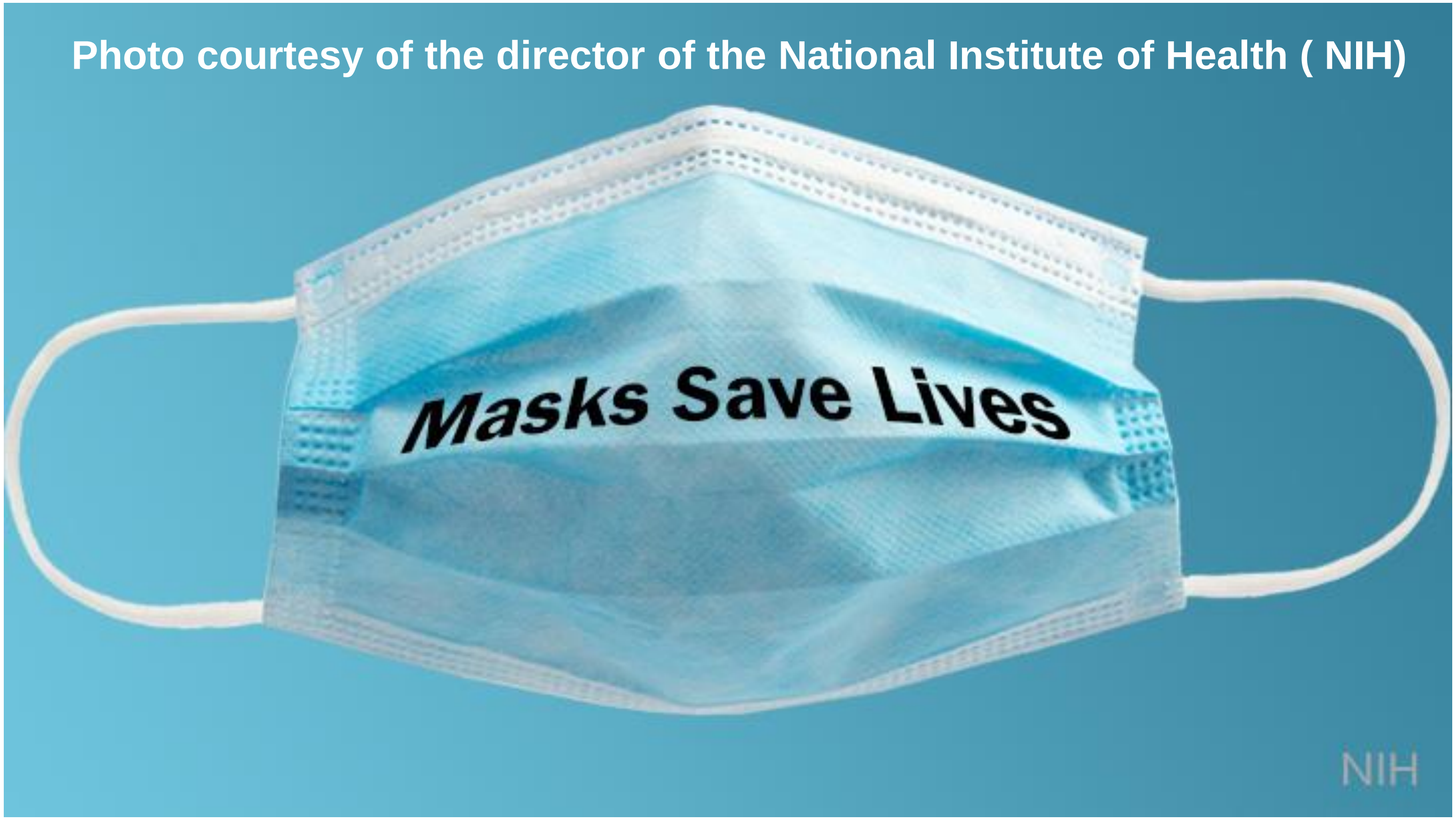
EE 330
Lecture 34

- High Gain Amplifiers
- Cascode and Cascade Configurations

Exam Schedule

Exam 1	Friday Sept 24
Exam 2	Friday Oct 22
Exam 3	Friday Nov 19
Final	Tues Dec 14 12:00 p.m.

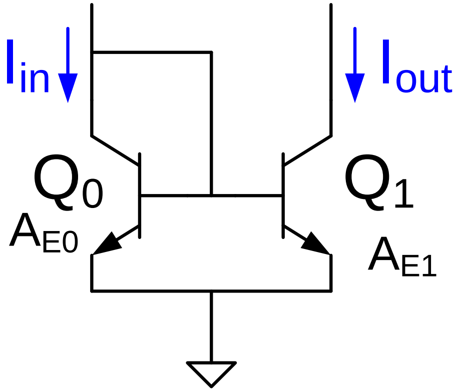


As a courtesy to fellow classmates, TAs, and the instructor

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

Review from Last Lecture

Current Sources/Mirrors



npn Current Mirror

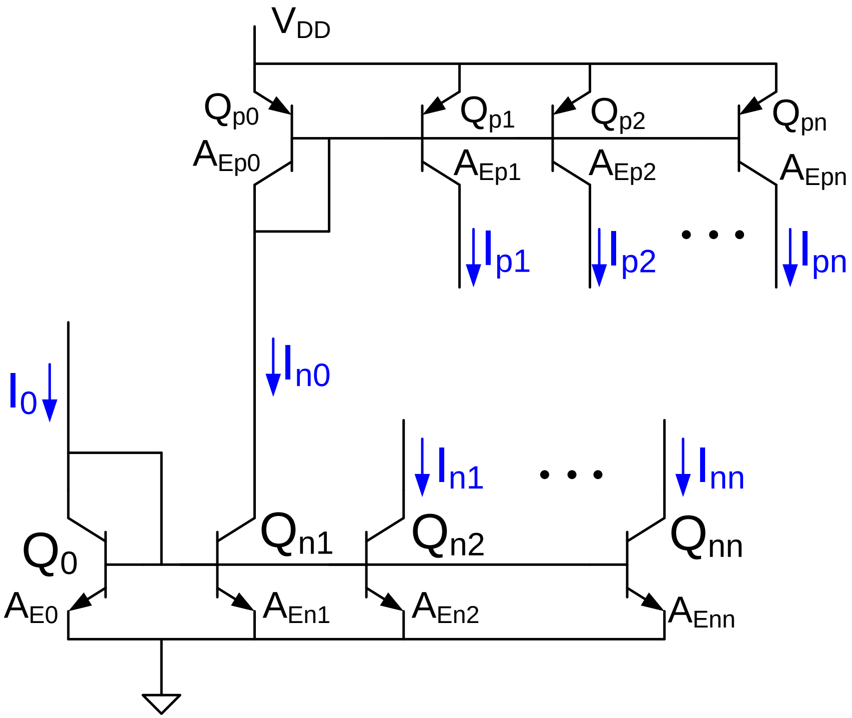
$$I_{out} = \left[\frac{A_{E1}}{A_{E0}}\right] I_{in}$$

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

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

Review from Last Lecture

Current Sources/Mirrors

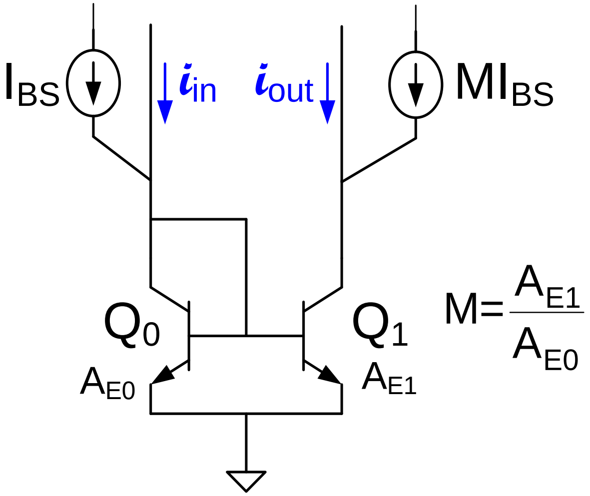


Multiple-Output Bipolar Current Source and Sink

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

Review from Last Lecture

Current Sources/Mirrors



npn current mirror amplifier

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

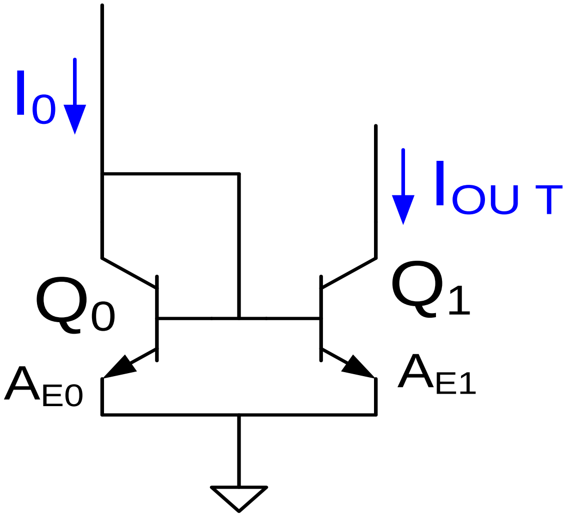
Amplifiers both positive and negative currents (provided $i_{IN}>-I_{BS}$)

Current amplifiers are easy to build !!

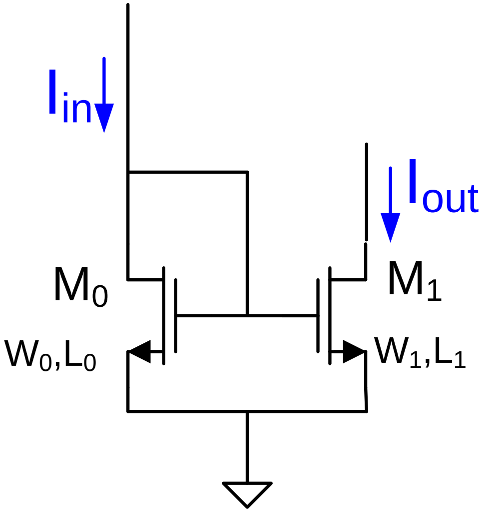
Current gain can be accurately controlled with appropriate layout !!

Review from Last Lecture

Current Sources/Mirrors Summary



npn Current Mirror



n-channel Current Mirror

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

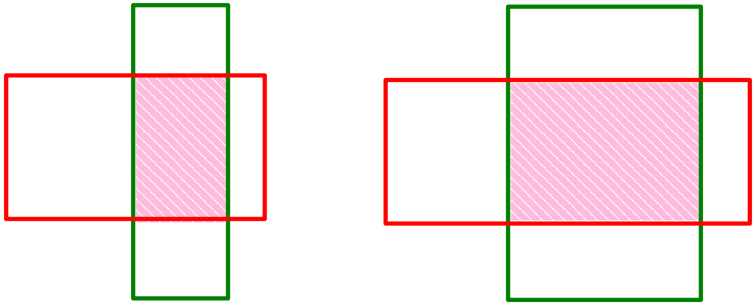
$$I_{out} = \left[\frac{W_1}{W_0}\frac{L_0}{L_1}\right] I_{in}$$

Review from Last Lecture

Layout of Current Mirrors

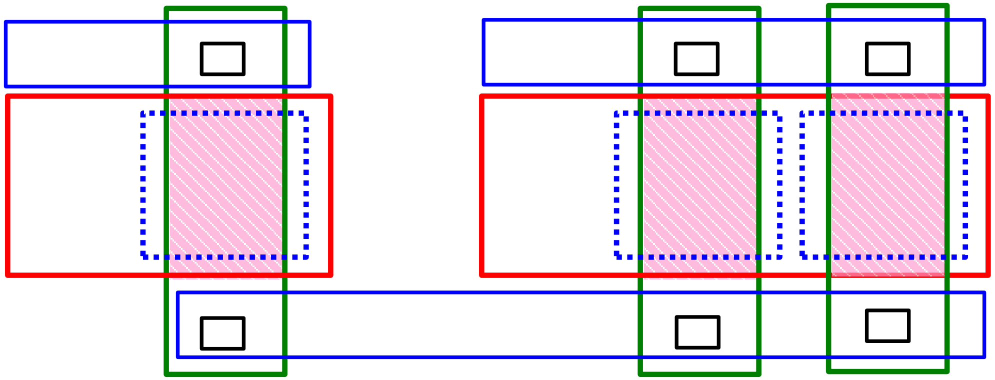
Example with M = 2

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



Standard layout

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



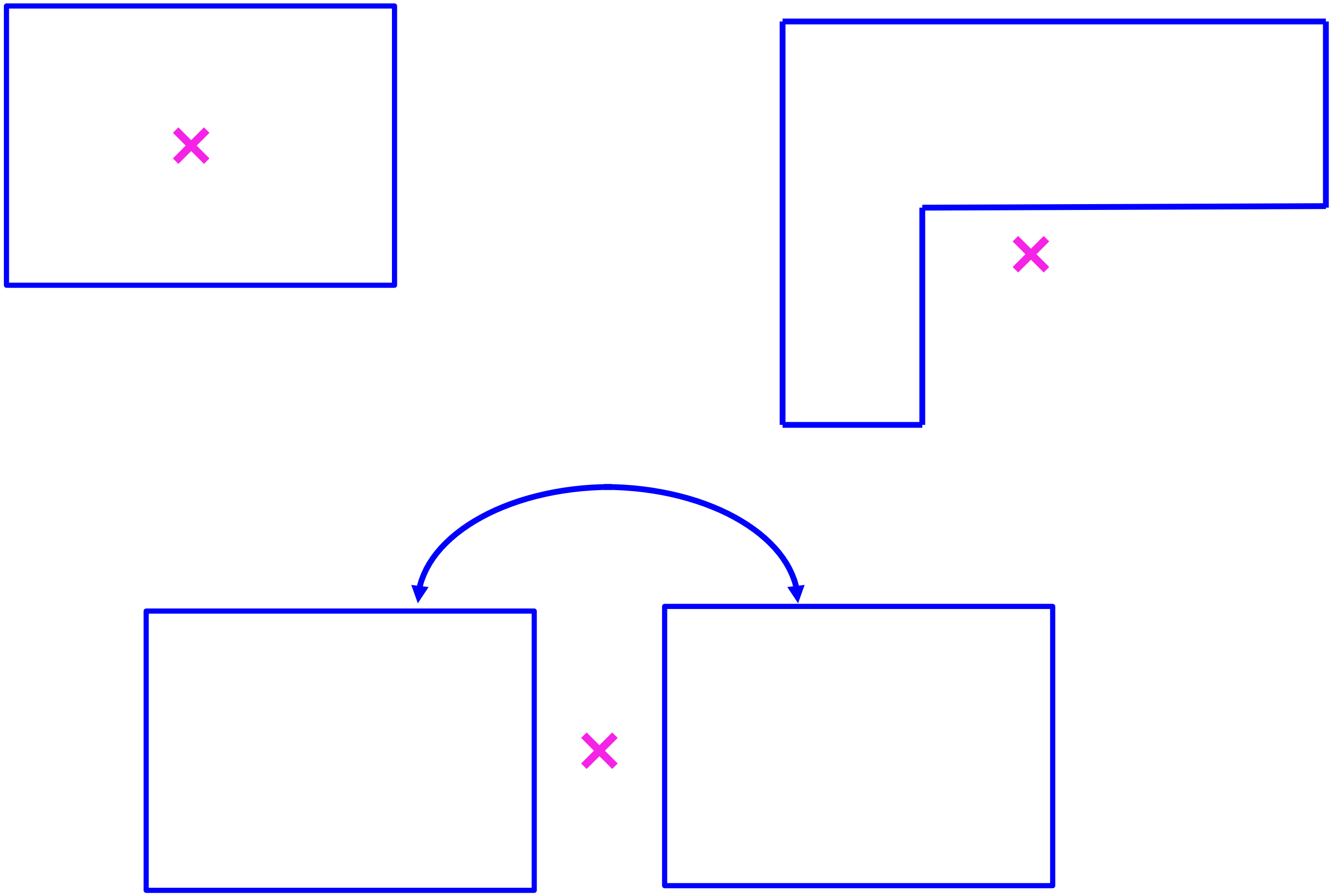
Better Layout

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

Review from Last Lecture

Centroid and Common Centroid

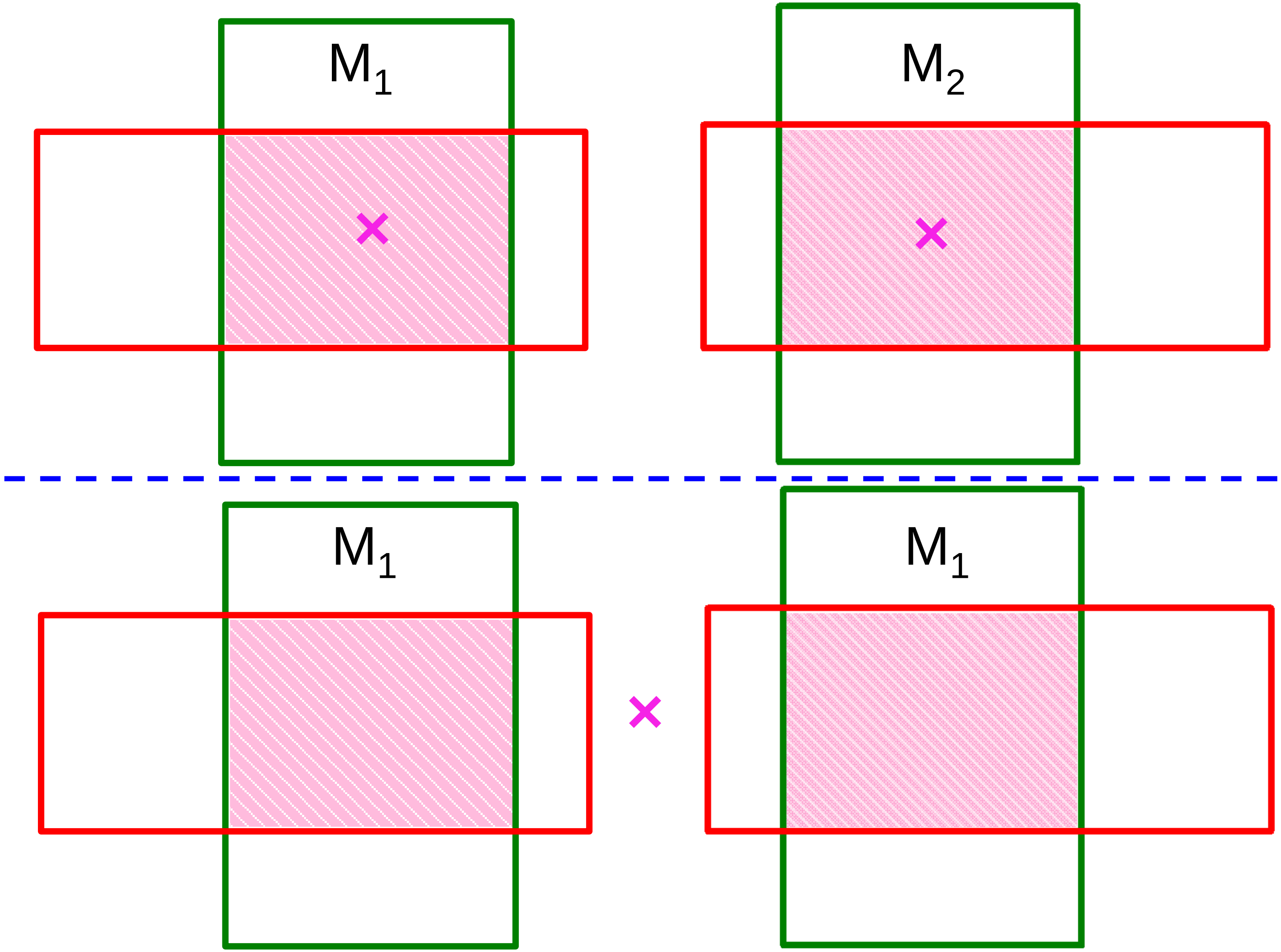
× Denotes Geometric Centroid



Review from Last Lecture

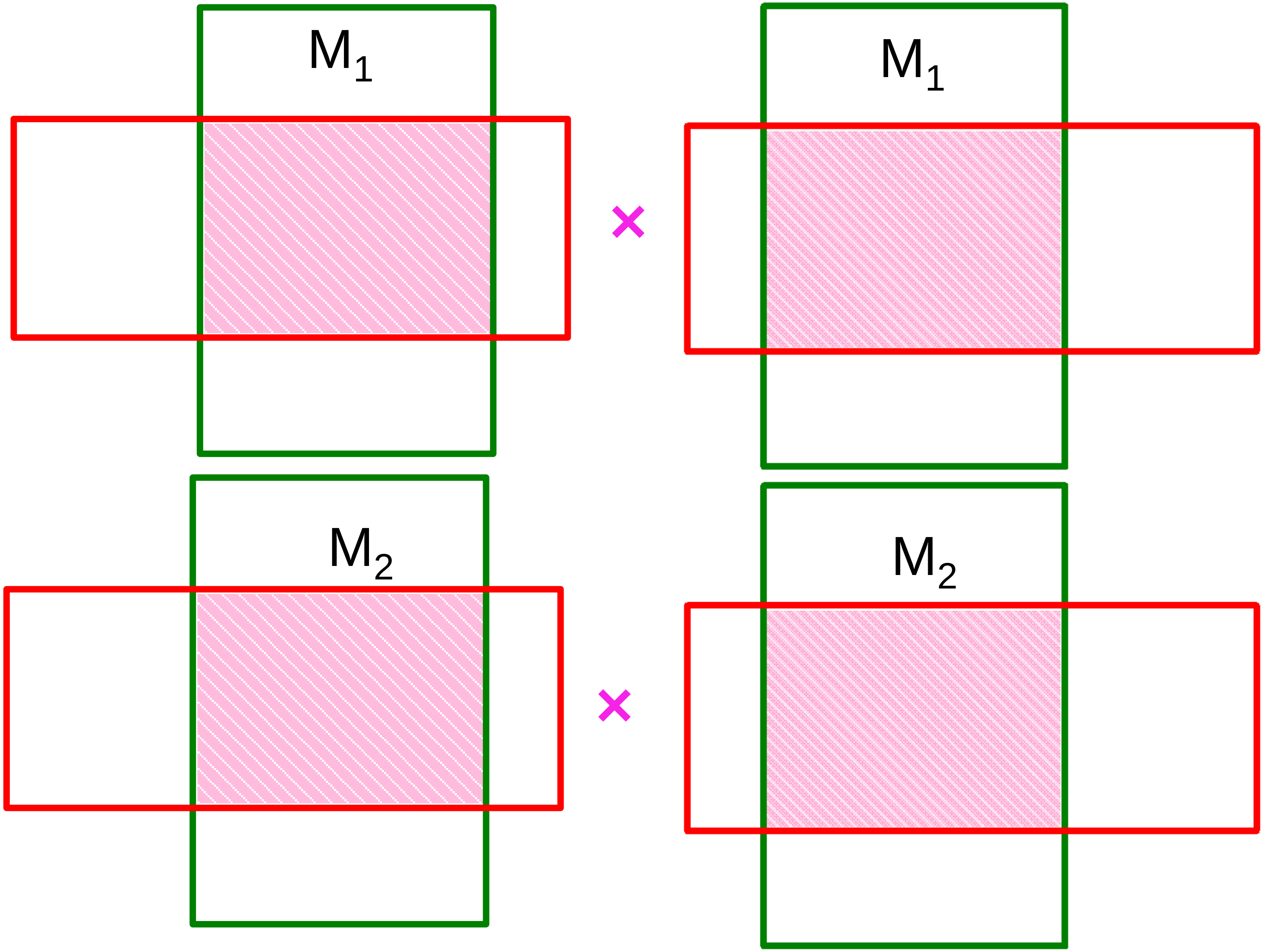
Centroid and Common Centroid

Geometric Centroids of Channel



Review from Last Lecture

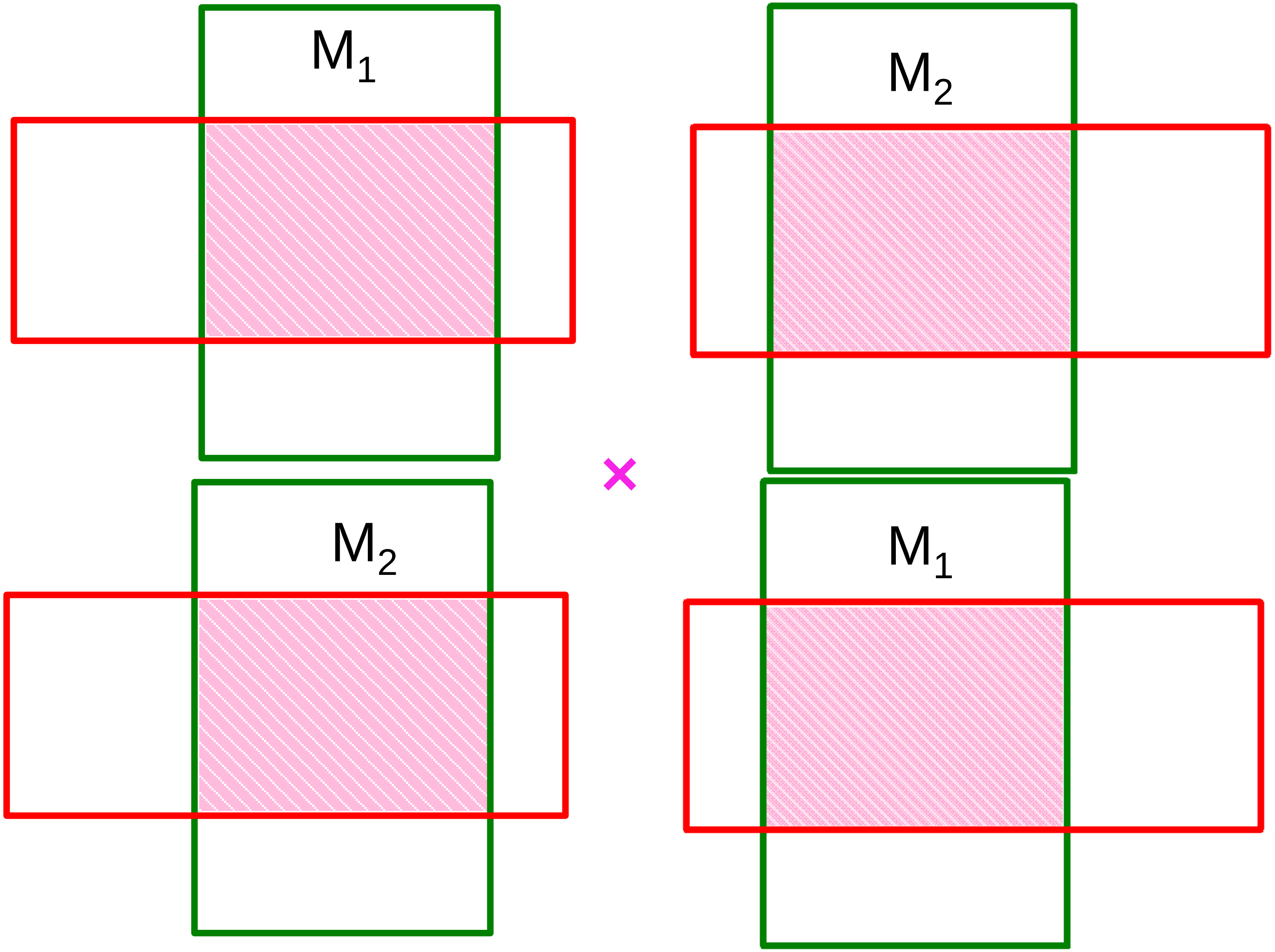
Centroid and Common Centroid



Review from Last Lecture

Centroid and Common Centroid

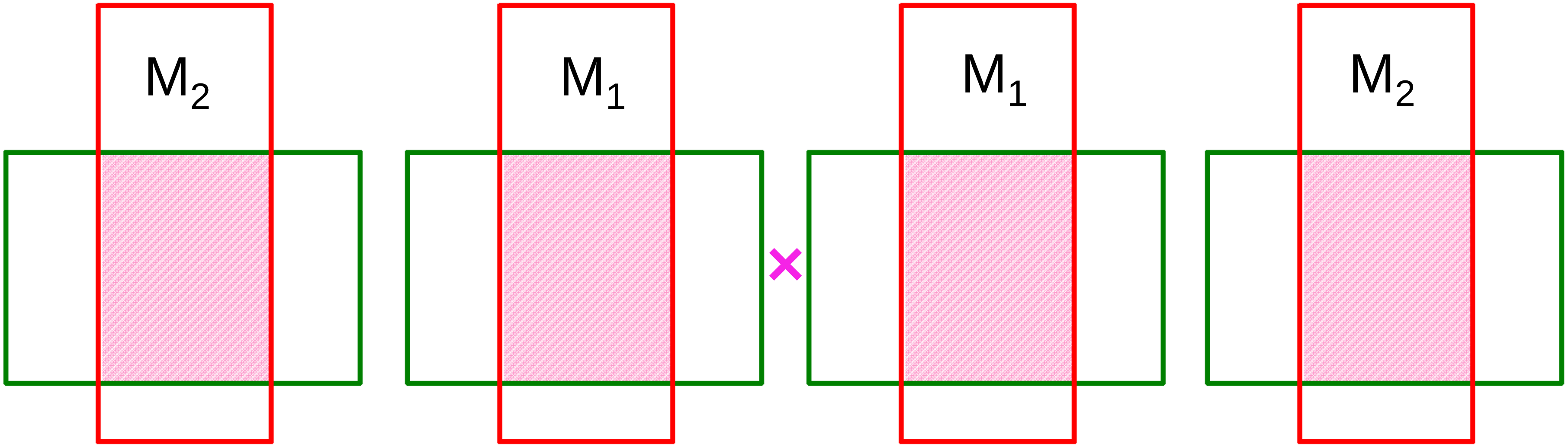
Common Centroid for Matched Devices



Review from Last Lecture

Centroid and Common Centroid

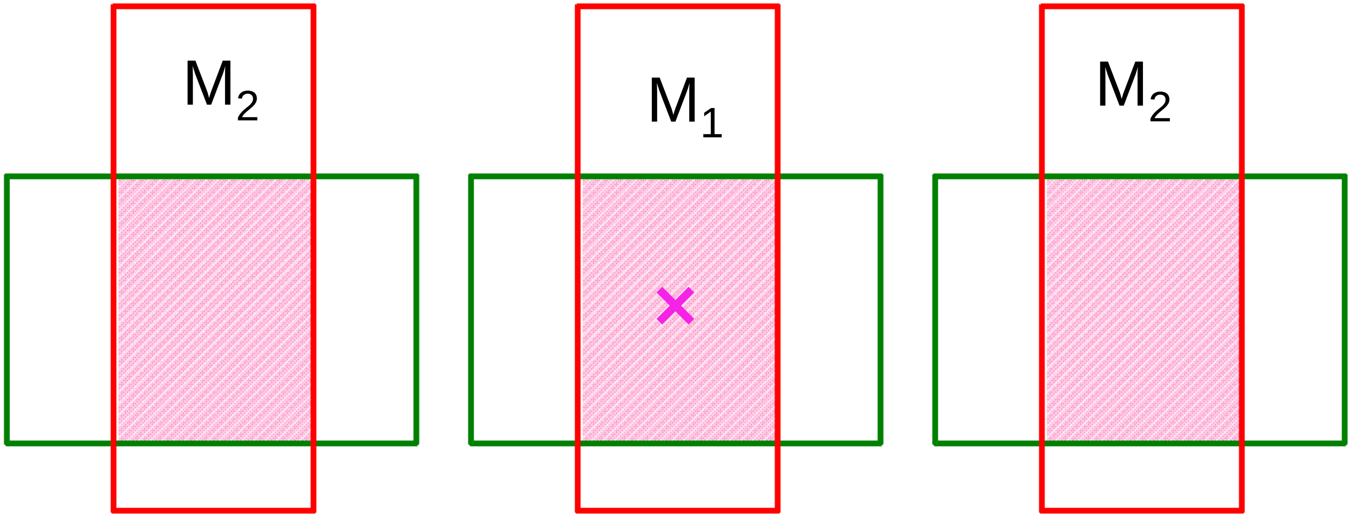
Common Centroid for Matched Devices



Review from Last Lecture

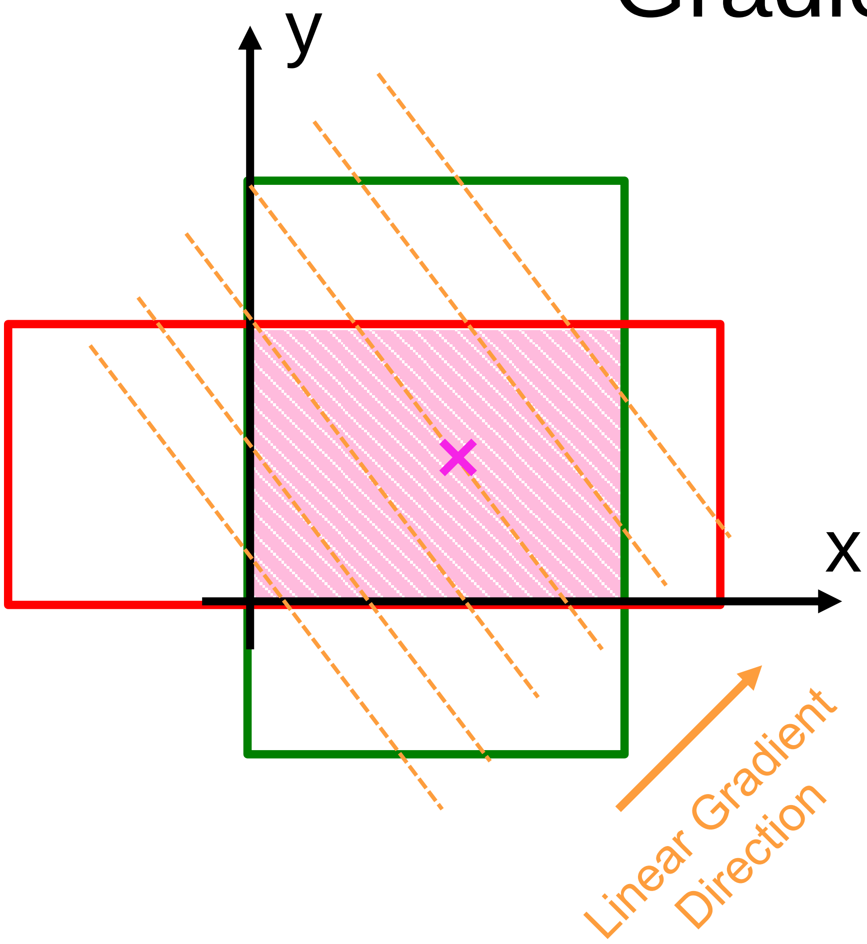
Centroid and Common Centroid

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



Review from Last Lecture

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

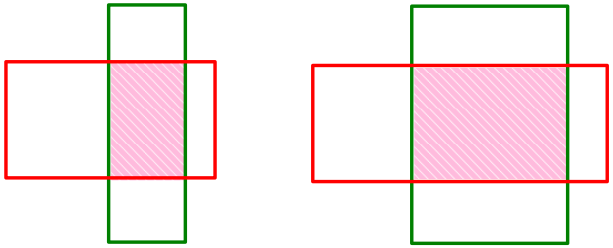
- If the threshold voltage of a transistor changes with position, it can be reasonably accurately modeled with an “equivalent” threshold voltage
- For linear gradient, $V_{THEQ}=V_{TH}(X_C,Y_C)$

✕ : (X_C,Y_C)

Review from Last Lecture

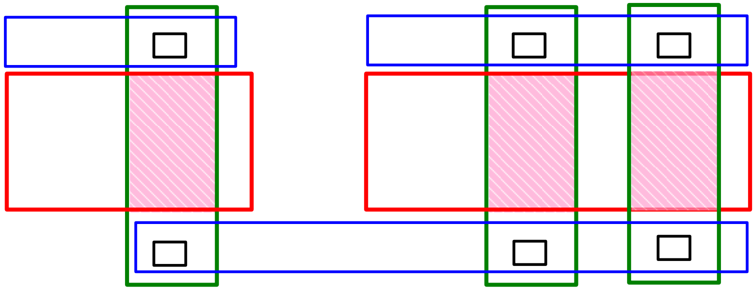
Layout of Current Mirrors

Example with M = 2



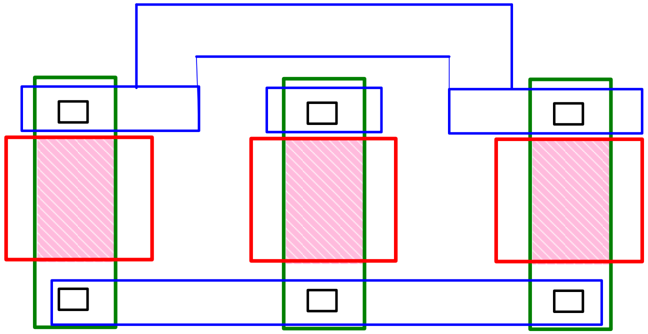
Standard layout

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



Better Layout

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

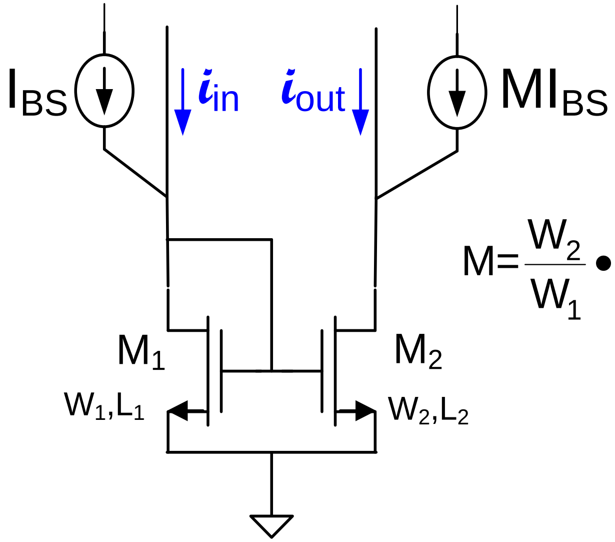


Even Better Layout

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

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

n-channel current mirror current amplifier

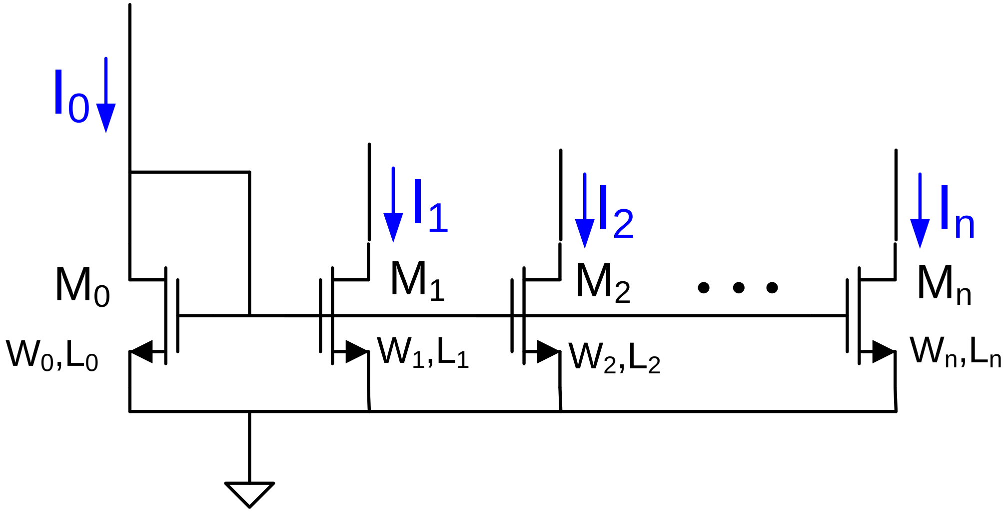


$$M = \frac{W_2}{W_1} \bullet \frac{L_1}{L_2}$$

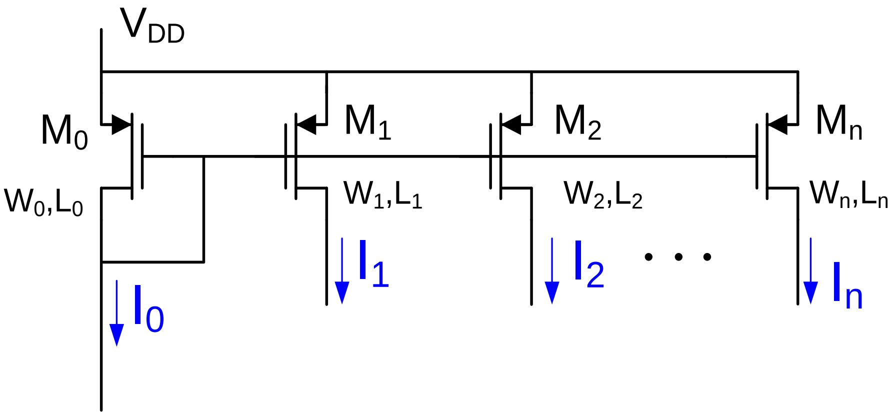
$$i_{out} = \left[\frac{W_2}{W_1} \frac{L_1}{L_2} \right] i_{in}$$

Amplifies both positive and negative currents

Current Sources/Mirrors



multiple output n-channel current sink array

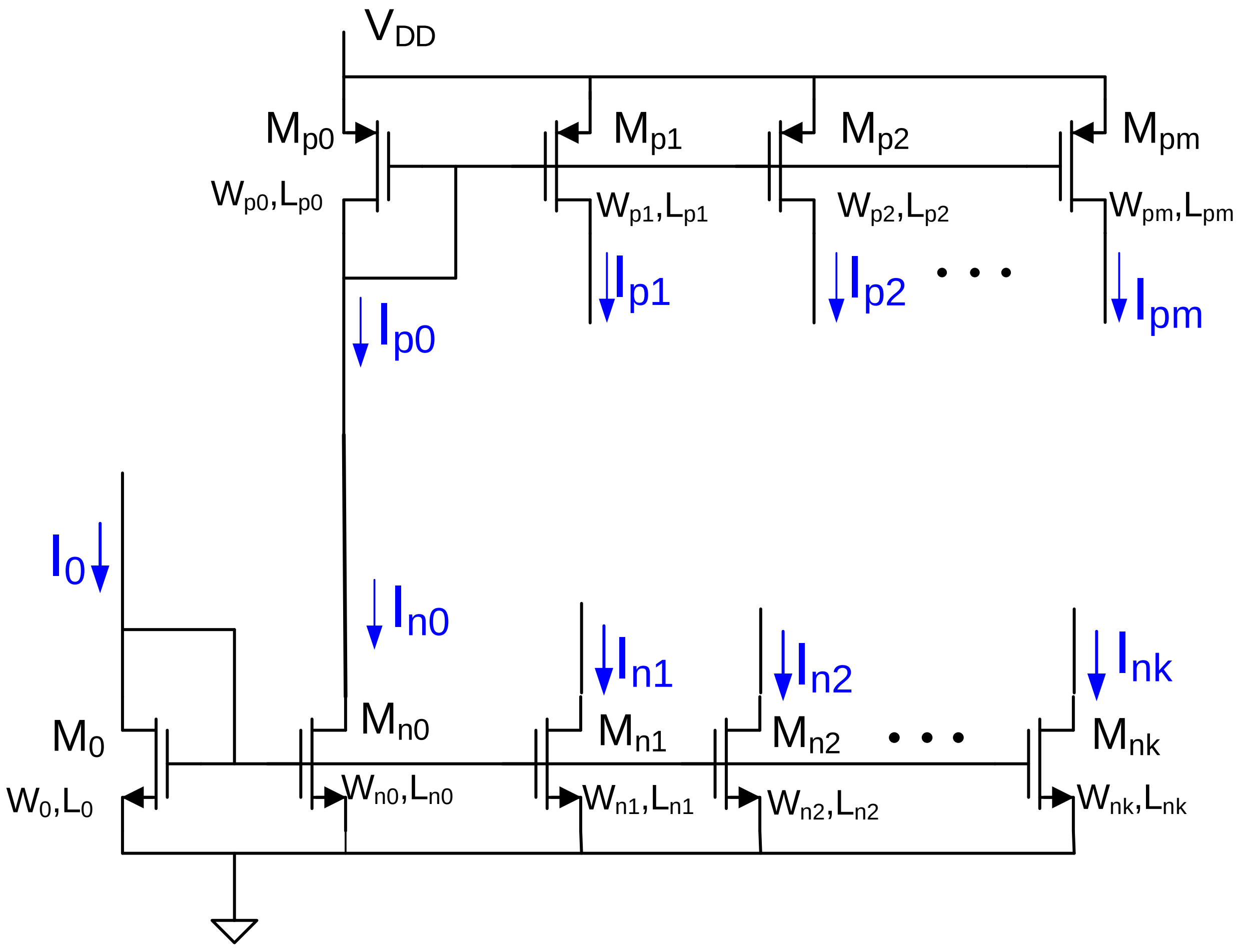


multiple output p-channel current source array

$$
\left.\begin{array}{c} \\ \\ \\ \end{array}\right\} \quad I_k = \left[\frac{W_k}{W_0} \frac{L_0}{L_k} \right] I_0
$$

Current Sources/Mirrors

multiple sourcing and sinking current outputs



$$I_{pj}=\left[\frac{W_{pj}}{L_{pj}}\bullet\frac{L_{p0}}{W_{p0}}\right]MI_0$$

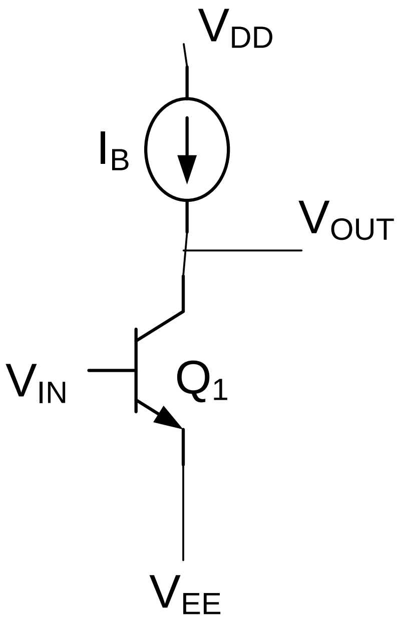
$$M=\left[\frac{W_{n0}}{L_{n0j}}\bullet\frac{L_0}{W_0}\right]$$

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

m and k may be different

Often M=1

High-gain amplifier



$$A_V \cong -8000$$

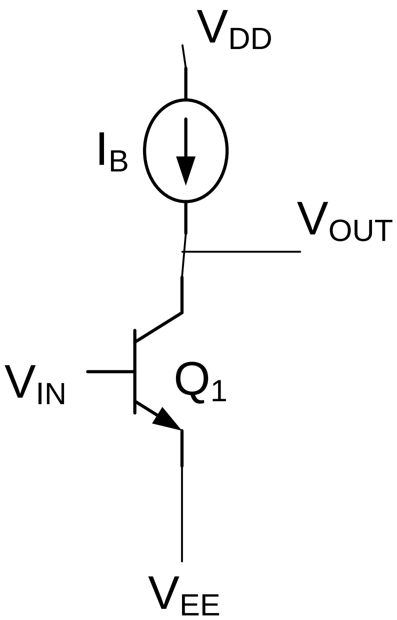
Why are we interested in high-gain amplifiers?

- 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



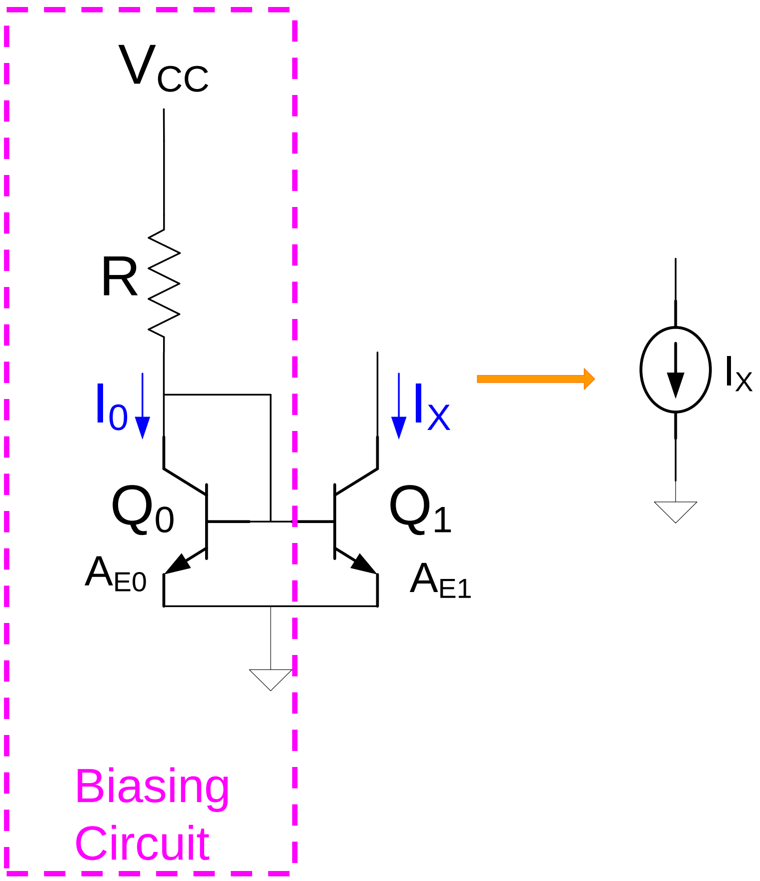
$$A_V \cong -8000$$

→ How can we build the current source?

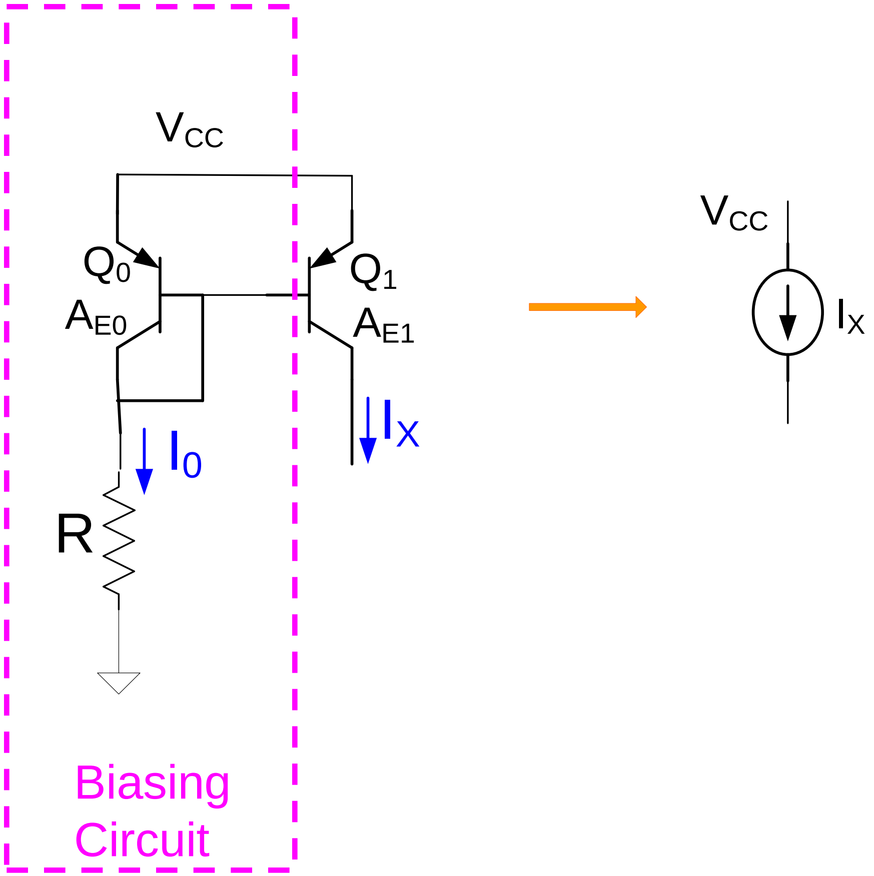
What is the small-signal model of an actual current source?

Basic Current Sources and Sinks

Bipolar Mirror-Based Current Sink

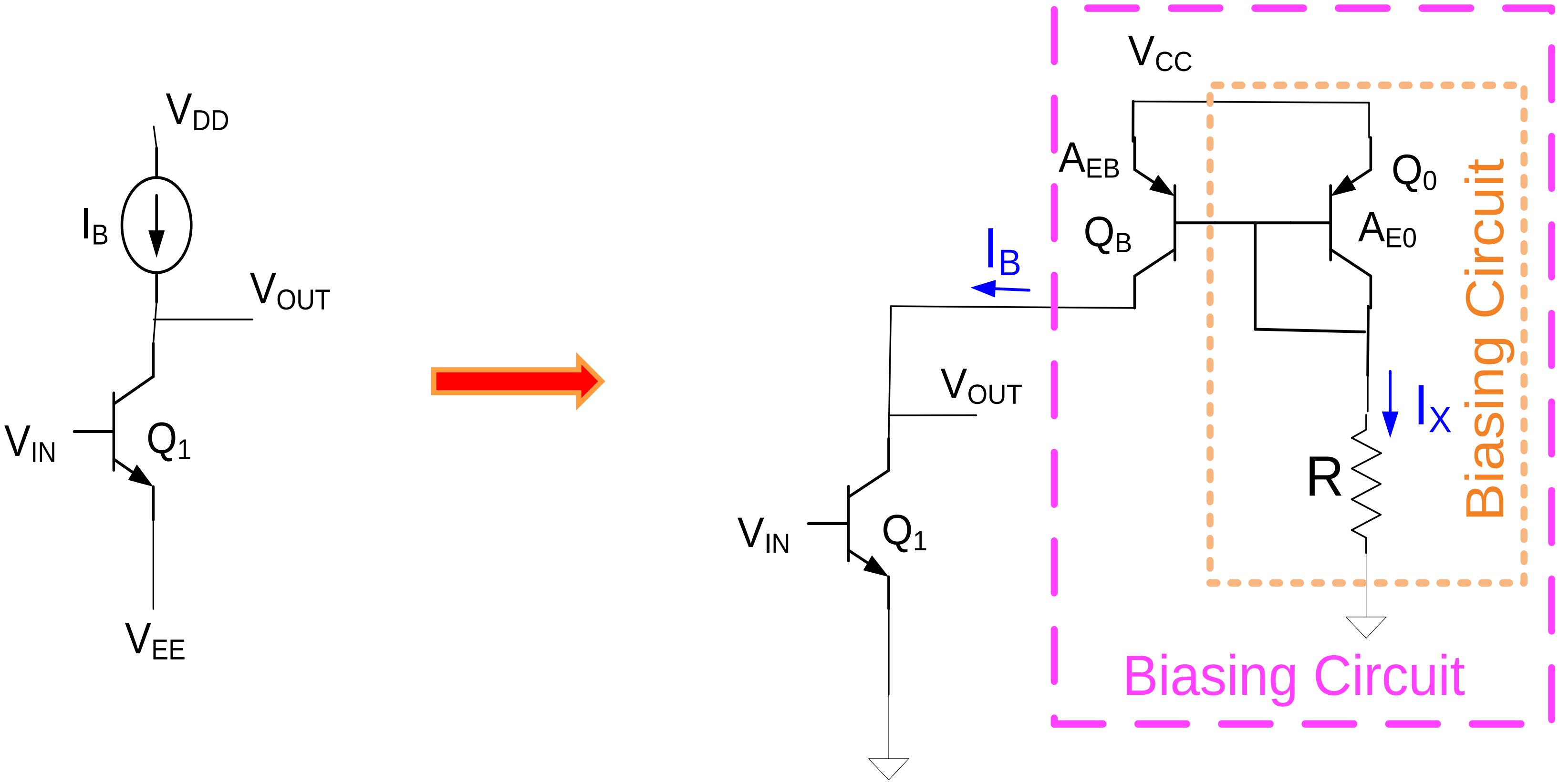


Bipolar Mirror-Based Current Source



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

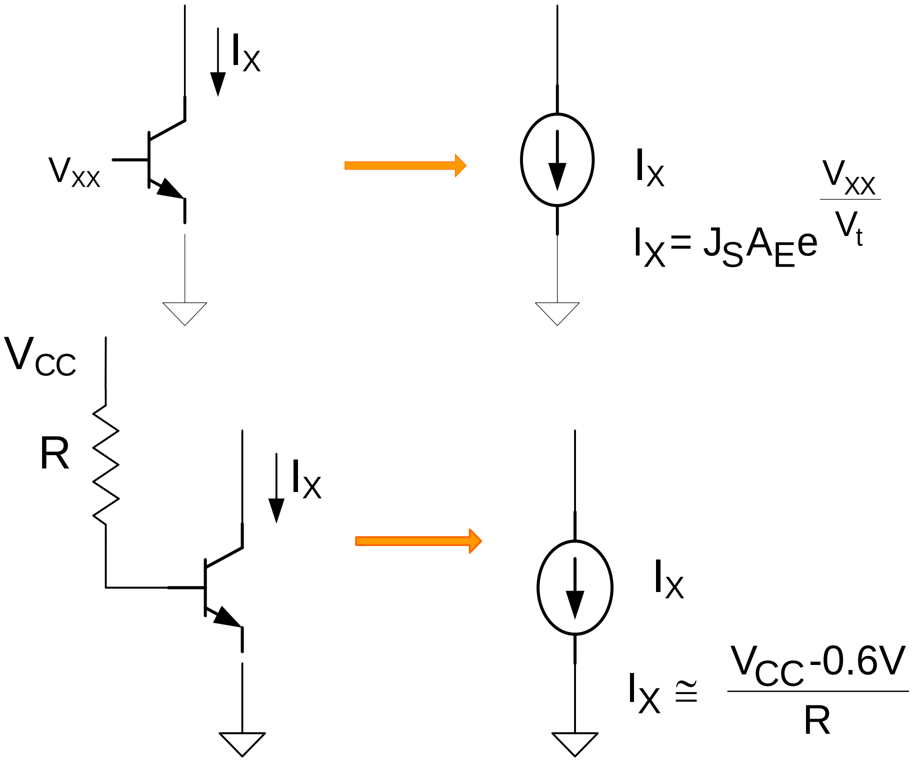
High-gain amplifier



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

Basic Current Sources and Sinks

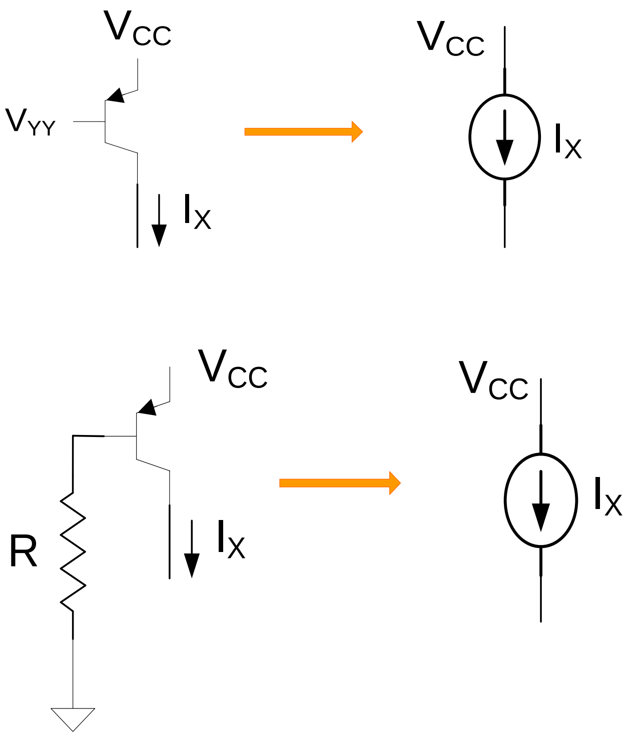
Basic Bipolar Current Sinks



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

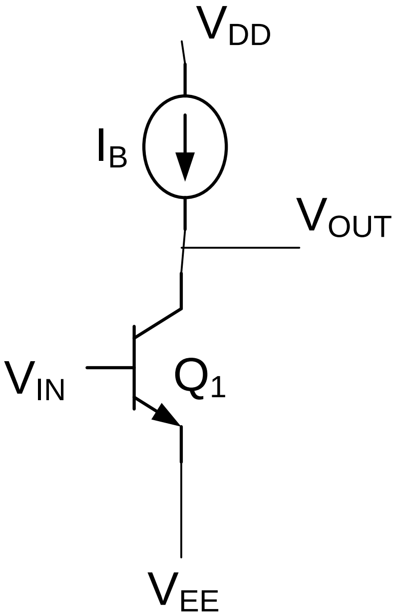
$$I_X \cong \frac{V_{CC}\text{-}0.6V}{R}$$

Basic Bipolar Current Sources



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

High-gain amplifier



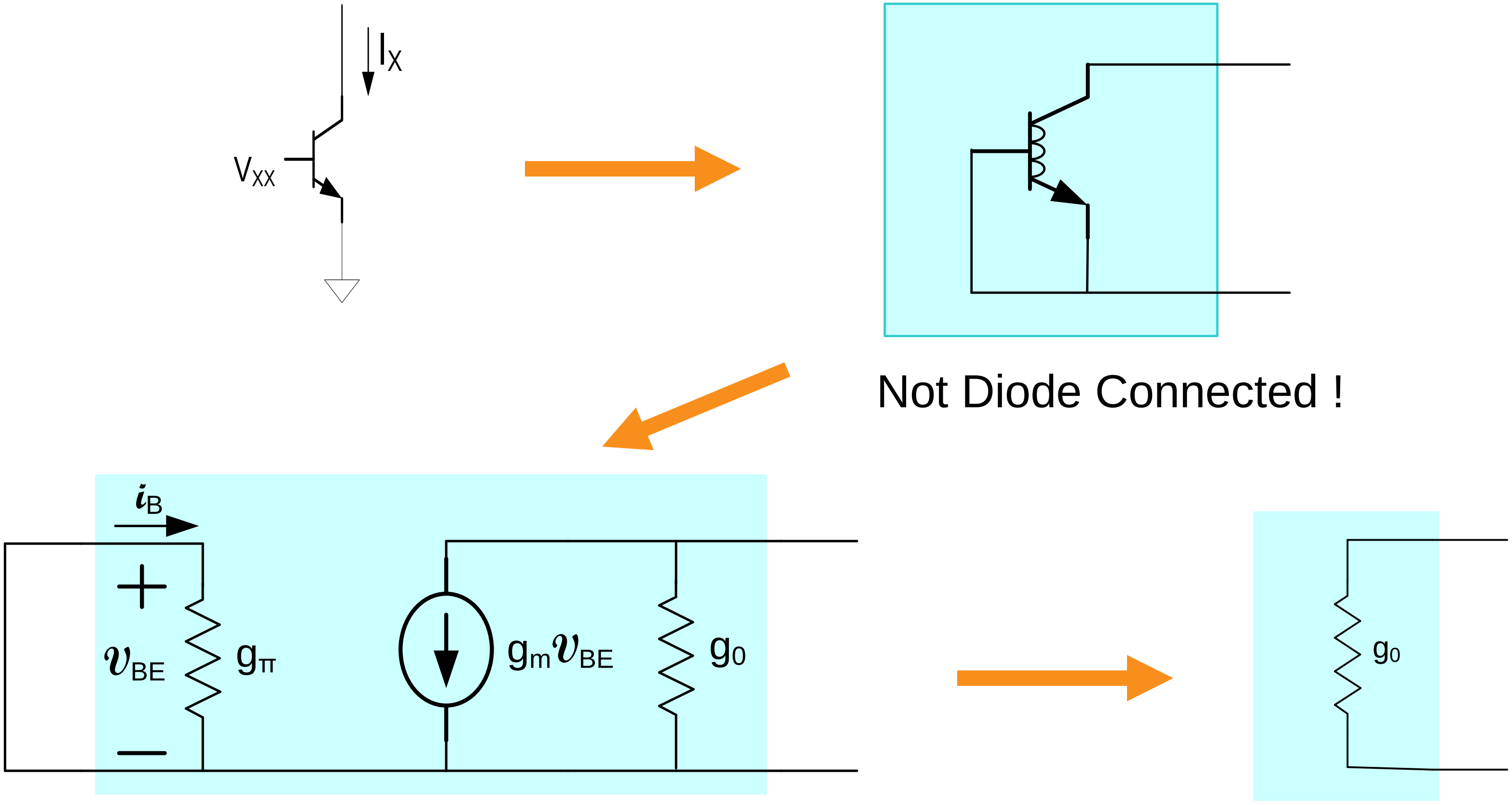
$A_V \cong -8000$

How can we build the current source?

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

Basic Current Sources and Sinks

Small-signal Model of BJT Current Sinks and Sources

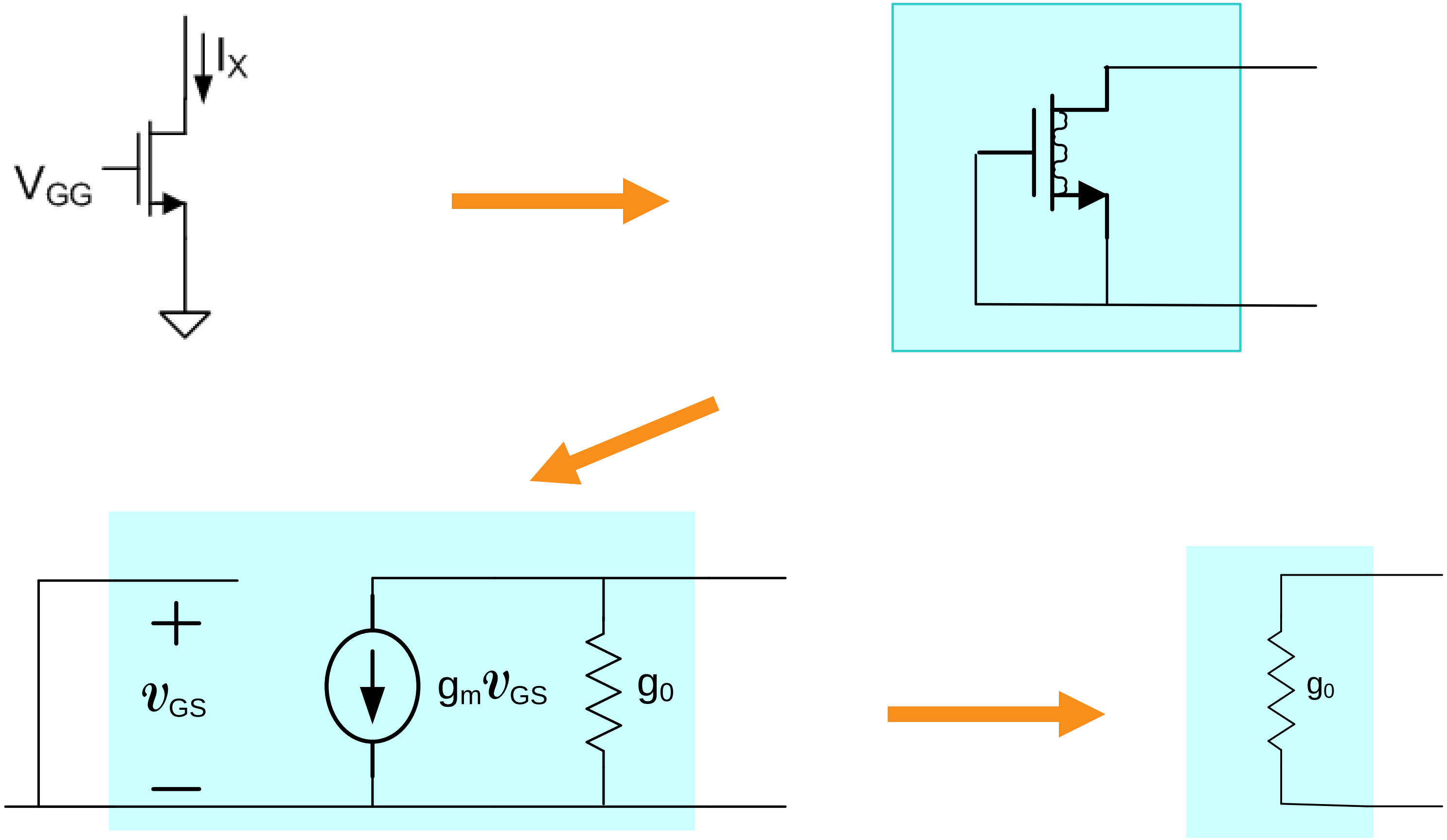


Not Diode Connected !

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

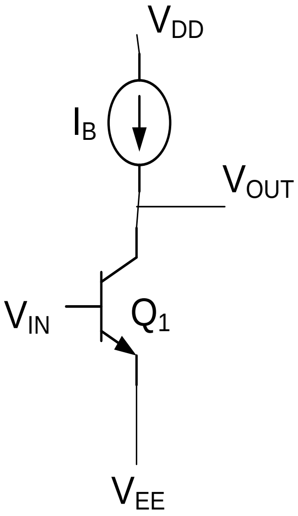
Basic Current Sources and Sinks

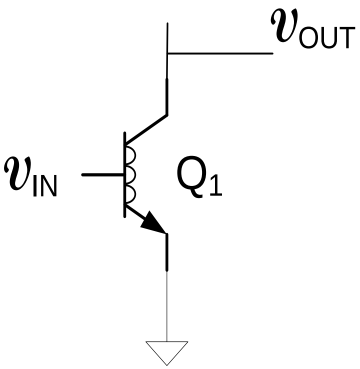
Small-signal Model of MOS Current Sinks and Sources



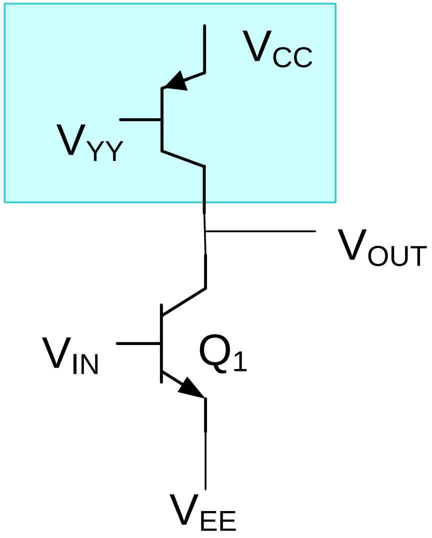
Small-signal model of all other MOS Sinks and Sources introduced thus far are the same

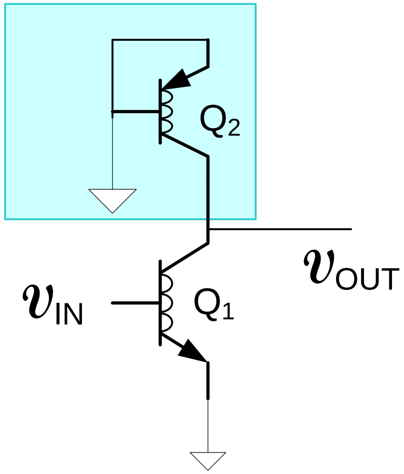
High-gain amplifier

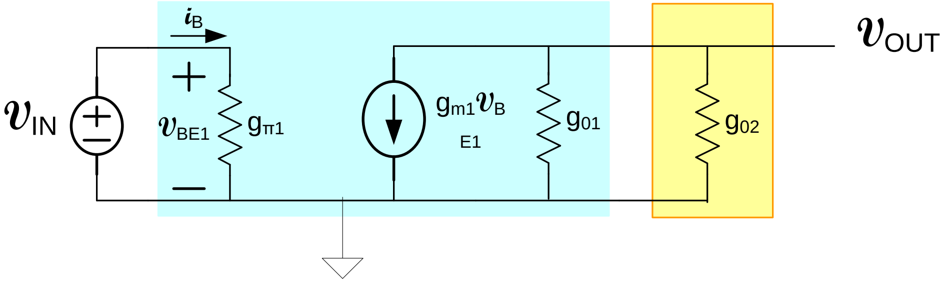




$$A_V = \frac{-g_m}{g_0}$$

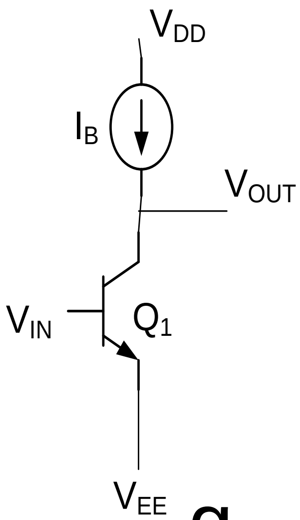




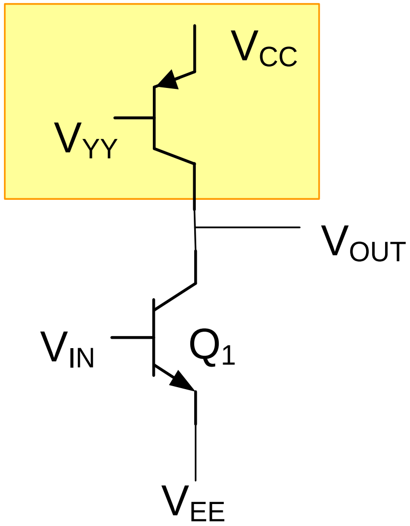


$$A_V = \frac{-g_{m1}}{g_{01} + g_{02}} \cong \frac{-g_{m1}}{2g_{01}}$$

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)**

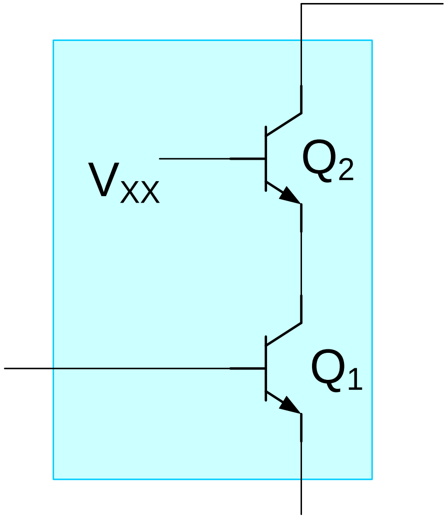
Can the gain be made even larger?

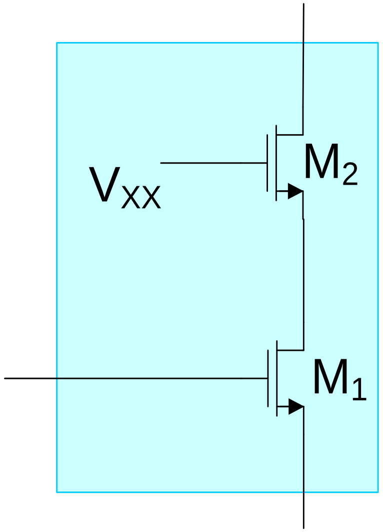
High-gain amplifier

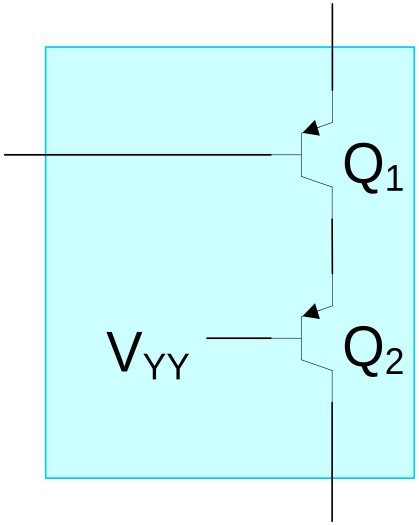
Can the gain be made even larger?

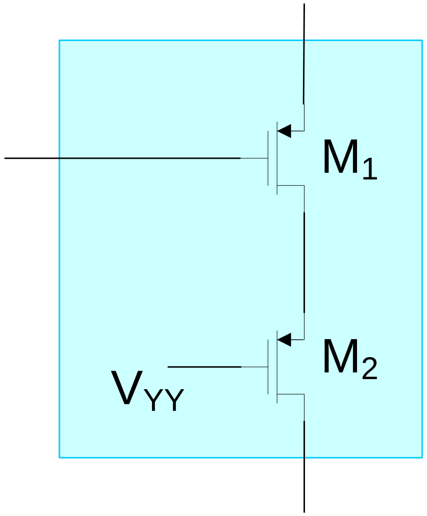
Discuss

The Cascode Configuration

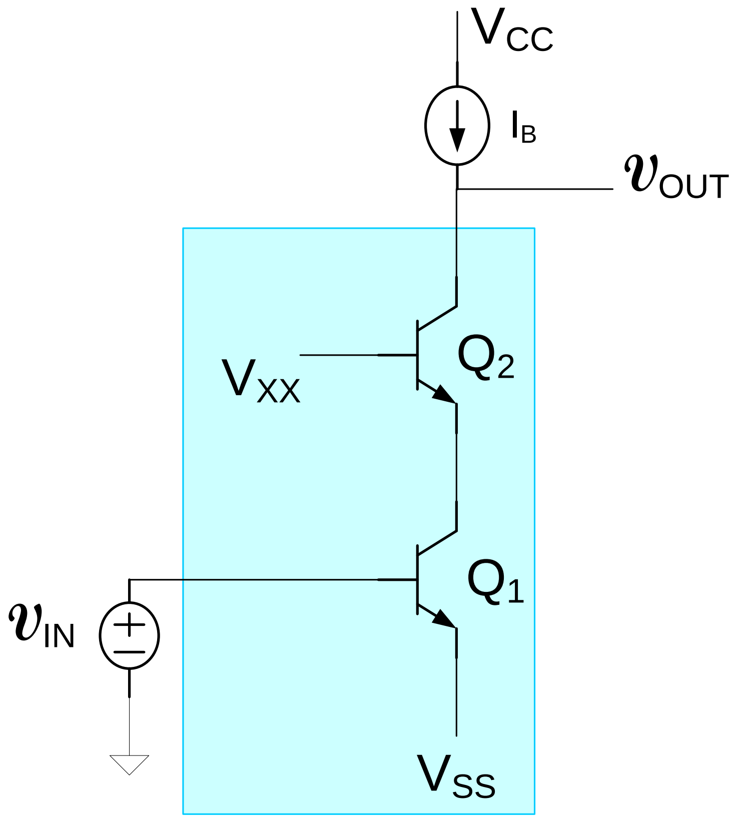








The Cascode Amplifier (consider npn BJT version)



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

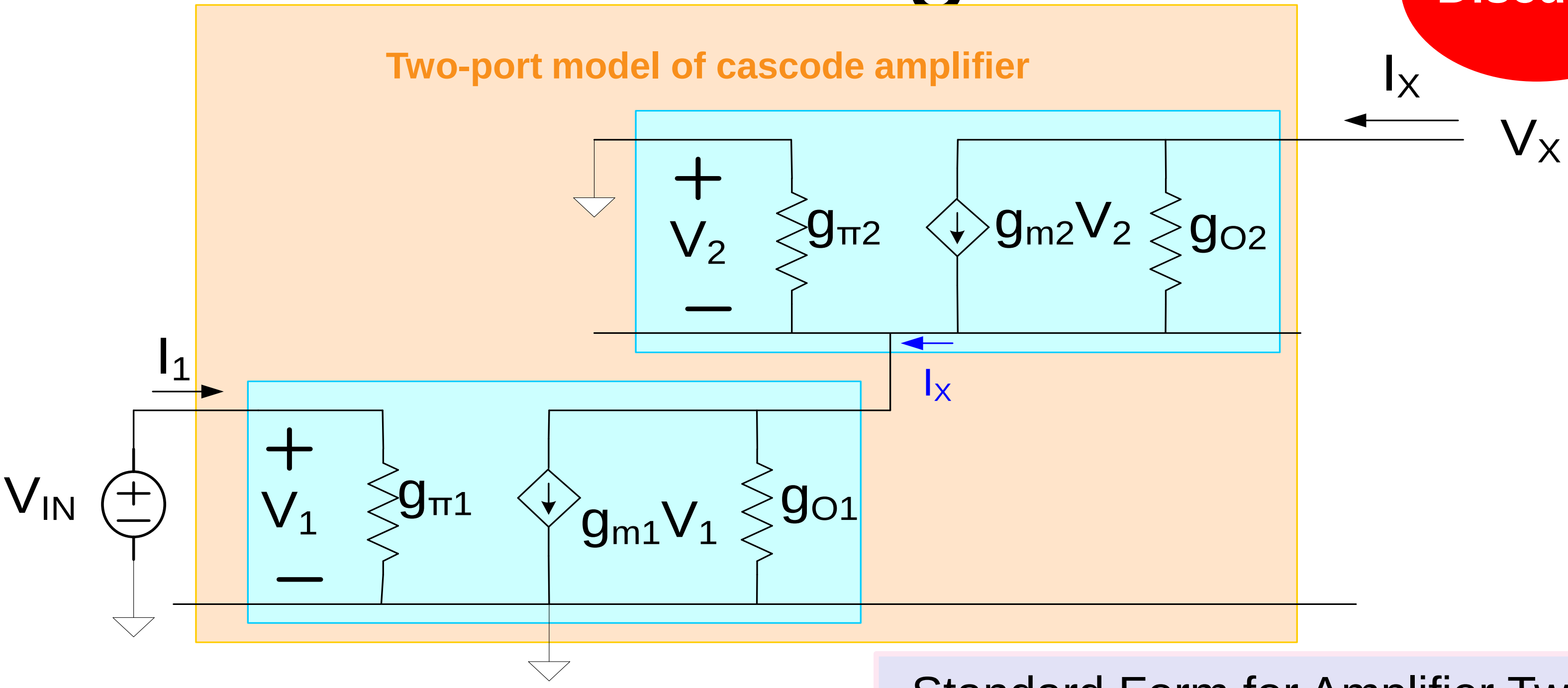
→

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

The first 4 are most popular

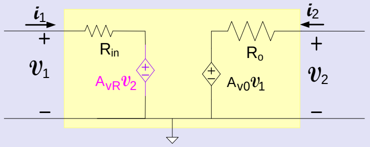
Cascode Configuration

Discuss



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

Standard Form for Amplifier Two-Port



$$\Longleftrightarrow\quad \begin{aligned}v_1 &= i_1 R_{IN} + A_{VR} v_2\\ v_2 &= i_2 R_O + A_{V0} v_1\end{aligned}$$

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

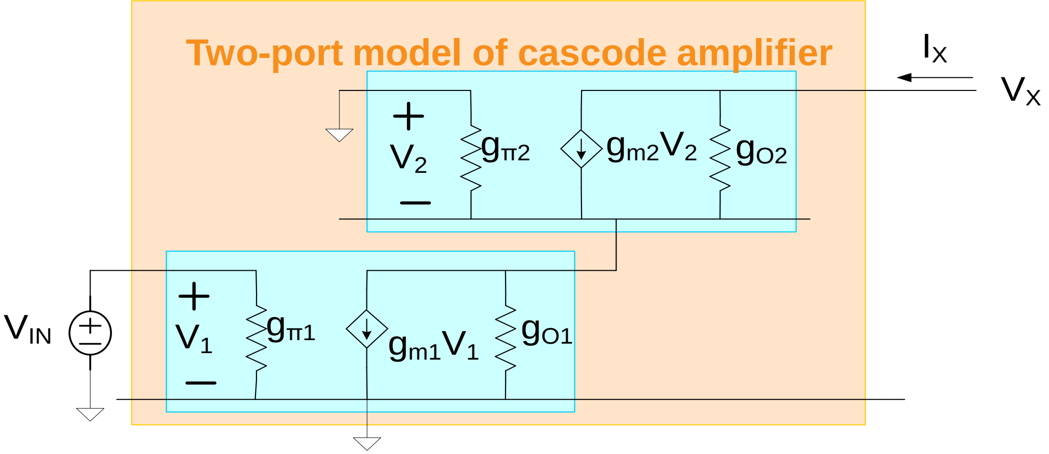
$$V_{IN}=I_1 \bullet \frac{1}{g_{\pi 1}}$$

and

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

Cascode Configuration

Discuss


Two-port model of cascode amplifier

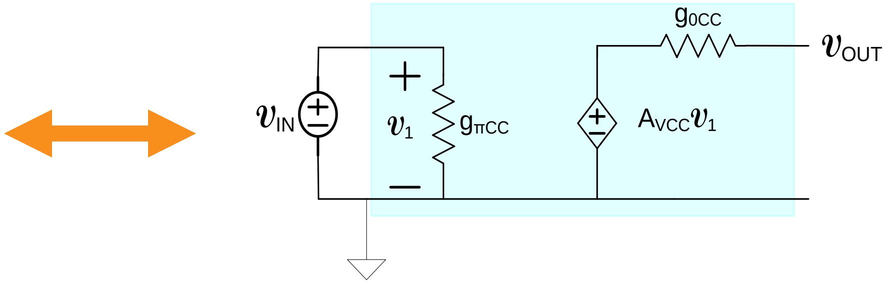
$$V_X = I_X \bullet \left[\frac{g_{01}+g_{02}+g_{\pi2}+g_{m2}}{g_{02}\left(g_{01}+g_{\pi2}\right)}\right] - V_{IN} \bullet \left[\frac{g_{m1}\left(g_{02}+g_{m2}\right)}{g_{02}\left(g_{\pi2}+g_{01}\right)}\right]$$

$$V_{IN} = I_1 \bullet \frac{1}{g_{\pi1}}$$

It thus follows for the npn bipolar structure that :

$$A_{VCC} = -\left[\frac{g_{m1}\left(g_{02}+g_{m2}\right)}{g_{02}\left(g_{\pi2}+g_{01}\right)}\right] \cong -\left[\frac{g_{m1}g_{m2}}{g_{02}g_{\pi2}}\right]$$

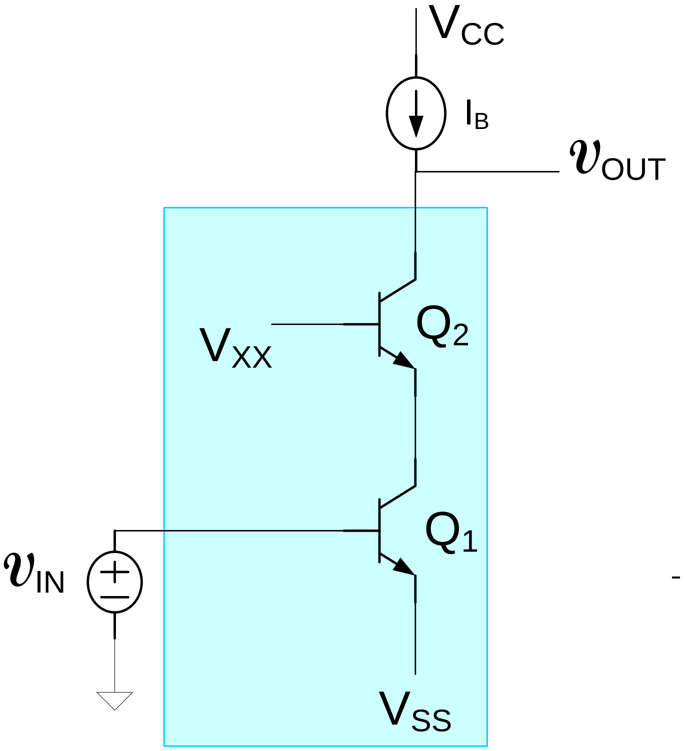
$$g_{0CC} = \left[\frac{g_{02}\left(g_{01}+g_{\pi2}\right)}{g_{01}+g_{02}+g_{\pi2}+g_{m2}}\right] \cong \left[\frac{g_{02}g_{\pi2}}{g_{m2}}\right]$$



$$g_{\pi CC} = g_{\pi1}$$

Cascode Configuration

Discuss



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

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

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

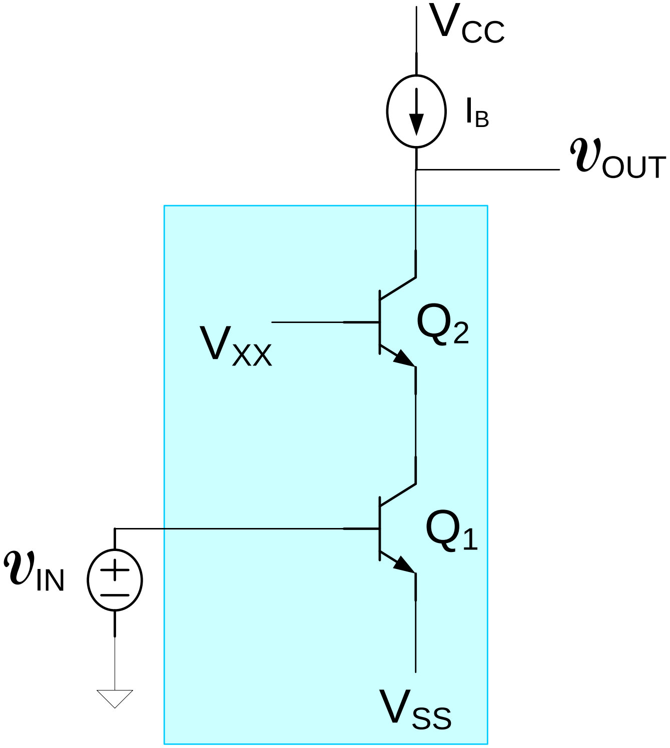
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{02}}\beta\right] \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

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

- **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



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

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

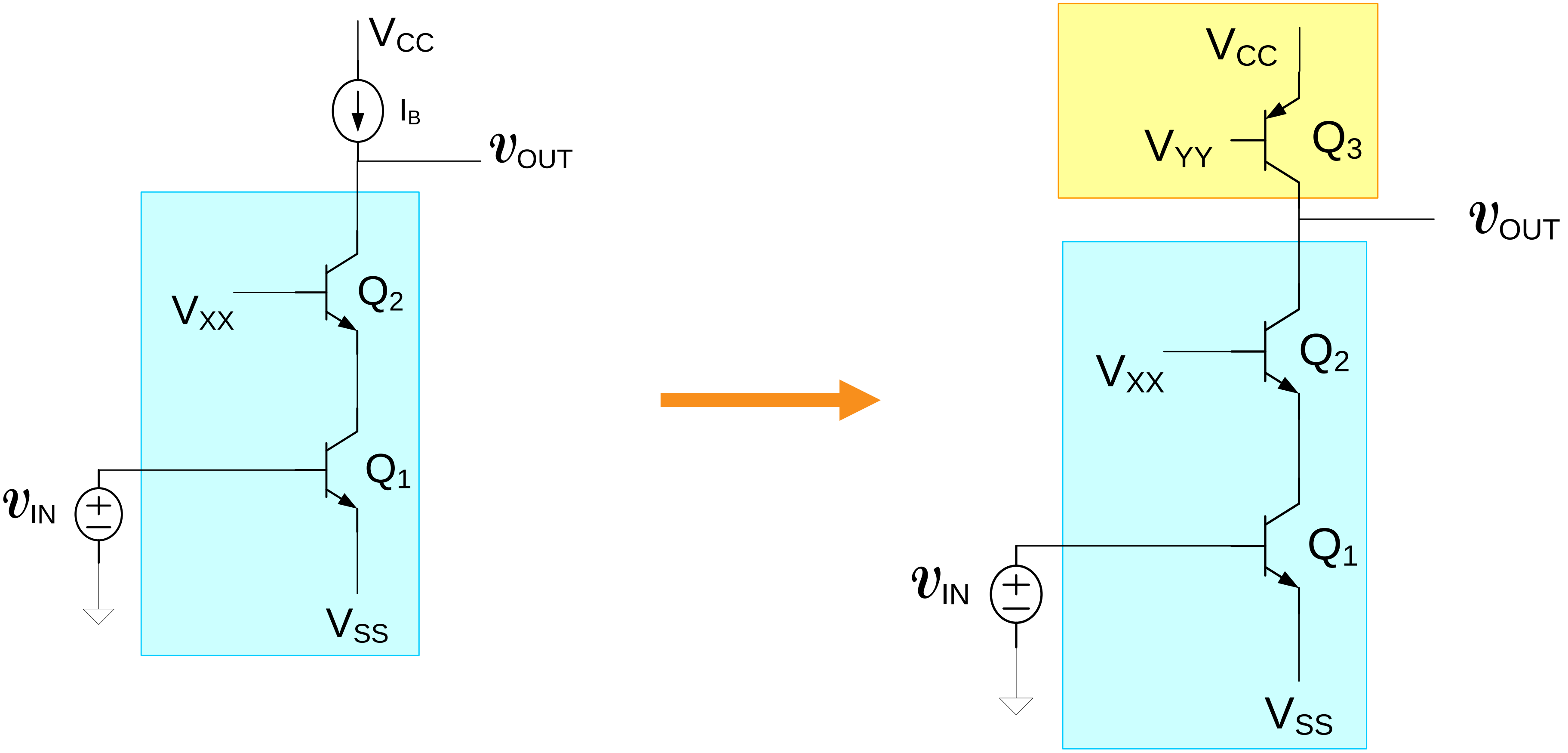
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta = \left[\frac{2V_{AF}}{V_t}\right]\beta = [-8000]100$$

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

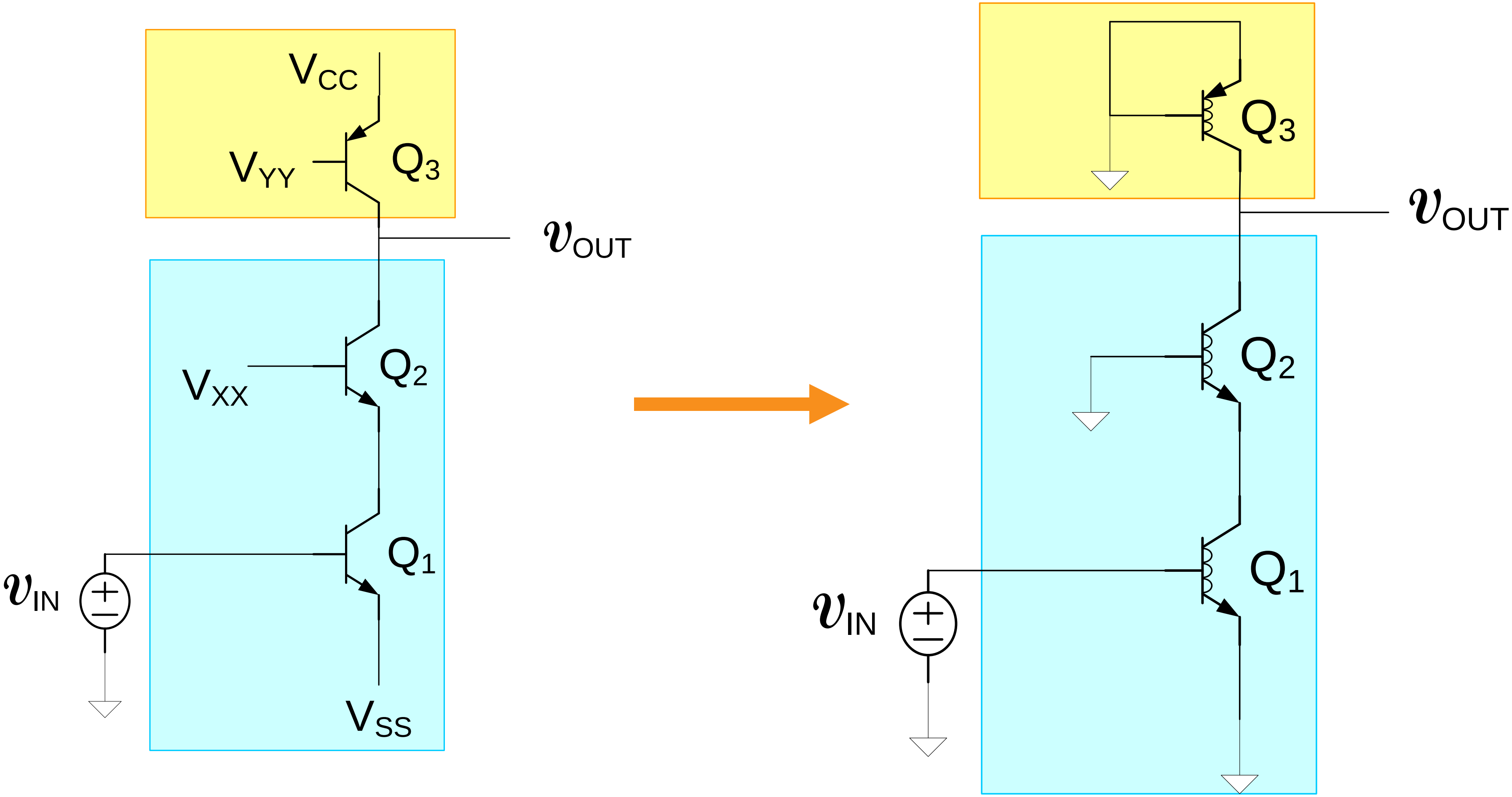
This gain is very large and only requires two transistors!

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

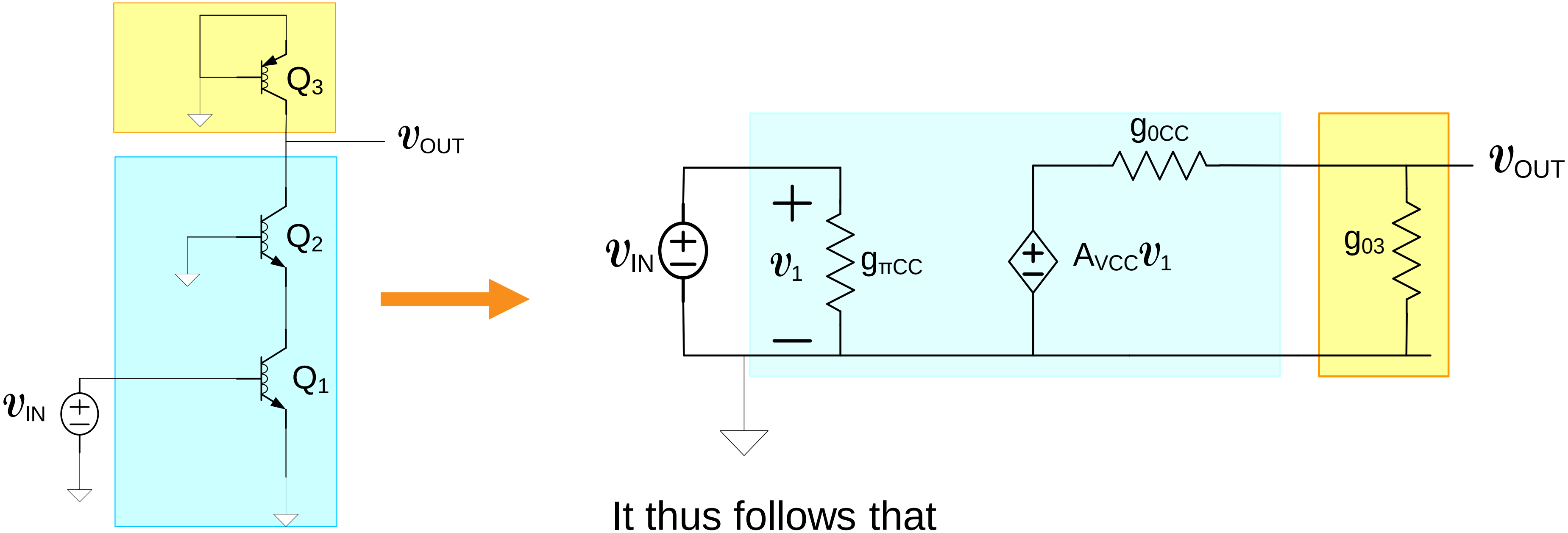
Cascode Configuration



Cascode Configuration



High-gain amplifier comparisons



It thus follows that

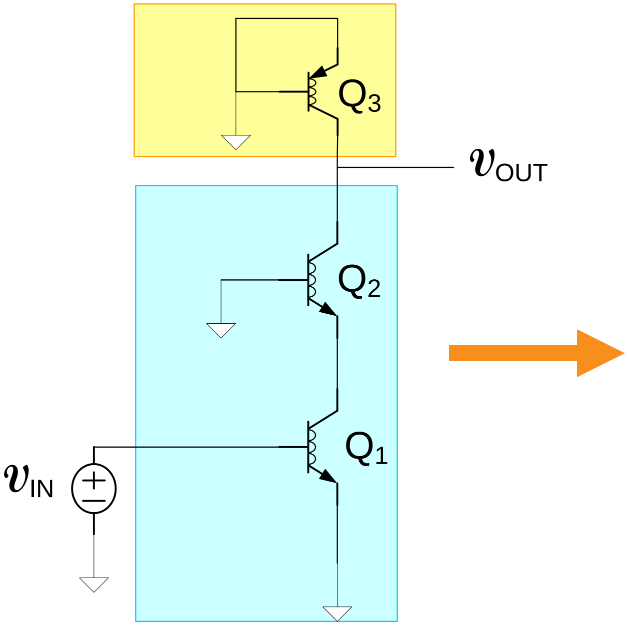
$$A_V = A_{VCC}\left[\frac{g_{0CC}}{g_{03}+g_{0CC}}\right]$$

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

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

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

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

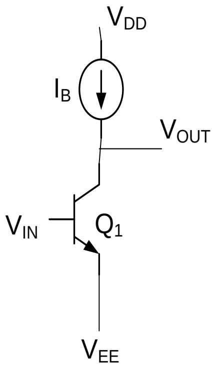
Thus

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

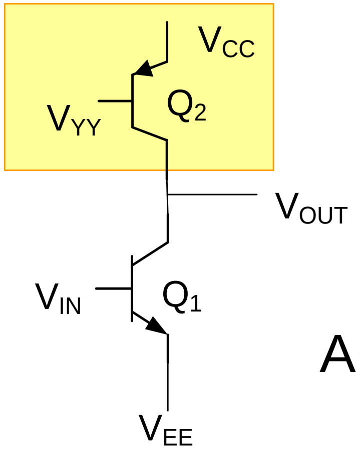
$$A_V \cong -\left[\frac{I_{CQ}/V_t}{I_{CQ}/V_{AF}}\right] = -\left[\frac{V_{AF}}{V_t}\right] \cong -8000$$

- **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**

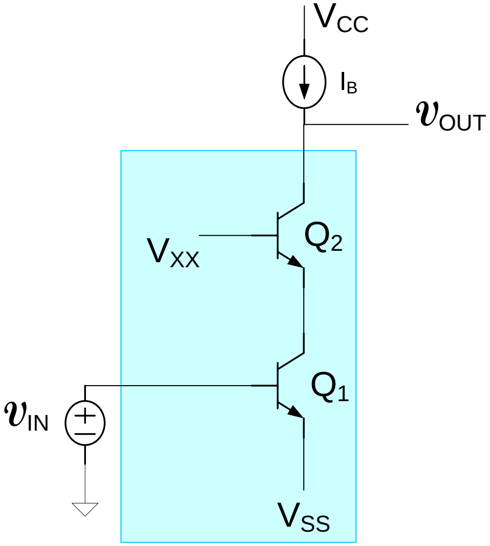
Cascode Configuration Comparisons



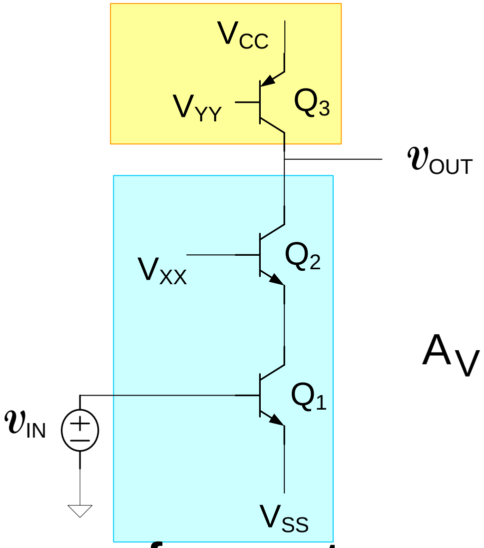
$$A_V = \frac{-g_m}{g_0}$$



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



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



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

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

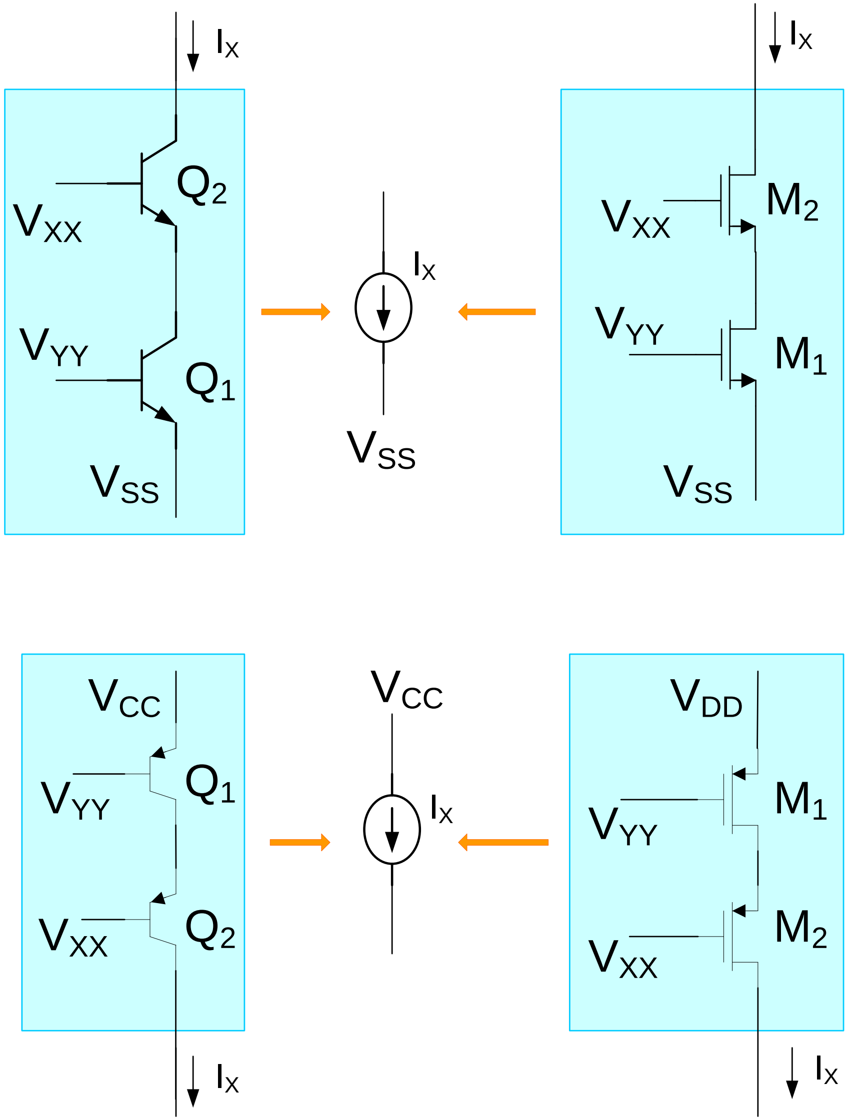
Need a higher output impedance than g_o

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

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

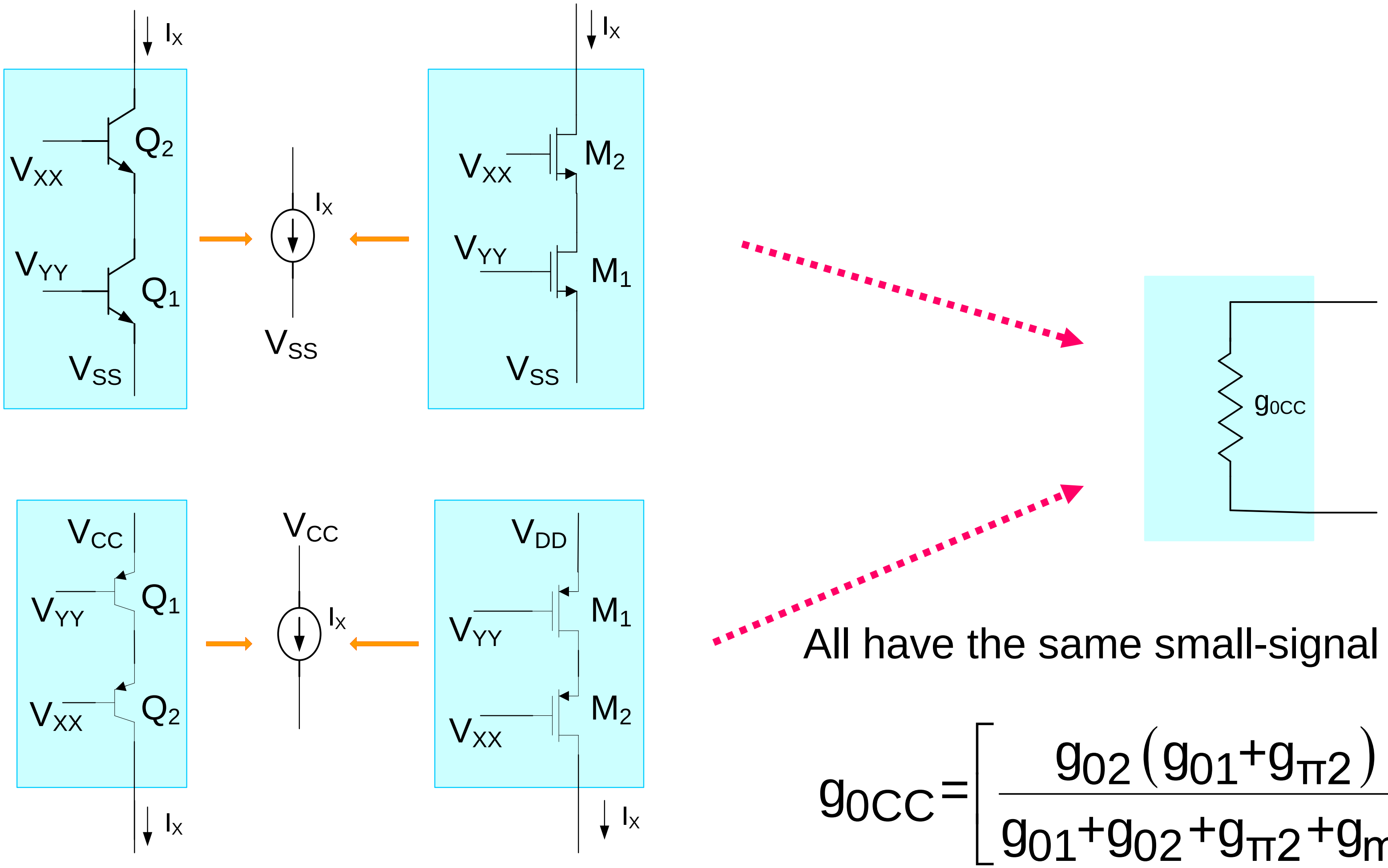
Can a current source be built with the cascode circuit ?

Cascode current sources



Discuss

Cascode current sources

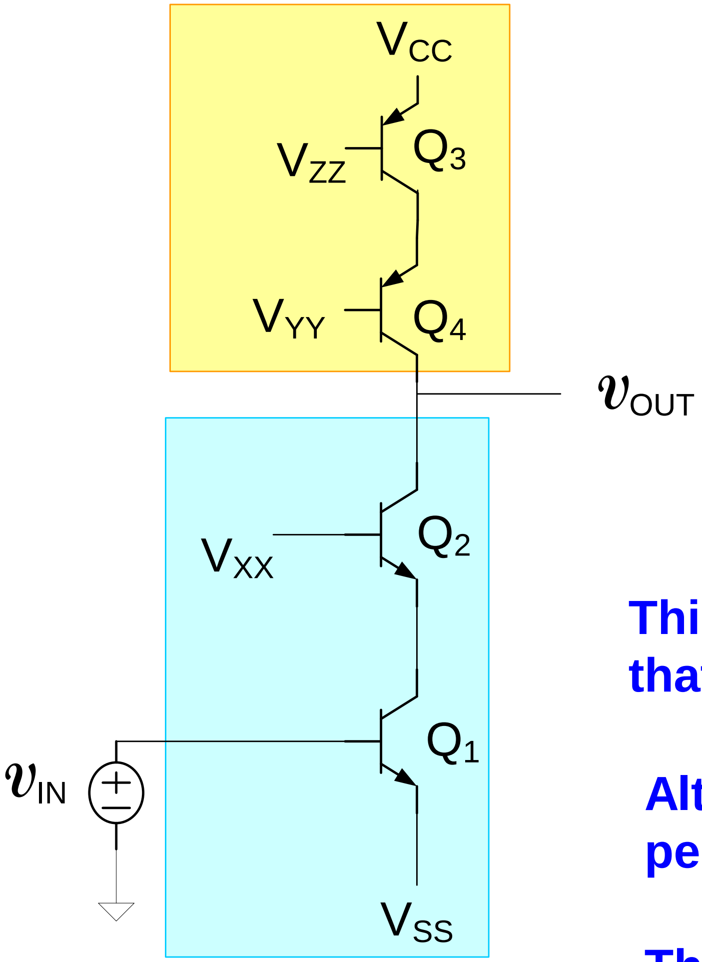


All have the same small-signal model

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

Cascode Configuration

Discuss



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

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

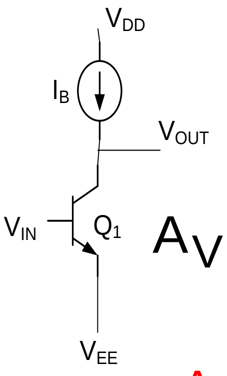
This gain is very large and is a factor of 2 below that obtained with an ideal current source biasing

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

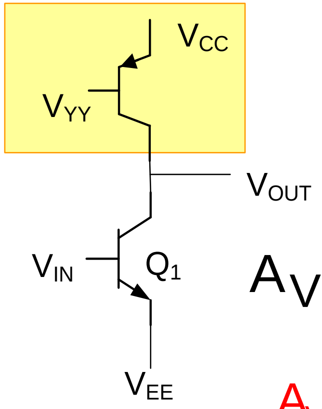
Cascode Configuration Comparisons

Discuss



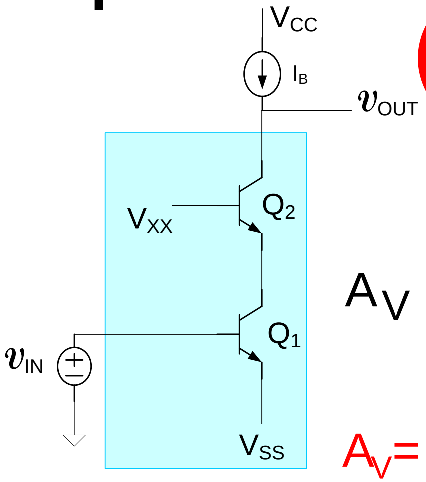
$$A_V = \frac{-g_m}{g_0}$$

A_V= -8,000



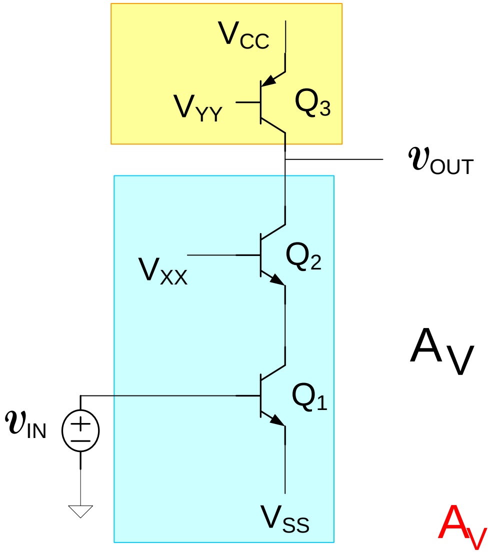
$$A_V \cong \frac{-g_{m1}}{2g_{01}}$$

A_V= -4,000



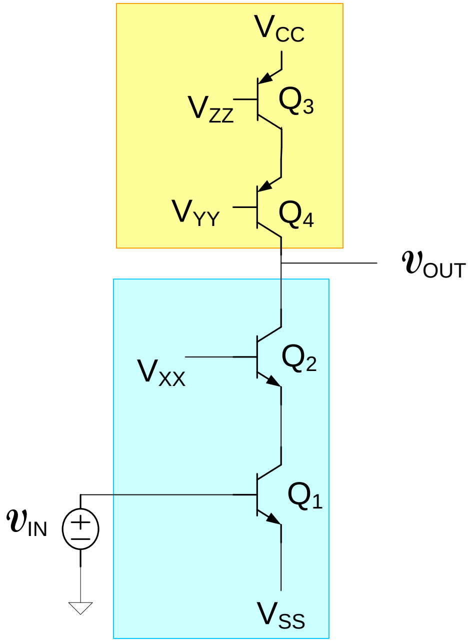
$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

A_V= -800,000



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

A_V= -8,000



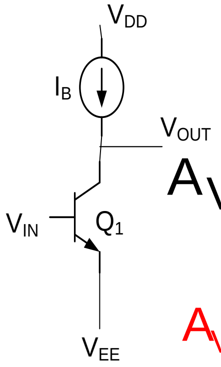
$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

A_V= -400,000

Can we use more cascoding to further increase the gain?

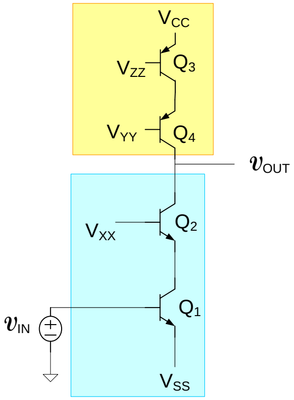
High Gain Amplifiers Seldom Used Open Loop

Discuss



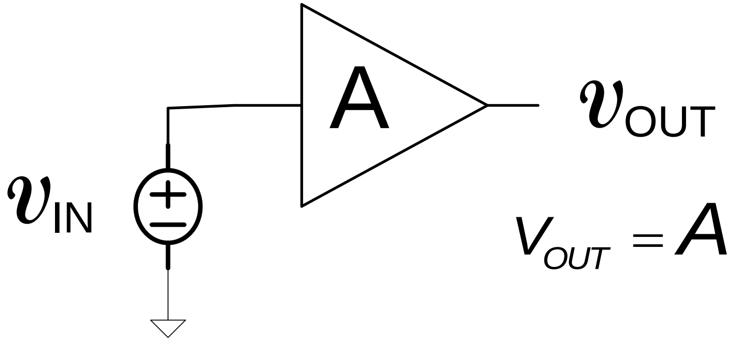
$$A_V = \frac{-g_m}{g_0}$$

A_V= -8,000



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

A_V= -400,000



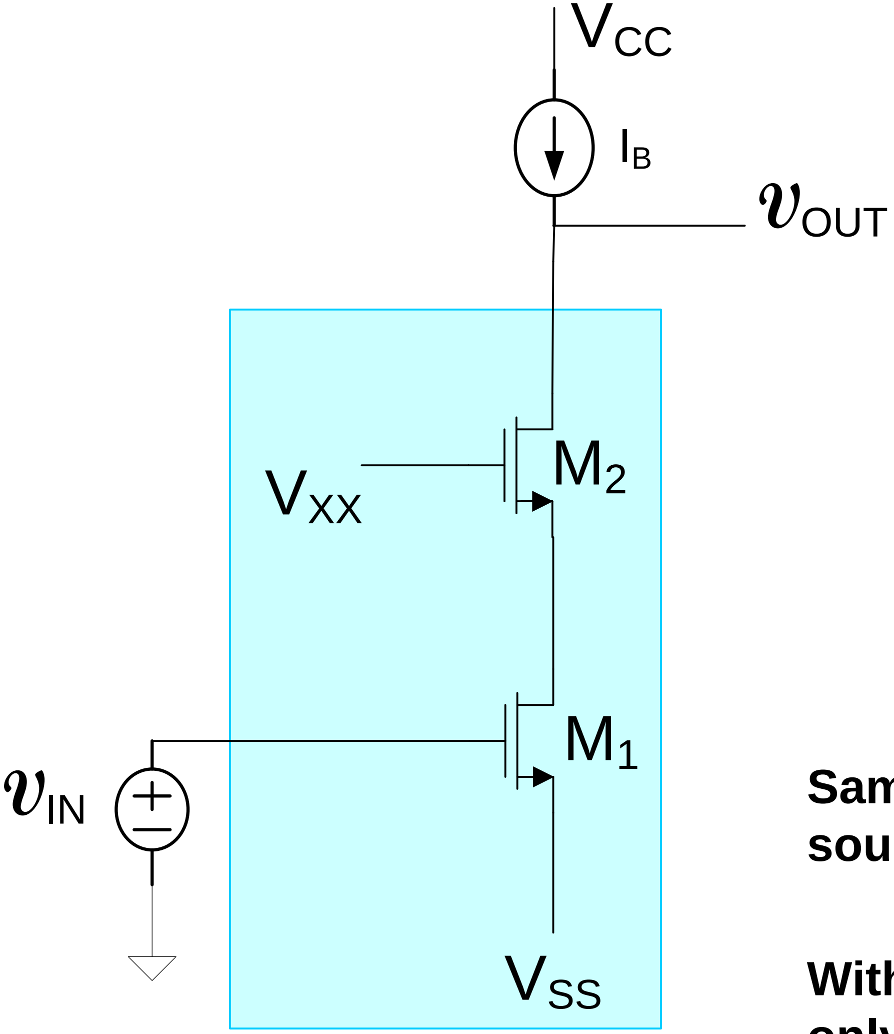
$$V_{OUT} = A\,v_{IN} + V_{OUTQ}$$

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



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

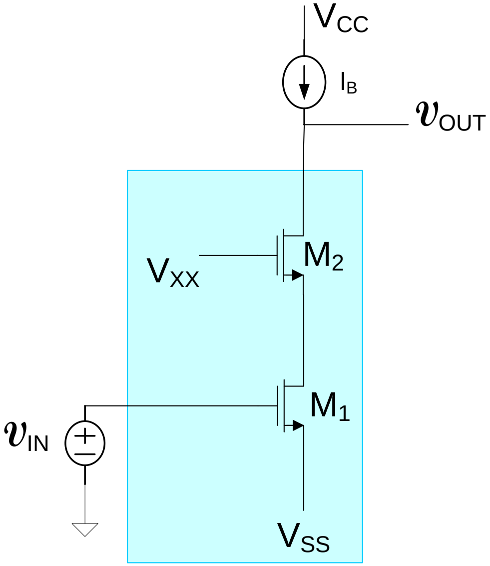
$$g_{0CC} \cong \left[\frac{g_{01}g_{02}}{g_{m2}}\right]$$

Same issues for biasing with current source as for BJT case

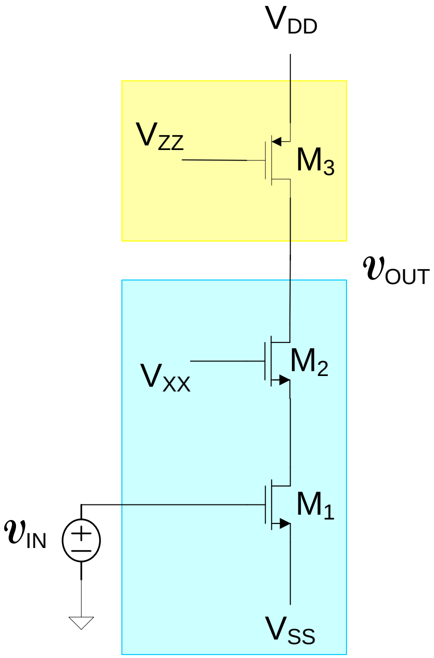
With cascode current source for I_B, gain only drops by a factor of 2 from value with ideal current source

The Cascode Amplifier (consider n-ch MOS version)

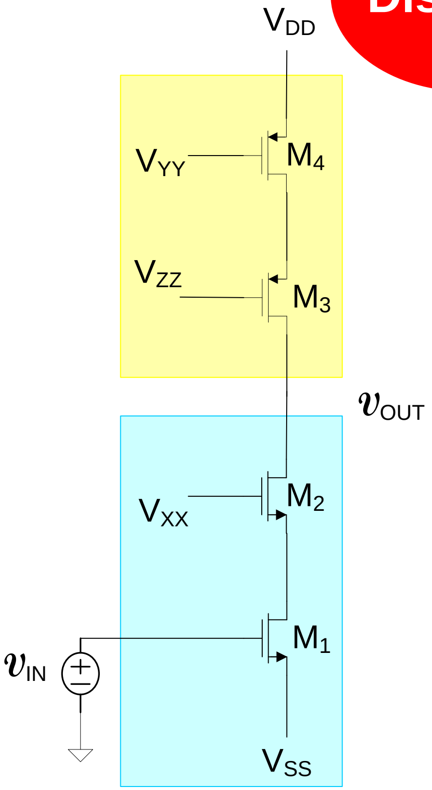
Discuss



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



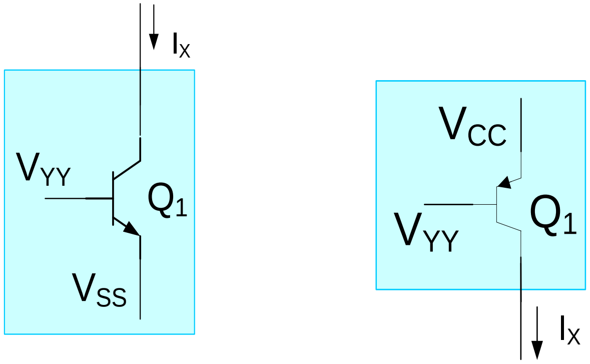
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

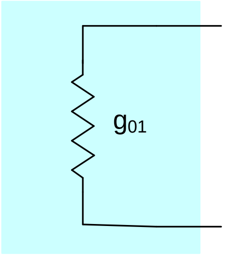


$$A_{VCC} \cong -\frac{1}{2}\left[\frac{g_{m1}g_{m2}}{g_{01}g_{02}}\right]$$

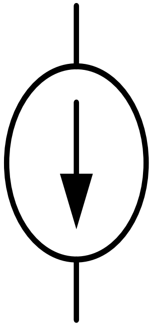
Current Source Summary (BJT)

Basic

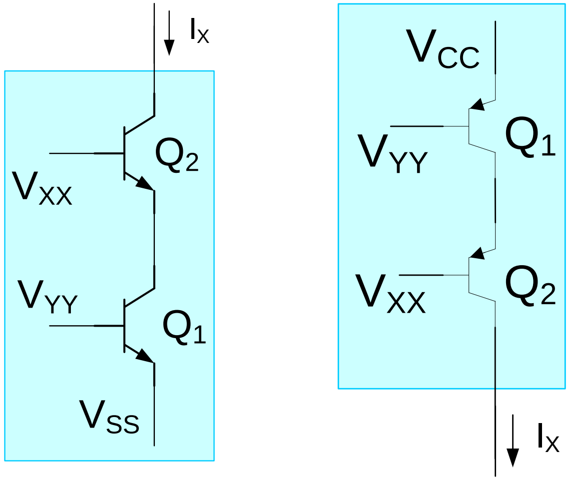


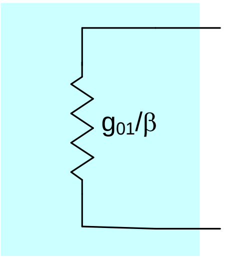


$$g_0 \cong g_{01}$$



Cascode



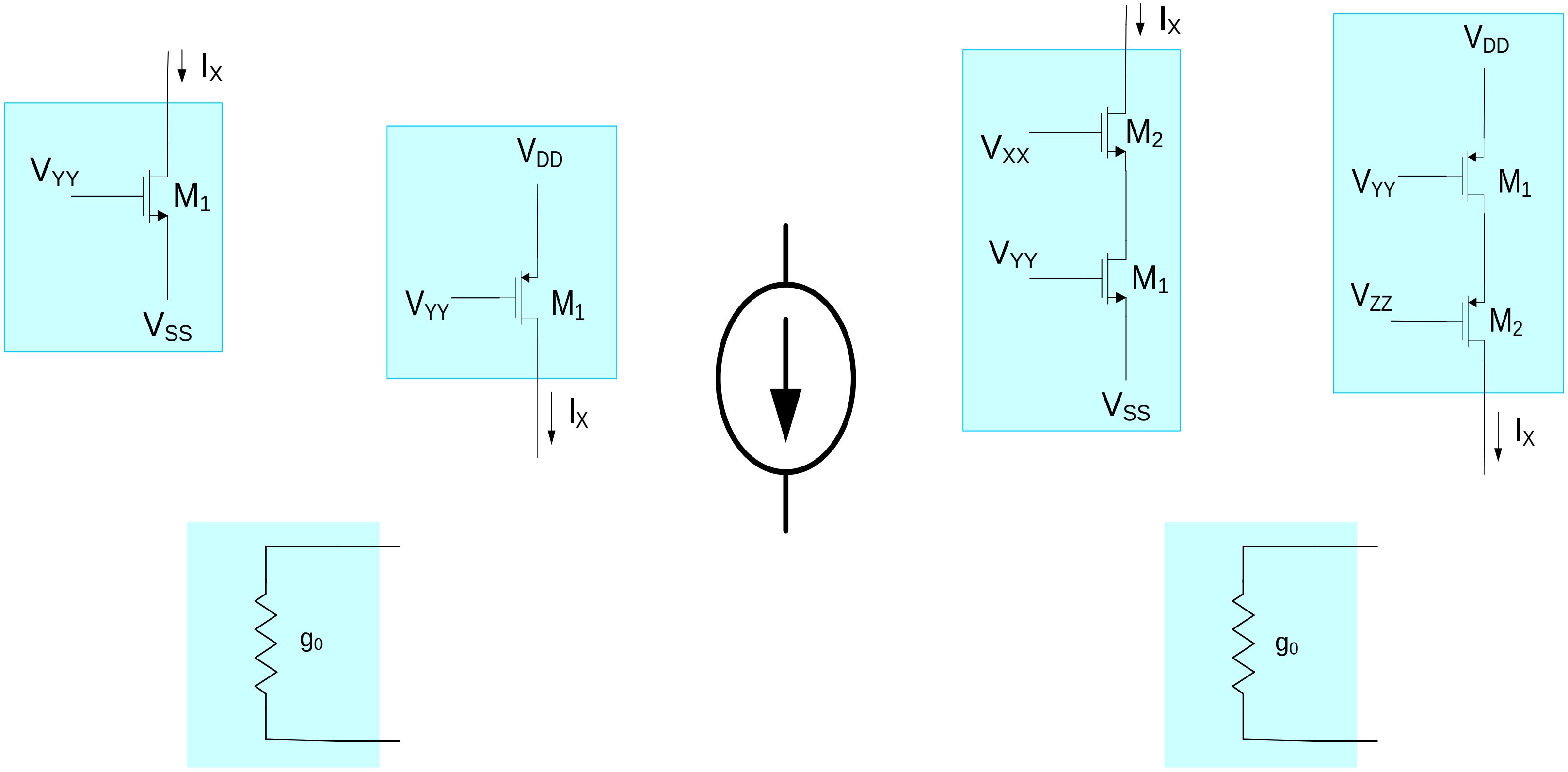


$$g_{0CC} \cong \frac{g_{01}}{\beta}$$

Current Source Summary (MOS)

Basic

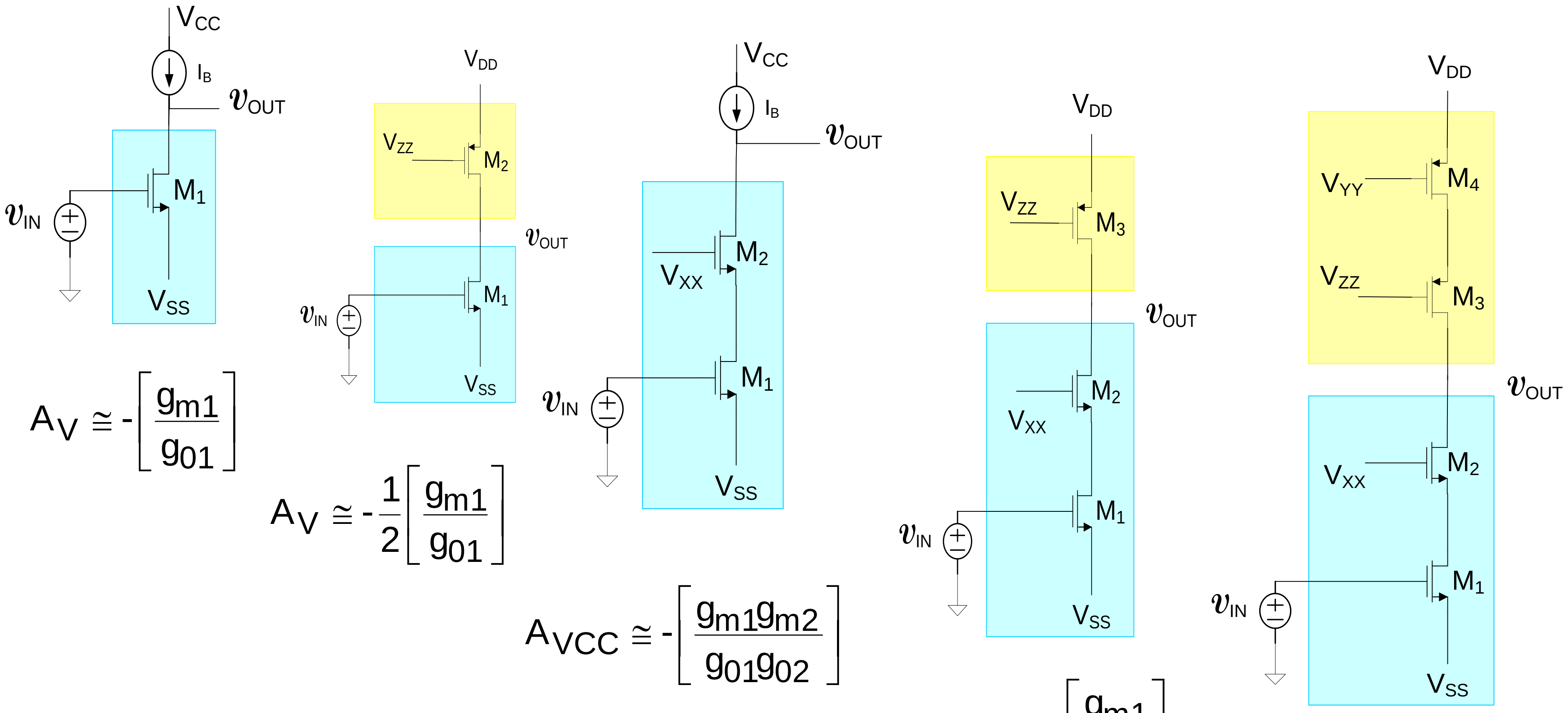
Cascode



$$g_0 \cong g_{01}$$

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

High Gain Amplifier Comparisons (n-ch MOS)



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

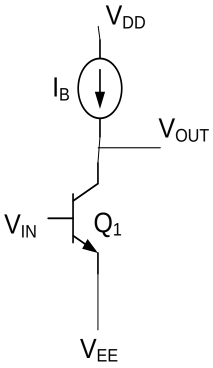
$$A_V \cong -\frac{1}{2}\left[\frac{g_{m1}}{g_{01}}\right]$$

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

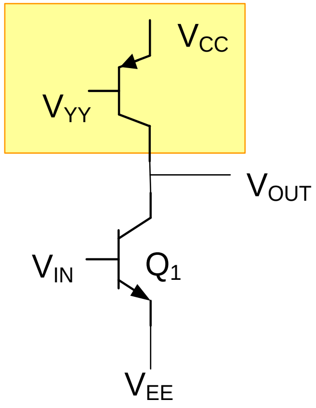
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

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

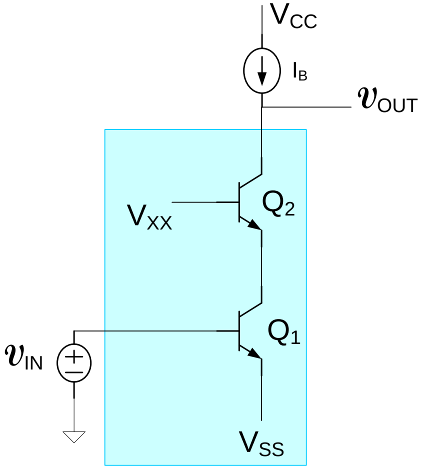
High Gain Amplifier Comparisons (BJT)



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

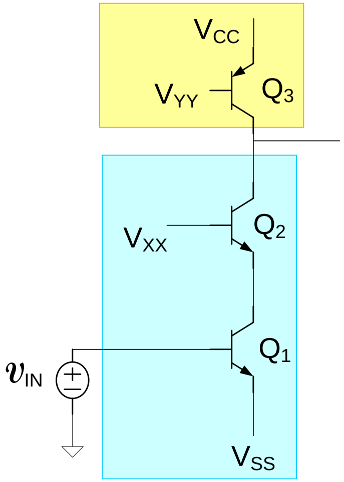


$$A_V \cong -\frac{1}{2}\frac{g_{m1}}{g_{01}}$$

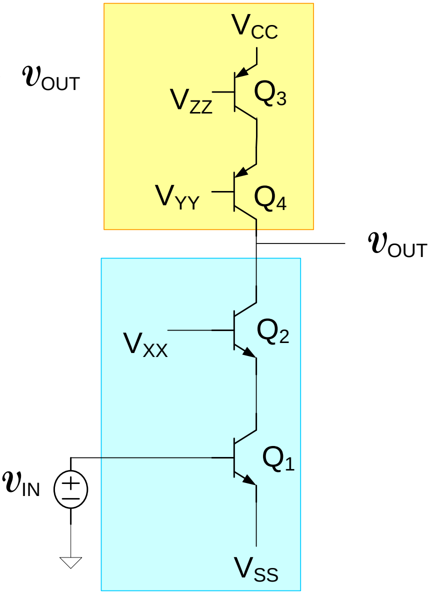


$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

- 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



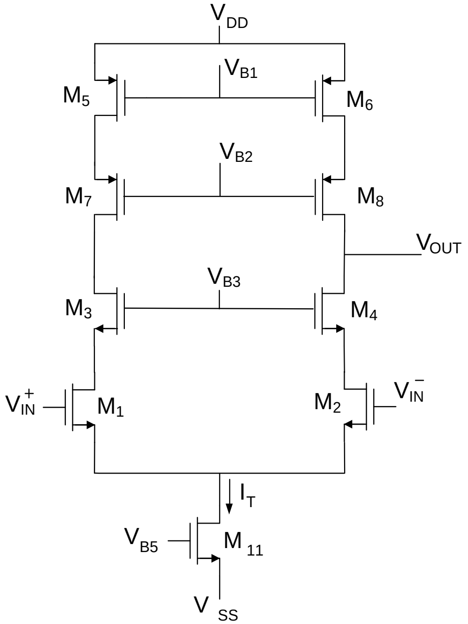
$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$



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

The Cascode Amplifier

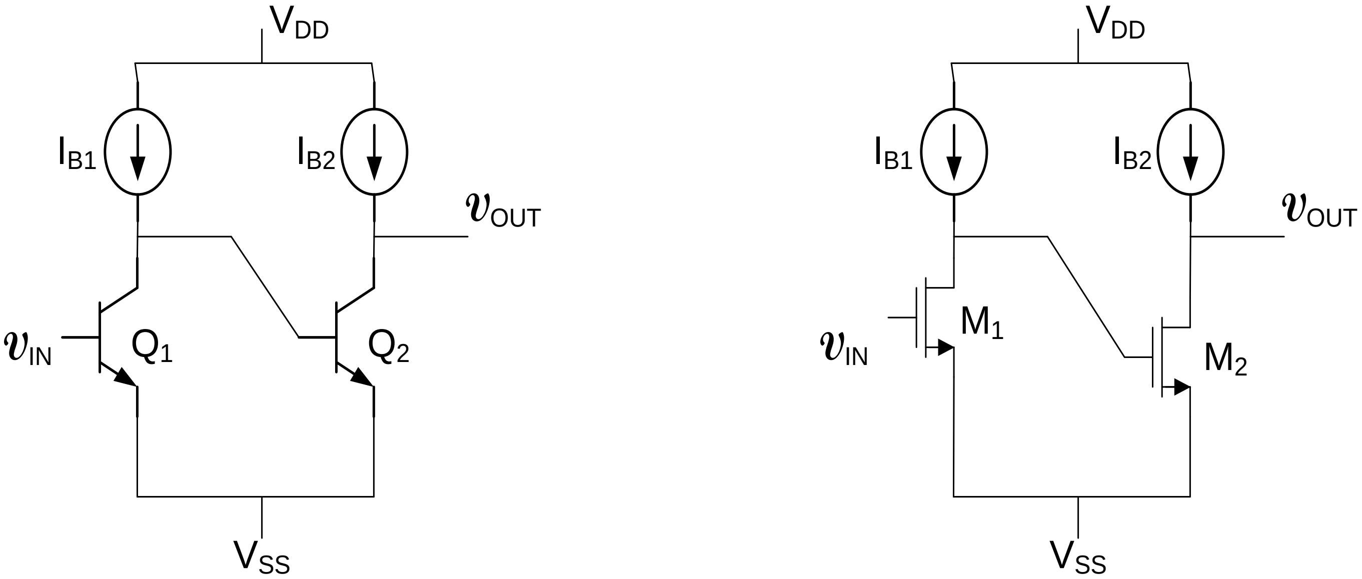
- **Operational amplifiers often built with basic cascode configuration**
- **CMFB used to address the biasing problem**
- **Usually configured as a differential structure when building op amps**
- **Have high output impedance (but can be bufferred)**
- **Terms "telescopic cascode", "folded-cascode", and "regulated cascode" often refer to op amps based upon the cascode configuration**



Telescopic Cascode Op Amp

(CMFB feedback biasing not shown)

Cascade Configurations

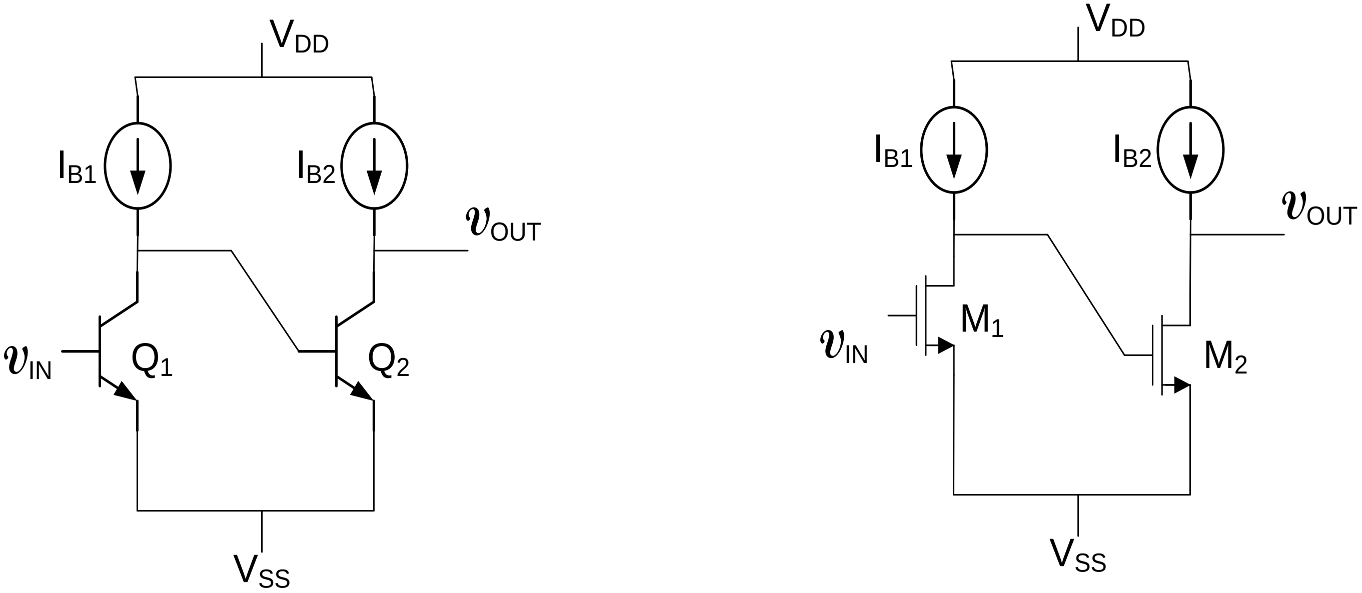


Two-stage CE:CE or CS:CS Cascade

$$A_{VCB} = ?$$

$$A_{VCM} = ?$$

Cascade Configurations



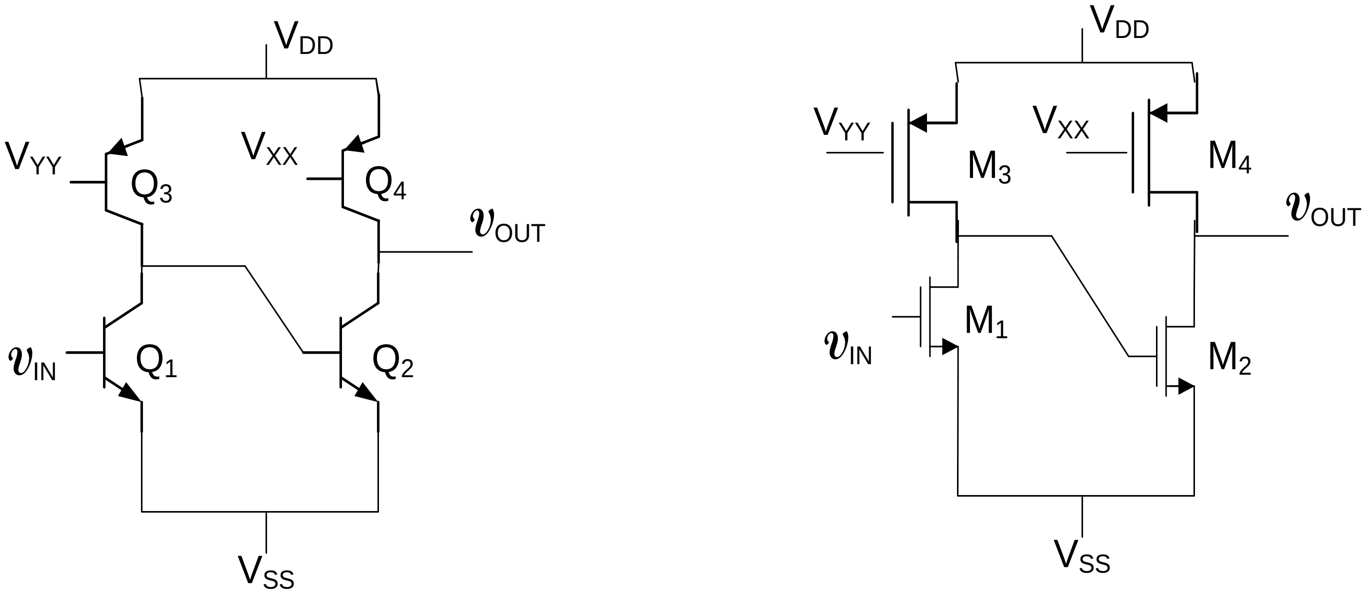
Two-stage CE:CE or CS:CS Cascade

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

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

- **Significant increase in gain**
- **Gain is noninverting**
- **Comparable to that obtained with the cascode but noninverting**

Cascade Configurations



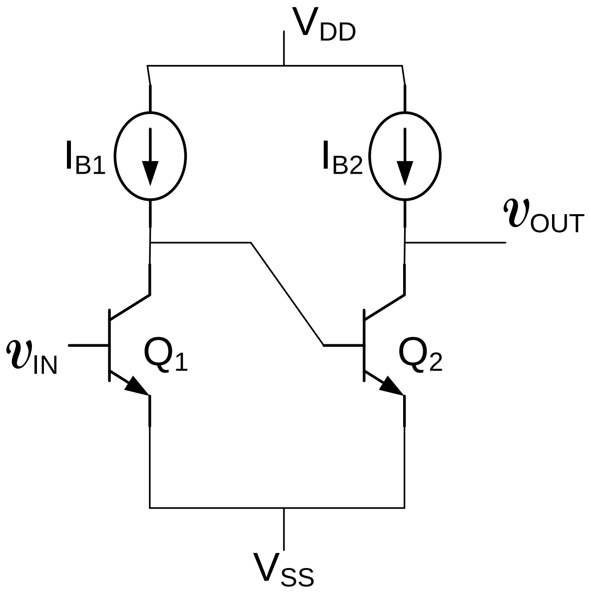
Two-stage CE:CE or CS:CS Cascade

$$A_{VCB} \cong \left[\frac{-g_{m1}}{g_{01}+g_{03}+g_{\pi 2}}\right]\left[\frac{-g_{m2}}{g_{02}+g_{04}}\right] \cong \frac{g_{m1}g_{m2}}{2g_{\pi 2}g_{02}} = \beta\frac{g_{m1}}{2g_{02}}$$

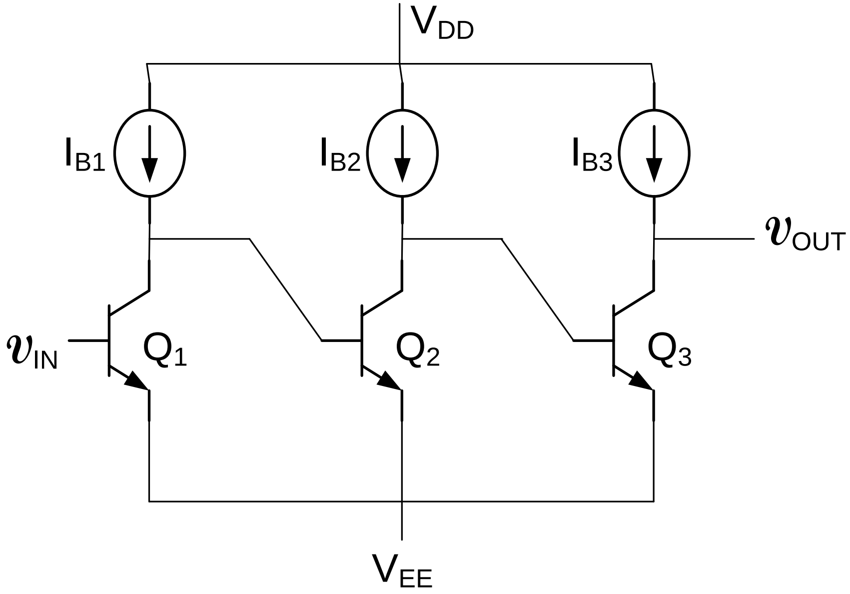
$$A_{VCM} = \left[\frac{-g_{m1}}{g_{01}+g_{03}}\right]\left[\frac{-g_{m2}}{g_{02}+g_{04}}\right] = \frac{g_{m1}g_{m2}}{4g_{01}g_{02}}$$

Note factor or 2 and 4 reduction in gain due to actual current source bias

Cascade Configurations



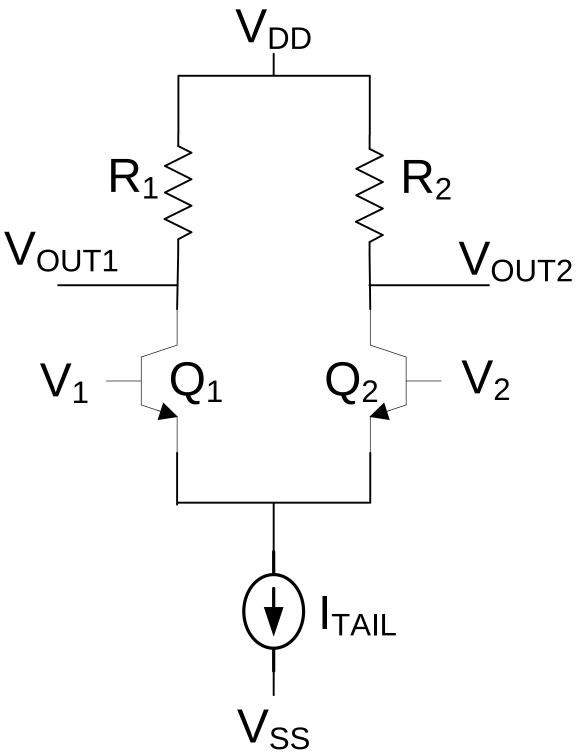
Two-stage CE Cascade



Three-stage CE Cascade

- Large gains can be obtained by cascading
- Gains are multiplicative (when loading is included)
- Large gains used to build “Op Amps” and feedback used to control gain value
- Some attention is needed for biasing but it is manageable
- Minor variant of the two-stage cascade often used to build Op Amps
- Compensation of two-stage cascade needed if feedback is applied to maintain stability
- For many years three or more stages were seldom cascaded because of challenges in compensation to maintain stability though recently some industrial adoptions

Differential Amplifiers



Basic operational amplifier circuit

Stay Safe and Stay Healthy !

End of Lecture 34