EE 330
Lecture 33

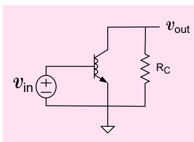
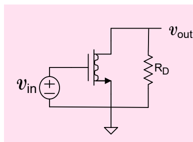
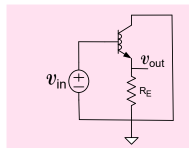
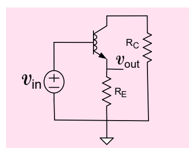
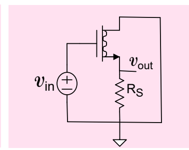
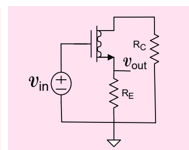
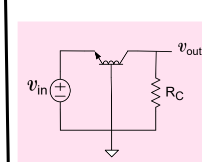
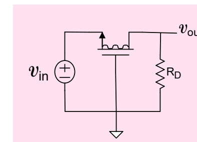
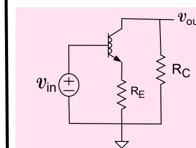
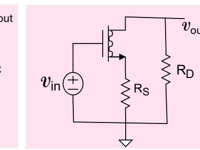
- High Gain Amplifiers
- Current Sources and Mirrors

Spring 2024 Exam Schedule

Exam 1	Friday Feb 16
Exam 2	Friday March 8
Exam 3	Friday April 19
Final Exam	Tuesday May 7 7:30 AM - 9:30 AM

Review From Previous Lecture

Basic Amplifier Application Gain Table

	CE/CS BJT	CE/CS MOS	CC/CD BJT	CC/CD MOS	CB/CG BJT	CB/CG MOS	CEwRE/CSwRS BJT	CEwRE/CSwRS MOS
Circuit			 	 				
A_V	$-g_mR_C$		$\frac{g_m}{g_m+g_E}$		g_mR_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	
			$\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$				

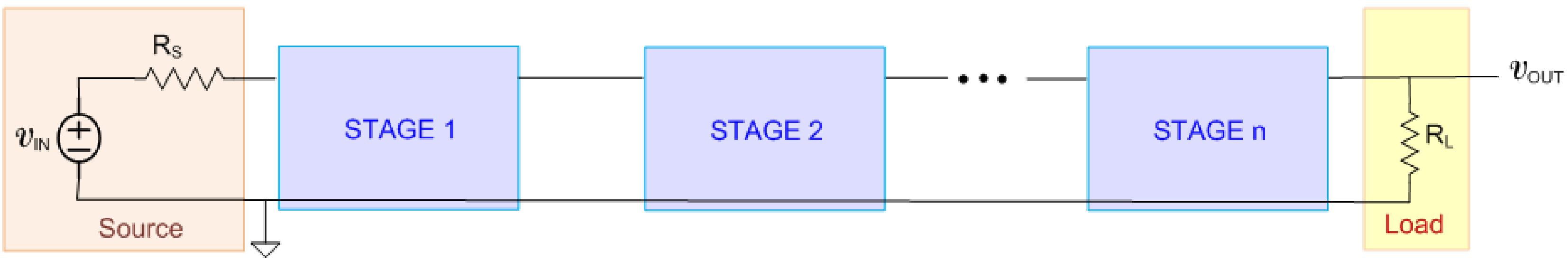
(not two-port models for the four structures)

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

Review From Previous Lecture

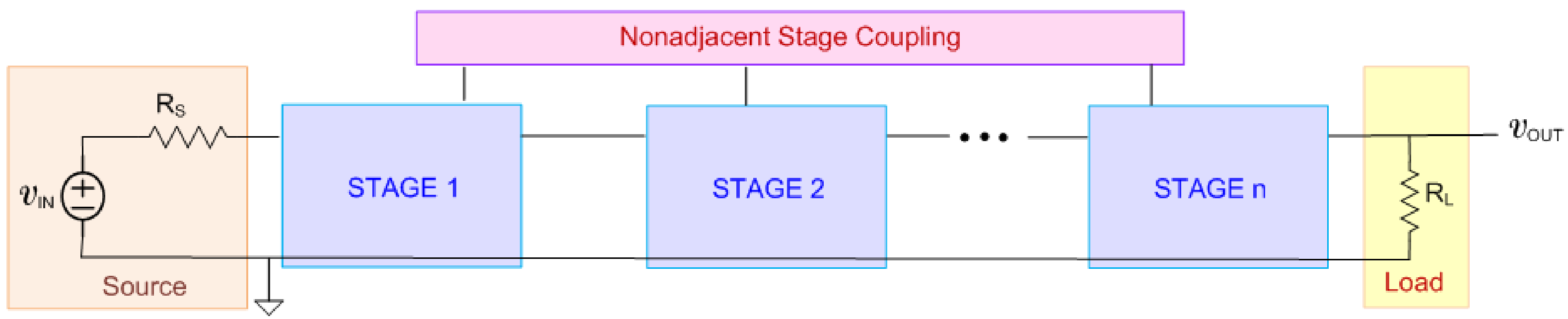
Cascaded Amplifier Analysis and Operation

Adjacent Stage Coupling Only



- Systematic Methods of Analysis/Design will be Developed

One or more couplings of nonadjacent stages

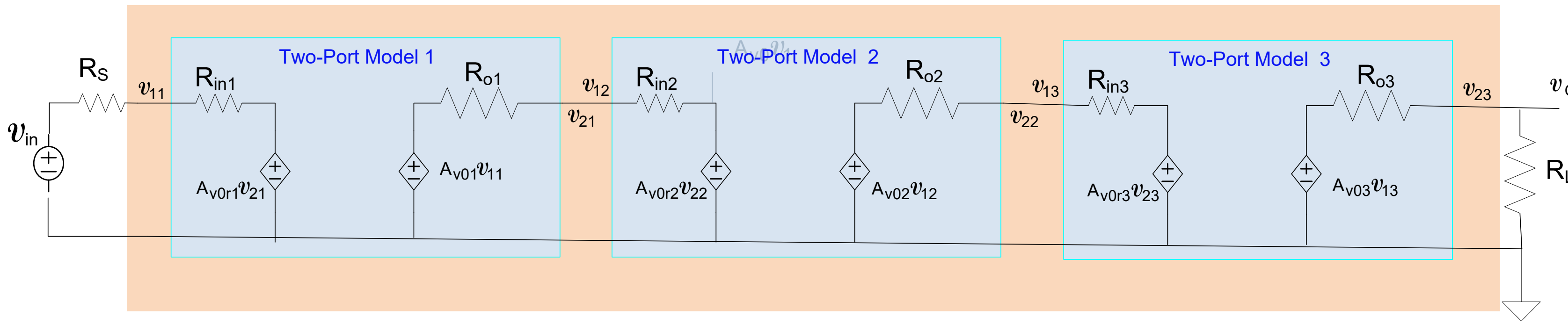


Review From Previous Lecture

Cascaded Amplifier Analysis and Operation

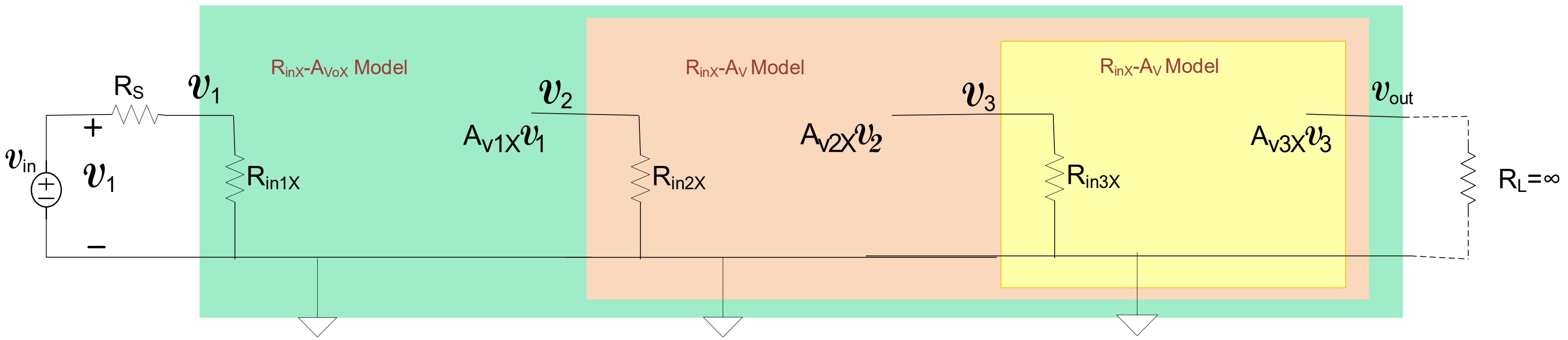
Case 2: One or more stages are not unilateral

- Standard two-port cascade



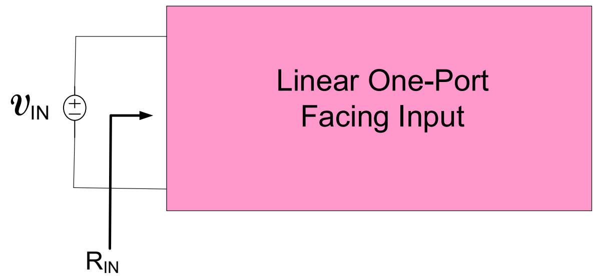
Analysis by creating new two-port of entire amplifier quite tedious because of the reverse-gain elements

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

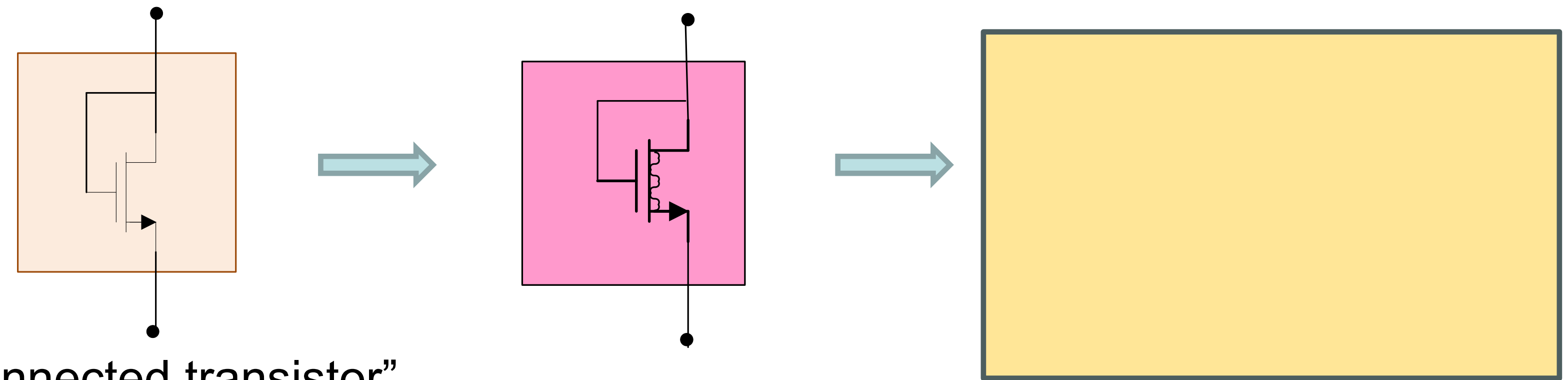


- R_{inx} includes effects of all loading
- A_{VKX} is the voltage ratio from input to output of a stage
- A_{VKX}'s include all loading
- Can not change any loading without recalculating everthing!

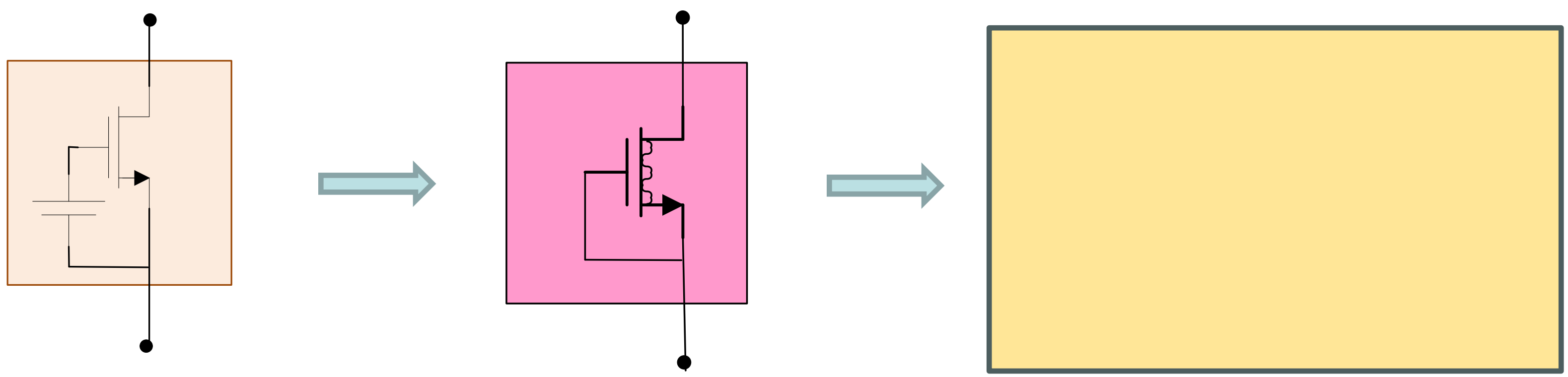
Review: Small-signal equivalent of a one-port



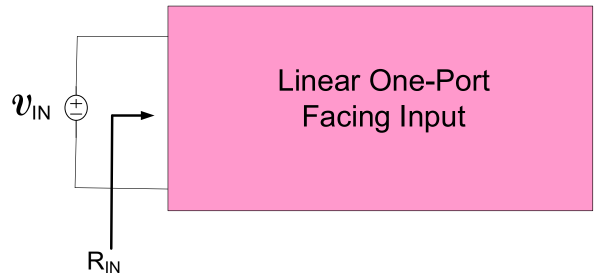
"Diode-connected transistor"



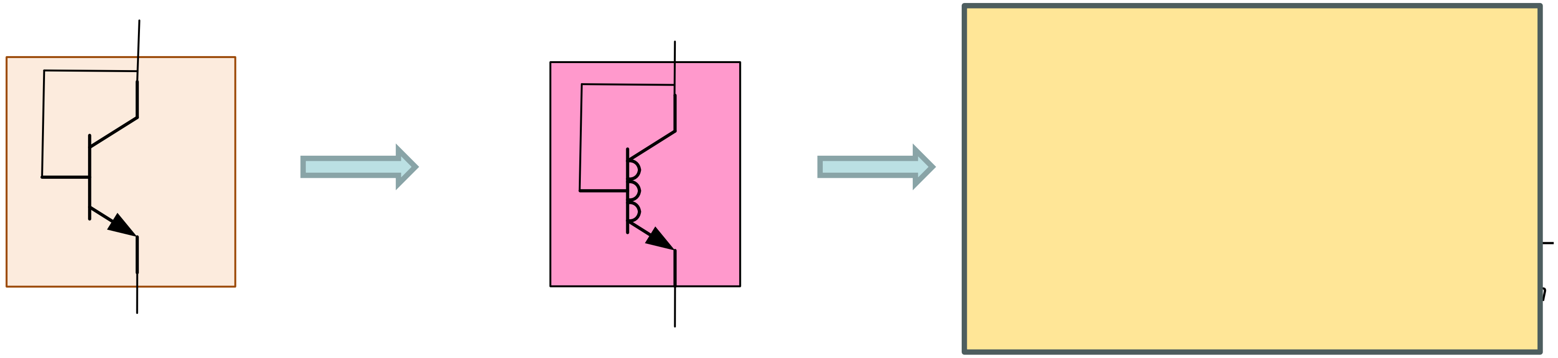
"GS - connected transistor"



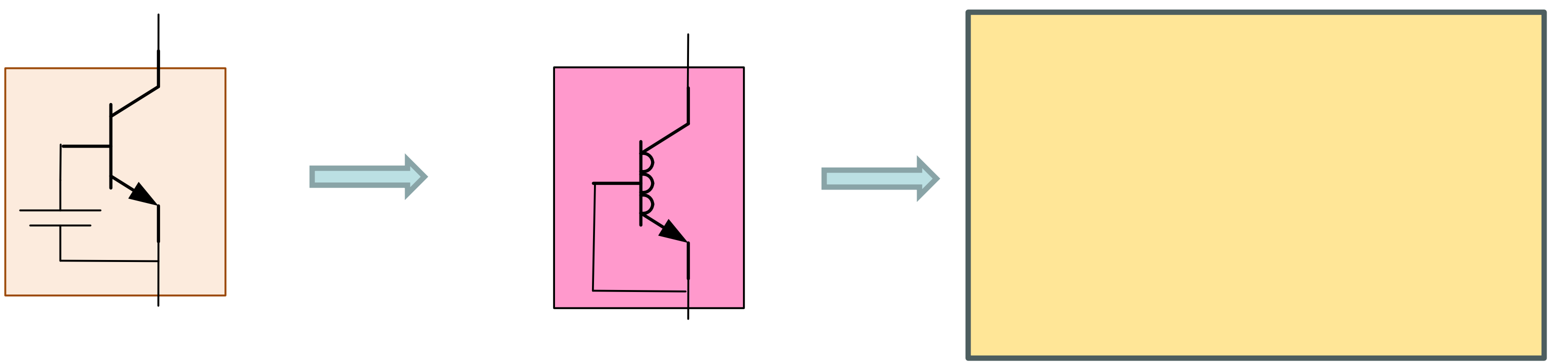
Review: Small-signal equivalent of a one-port



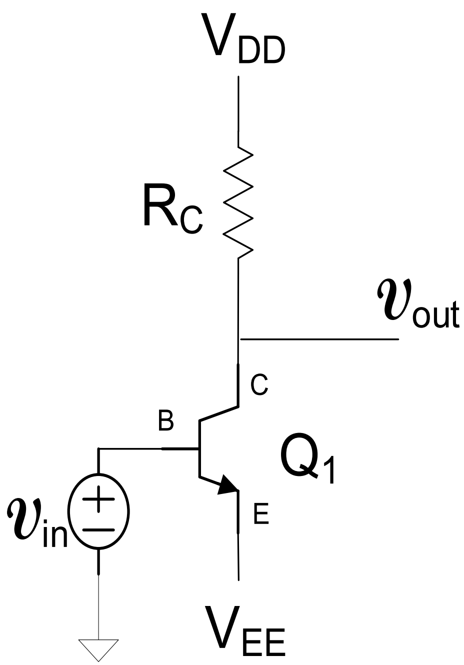
"Diode-connected transistor"



"BE - connected transistor"



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 to keep Q1 in forward active with large signal swing, $I_{CQ}R_C<(V_{DD} - V_{EE})/2$

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

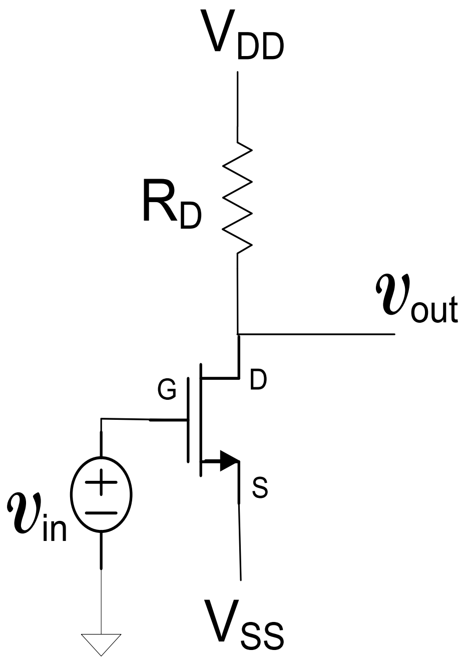
If V_{DD}-V_{EE}=5V,

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

- **Gain is practically limited with this supply voltage to around 100**
- **And in extreme case, limited to about 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 !

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

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

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

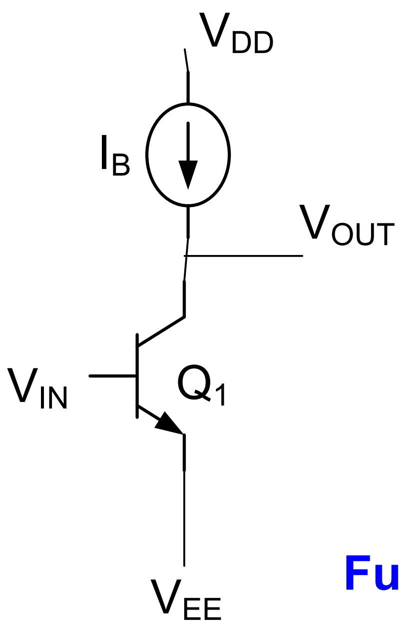
If V_{DD} -V_{SS}=5V and V_{EB}=100mV,

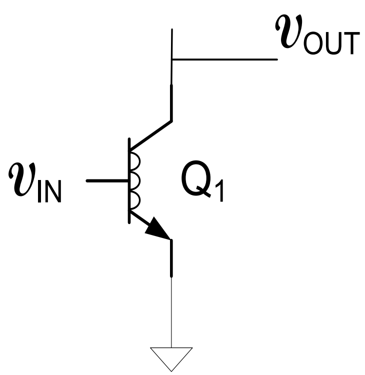
$$|A_V| < \frac{5\text{V}}{100\text{mV}} = 50$$

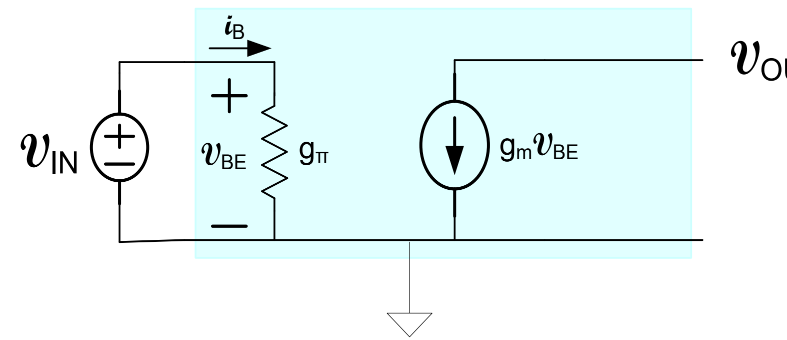
Gain is practically limited with this supply voltage to around 50

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

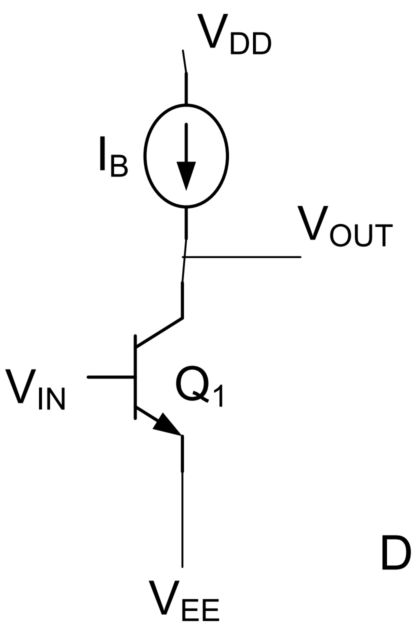
Current source is biasing Q_1

This gain is very large !

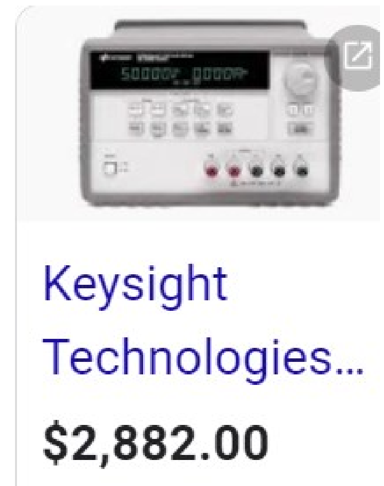
Too good to be true !

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

But are current sources really available?



Current Source ???



Voltage Source

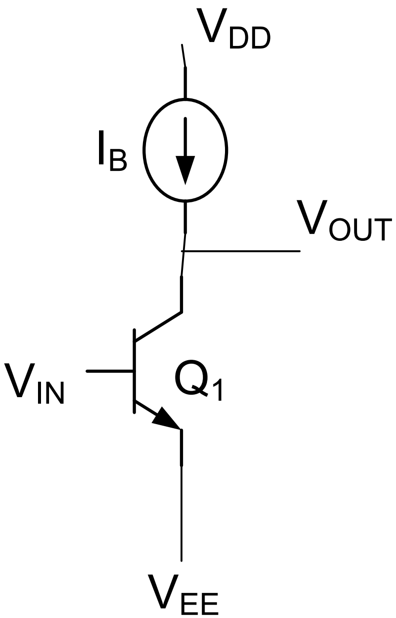
Did you discuss current sources in EE 201?

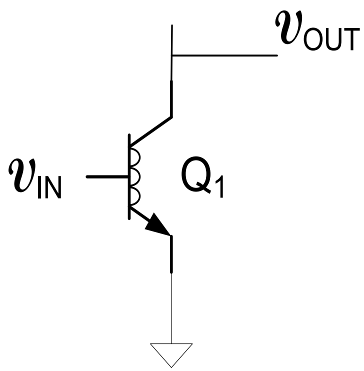
Did you have any current sources in the EE 201 laboratory?

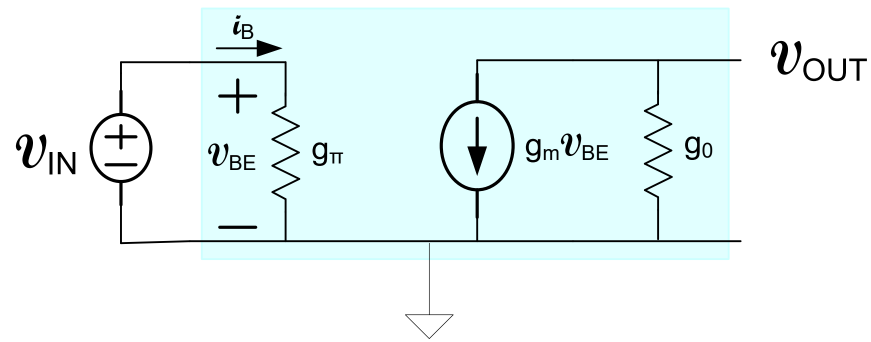
Did you have any current sources in the EE 230 laboratory?

Do current sources really exist?

High-gain amplifier







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

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

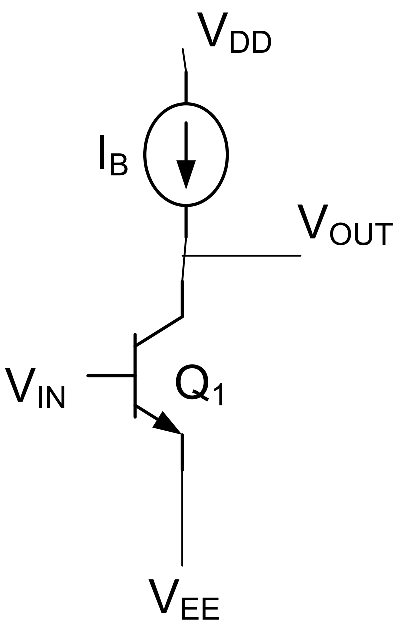
$$A_V = -\frac{V_{AF}}{V_t} \cong \frac{200V}{25mV} = -8000$$

This gain is very large (but realistic) !

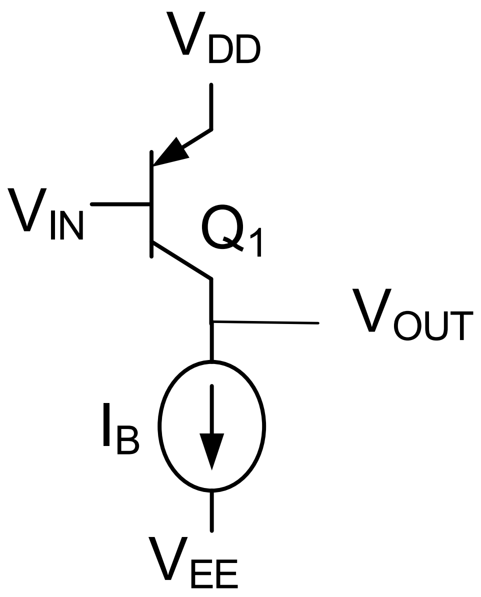
And no design parameters affect the gain

But how can we make a current source?

High-gain amplifier



$$A_V \cong -8000$$

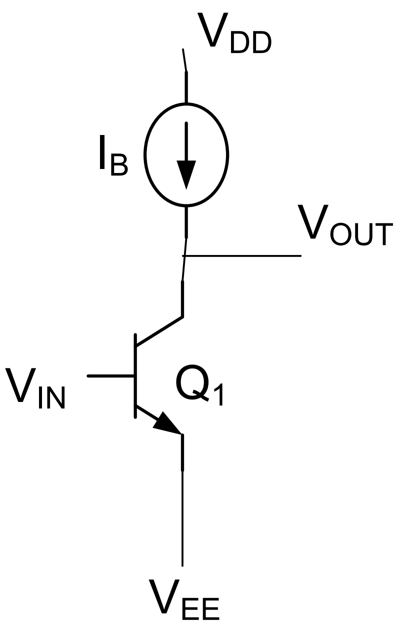


Same gain with both npn and pnp transistors

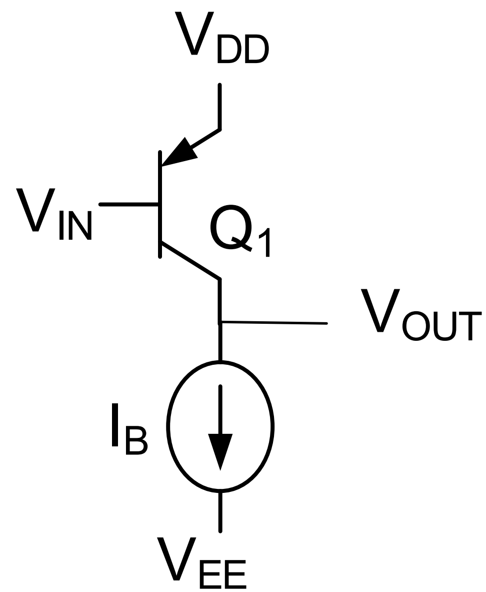
How can we build the ideal current source?

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

High-gain amplifier



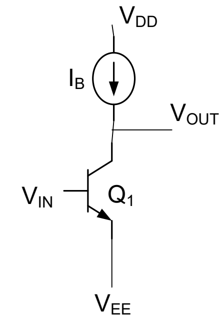
$$A_V \cong -8000$$



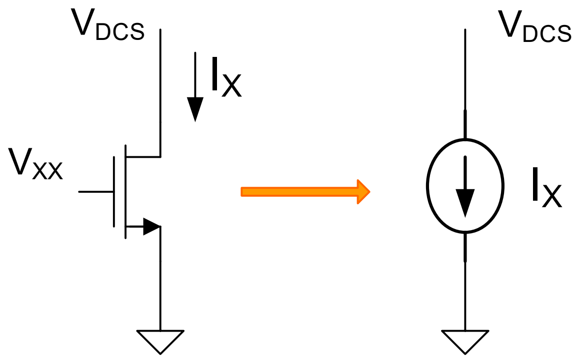
Same gain with both npn and pnp transistors

Will now focus on creating current sources and then return to using these current sources to build high gain amplifiers.

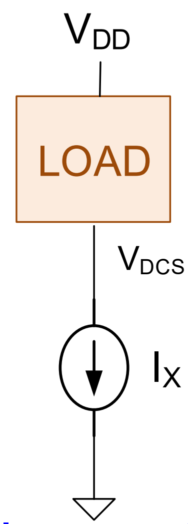
Simple Current Sources



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)

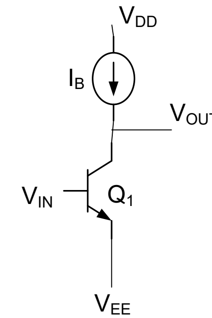
But how good is this current "sink"?

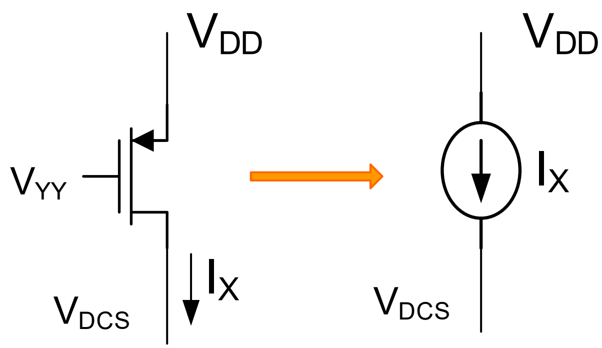
And may not have both MOS and Bipolar devices in most processes!

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

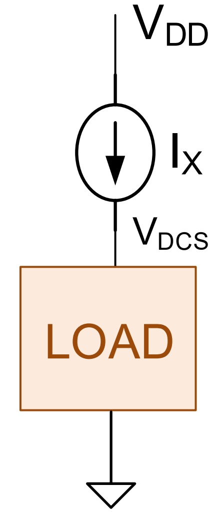
Simple Current Sources

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 !

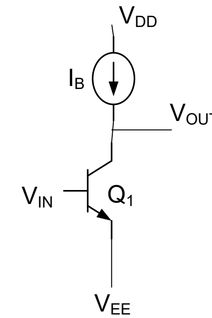
Have several methods for generating V_{YY} from V_{DD} (see HW problems)

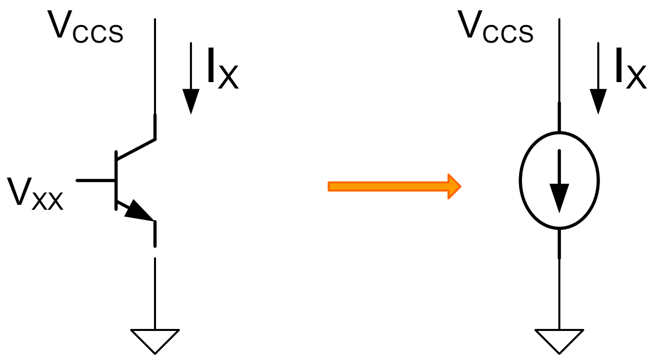
But how good is this current “source”?

And may not have both MOS and Bipolar devices in most processes!

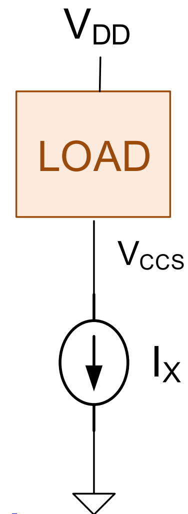
Simple Current Sources

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 !

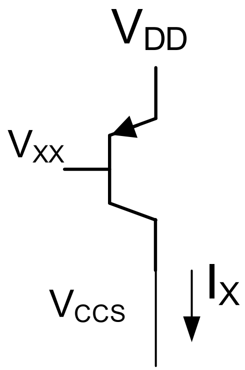
Have several methods for generating V_{XX} from V_{DD} (see HW problems)

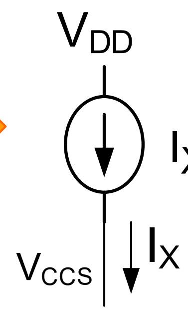
But for the npn high-gain amplifier considered need a sourcing current

But how good is this current "sink"?

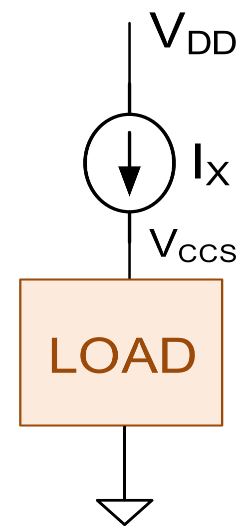
Simple Current Sources

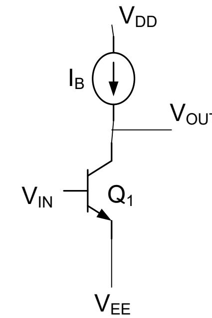
a "sourcing" current source





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





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 !

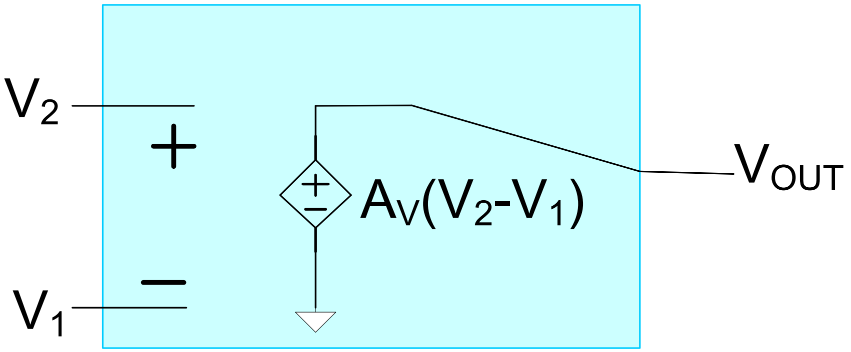
Current highly sensitive to V_{XX} if generated with dc voltage source

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

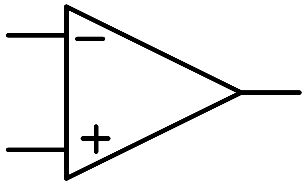
But how good is this current "source"?

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

The Basic Differential Amplifier

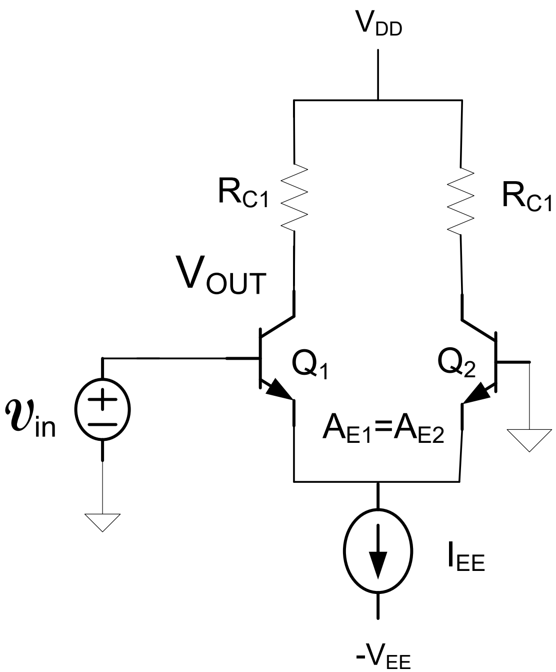


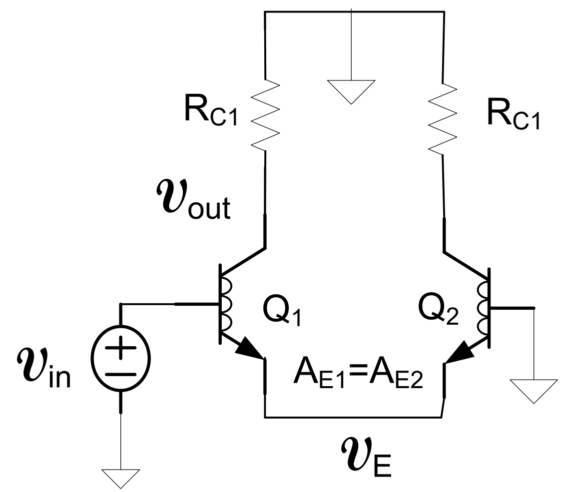
If A_V is large



Operational Amplifier (Op Amp)

Example: Determine the voltage gain of the following circuit

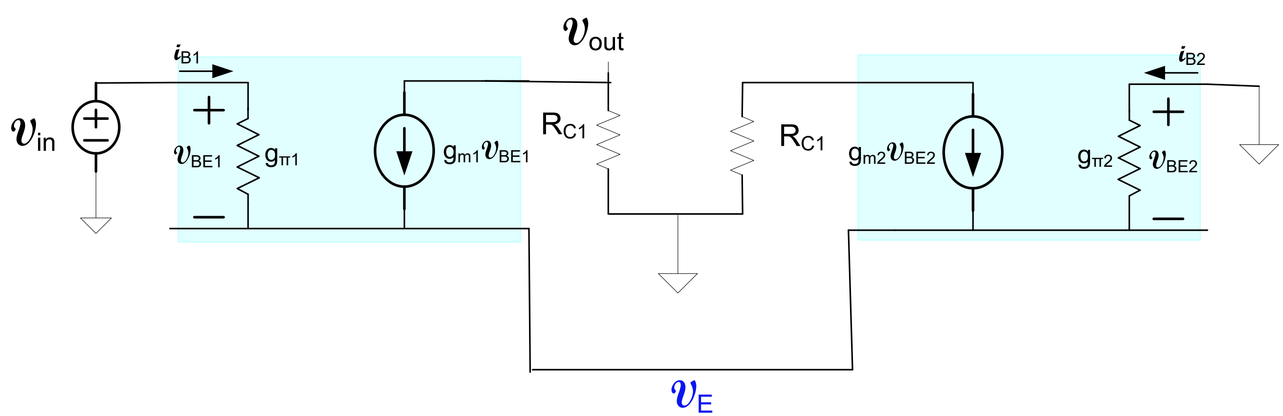




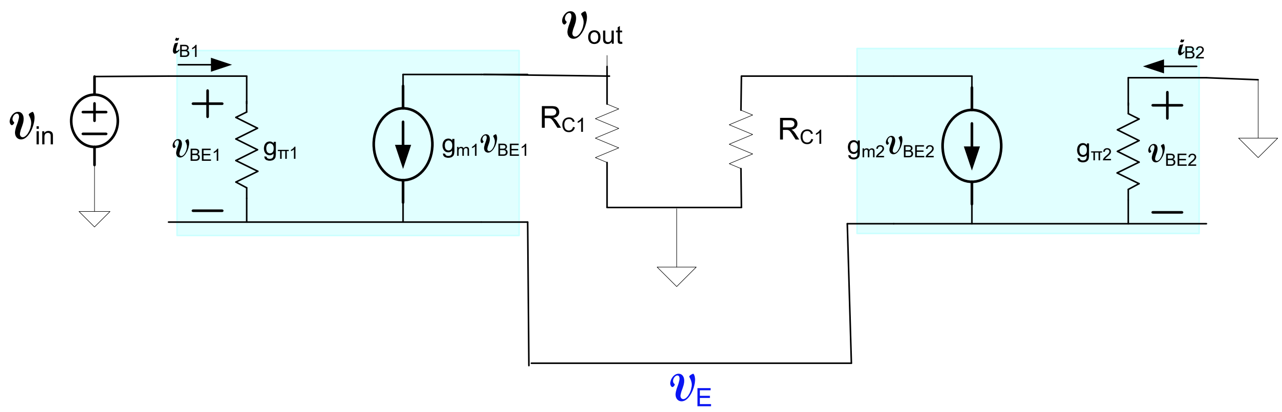
Since symmetric when v_{IN}=0

$$I_{C1Q} = I_{C2Q} = \frac{I_{EE}}{2}$$

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



Example: Determine the voltage gain of the following circuit



$$v_E\left(g_{\pi 1}+g_{\pi 1}\right)=g_{\pi 1}v_{IN}+g_{m1}\left(v_{IN}-v_E\right)+g_{m2}\left(-v_E\right)$$

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

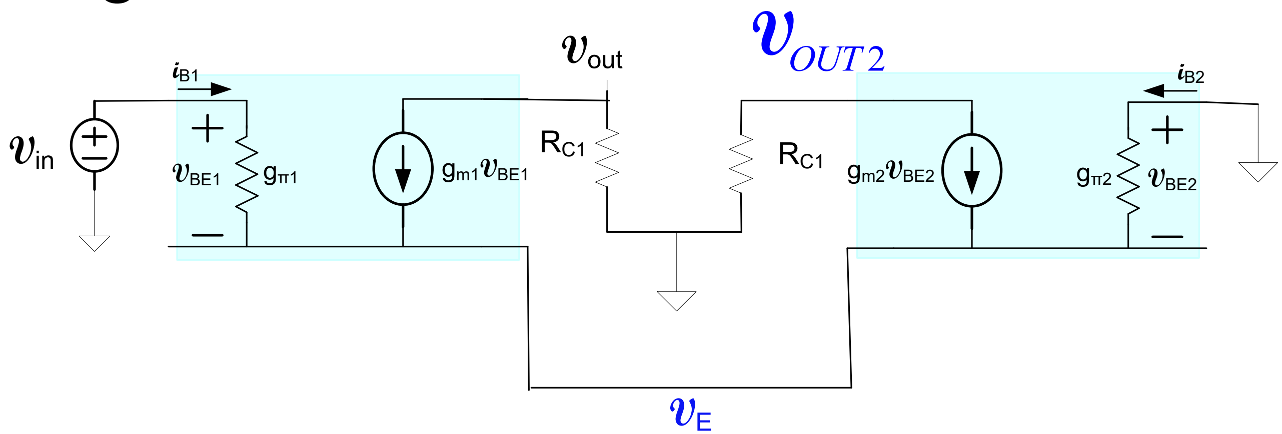
$$v_E\left(g_{\pi 1}+g_{\pi 2}+g_{m1}+g_{m2}\right)=v_{IN}\left(g_{m1}+g_{\pi 1}\right)$$

$$v_E=\frac{\left(g_{m1}+g_{\pi 1}\right)}{\left(g_{\pi 1}+g_{\pi 2}+g_{m1}+g_{m2}\right)}v_{IN}$$

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

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

Example: Determine the voltage gain of the following circuit



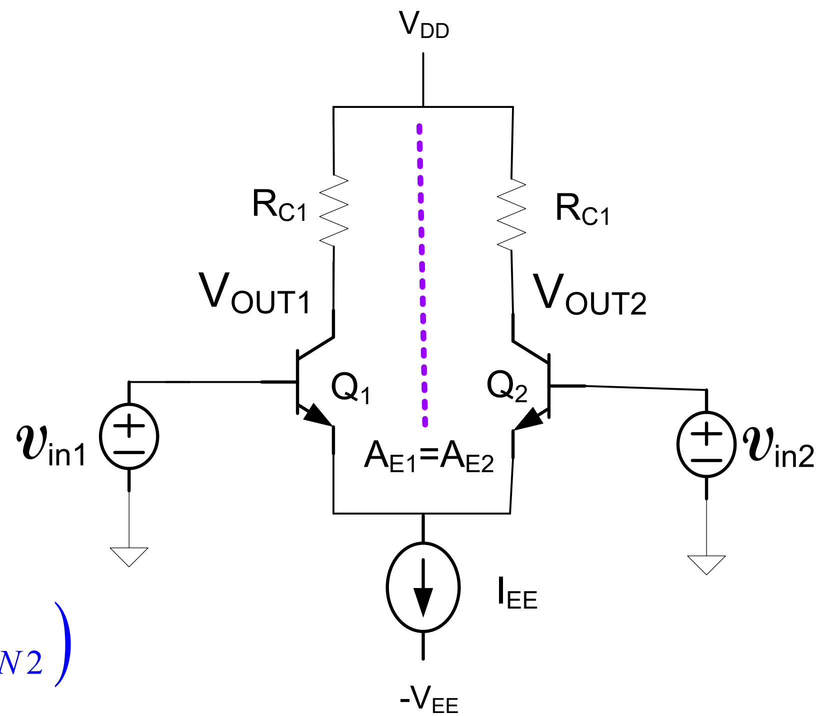
$$v_{OUT} = -R_{C1}g_{m1}v_{IN}\left[\frac{g_{\pi1}+g_{\pi2}+g_{m1}+g_{m2}-(g_{m1}+g_{\pi1})}{(g_{\pi1}+g_{\pi2}+g_{m1}+g_{m2})}\right]$$

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

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

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

Differential amplifier

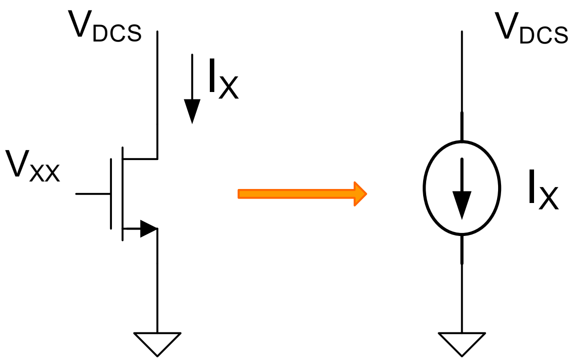


$$v_{OUT1} \cong -\left[\frac{R_{C1}g_{m1}}{2}\right]\left(v_{IN1} - v_{IN2}\right)$$

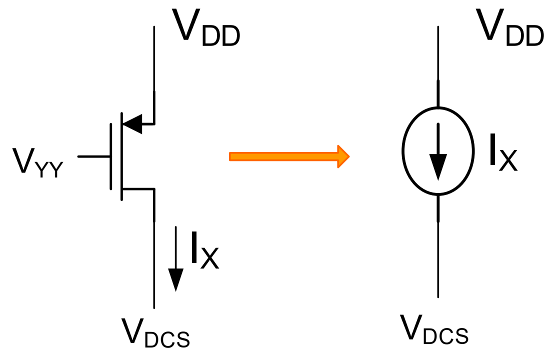
$$v_{OUT2} \cong \left[\frac{R_{C1}g_{m1}}{2}\right]\left(v_{IN1} - v_{IN2}\right)$$

- 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



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

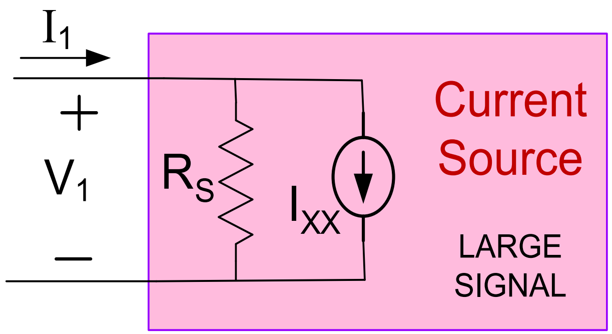


$$I_X = \frac{\mu C_{OX} W}{2L}\left(V_{DD} - V_{YY} + V_{Tp}\right)^2$$

But how good are these current sources?

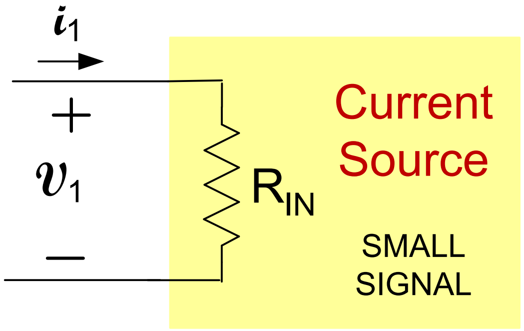
Model of dc Current Source

"Reasonable dc Current Source"



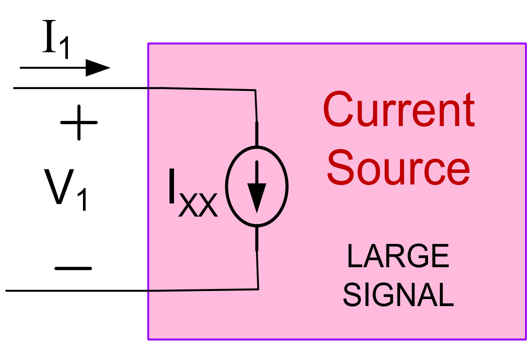
I_{XX} independent of V_1 and t , R_S large

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

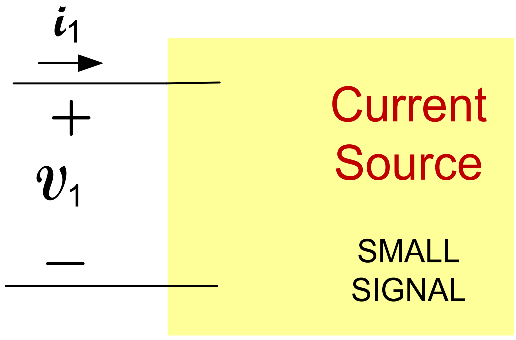


want R_{IN} large

Ideal dc Current Source



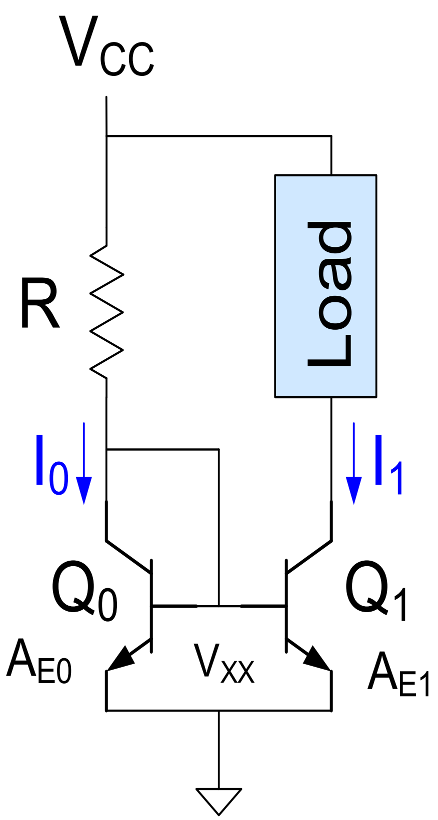
I_{XX} independent of V_1 and t

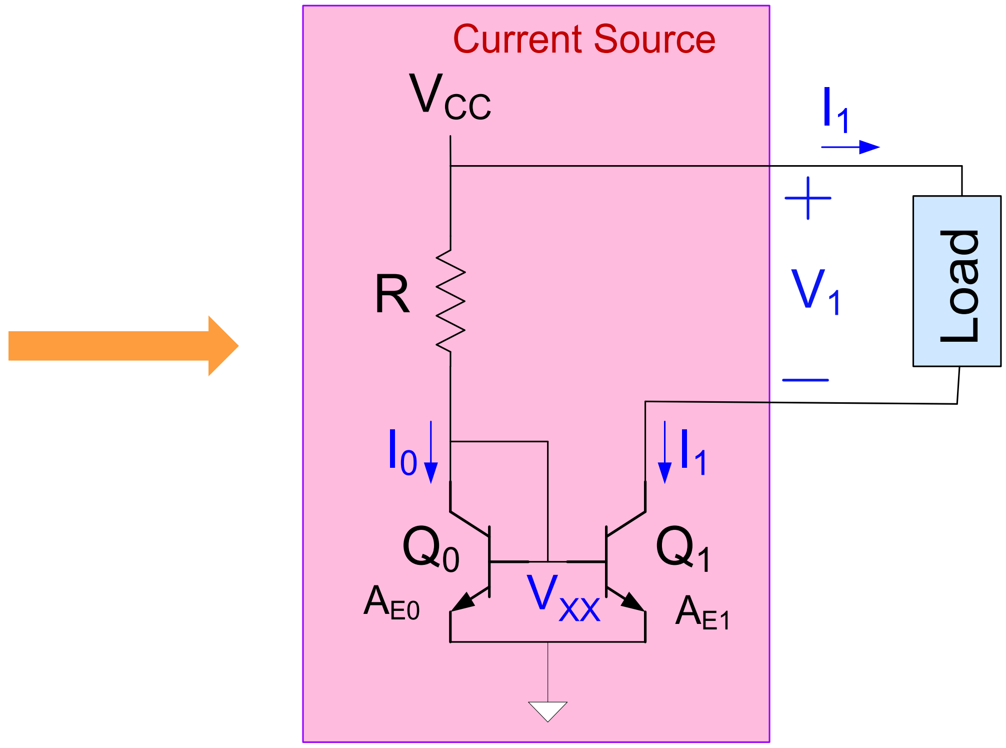


$R_{IN}=\infty$

Current Sources/Mirrors

Will show circuit in red behaves as a current source

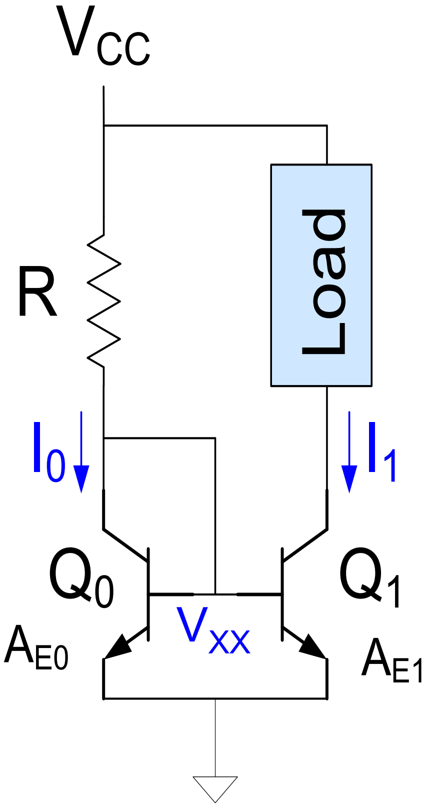




R and Q_0 simply generate voltage V_{XX} in previous circuit

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

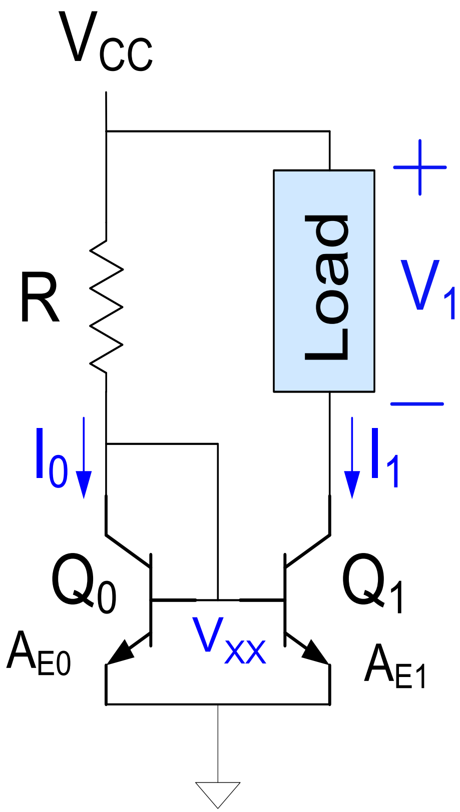
Current Sources/Mirrors



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

If the base currents are neglected

Current Sources/Mirrors



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

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 $V_{BE1}=V_{BE2}$

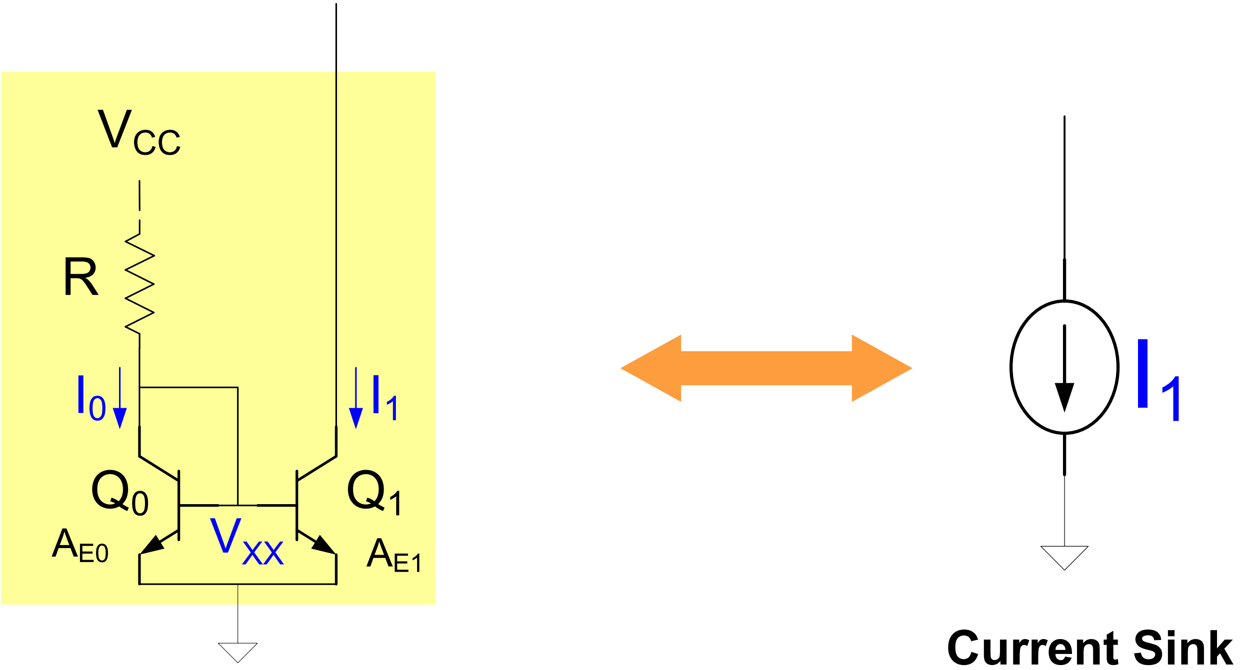
$$I_1 \cong \left(\frac{A_{E1}}{A_{E0}}\right) I_0 = \left(\frac{A_{E1}}{A_{E0}}\right)\frac{V_{CC}-0.6V}{R}$$

Note I_1 is not a function of V_1

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

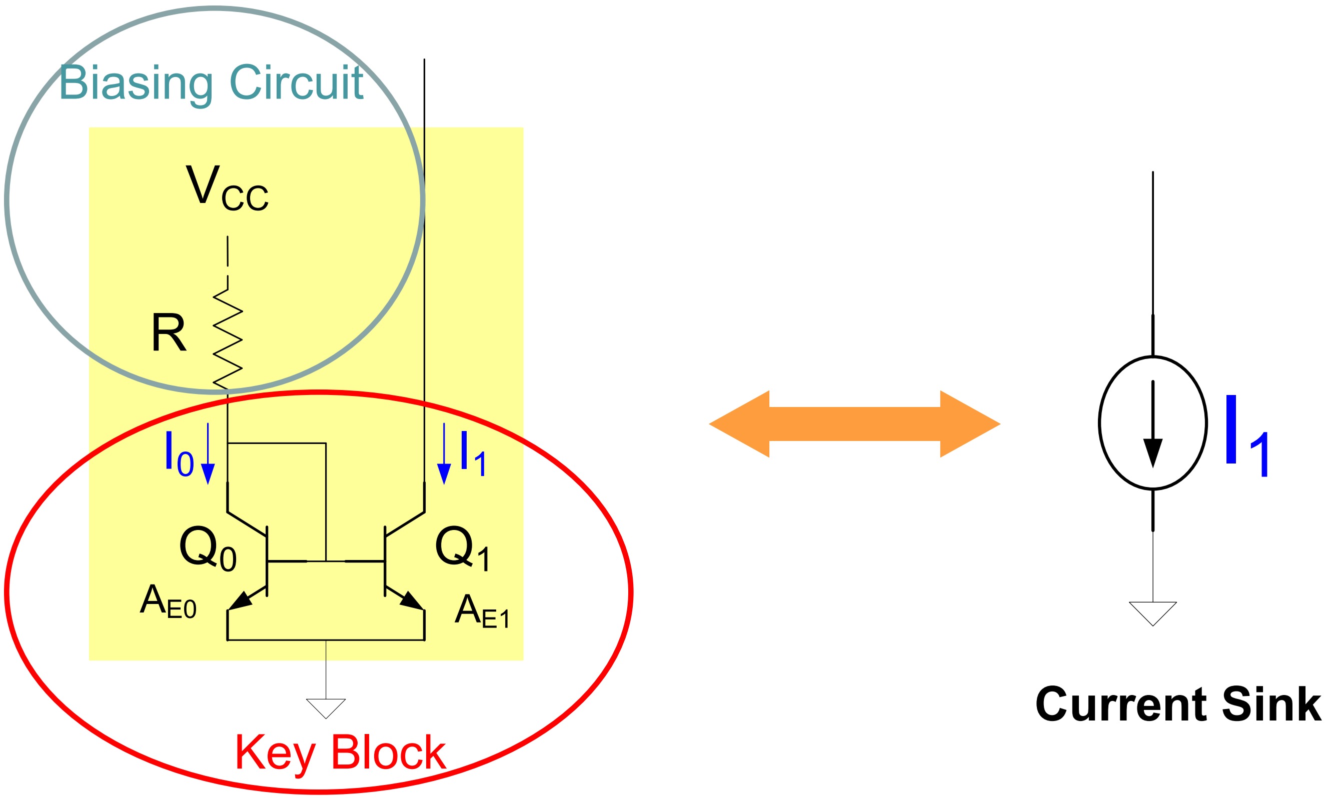
And does not require an <u>additional</u> dc voltage source !!!

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**

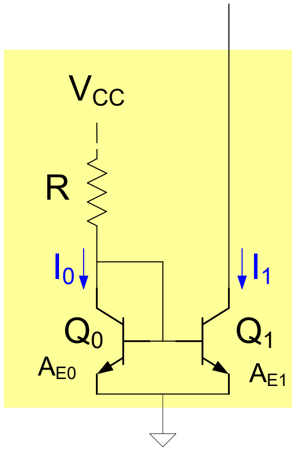
Current Sources/Mirrors

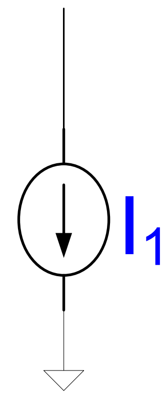


Two ways to look at this circuit:

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

Current Sources/Mirrors





Current Sources are Seldom Available in Basic Laboratories:

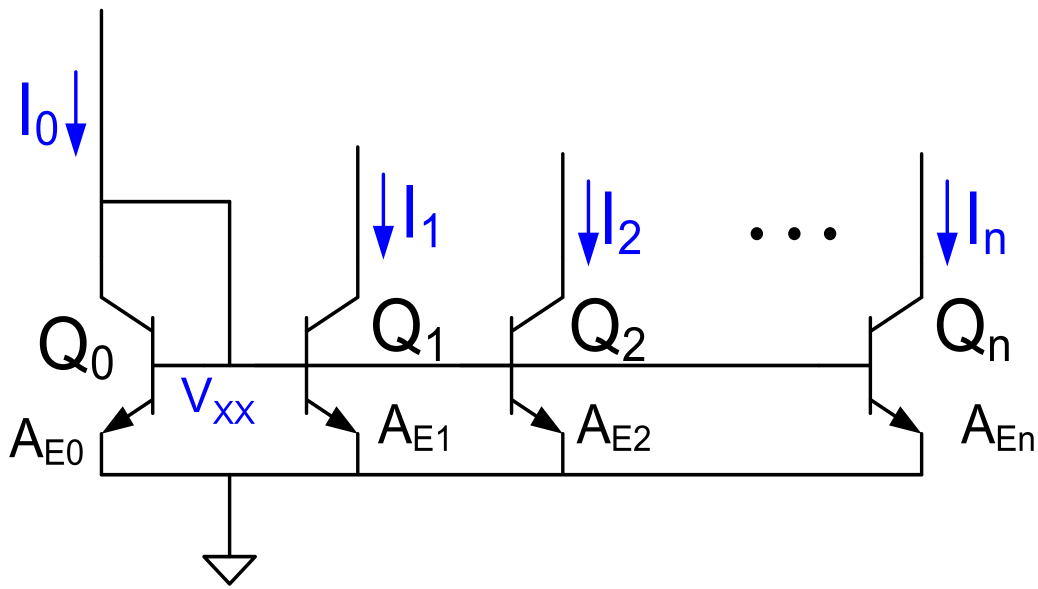
Biasing of board-level and discrete electronic circuits is usually done with voltage sources, resistors, and capacitors

Biasing resistors and capacitors are used very sparingly in MOS circuits

Will show on-chip current sources can be very small

Biasing of on-chip circuits is often done with current sources instead of R's and C's

Current Sources/Mirrors

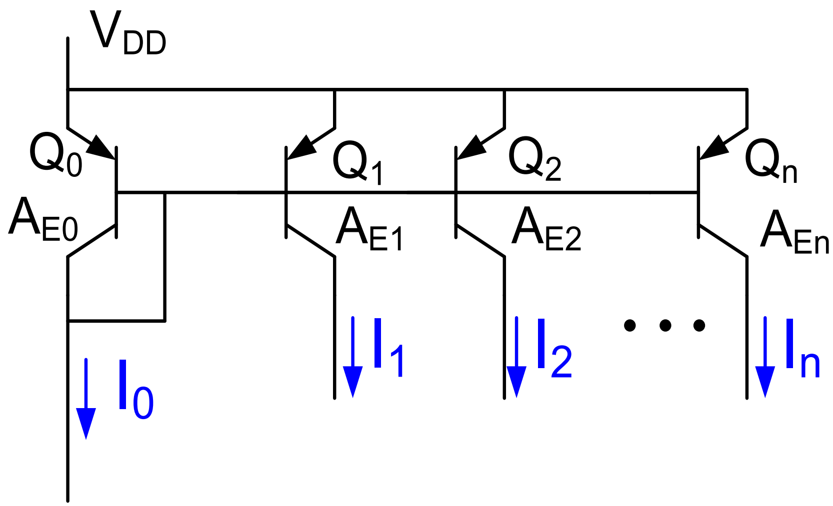


Multiple-Output Bipolar Current Sink

If the base currents are neglected

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

Current Sources/Mirrors

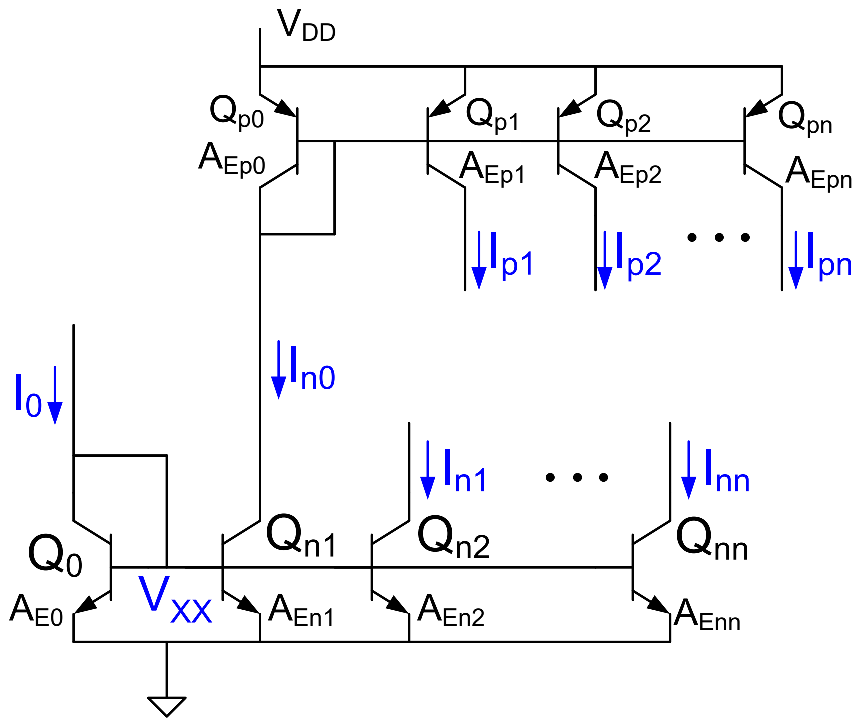


Multiple-Output Bipolar Current Source

If the base currents are neglected

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

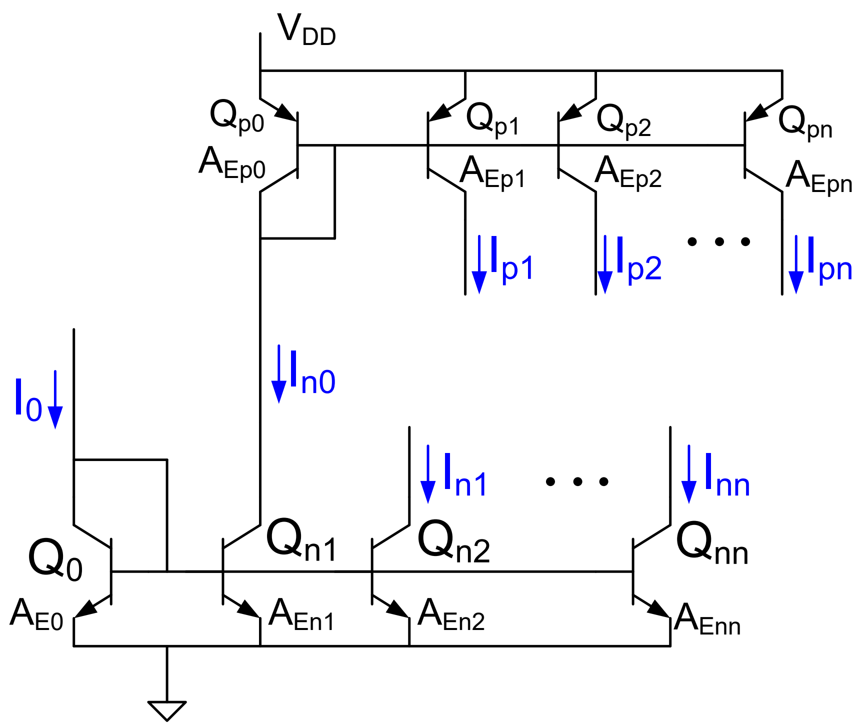
Current Sources/Mirrors



Multiple-Output Bipolar Current Source and Sink

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

Current Sources/Mirrors

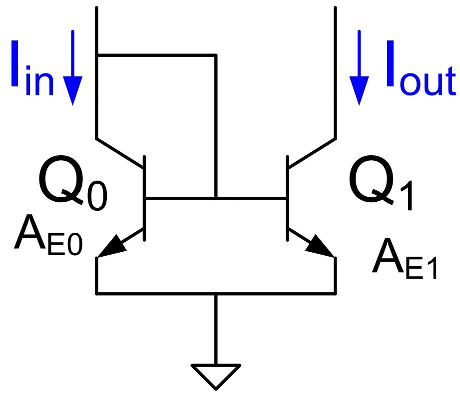


Multiple-Output Bipolar Current Source and Sink

If the base currents are neglected

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

Current Sources/Mirrors



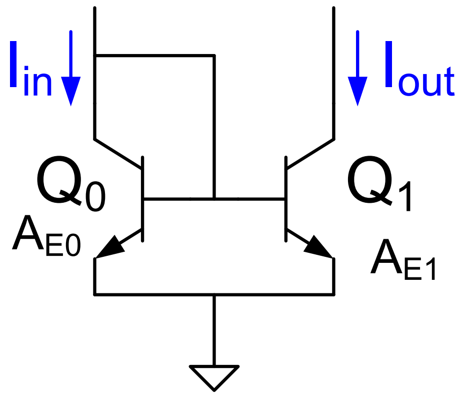
$$I_{out} = \left[\frac{A_{E1}}{A_{E0}}\right] I_{in}$$

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

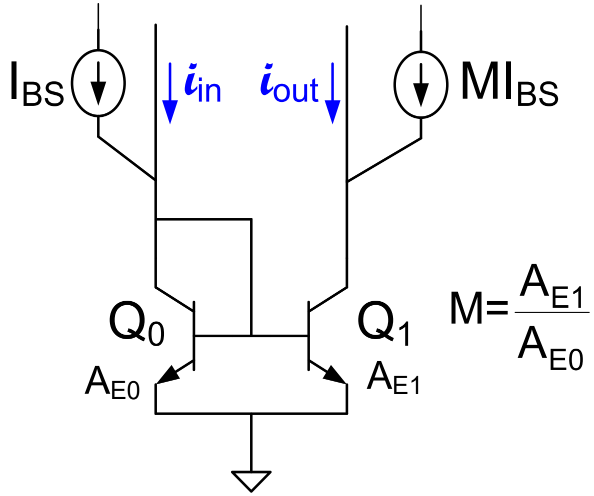
If the base currents are neglected

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

- **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



npn current mirror amplifier

$i_{out}=?$

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

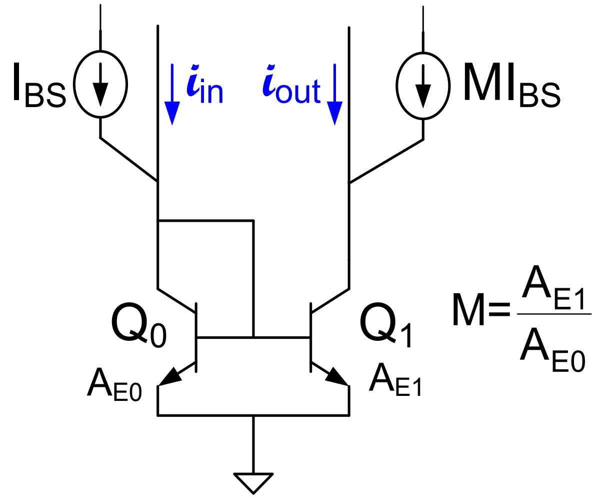
$$i_{OUT}+MI_{BS}=M\left(i_{in}+I_{BS}\right)$$

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

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

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

Current Sources/Mirrors



npn current mirror amplifier

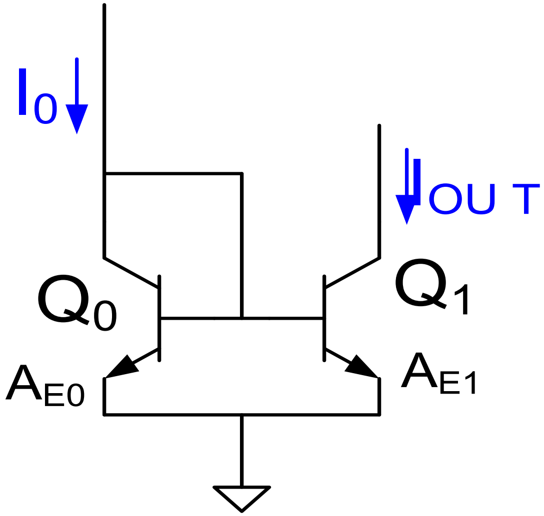
$$i_{out} = \left[\frac{A_{E1}}{A_{E0}}\right] i_{in}$$

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

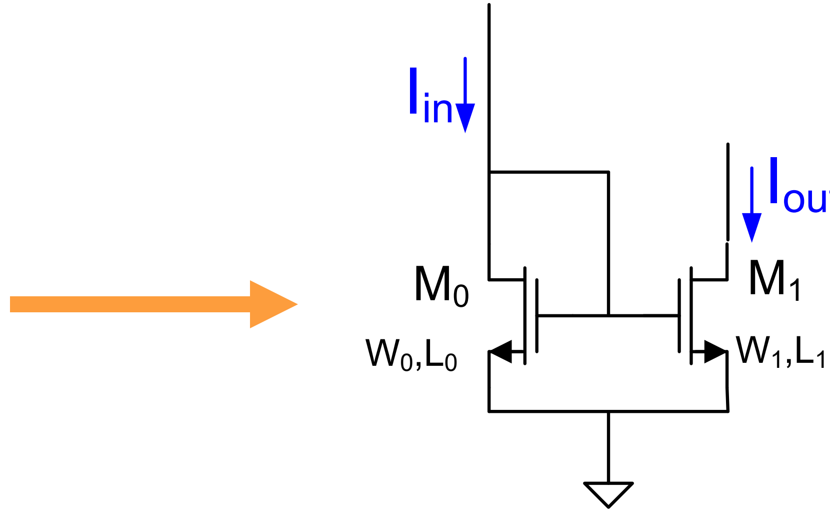
Current amplifiers are easy to build !!

Current gain can be accurately controlled with appropriate layout !!

Current Sources/Mirrors



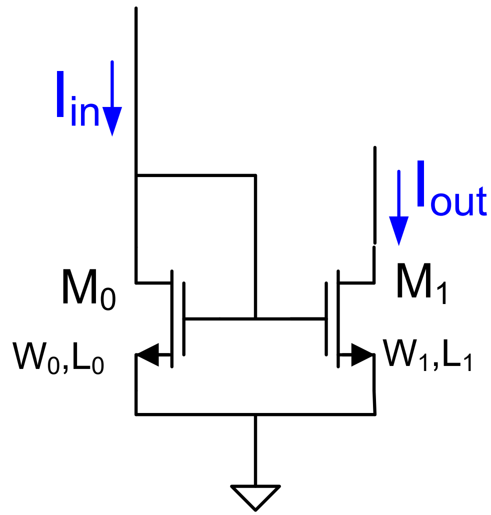
npn Current Mirror



n-channel Current Mirror

$I_{out} = ?$

Current Sources/Mirrors



n-channel Current Mirror

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

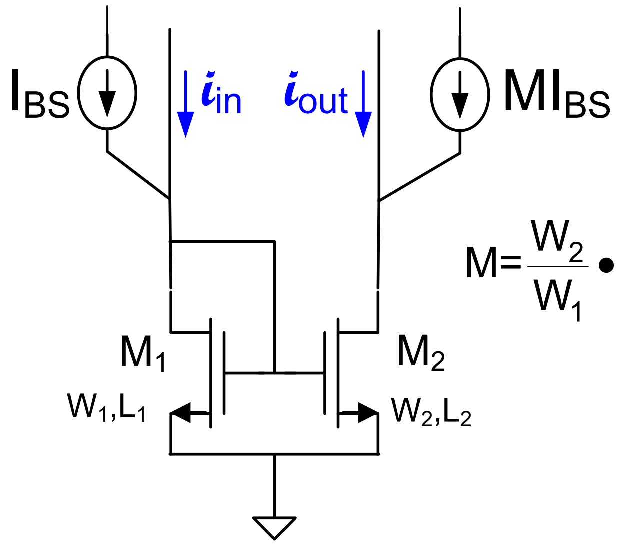
$$I_{out} = \frac{\mu\, C_{OX} W_1}{2L_1}\left(V_{GS1} - V_{T1}\right)^2$$

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)

n-channel current mirror current amplifier

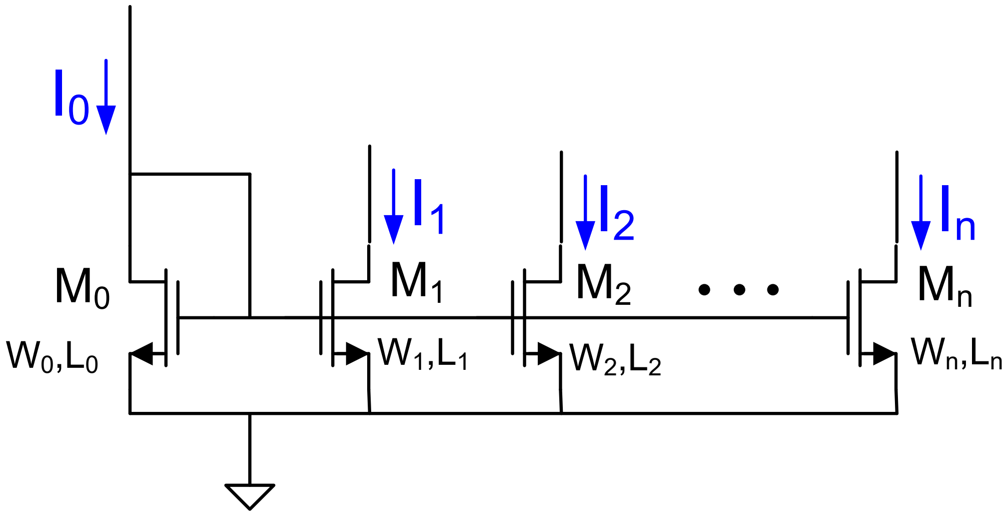


$$M = \frac{W_2}{W_1} \bullet \frac{L_1}{L_2}$$

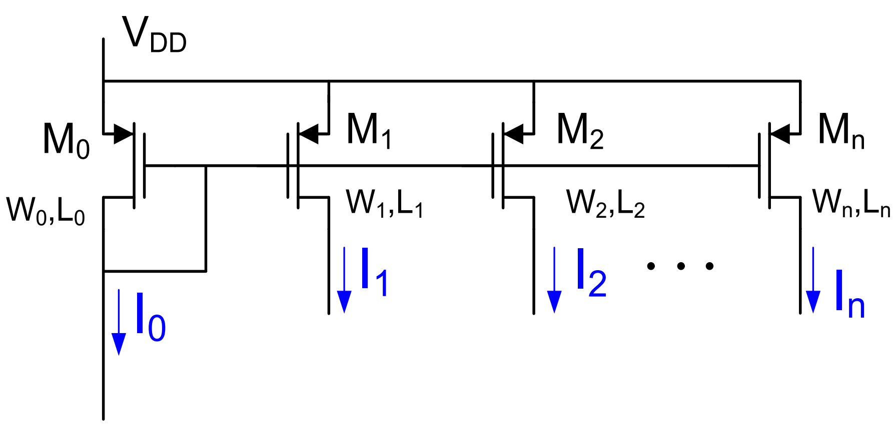
$$i_{out} = \left[\frac{W_2}{W_1} \frac{L_1}{L_2} \right] i_{in}$$

Amplifies both positive and negative currents

Current Sources/Mirrors



multiple output n-channel current sink array

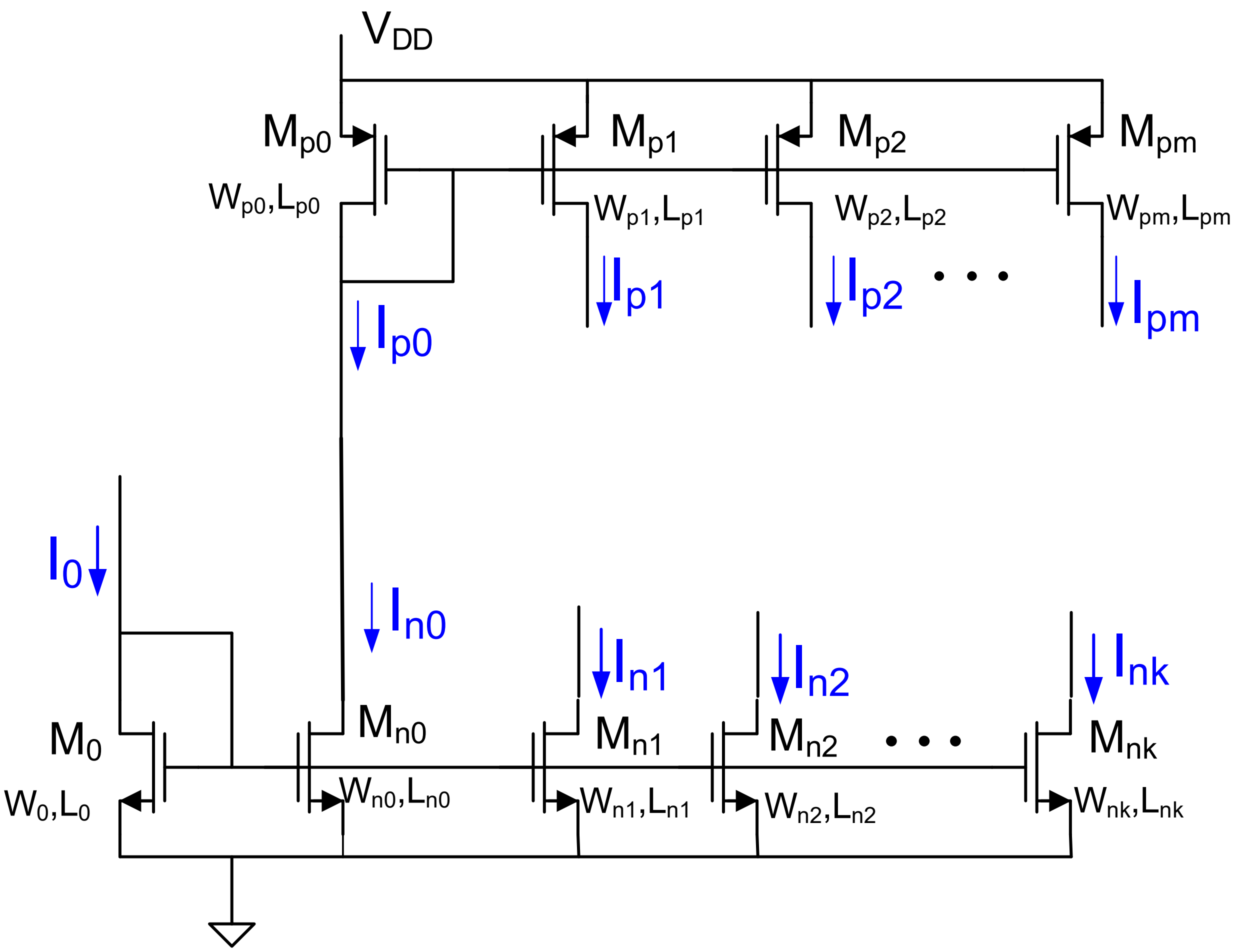


multiple output p-channel current source array

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

Current Sources/Mirrors

multiple sourcing and sinking current outputs



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

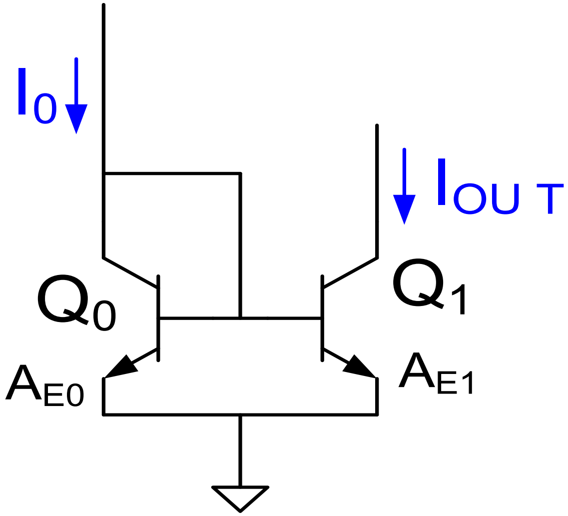
$$M = \left[\frac{W_{n0}}{L_{n0j}} \bullet \frac{L_0}{W_0}\right]$$

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

m and k may be different

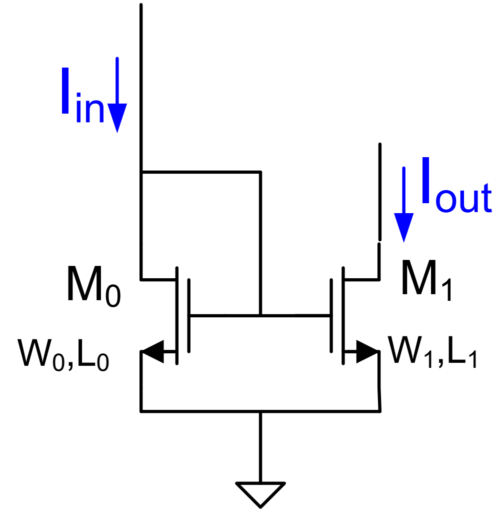
Often M=1

Current Sources/Mirrors Summary



npn Current Mirror

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



n-channel Current Mirror

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

- 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