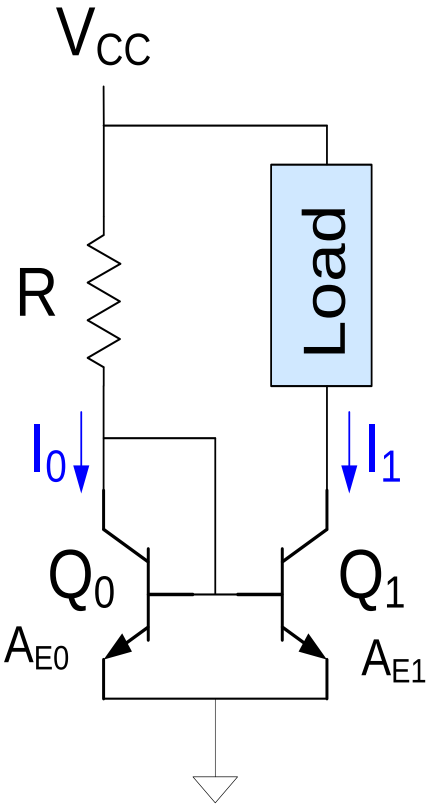
Current Sources/Mirrors

Will show circuit in red behaves as a current source



R and Q_0 simply generate voltage V_{XX} in previous circuit

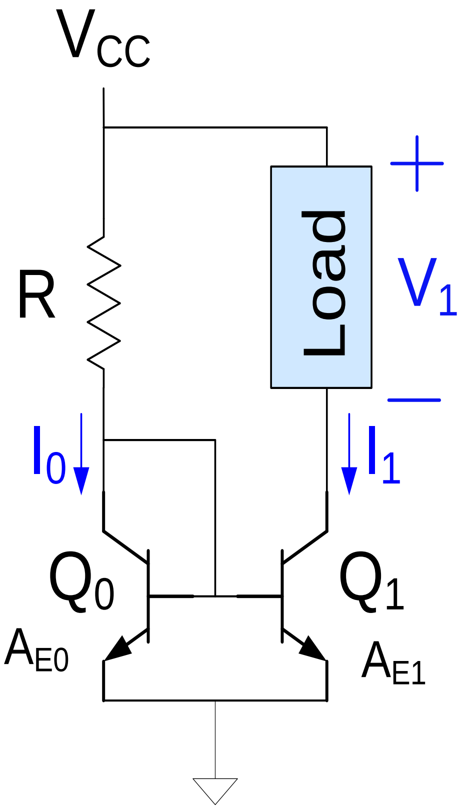
Current Sources/Mirrors



$$I_0 \cong \frac{\left(V_{CC}\text{-}0.6V\right)}{R}$$

If the base currents are neglected

Current Sources/Mirrors



$$I_0 \cong \frac{(V_{CC} - 0.6V)}{R}$$

If the base currents are neglected

$$\left.\begin{aligned} I_0 &= J_S A_{E0} e^{\frac{V_{BE0}}{V_t}} \\ I_1 &= J_S A_{E1} e^{\frac{V_{BE1}}{V_t}} \end{aligned}\right\}$$

since $V_{BE1}=V_{BE2}$

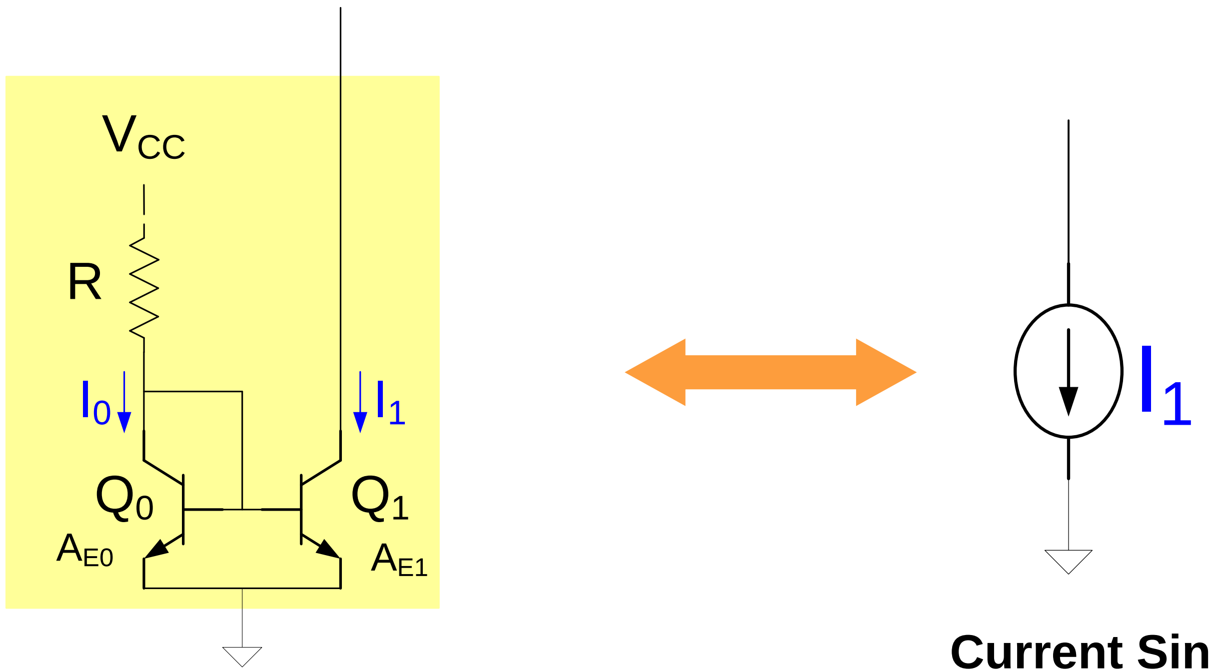
$$I_1 \cong \left(\frac{A_{E1}}{A_{E0}}\right) I_0 = \left(\frac{A_{E1}}{A_{E0}}\right) \frac{V_{CC} - 0.6V}{R}$$

Note I_1 is not a function of V_1

Behaves as a current sink ! So is ideal with this model !!

And does not require an <u>additional</u> dc voltage source !!!

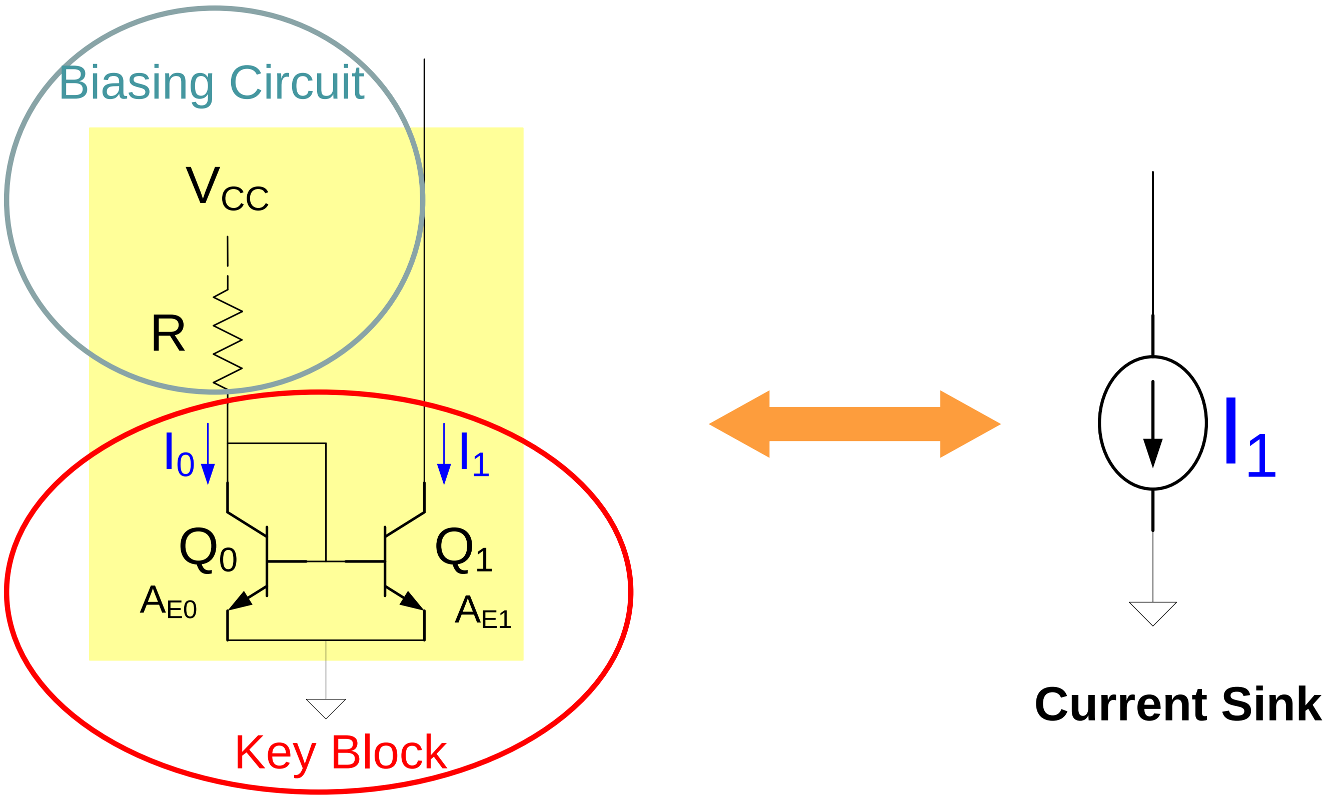
Current Sources/Mirrors



Current Sink

- **Multiple Outputs Possible**
- **Can be built for sourcing or sinking currents**
- **Also useful as a current amplifier**
- **MOS counterparts work very well and are not plagued by base current**

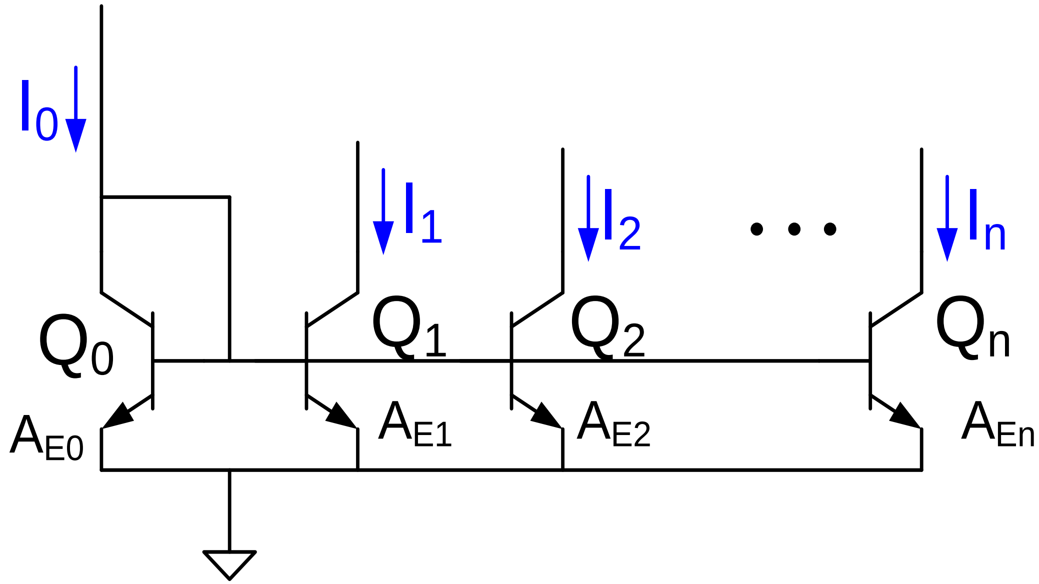
Current Sources/Mirrors



Two ways to look at this circuit:

- Q_0 and R bias Q_1
- R biases the $Q_0 : Q_1$ block

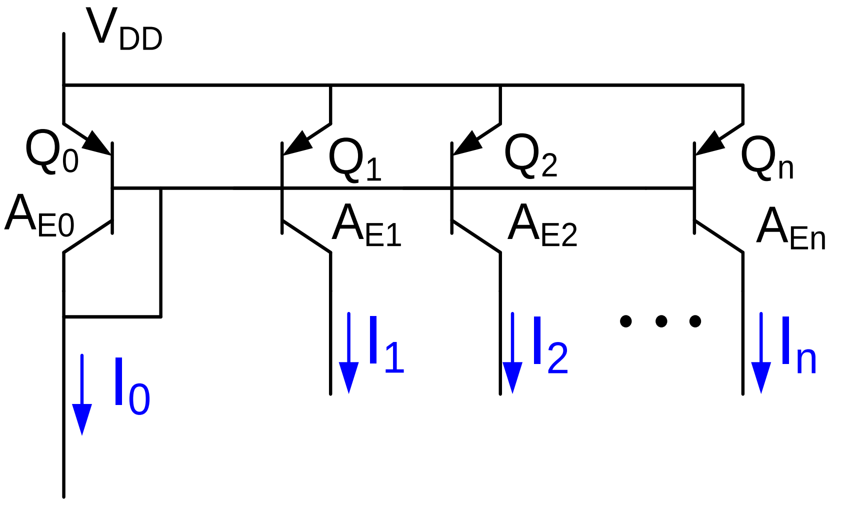
Current Sources/Mirrors



Multiple-Output Bipolar Current Sink

$$I_k = \left[\frac{A_{Ek}}{A_{E0}}\right] I_0$$

Current Sources/Mirrors



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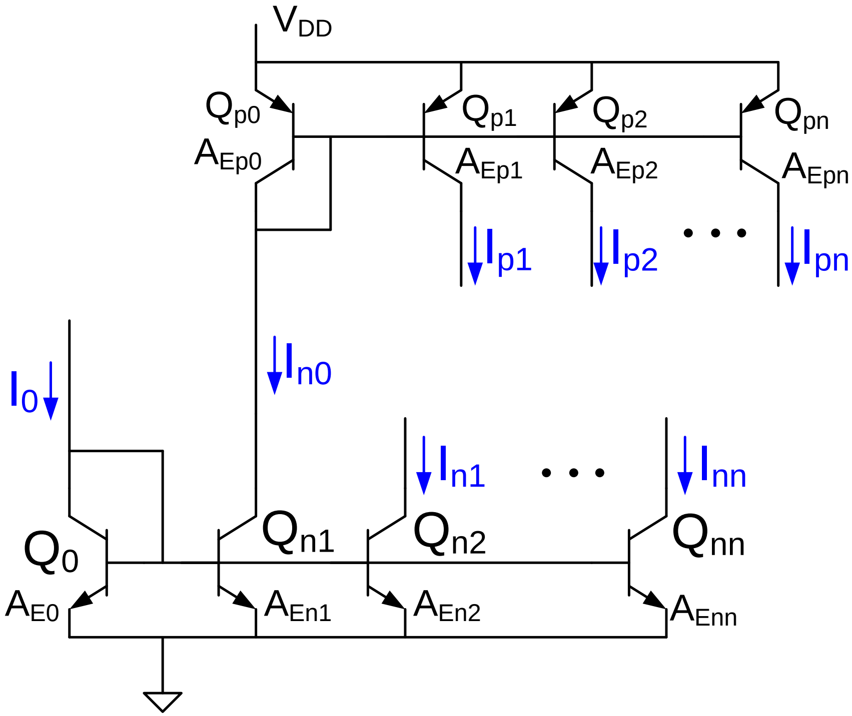
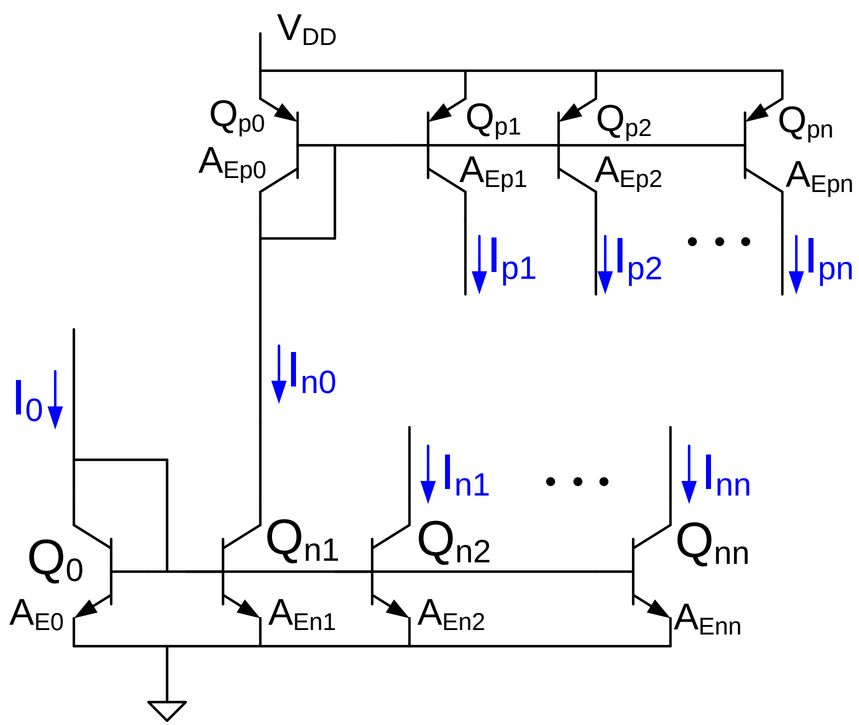
Current Sources/Mirrors



Multiple-Output Bipolar Current Source and Sink

$I_{nk} = ?$ $\quad I_{pk} = ?$

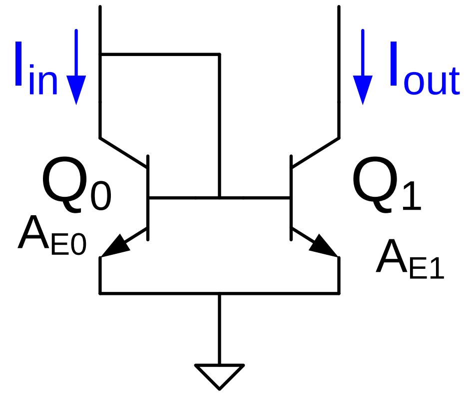
Current Sources/Mirrors



Multiple-Output Bipolar Current Source and Sink

$$I_{nk} = \left[\frac{A_{Enk}}{A_{E0}}\right] I_0 \qquad I_{pk} = \left[\frac{A_{En1}}{A_{E0}}\right]\left[\frac{A_{Epk}}{A_{Ep0}}\right] I_0$$

Current Sources/Mirrors



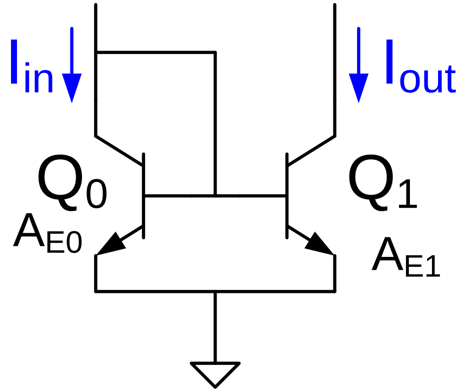
npn Current Mirror

$$I_{out} = \left[\frac{A_{E1}}{A_{E0}}\right] I_{in}$$

- **Termed a “current mirror”**
- **Output current linearly dependent on I_{in}**
- **Serves as a current amplifier**
- **Widely used circuit**

  But I_{in} and I_{out} must be positive !

Current Sources/Mirrors



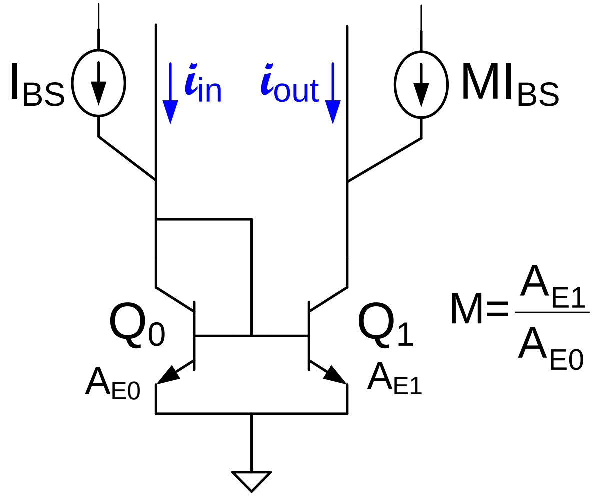
npn Current Mirror

$$I_{out} = \left[\frac{A_{E1}}{A_{E0}} \right] I_{in}$$

- **Termed a “current mirror”**
- **Output current linearly dependent on I_{in}**
- **Small-signal and large-signal relationships the same since linear**
- **Serves as a current amplifier**
- **Widely used circuit**

But I_{in} must be positive !

Current Sources/Mirrors



npn current mirror amplifier

i_{out}=?

$$\frac{i_{OUT}+MI_{BS}}{i_{in}+I_{BS}}=M$$

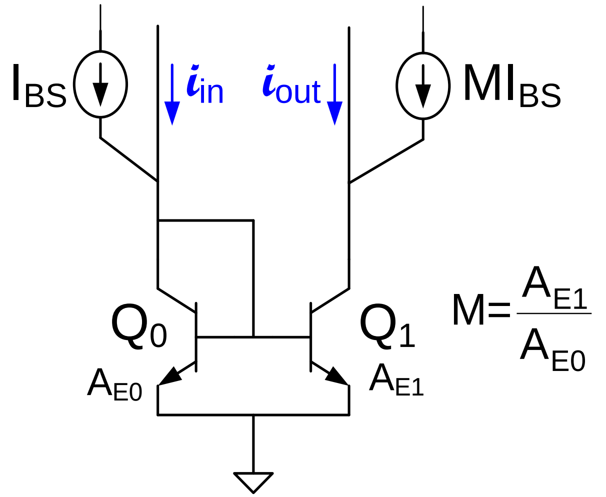
$$i_{OUT}+MI_{BS}=M\left(i_{in}+I_{BS}\right)$$

$$i_{OUT}+M\cancel{I}_{BS}=M\left(i_{in}+\cancel{I}_{BS}\right)$$

$$\frac{i_{OUT}}{i_{in}}=M$$

But $I_{BS}+i_{in}>0$!

Current Sources/Mirrors



npn current mirror amplifier

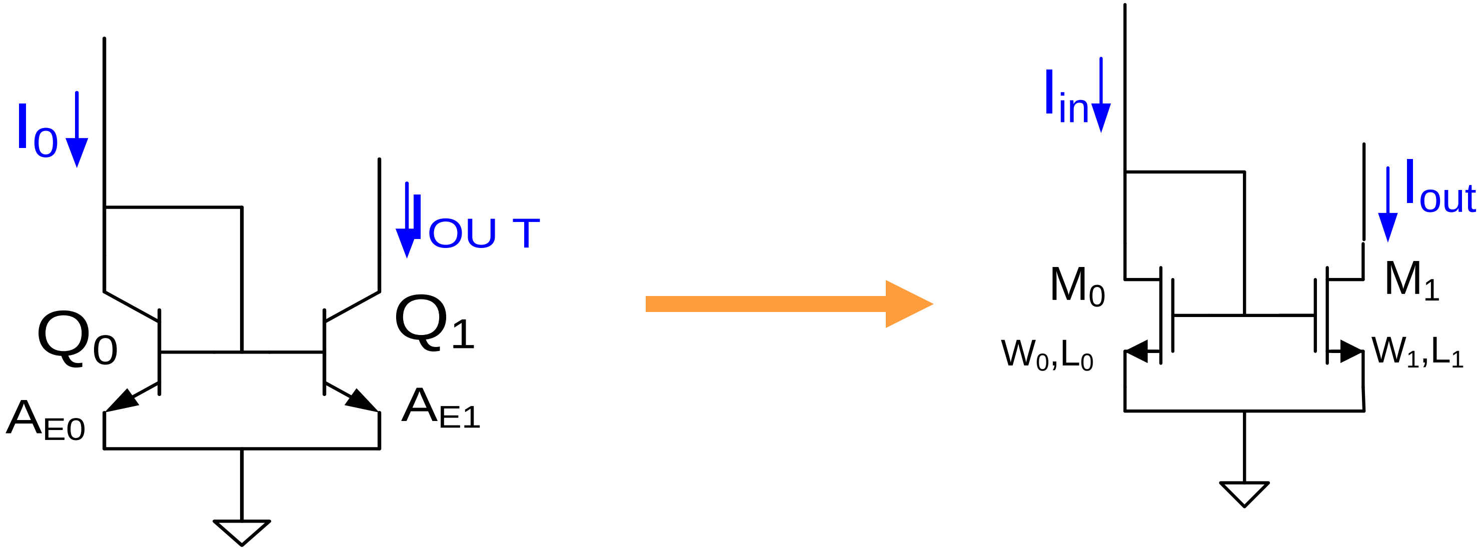
$$i_{out} = \left[\frac{A_{E1}}{A_{E0}}\right] i_{in}$$

Amplifiers both positive and negative currents (provided $i_{IN} > -I_{BS}$)

Current amplifiers are easy to build !!

Current gain can be accurately controlled with appropriate layout !!

Current Sources/Mirrors

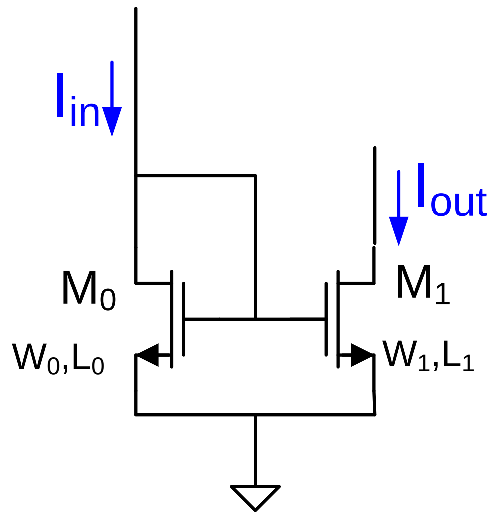


npn Current Mirror

n-channel Current Mirror

$I_{out} = ?$

Current Sources/Mirrors



n-channel Current Mirror

$$I_{in}=\frac{\mu C_{OX}W_0}{2L_0}\left(V_{GS0}-V_{T0}\right)^2$$

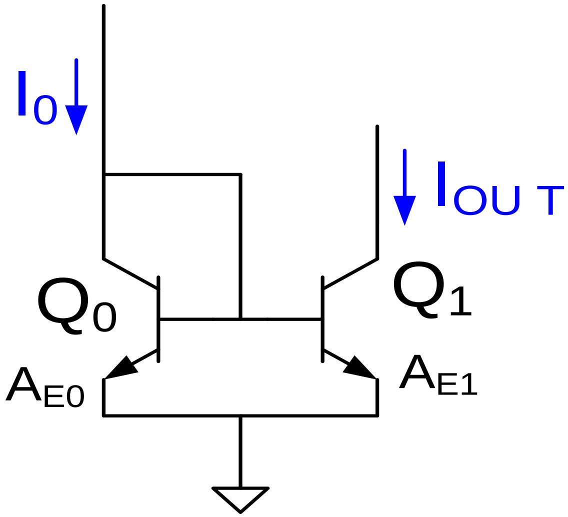
$$I_{out}=\frac{\mu\ C_{OX}W_1}{2L_1}\left(V_{GS1}-V_{T1}\right)^2$$

If process parameters are matched, it follows that

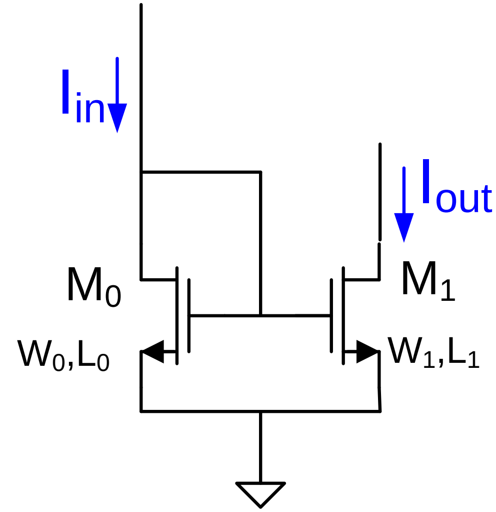
$$I_{out}=\left[\frac{W_1}{W_0}\frac{L_0}{L_1}\right]I_{in}$$

- Current mirror gain <u>can</u> be accurately controlled !
- Layout is important to get accurate gain (for both MOS and BJT)

Current Sources/Mirrors Summary



npn Current Mirror

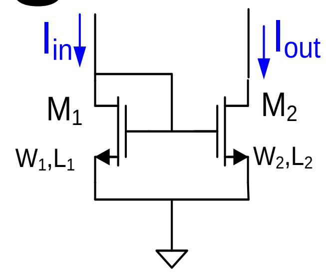


n-channel Current Mirror

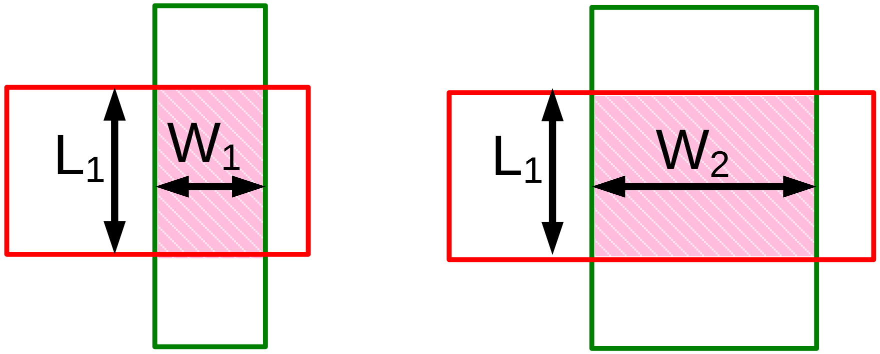
$$I_{out} = \left[\frac{A_{E1}}{A_{E0}} \right] I_{in}$$

$$I_{out} = \left[\frac{W_1}{W_0} \frac{L_0}{L_1} \right] I_{in}$$

Layout of Current Mirrors

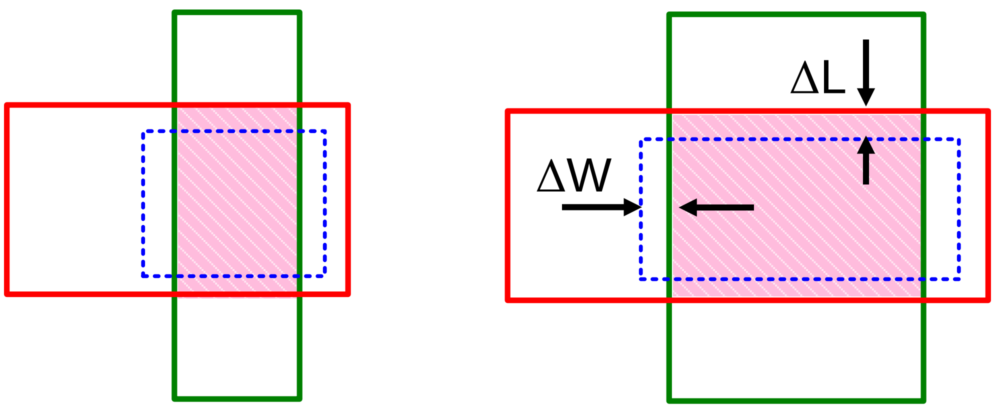


Example with M = 2



$$M = \left[\frac{W_2}{W_1}\frac{L_1}{L_2}\right]$$

Standard layout



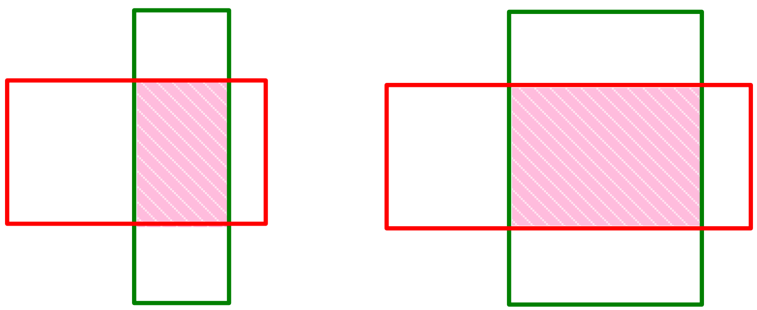
$$M = \left[\frac{W_2 + 2\Delta W}{W_1 + 2\Delta W} \bullet \frac{L_1 + 2\Delta L}{L_2 + 2\Delta L}\right]$$

$$M = \left[\frac{2W_1 + 2\Delta W}{W_1 + 2\Delta W} \bullet \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L}\right] \neq 2$$

Gate area after fabrication depicted

Layout of Current Mirrors

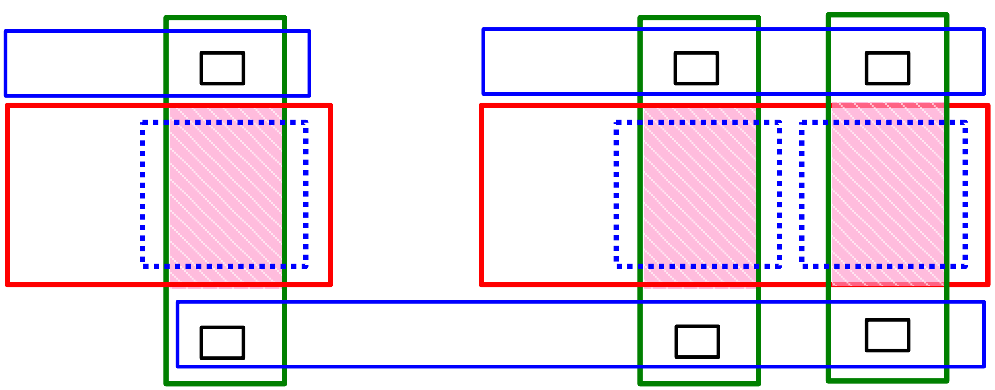
Example with M = 2



Standard layout

$$M = \left[\frac{W_2}{W_1} \frac{L_1}{L_2} \right]$$

$$M = \left[\frac{2W_1 + 2\Delta W}{W_1 + 2\Delta W} \bullet \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \right] \neq 2$$

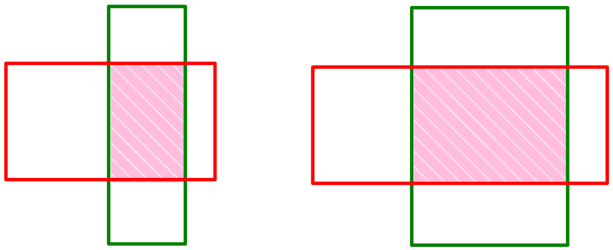


Better Layout

$$M = \left[\frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} \bullet \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \right] = 2$$

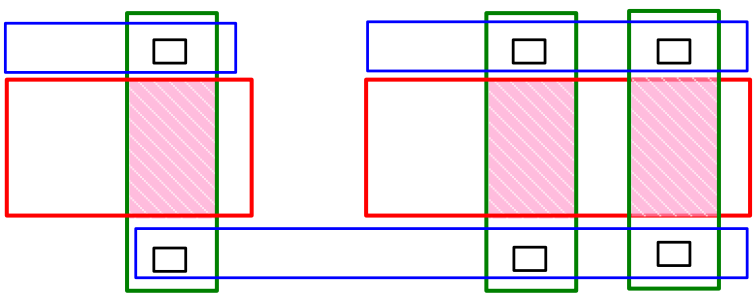
Layout of Current Mirrors

Example with M = 2



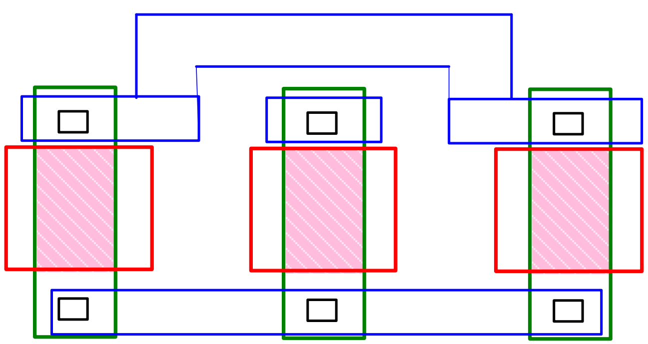
Standard layout

$$M = \left[\frac{W_2}{W_1} \frac{L_1}{L_2} \right]$$



Better Layout

$$M = \left[\frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} \bullet \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \right] = 2$$

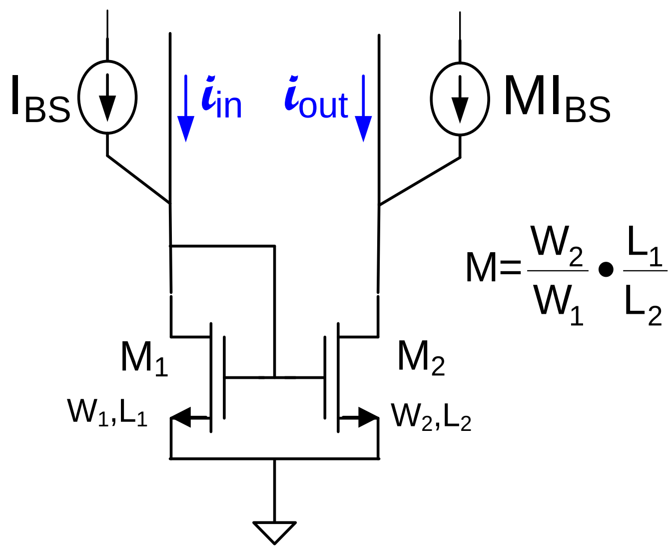


Even Better Layout

$$M = \left[\frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} \bullet \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \right] = 2$$

This is termed a common-centroid layout

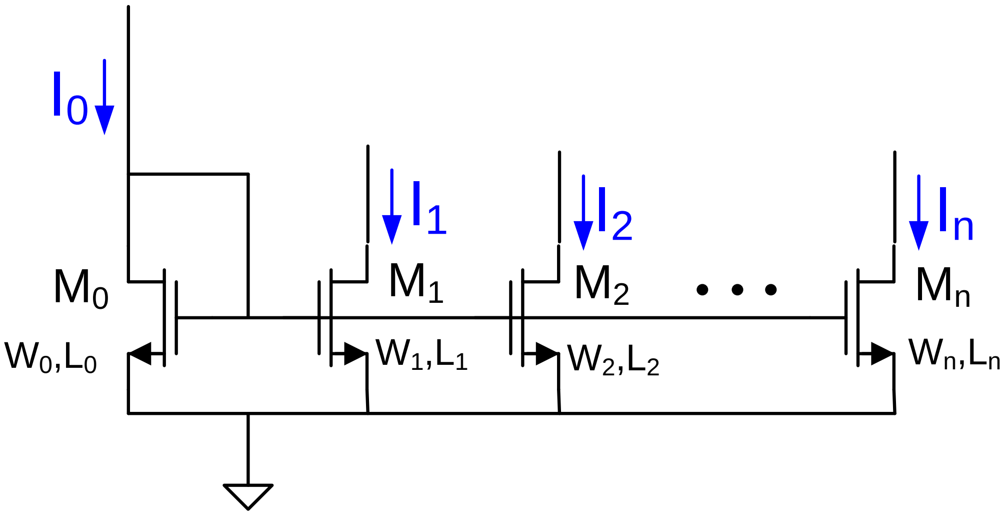
n-channel current mirror current amplifier



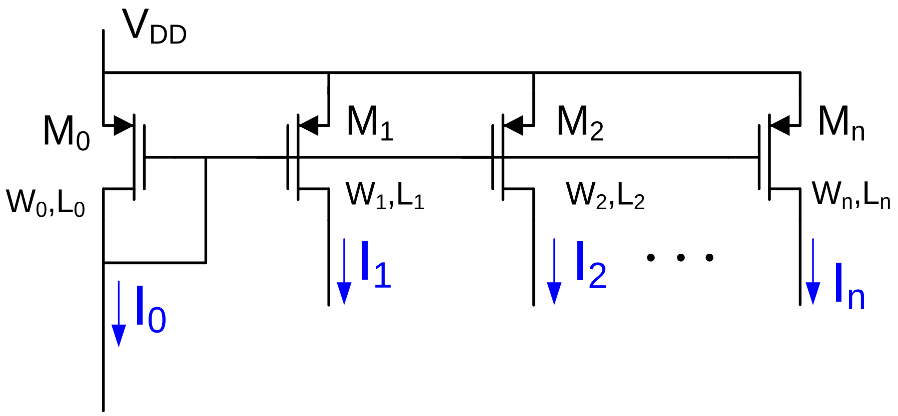
$$i_{out} = \left[\frac{W_2}{W_1} \frac{L_1}{L_2} \right] i_{in}$$

Amplifies both positive and negative currents

Current Sources/Mirrors



multiple output n-channel current sink array

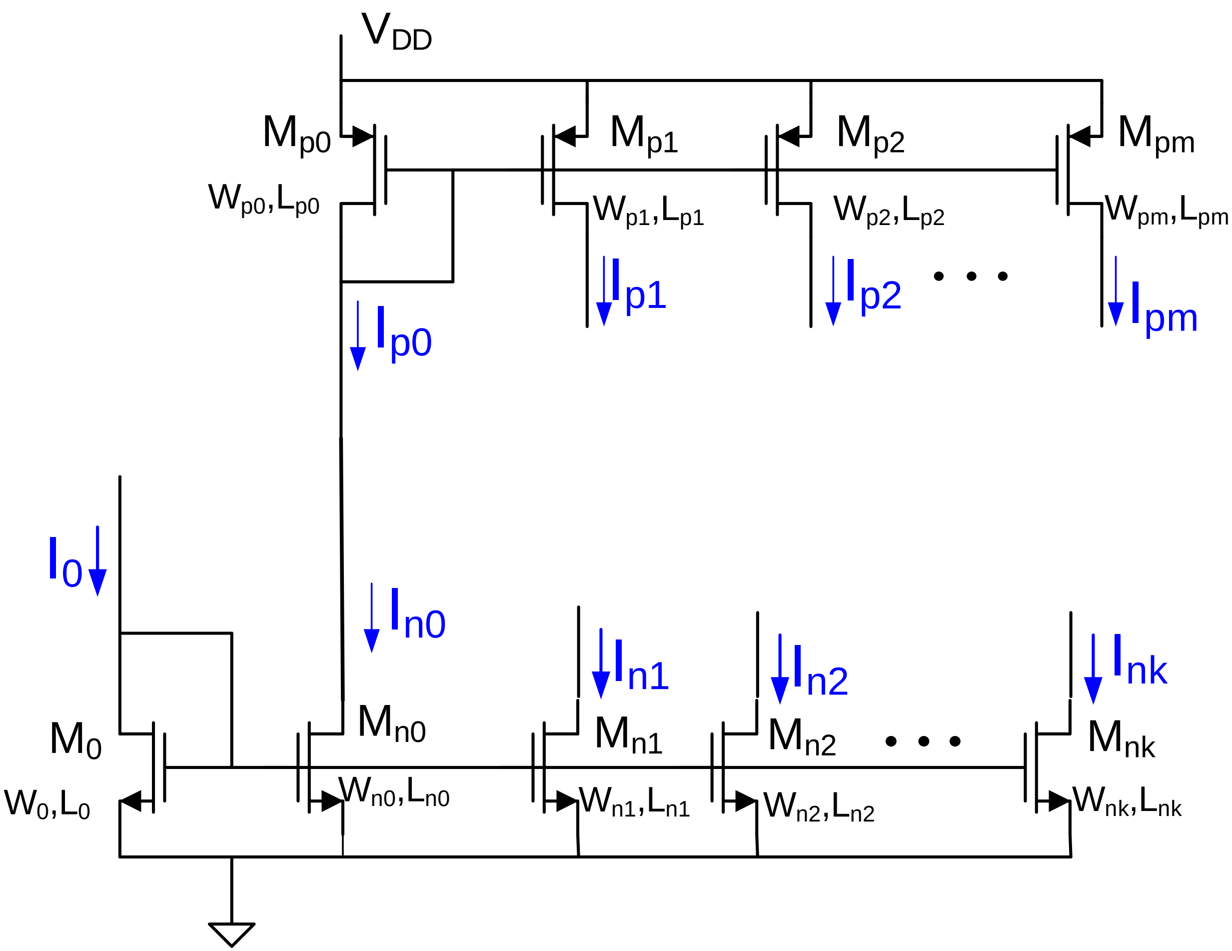


multiple output p-channel current source array

$$I_k = \left[\frac{W_k}{W_0} \frac{L_0}{L_k} \right] I_0$$

Current Sources/Mirrors

multiple sourcing and sinking current outputs



$$I_{pj} = \left[\frac{W_{pj}}{L_{pj}} \bullet \frac{L_{p0}}{W_{p0}}\right] M I_0$$

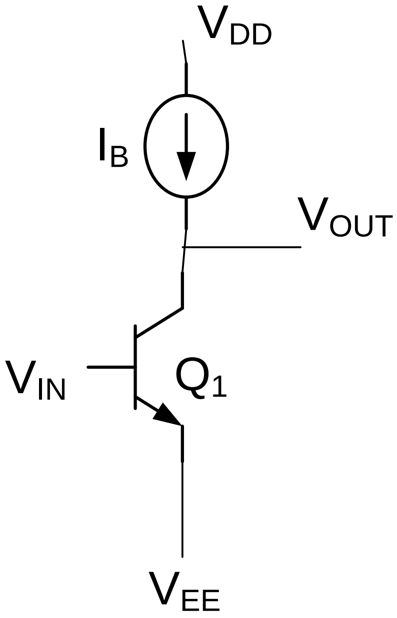
$$M = \left[\frac{W_{n0}}{L_{n0j}} \bullet \frac{L_0}{W_0}\right]$$

$$I_{nj} = \left[\frac{W_{nj}}{L_{nj}} \bullet \frac{L_0}{W_0}\right] I_0$$

m and k may be different

Often M=1

High-gain amplifier



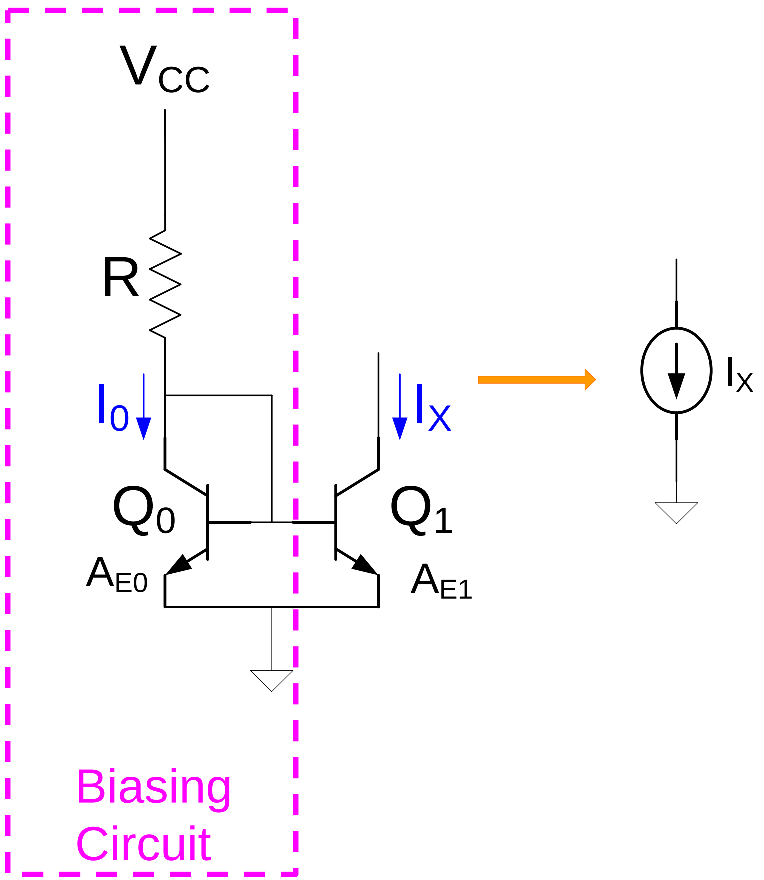
$$A_V \cong -8000$$

→ How can we build the current source?

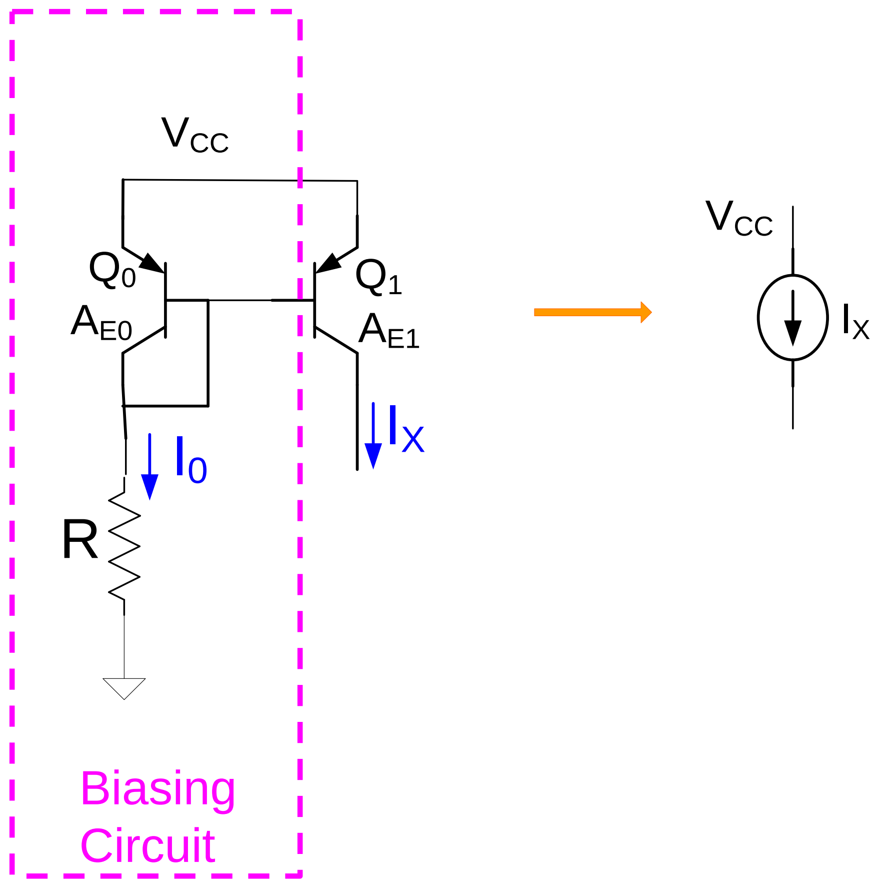
What is the small-signal model of an actual current source?

Basic Current Sources and Sinks

Bipolar Mirror-Based Current Sink

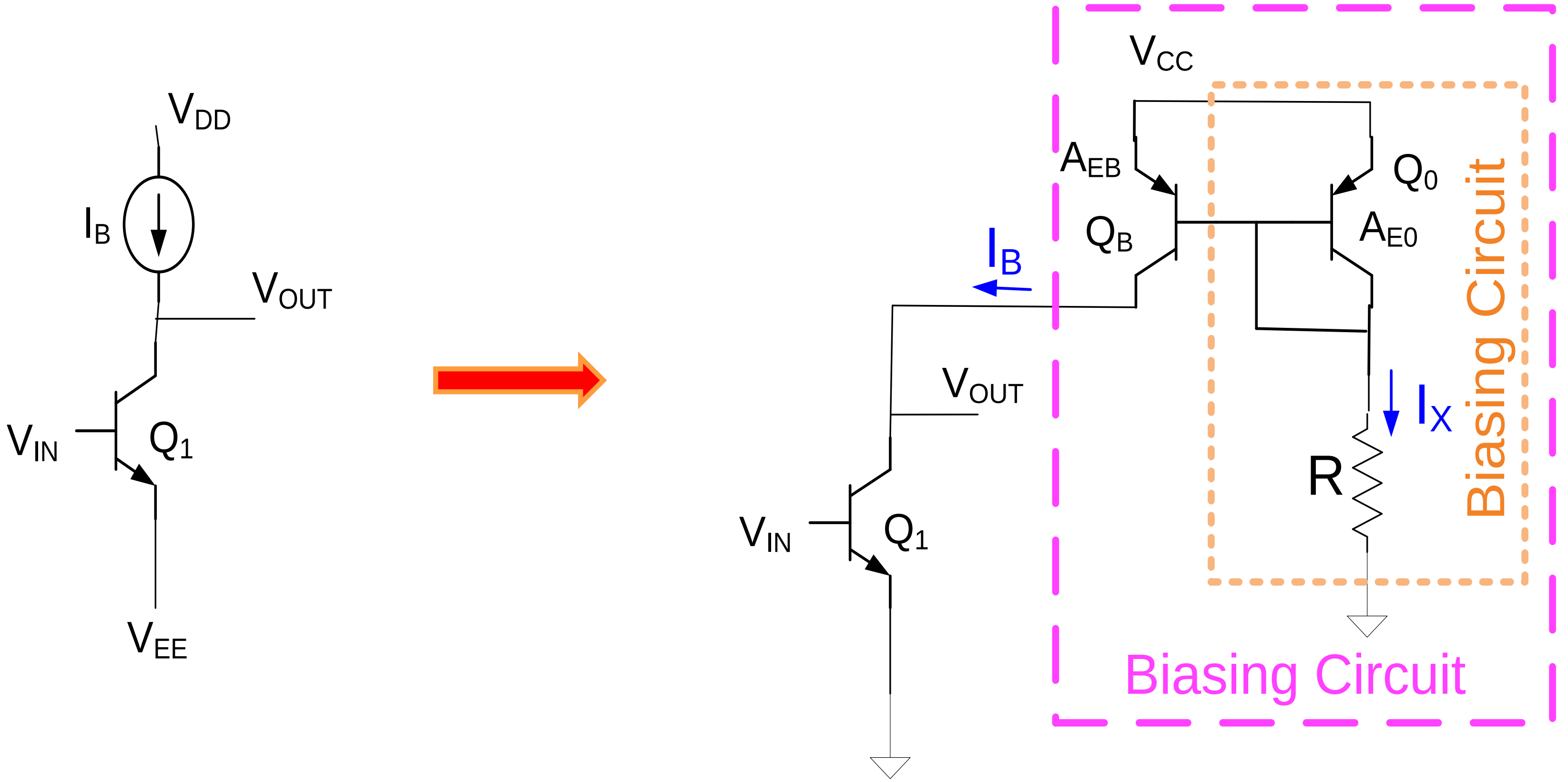


Bipolar Mirror-Based Current Source



Biasing circuit uses same V_{CC} as amplifier and no other independent sources

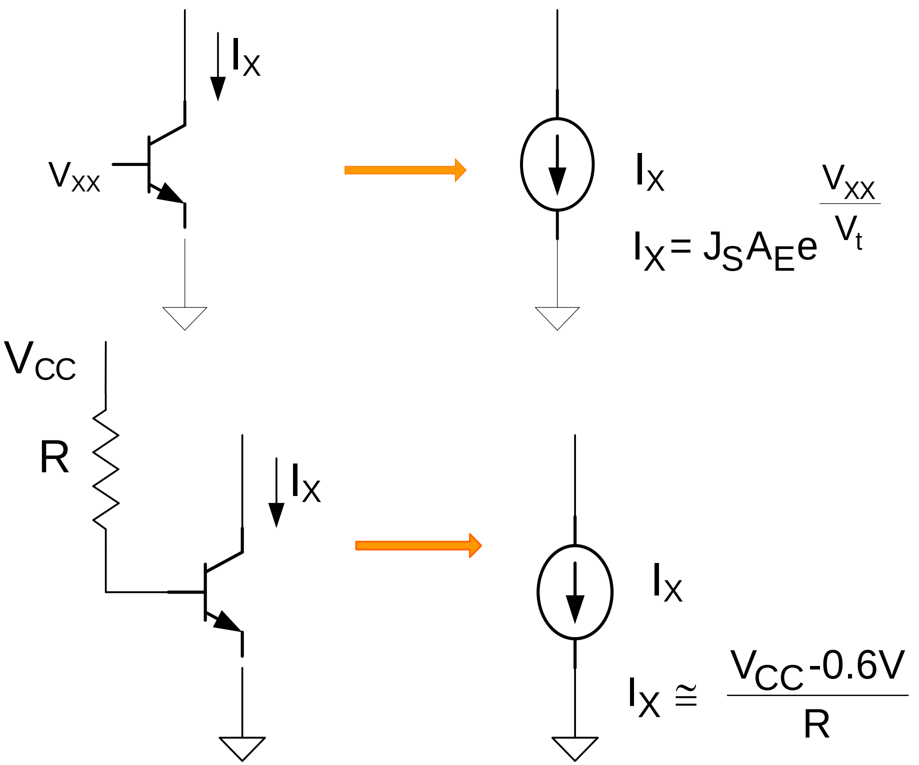
High-gain amplifier



- Bias circuitry requires only a single independent dc voltage source !
- Incremental overhead is only one transistor, Q_B

Basic Current Sources and Sinks

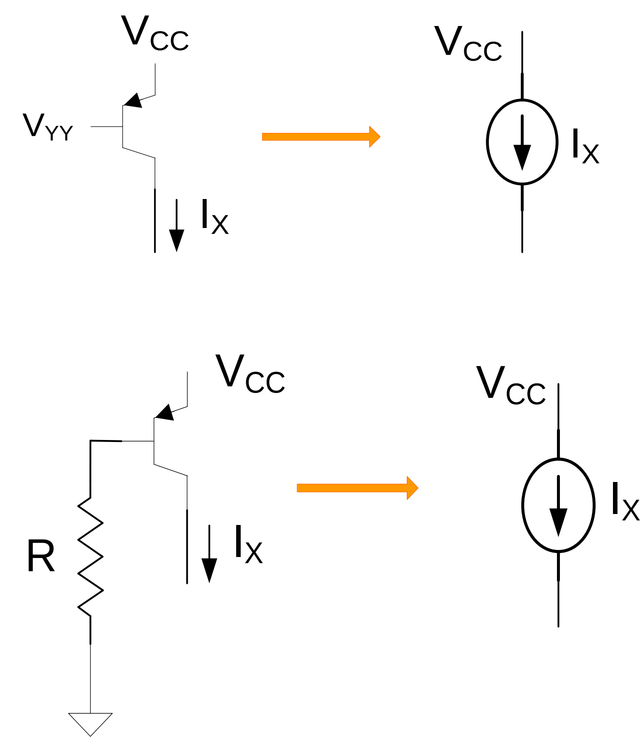
Basic Bipolar Current Sinks



$$I_X = J_S A_E e^{\frac{V_{XX}}{V_t}}$$

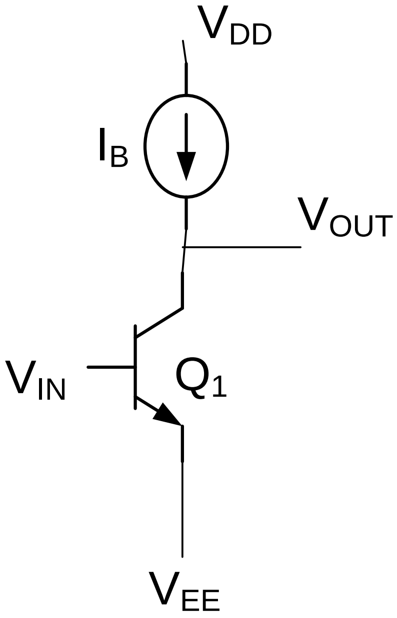
$$I_X \cong \frac{V_{CC} - 0.6V}{R}$$

Basic Bipolar Current Sources



- Very practical methods for biasing the BJTs (or MOSFETs) can be used
- Current Mirrors often used for generating sourcing and sinking currents
- Can think of biasing transistors with V_{XX} and V_{YY} in these current sources

High-gain amplifier



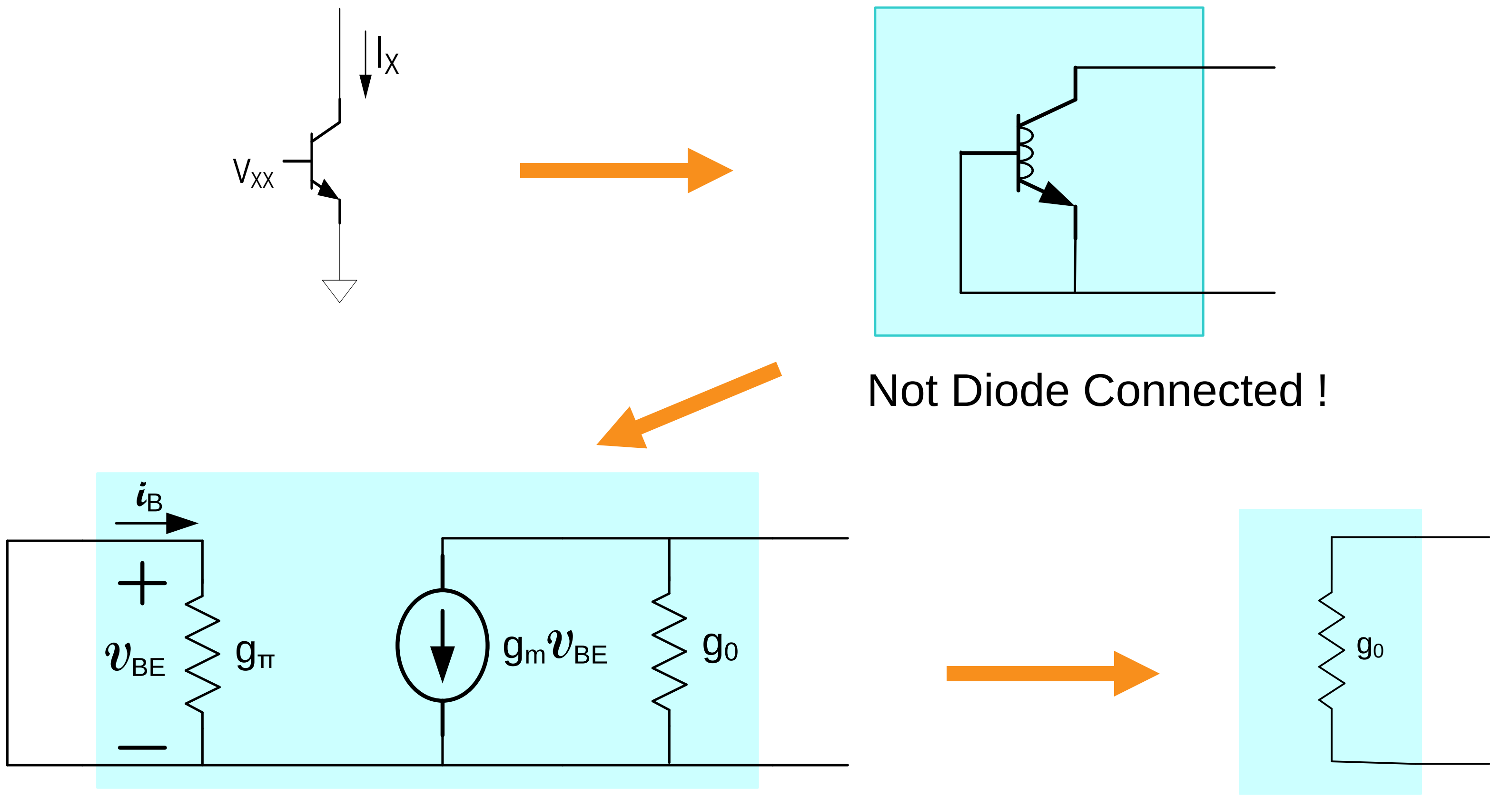
$$A_V \cong -8000$$

How can we build the current source?

→ What is the small-signal model of an actual current source?

Basic Current Sources and Sinks

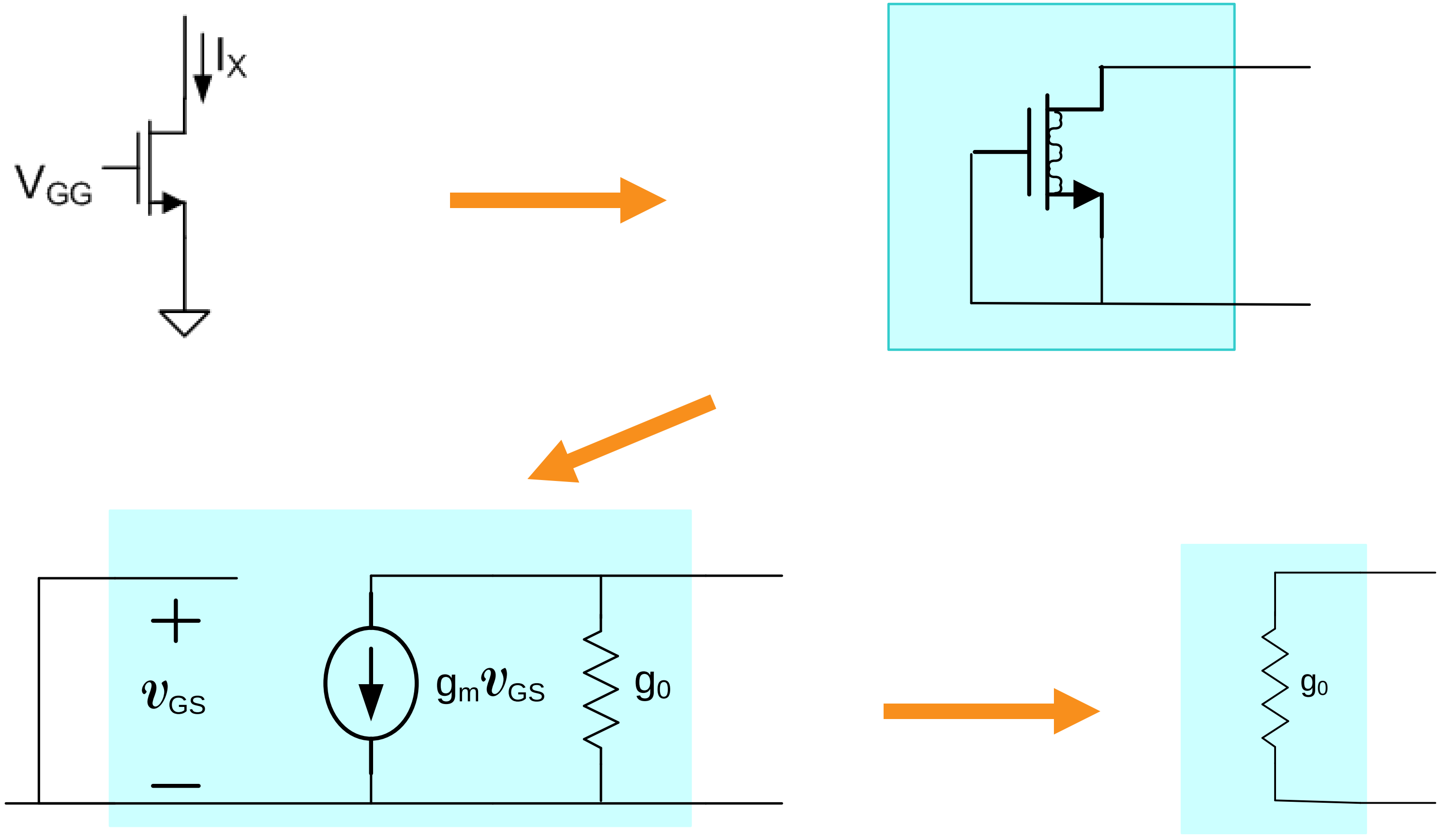
Small-signal Model of BJT Current Sinks and Sources



Small-signal model of all other BJT Sinks and Sources introduced so far are the same

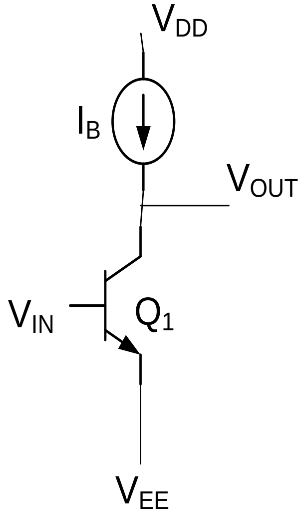
Basic Current Sources and Sinks

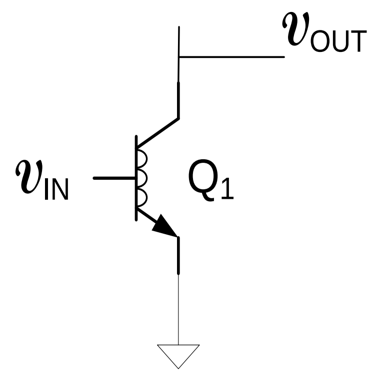
Small-signal Model of MOS Current Sinks and Sources



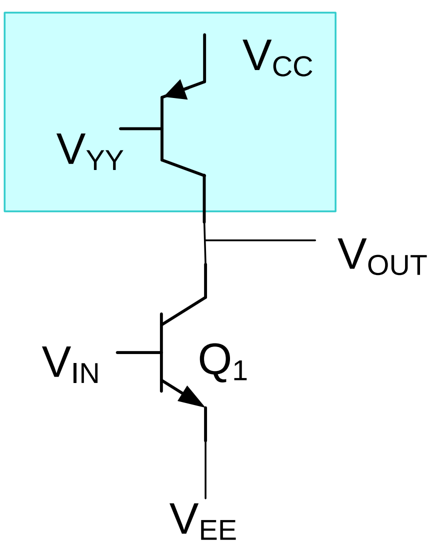
Small-signal model of all other MOS Sinks and Sources introduced thus far are the same

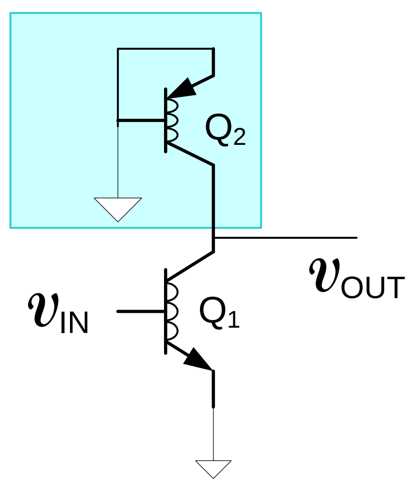
High-gain amplifier

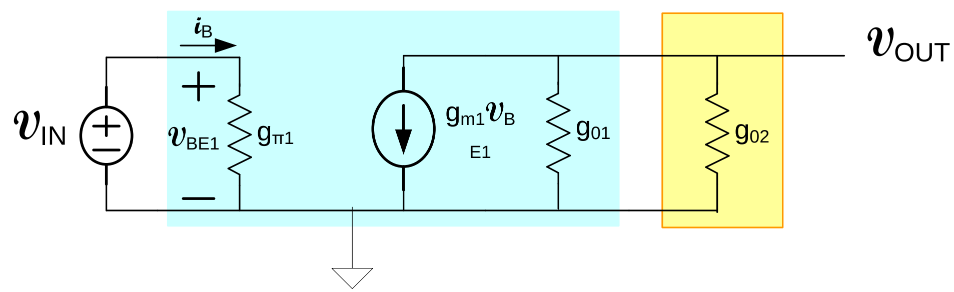




$$A_V = \frac{-g_m}{g_0}$$

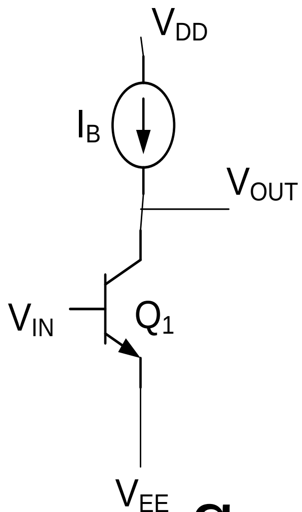




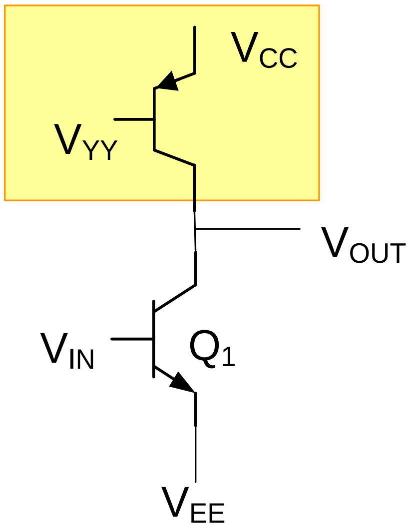


$$A_V = \frac{-g_{m1}}{g_{01} + g_{02}} \cong \frac{-g_{m1}}{2g_{01}}$$

High-gain amplifier



$$\frac{g_m}{g_0} = \frac{g_{m1}}{g_{01}} = \frac{V_{AF}}{V_t} \cong 8000$$



$$A_V = \frac{-g_m}{g_0} = -8000$$

$$A_V \cong \frac{-g_{m1}}{2g_{01}} = -4000$$

- **Nonideal current source decreased the gain by a factor of 2**
- **But the voltage gain is still quite large (-4000)**

Can the gain be made even larger?

End of Lecture 33