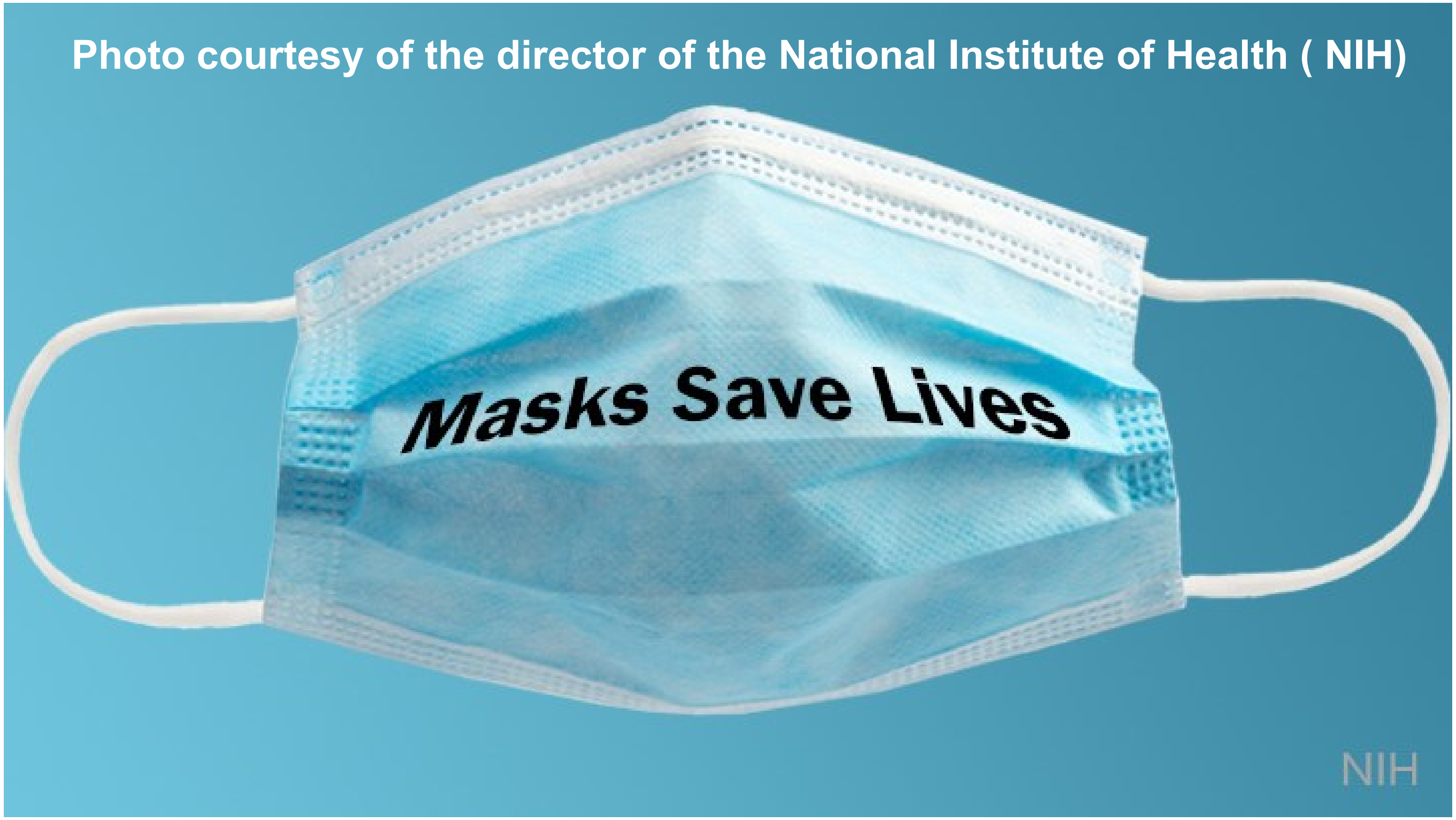
EE 330
Lecture 33

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

Exam Schedule

Exam 2 will be given on Friday March 11

Exam 3 will be given on Friday April 15

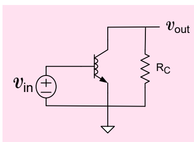
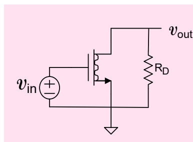
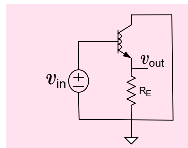
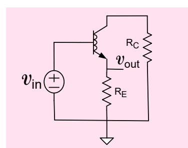
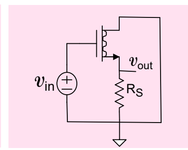
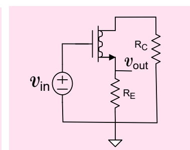
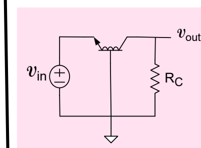
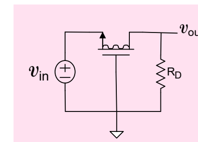
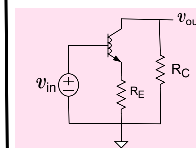
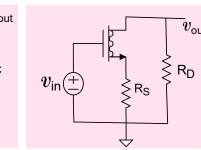


As a courtesy to fellow classmates, TAs, and the instructor

Wearing of masks during lectures and in the laboratories for this course would be appreciated irrespective of vaccination status

Review From Previous Lecture

Basic Amplifier Application 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	
			$\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$				

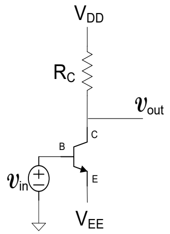
(not two-port models for the four structures)

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

Review From Previous Lecture

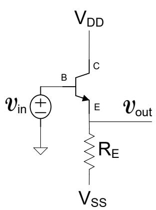
Basic Amplifier Characteristics Summary

CE/CS



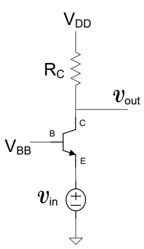
- **Large inverting gain**
- **Moderate input impedance**
- **Moderate (or high) output impedance**
- **Widely used as the basic high gain inverting amplifier**

CC/CD



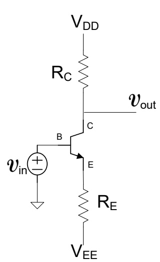
- **Gain very close to +1 (little less)**
- **High input impedance for BJT (high for MOS)**
- **Low output impedance**
- **Widely used as a buffer**

CB/CG



- **Large noninverting gain**
- **Low input impedance**
- **Moderate (or high) output impedance**
- **Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode**

CEwRE/
CSwRS

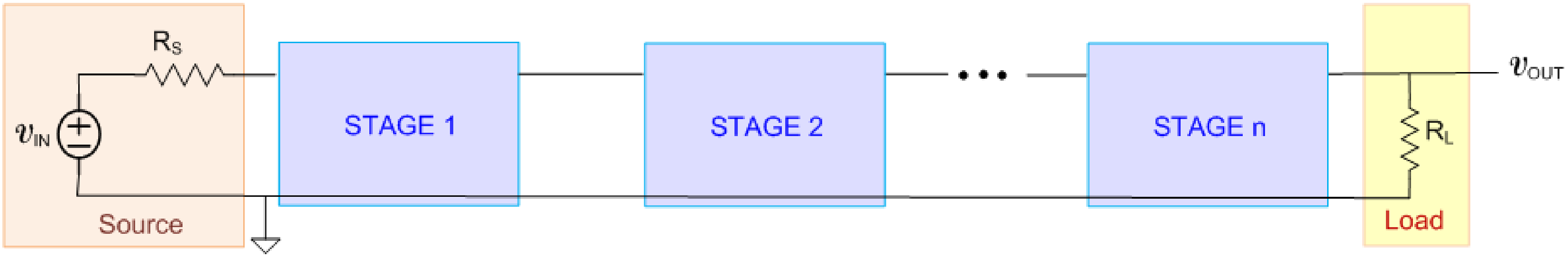


- **Reasonably accurate but somewhat small gain (resistor ratio)**
- **High input impedance**
- **Moderate output impedance**
- **Used when more accurate gain is required**

Review From Previous Lecture

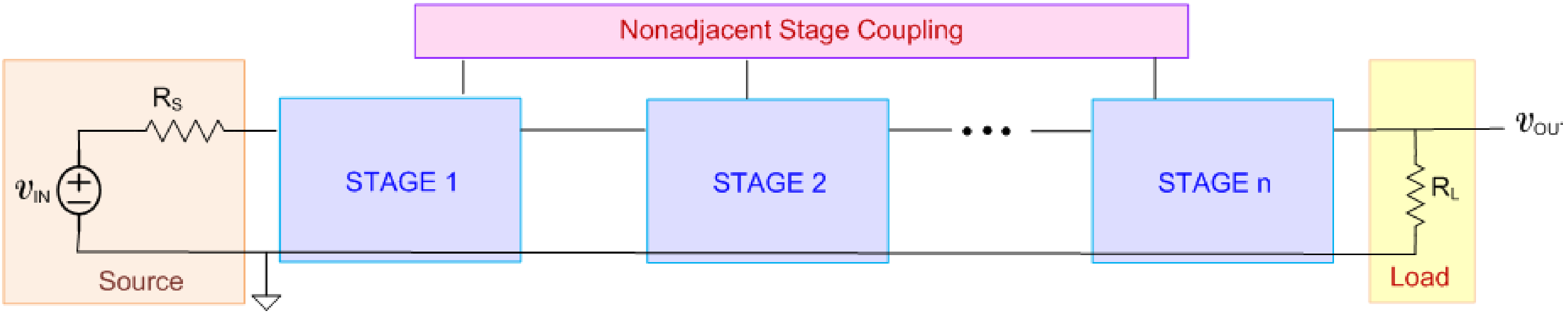
Cascaded Amplifier Analysis and Operation

Adjacent Stage Coupling Only



- Systematic Methods of Analysis/Design will be Developed

One or more couplings of nonadjacent stages

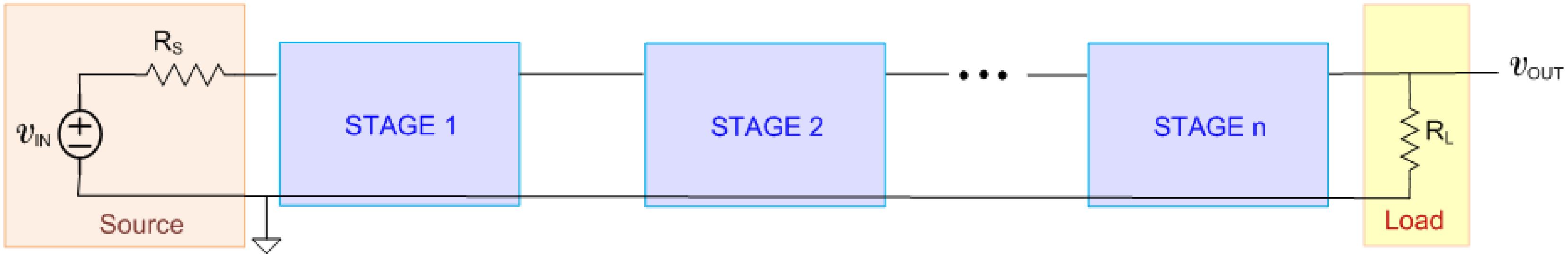


- Less Common
- Analysis Generally Much More Involved, Use Basic Circuit Analysis Methods

Review From Previous Lecture

Cascaded Amplifier Analysis and Operation

Adjacent Stage Coupling Only

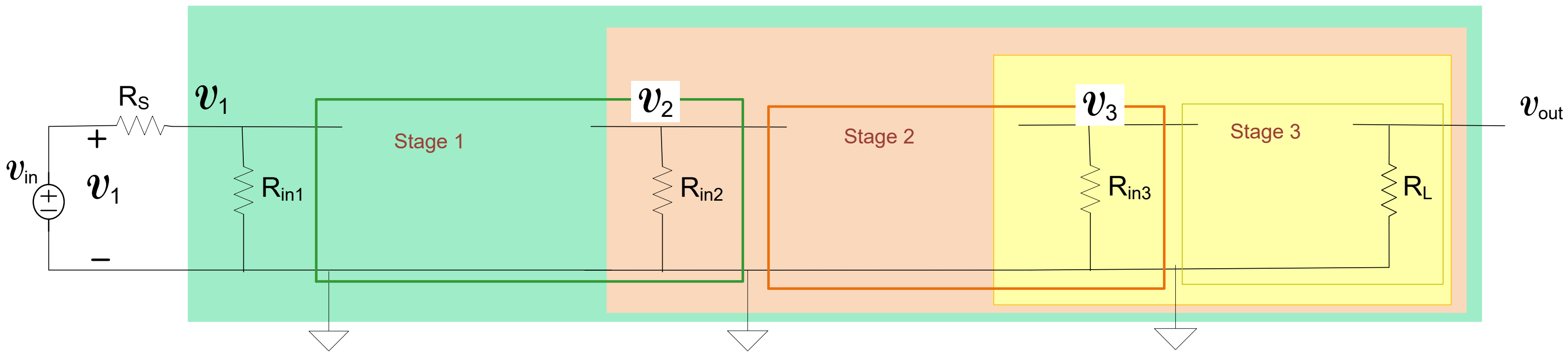


- Systematic Methods of Analysis/Design will be Developed

Case 1: All stages Unilateral

Case 2: One or more stages are not unilateral

Formalization of cascade circuit analysis working from load to input: (when stages are unilateral or not unilateral)

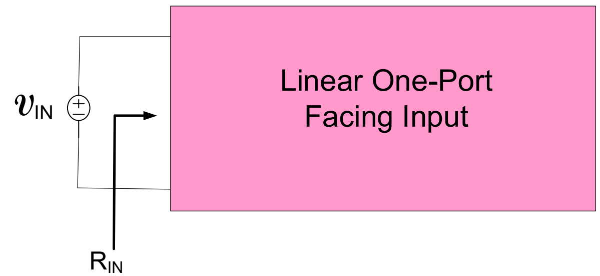


R_{ink} includes effects of all loading
Must recalculate if any change in loading
Analysis systematic and rather simple

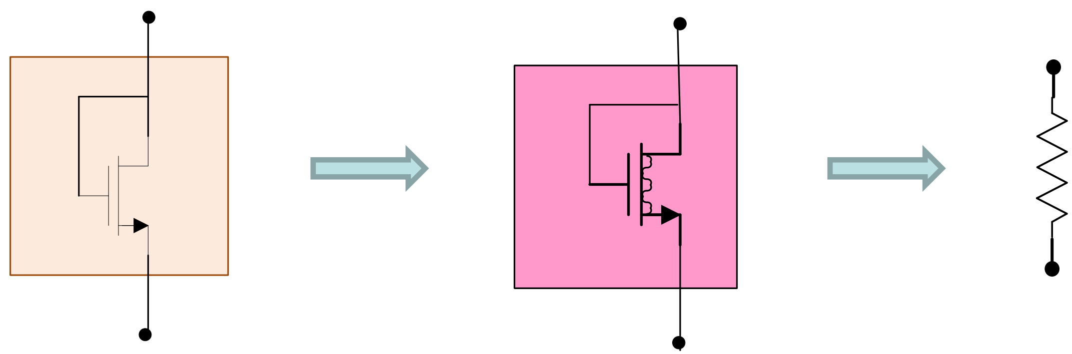
$$\frac{v_{OUT}}{v_{IN}} = \frac{v_1}{v_{IN}} \frac{v_2}{v_1} \frac{v_3}{v_2} \frac{v_{OUT}}{v_3}$$

This was the approach used in analyzing the previous cascaded amplifier

Review: Small-signal equivalent of a one-port

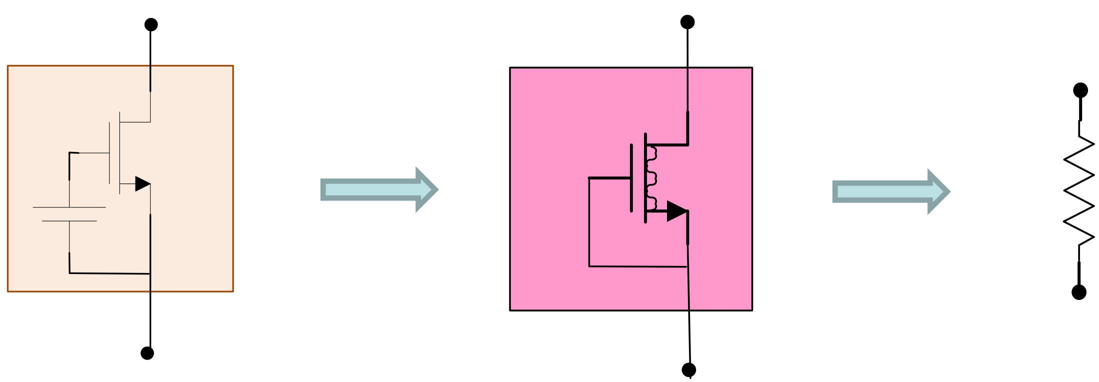


"Diode-connected transistor"



$$g = g_m + g_0 \approx g_m$$

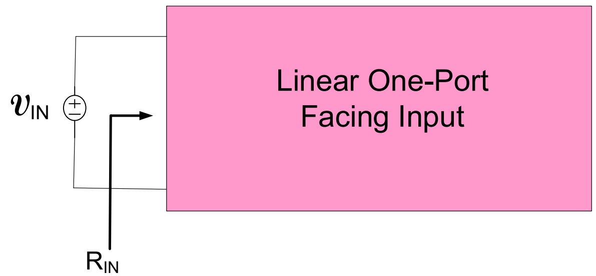
$$R = \frac{1}{g_m + g_0} \approx \frac{1}{g_m}$$



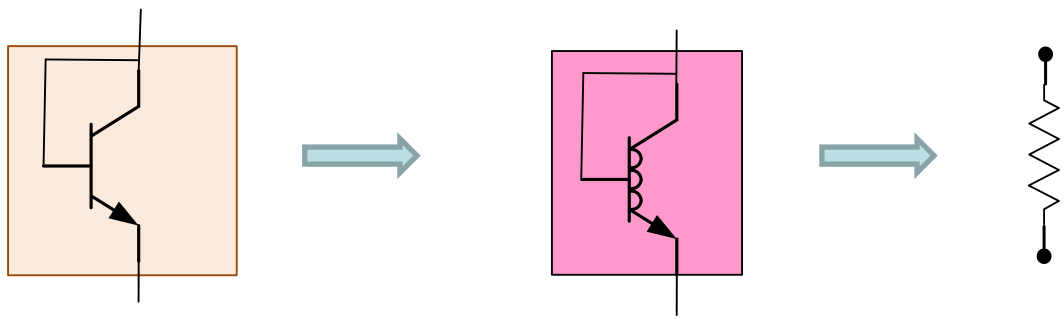
$$g = g_0$$

$$R = \frac{1}{g_0}$$

Review: Small-signal equivalent of a one-port



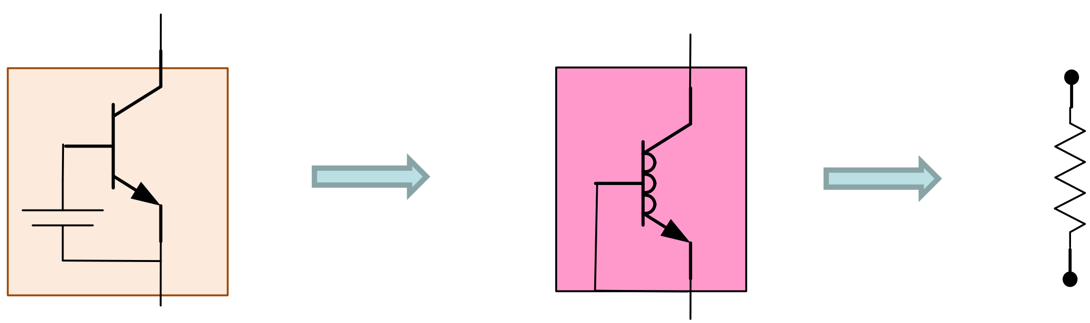
"Diode-connected transistor"



$$g = g_m + g_\pi + g_0 \approx g_m$$

$$R = \frac{1}{g_m + g_\pi + g_0} \approx \frac{1}{g_m}$$

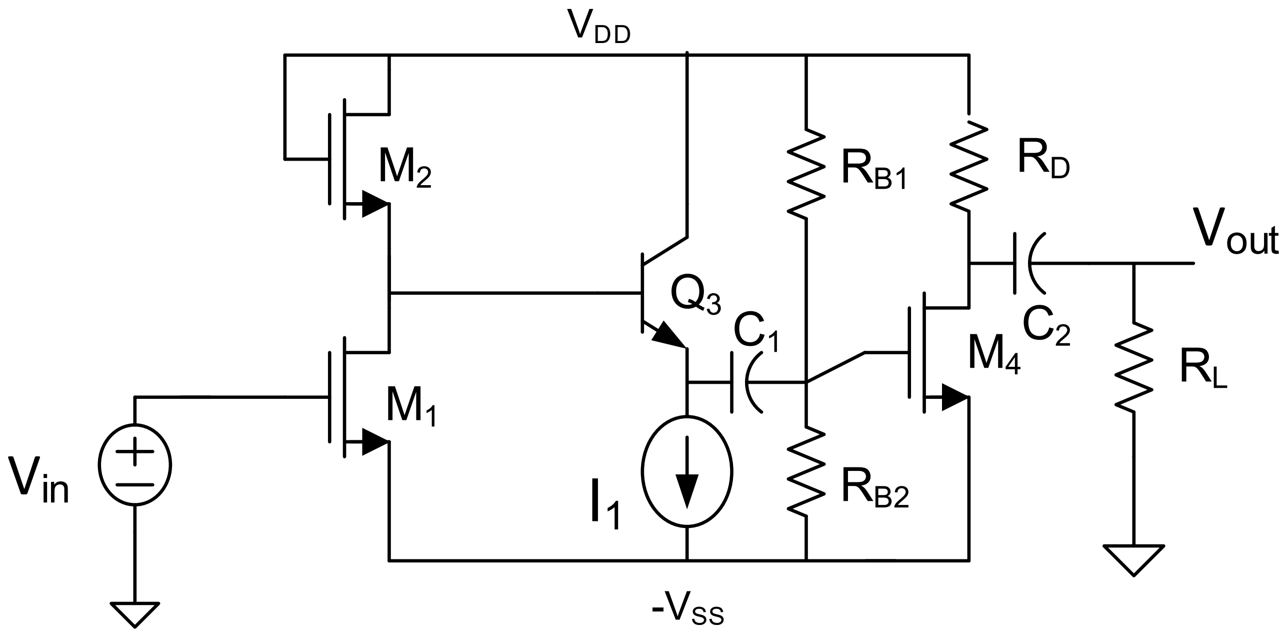
"GS or BE - connected transistor"



$$g = g_0$$

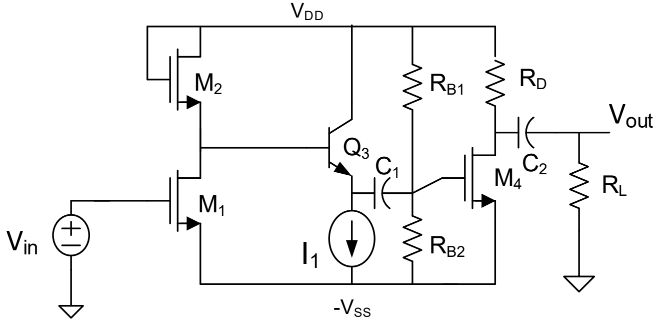
$$R = \frac{1}{g_0}$$

Example 2: $A_V = \frac{v_{out}}{v_{in}} = ?$ Express in terms of small-signal parameters

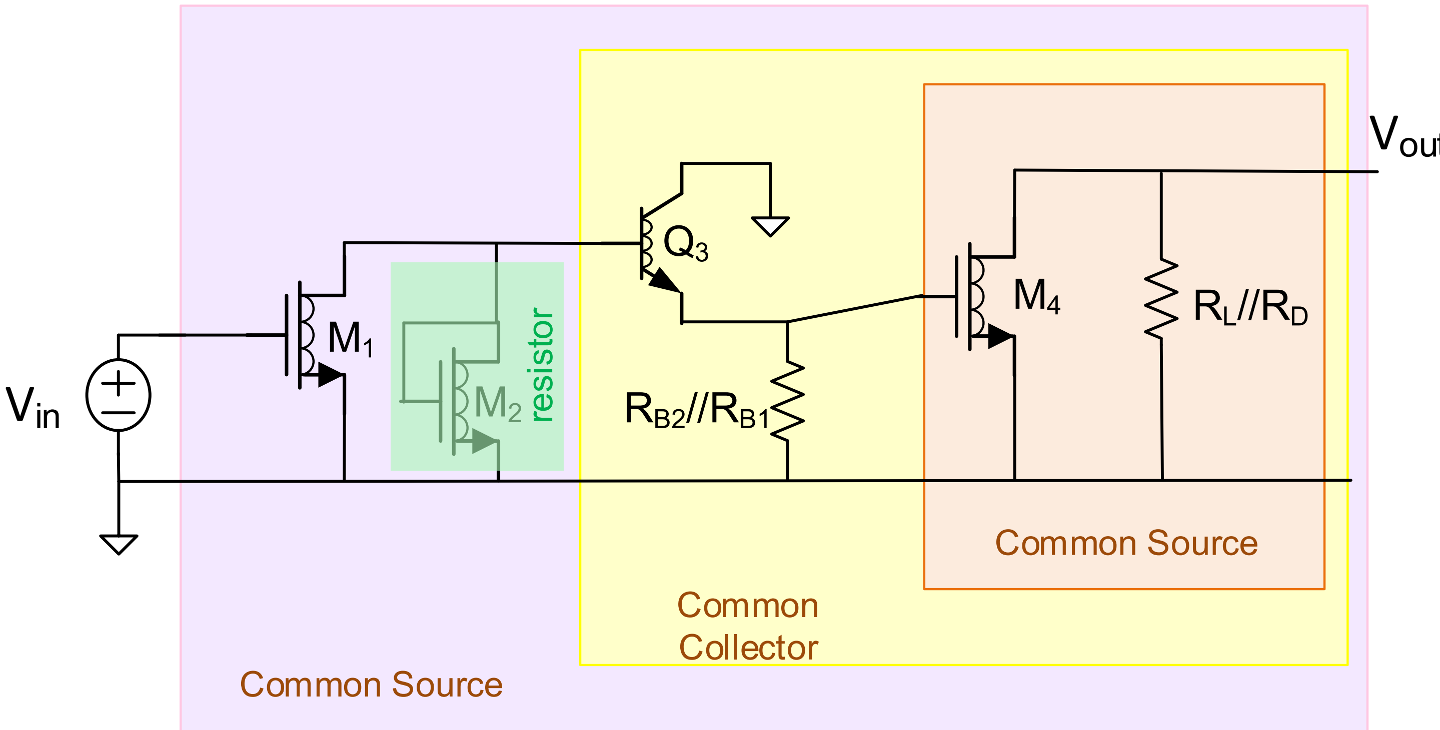


Example 2: $A_V = \frac{v_{out}}{v_{in}} = ?$

Express in terms of small-signal parameters

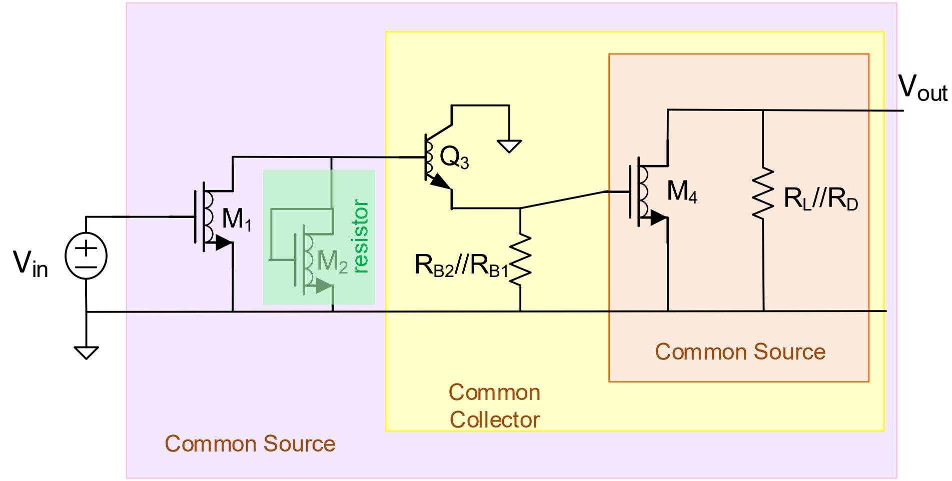


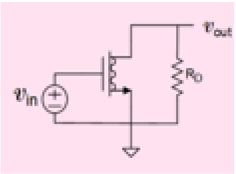
visualize

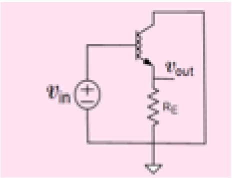


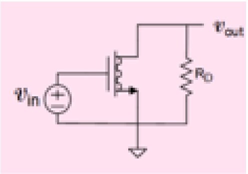
Example 2: $A_V = \frac{v_{out}}{v_{in}} = ?$

Express in terms of small-signal parameters

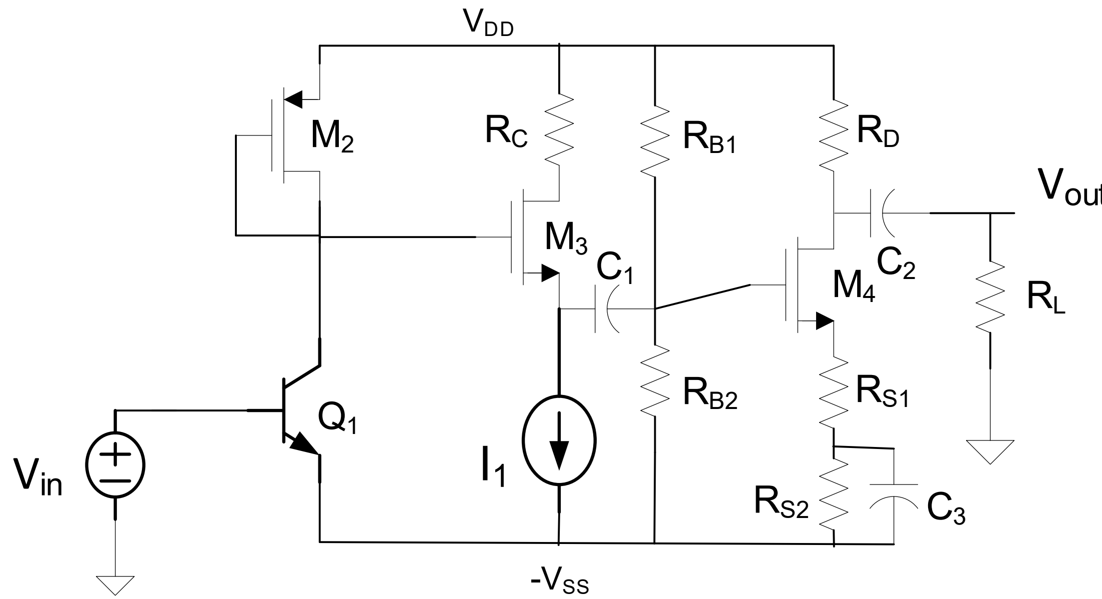


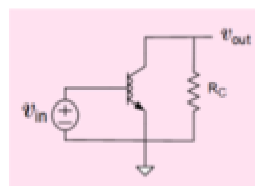


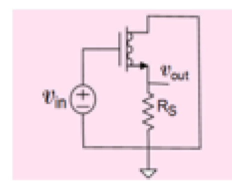


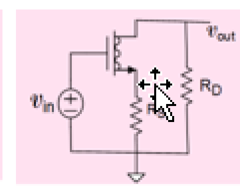


Example 3:

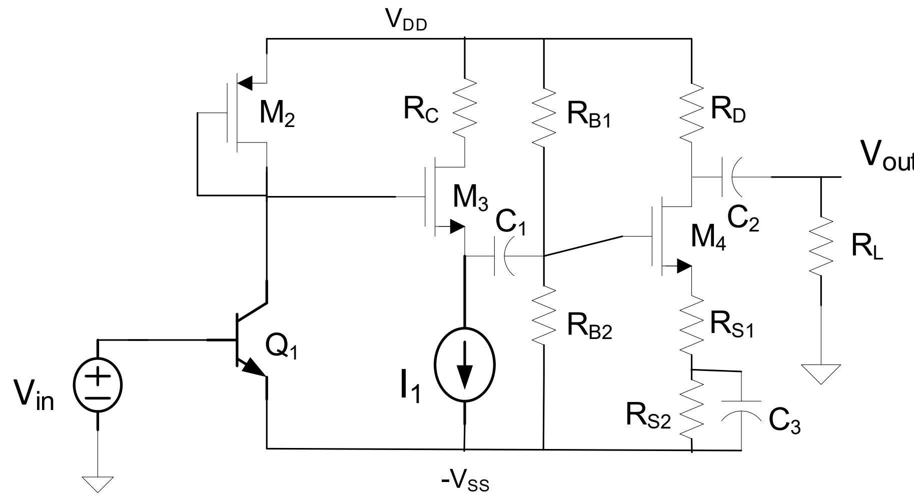

V_DD
M_2
R_C
R_B1
R_D
V_out
M_3
C_1
C_2
M_4
R_L
Q_1
R_B2
R_S1
V_in
I_1
R_S2
C_3
-V_SS


v_out
v_in
R_C

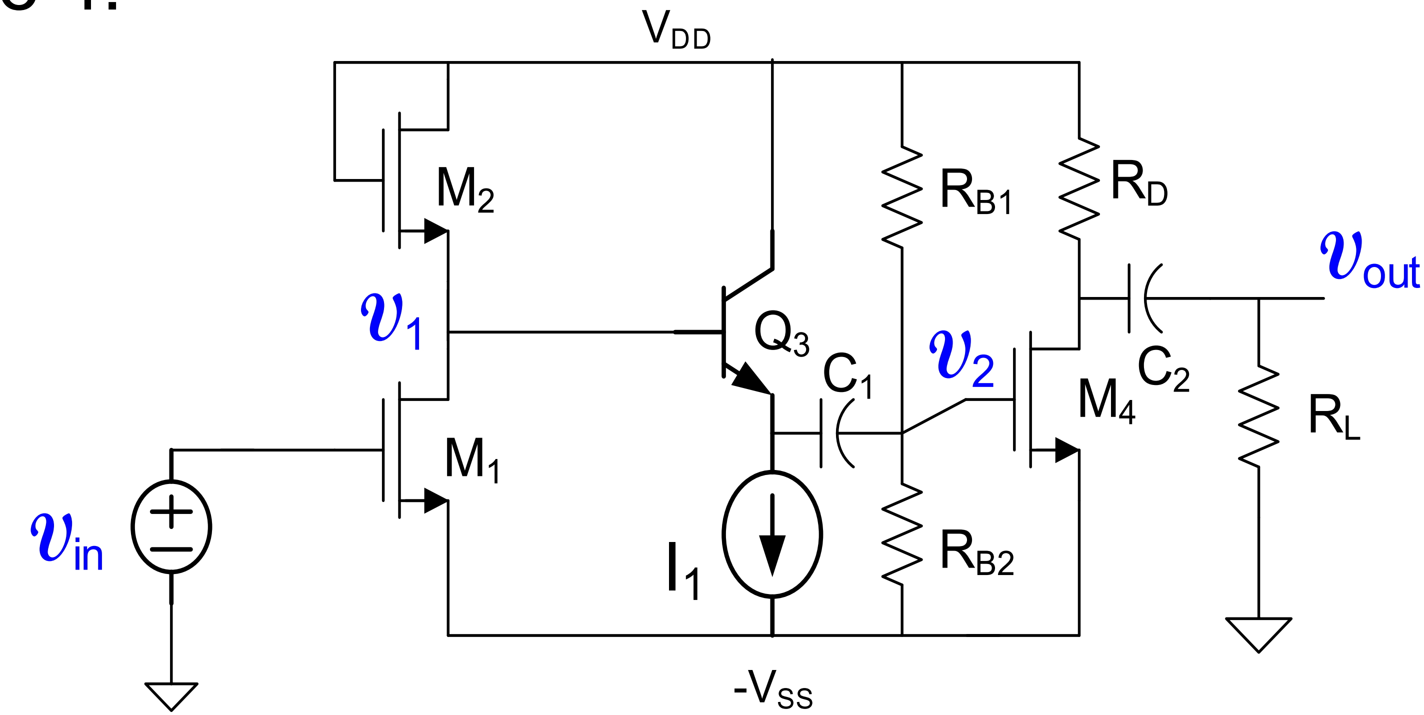

v_out
v_in
R_S


v_out
v_in
R_D

Example 3:

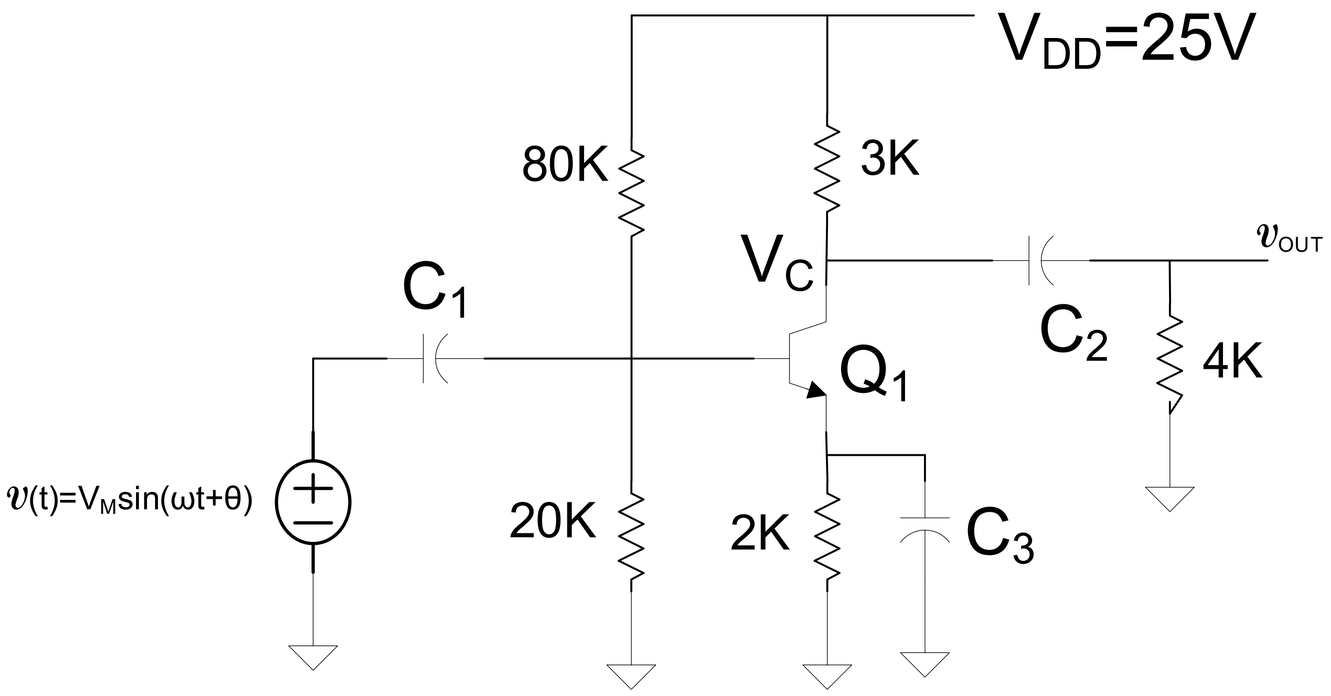


Example 4:

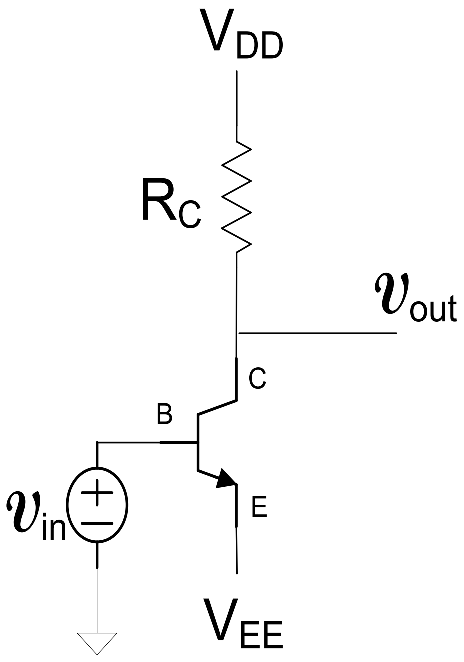


$$A_V = \frac{v_{out}}{v_2}\frac{v_2}{v_1}\frac{v_1}{v_{in}} \cong \left[-g_{m4}\left(R_D//R_L\right)\right][1]\left[\frac{-g_{m1}}{g_{m2}+\left(\beta_3\left(R_{B1}//R_{B2}\right)\right)^{-1}}\right]$$

Example 5:



High-gain BJT amplifier



$$A_V = \frac{-g_m}{g_0 + G_C} \cong -g_m R_C$$

To make the gain large, it appears that all one needs to do is make R_C large !

$$A_V \cong -g_m R_C = \frac{-I_{CQ} R_C}{V_t}$$

But V_t is fixed at approx 25mV and for good signal swing, $I_{CQ}R_C<(V_{DD} - V_{EE})/2$

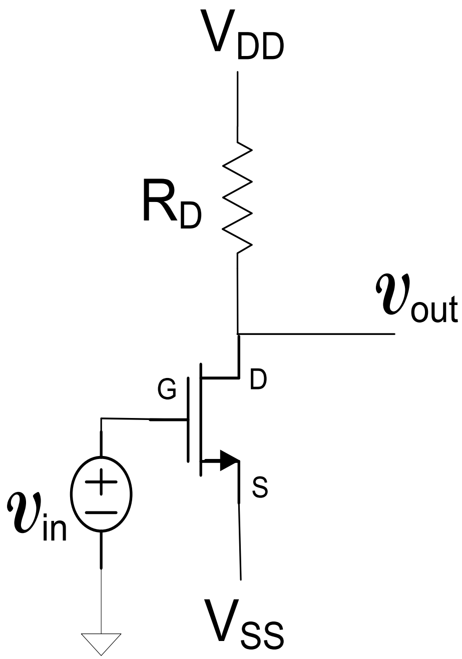
$$|A_V| < \frac{V_{DD} - V_{EE}}{2V_t}$$

If V_{DD}-V_{EE}=5V,

$$|A_V| < \frac{5V}{2 \bullet 25mV} = 100$$

- **Gain is practically limited with this supply voltage to around 100**
- **And in extreme case, limited to 200 with this supply voltage with very small signal swing**

High-gain MOS amplifier



$$A_V = \frac{-g_m}{g_0 + G_D} \cong -g_m R_D$$

To make the gain large, it appears that all one needs to do is make R_D large !

$$A_V \cong -g_m R_D = \frac{-2I_{DQ}R_D}{V_{EB}}$$

But V_{EB} is practically limited to around 100mV and for good signal swing, $I_{DQ}R_D<(V_{DD}-V_{SS})/2$

$$|A_V| < \frac{V_{DD}-V_{SS}}{V_{EB}}$$

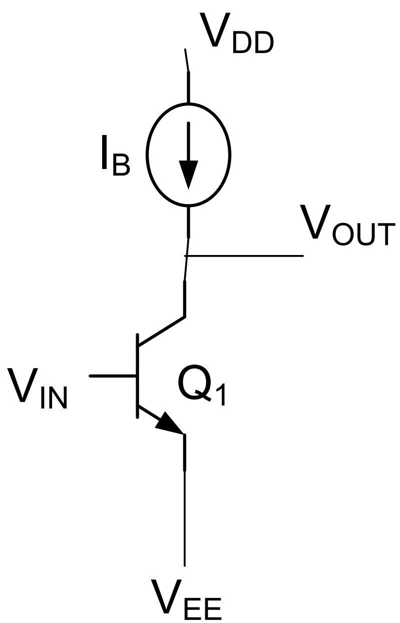
If V_{DD} -V_{SS}=5V and V_{EB}=100mV,

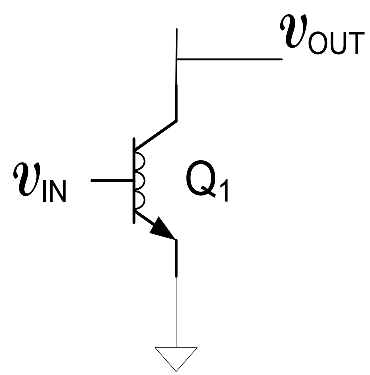
$$|A_V| < \frac{5V}{100mV} = 50$$

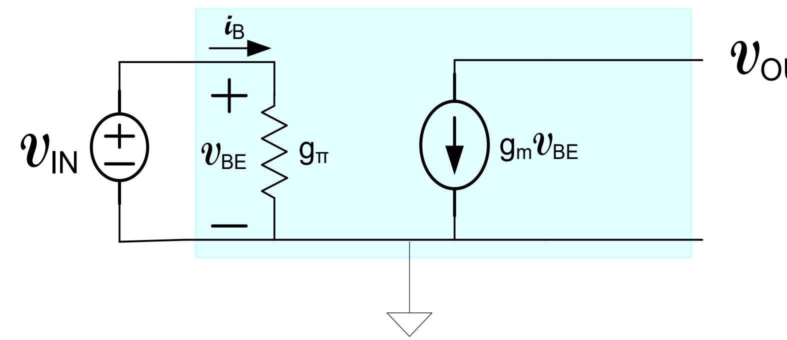
Gain is practically limited with this supply voltage to around 50

Are these fundamental limits on the gain of the BJT and MOS Amplifiers?

High-gain amplifier







$$A_V = \frac{-g_m}{0} = -\infty$$

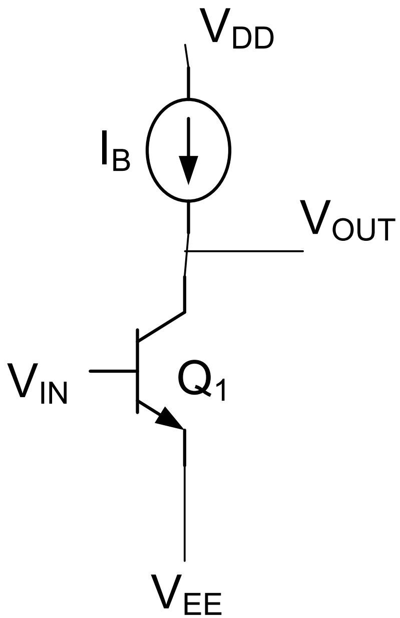
Fundamentally a different circuit

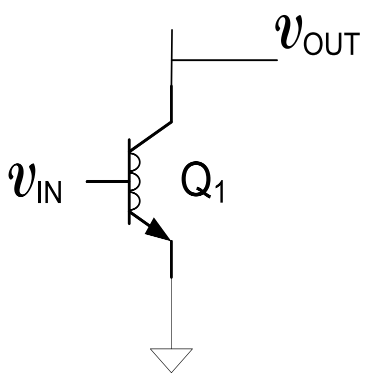
This gain is very large !

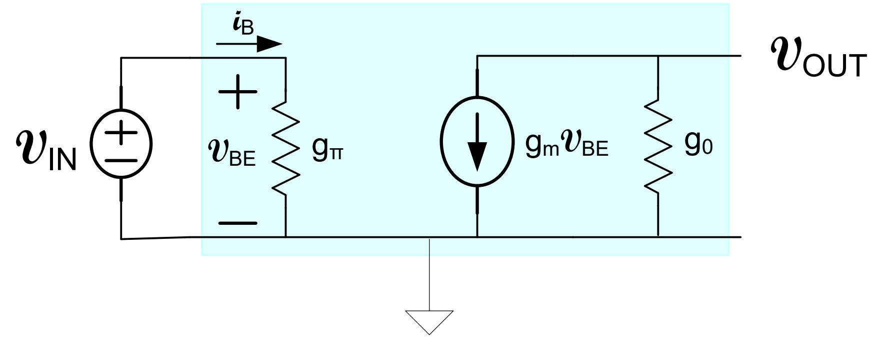
Too good to be true !

Need better model of BJT and MOS device (but we already have it) !

High-gain amplifier







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

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

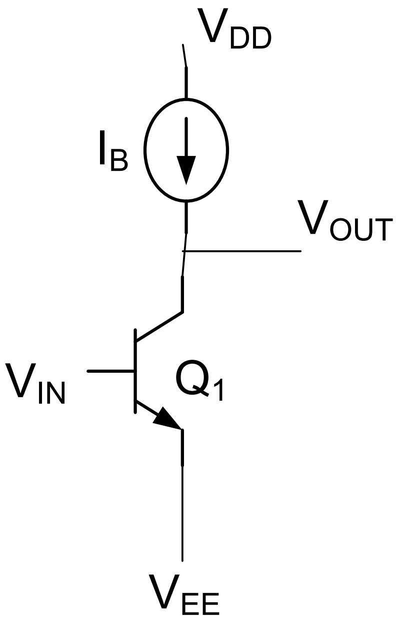
$$A_V = -\frac{V_{AF}}{V_t} \cong \frac{200\text{V}}{25\text{mV}} = -8000$$

This gain is very large (but realistic) !

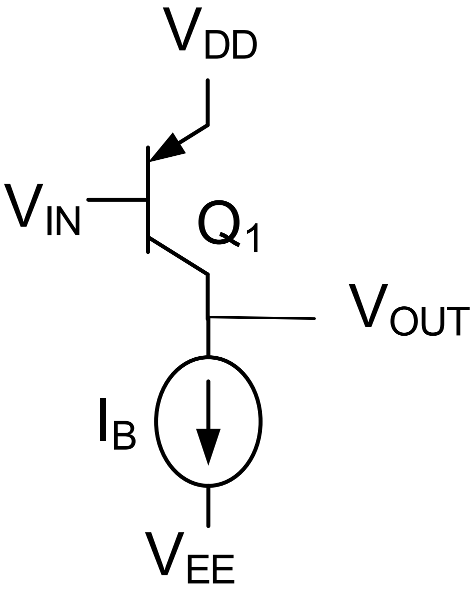
And no design parameters affect the gain

But how can we make a current source?

High-gain amplifier



$$A_V \cong -8000$$



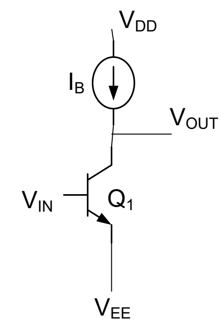
Same gain with both npn and pnp transistors

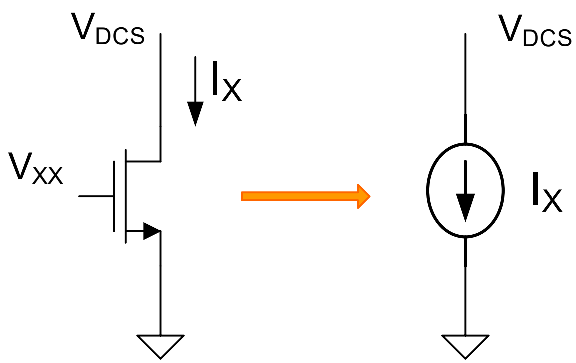
How can we build the ideal current source?

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

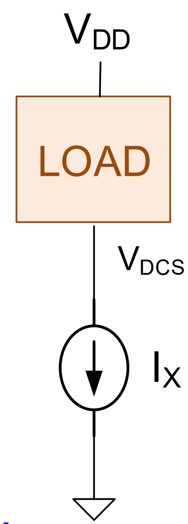
Simple Current Sources

a “sinking” current source





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



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 !

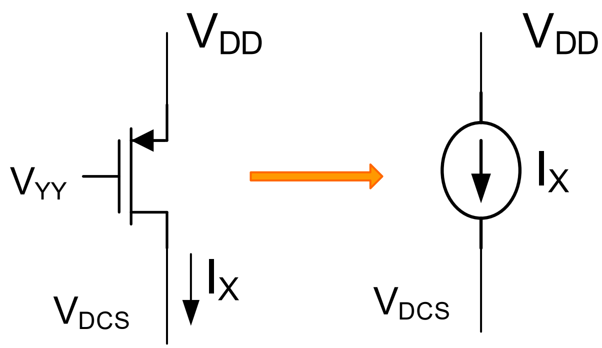
Have several methods for generating V_{XX} from V_{DD} (see HW problems)

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

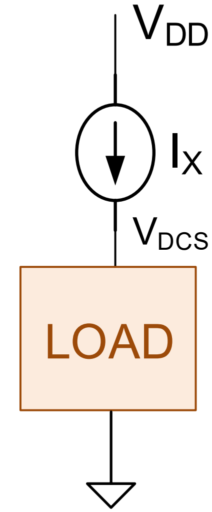
But how good is this current “sink”?

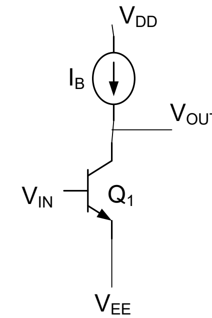
Simple Current Sources

a “sourcing” current source



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





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

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

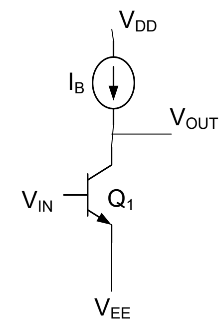
If V_{YY} is available, each dc current source requires only one additional transistor !

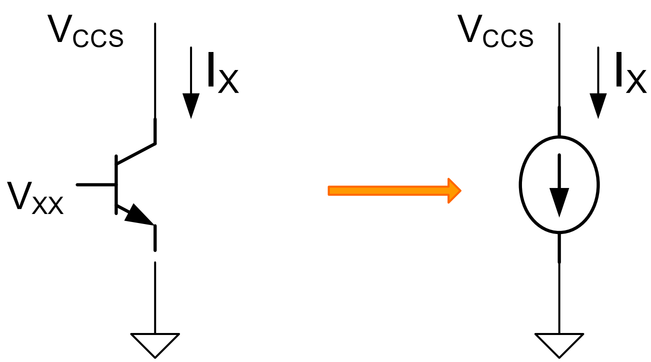
Have several methods for generating V_{YY} from V_{DD} (see HW problems)

But how good is this current “source”?

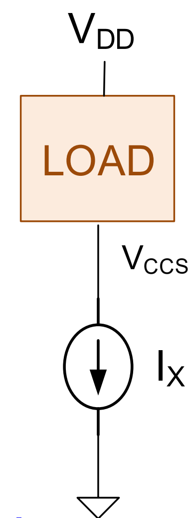
Simple Current Sources

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)

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 !

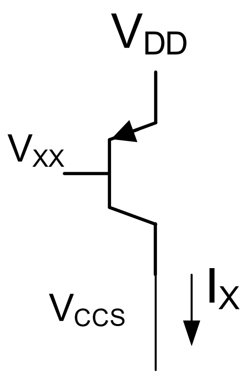
Have several methods for generating V_{XX} from V_{DD} (see HW problems)

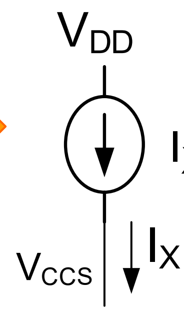
But for the npn high-gain amplifier considered need a sourcing current

But how good is this current "sink"?

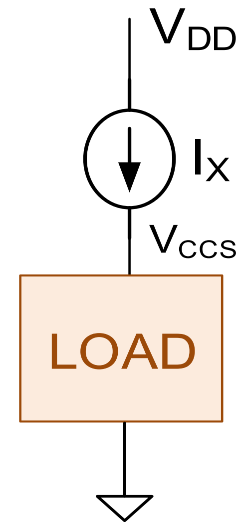
Simple Current Sources

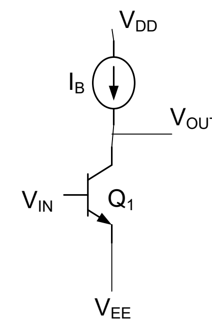
a "sourcing" current source





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





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 !

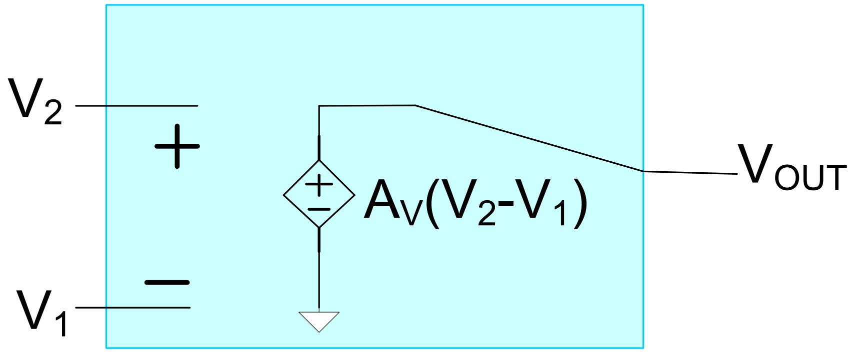
Current highly sensitive to V_{XX} if generated with dc voltage source

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

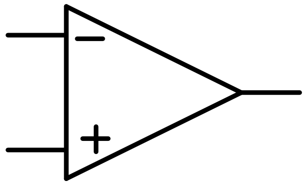
But how good is this current "source"?

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

The Basic Differential Amplifier

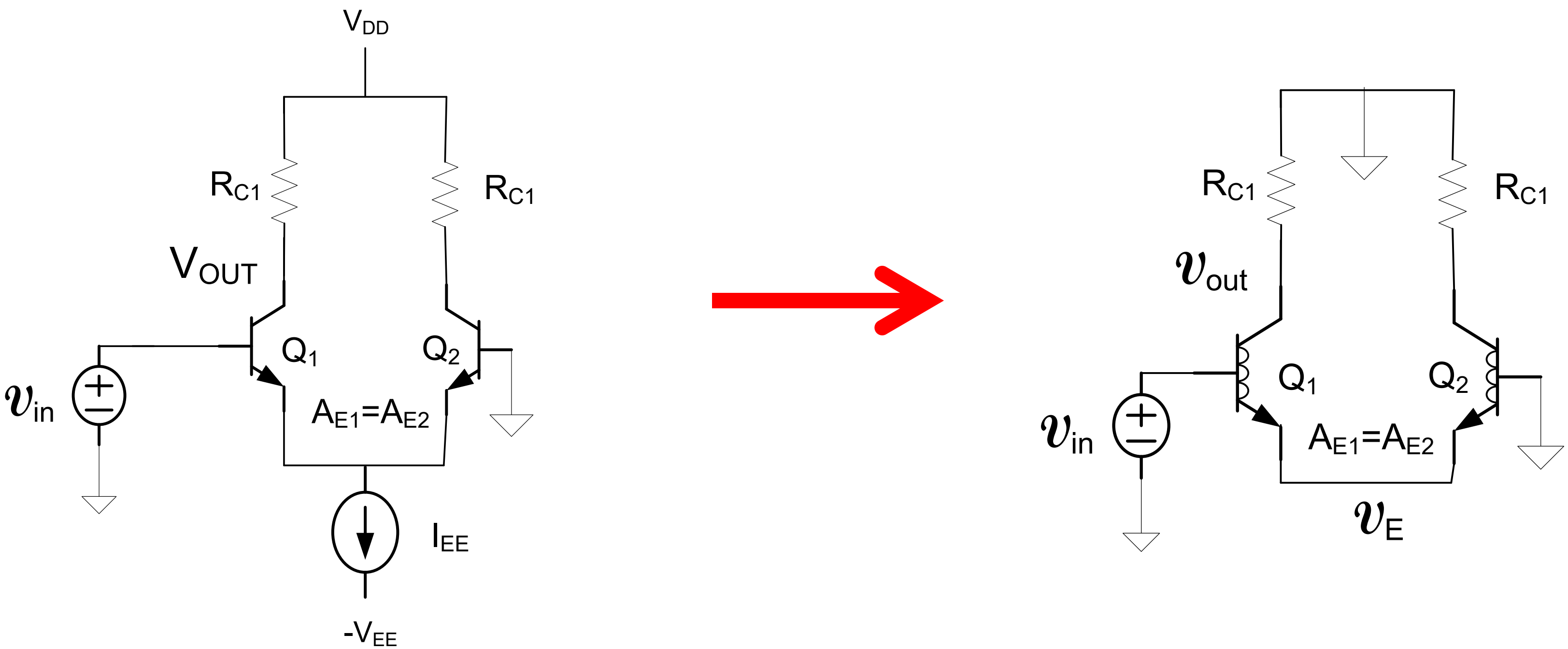


If A_V is large



Operational Amplifier (Op Amp)

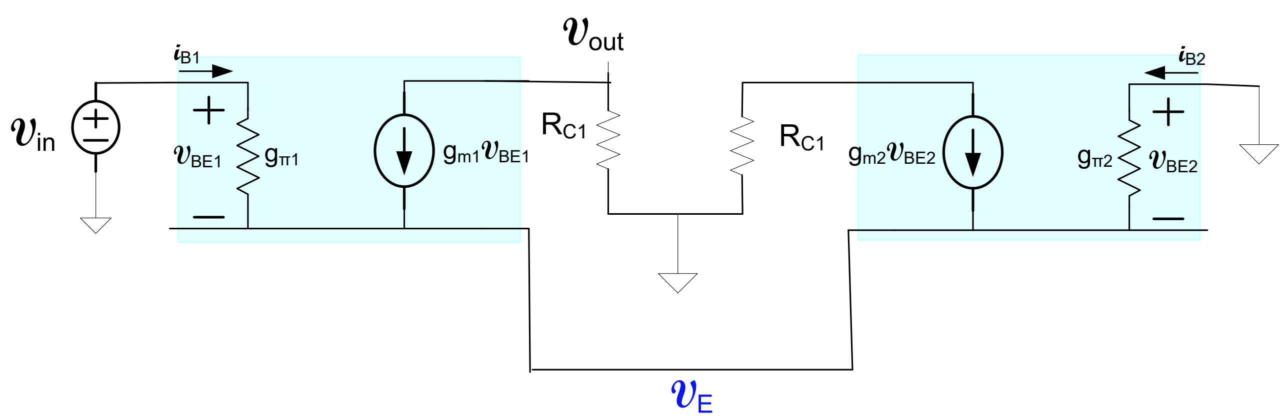
Example: Determine the voltage gain of the following circuit



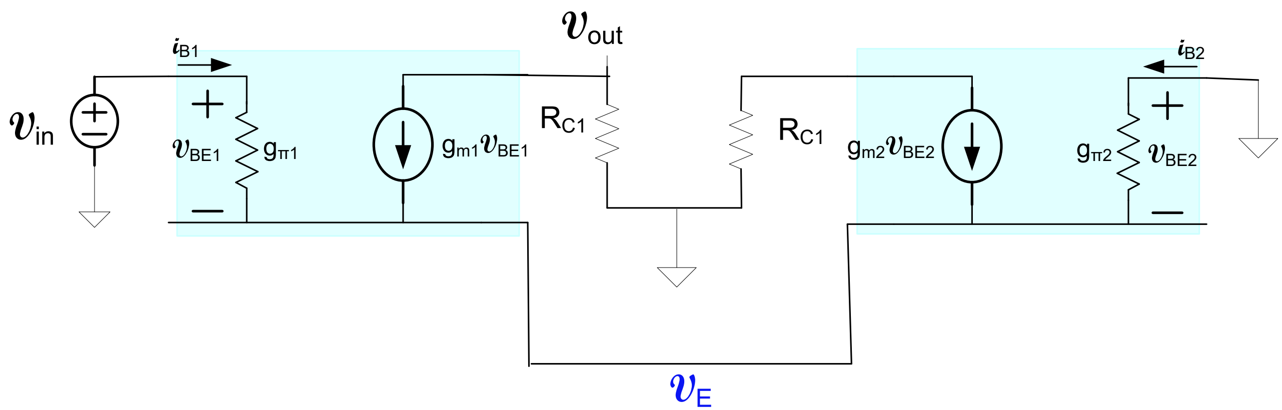
Since symmetric when v_{IN}=0

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

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



Example: Determine the voltage gain of the following circuit



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

$$v_{OUT}=-R_{C1}g_{m1}\left(v_{IN}-v_E\right)$$

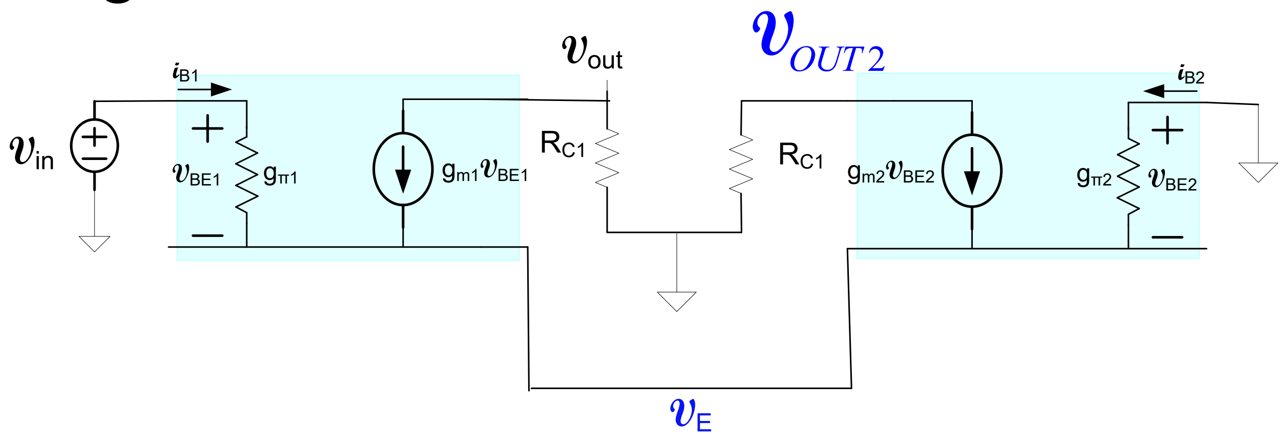
$$v_E\left(g_{\pi1}+g_{\pi2}+g_{m1}+g_{m2}\right)=v_{IN}\left(g_{m1}+g_{\pi1}\right)$$

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

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

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

Example: Determine the voltage gain of the following circuit



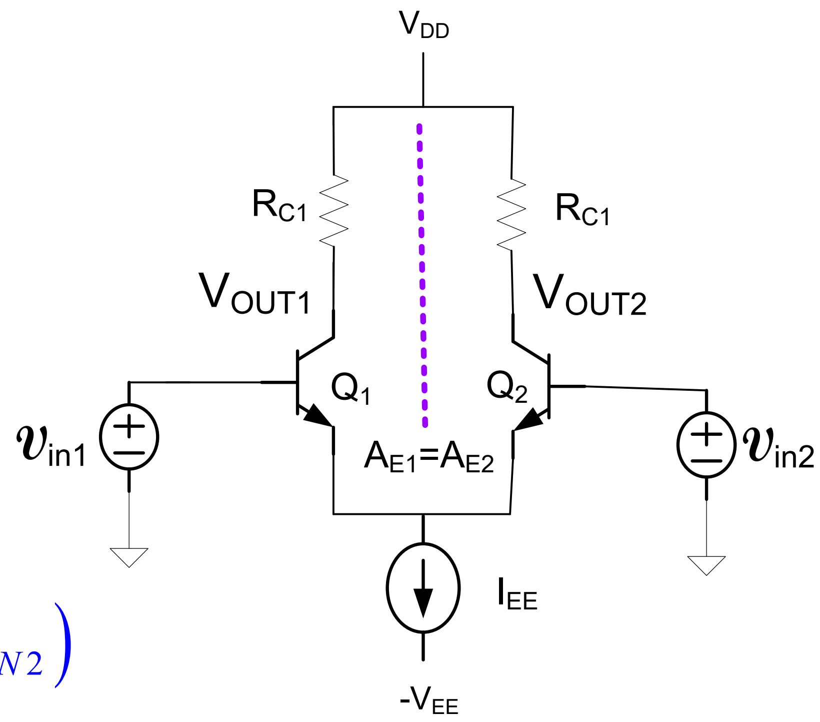
$$v_{OUT} = -R_{C1}g_{m1}v_{IN}\left[\frac{g_{\pi1}+g_{\pi2}+g_{m1}+g_{m2}-\left(g_{m1}+g_{\pi1}\right)}{\left(g_{\pi1}+g_{\pi2}+g_{m1}+g_{m2}\right)}\right]$$

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

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

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

Differential amplifier

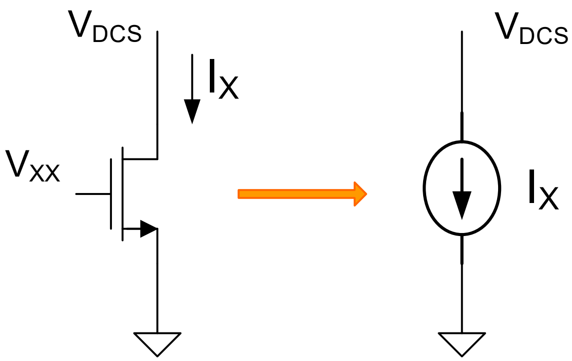


$$v_{OUT1} \cong -\left[\frac{R_{C1}g_{m1}}{2}\right](v_{IN1} - v_{IN2})$$

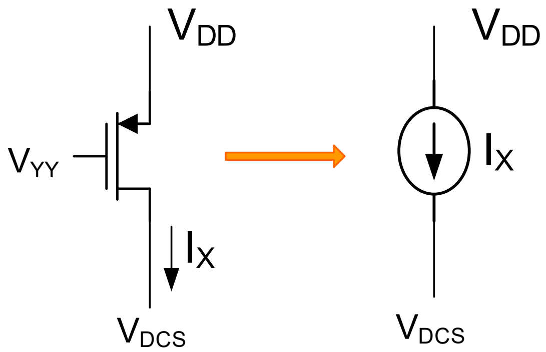
$$v_{OUT2} \cong \left[\frac{R_{C1}g_{m1}}{2}\right](v_{IN1} - v_{IN2})$$

- 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



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

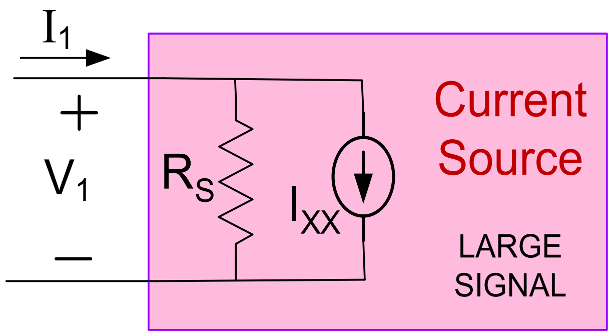


$$I_X=\frac{\mu C_{OX} W}{2L}\left(V_{DD}-V_{YY}+V_{Tp}\right)^2$$

But how good are these current sources?

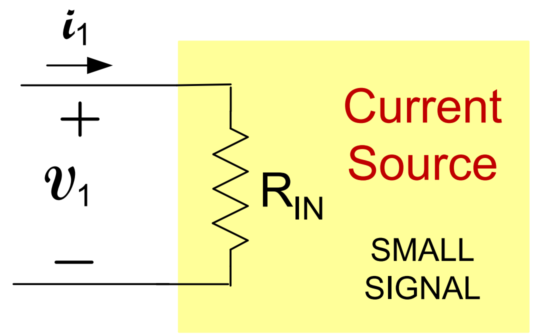
Model of dc Current Source

"Reasonable dc Current Source"



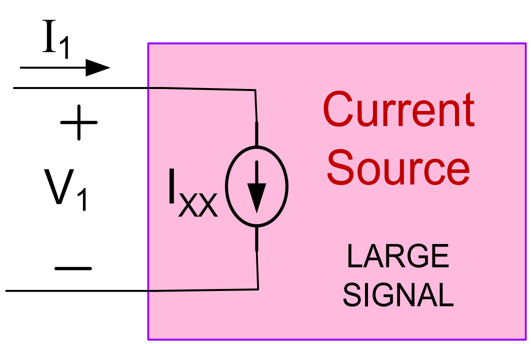
I_{XX} independent of V_1 and t , R_S large

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

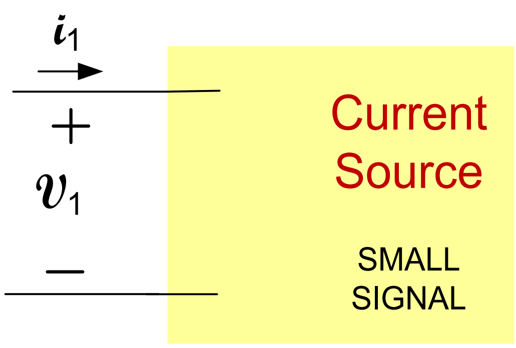


want R_{IN} large

Ideal dc Current Source



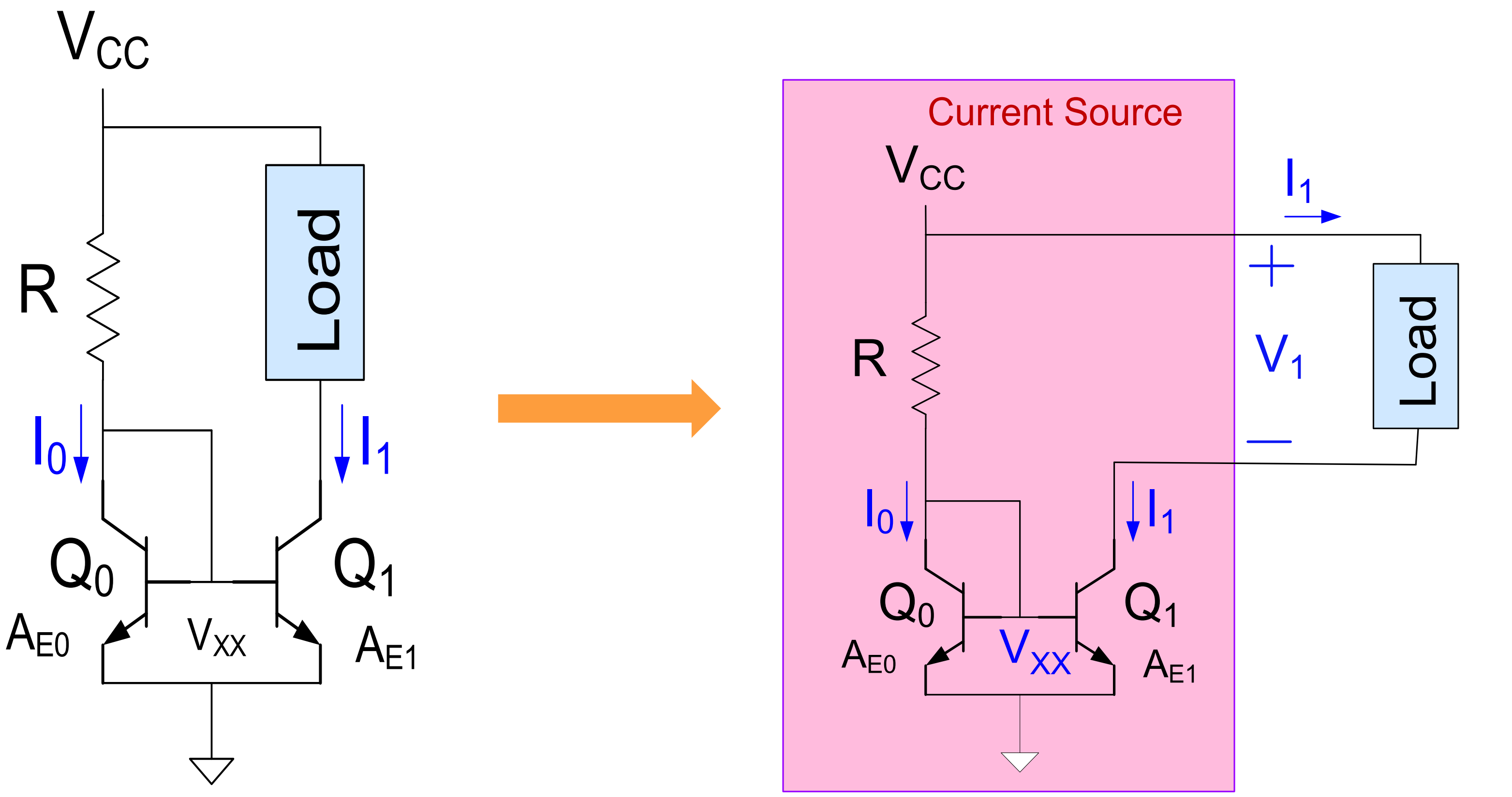
I_{XX} independent of V_1 and t



$R_{IN}=\infty$

Current Sources/Mirrors

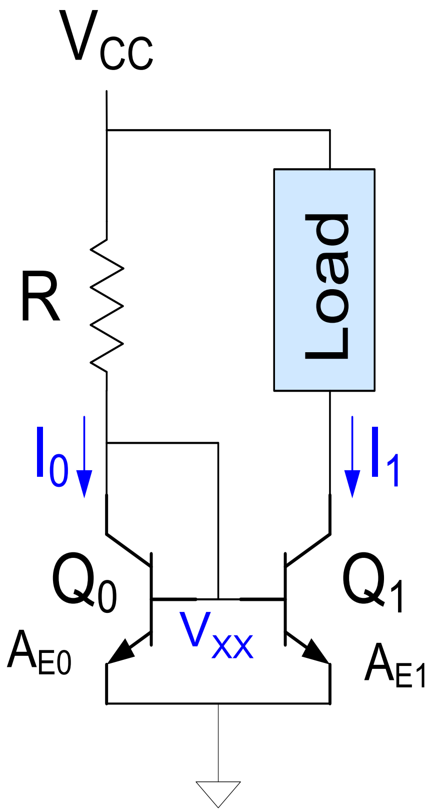
Will show circuit in red behaves as a current source



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

But sensitivity of I_1 is much smaller than using voltage source for generating V_{XX}

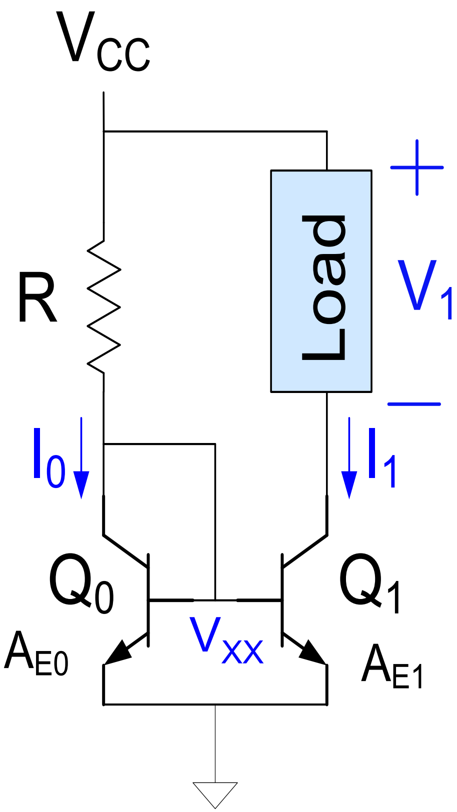
Current Sources/Mirrors



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

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 $V_{BE1}=V_{BE2}$

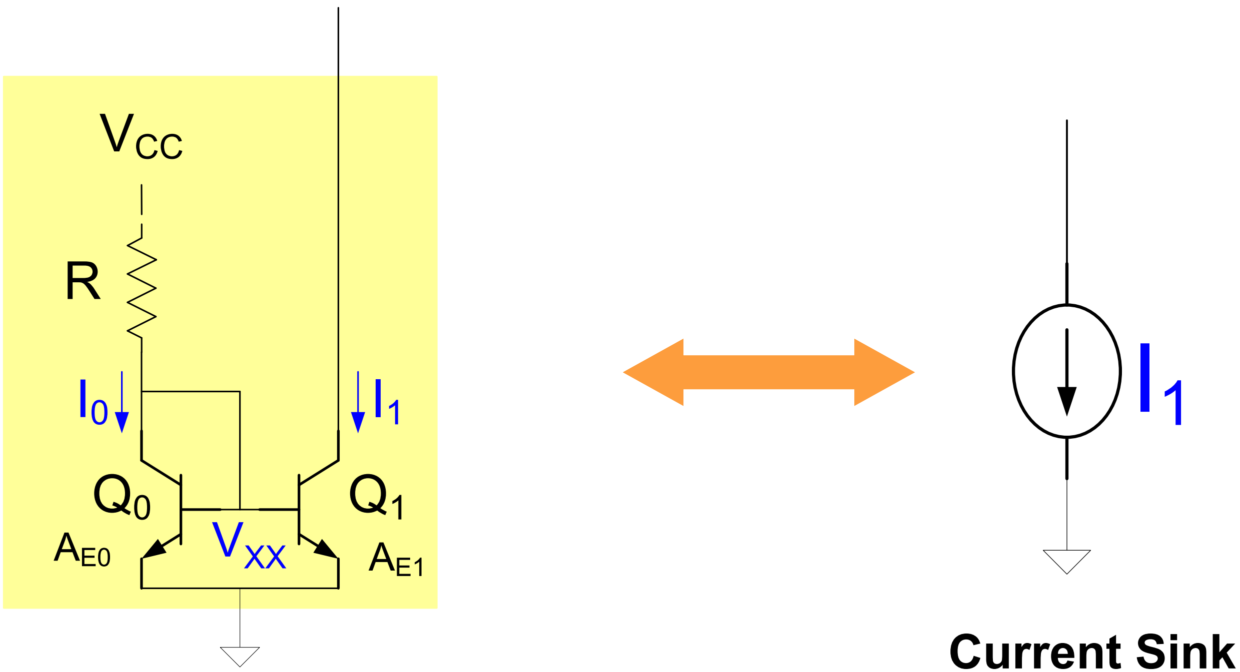
$$I_1 \cong \left(\frac{A_{E1}}{A_{E0}}\right) I_0 = \left(\frac{A_{E1}}{A_{E0}}\right) \frac{V_{CC} - 0.6V}{R}$$

Note I_1 is not a function of V_1

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

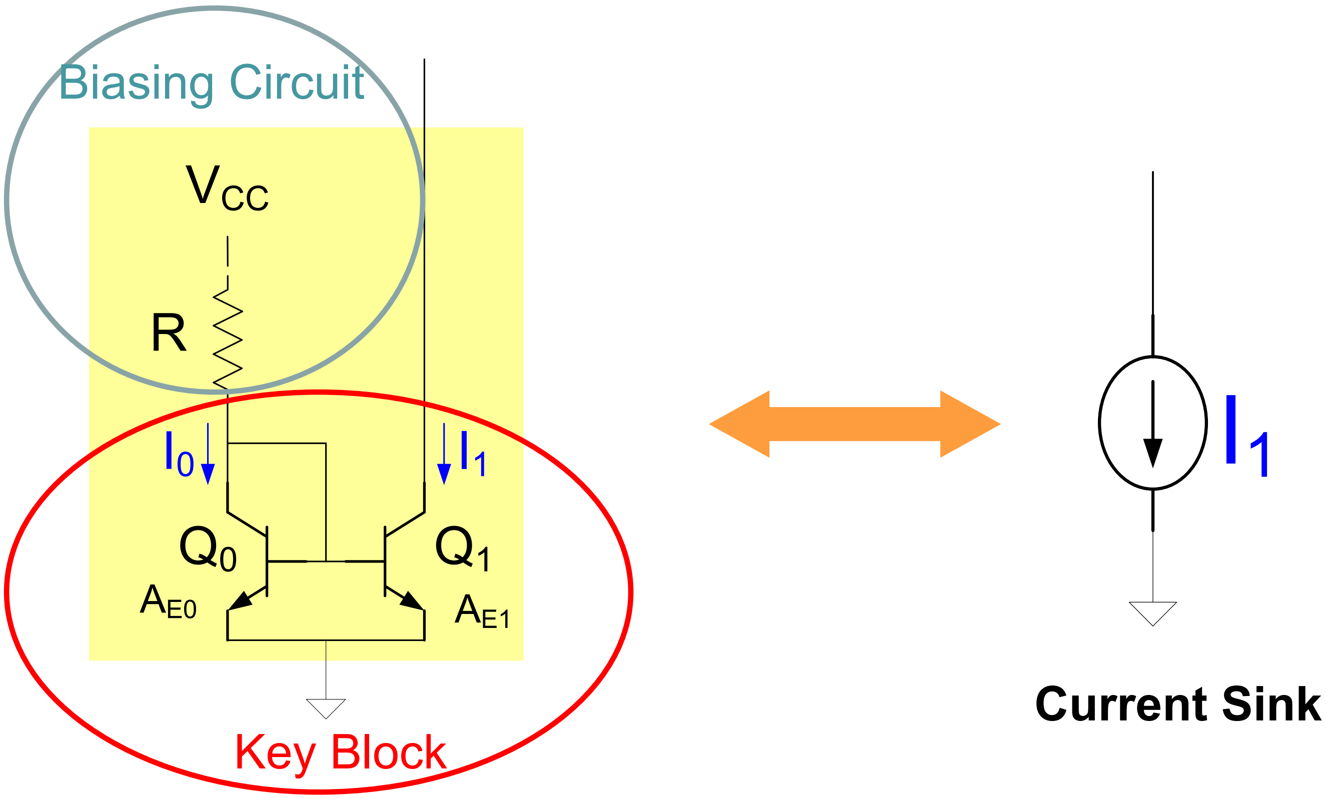
And does not require an <u>additional</u> dc voltage source !!!

Current Sources/Mirrors



- **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**

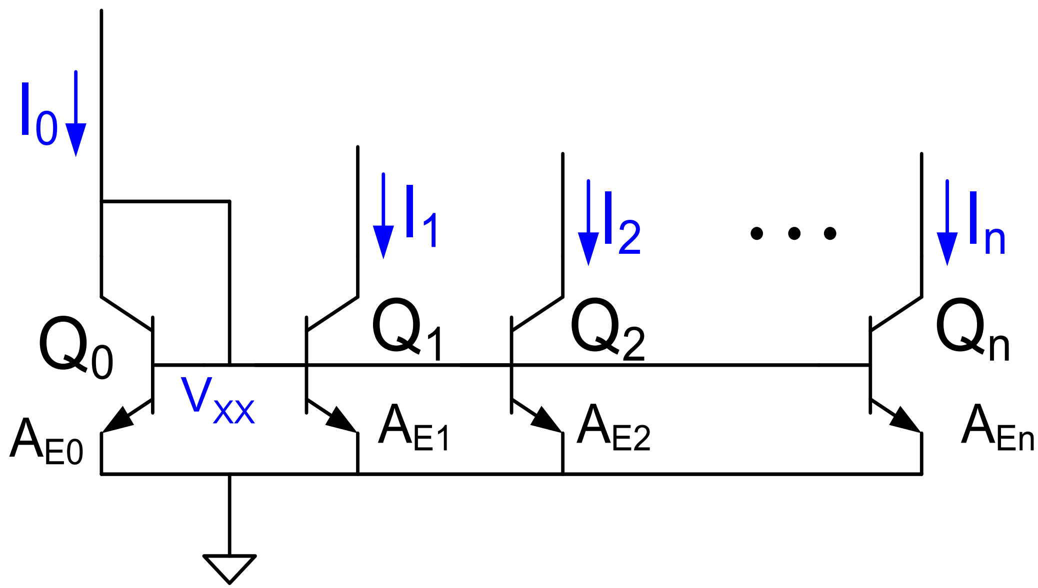
Current Sources/Mirrors



Two ways to look at this circuit:

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

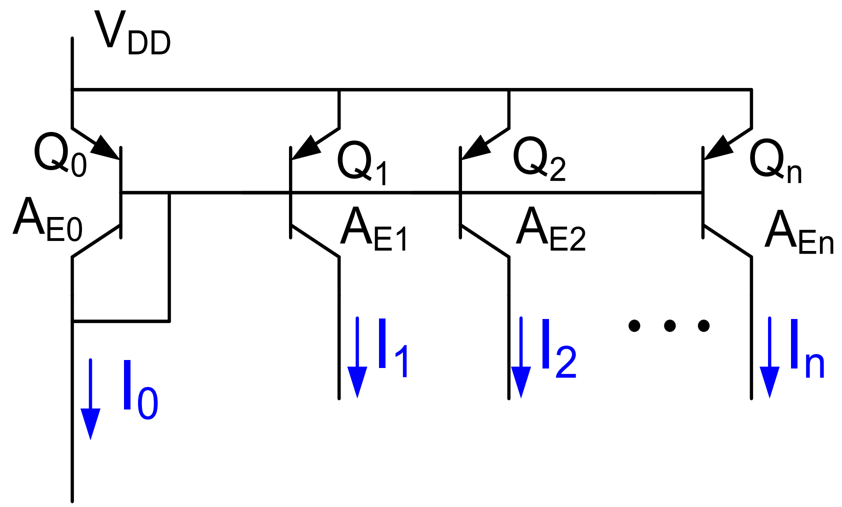
Current Sources/Mirrors



Multiple-Output Bipolar Current Sink

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

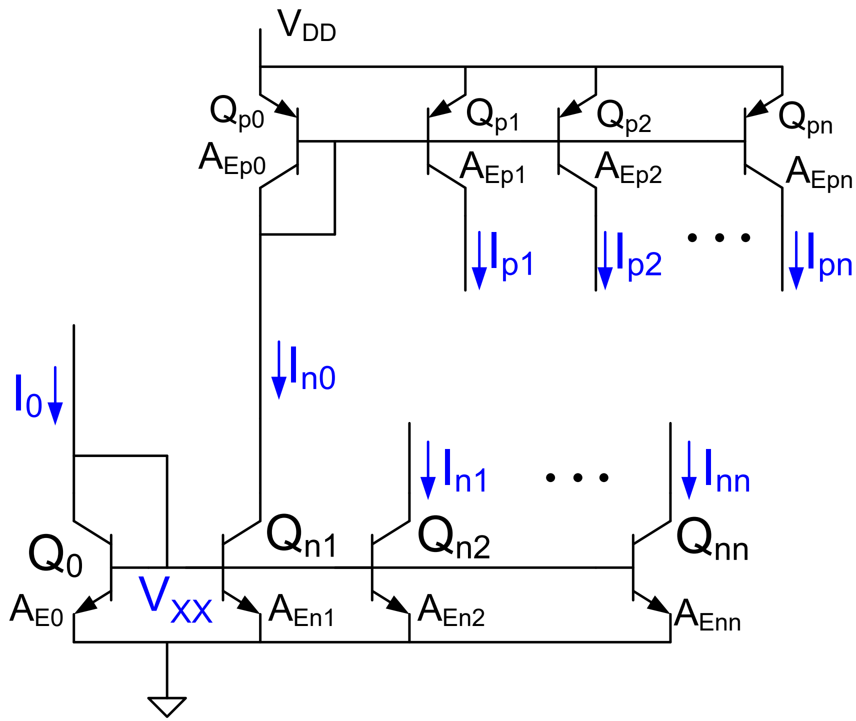
Current Sources/Mirrors



Multiple-Output Bipolar Current Source

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

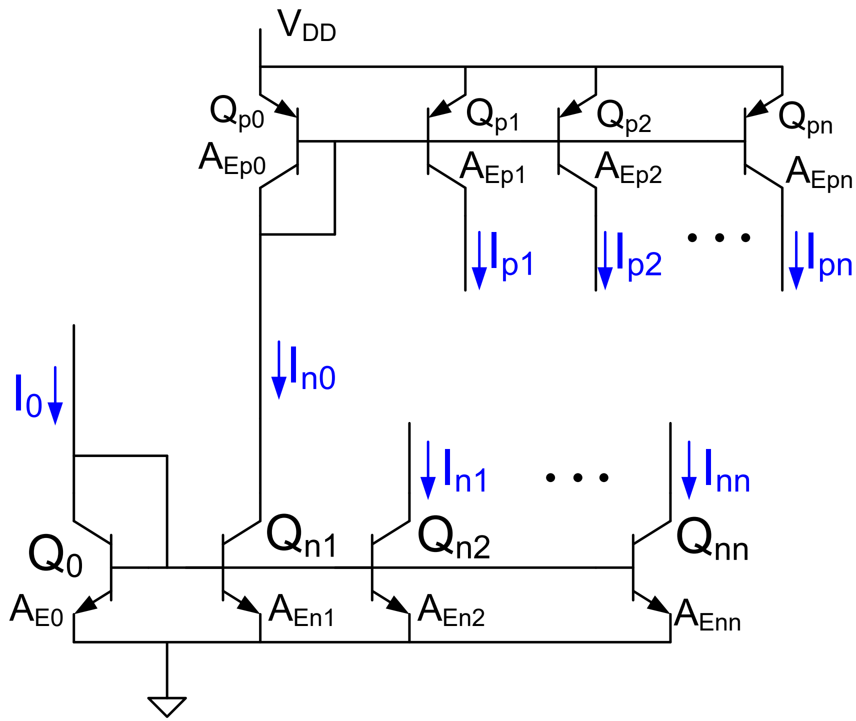
Current Sources/Mirrors



Multiple-Output Bipolar Current Source and Sink

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

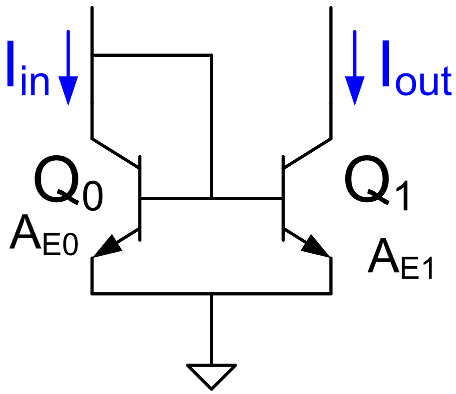
Current Sources/Mirrors



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



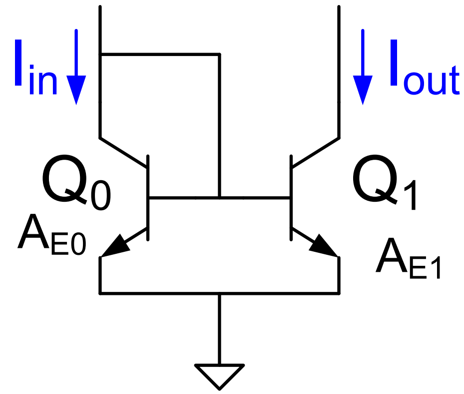
$$I_{out} = \left[\frac{A_{E1}}{A_{E0}}\right] I_{in}$$

This circuit is termed a “current mirror”

Will re-derive the transfer characteristics of the current mirror assuming I_B is small compared to I_C

$$\left.\begin{aligned} I_{IN} &= J_S A_{E0} e^{\frac{V_{BE}}{V_t}} \\ I_{OUT} &= J_S A_{E1} e^{\frac{V_{BE}}{V_t}} \end{aligned}\right\} \Rightarrow \frac{I_{OUT}}{I_{IN}} = \frac{J_S A_{E1} e^{\frac{V_{BE}}{V_t}}}{J_S A_{E0} e^{\frac{V_{BE}}{V_t}}} = \frac{A_{E1}}{A_{E0}}$$

Current Sources/Mirrors



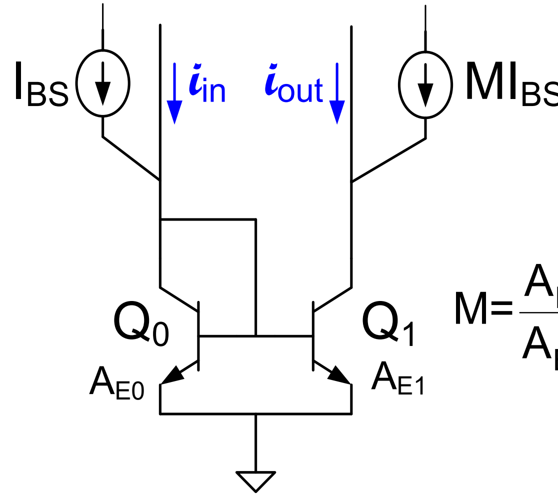
npn Current Mirror

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

- **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



$$M=\frac{A_{E1}}{A_{E0}}$$

npn current mirror amplifier

$$i_{out}=?$$

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

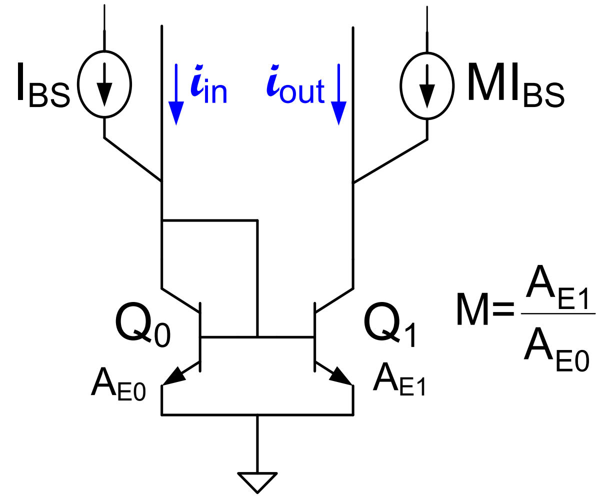
$$i_{OUT}+MI_{BS}=M\left(i_{in}+I_{BS}\right)$$

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

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

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

Current Sources/Mirrors



npn current mirror amplifier

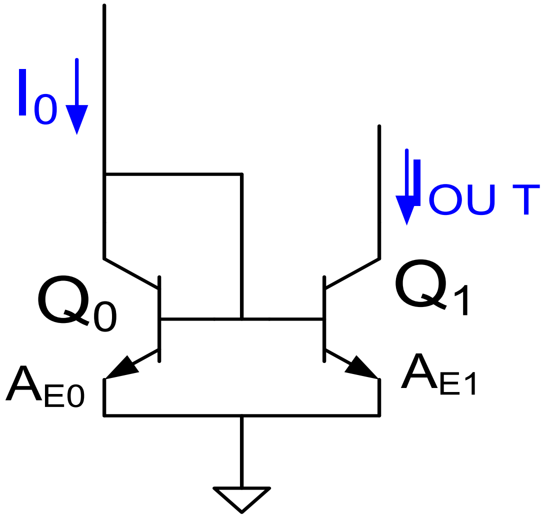
$$i_{out} = \left[\frac{A_{E1}}{A_{E0}} \right] i_{in}$$

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

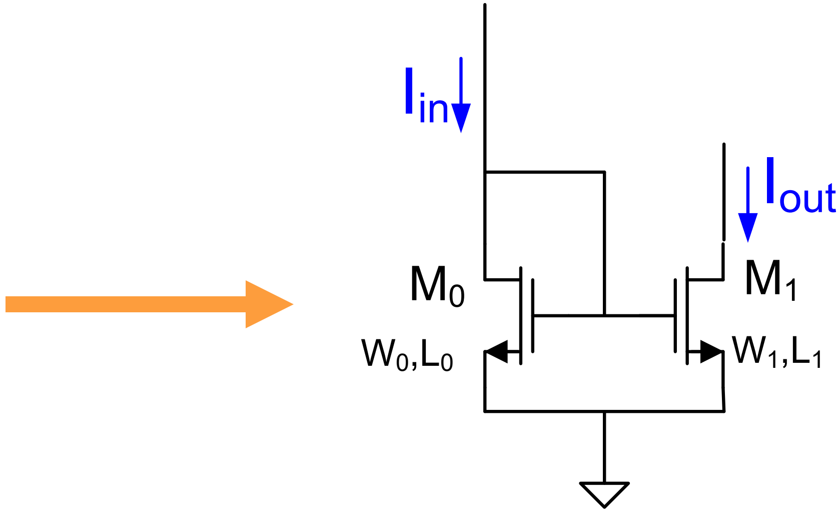
Current amplifiers are easy to build !!

Current gain can be accurately controlled with appropriate layout !!

Current Sources/Mirrors



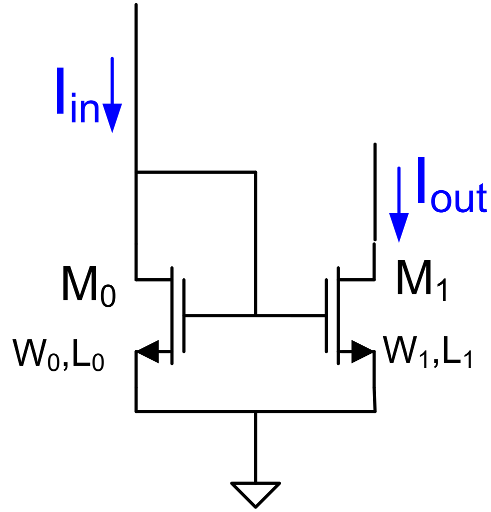
npn Current Mirror



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)

Stay Safe and Stay Healthy !

End of Lecture 33