EE 330

Lecture 34

Layout of Current Mirrors

Common-Centroid Layouts

High Gain Amplifiers

Cascode Amplifiers

Spring 2024 Exam Schedule

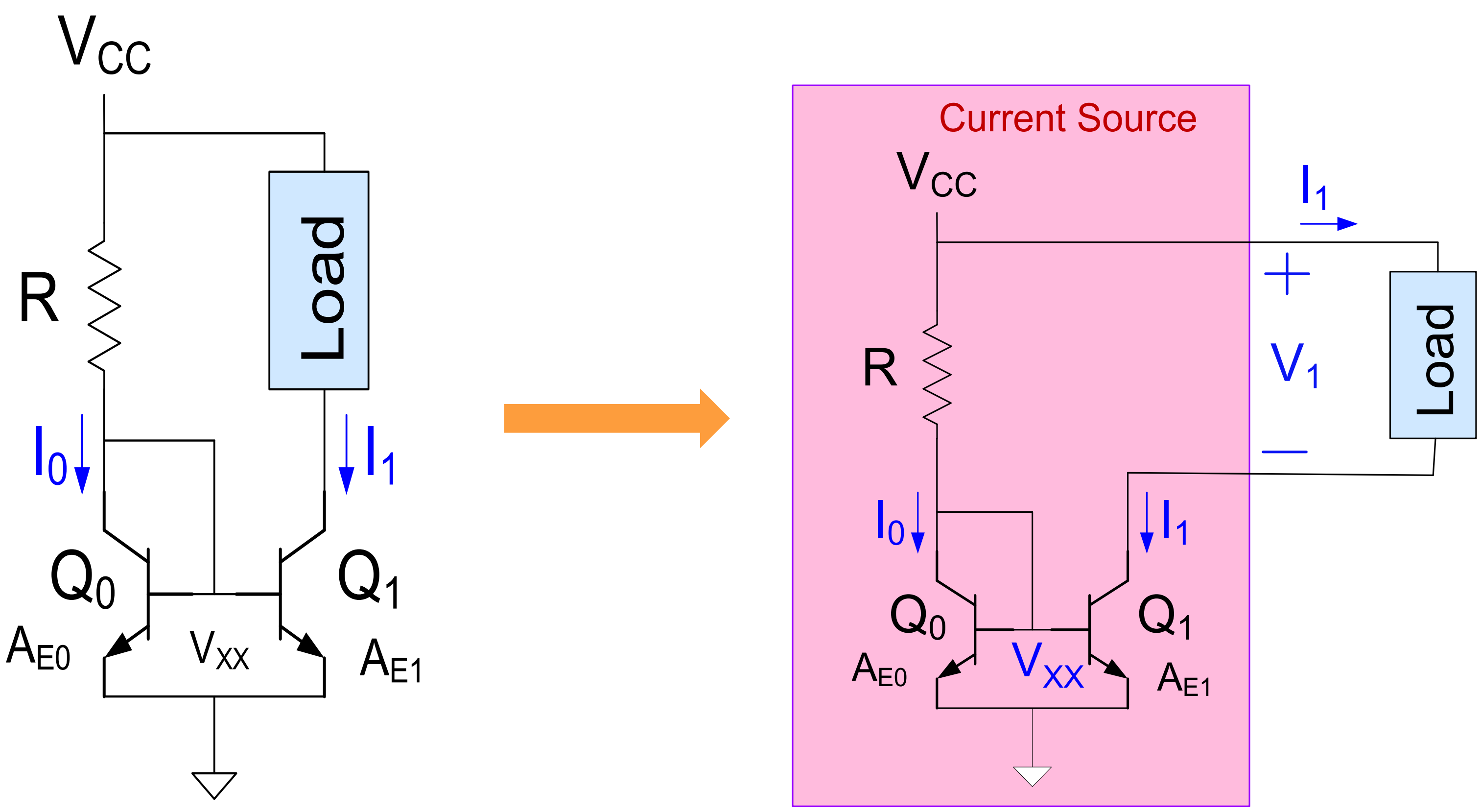
Exam 1	Friday Feb 16
Exam 2	Friday March 8
Exam 3	Friday April 19

Final Exam Tuesday May 7 7:30 AM - 9:30 AM

Review From Previous Lecture

Current Sources/Mirrors

Will show circuit in red behaves as a current source

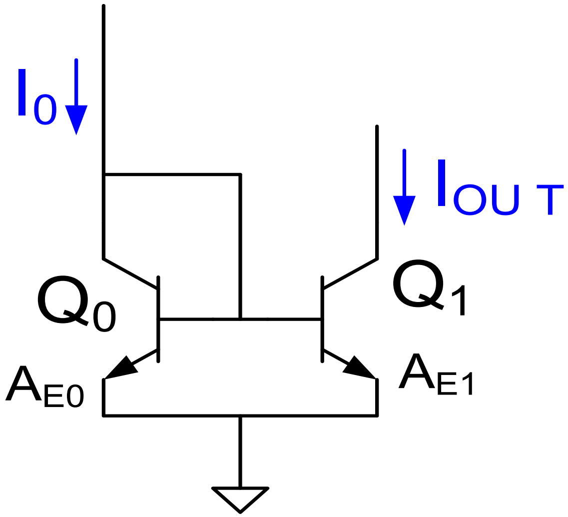


R and Q_0 simply generate voltage V_{XX} in previous circuit

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

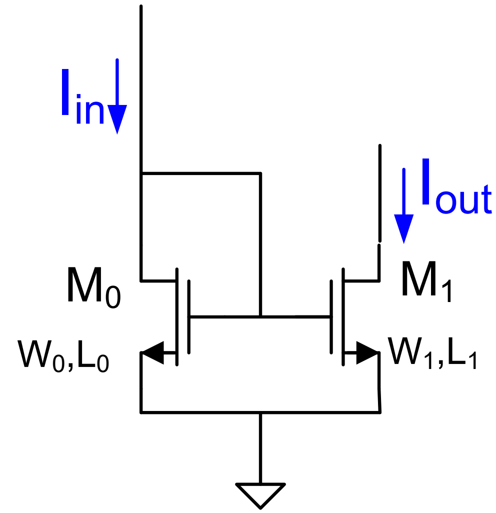
Review From Previous Lecture

Current Sources/Mirrors Summary



npn Current Mirror

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

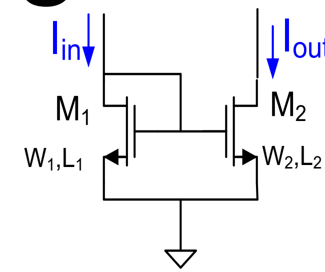


n-channel Current Mirror

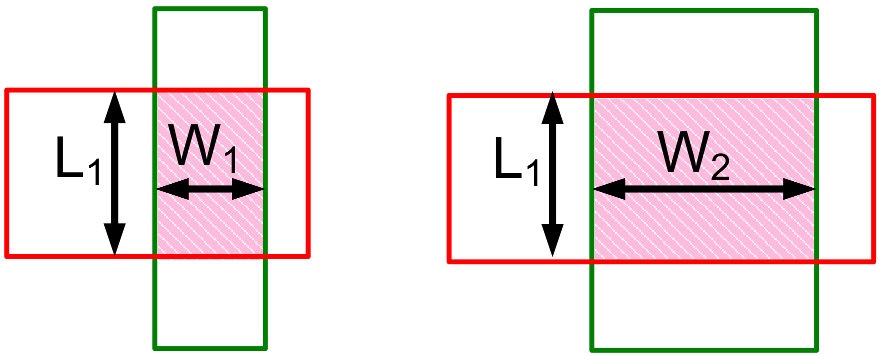
$$I_{out} = \left[\frac{W_1}{W_0} \frac{L_0}{L_1} \right] I_{in}$$

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

Layout of Current Mirrors

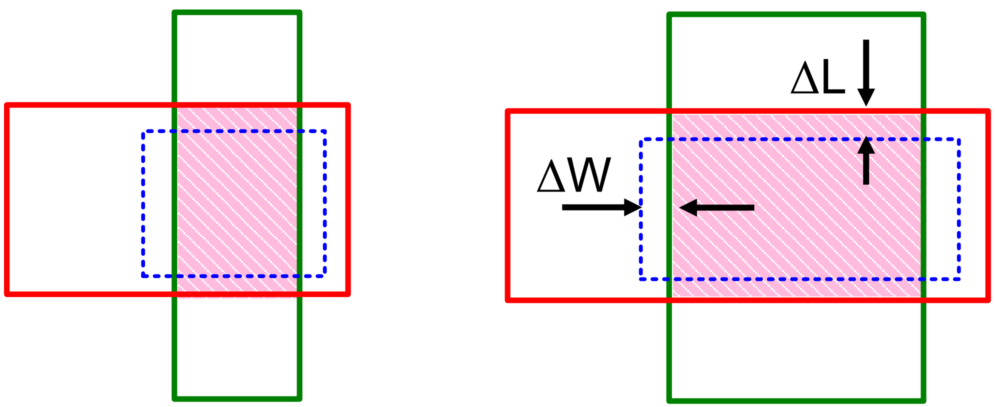


Example with M = 2



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

Standard layout



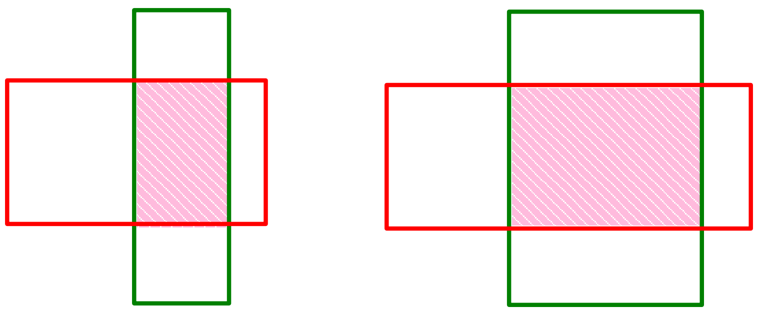
$$M = \left[\frac{W_2 + 2\Delta W}{W_1 + 2\Delta W} \bullet \frac{L_1 + 2\Delta L}{L_2 + 2\Delta L}\right]$$

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

Gate area after fabrication depicted

Layout of Current Mirrors

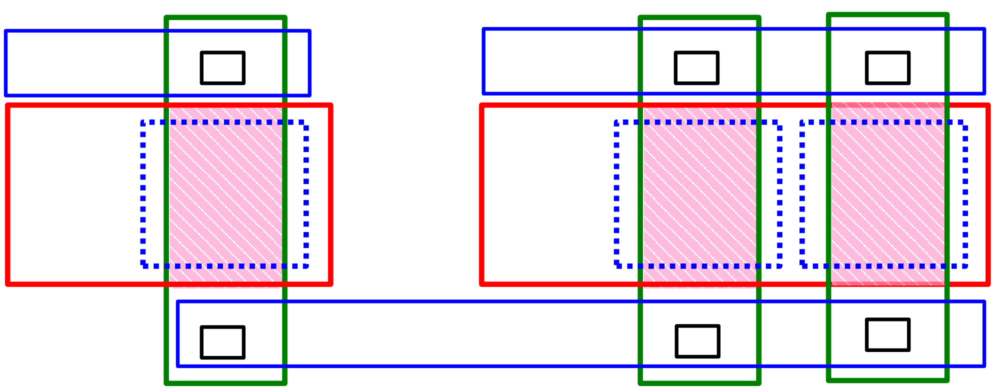
Example with M = 2



Standard layout

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

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



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

Better Layout

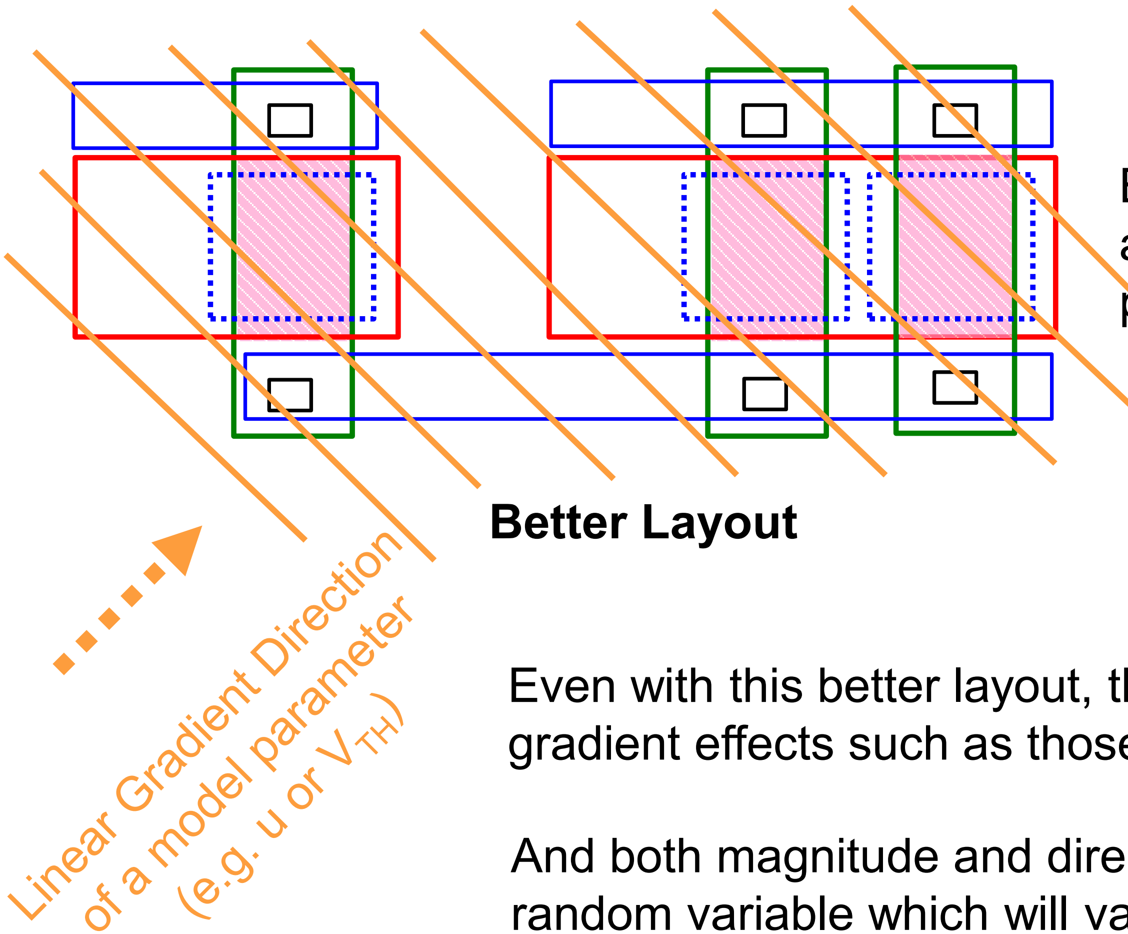
Layout of Current Mirrors

Example with M = 2

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

But this analysis was based upon assumption of matching of process parameters

$$\left.\begin{aligned} I_{in} &= \frac{\mu_0 C_{OX} W_0}{2L_0}\left(V_{GS0}-V_{T0}\right)^2 \\ I_{out} &= \frac{\mu_1 C_{OX} W_1}{2L_1}\left(V_{GS1}-V_{T1}\right)^2 \end{aligned}\right\}$$

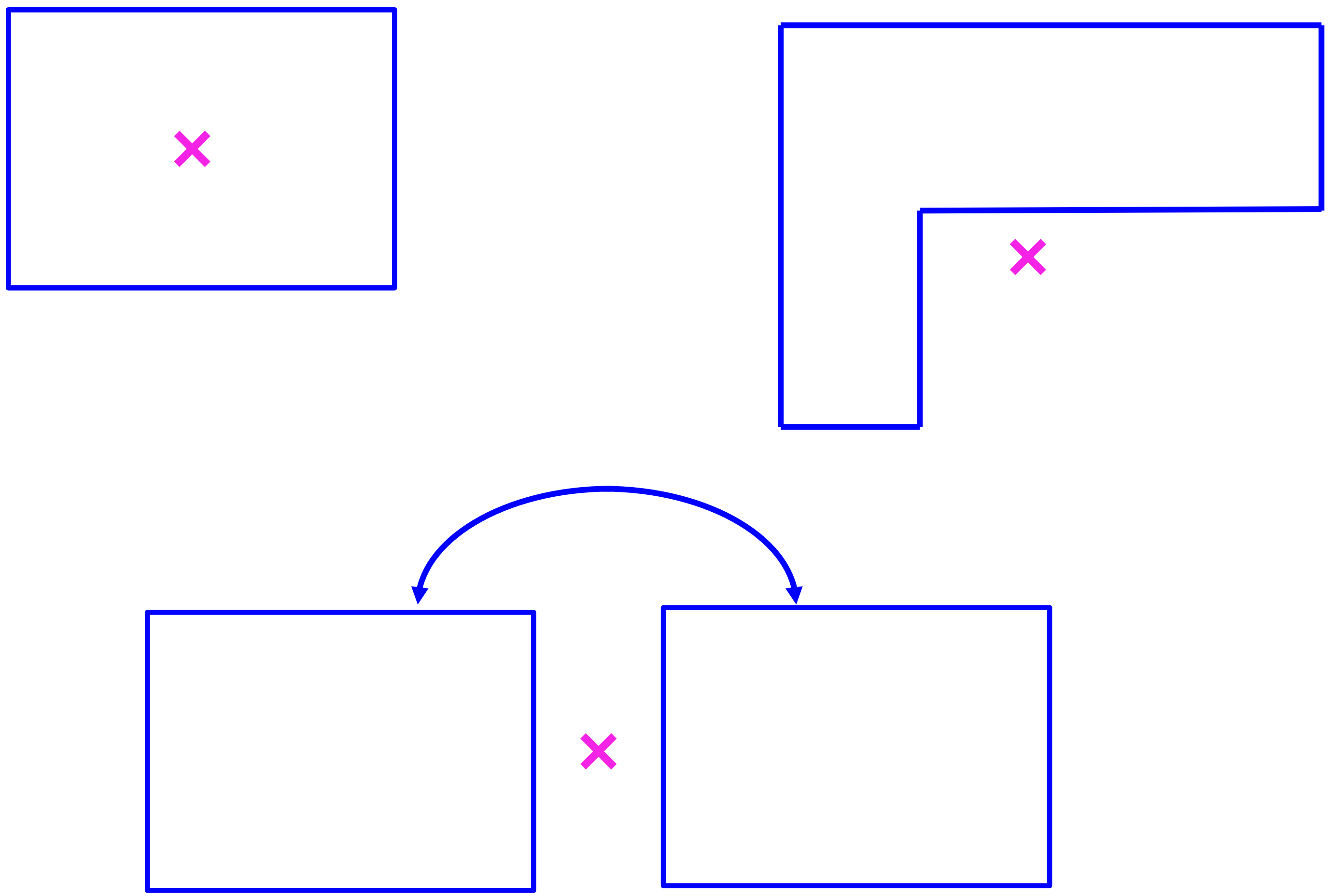


Even with this better layout, the current ratio will not be 2 if gradient effects such as those depicted here are shown

And both magnitude and direction of gradient effects are a random variable which will vary across a die

Centroid and Common Centroid

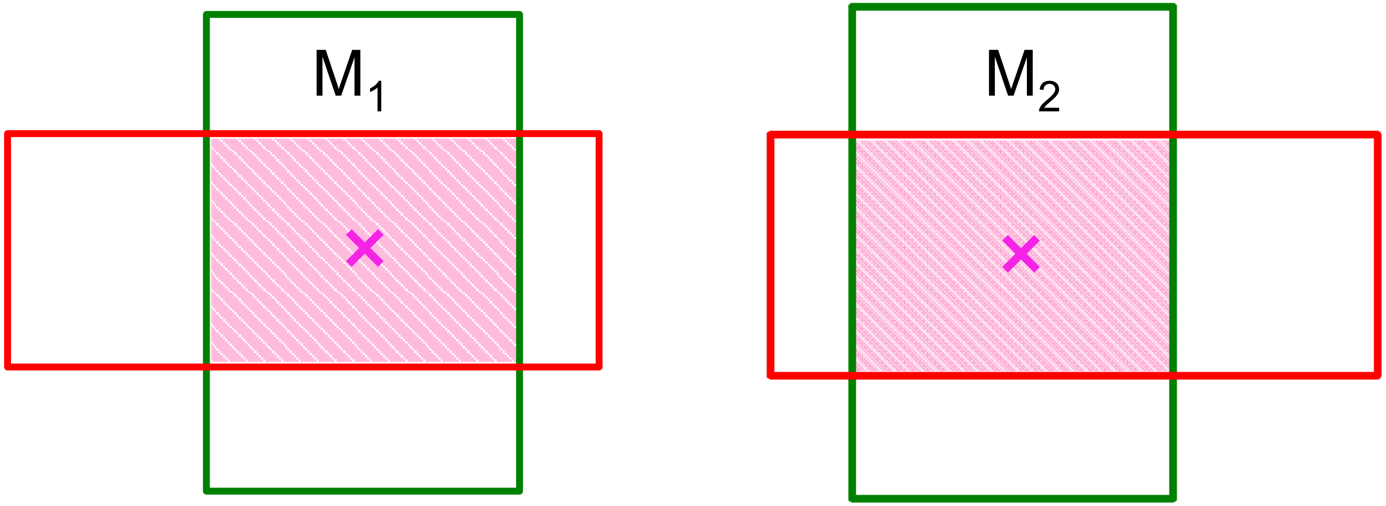
× Denotes Geometric Centroid



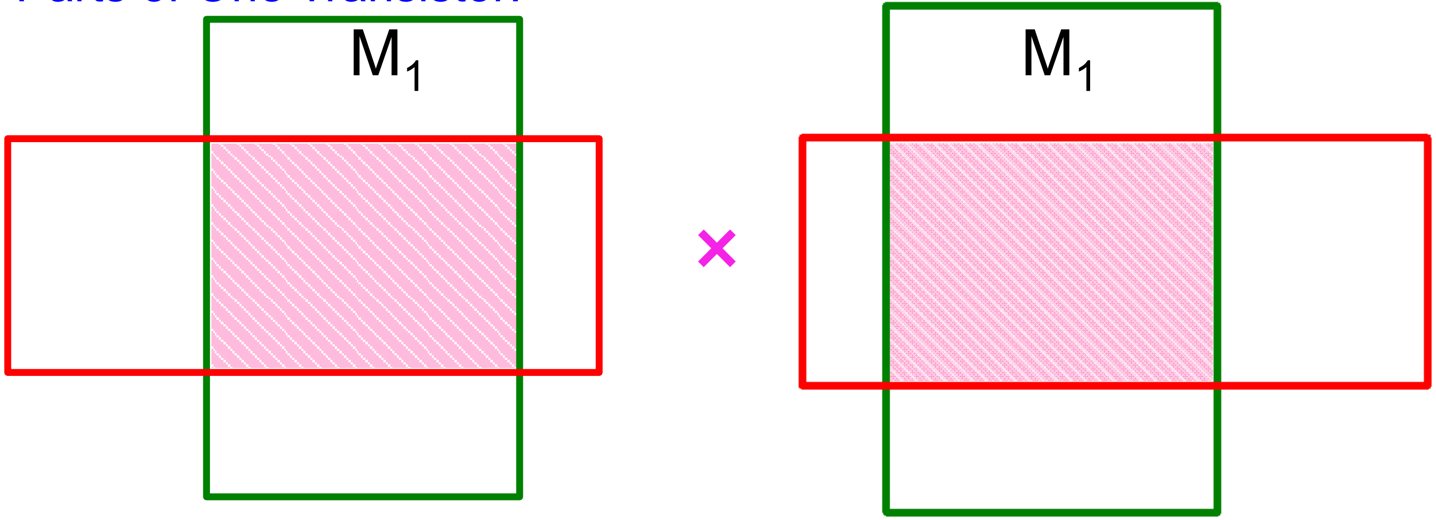
Centroid and Common Centroid

Geometric Centroids of Channel

Two Transistors:

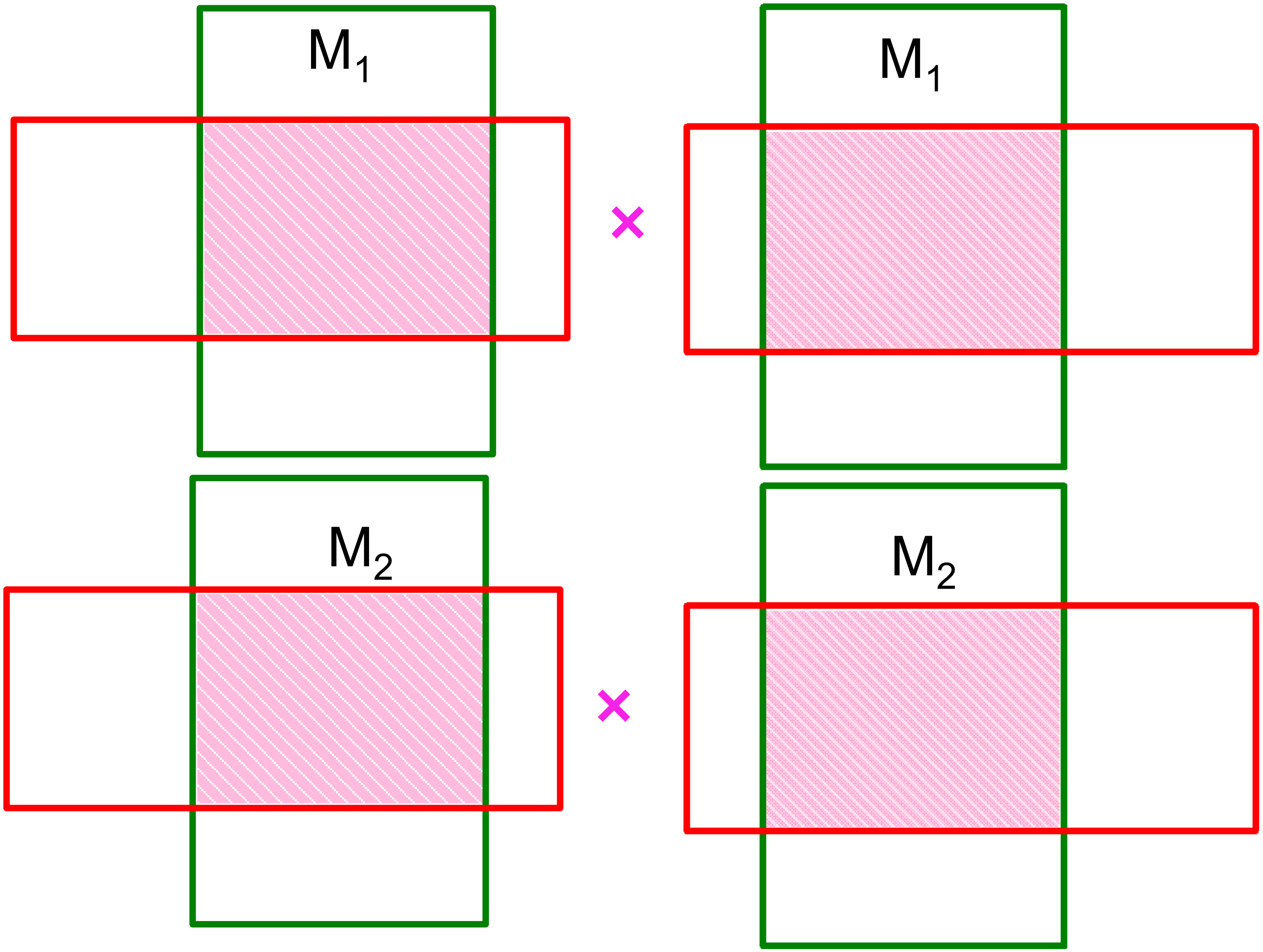


Two Parts of One Transistor:



Centroid and Common Centroid

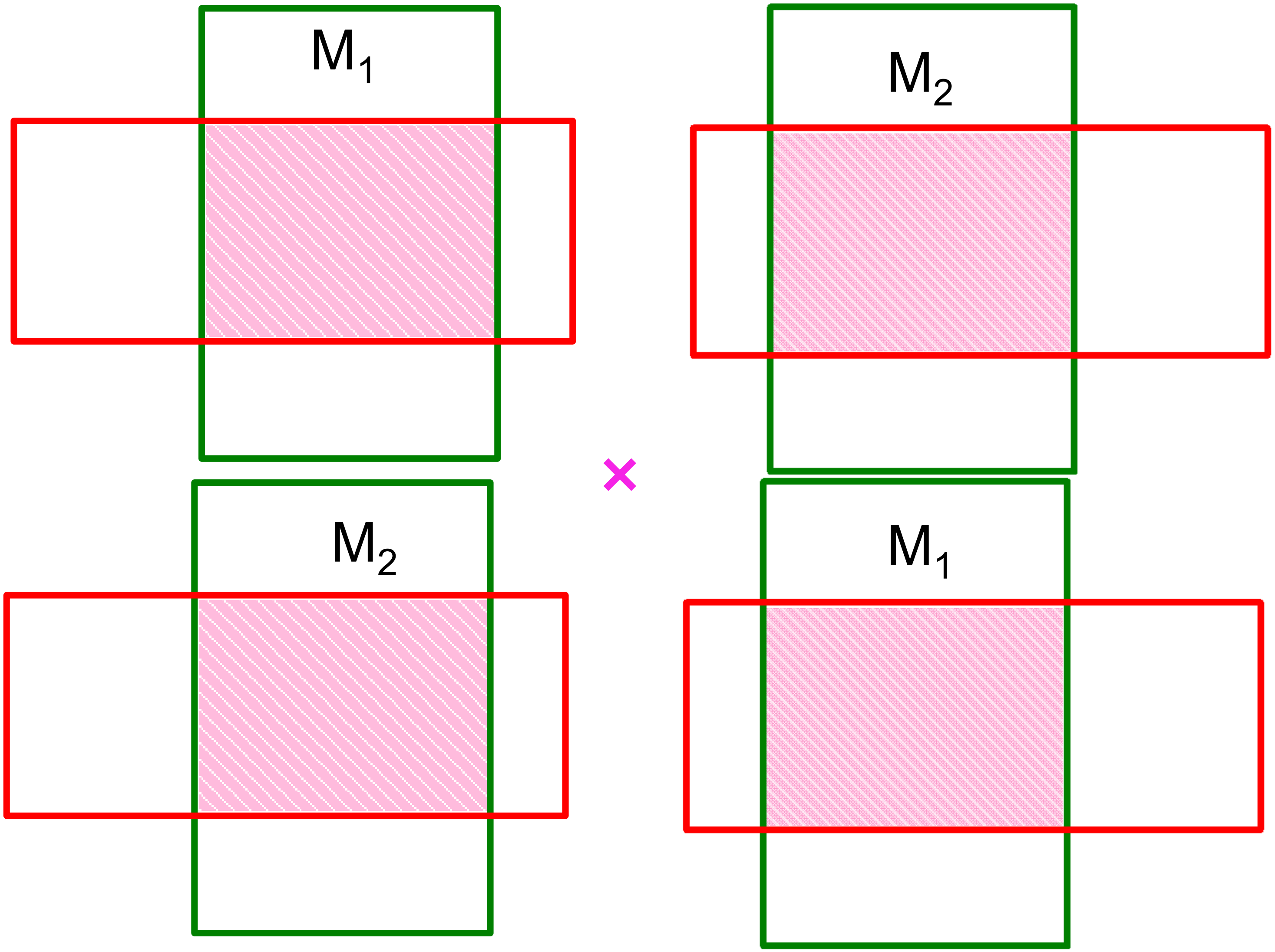
Two Transistors each with two parts:



Centroid and Common Centroid

Common Centroid for Ideally Matched Devices

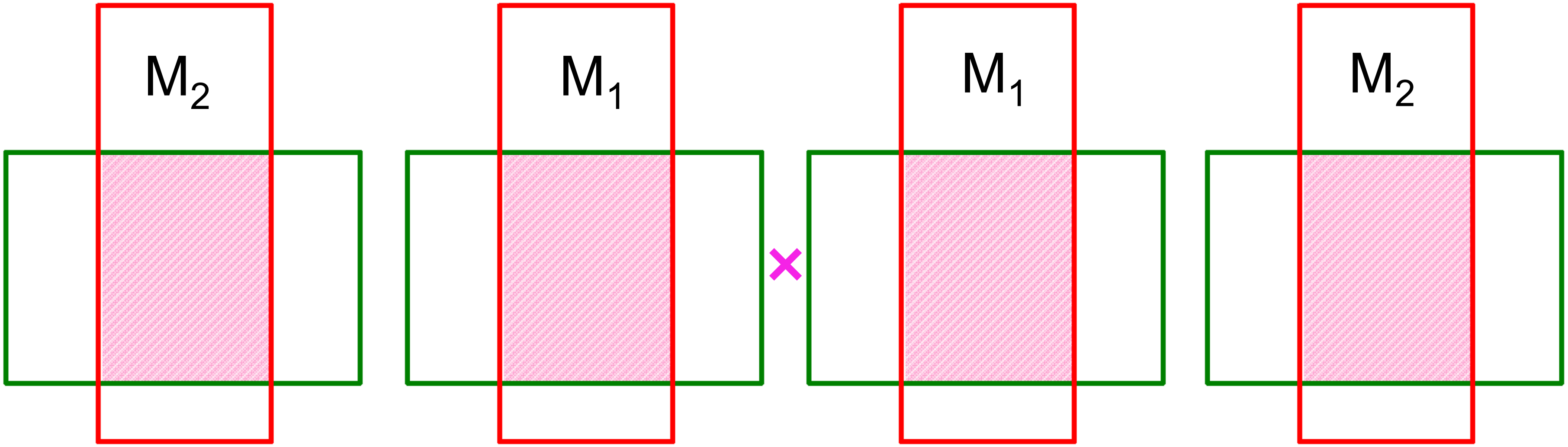
Two Transistors each with two parts:



Centroid and Common Centroid

Common Centroid for Matched Devices

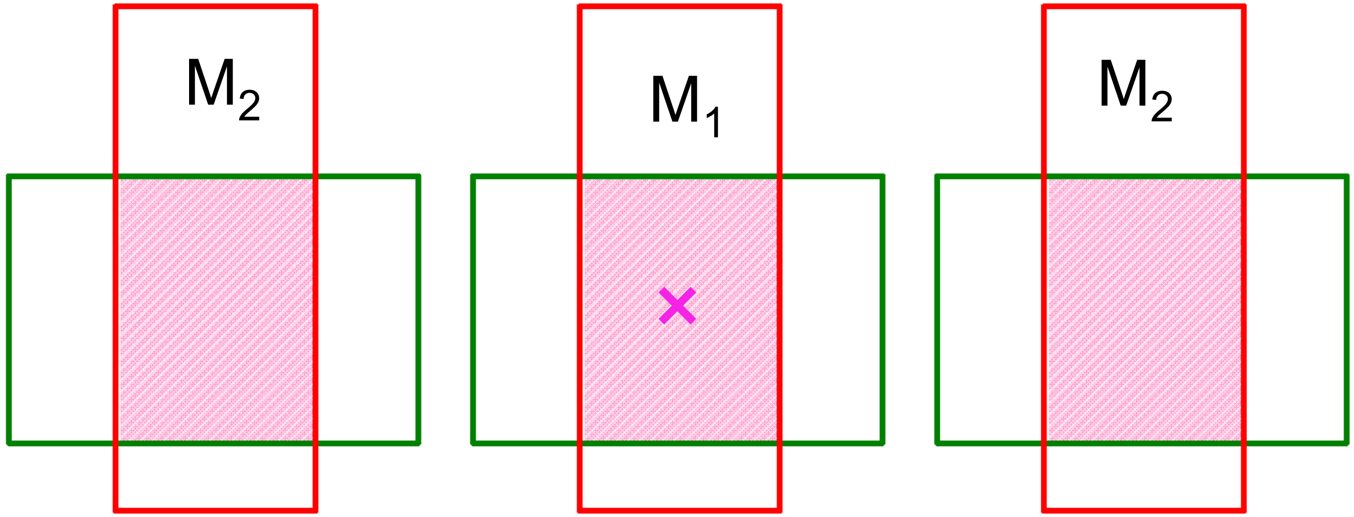
Two Transistors each with two parts:



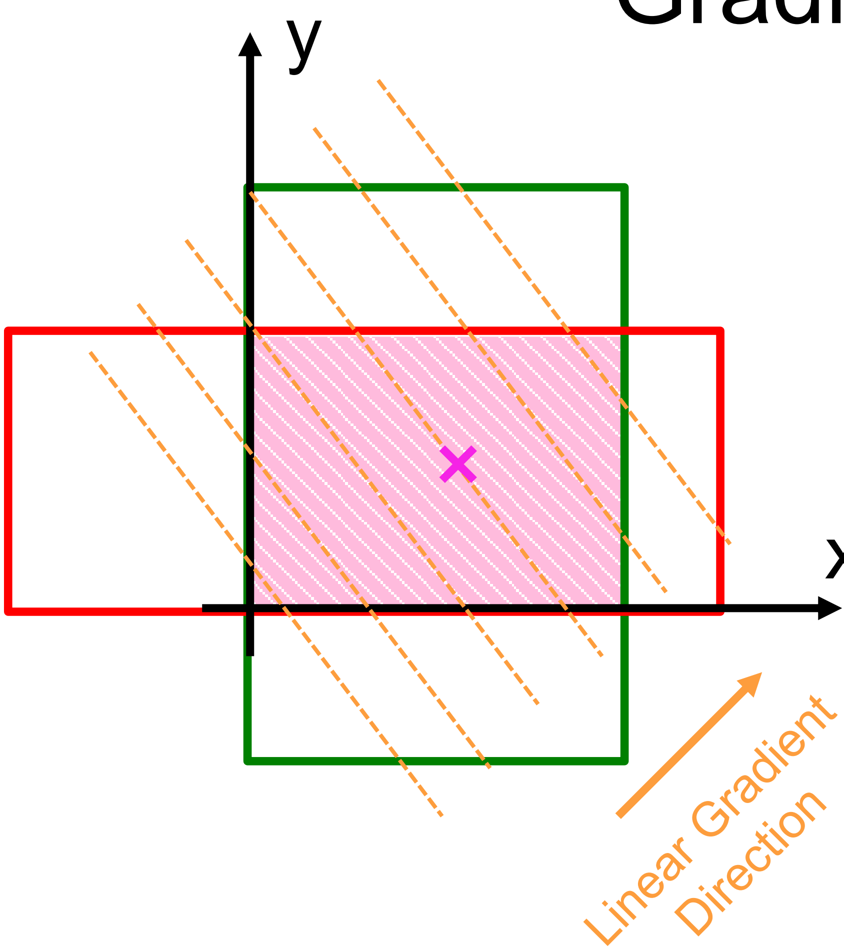
Centroid and Common Centroid

Common Centroid for Ratioed Devices $M = \frac{W_2}{W_1}\frac{L_1}{L_2} = 2$

Two Transistors with different effective widths:



Gradient



Threshold voltage dependent upon position

$V_{TH}(x,y)$

– Significant changes in threshold voltage can occur due to gradient effects

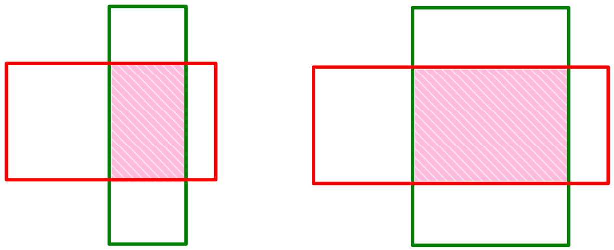
– This can seriously degrade matching in matching-critical circuits

- If the threshold voltage of a transistor changes with position, it can be reasonably accurately modeled with an “equivalent” threshold voltage
- For linear gradient, $V_{THEQ}=V_{TH}(X_C,Y_C)$

× : (X_C,Y_C)

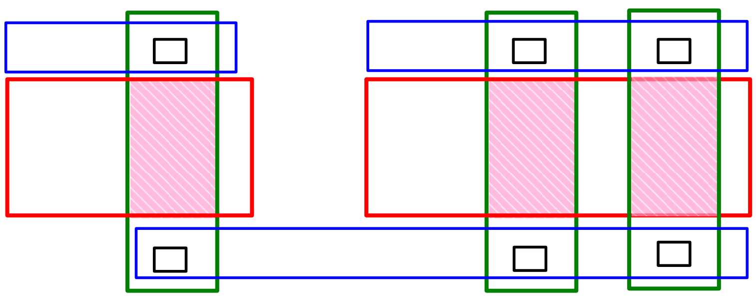
Layout of Current Mirrors

Example with M = 2



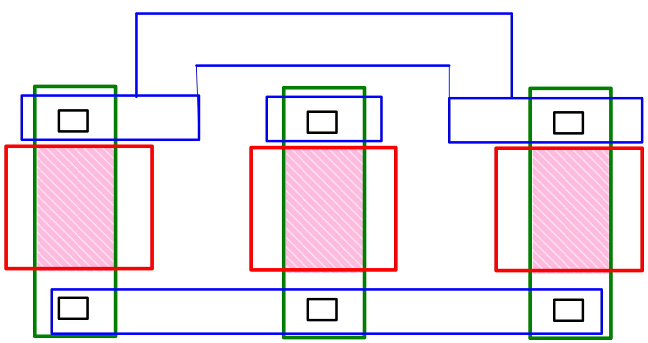
Standard layout

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



Better Layout

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

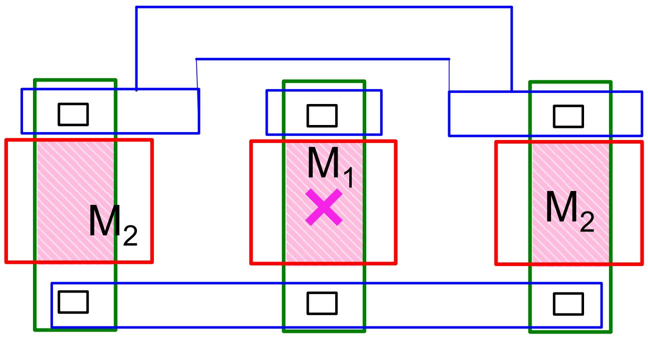


Even Better Layout

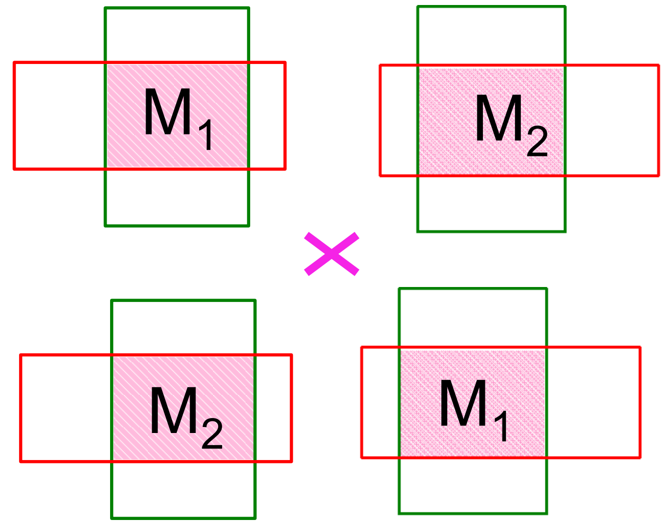
$$M = \left[\frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} \bullet \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \right] = 2$$

- **This is termed a common-centroid layout**
- **Linear gradient mismatch eliminated with common-centroid layout !**

Common-Centroid Layouts



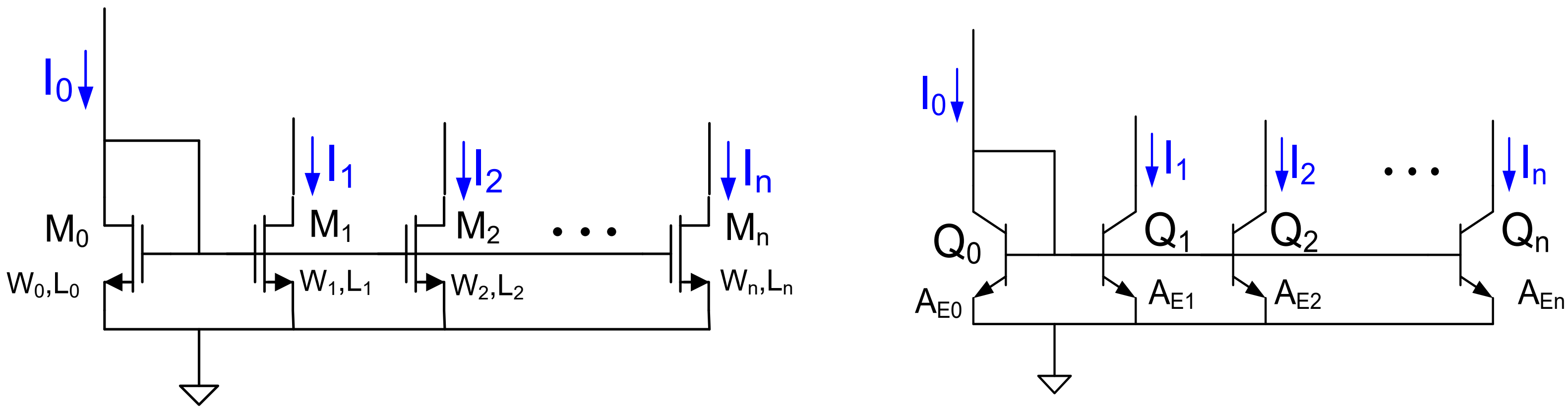
$$M=\left[\frac{2W_1}{W_1}\bullet\frac{L_1}{L_1}\right]=2$$



$$M=\left[\frac{2W_1}{2W_1}\bullet\frac{L_1}{L_1}\right]=1$$

- Individual transistors often decomposed into parallel multiple unary devices connected in parallel
- Common-Centroid layout approach widely used to minimize (ideally cancel) gradient effects in matching-critical circuits
- Applications extend well beyond current mirrors
- More than 2 devices can share a common centroid

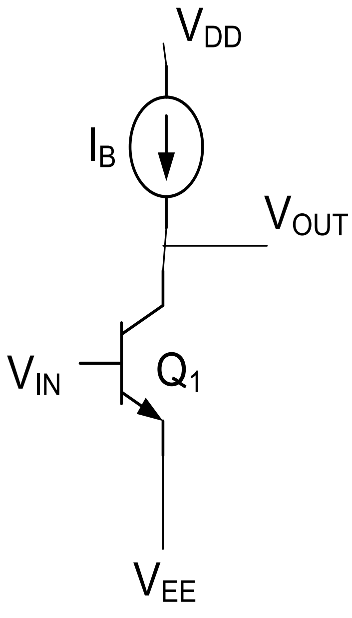
Current Sources/Mirrors



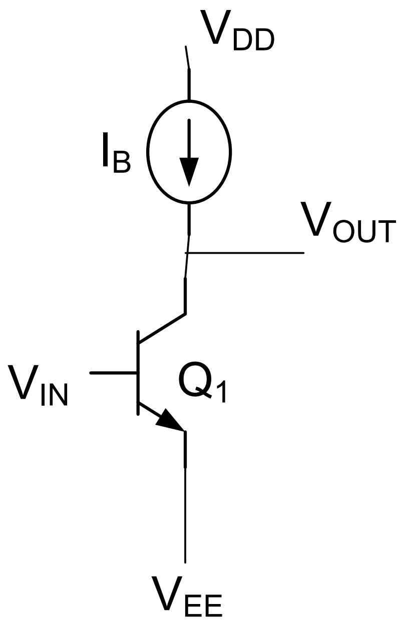
If I_0 is practically generated (it can be), now have available a large number of accurate current sources or sinks that can be used for biasing and for other purposes on chip !

High-gain amplifier

Will now return to discussion of high gain amplifiers



High-gain amplifier



$$A_V \cong -8000$$

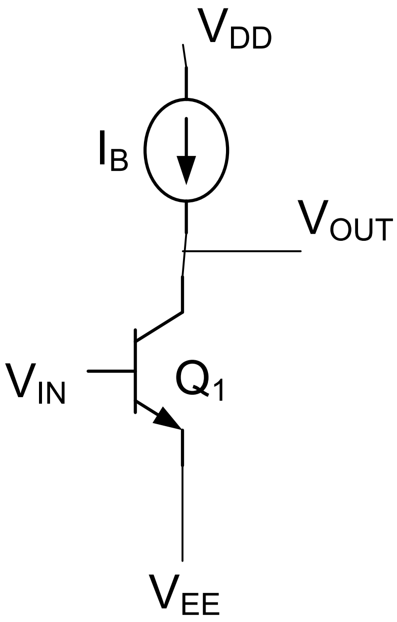
Why are we interested in high-gain amplifiers?

- High gain amplifiers typically have some very undesirable properties

  Nonlinear, gain highly dependent upon process variations and temperature, frequency response poor, noisy, ….

- So we can build feedback amplifiers !!

High-gain amplifier



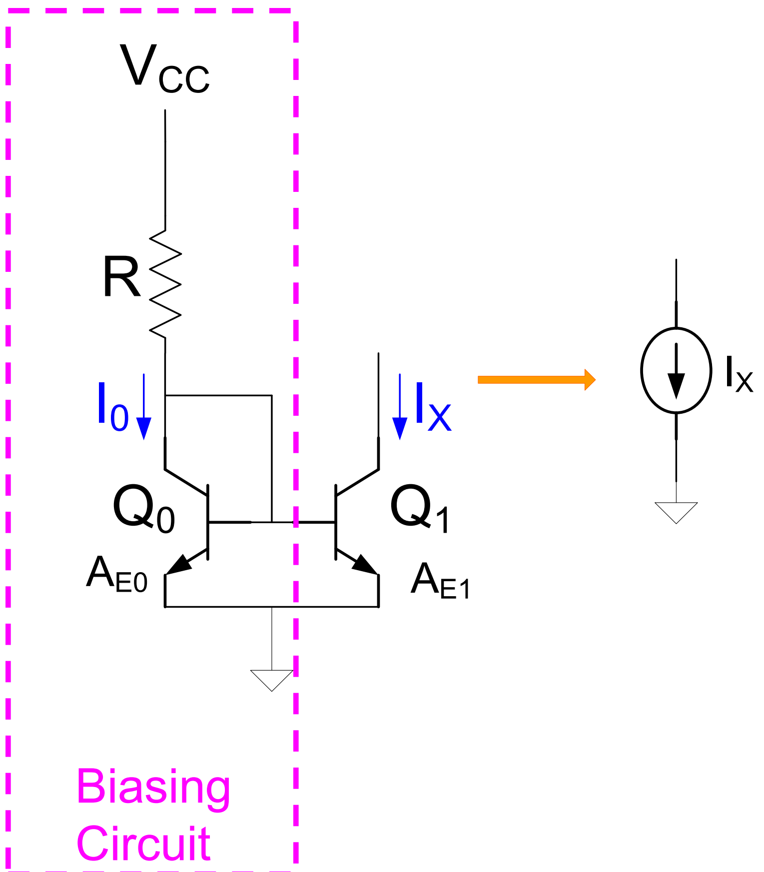
$$A_V \cong -8000$$

How can we build the current source?

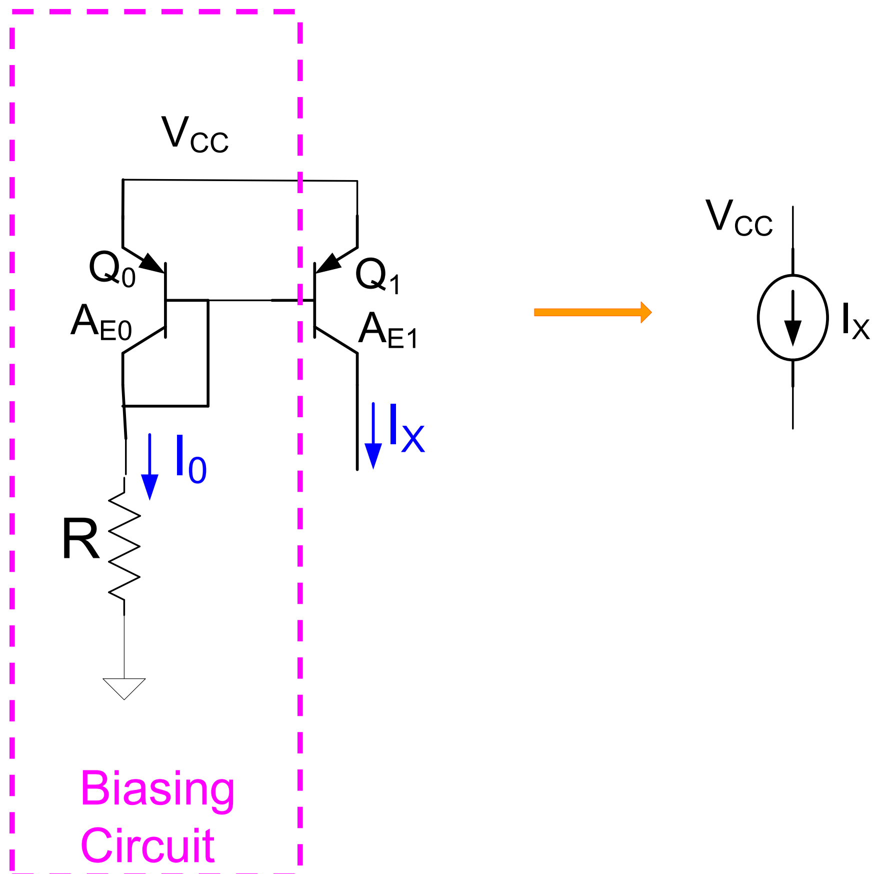
What is the small-signal model of an actual current source?

Basic Current Sources and Sinks

Bipolar Mirror-Based Current Sink

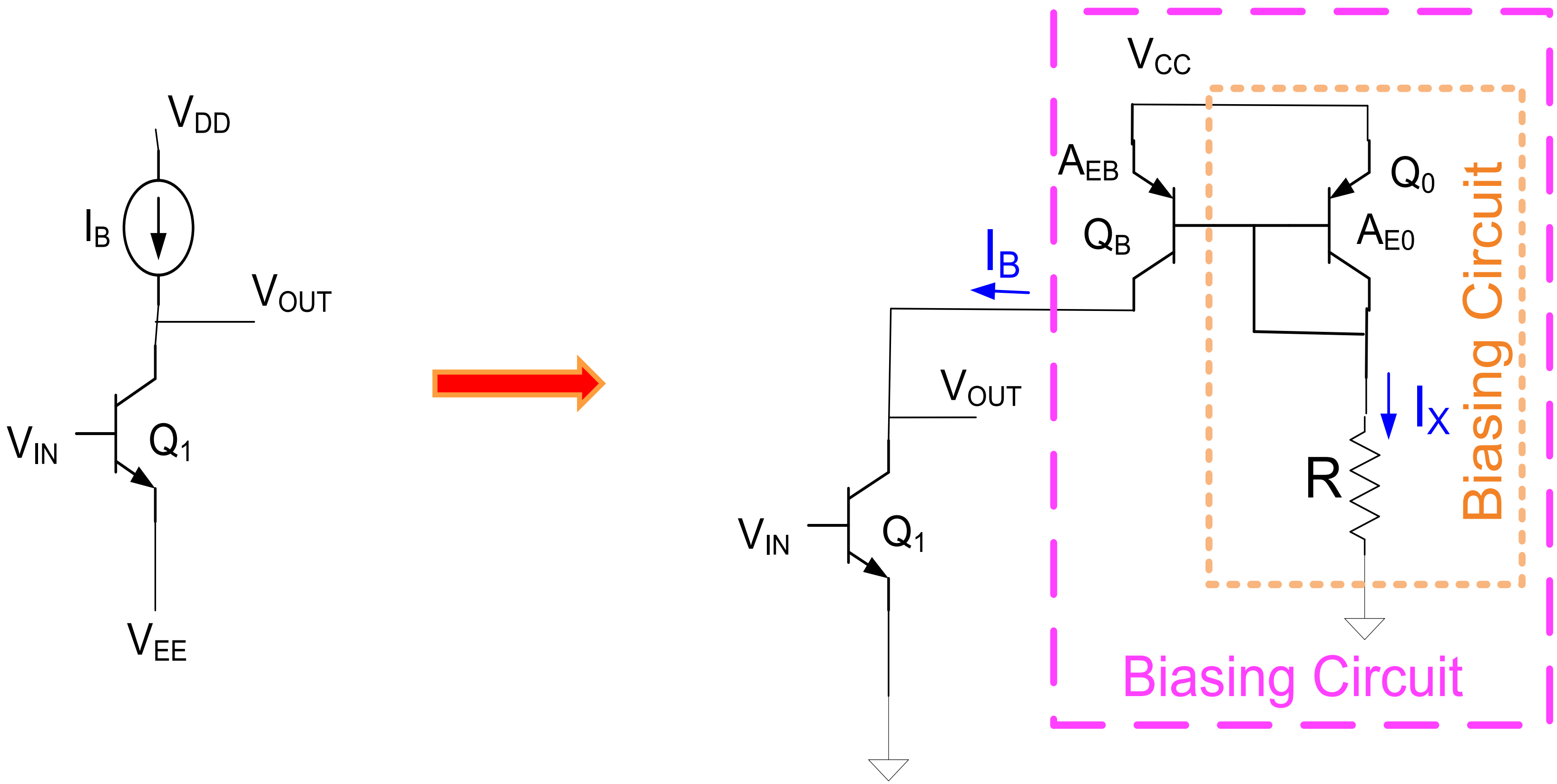


Bipolar Mirror-Based Current Source



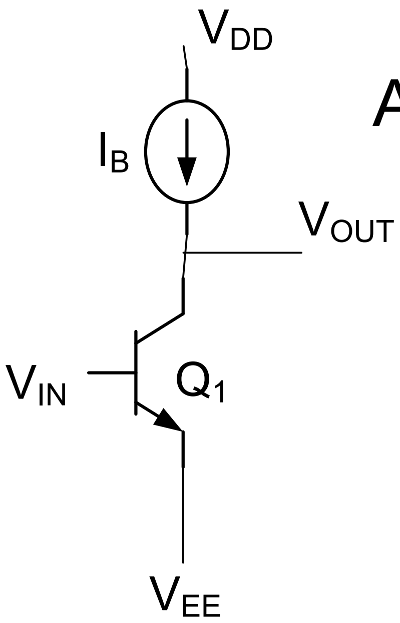
Biasing circuit uses same V_{CC} as amplifier and no other independent sources

High-gain amplifier

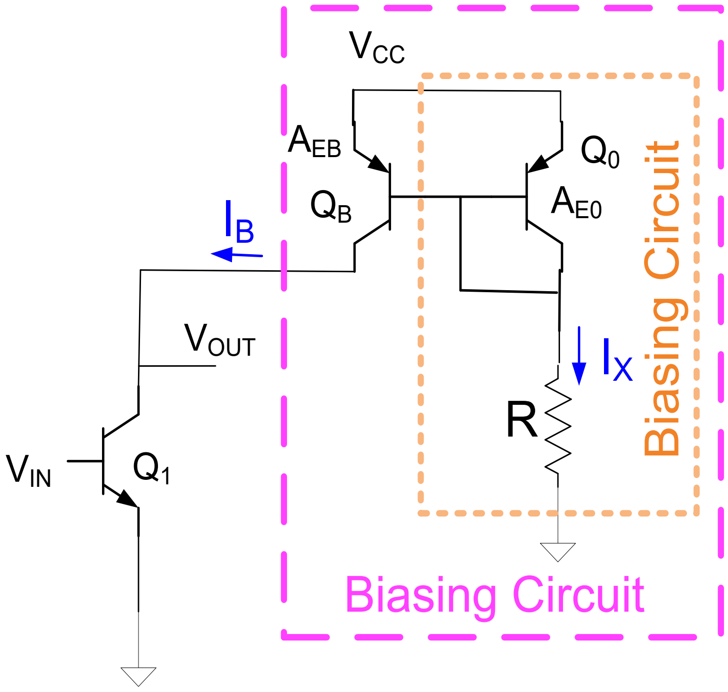


- Bias circuitry requires only a single independent dc voltage source, resistor, and BJT !
- <u>Incremental</u> overhead is only one transistor, Q_B

High-gain amplifier



$A_V \cong -8000$



How can we build the current source?

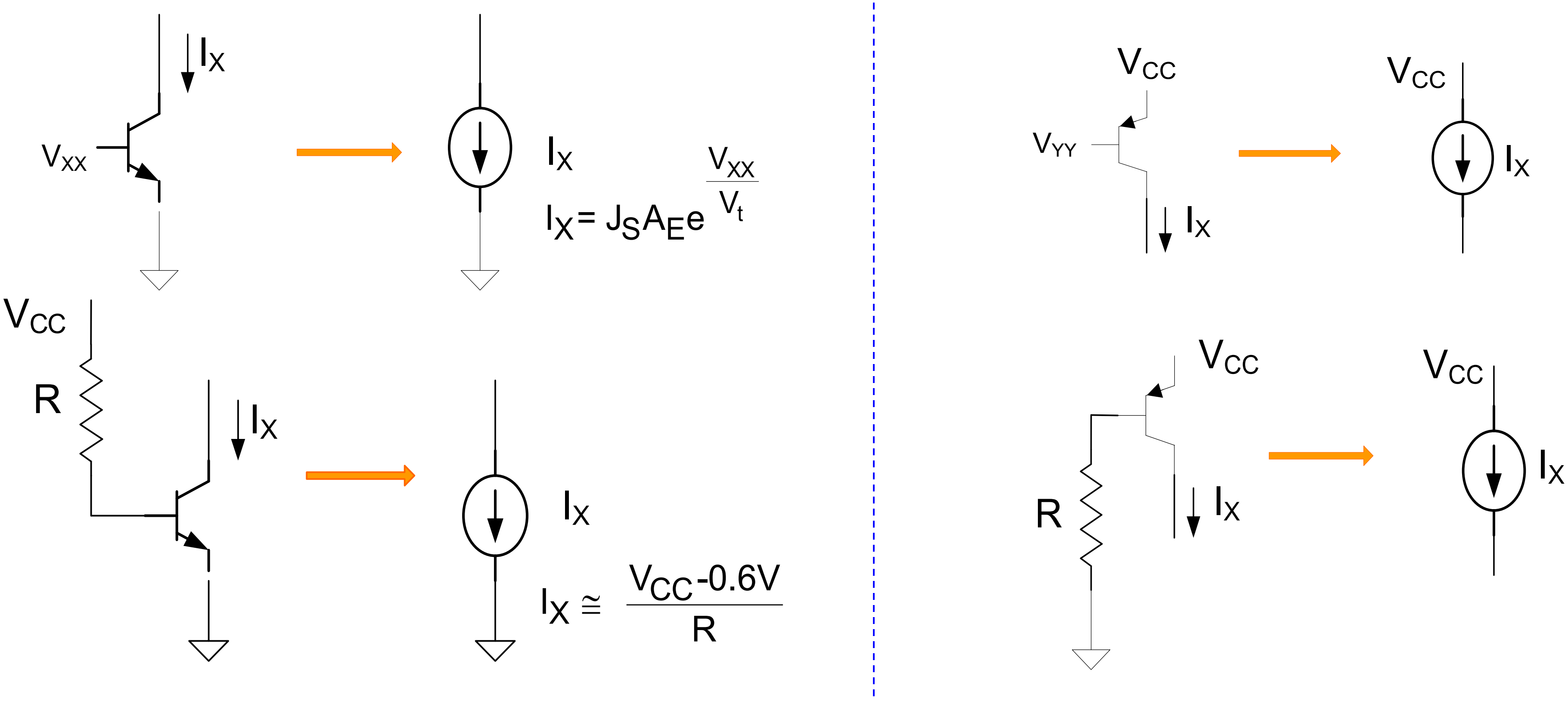
→ What is the small-signal model of an actual current source?

Basic Current Sources and Sinks

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

Basic Bipolar Current Sinks

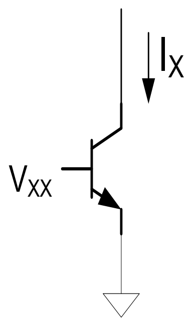
Basic Bipolar Current Sources

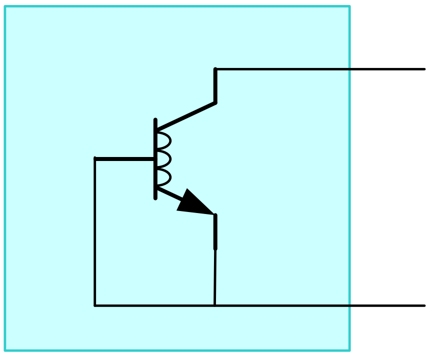


- Very practical methods for biasing the BJTs (or MOSFETs) can be used
- Current Mirrors often used for generating sourcing and sinking currents
- Can think of biasing transistors with V_{XX} and V_{YY} in these current sources

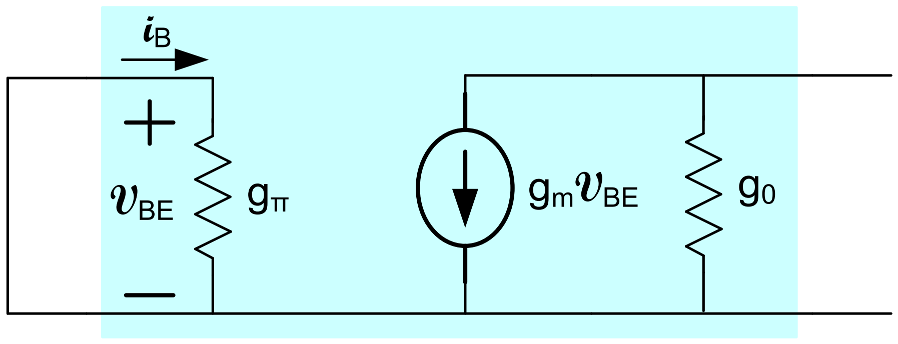
Basic Current Sources and Sinks

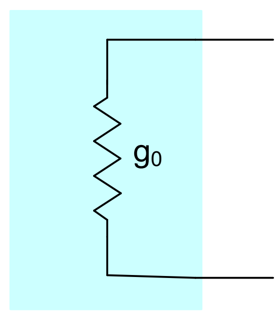
Small-signal Model of BJT Current Sinks and Sources





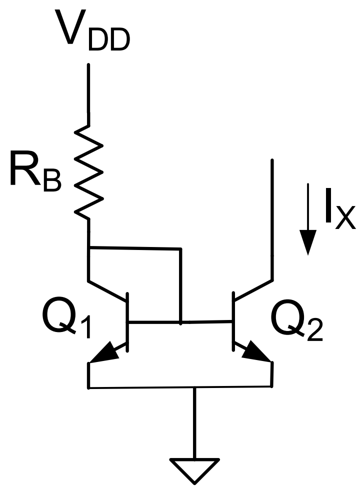
Small-signal BE-Connected
(Not Diode Connected !)

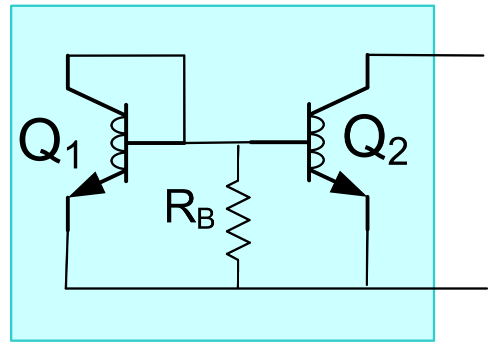




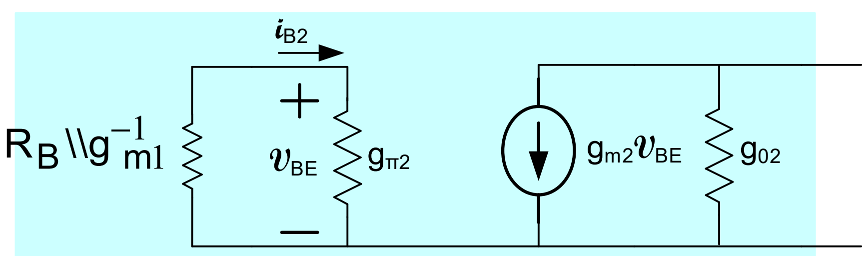
Basic Current Sources and Sinks

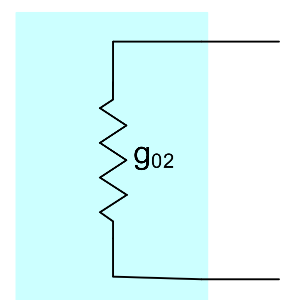
Small-signal Model of BJT Current Sinks and Sources





Small-signal of Q_1
Diode connected

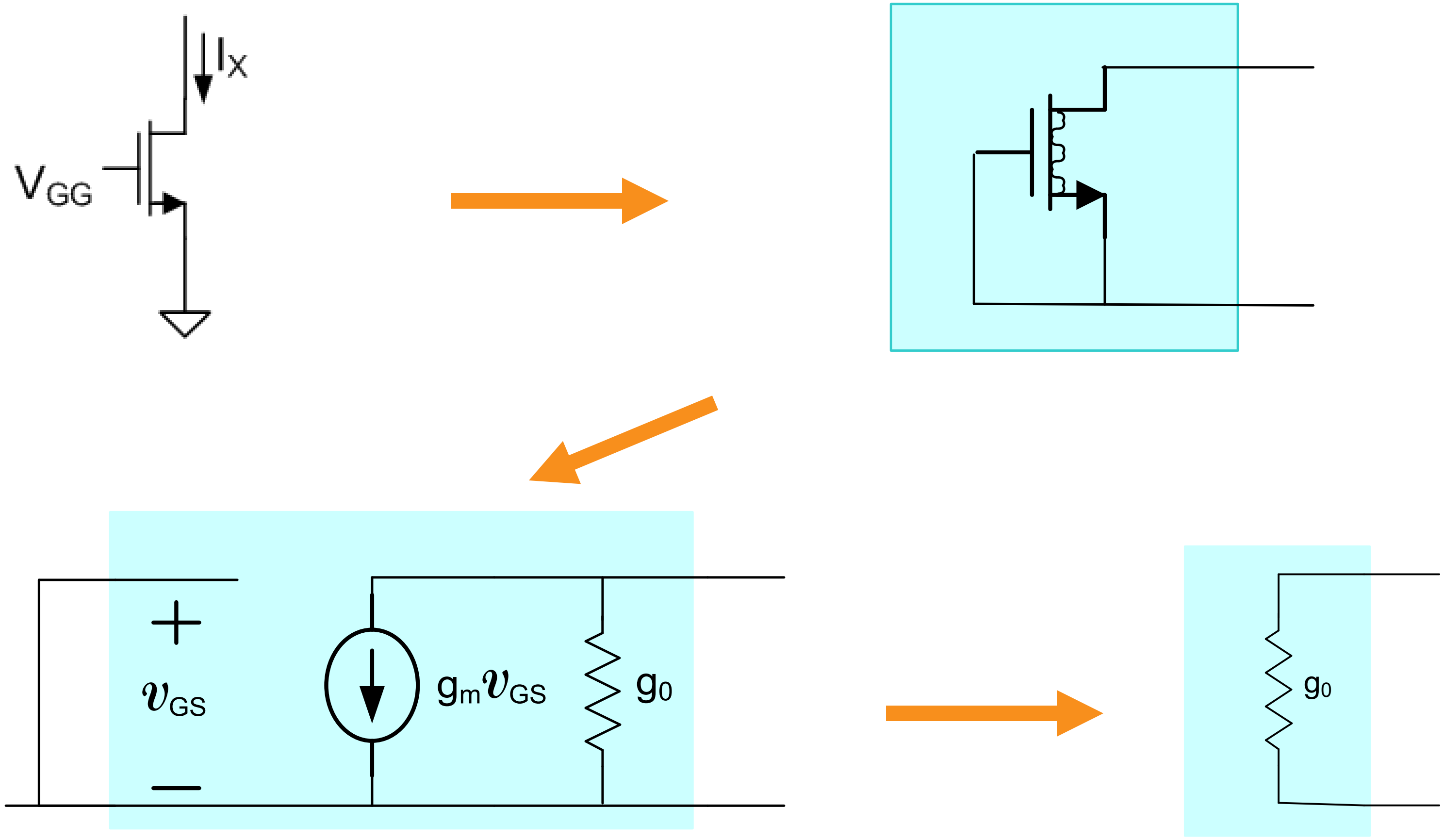




Small-signal model of all other BJT Sinks and Sources introduced so far are the same

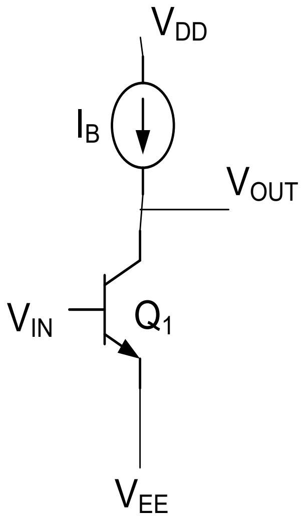
Basic Current Sources and Sinks

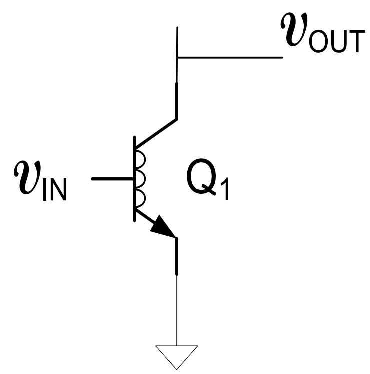
Small-signal Model of MOS Current Sinks and Sources



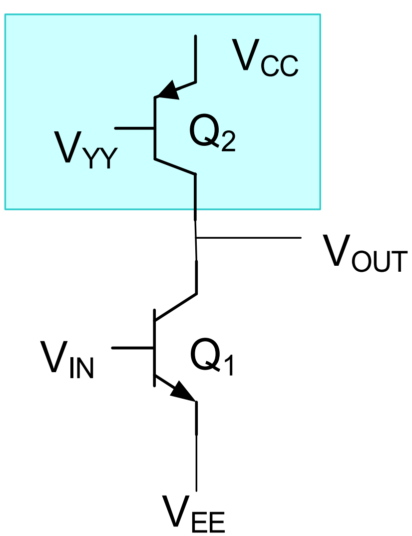
Small-signal model of all other MOS Sinks and Sources introduced thus far are the same

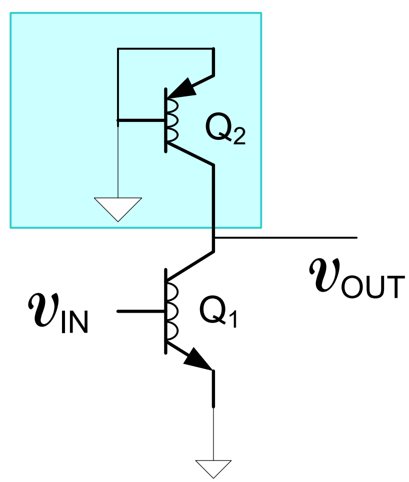
High-gain amplifier

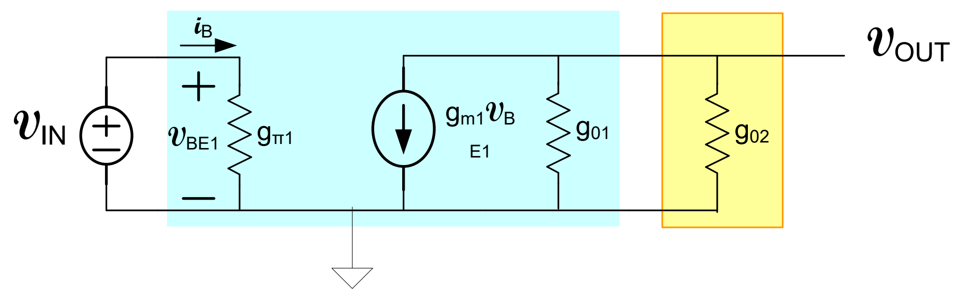




$$A_V = \frac{-g_m}{g_0}$$

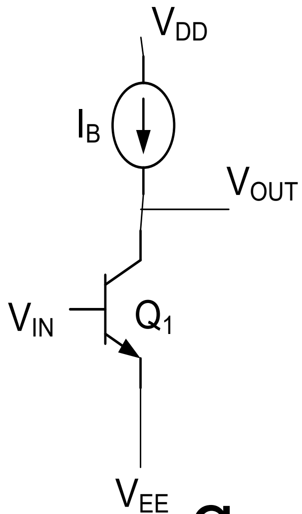




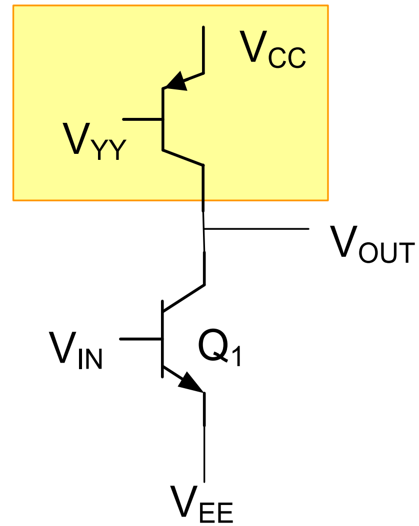


$$A_V = \frac{-g_{m1}}{g_{01} + g_{02}} \cong \frac{-g_{m1}}{2g_{01}}$$

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)**

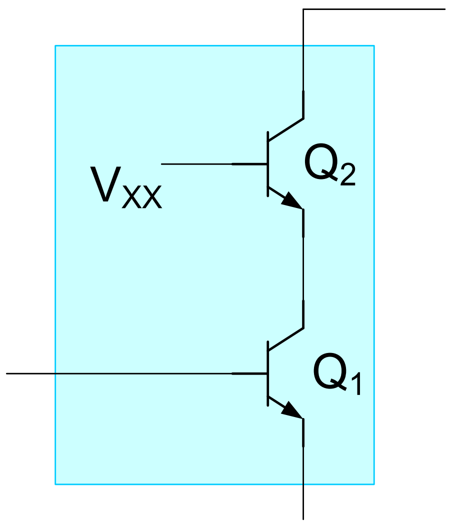
Can the gain be made even larger?

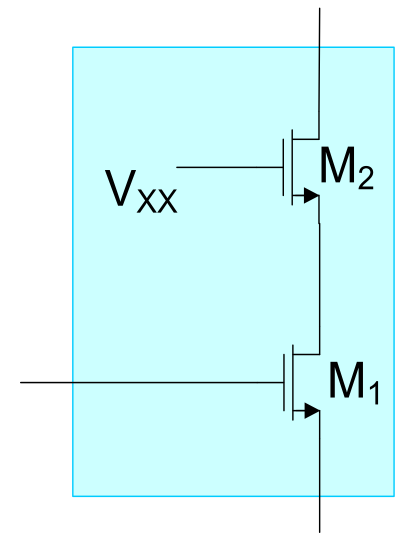
High-gain amplifier

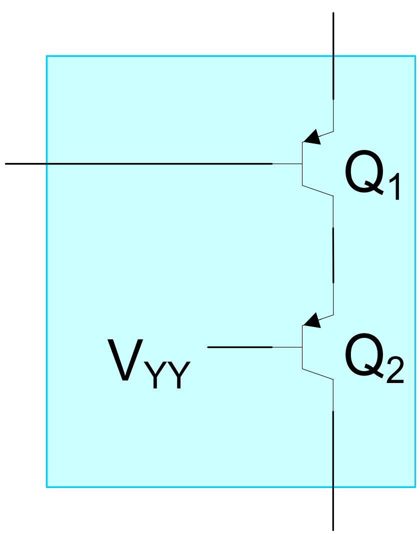
Discuss

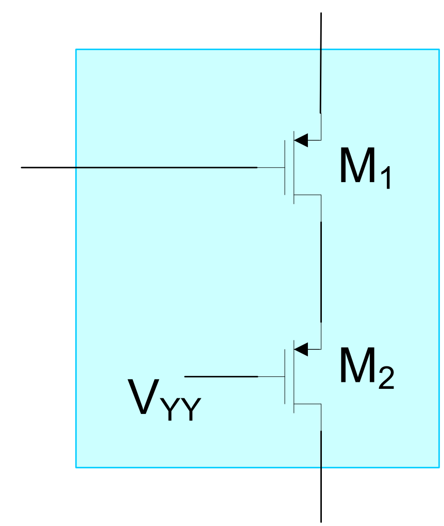
Can the gain be made even larger?

The Cascode Configuration



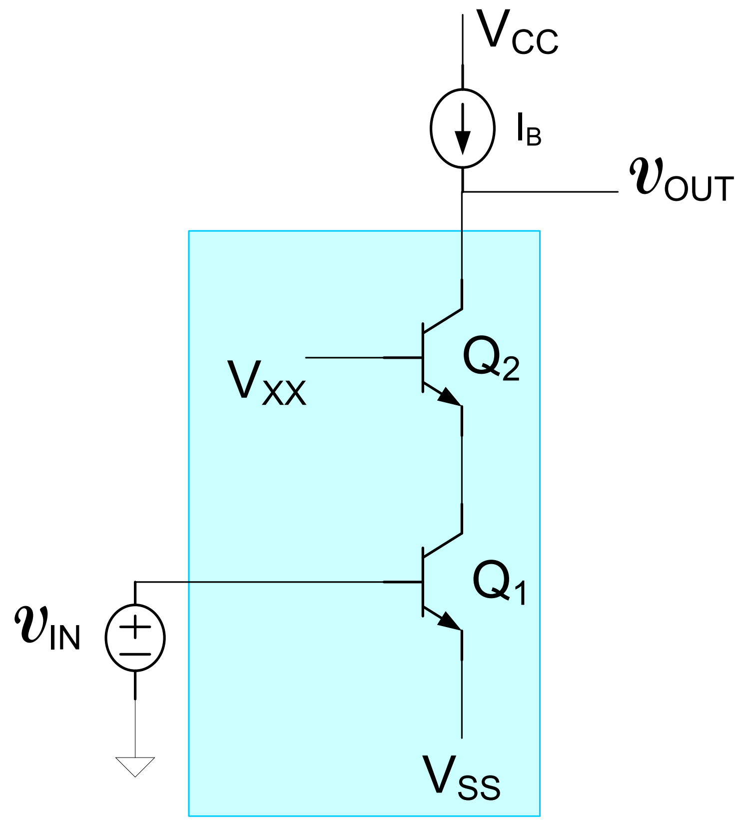






The Cascode Amplifier (consider npn BJT version)

Discuss



- **Actually a cascade of a CE stage followed by a CB stage but usually viewed as a "single-stage" structure**
- **Cascode structure is widely used**

Basic Amplifier Structures

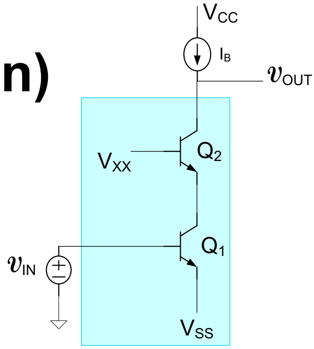
Discuss

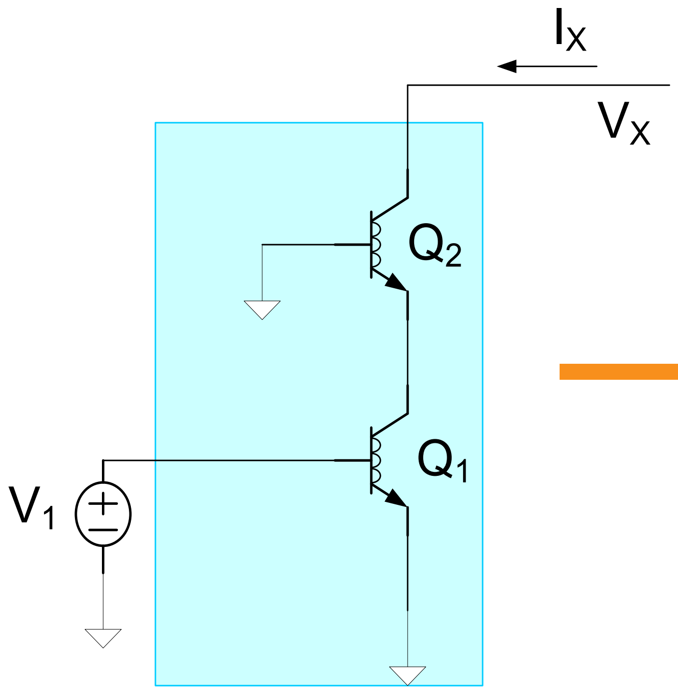
1. Common Emitter/Common Source
2. Common Collector/Common Drain
3. Common Base/Common Gate
4. Common Emitter with R_E/ Common Source with R_S

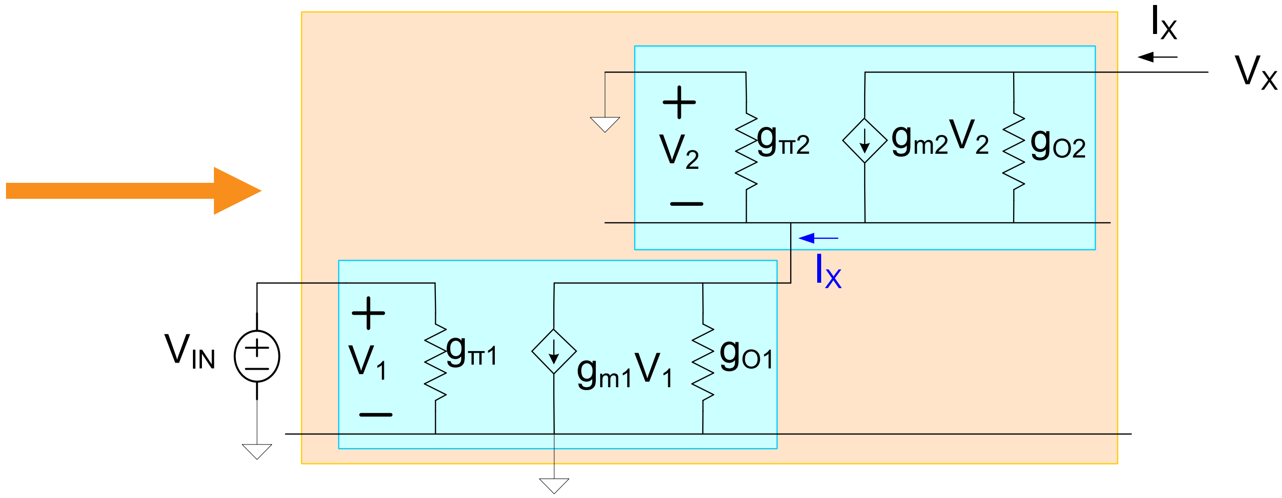
5. Cascode (actually CE:CB or CS:CD cascade)
6. Darlington (special CE:CE or CS:CS cascade)

The first 4 are most popular

The Cascode Amplifier (consider npn BJT version)

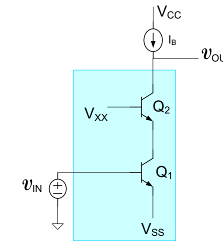


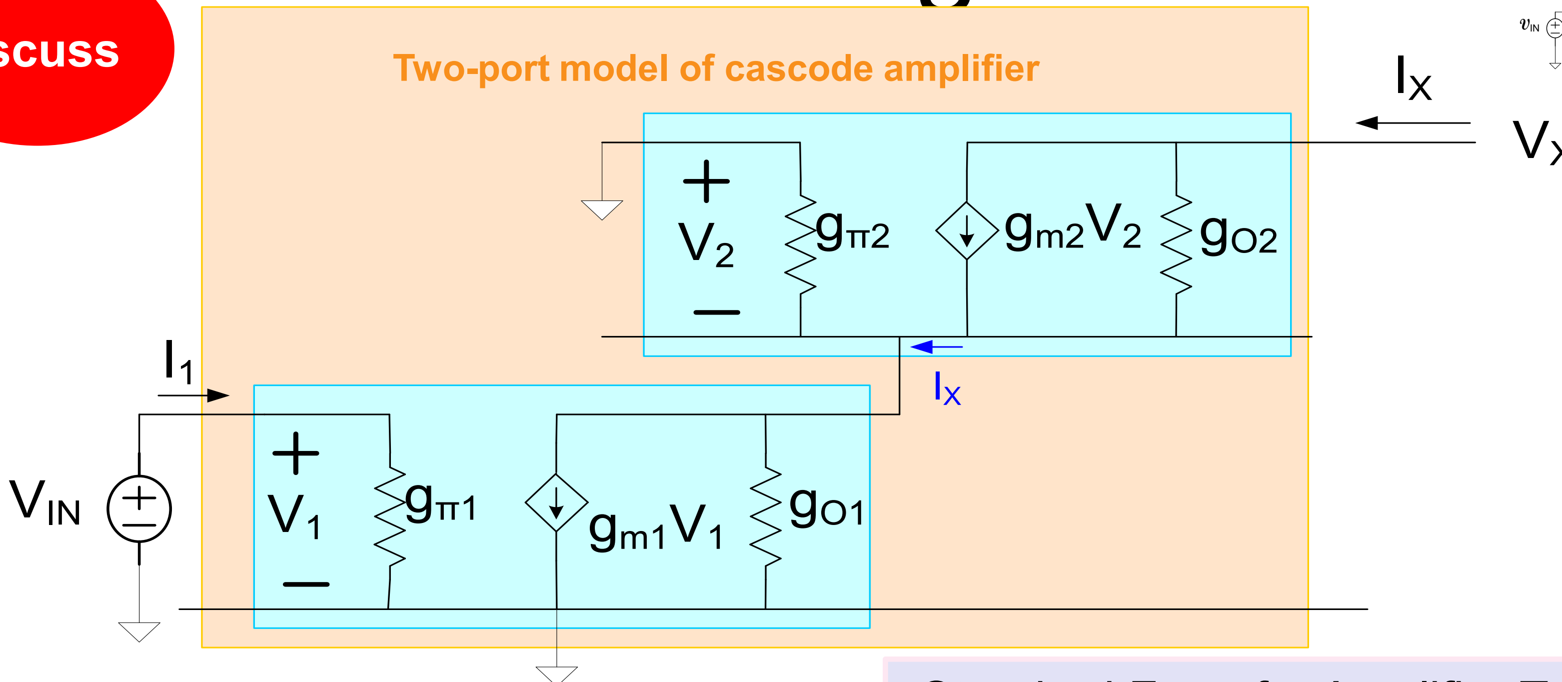




Cascode Configuration

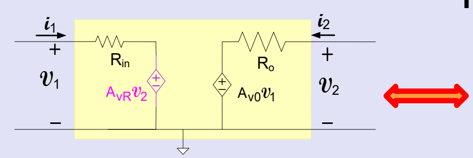
Discuss





$$\left.\begin{aligned}(V_X+V_2)g_{02}+V_2g_{m2}&=I_X\\ V_1\,g_{m1}-V_2(g_{01}+g_{\pi 2})&=I_X\end{aligned}\right\}$$

Standard Form for Amplifier Two-Port



$$v_1 = i_1R_{IN} + A_{VR}v_2$$
$$v_2 = i_2R_O + A_{V0}v_1$$

Observing V_1=V_{IN} and eliminating V_2 between these two equations, we obtain

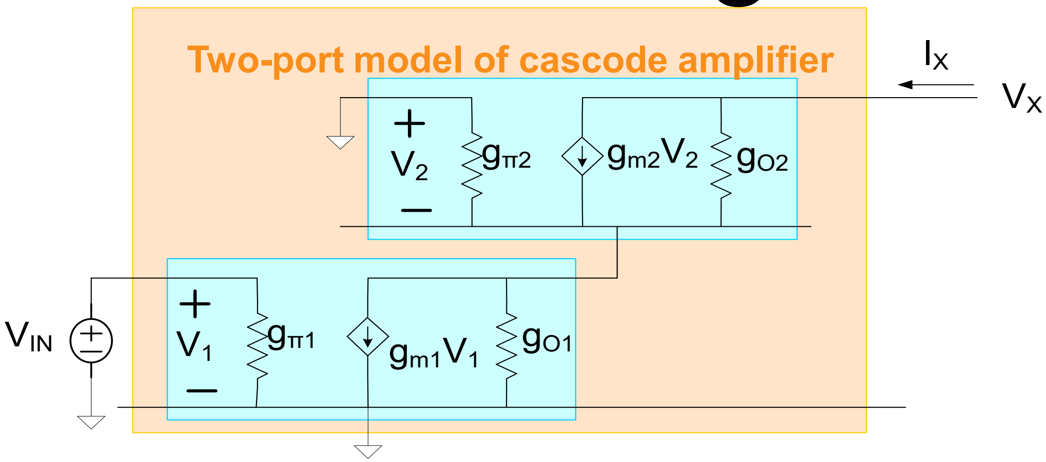
$$V_{IN}=I_1 \bullet \frac{1}{g_{\pi 1}}$$

and

$$V_X=I_X \bullet \left[\frac{g_{01}+g_{02}+g_{\pi 2}+g_{m2}}{g_{02}(g_{01}+g_{\pi 2})}\right]-V_{IN} \bullet \left[\frac{g_{m1}(g_{02}+g_{m2})}{g_{02}(g_{\pi 2}+g_{01})}\right]$$

Cascode Configuration

Discuss



$$V_X = I_X \bullet \left[\frac{g_{01}+g_{02}+g_{\pi 2}+g_{m2}}{g_{02}(g_{01}+g_{\pi 2})}\right] - V_{IN} \bullet \left[\frac{g_{m1}(g_{02}+g_{m2})}{g_{02}(g_{\pi 2}+g_{01})}\right]$$

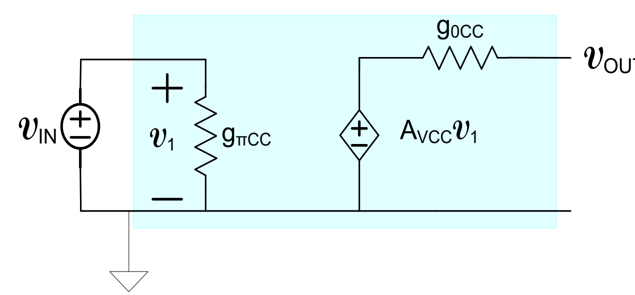
$$V_{IN} = I_1 \bullet \frac{1}{g_{\pi 1}}$$

It thus follows for the npn bipolar structure that :

$$A_{VCC} = -\left[\frac{g_{m1}(g_{02}+g_{m2})}{g_{02}(g_{\pi 2}+g_{01})}\right] \cong -\left[\frac{g_{m1}g_{m2}}{g_{02}g_{\pi 2}}\right]$$

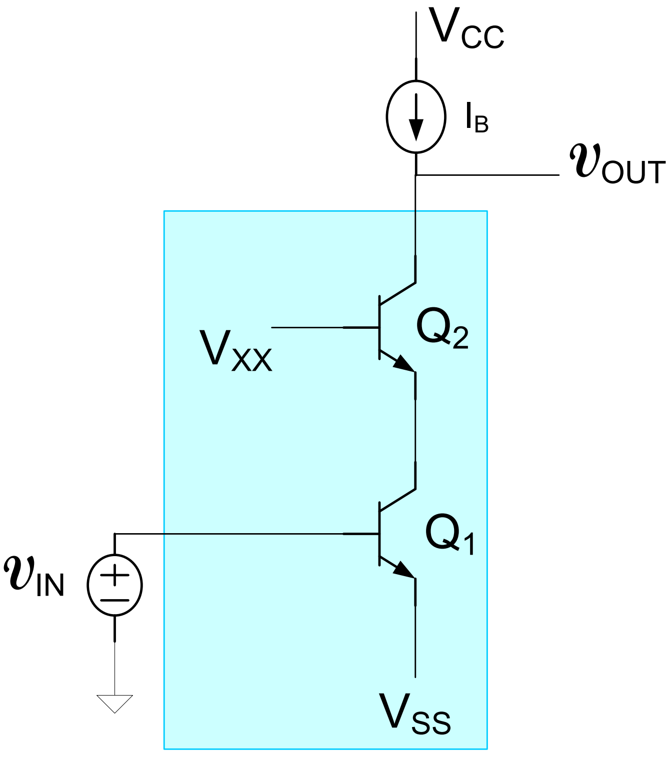
$$g_{0CC} = \left[\frac{g_{02}(g_{01}+g_{\pi 2})}{g_{01}+g_{02}+g_{\pi 2}+g_{m2}}\right] \cong \left[\frac{g_{02}g_{\pi 2}}{g_{m2}}\right]$$

$$g_{\pi CC} = g_{\pi 1}$$



Cascode Configuration

Discuss



$$A_{VCC} \cong -\left[\frac{g_{m1}g_{m2}}{g_{02}g_{\pi 2}}\right]$$

$$g_{0CC} \cong \left[\frac{g_{02}g_{\pi 2}}{g_{m2}}\right]$$

$$g_{\pi CC} = g_{\pi 1}$$

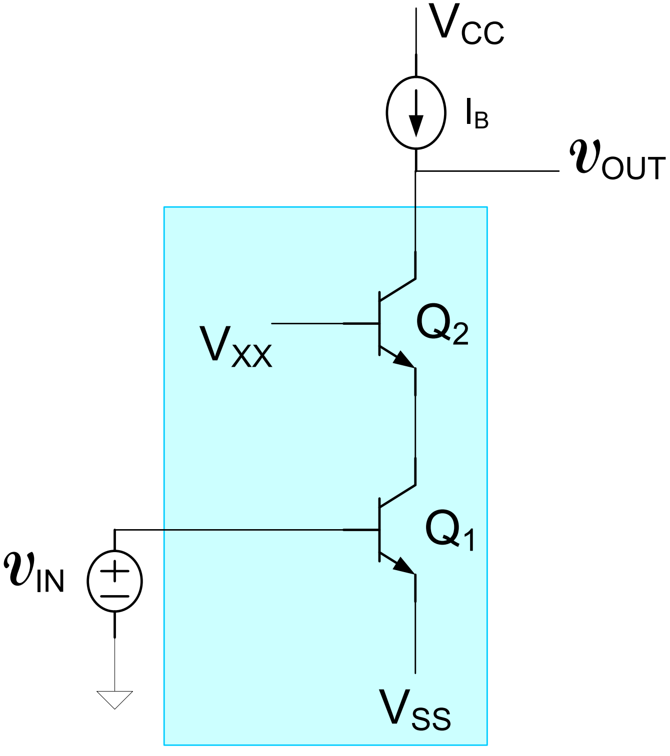
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{02}}\beta\right] \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

$$g_{0CC} \cong \frac{g_{01}}{\beta}$$

- **Voltage gain is a factor of β larger than that of the CE amplifier with current source load**
- **Output impedance is a factor of β larger than that of the CE amplifier**

Cascode Configuration

Discuss



$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{02}}\beta\right] \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

$$g_{0CC} \cong \frac{g_{02}}{\beta}$$

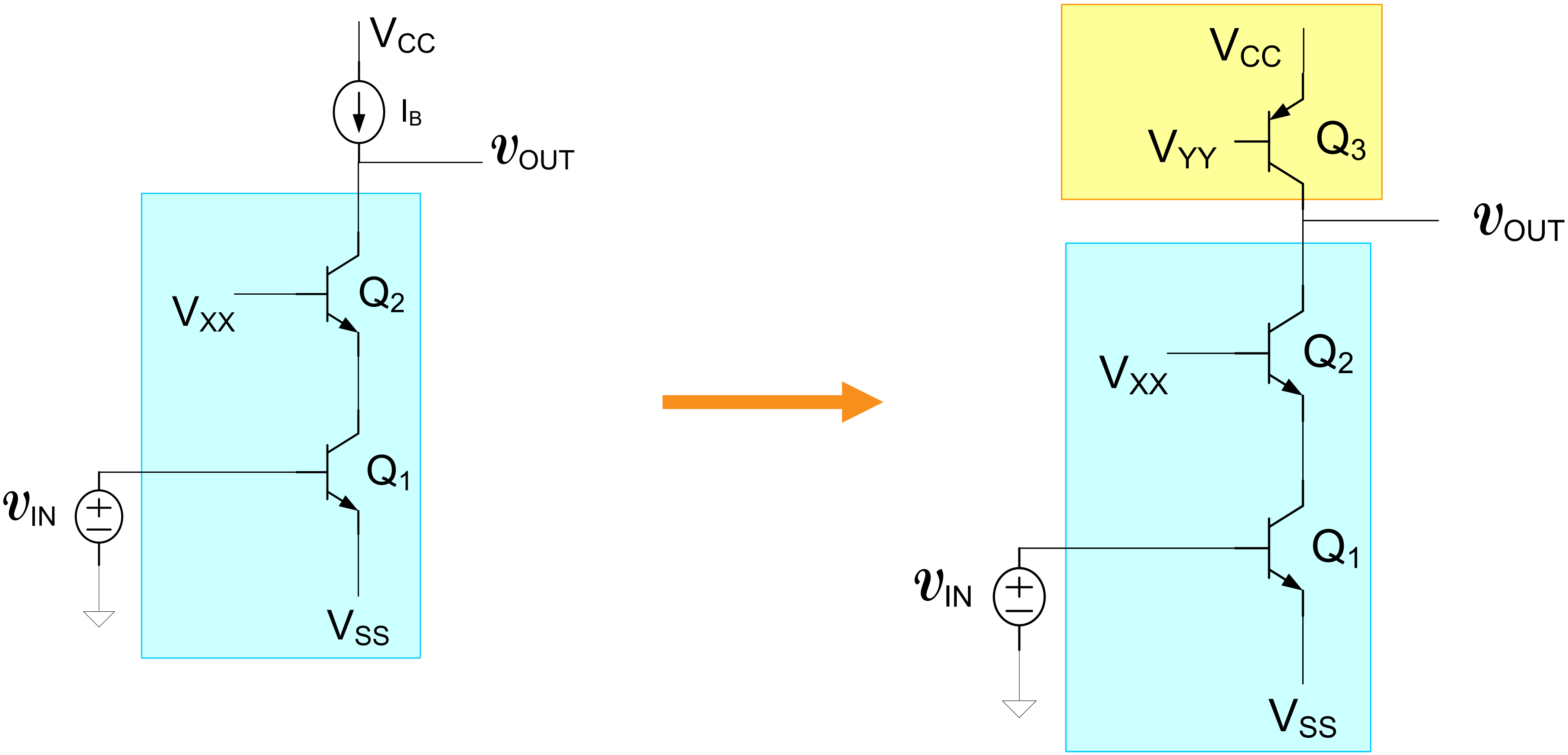
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta = \left[\frac{2V_{AF}}{V_t}\right]\beta = [-8000]100$$

$$A_{VCC} \cong -800{,}000$$

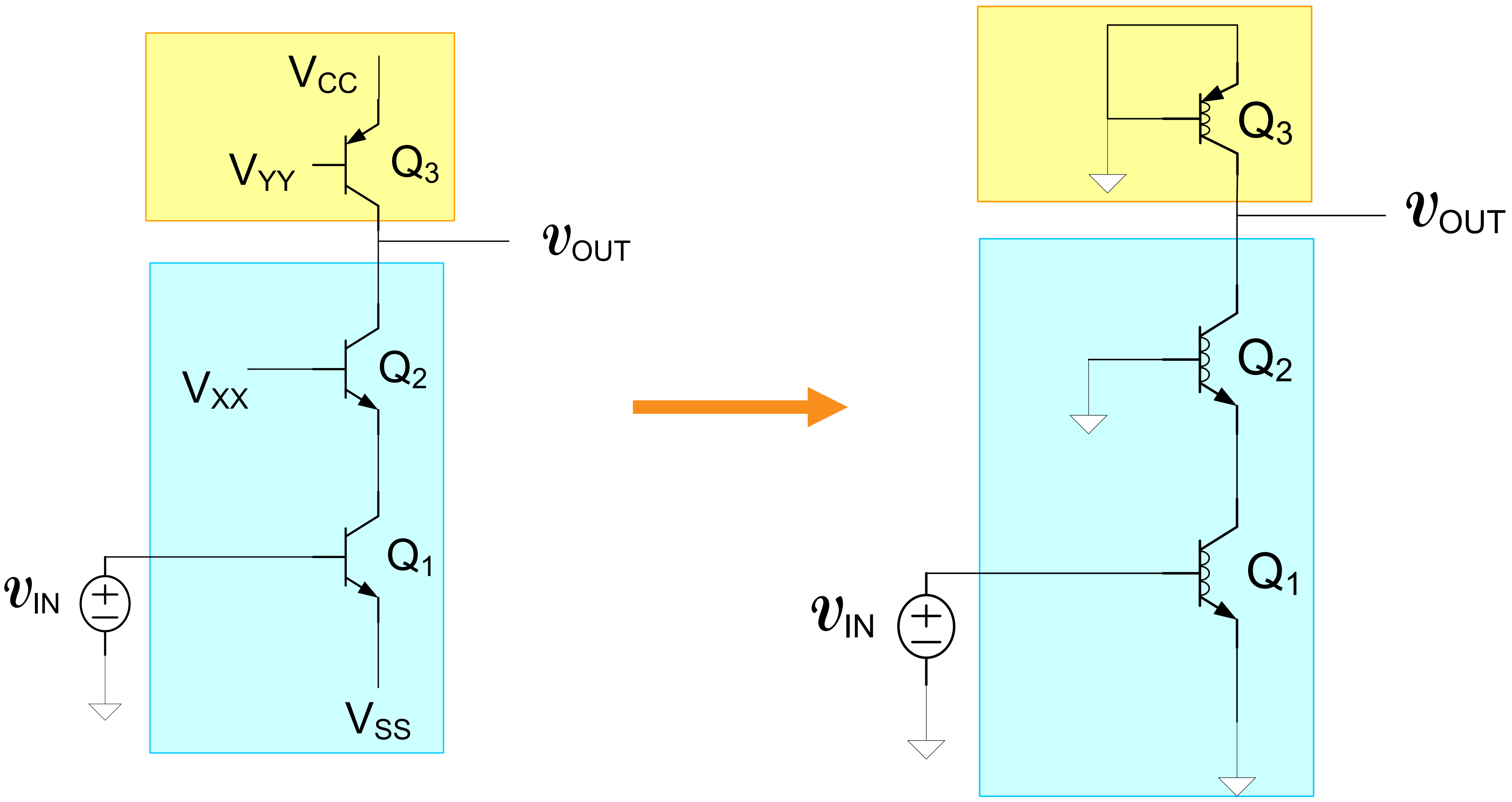
This gain is very large and only requires two transistors!

What happens to the gain if a transistor-level current source is used for I_B?

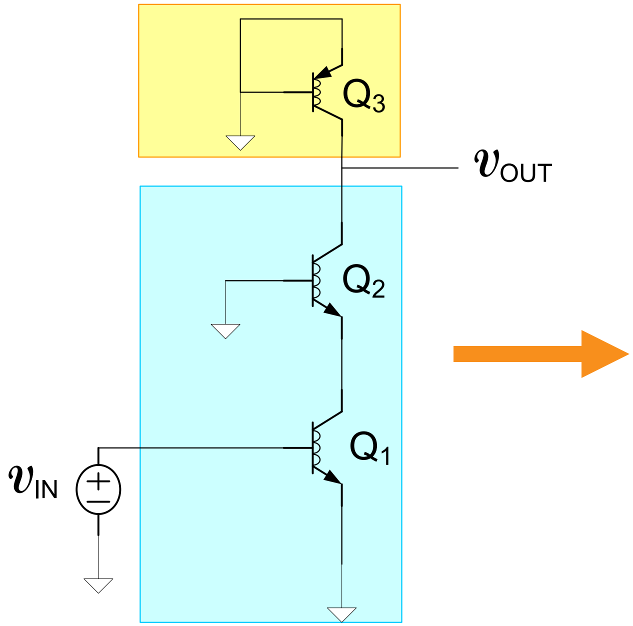
Cascode Configuration

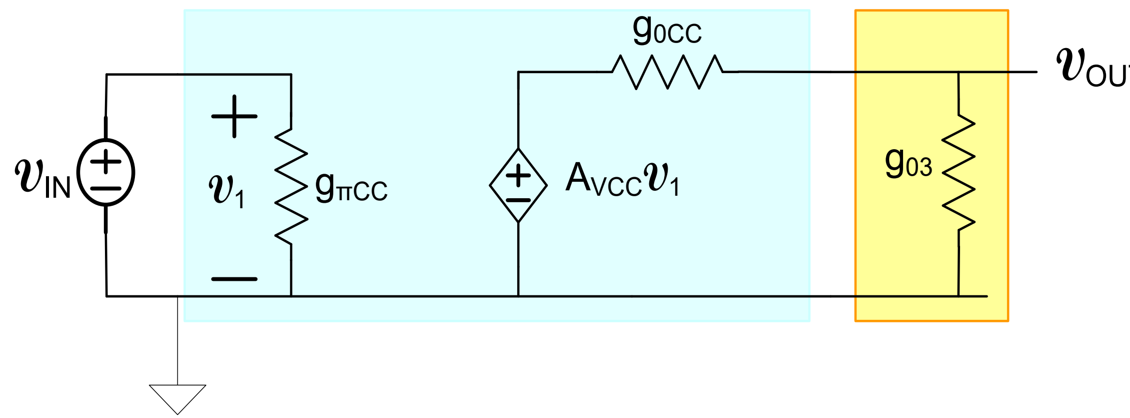


Cascode Configuration



High-gain amplifier comparisons





It thus follows that

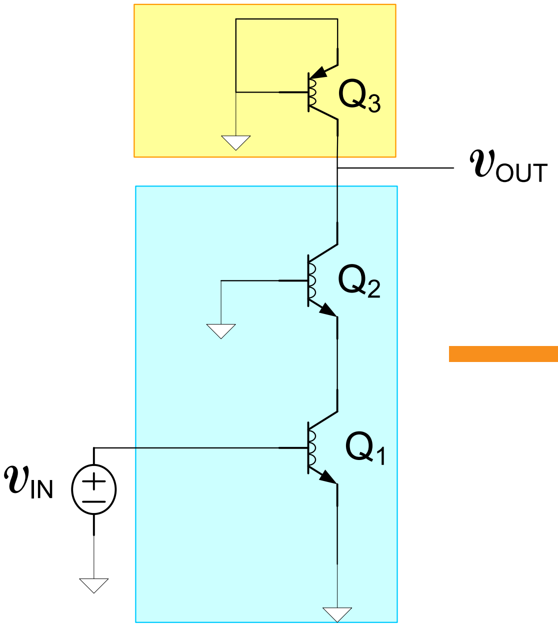
$$A_V = A_{VCC}\left[\frac{g_{0CC}}{g_{03}+g_{0CC}}\right]$$

But $\quad g_{0CC} \simeq g_{01}/\beta = g_{03}/\beta$

$$A_V \cong A_{VCC}\left[\frac{g_{0CC}}{g_{03}}\right] \cong \frac{A_{VCC}}{\beta}$$

This is a dramatic reduction in gain compared to what the ideal current source biasing provided

Cascode Configuration



$$A_V \cong A_{VCC}\left[\frac{g_{0CC}}{g_{03}}\right] \cong \frac{A_{VCC}}{\beta}$$

But recall

$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

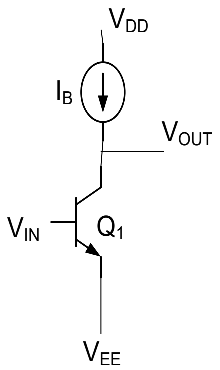
Thus

$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

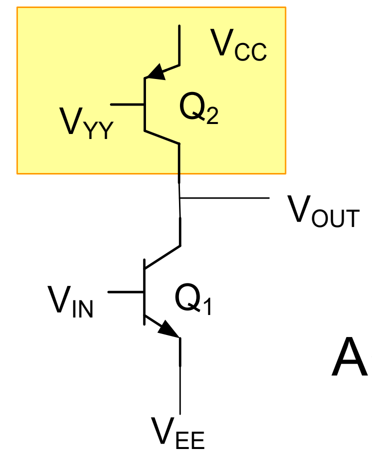
$$A_V \cong -\left[\frac{I_{CQ}/V_t}{I_{CQ}/V_{AF}}\right] = -\left[\frac{V_{AF}}{V_t}\right] \cong -8000$$

- **This is still a factor of 2 better than that of the CE amplifier with transistor current source** $\left(A_{VCE} \cong -\left[\frac{g_{m1}}{2g_{01}}\right]\right)$
- **It only requires one additional transistor**
- **But its not nearly as good as the gain the cascode circuit seemed to provide**

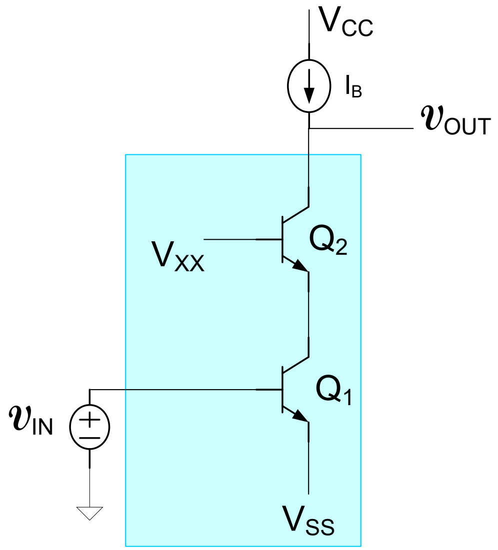
Cascode Configuration Comparisons



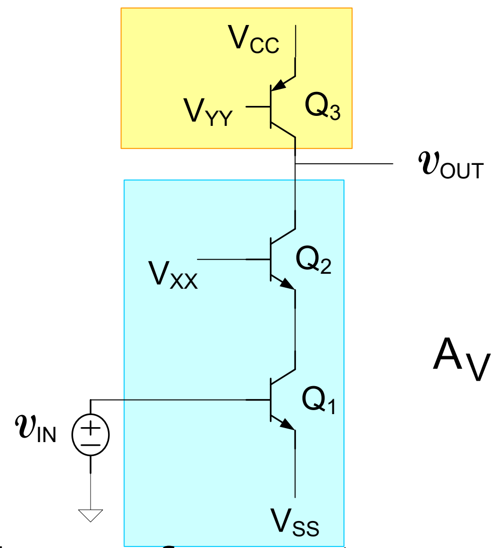
$$A_V = \frac{-g_m}{g_0}$$



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



$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$



$$A_V \cong -\left[\frac{g_{m1}}{\frac{g_{01}}{\beta}+g_{03}}\right] \cong -\left[\frac{g_{m1}}{g_{03}}\right]$$

Gain limited by output impedance of current scource !!

Can we design a better current source?

In particular, one with a higher output impedance?

Better current sources

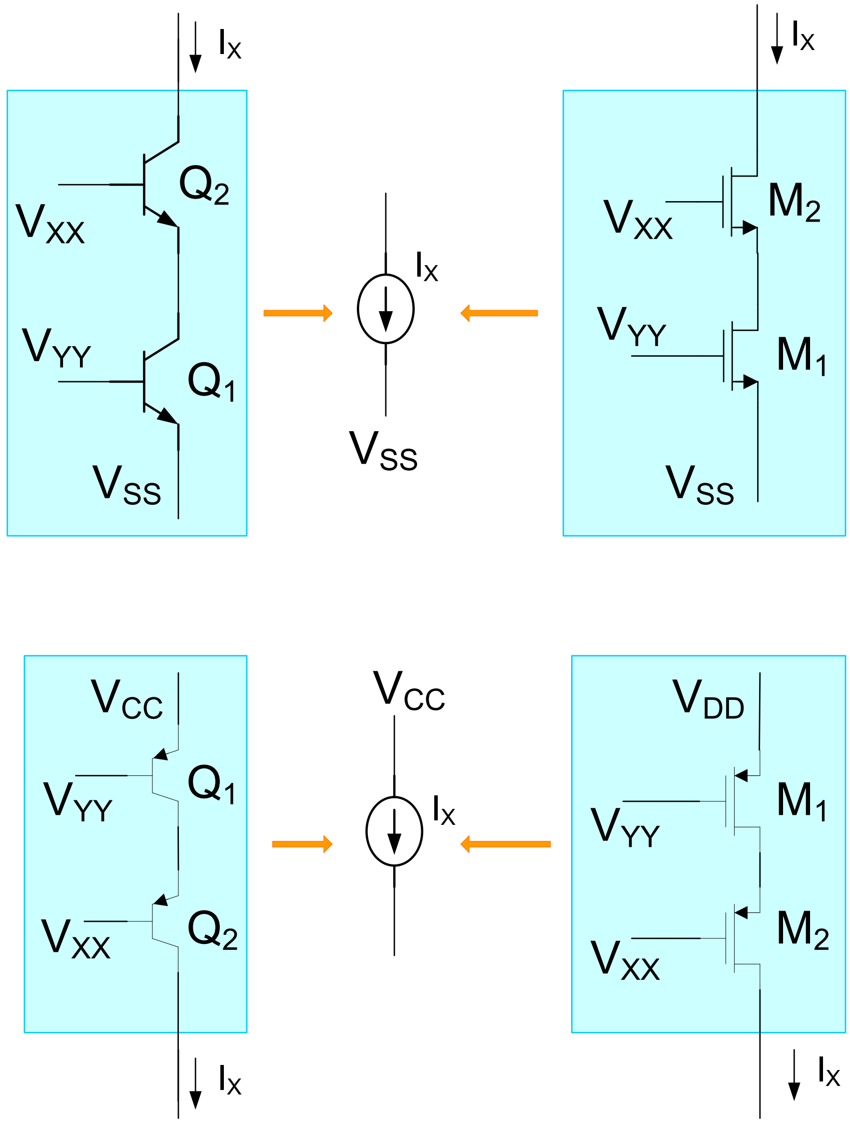
Need a higher output impedance than g_o

The output impedance of the cascode circuit itself was very large !

$$g_{0CC} \cong \frac{g_{01}}{\beta}$$

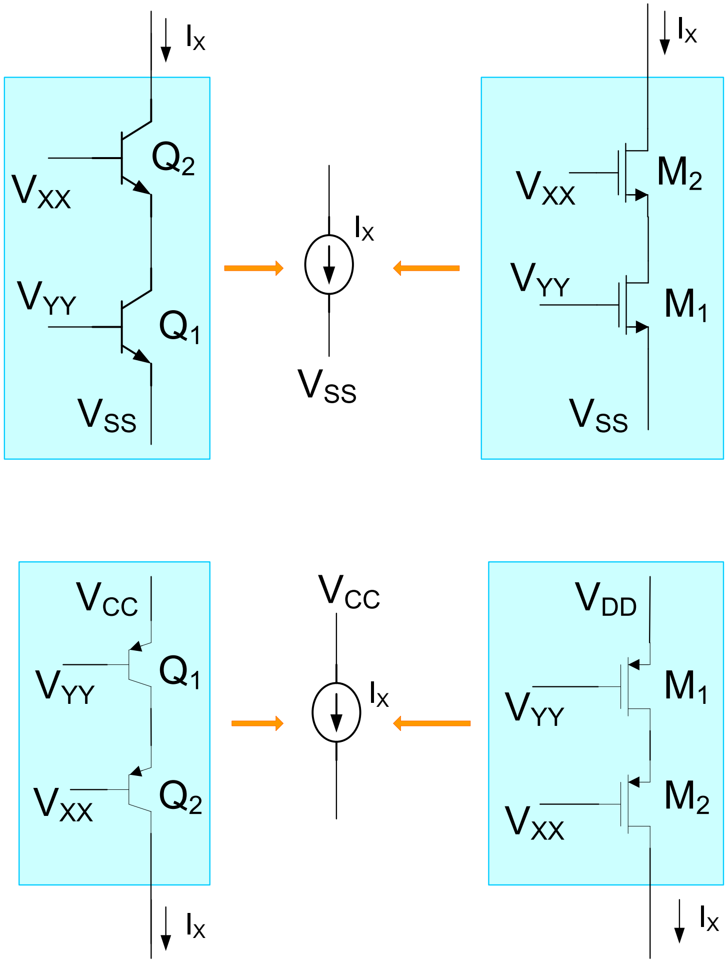
Can a current source be built with the cascode circuit ?

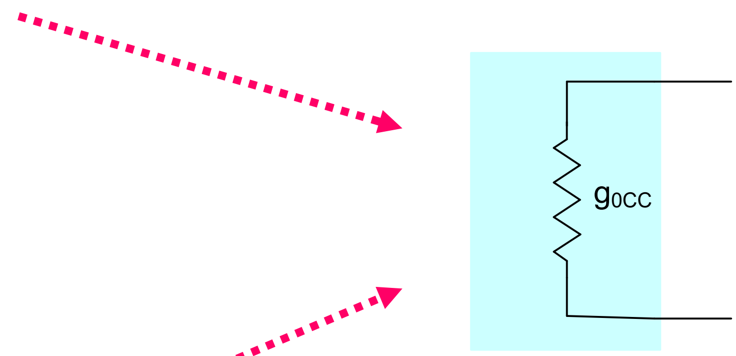
Cascode current sources



Discuss

Cascode current sources

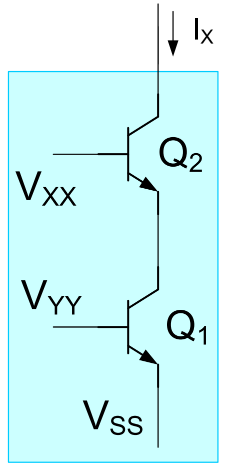


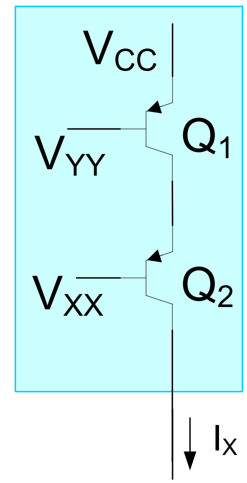


All have the same small-signal model

$$g_{0CC} = \left[\frac{g_{02}\left(g_{01} + g_{\pi 2}\right)}{g_{01} + g_{02} + g_{\pi 2} + g_{m2}} \right]$$

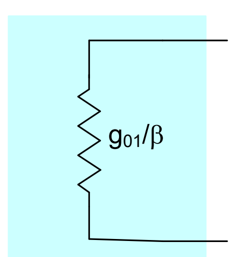
Cascode current sources



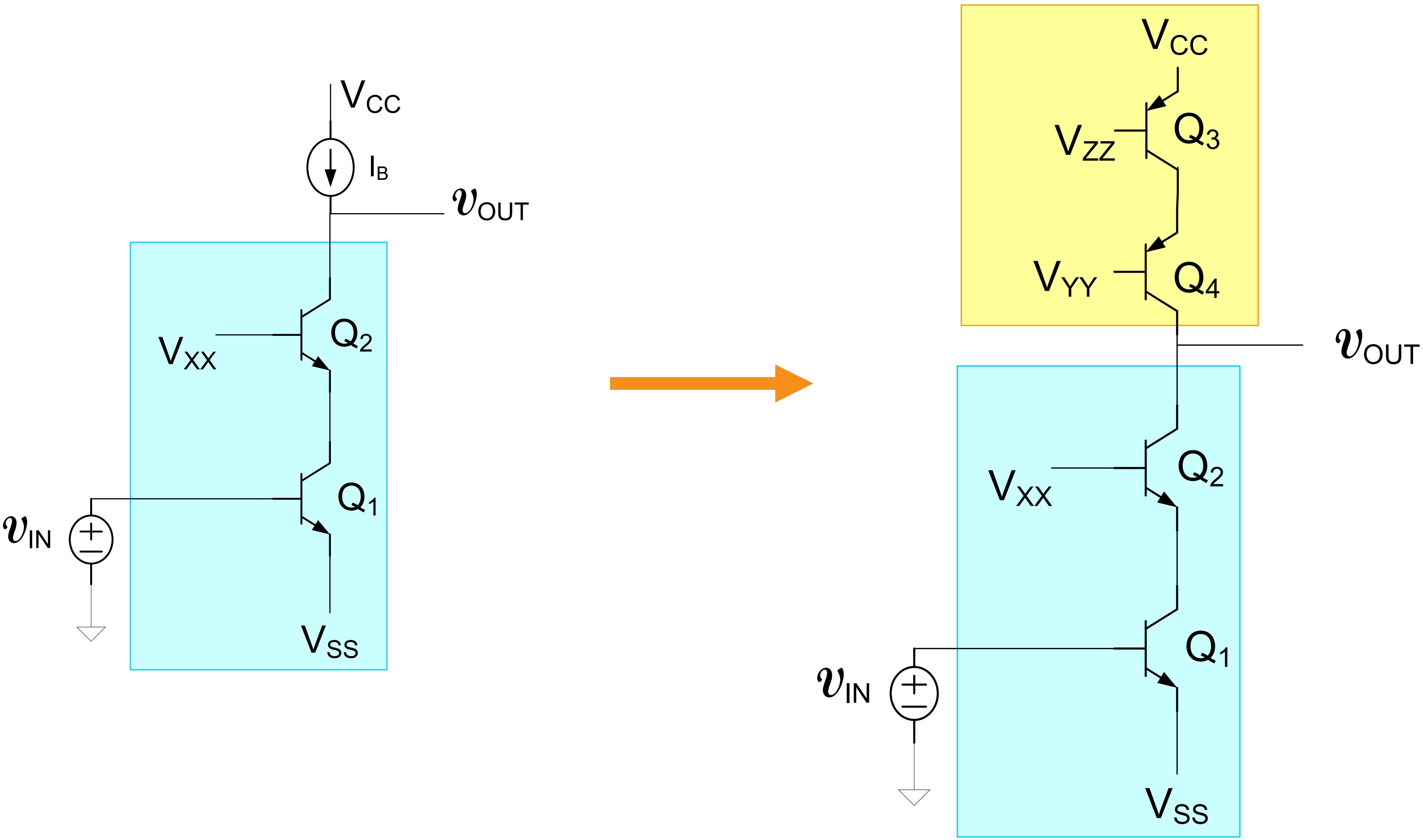


For the BJT cascode current sources

$$g_{0CC}=\left[\frac{g_{02}\left(g_{01}+g_{\pi 2}\right)}{g_{01}+g_{02}+g_{\pi 2}+g_{m2}}\right]\cong\left[\frac{g_{02}g_{\pi 2}}{g_{m2}}\right]=\frac{g_{01}}{\beta}$$

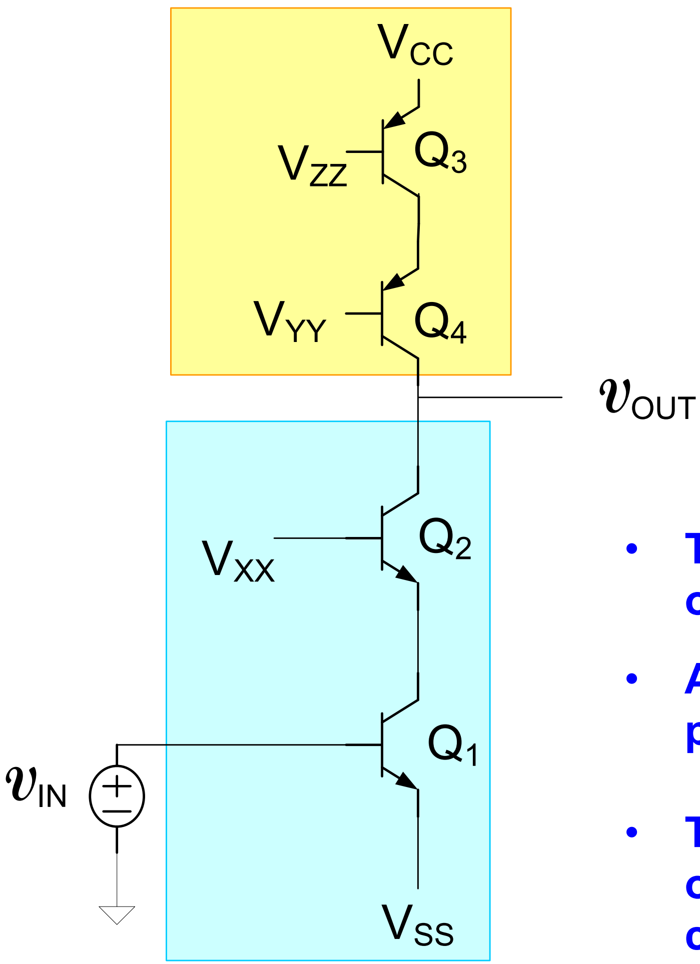


Cascode Configuration



Cascode Configuration

Discuss



$$A_V \cong -\left[\frac{g_{m1}}{\frac{g_{01}}{\beta_1}+g_{0CC}}\right] \cong -\left[\frac{g_{m1}}{\frac{g_{01}}{\beta_1}+\frac{g_{03}}{\beta_3}}\right]$$

If $\beta_1=\beta_3=\beta$

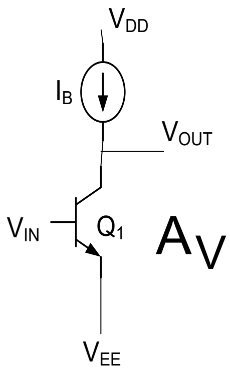
$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

$$A_V = -[8000]\frac{100}{2} \cong -400{,}000$$

- **This gain is very large and is a factor of 2 below that obtained with an ideal current source biasing**
- **Although the factor of 2 is not desired, the performance of this circuit is still very good**
- **This factor of 2 gain reduction is that same as was observed for the CE amplifier when a transistor-level current source was used**
- **Biasing voltages V_{ZZ} and V_{SS} are critical so seldom used single-ended but good biasing strategies exist for differential operation**

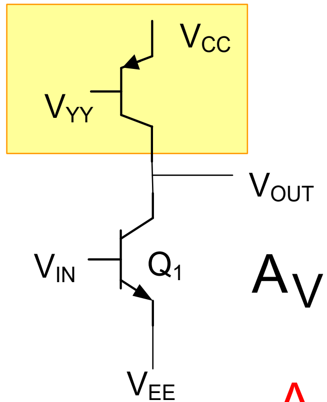
Cascode Configuration Comparisons

Discuss



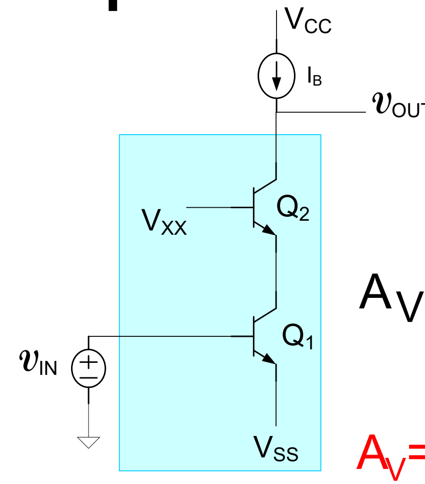
$$A_V = \frac{-g_m}{g_0}$$

$A_V = -8{,}000$



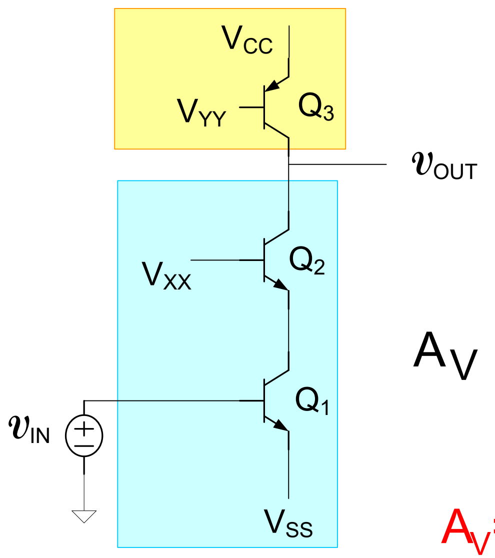
$$A_V \cong \frac{-g_{m1}}{2g_{01}}$$

$A_V = -4{,}000$



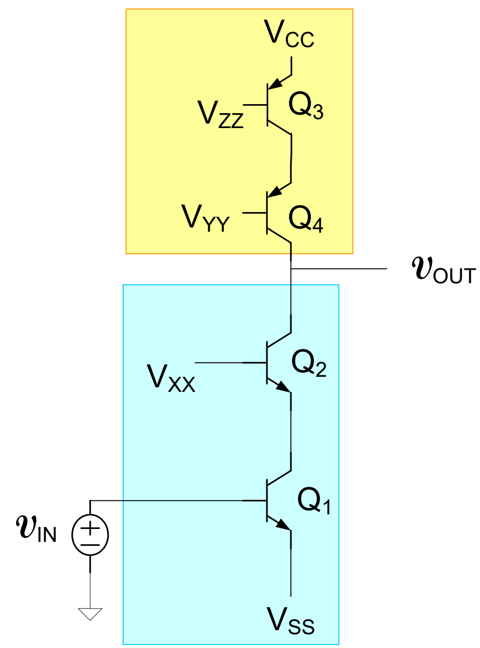
$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

$A_V = -800{,}000$



$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

$A_V = -8{,}000$



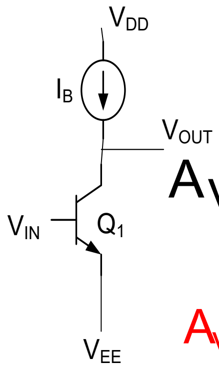
$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

$A_V = -400{,}000$

Can we use more cascoding to further increase the gain?

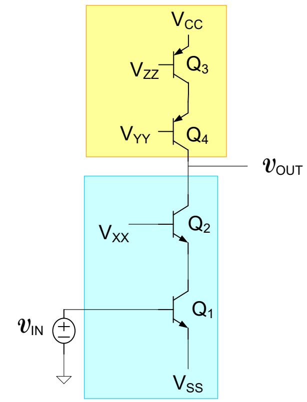
High Gain Amplifiers Seldom Used Open Loop

Discuss



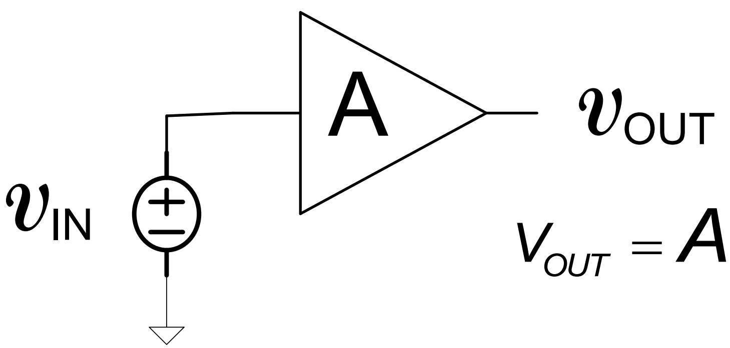
$$A_V = \frac{-g_m}{g_0}$$

A_V= -8,000



$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

A_V= -400,000



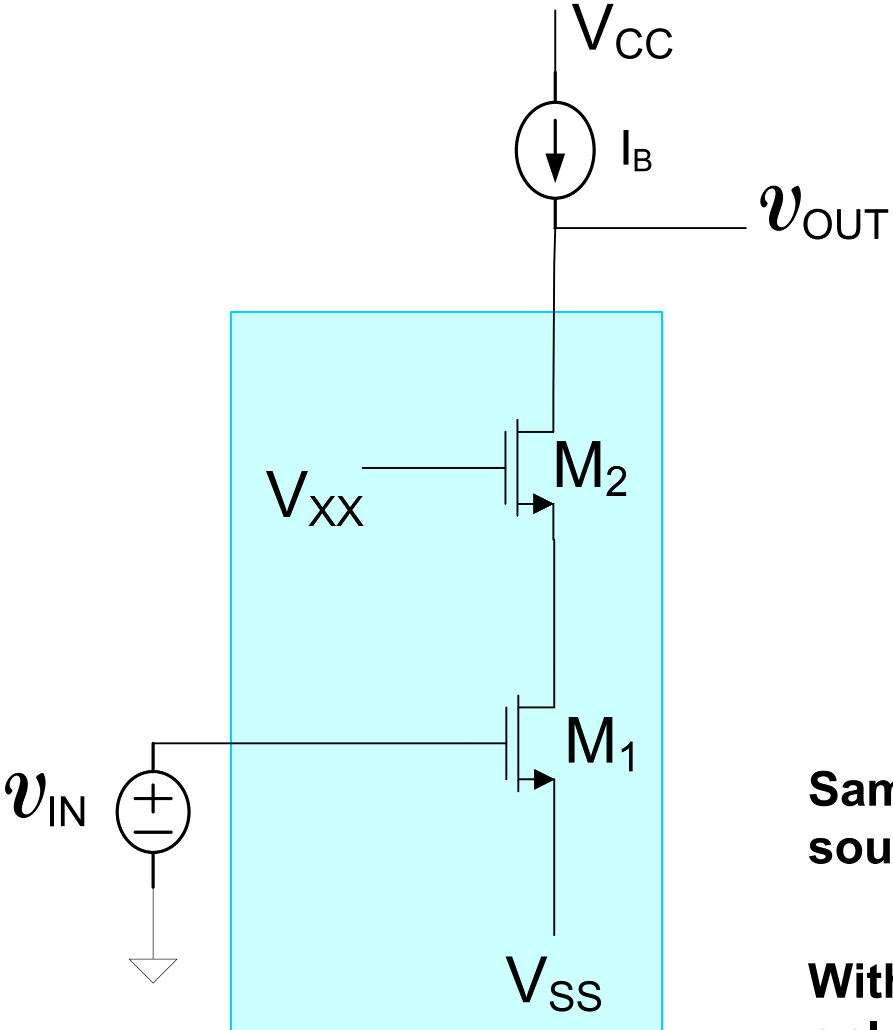
$$V_{OUT} = A\, v_{IN} + V_{OUTQ}$$

If A_V=-400,000 and V_{IN} increases by 1mV, what would happen at the output?

V_{OUT} would decrease by 400,000 x 1mV=-400V

The Cascode Amplifier (consider n-ch MOS version)

Discuss



$$A_{VCC} \cong -\left[\frac{g_{m1}g_{m2}}{g_{01}g_{02}}\right]$$

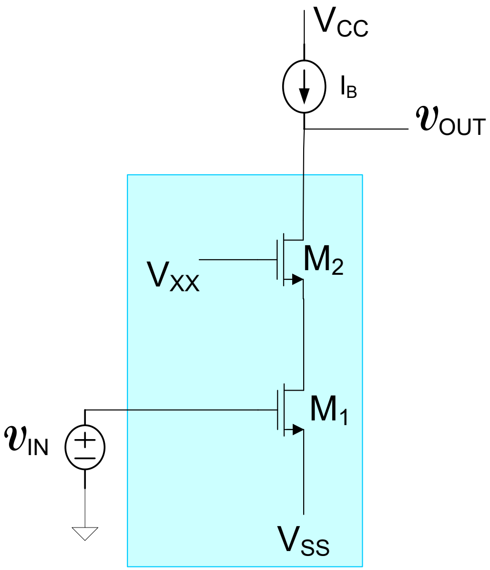
$$g_{0CC} \cong \left[\frac{g_{01}g_{02}}{g_{m2}}\right]$$

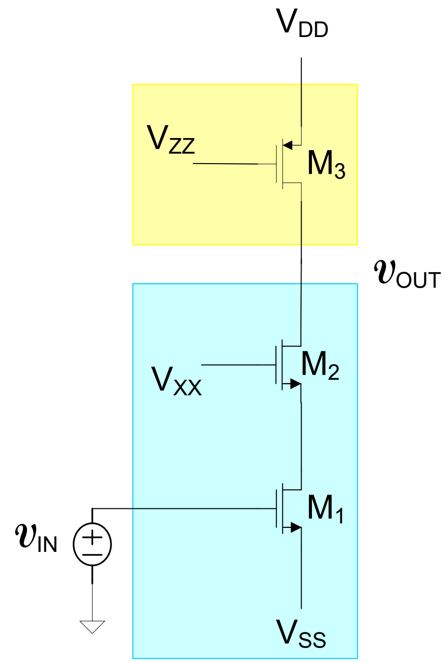
Same issues for biasing with current source as for BJT case

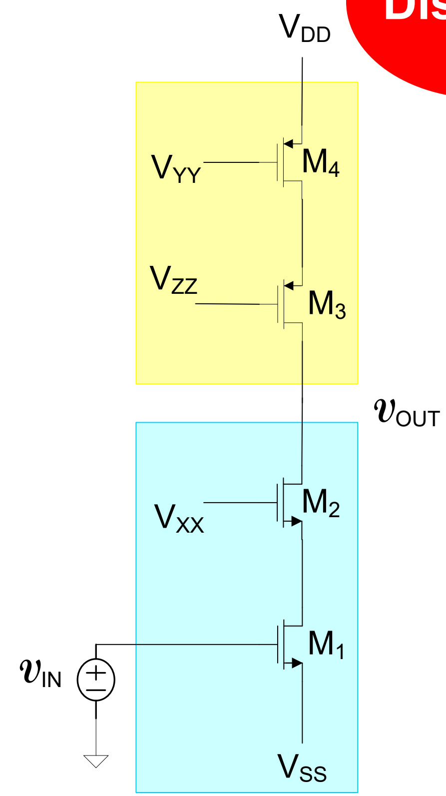
With cascode current source for I_B, gain only drops by a factor of 2 from value with ideal current source

The Cascode Amplifier (consider n-ch MOS version)

Discuss







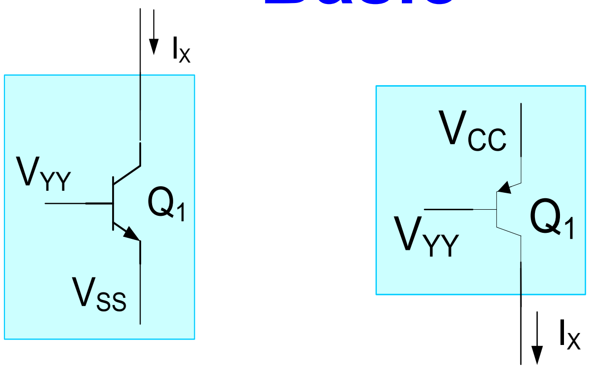
$$A_{VCC} \cong -\left[\frac{g_{m1}g_{m2}}{g_{01}g_{02}}\right]$$

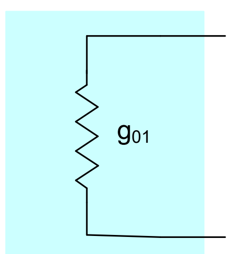
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

$$A_{VCC} \cong -\frac{1}{2}\left[\frac{g_{m1}g_{m2}}{g_{01}g_{02}}\right]$$

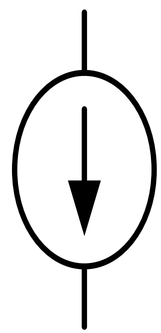
Current Source Summary (BJT)

Basic

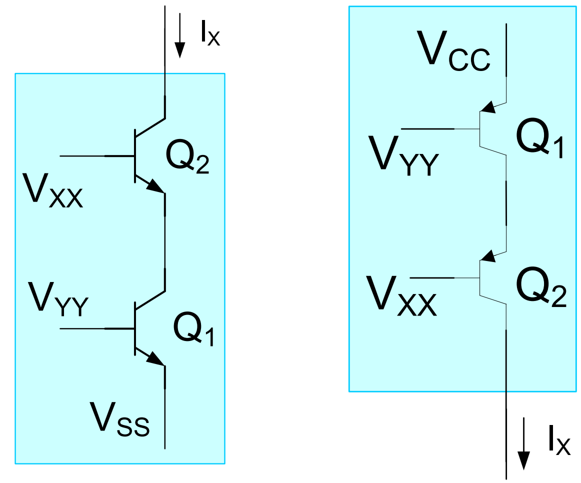


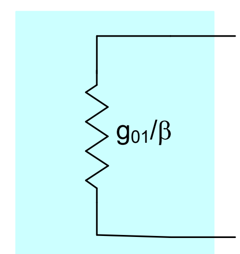


$$g_0 \cong g_{01}$$



Cascode

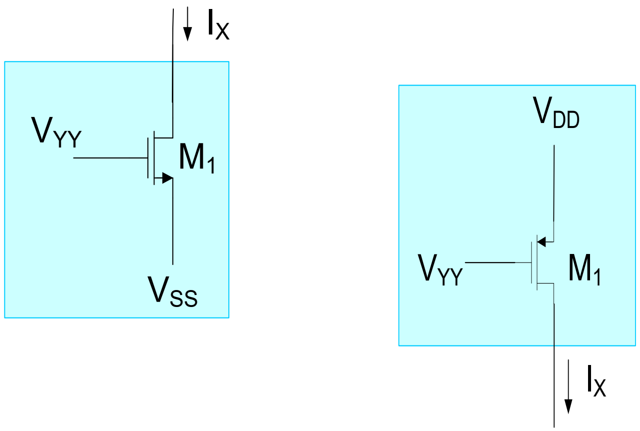


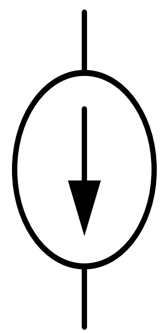


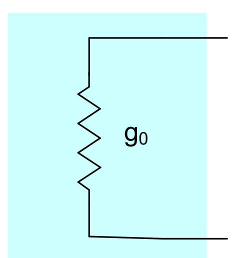
$$g_{0CC} \cong \frac{g_{01}}{\beta}$$

Current Source Summary (MOS)

Basic

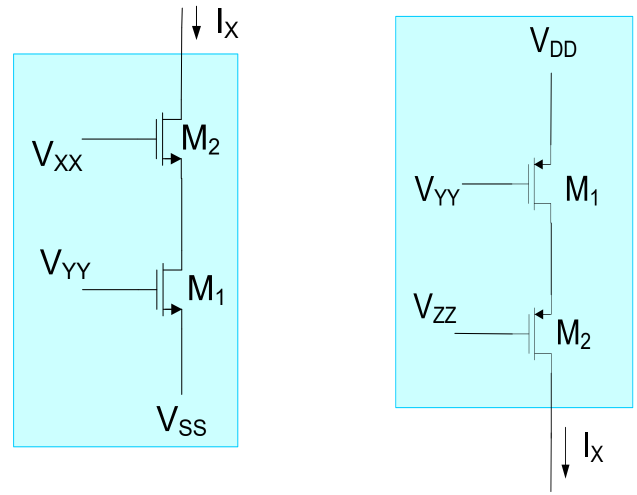


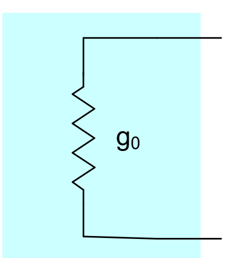




$$g_0 \cong g_{01}$$

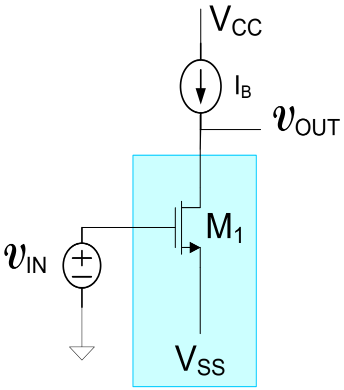
Cascode



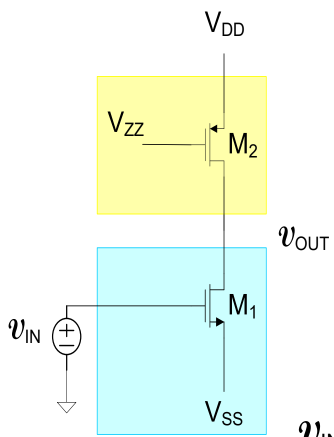


$$g_0 \cong g_{01}\frac{g_{02}}{g_{m2}}$$

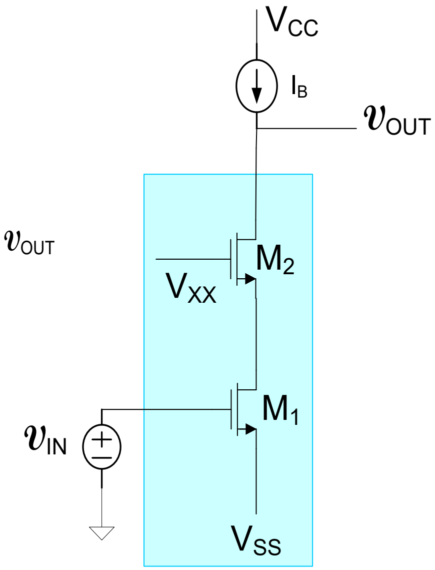
High Gain Amplifier Comparisons (n-ch MOS)



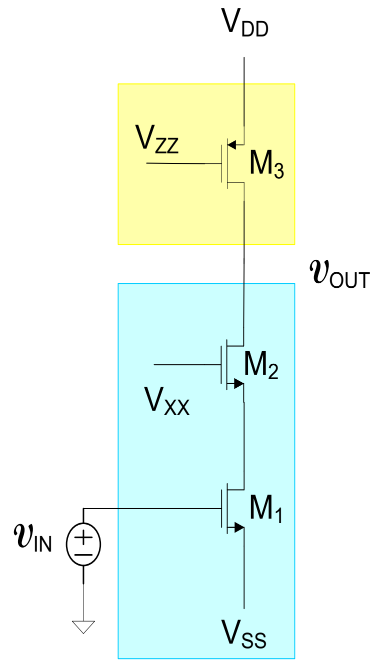
$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$



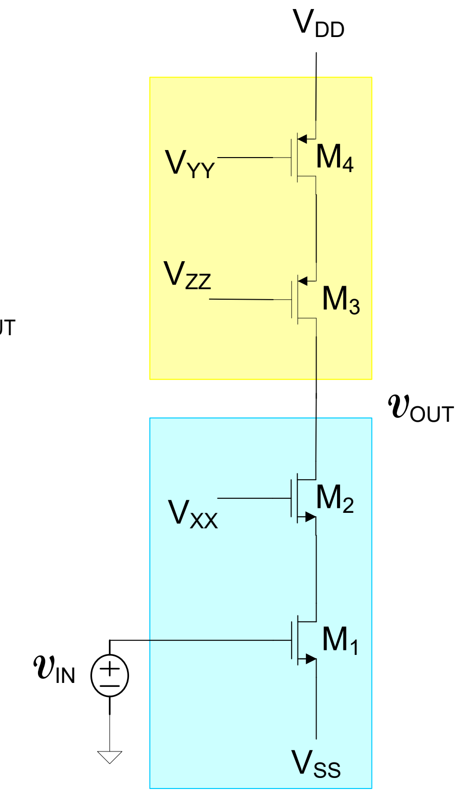
$$A_V \cong -\frac{1}{2}\left[\frac{g_{m1}}{g_{01}}\right]$$



$$A_{VCC} \cong -\left[\frac{g_{m1}g_{m2}}{g_{01}g_{02}}\right]$$

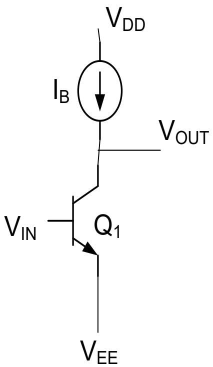


$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

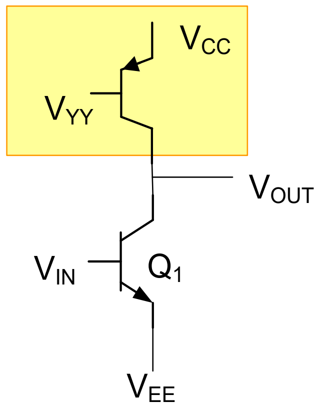


$$A_{VCC} \cong -\frac{1}{2}\left[\frac{g_{m1}g_{m2}}{g_{01}g_{02}}\right]$$

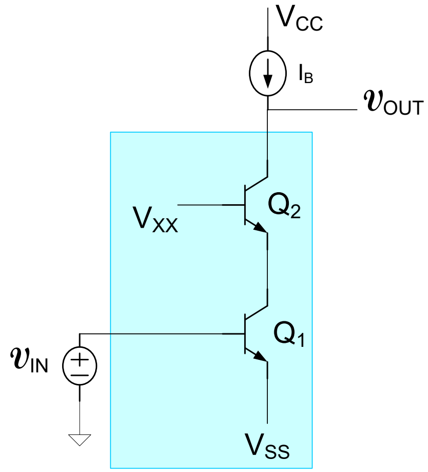
High Gain Amplifier Comparisons (BJT)



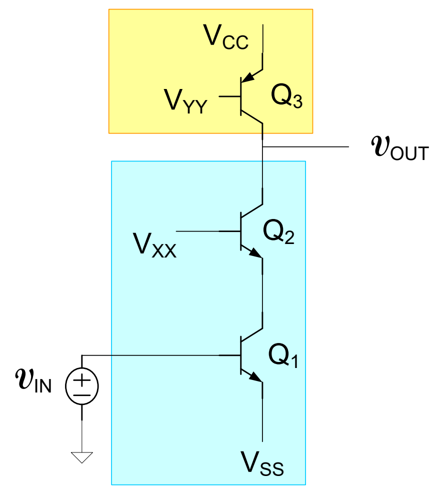
$$A_V = \frac{-g_m}{g_0}$$



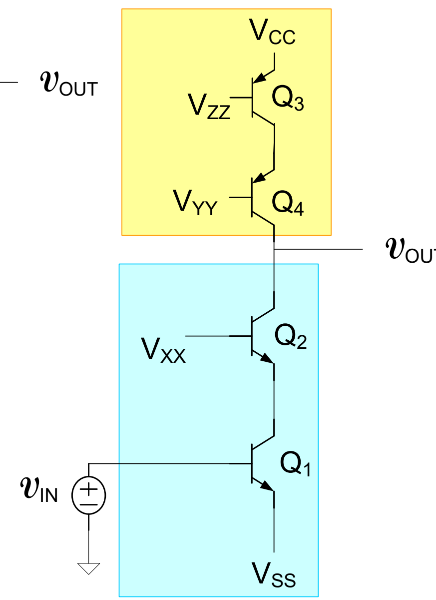
$$A_V \cong -\frac{1}{2}\frac{g_{m1}}{g_{01}}$$



$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$



$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$



$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

- Single-ended high-gain amplifiers inherently difficult to bias (because of the high gain)
- Biasing becomes practical when used in differential applications
- These structures are widely used but usually with differential inputs

Stay Safe and Stay Healthy !

End of Lecture 34