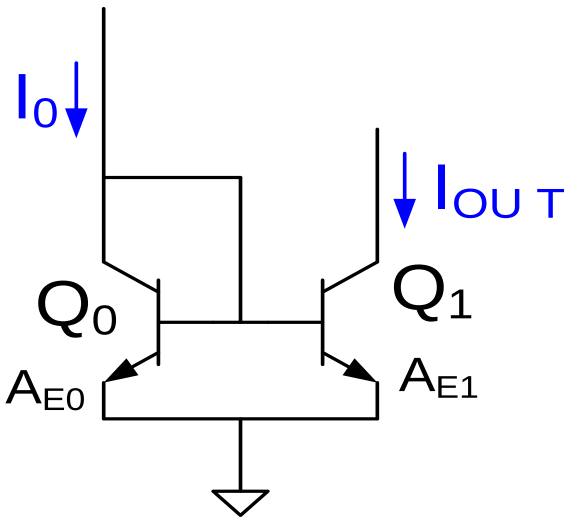
EE 330
Lecture 35

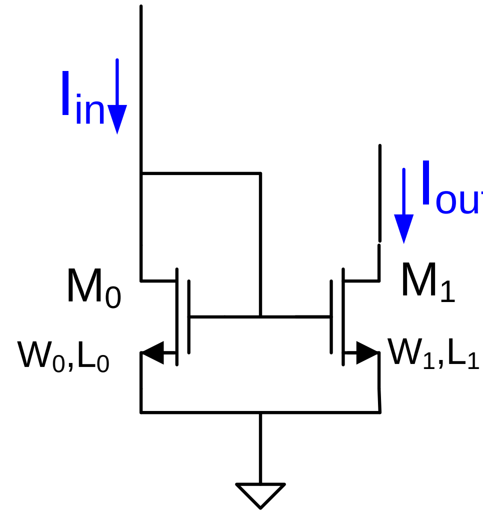
- High Gain Amplifiers
- Cascode and Cascade Configurations
- Biasing

Review from Last Lecture

Current Sources/Mirrors Summary



npn Current Mirror



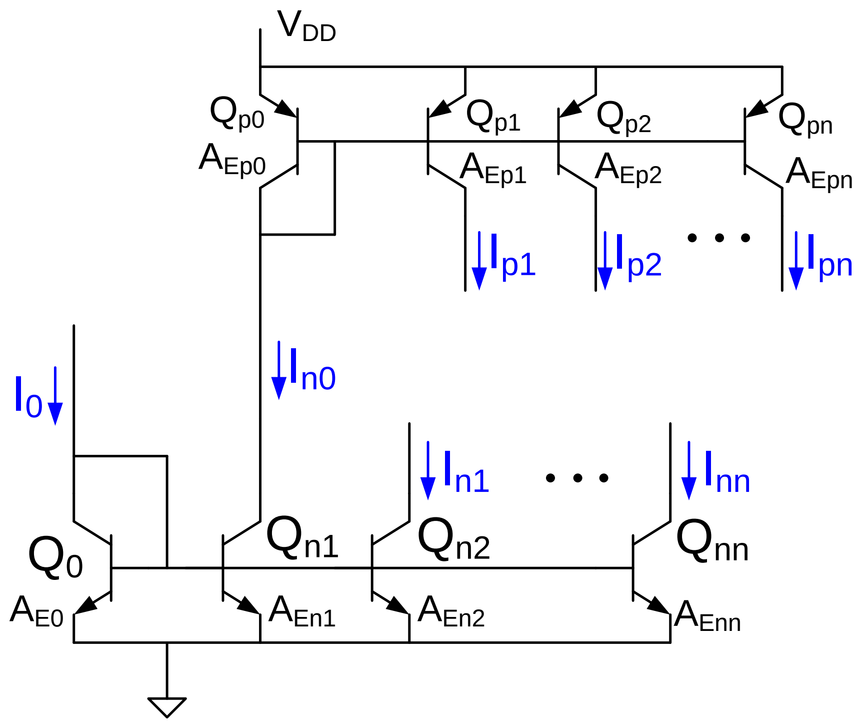
n-channel Current Mirror

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

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

Review from Last Lecture

Current Sources/Mirrors



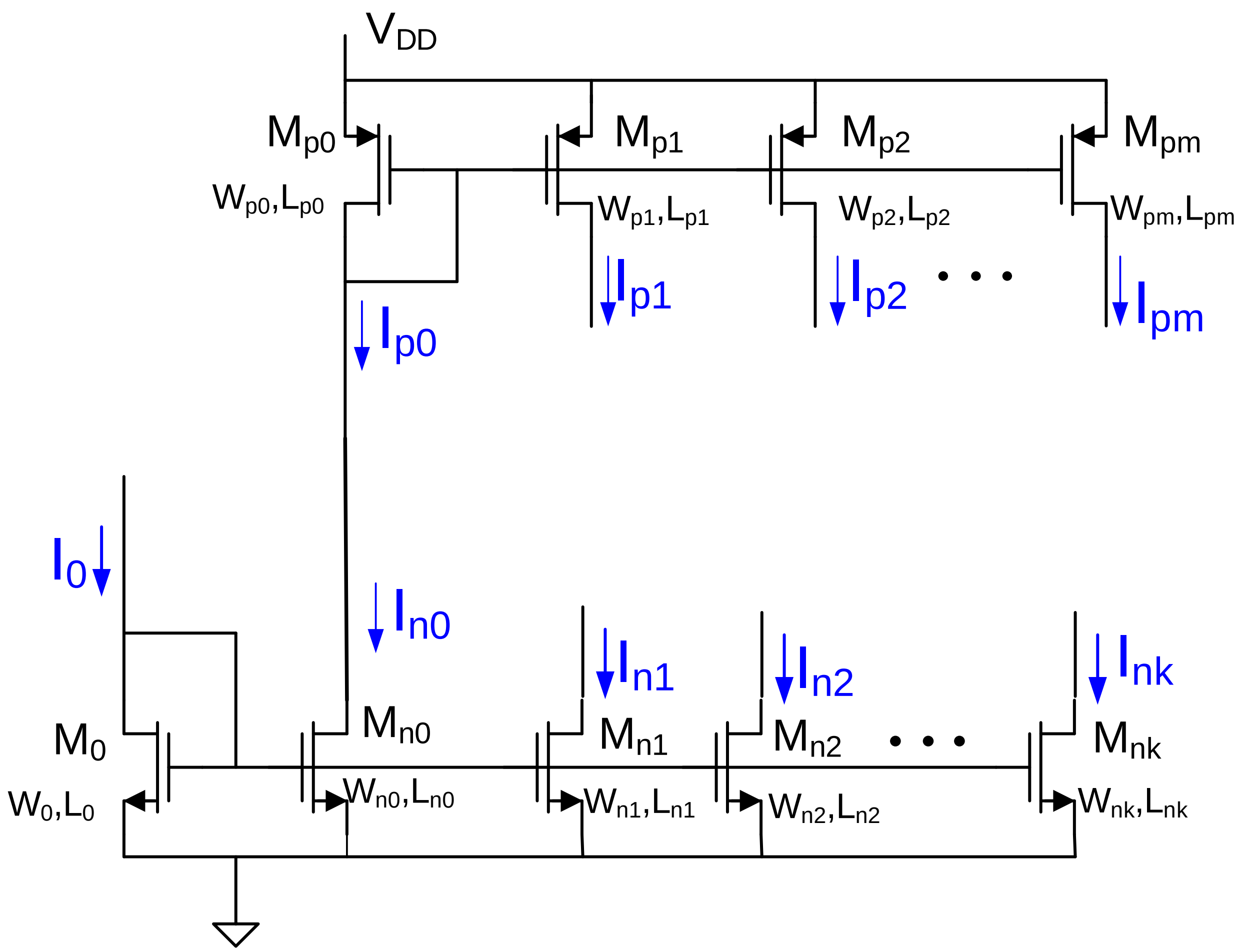
Multiple-Output Bipolar Current Source and Sink

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

Review from Last Lecture

Current Sources/Mirrors

multiple sourcing and sinking current outputs



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

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

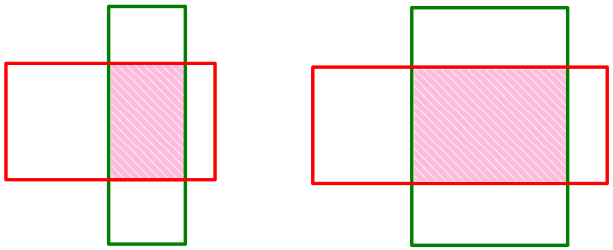
$$I_{nj}=\left[\frac{W_{nj}}{L_{nj}}\bullet\frac{L_0}{W_0}\right]I_0$$

m and k may be different
Often M=1

Review from Last Lecture

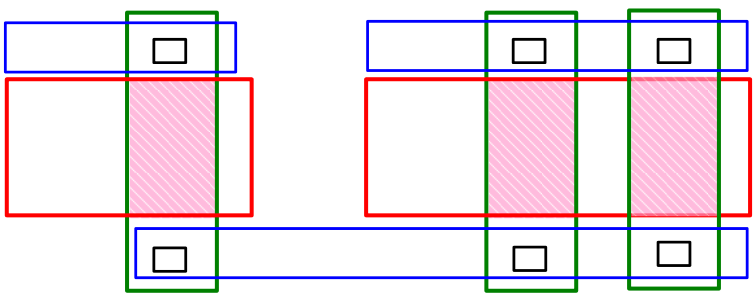
Layout of Current Mirrors

Example with M = 2



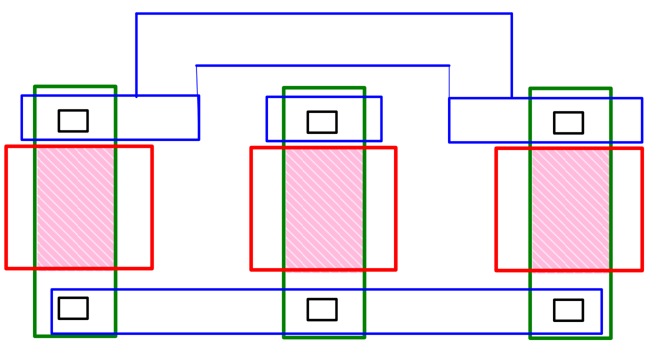
Standard layout

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



Better Layout

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



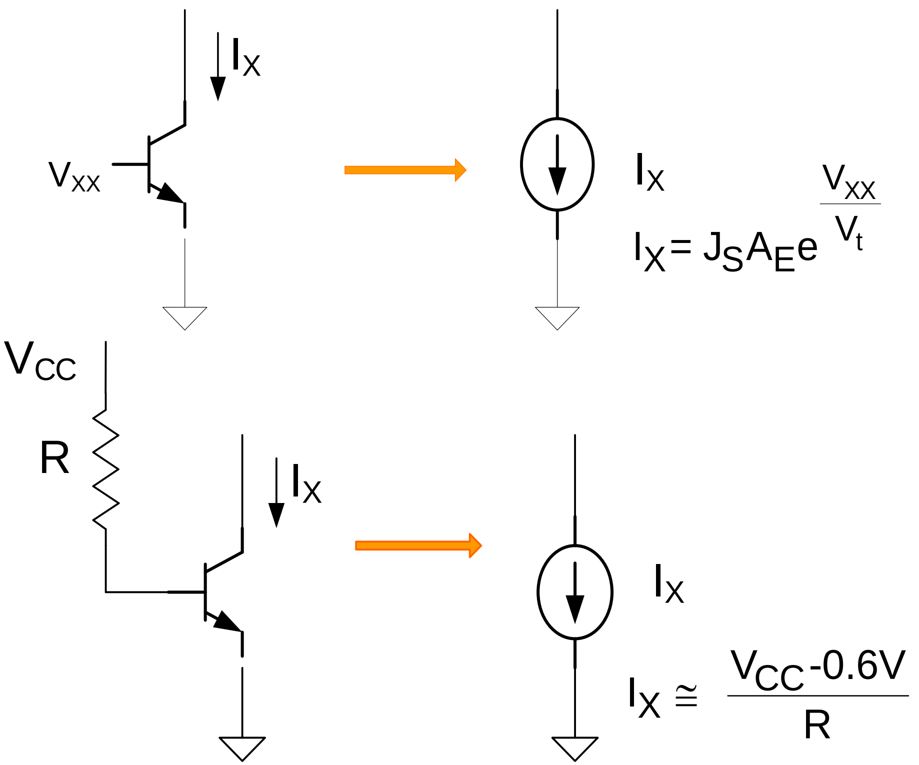
Even Better Layout

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

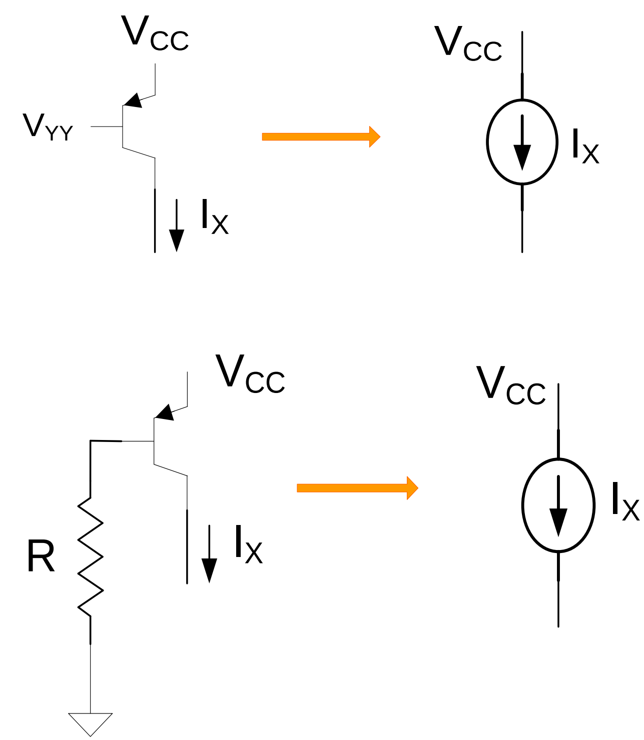
This is termed a common-centroid layout

Basic Current Sources and Sinks

Basic Bipolar Current Sinks

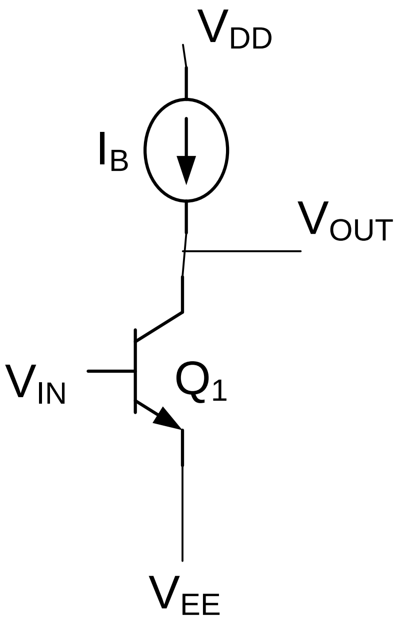


Basic Bipolar Current Sources



- 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

High-gain amplifier



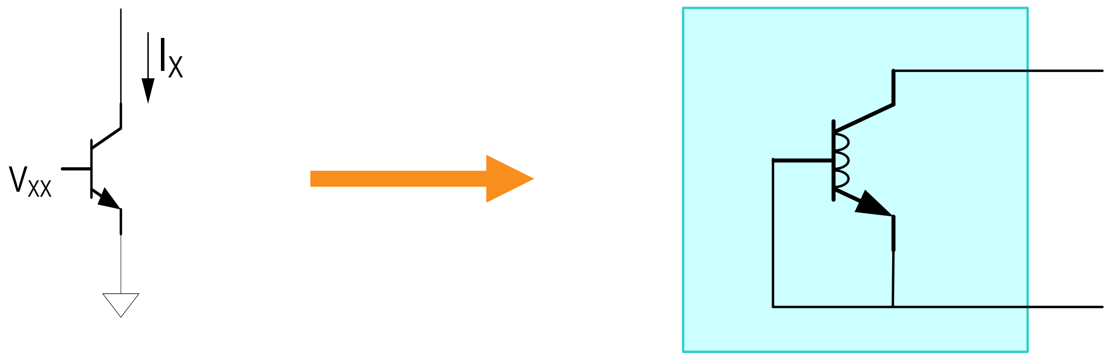
$$A_V \cong -8000$$

How can we build the current source?

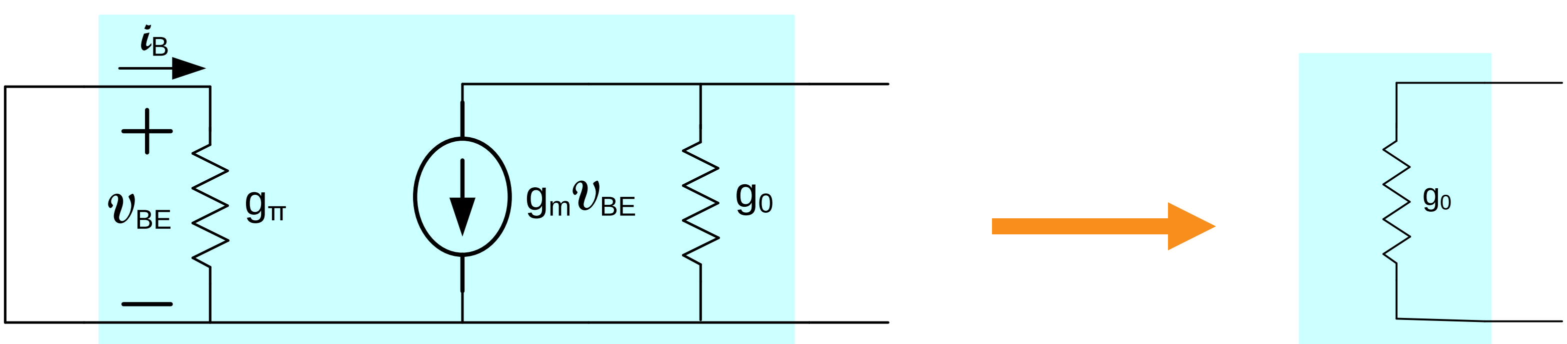
What is the small-signal model of an actual current source?

Basic Current Sources and Sinks

Small-signal Model of BJT Current Sinks and Sources



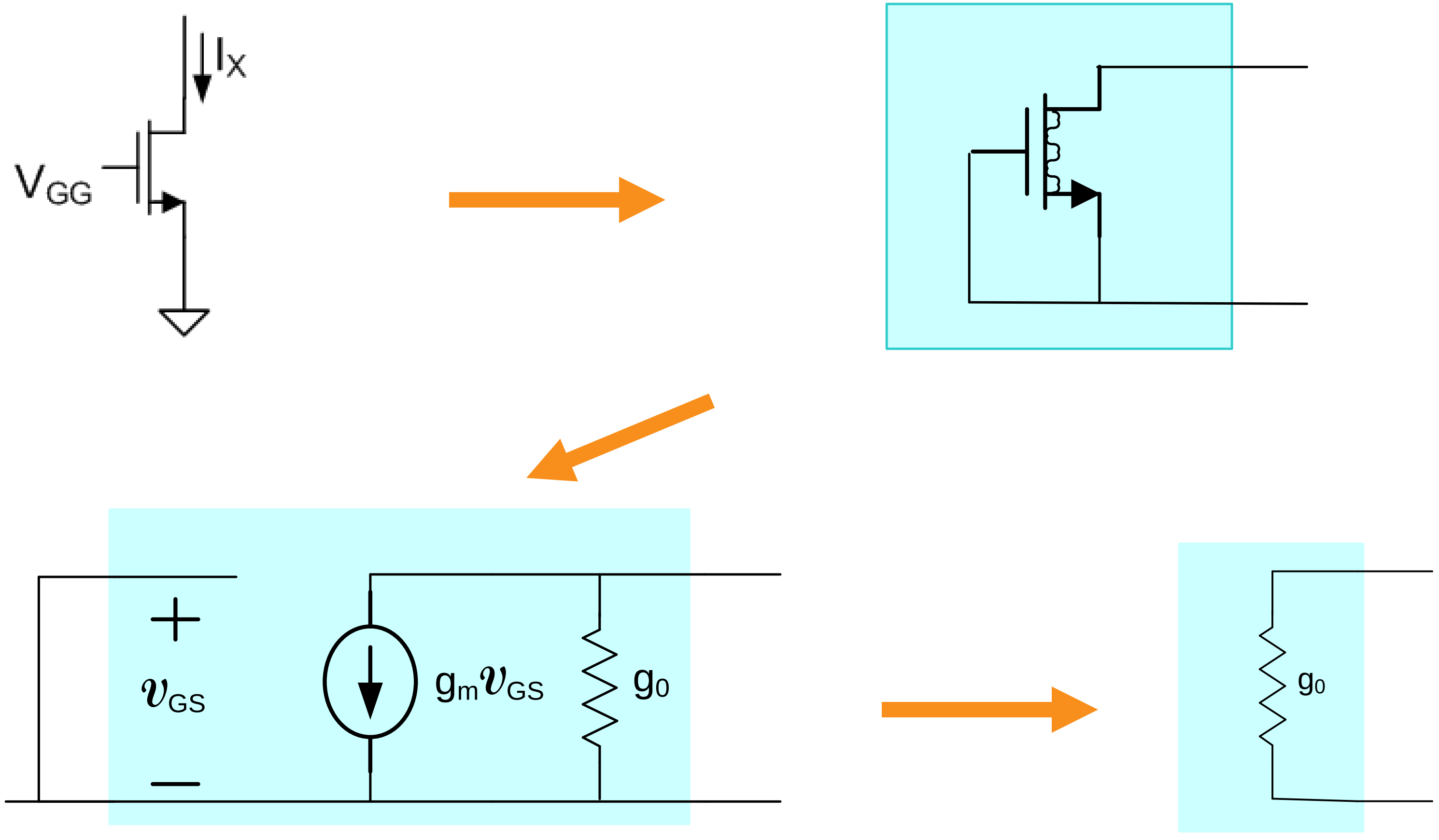
Not Diode Connected !



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

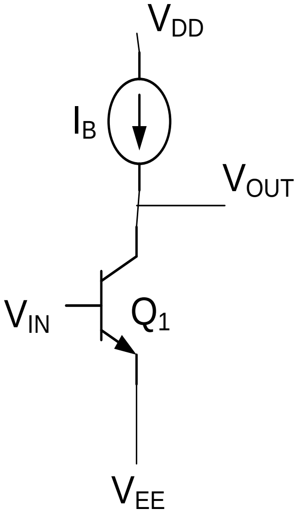
Basic Current Sources and Sinks

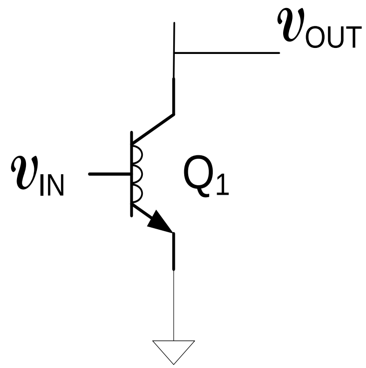
Small-signal Model of MOS Current Sinks and Sources



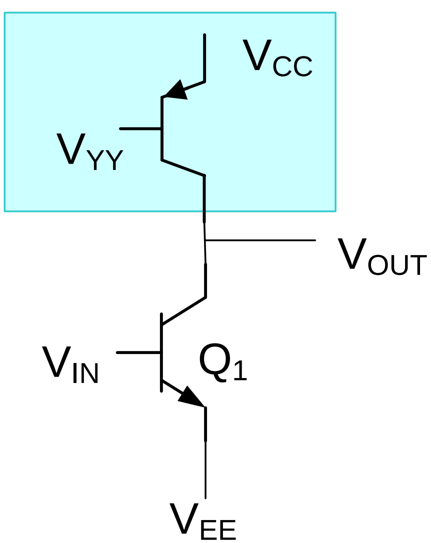
Small-signal model of all other MOS Sinks and Sources introduced thus far are the same

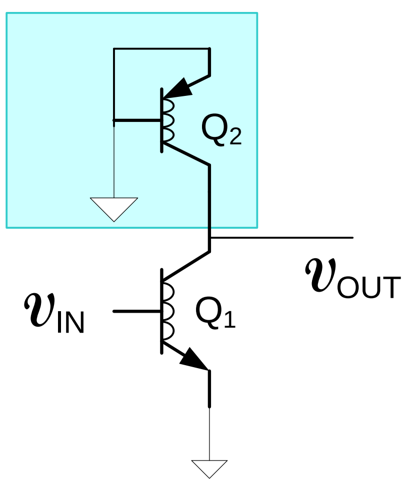
High-gain amplifier

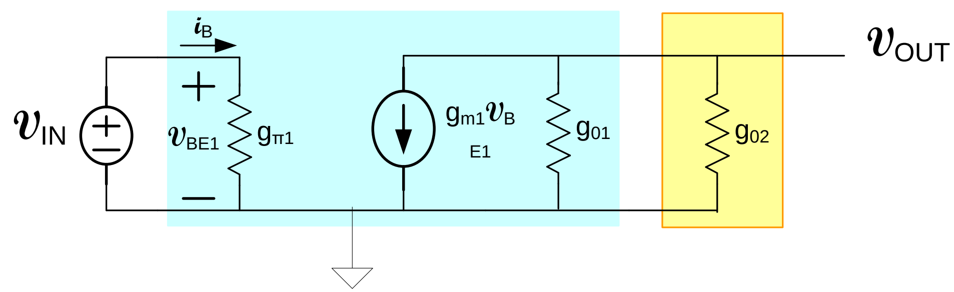




$$A_V = \frac{-g_m}{g_0}$$

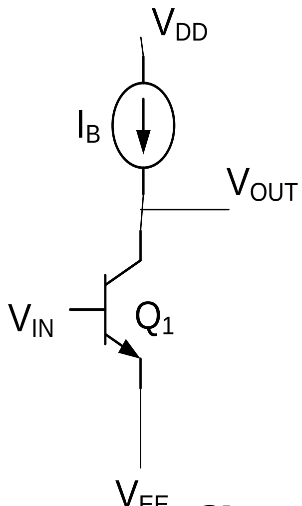


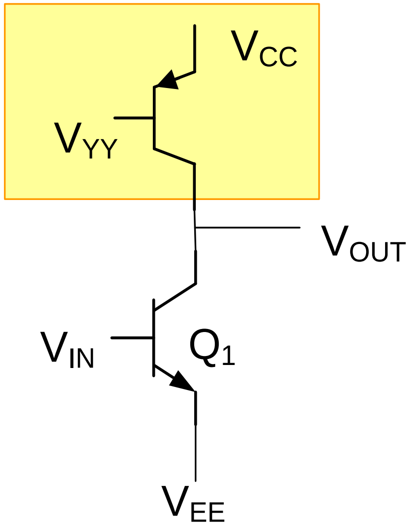




$$A_V = \frac{-g_{m1}}{g_{01} + g_{02}} \cong \frac{-g_{m1}}{2g_{01}}$$

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)**

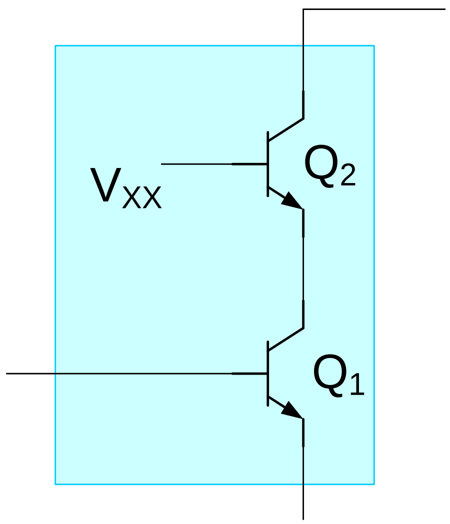
Can the gain be made even larger?

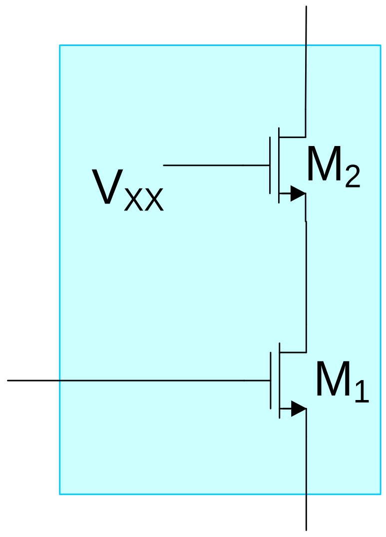
High-gain amplifier

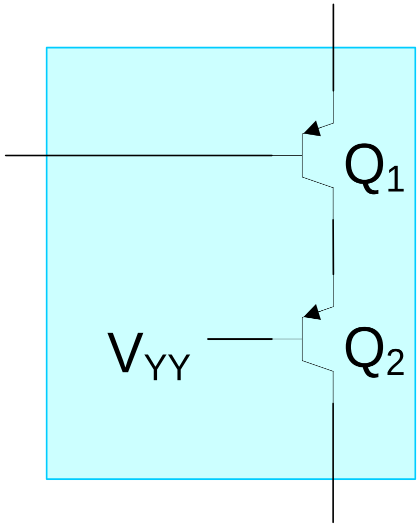
Discuss

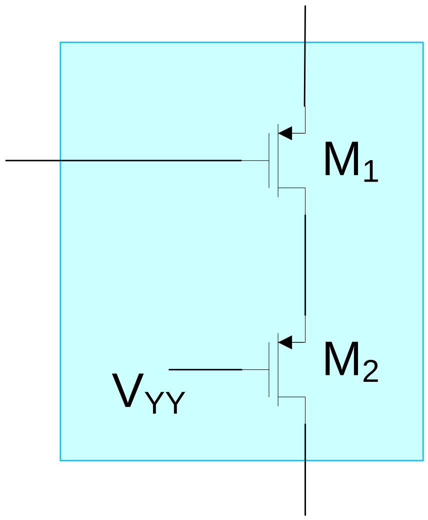
Can the gain be made even larger?

The Cascode Configuration

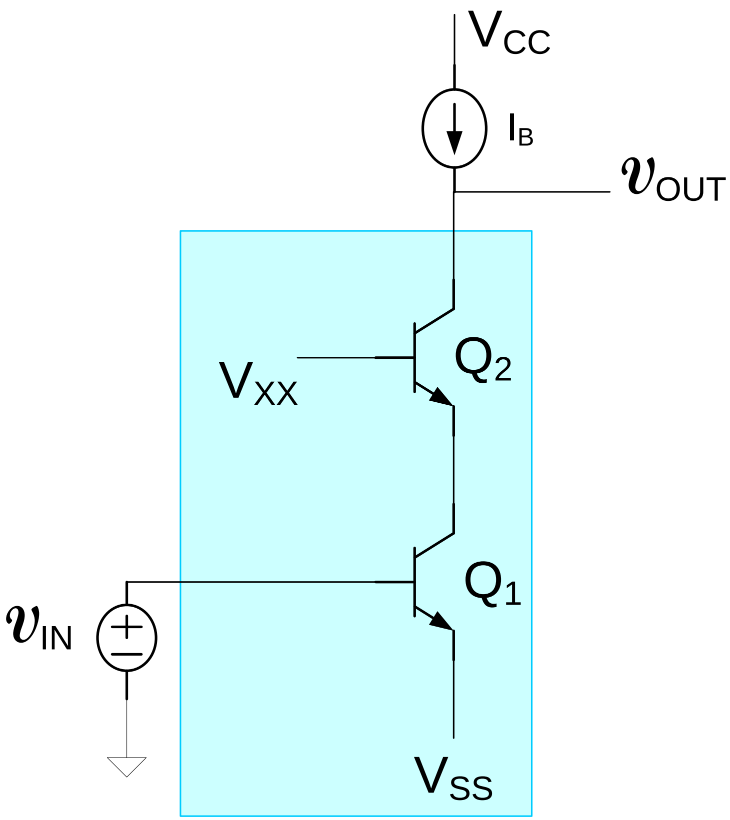








The Cascode Amplifier (consider npn BJT version)



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

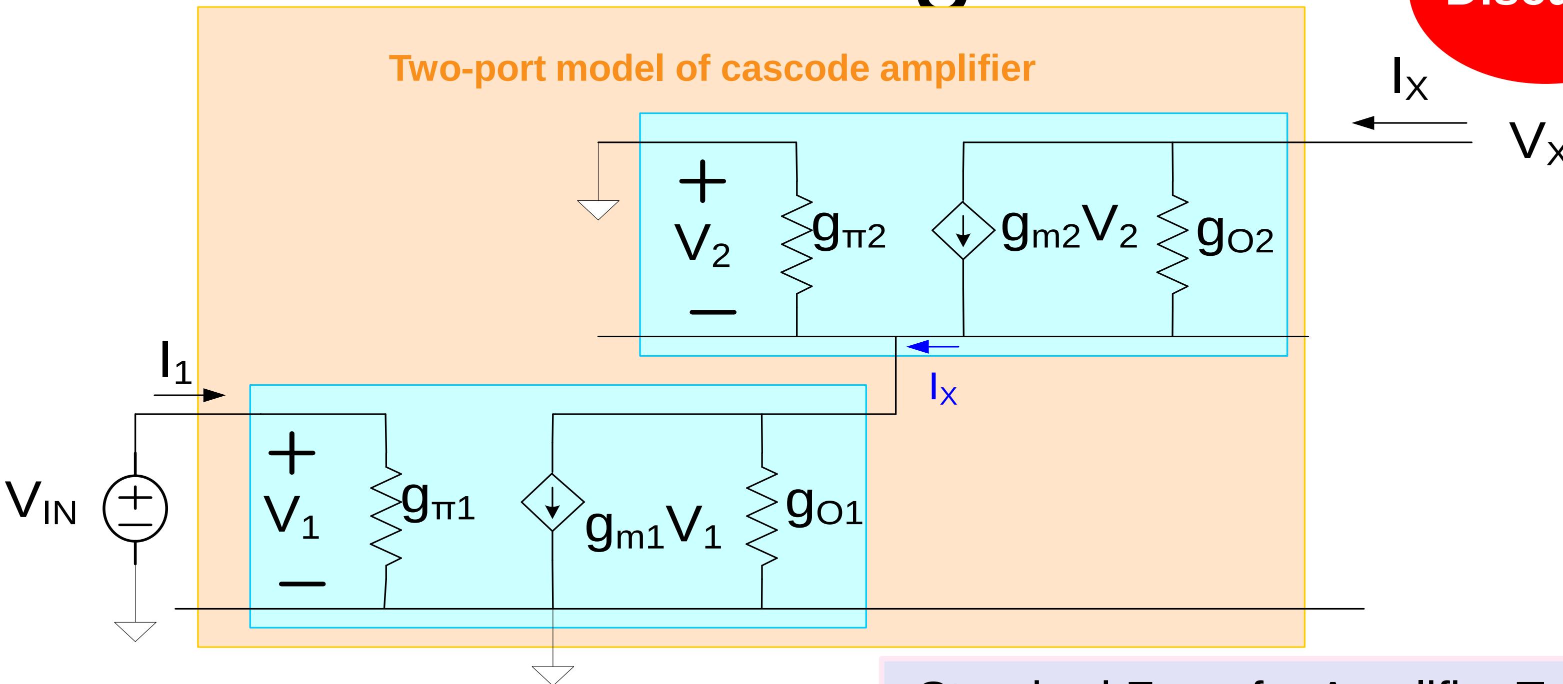
1. Common Emitter/Common Source
2. Common Collector/Common Drain
3. Common Base/Common Gate
4. Common Emitter with R_E/ Common Source with R_S

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

The first 4 are most popular

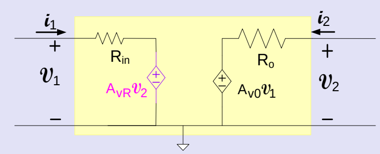
Cascode Configuration

Discuss



$$\left.\begin{aligned}(V_X+V_2)g_{O2}+V_2 g_{m2}&=I_X\\ V_1\, g_{m1}-V_2\left(g_{O1}+g_{\pi 2}\right)&=I_X\end{aligned}\right\}$$

Standard Form for Amplifier Two-Port



$$v_1 = i_1 R_{IN} + A_{VR} v_2$$
$$v_2 = i_2 R_O + A_{V0} v_1$$

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

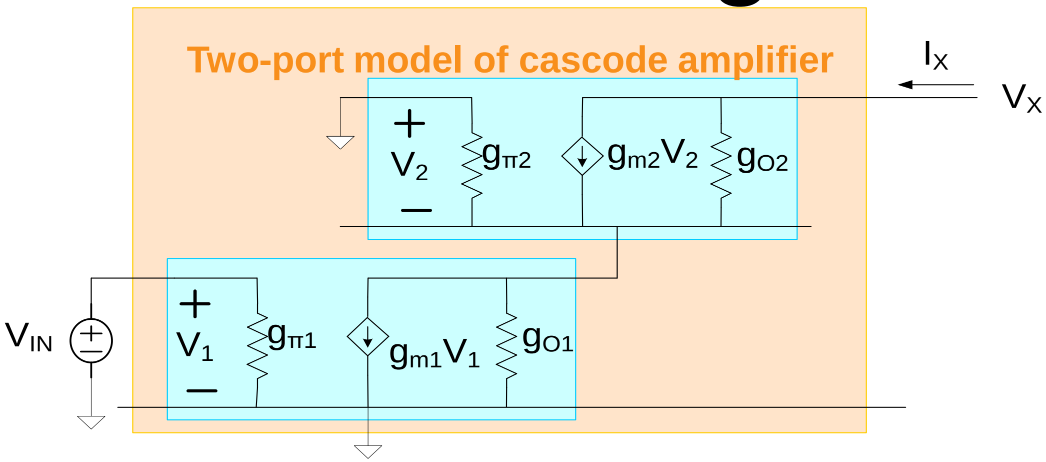
$$V_{IN}=I_1\bullet\frac{1}{g_{\pi 1}}$$

and

$$V_X=I_X\bullet\left[\frac{g_{O1}+g_{O2}+g_{\pi 2}+g_{m2}}{g_{O2}\left(g_{O1}+g_{\pi 2}\right)}\right]-V_{IN}\bullet\left[\frac{g_{m1}\left(g_{O2}+g_{m2}\right)}{g_{O2}\left(g_{\pi 2}+g_{O1}\right)}\right]$$

Cascode Configuration

Discuss



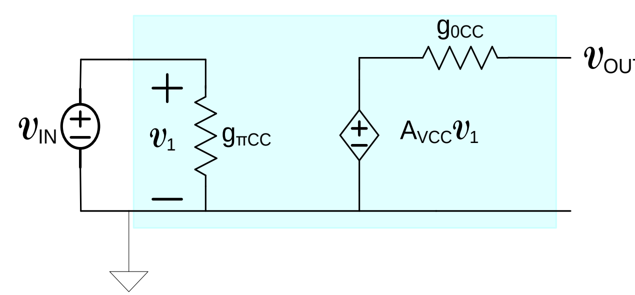
$$V_X = I_X \bullet \left[\frac{g_{o1}+g_{o2}+g_{\pi 2}+g_{m2}}{g_{o2}\left(g_{o1}+g_{\pi 2}\right)}\right] - V_{IN} \bullet \left[\frac{g_{m1}\left(g_{o2}+g_{m2}\right)}{g_{o2}\left(g_{\pi 2}+g_{o1}\right)}\right]$$

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

It thus follows for the npn bipolar structure that :

$$A_{VCC} = -\left[\frac{g_{m1}\left(g_{o2}+g_{m2}\right)}{g_{o2}\left(g_{\pi 2}+g_{o1}\right)}\right] \cong -\left[\frac{g_{m1}g_{m2}}{g_{o2}g_{\pi 2}}\right]$$

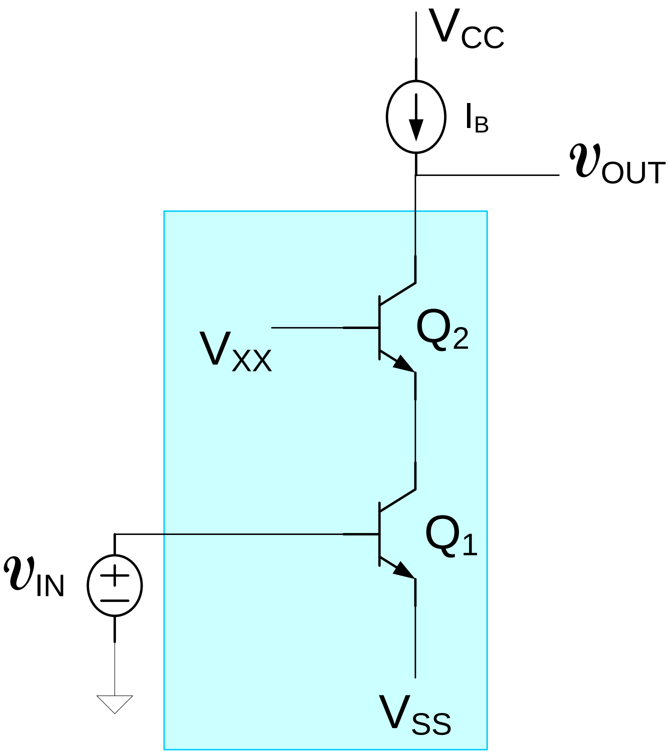
$$g_{oCC} = \left[\frac{g_{o2}\left(g_{o1}+g_{\pi 2}\right)}{g_{o1}+g_{o2}+g_{\pi 2}+g_{m2}}\right] \cong \left[\frac{g_{o2}g_{\pi 2}}{g_{m2}}\right]$$



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

Cascode Configuration

Discuss



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

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

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

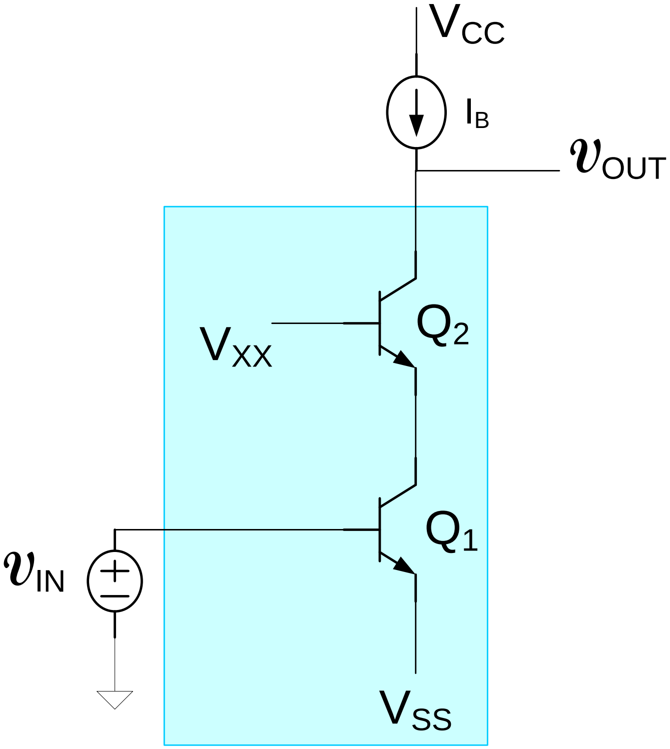
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{02}}\beta\right] \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

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

- **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



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

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

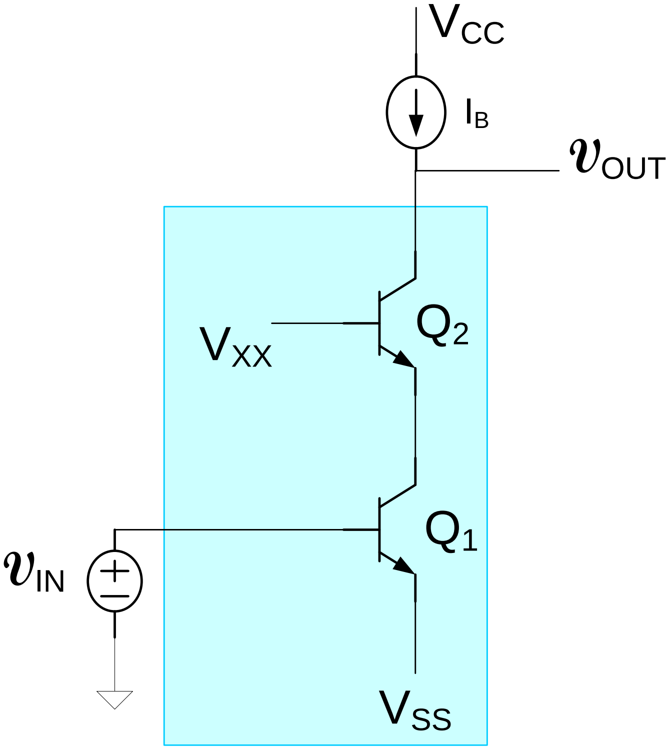
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta = \left[\frac{2V_{AF}}{V_t}\right]\beta = [-8000]100$$

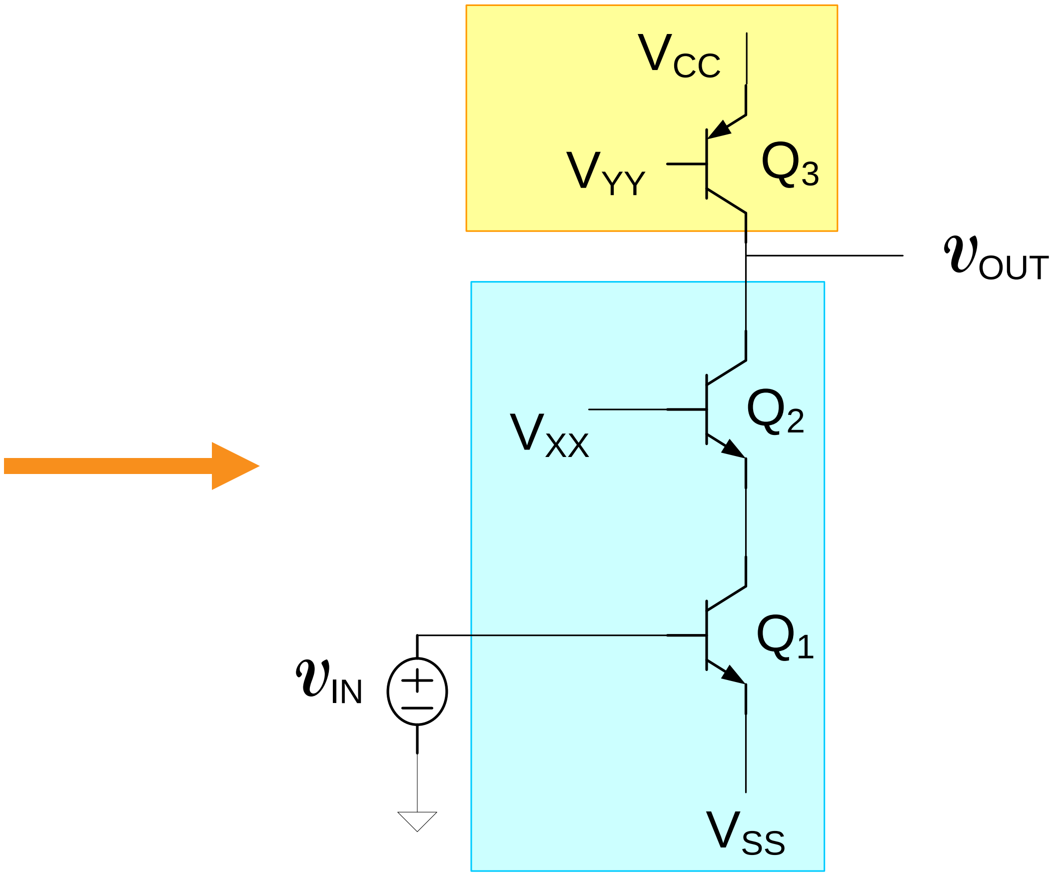
$$A_{VCC} \cong -800{,}000$$

This gain is very large and only requires two transistors!

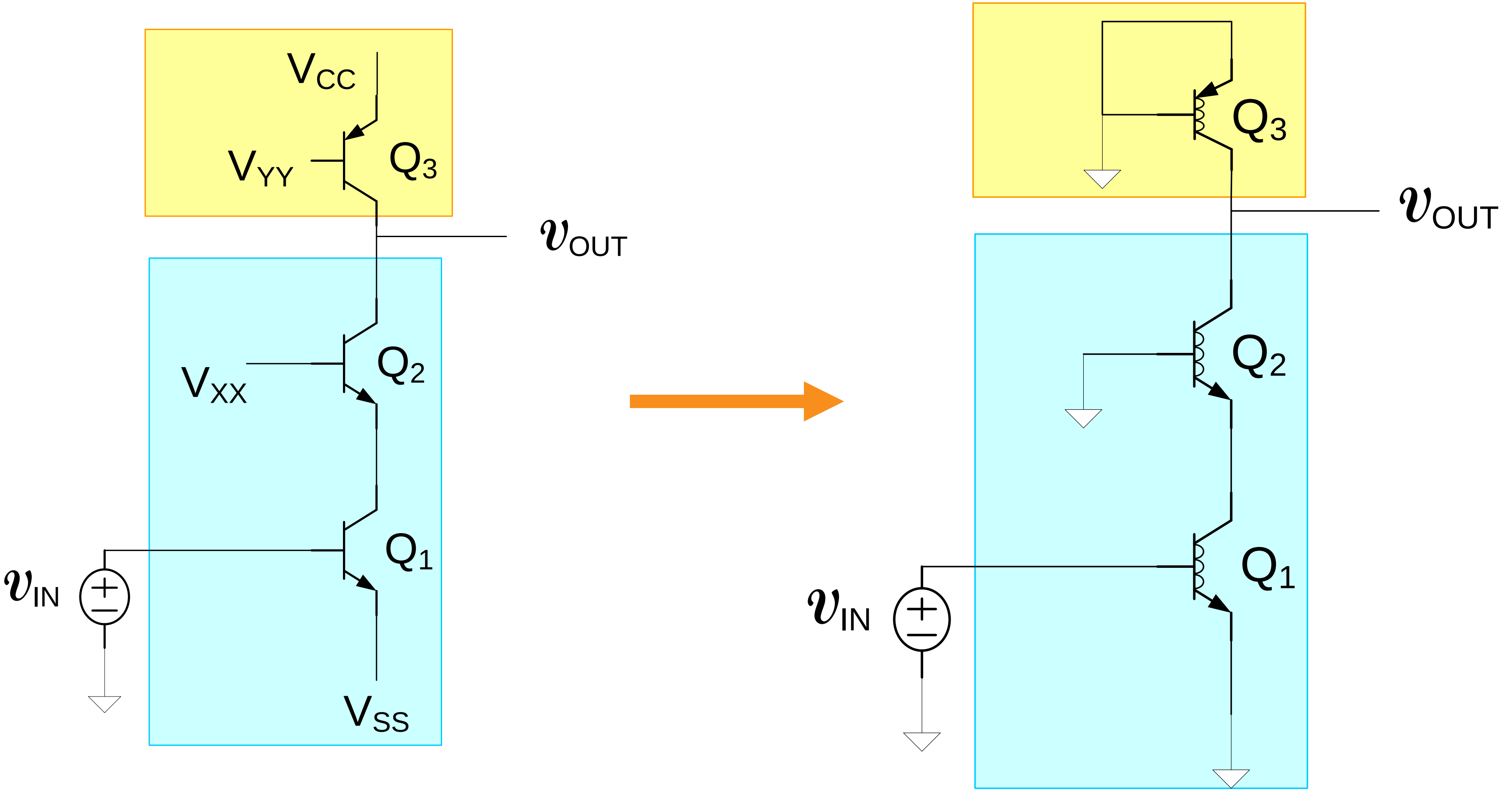
What happens to the gain if a transistor-level current source is used for I_B?

Cascode Configuration

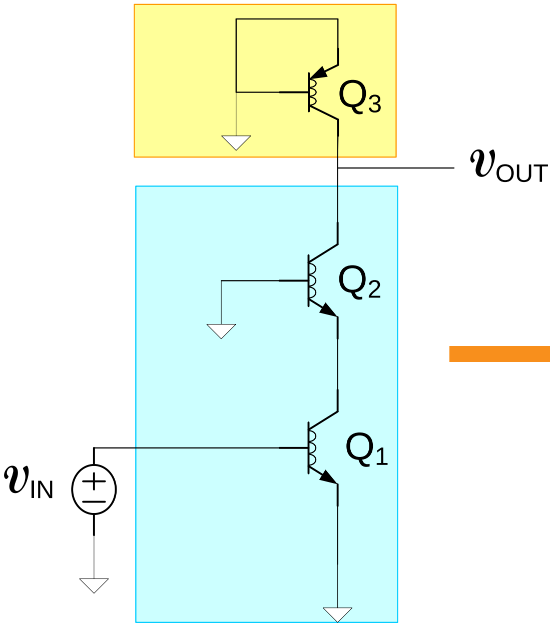


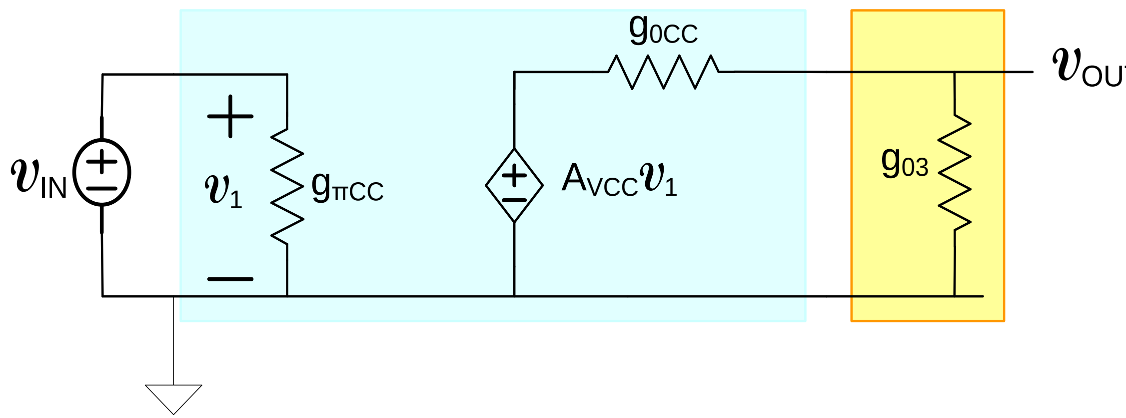


Cascode Configuration



High-gain amplifier comparisons





It thus follows that

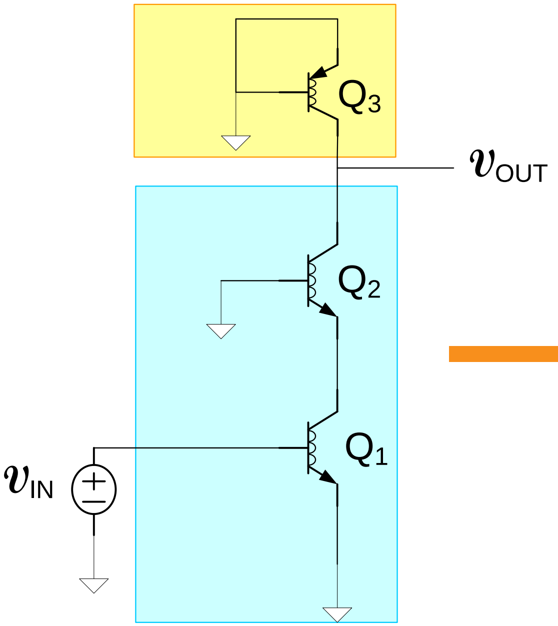
$$A_V = A_{VCC}\left[\frac{g_{0CC}}{g_{03}+g_{0CC}}\right]$$

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

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

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

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

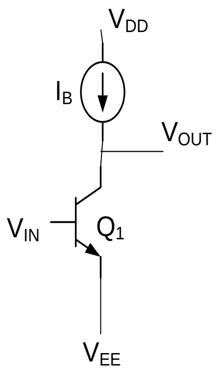
Thus

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

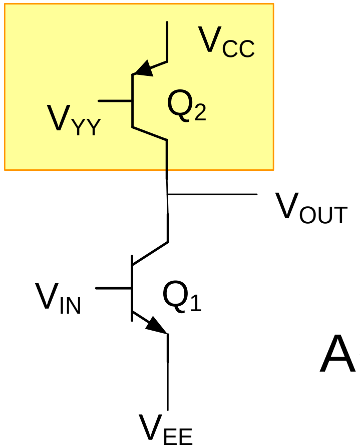
$$A_V \cong -\left[\frac{I_{CQ}/V_t}{I_{CQ}/V_{AF}}\right] = -\left[\frac{V_{AF}}{V_t}\right] \cong -8000$$

- **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**

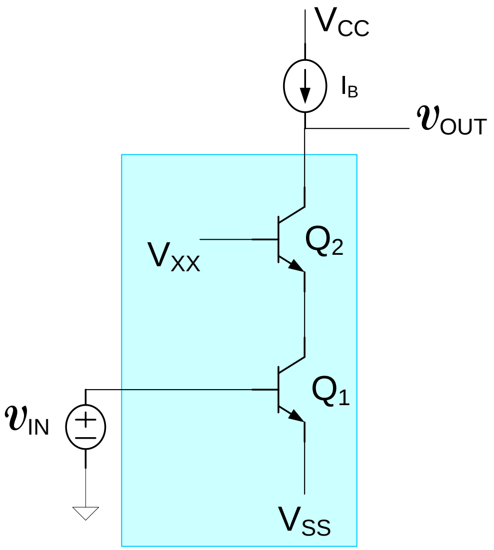
Cascode Configuration Comparisons



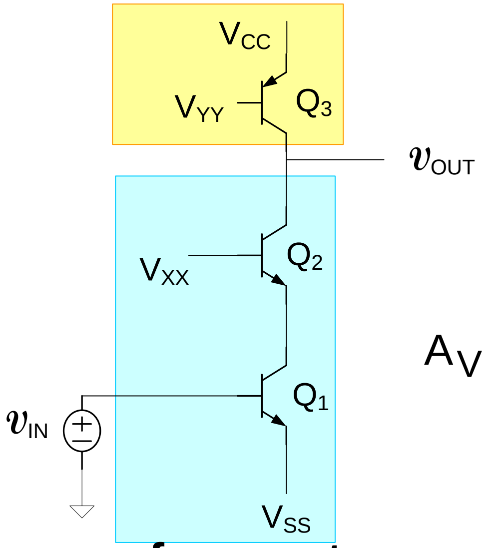
$$A_V = \frac{-g_m}{g_0}$$



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



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



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

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

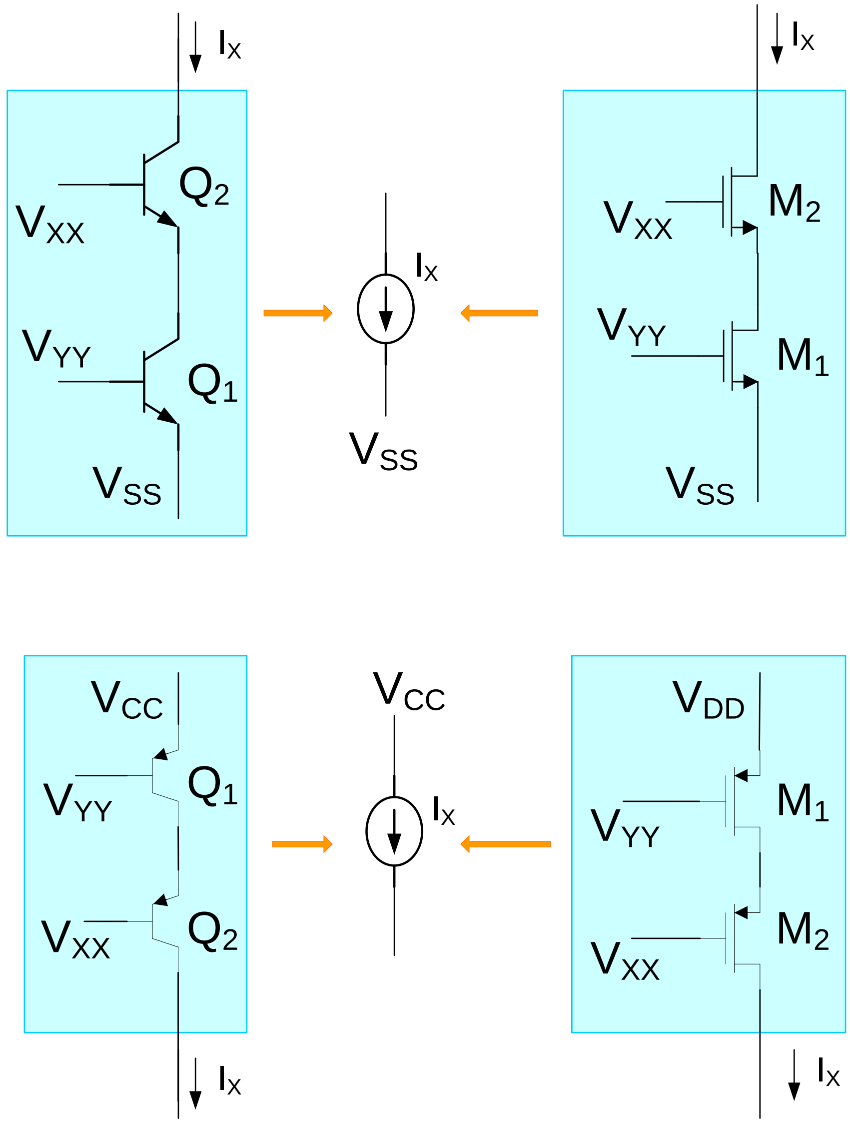
Need a higher output impedance than g_o

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

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

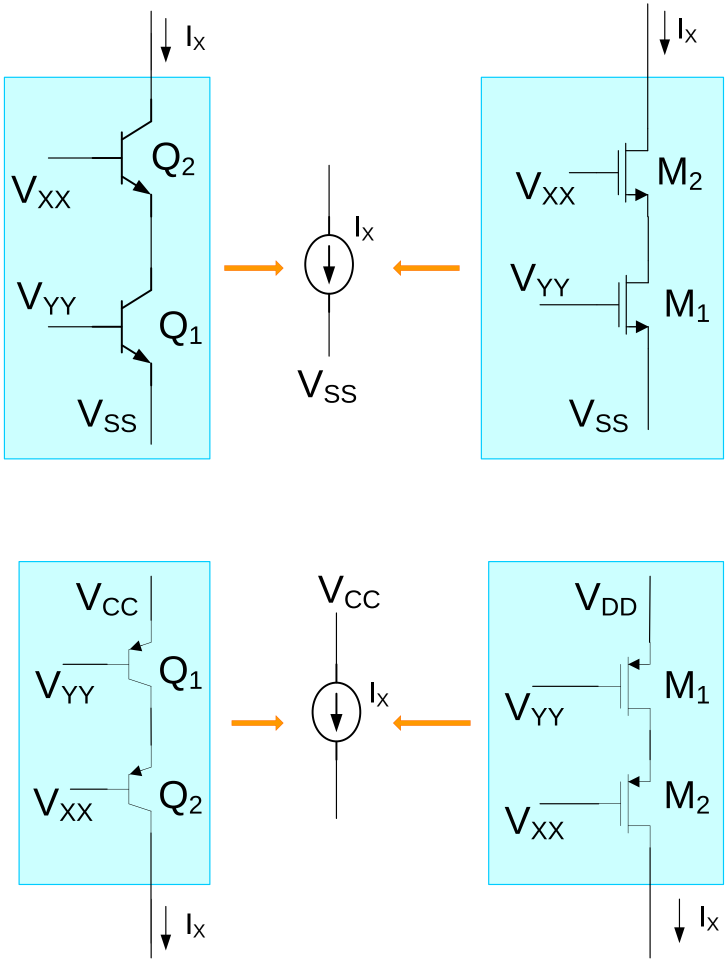
Can a current source be built with the cascode circuit ?

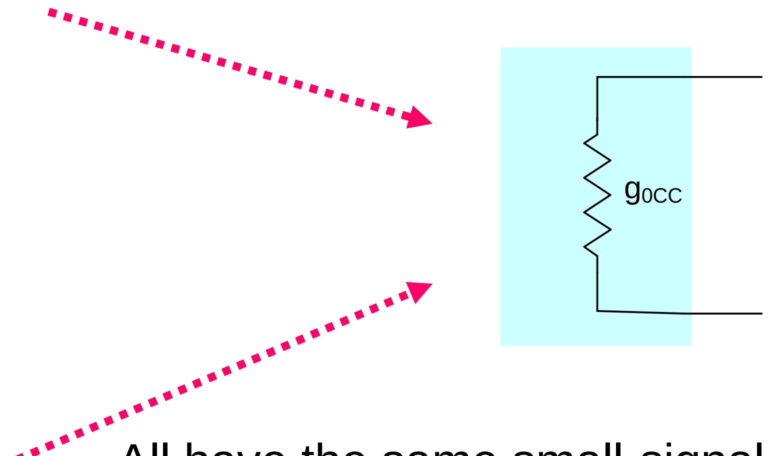
Cascode current sources



Discuss

Cascode current sources



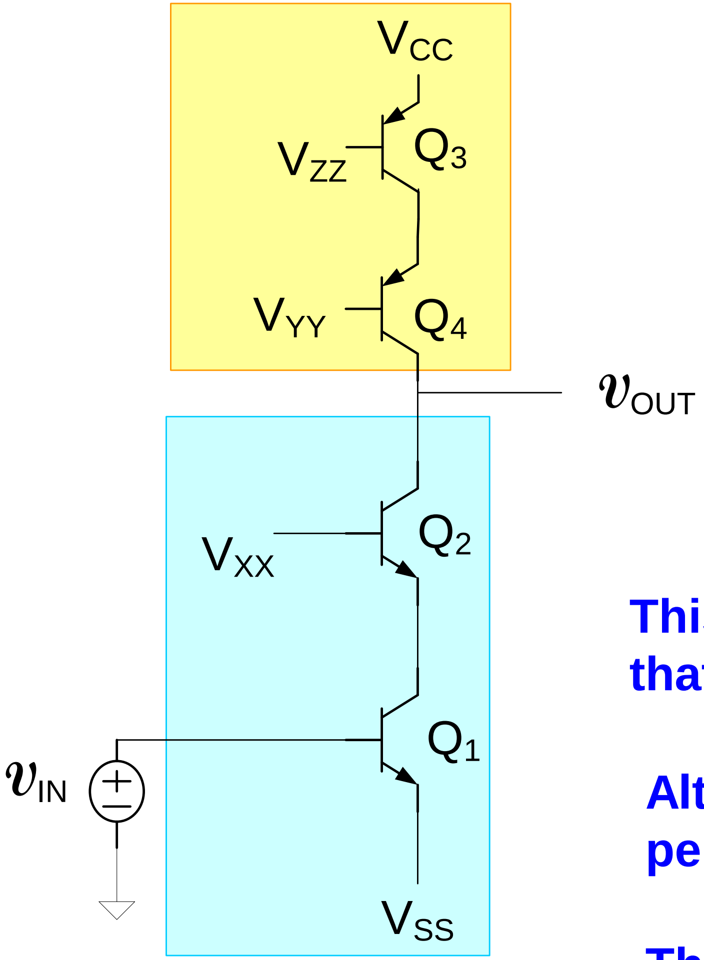


All have the same small-signal model

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

Cascode Configuration

Discuss



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

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

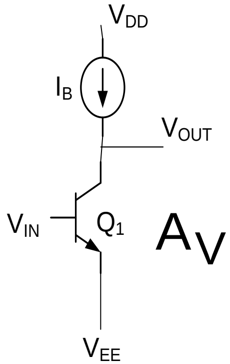
This gain is very large and is a factor of 2 below that obtained with an ideal current source biasing

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

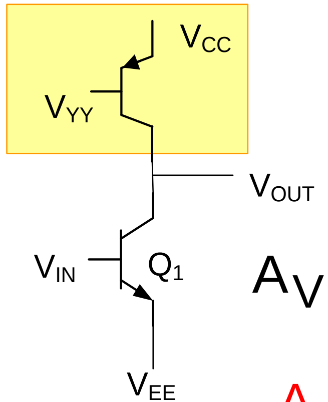
Cascode Configuration Comparisons

Discuss



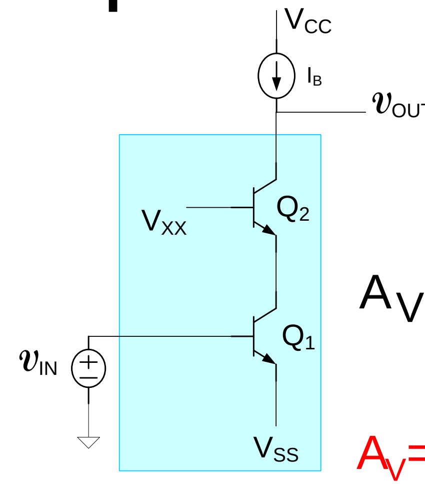
$$A_V = \frac{-g_m}{g_0}$$

$A_V = -8,000$



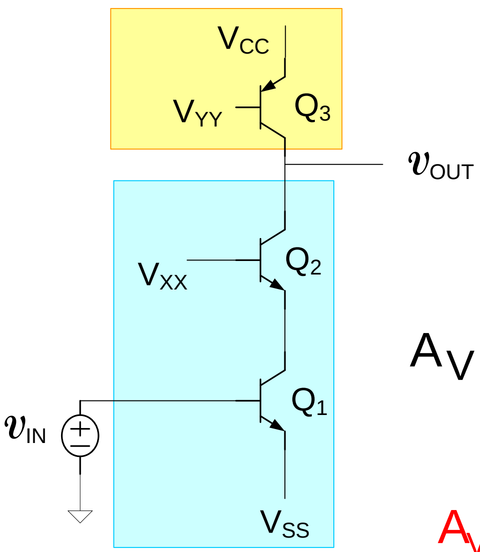
$$A_V \cong \frac{-g_{m1}}{2g_{01}}$$

$A_V = -4,000$



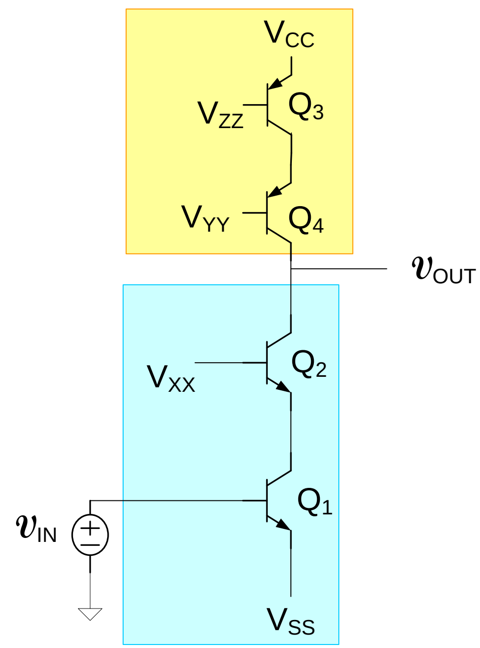
$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

$A_V = -800,000$



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

$A_V = -8,000$

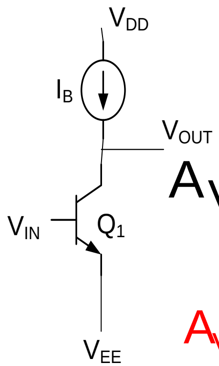


$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

$A_V = -400,000$

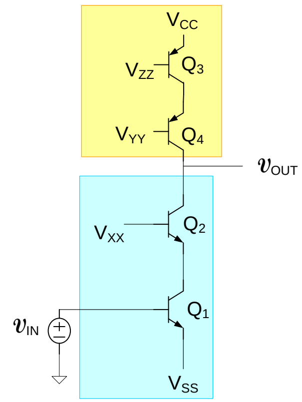
Can we use more cascoding to further increase the gain?

High Gain Amplifiers Seldom Used Open Loop



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

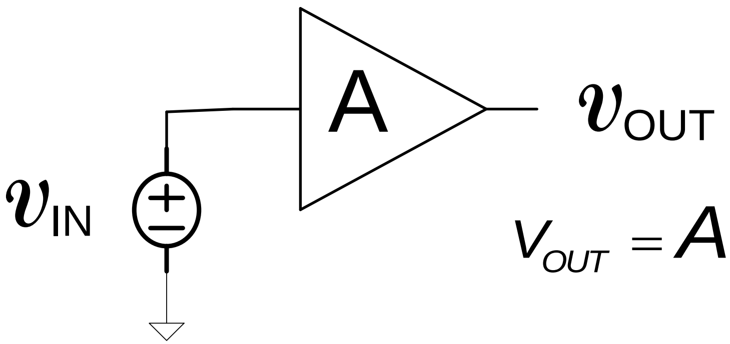
$A_V = -8{,}000$



Discuss

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

$A_V = -400{,}000$



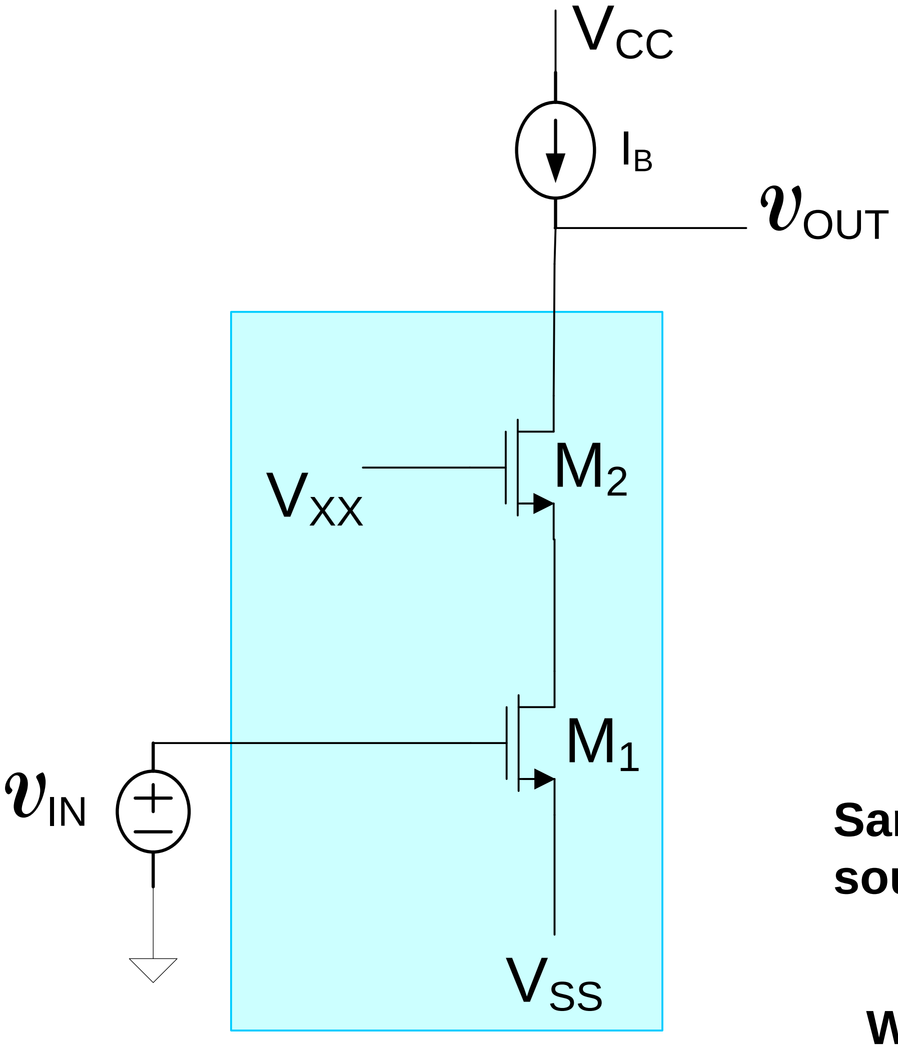
$$V_{OUT} = A\, v_{IN} + V_{OUTQ}$$

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



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

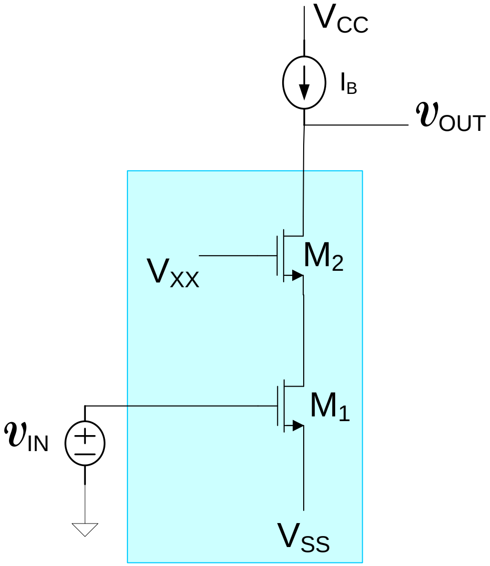
$$g_{0CC} \cong \left[\frac{g_{01}g_{02}}{g_{m2}}\right]$$

Same issues for biasing with current source as for BJT case

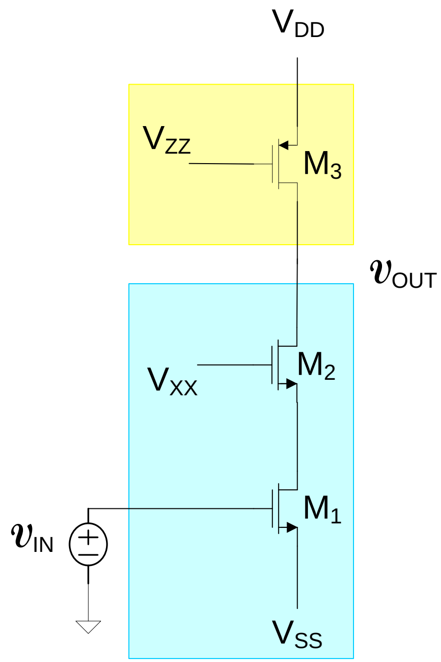
With cascode current source, gain only drops by a factor of 2

The Cascode Amplifier (consider n-ch MOS version)

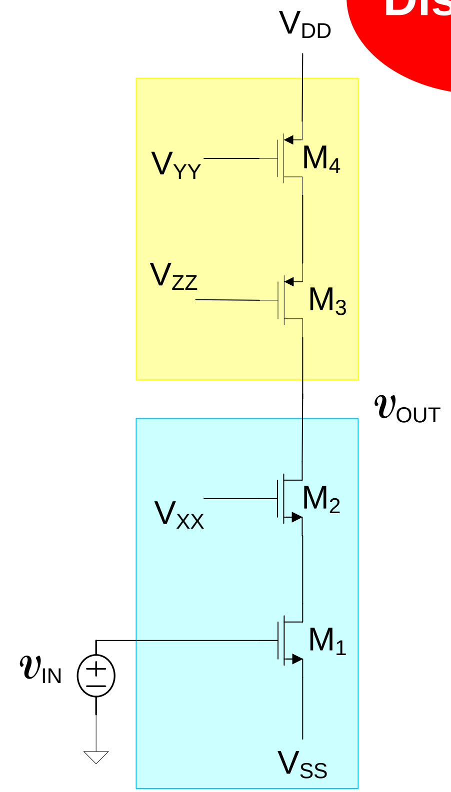
Discuss



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



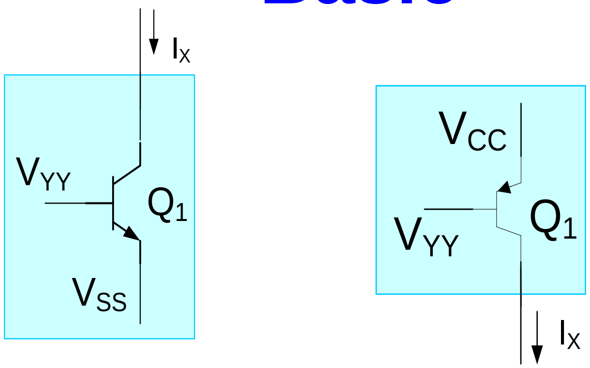
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

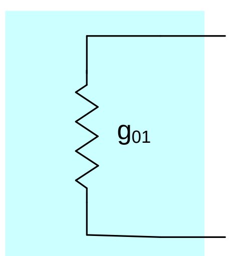


$$A_{VCC} \cong -\frac{1}{2}\left[\frac{g_{m1}g_{m2}}{g_{01}g_{02}}\right]$$

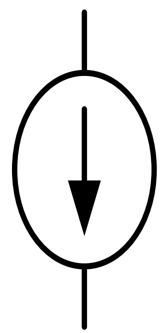
Current Source Summary (BJT)

Basic

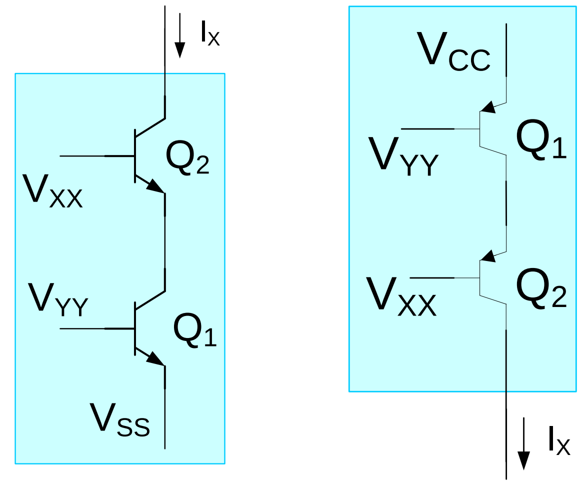


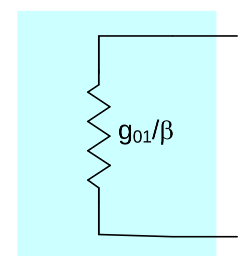


$$g_0 \cong g_{01}$$



Cascode

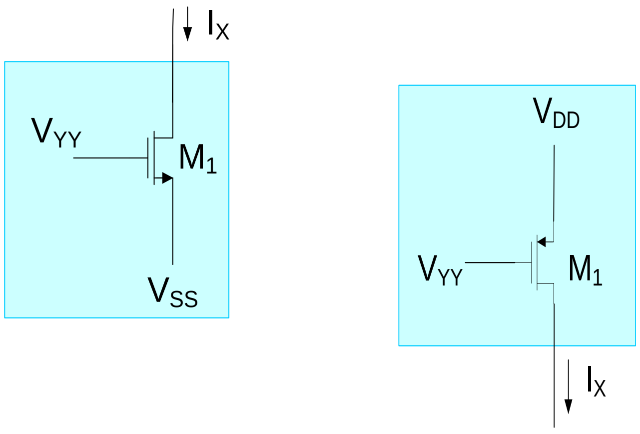




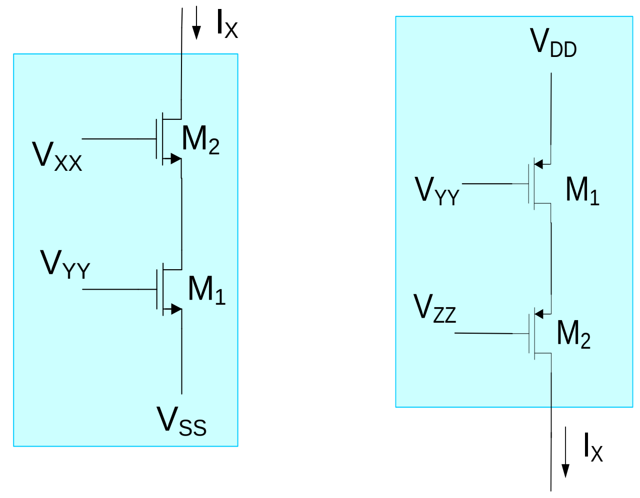
$$g_{0CC} \cong \frac{g_{01}}{\beta}$$

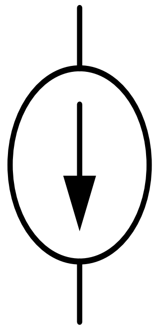
Current Source Summary (MOS)

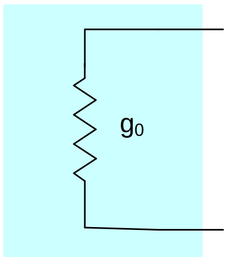
Basic

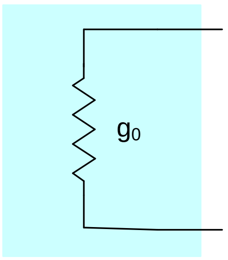


Cascode





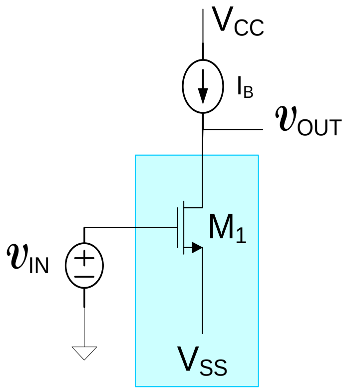




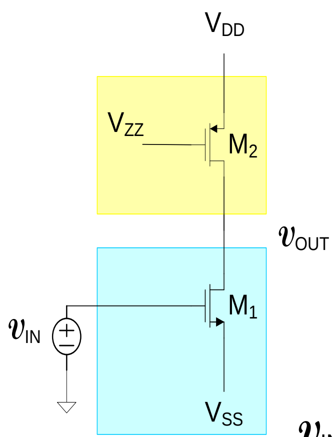
$$g_0 \cong g_{01}$$

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

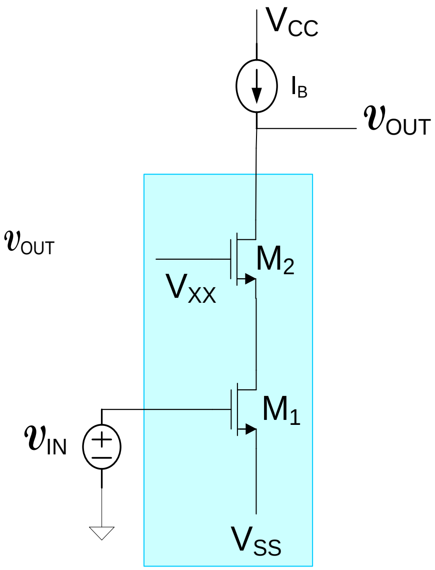
High Gain Amplifier Comparisons (n-ch MOS)



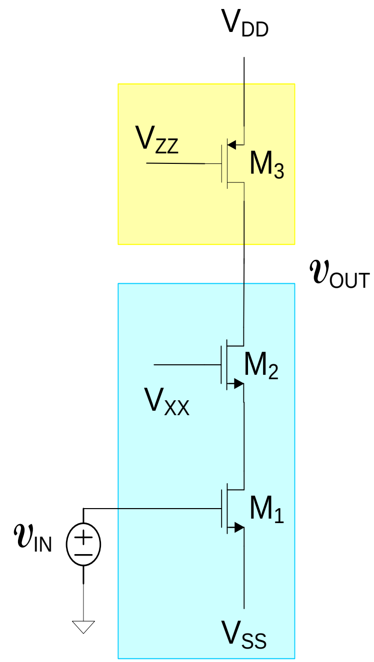
$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$



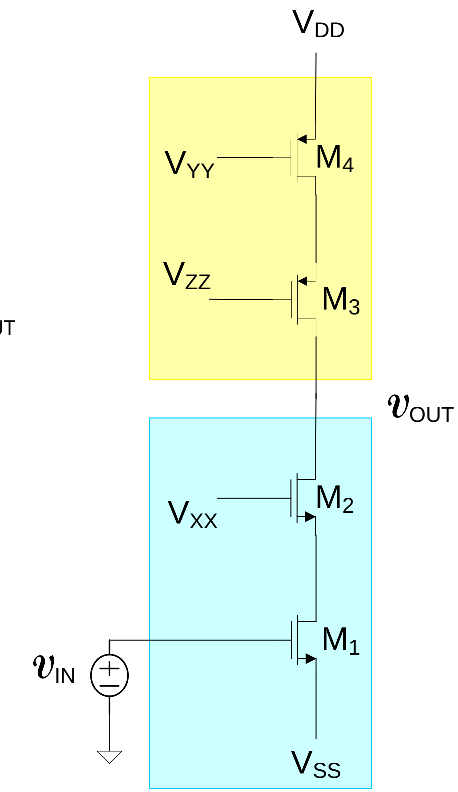
$$A_V \cong -\frac{1}{2}\left[\frac{g_{m1}}{g_{01}}\right]$$



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

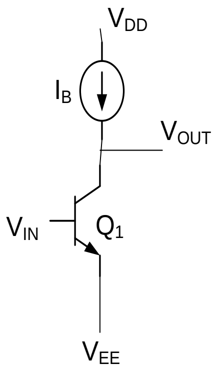


$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

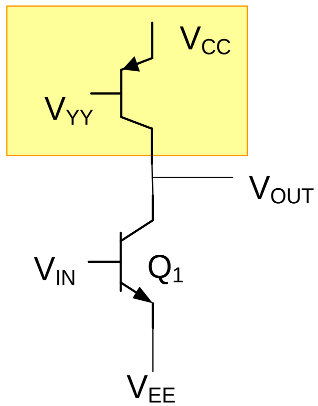


$$A_{VCC} \cong -\frac{1}{2}\left[\frac{g_{m1}g_{m2}}{g_{01}g_{02}}\right]$$

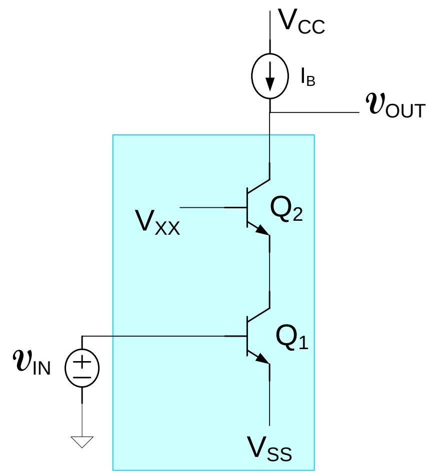
High Gain Amplifier Comparisons (BJT)



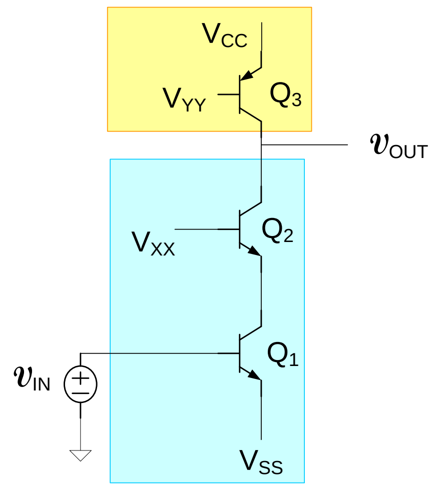
$$A_V = \frac{-g_m}{g_0}$$



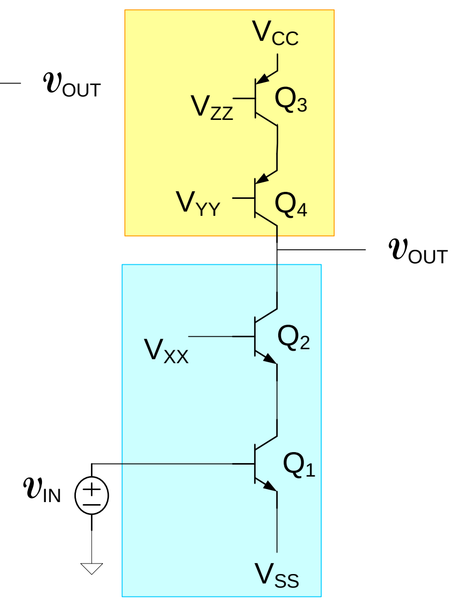
$$A_V \cong -\frac{1}{2}\frac{g_{m1}}{g_{01}}$$



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



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

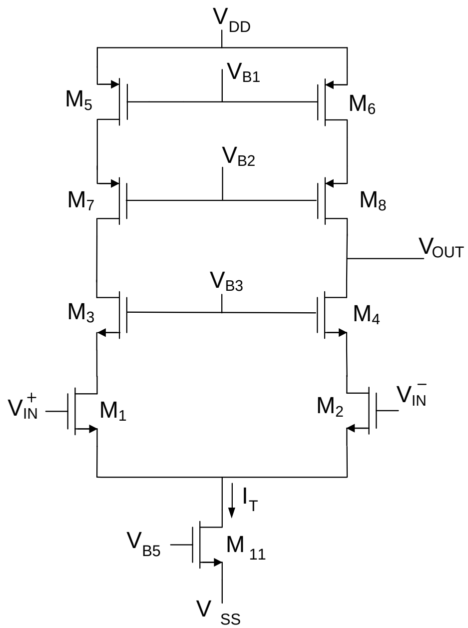


$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

- 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

The Cascode Amplifier

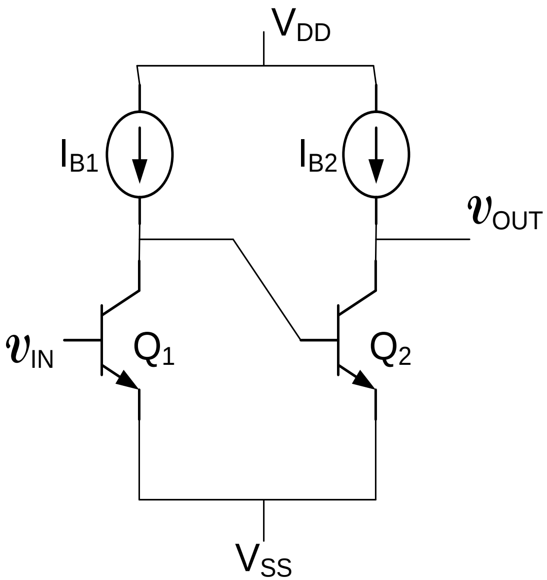
- Operational amplifiers often built with basic cascode configuration
- CMFB used to address the biasing problem
- Usually configured as a differential structure when building op amps
- Have high output impedance (but can be bufferred)
- Terms “telescopic cascode”, “folded-cascode”, and “regulated cascode”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

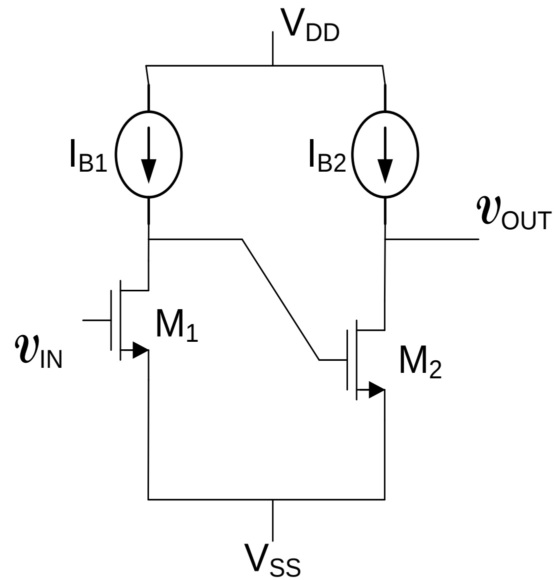


Telescopic Cascode Op Amp

(CMFB feedback biasing not shown)

Cascade Configurations



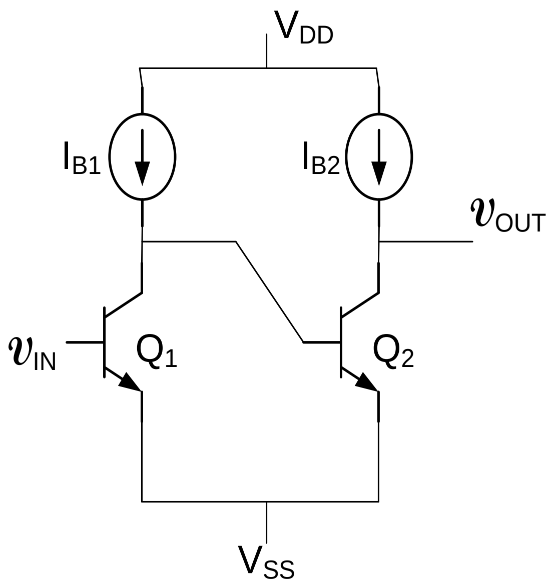


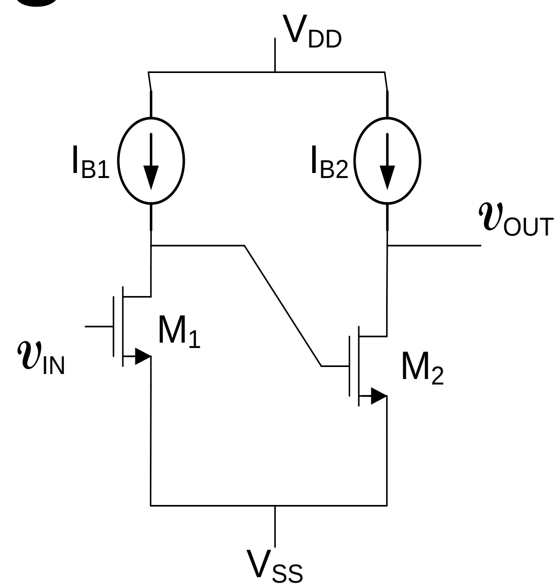
Two-stage CE:CE or CS:CS Cascade

$$A_{VCB} = ?$$

$$A_{VCM} = ?$$

Cascade Configurations





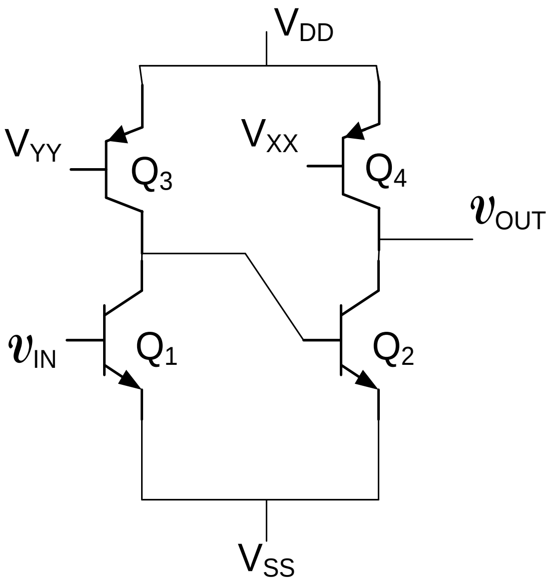
Two-stage CE:CE or CS:CS Cascade

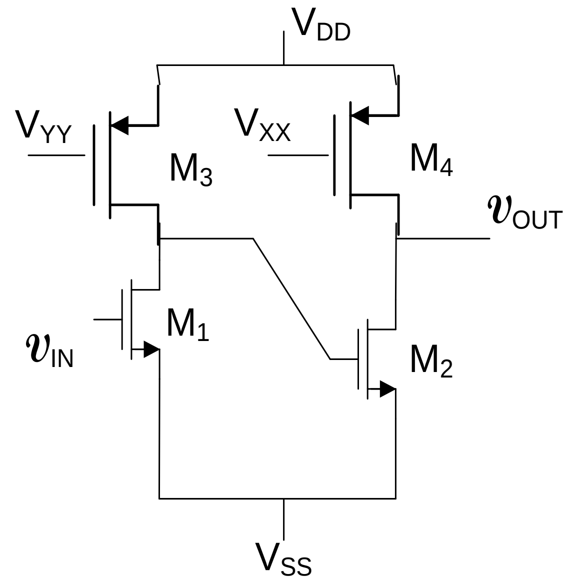
$$A_{VCB} \cong \left[\frac{-g_{m1}}{g_{01}+g_{\pi 2}}\right]\left[\frac{-g_{m2}}{g_{02}}\right] \cong \frac{g_{m1}g_{m2}}{g_{\pi 2}g_{02}} = \beta\frac{g_{m1}}{g_{02}}$$

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

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

Cascade Configurations





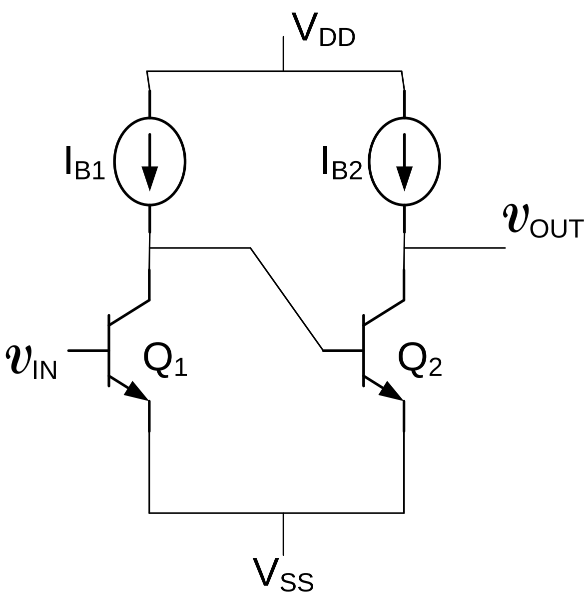
Two-stage CE:CE or CS:CS Cascade

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

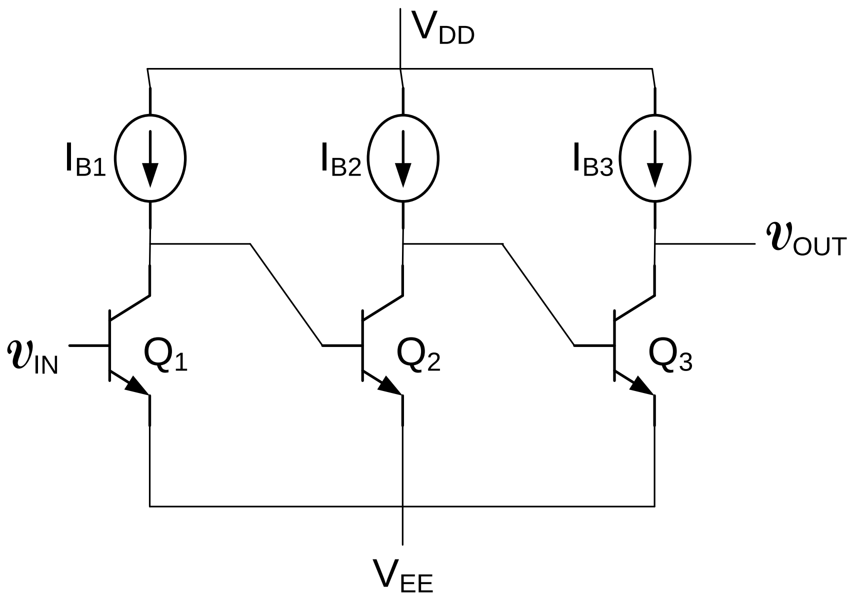
$$A_{VCM} = \left[\frac{-g_{m1}}{g_{01}+g_{03}}\right]\left[\frac{-g_{m2}}{g_{02}+g_{04}}\right] = \frac{g_{m1}g_{m2}}{4g_{01}g_{02}}$$

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

Cascade Configurations



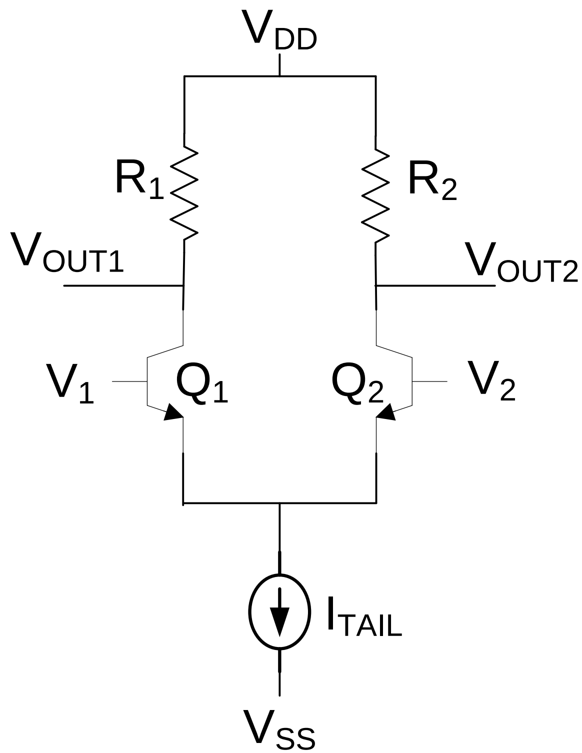
Two-stage CE Cascade



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 built 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

Amplifier Biasing

Amplifier biasing is that part of the design of a circuit that establishes the desired operating point (or Q-point)

Goal is to invariably minimize the impact the biasing circuit has on the small-signal performance of a circuit

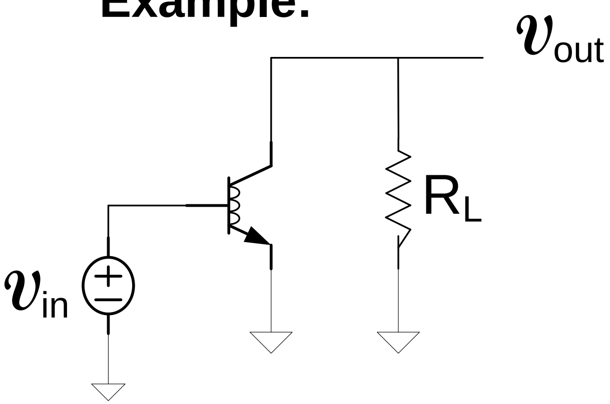
Usually at most 2 dc power supplies are available and these are often fixed in value by system requirements – this restriction is cost driven

Discrete amplifiers invariable involve adding biasing resistors and use capacitor coupling and bypassing

Integrated amplifiers often use current sources which can be used in very large numbers and are very inexpensive

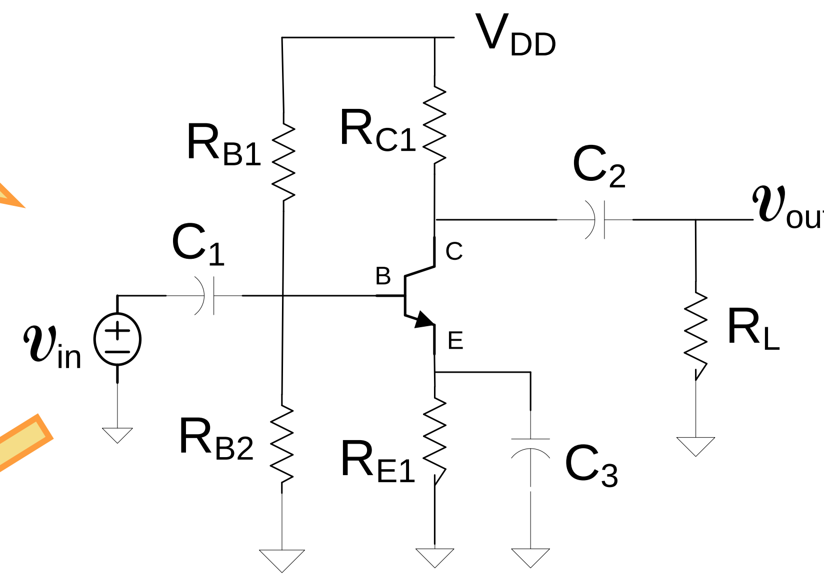
Amplifier Biasing

Example:

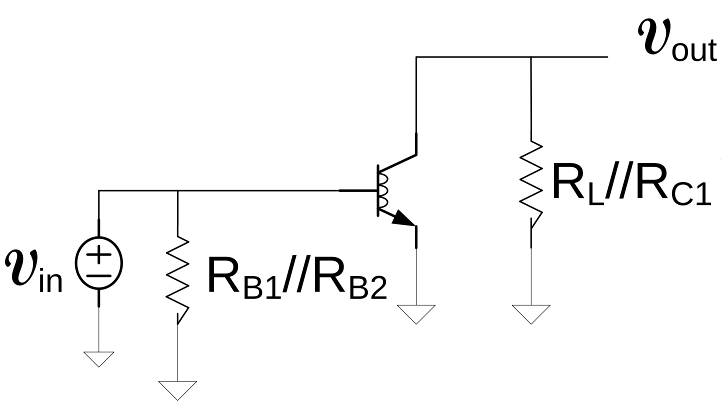


$$A_V = -g_m R_L$$

Desired small-signal circuit
Common Emitter Amplifier



Biased circuit

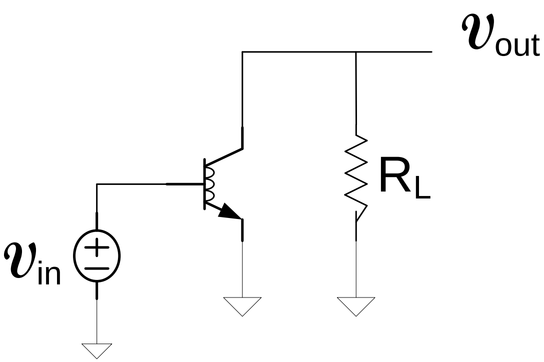


Actual small-signal circuit

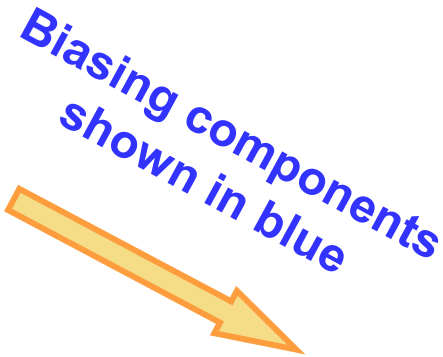
$$A_V = -g_m \left(R_L \,//\, R_{C1}\right)$$

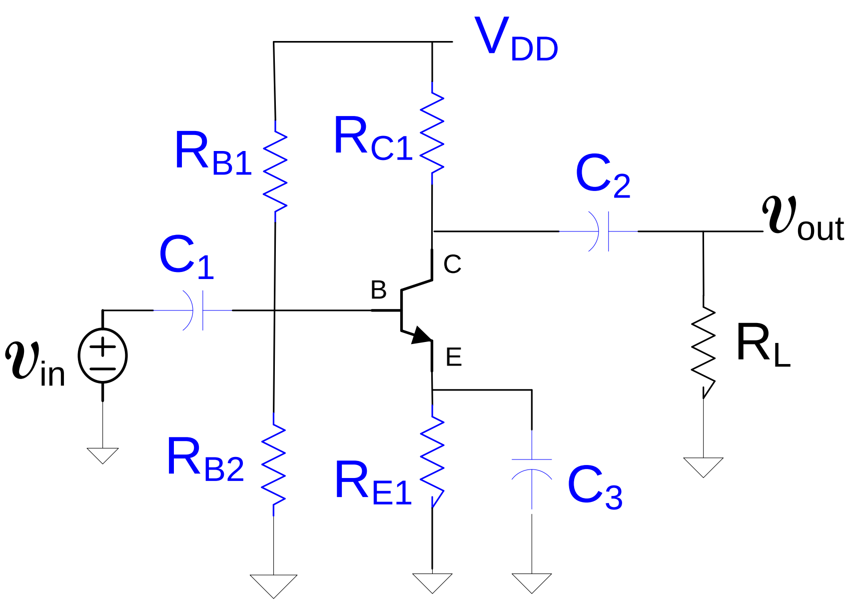
Amplifier Biasing

Example:



Desired small-signal circuit
Common Emitter Amplifier

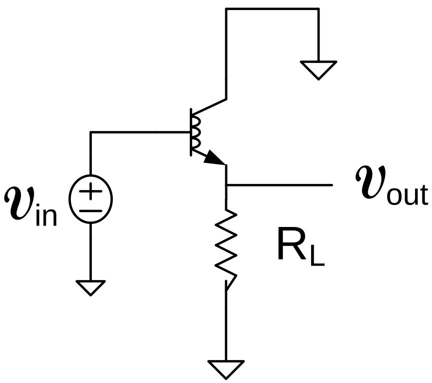




Biased small-signal circuit

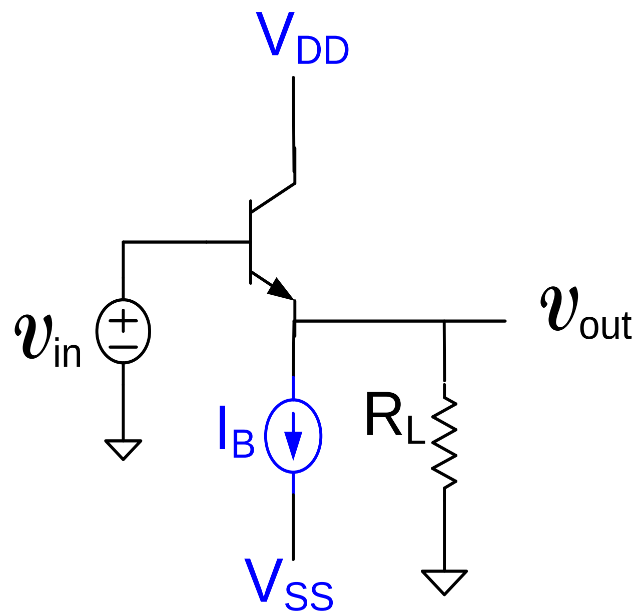
Amplifier Biasing

Example:



Desired small-signal circuit
Common Collector Amplifier

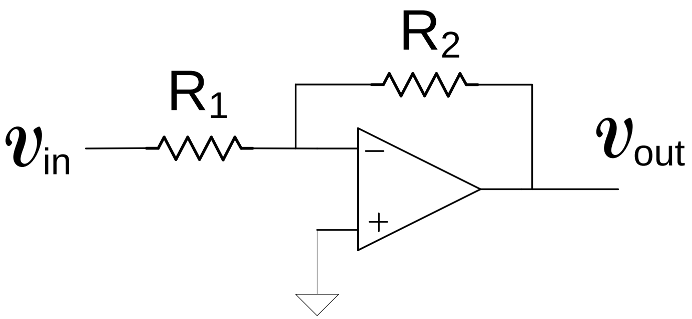
Biasing components shown in blue



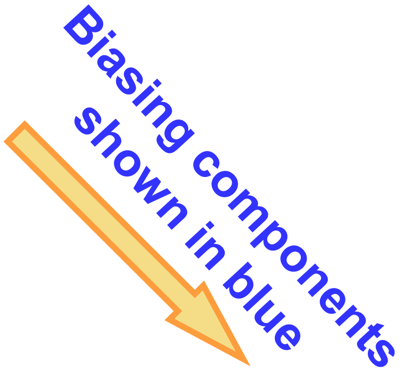
Biased circuit

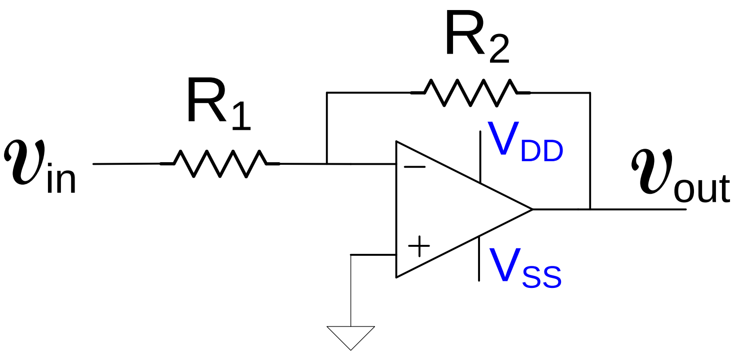
Amplifier Biasing

Example:



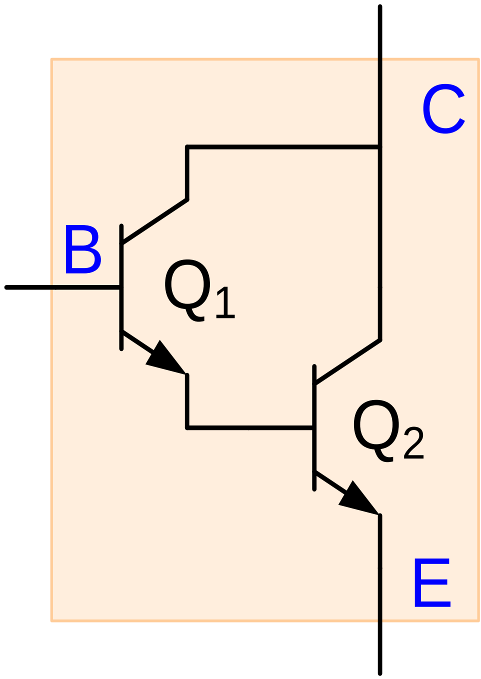
Desired small-signal circuit
Inverting Feedback Amplifier



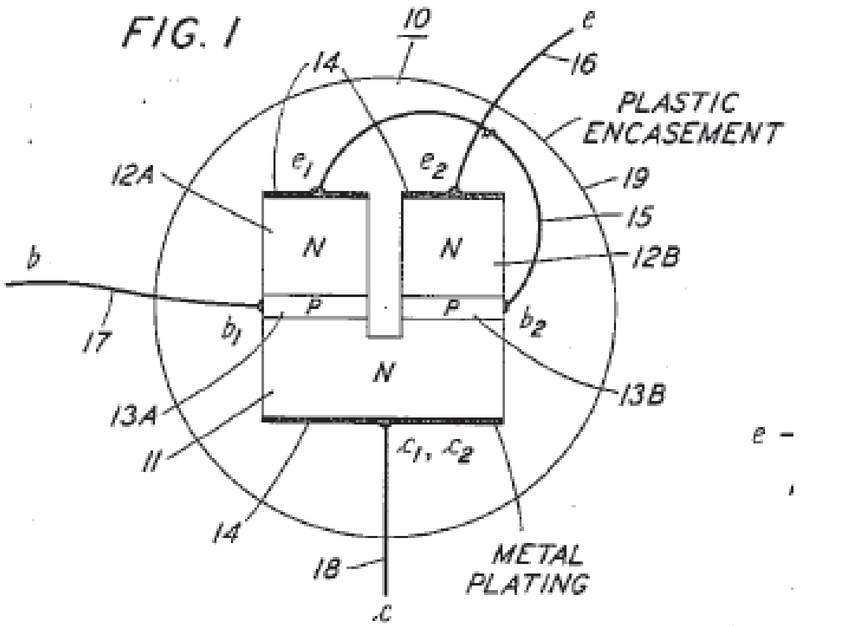


Biased circuit

Other Basic Configurations



Darlington Configuration



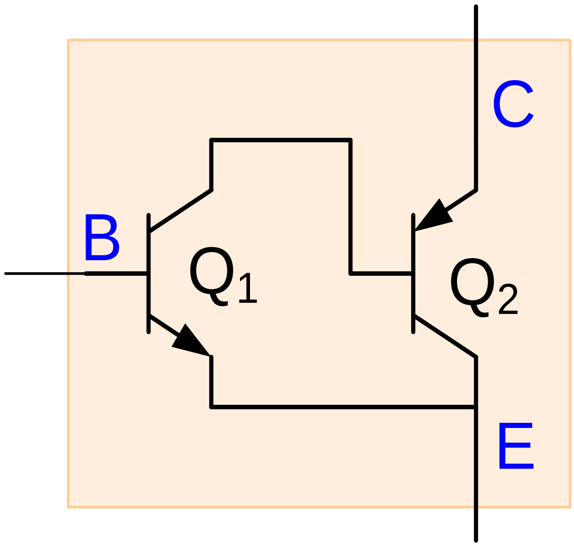
S. DARLINGTON 2,663,806

SEMICONDUCTOR SIGNAL TRANSLATING DEVICE

Filed May 9, 1952

- **Current gain is approximately β^2**
- **Two diode drop between B_{eff} and E_{eff}**

Other Basic Configurations



Sziklai Pair

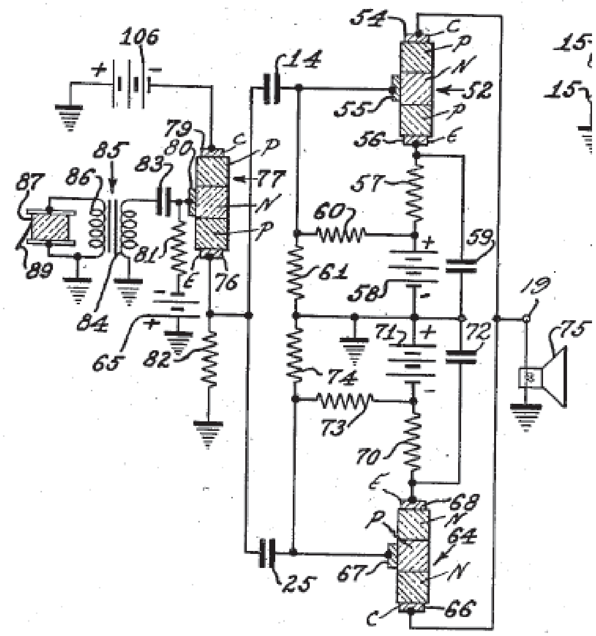


Fig. 3.

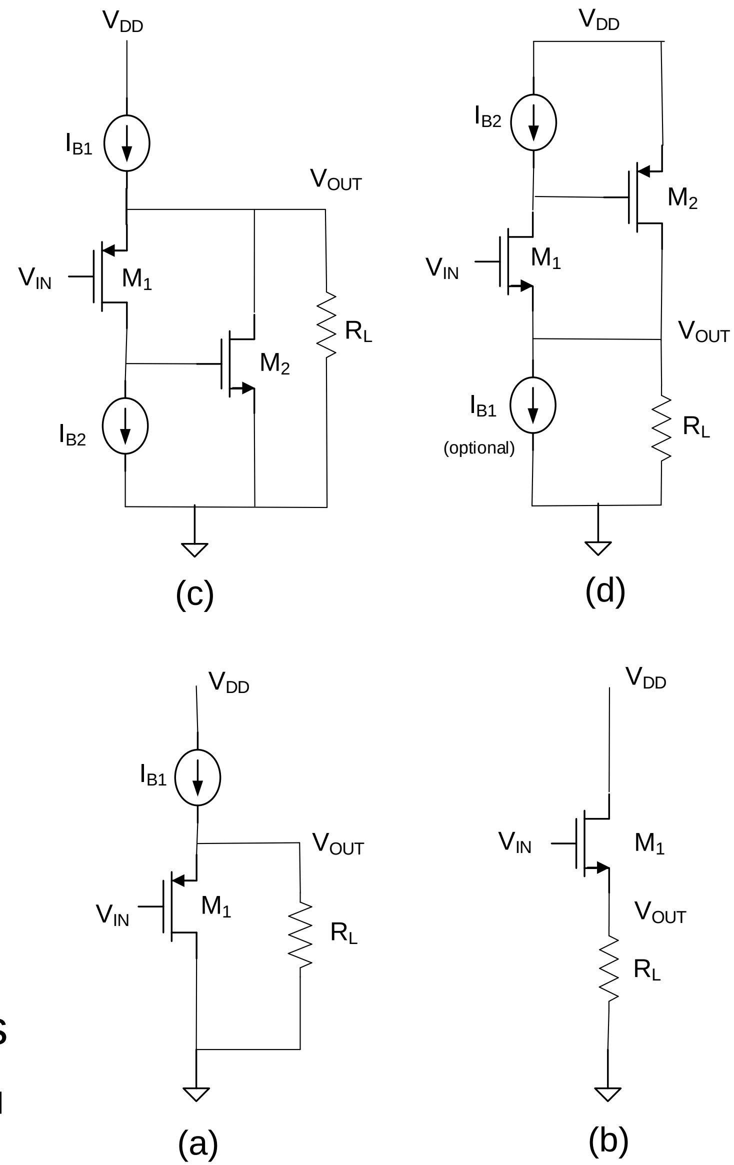
May 7, 1957 G. C. SZIKLAI 2,791,644

PUSH-PULL AMPLIFIER WITH COMPLEMENTARY TYPE TRANSISTORS

Filed Nov. 7, 1952

- **Same basic structure as Darlington Pair**
- **Current gain is approximately $\beta_n\ \beta_p$**
- **Current gain will not be as large when $\beta_p < \beta_n$**
- **Only one diode drop between B_{eff} and E_{eff}**

Other Basic Configurations

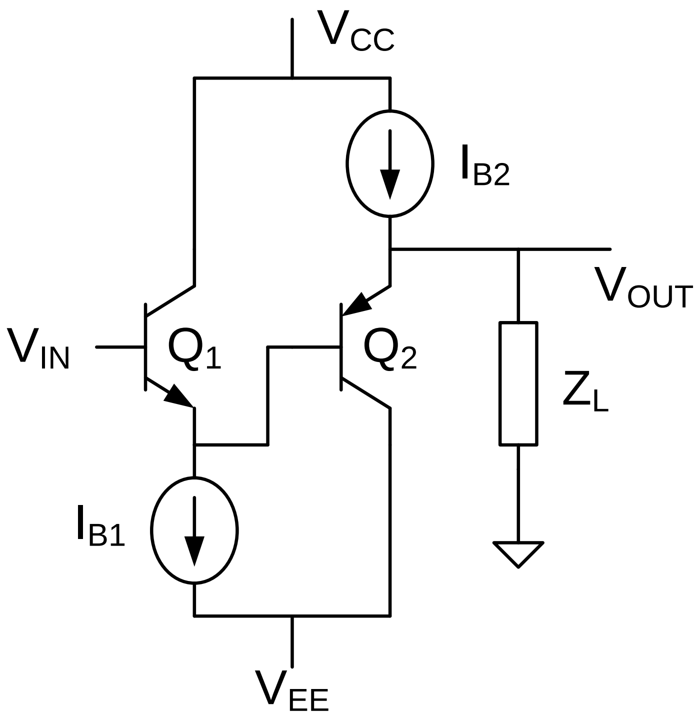


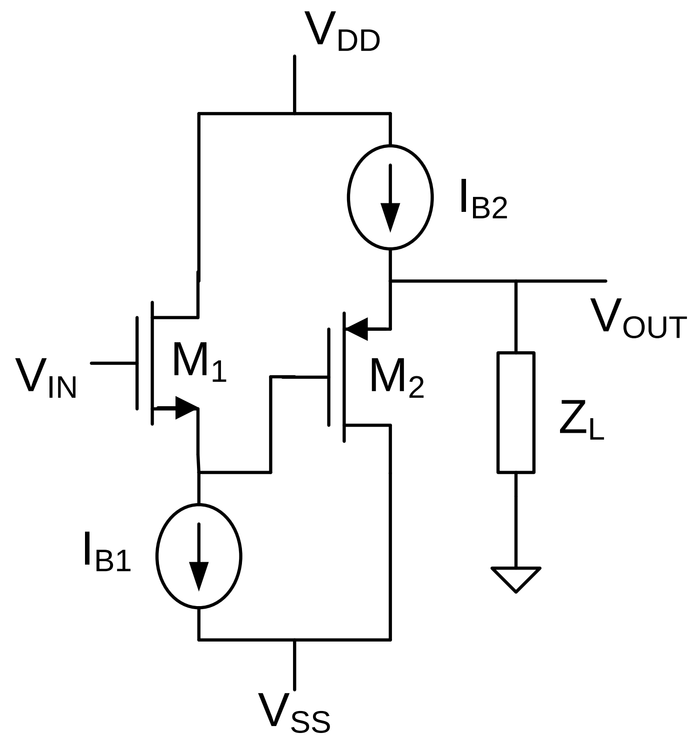
Buffer and Super Buffer

- Voltage shift varies with V_{IN} in buffer
- Current through shift transistor is constant for Super Buffer as V_{IN} changes so voltage shift does not change with V_{IN}
- Same nominal voltage shift

Other Basic Configurations

Low offset buffers

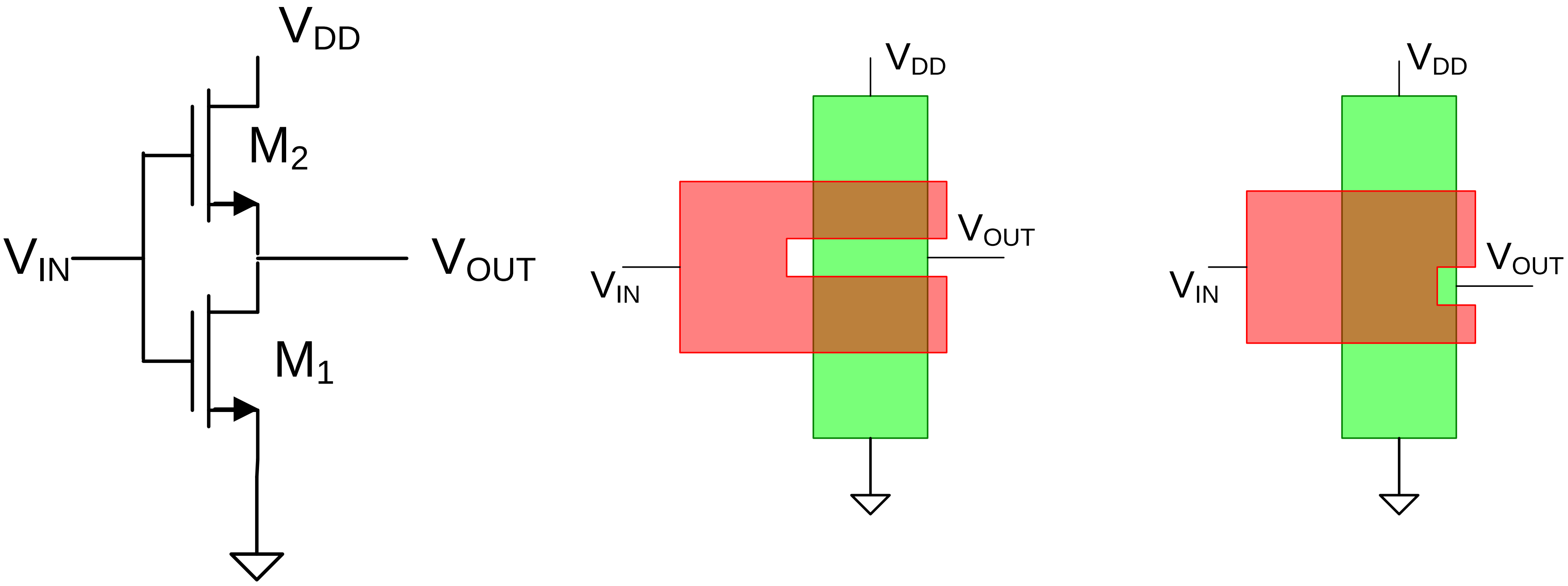




- **Actually a CC-CC or a CD-CD cascade**
- **Significant drop in offset between input and output**
- **Biasing with DC current sources**
- **Can Add Super Buffer to Output**

Other Basic Configurations

Voltage Attenuator



- **Attenuation factor is quite accurate (Determined by geometry)**
- **Infinite input impedance**
- **M_1 in triode, M_2 in saturation**
- **Actually can be a channel-tapped structure**

End of Lecture 35