EE 330
Lecture 33

Basic Amplifiers

- Analysis, Operation, and Design

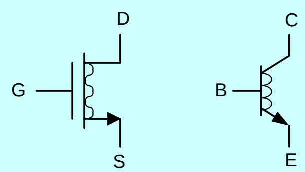
Cascaded Amplifiers

High Gain Amplifiers

Exam 3
Friday November 22

Review Previous Lecture

Basic Amplifier Structures



Small Signal Transistor Models as 3-terminal Devices

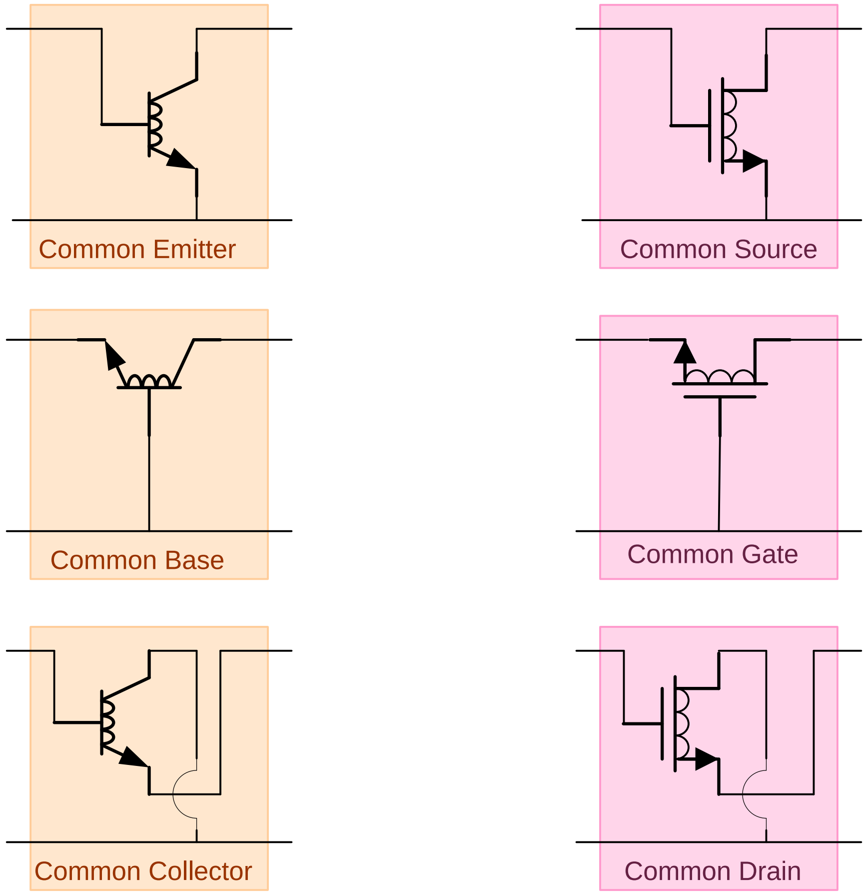
	MOS			BJT		
	Common	Input	Output	Common	Input	Output
Common Source or Common Emitter	S	G	D	E	B	C
Common Gate or Common Base	G	S	D	B	E	C
Common Drain or Common Collector	D	G	S	C	B	E

Objectives in Study of Basic Amplifier Structures

1. Obtain key properties of each basic amplifier
2. Develop method of designing amplifiers with specific characteristics using basic amplifier structures

The three basic amplifier types for both MOS and bipolar processes

Review Previous Lecture

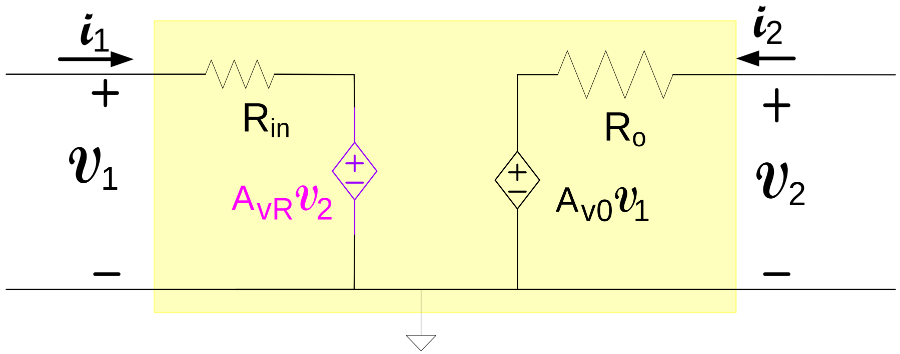


Will focus on the performance of the bipolar structures and then obtain performance of the MOS structures by observation

Review From Previous Lecture

Two-Port Models of Basic Amplifiers widely used for Analysis and Design of Amplifier Circuits

Methods of Obtaining Amplifier Two-Port Network



1. v_{TEST} : i_{TEST} Method (considered in last lecture)

2. Write v_1 : v_2 equations in standard form

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

$$v_2 = i_2 R_O + A_{V0} v_1$$

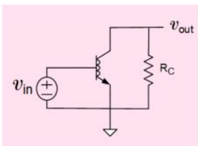
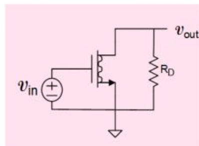
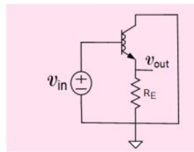
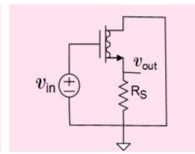
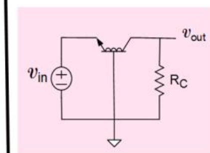
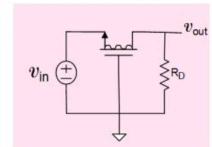
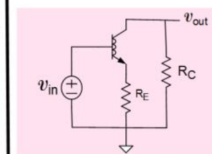
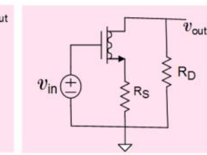
3. Thevenin-Norton Transformations

4. Ad Hoc Approaches

Any of these methods can be used to obtain the two-port model

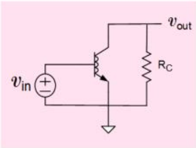
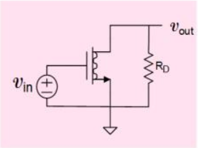
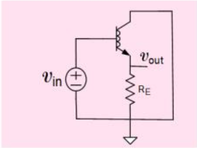
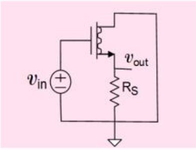
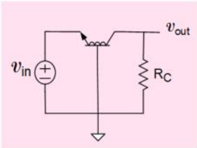
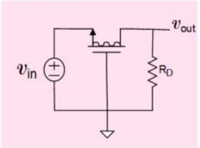
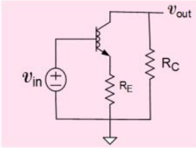
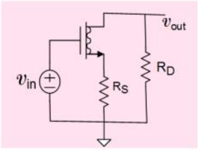
Review From Previous Lecture

Basic Amplifier Gain Table

	CE/CS		CC/CD		CB/CG		CEwRE/CSwRS	
	BJT	MOS	BJT	MOS	BJT	MOS	BJT	MOS
								
A_V	$-g_mR_C$		$\frac{g_m}{g_m+g_E}$		g_mR_C		$-\frac{R_C}{R_E}$	
	$-\frac{I_{CQ}R_C}{V_t}$	$-\frac{2I_{DQ}R_D}{V_{EB}}$	$\frac{I_{CQ}R_E}{I_{CQ}R_E+V_t}$	$\frac{2I_{DQ}R_E}{2I_{DQ}R_E+V_{EB}}$	$\frac{I_{CQ}R_C}{V_t}$	$\frac{2I_{DQ}R_C}{V_{EB}}$		
R_{in}	r_π		$r_\pi+\beta R_E$		g_m^{-1}		$r_\pi+\beta R_E$	
	$\frac{\beta V_t}{I_{CQ}}$	∞	$\beta\left(\frac{V_t}{I_{CQ}}+R_E\right)$	∞	$\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$	$\beta\left(\frac{V_t}{I_{CQ}}+R_E\right)$	∞
R_{out}	R_C		g_m^{-1}		R_C		R_C	
			$\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$				

(not two-port models for the four structures)

Basic Amplifier Gain Table

	CE/CS		CC/CD		CB/CG		CEwRE/CSwRS	
	BJT	MOS	BJT	MOS	BJT	MOS	BJT	MOS
								
A_V	$-g_m R_C$		$\frac{g_m}{g_m+g_E}$		$g_m R_C$		$-\frac{R_C}{R_E}$	
	$-\frac{I_{CQ}R_C}{V_t}$	$-\frac{2I_{DQ}R_D}{V_{EB}}$	$\frac{I_{CQ}R_E}{I_{CQ}R_E+V_t}$	$\frac{2I_{DQ}R_E}{2I_{DQ}R_E+V_{EB}}$	$\frac{I_{CQ}R_C}{V_t}$	$\frac{2I_{DQ}R_C}{V_{EB}}$		
R_{in}	r_π		$r_\pi+\beta R_E$		g_m^{-1}		$r_\pi+\beta R_E$	
	$\frac{\beta V_t}{I_{CQ}}$	∞	$\beta\left(\frac{V_t}{I_{CQ}}+R_E\right)$	∞	$\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$	$\beta\left(\frac{V_t}{I_{CQ}}+R_E\right)$	∞
R_{out}	R_C		g_m^{-1}		R_C		R_C	
			$\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$				

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

Basic Amplifier Structures

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:CG cascade)
6. Darlington (special CC:CE or CD:CS cascade)

Will be discussed later

The first 4 are most popular

Why are we focusing on these basic circuits?

1. So that we can develop analytical skills
2. So that we can design a circuit
3. So that we can get the insight needed to design a circuit

Which is the most important?

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Which is the most important?

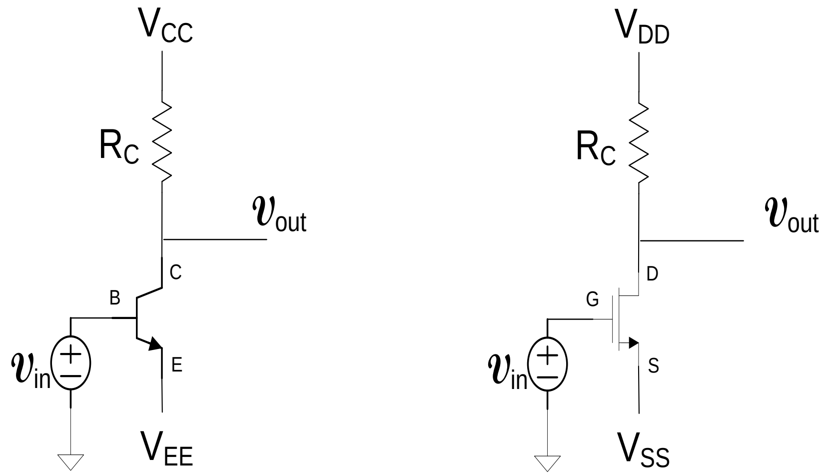
1. So that we can get the insight needed to design a circuit

2. So that we can design a circuit

3. So that we can develop analytical skills

Properties/Use of Basic Amplifiers

CE and CS



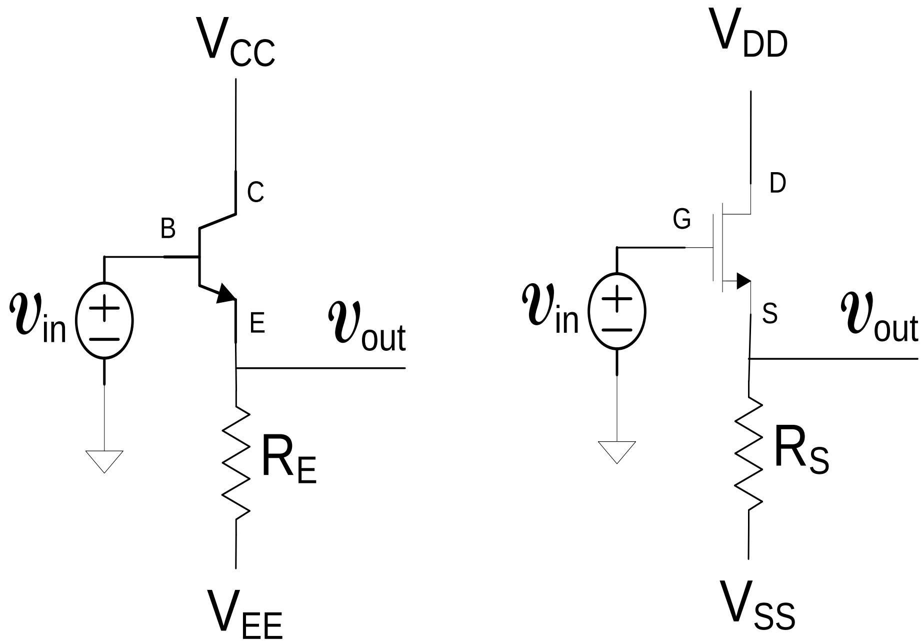
More practical biasing circuits usually used

R_C or R_D may (or may not) be load

- **Large inverting gain**
- **Moderate input impedance for BJT (high for MOS)**
- **Moderate output impedance**
- **Most widely used amplifier structure**

Properties/Use of Basic Amplifiers

CC and CD
(emitter follower or source follower)



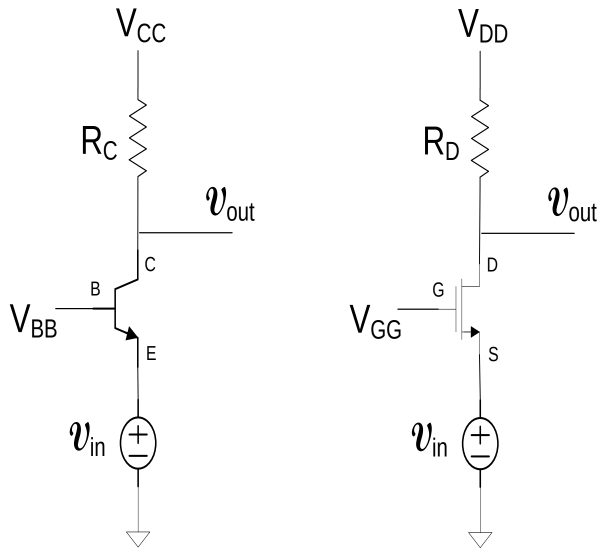
More practical biasing circuits usually used

R_E or R_S may (or may not) be load

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

Properties/Use of Basic Amplifiers

CB and CG



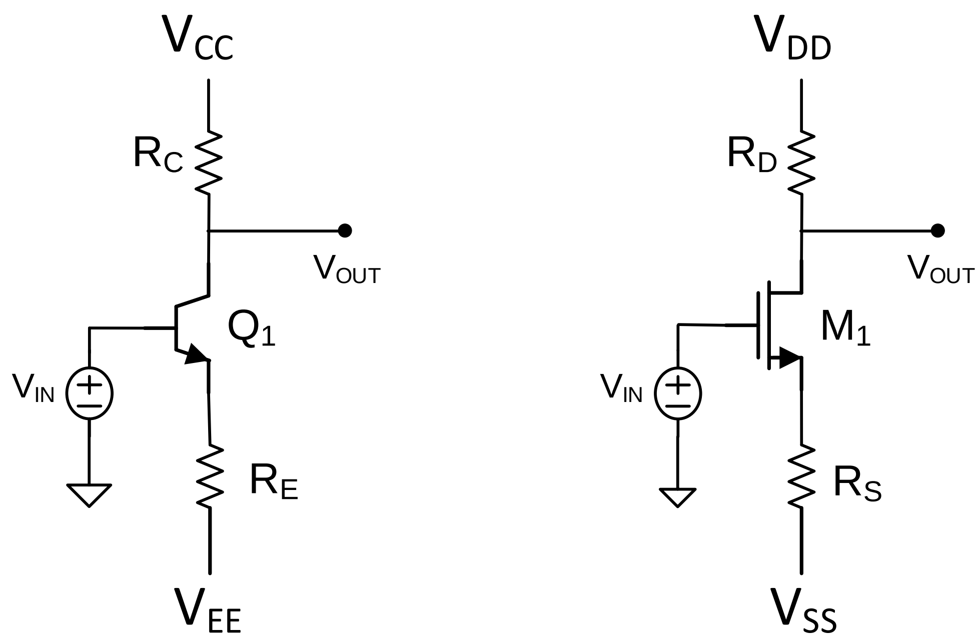
More practical biasing circuits usually used

R_C or R_D may (or may not) be load

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

Properties/Use of Basic Amplifiers

CEwRE and CSwRS



CE with R_E CS with R_S

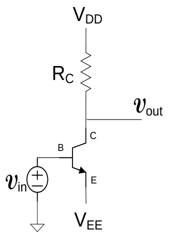
More practical biasing circuits usually used

R_C or R_D may (or may not) be load

- **Gain can be accurately controlled with resistor ratios**
- **Useful for reasonably accurate low gains**
- **Input impedance is high**

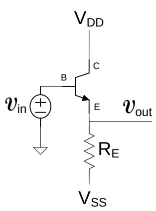
Basic Amplifier Characteristics Summary

CE/CS



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

CC/CD



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- **Low output impedance**
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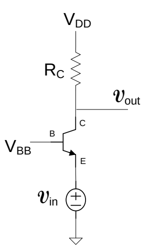
CB/CG



- **Large noninverting gain**
- **Low input impedance**
- **Moderate (or high) output impedance**
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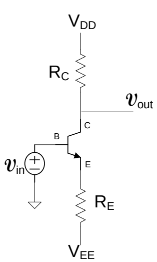
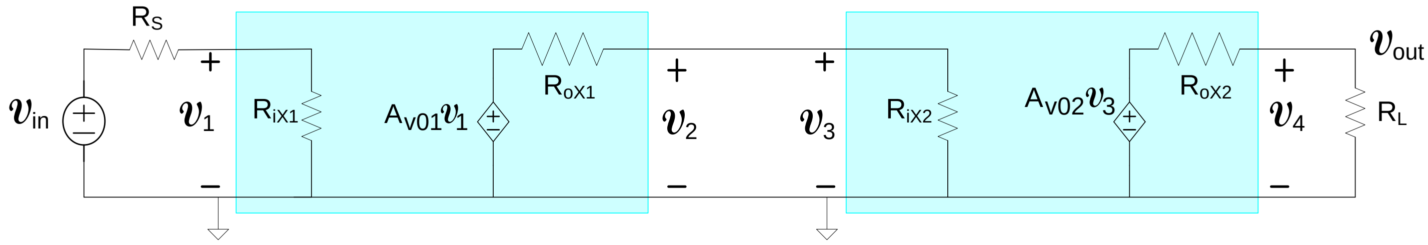
CEwRE/ CSwRS



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

Cascaded Amplifiers



$$A_V = \frac{v_{out}}{v_{in}} = \left(\frac{R_{iX1}}{R_{iX1}+R_S}\right) A_{V01} \left(\frac{R_{iX2}}{R_{iX2}+R_{0X1}}\right) A_{V02} \left(\frac{R_L}{R_L+R_{0X2}}\right)$$

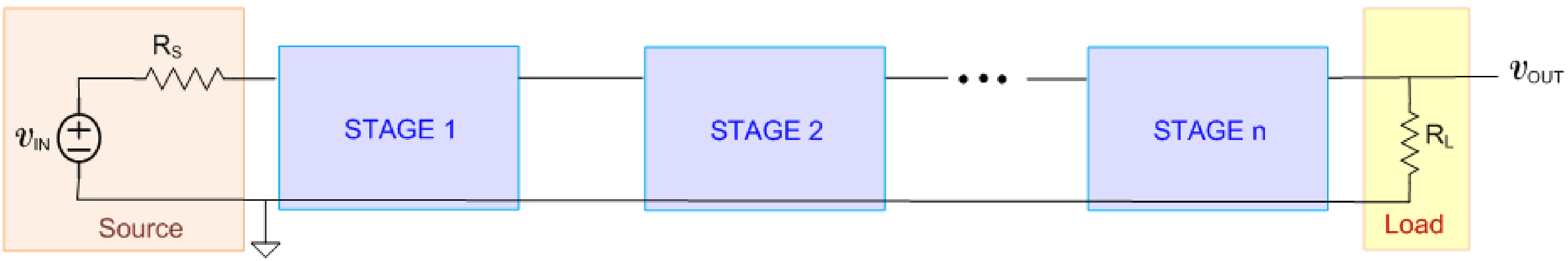
If $R_o << R_i$ $\qquad$ $R_S << R_i$ $\qquad$ $R_o << R_L$

$$A_V \cong A_{V01} A_{V02}$$

- Amplifier cascading widely used to enhance gain
- Amplifier cascading widely used to enhance other characteristics and/or alter functionality as well
  e.g. (R_{IN}, BW, Power, R_O, Linearity, Impedance Conversion..)

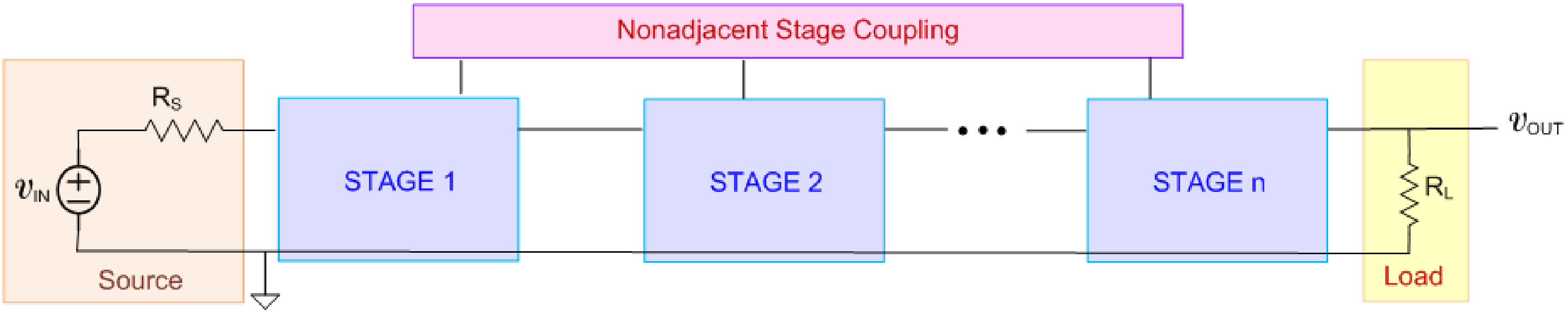
Cascaded Amplifier Analysis and Operation

Adjacent Stage Coupling Only



- Systematic Methods of Analysis/Design will be Developed

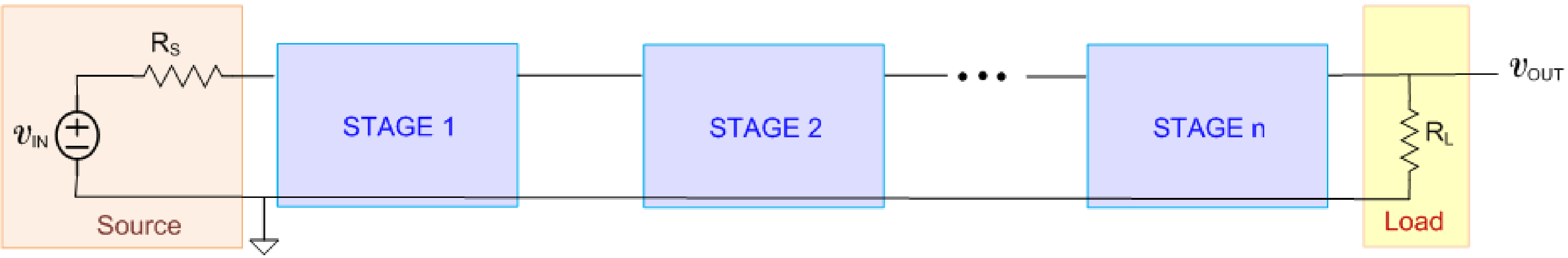
One or more couplings of nonadjacent stages



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

Cascaded Amplifier Analysis and Operation

Adjacent Stage Coupling Only



- Systematic Methods of Analysis/Design will be Developed

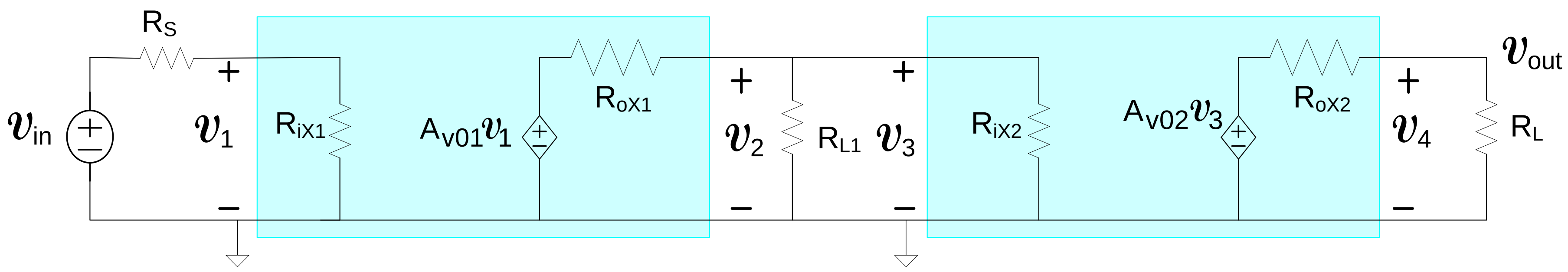
Case 1: All stages Unilateral

Case 2: One or more stages are not unilateral

Repeat from earlier discussions on amplifiers

Cascaded Amplifier Analysis and Operation

Case 1: All stages Unilateral



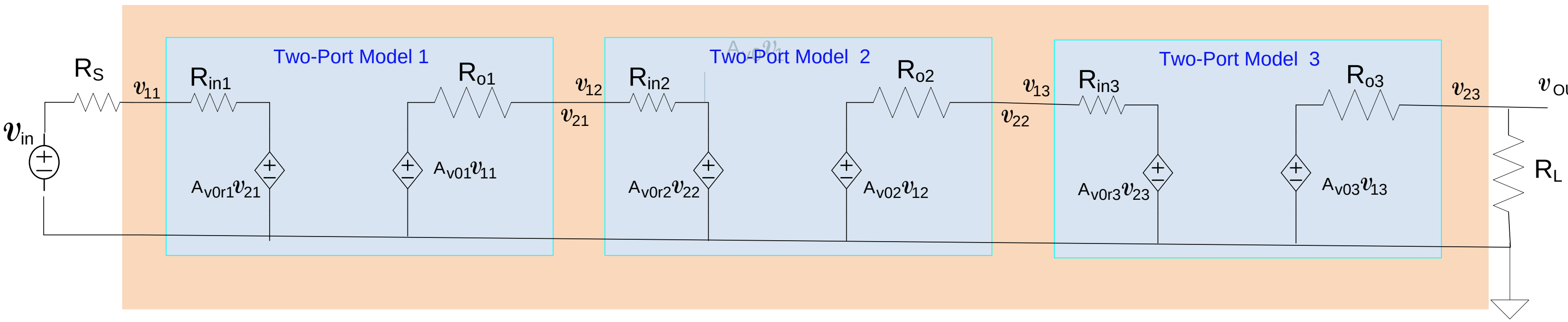
$$A_V = \frac{v_{out}}{v_{in}} = \left(\frac{R_{iX1}}{R_{iX1}+R_S}\right)A_{V01}\left(\frac{R_{L1}//R_{iX2}}{R_{L1}//R_{iX2}+R_{0X1}}\right)A_{V02}\left(\frac{R_L}{R_L+R_{0X2}}\right)$$

Accounts for all loading between stages !

Cascaded Amplifier Analysis and Operation

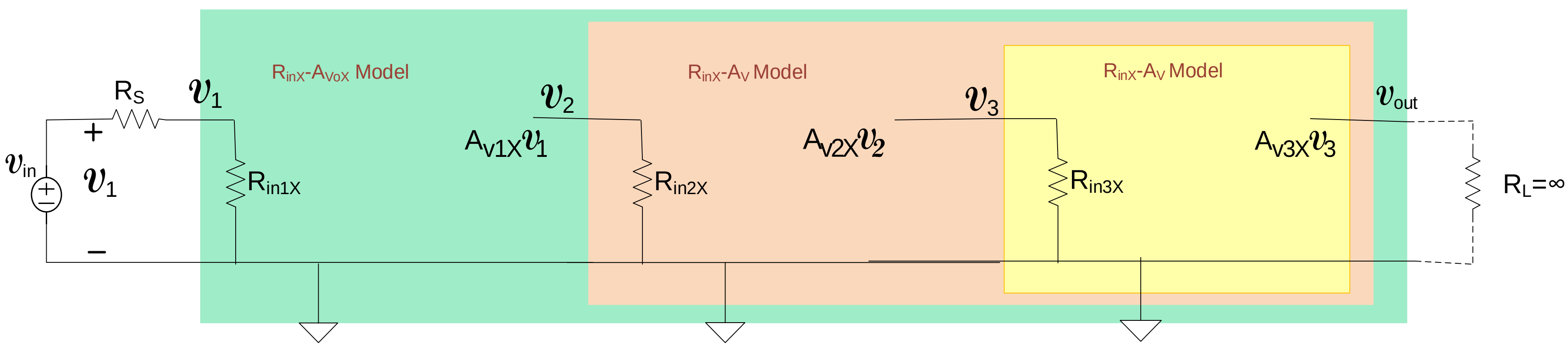
Case 2: One or more stages are not unilateral

- Standard two-port cascade



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

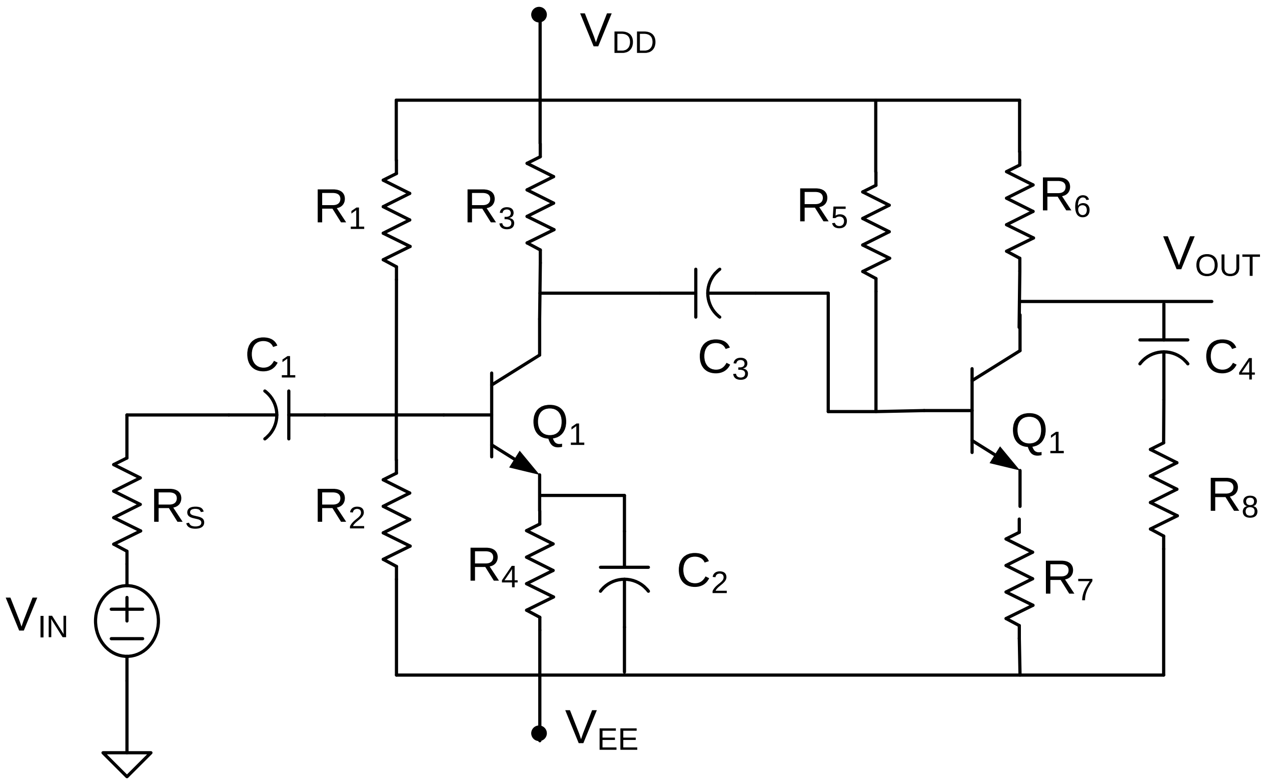
- Right-to-left nested R_{inx},A_{VKX} approach



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

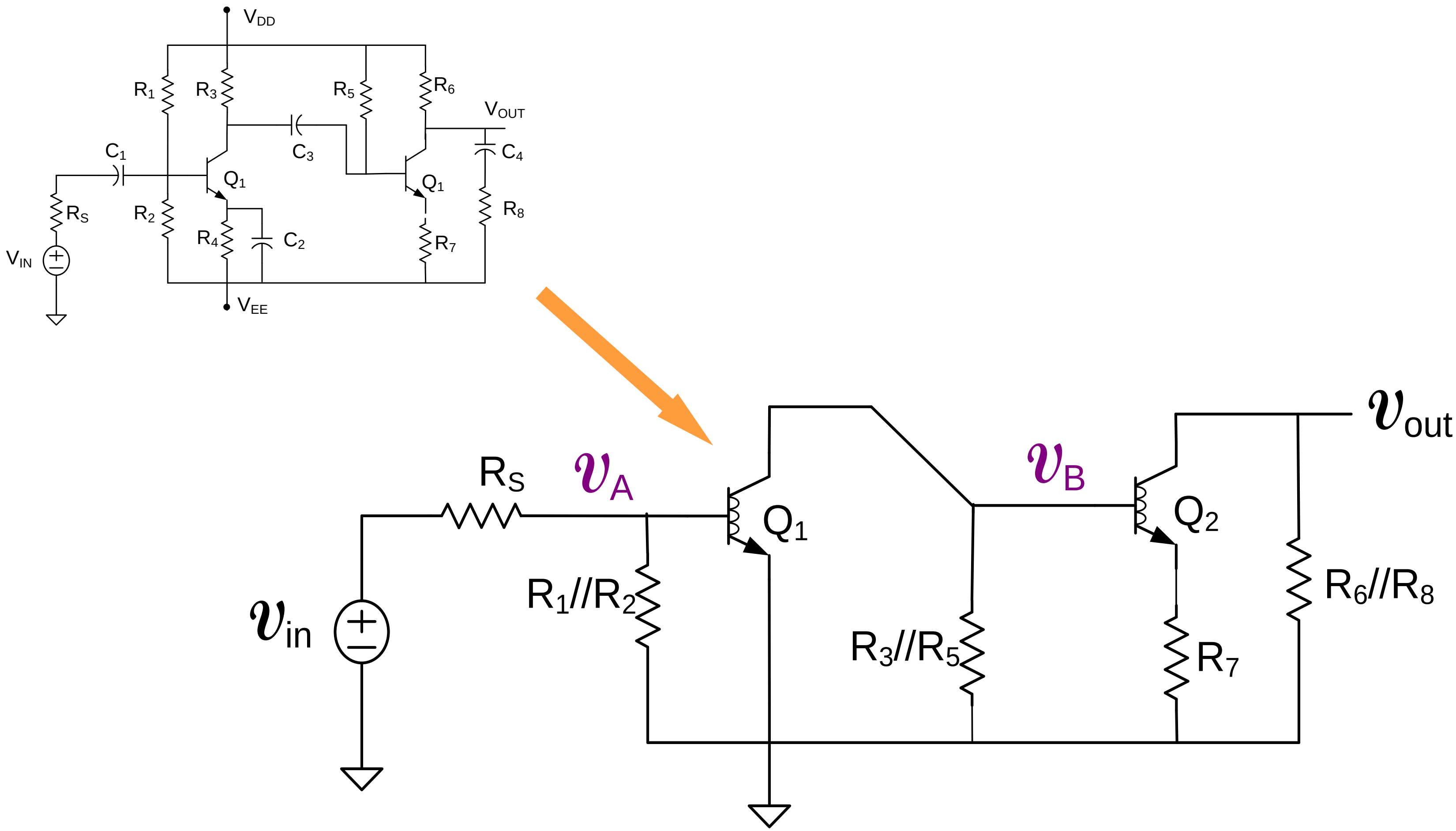
Example:

Determine the voltage gain of the following circuit <u>in terms of the small-signal</u> <u>parameters</u> of the transistors. Assume Q_1 and Q_2 are operating in the Forward Active region and $C_1 \ldots C_4$ are large.



In this form, does not look "EXACTLY" like any of the basic amplifiers !

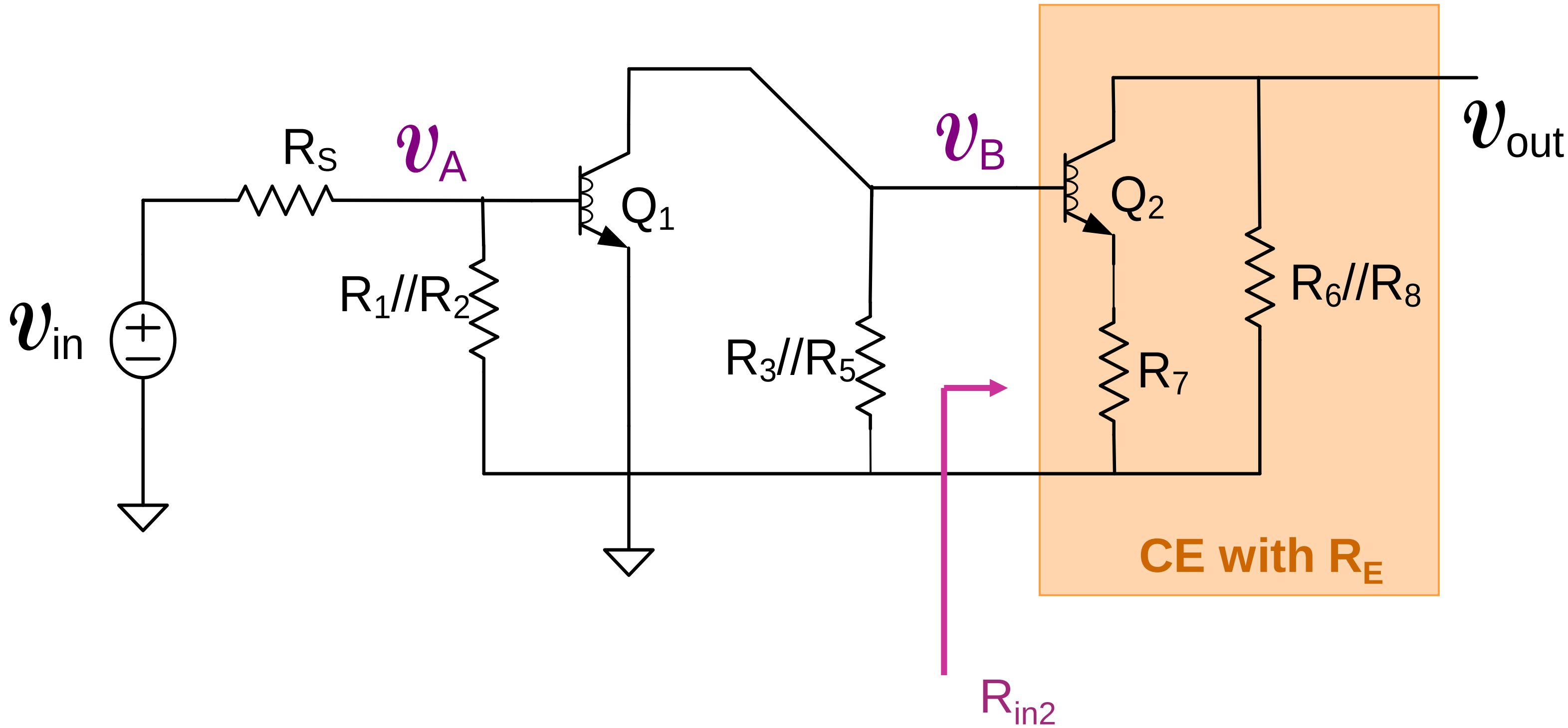
Example:



Will calculate A_V by determining the three ratios (not voltage gains of dependent source):

$$A_V = \frac{v_{out}}{v_{in}} = \frac{v_{out}}{v_B}\frac{v_B}{v_A}\frac{v_A}{v_{in}} = A_{V2}A_{V1}A_{V0}$$

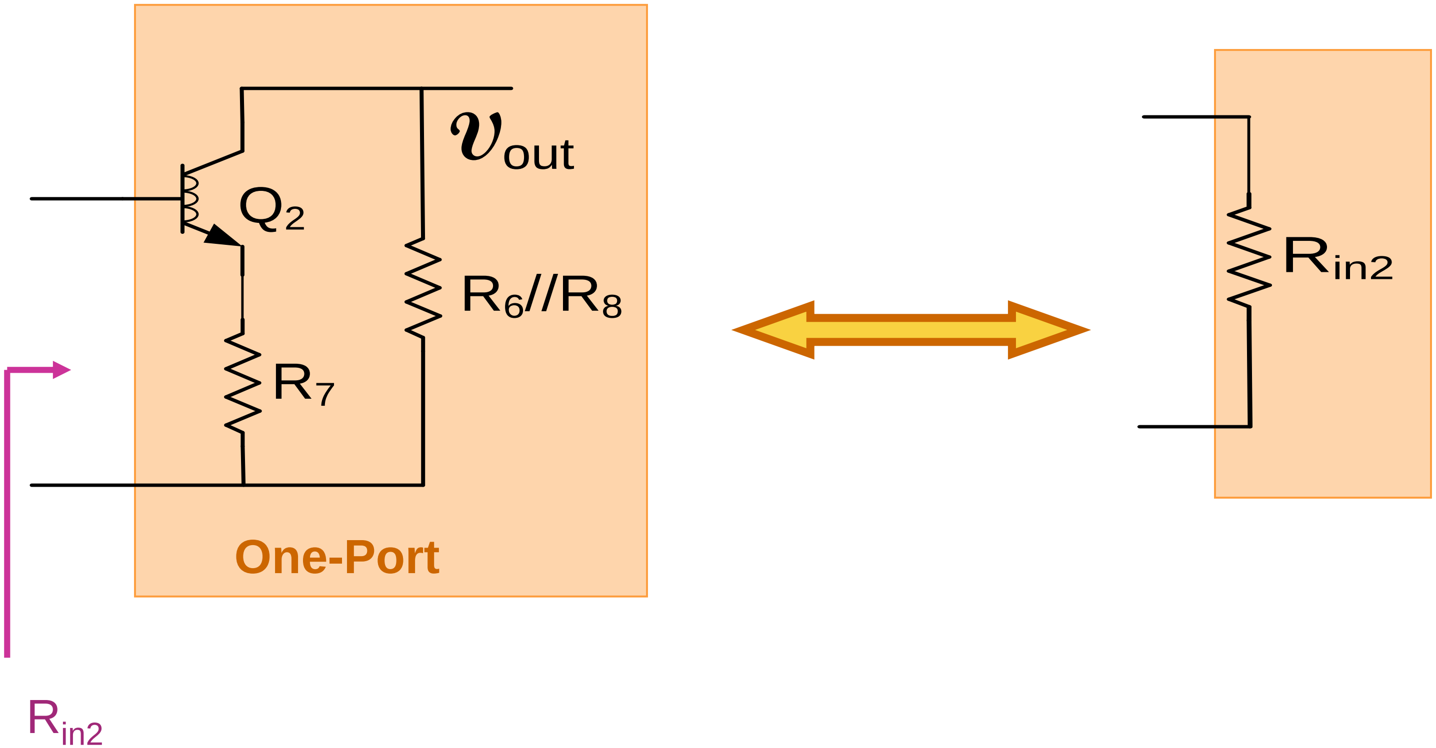
Example:



$$A_{V2} = \frac{v_{out}}{v_B} \cong -\frac{R_6//R_8}{R_7}$$

$$R_{in2} \cong \beta R_7$$

Example:



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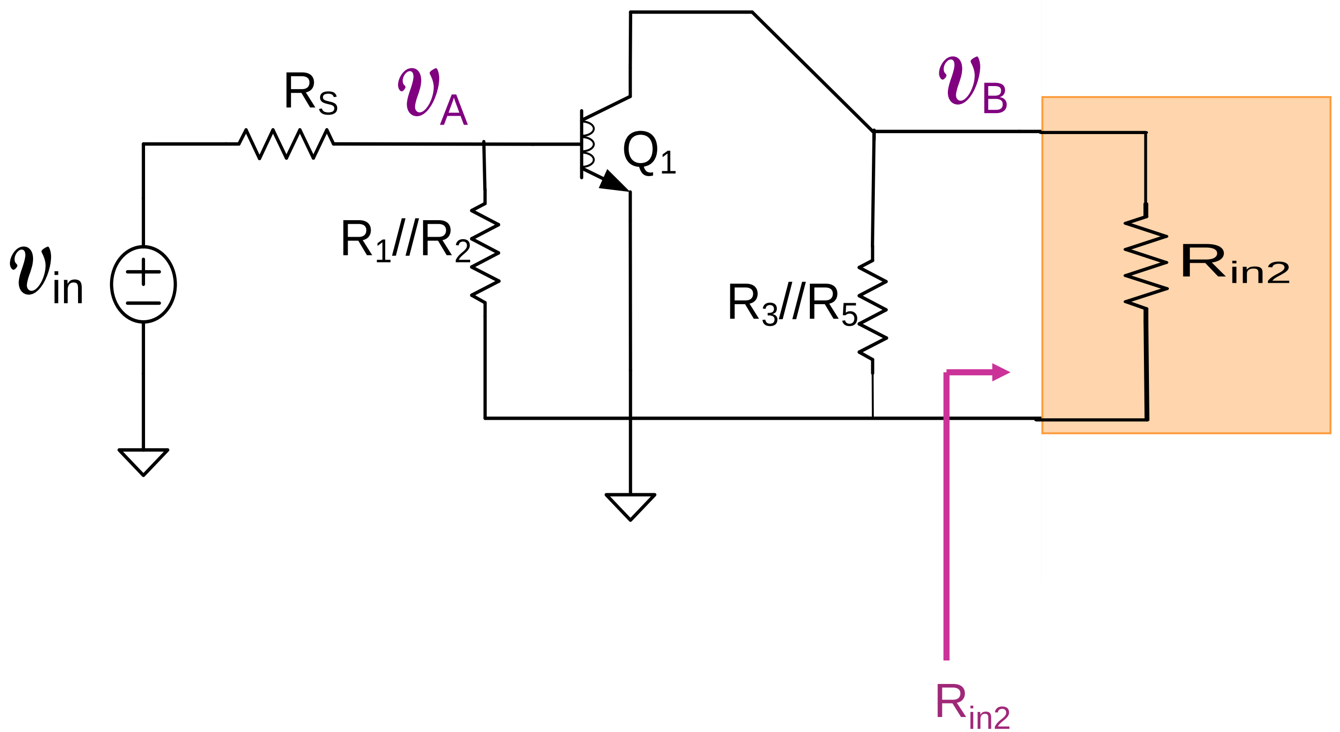

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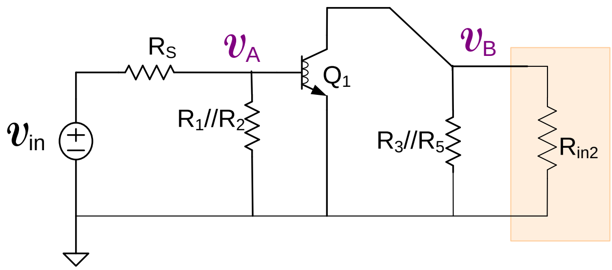
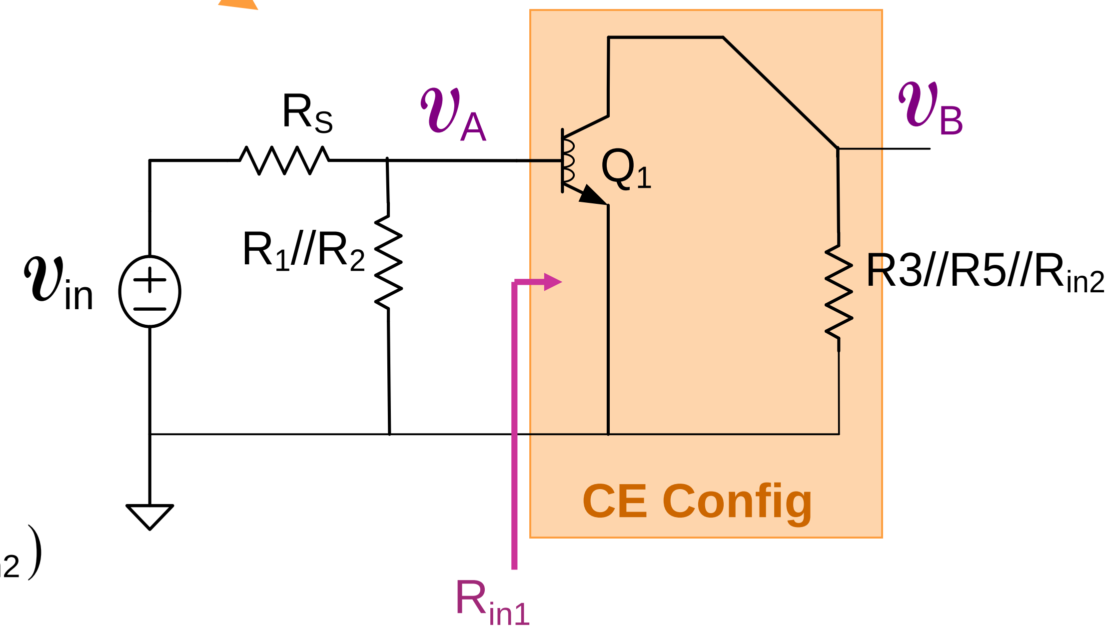
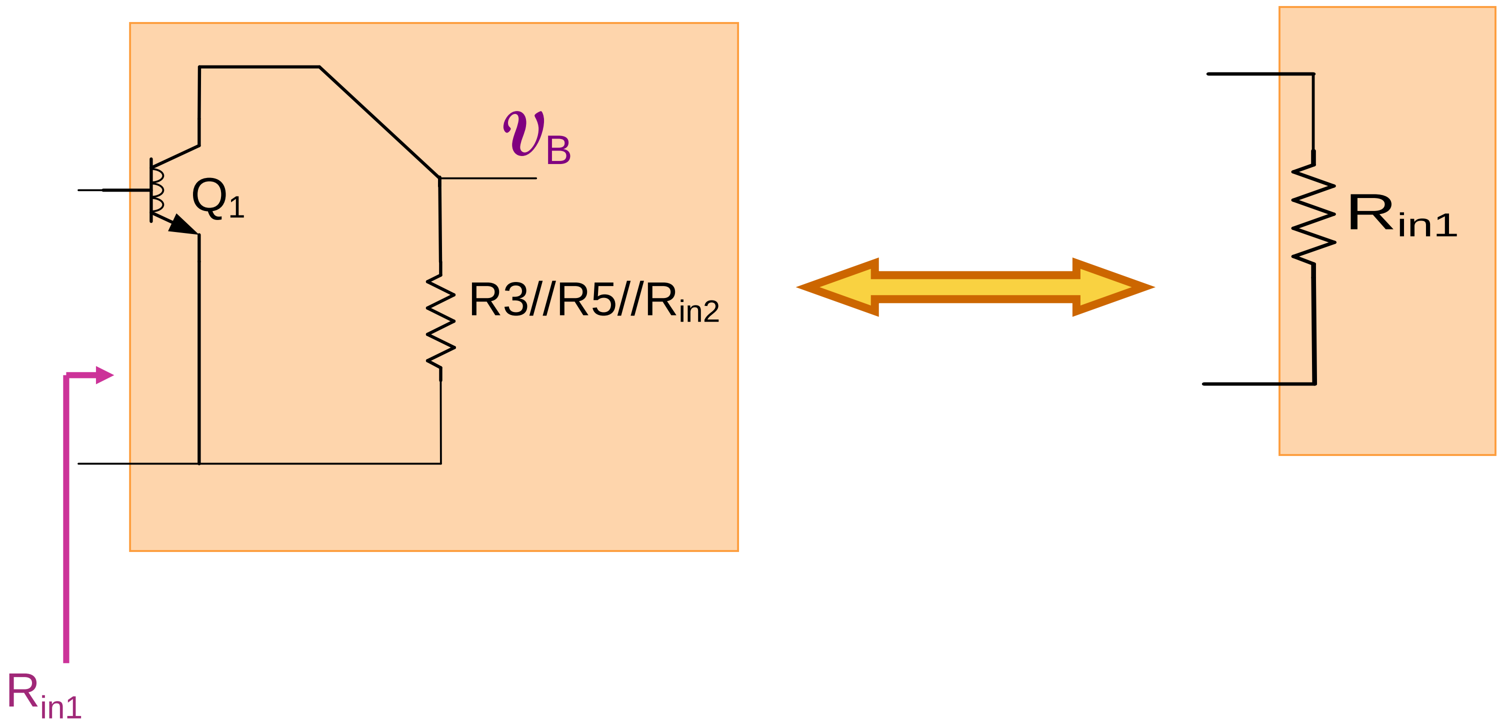




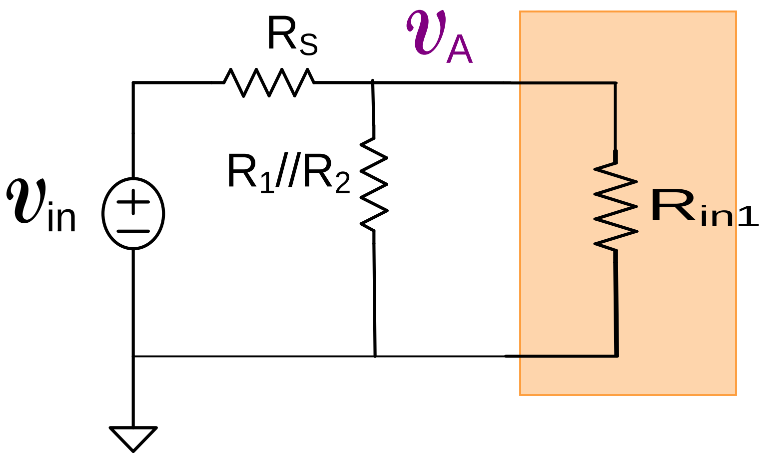
$$A_{V1} = \frac{v_B}{v_A} \cong -g_{m1}\left(R_3 // R_5 // R_{in2}\right)$$

$$R_{in1} \cong r_{\pi 1}$$

Example:

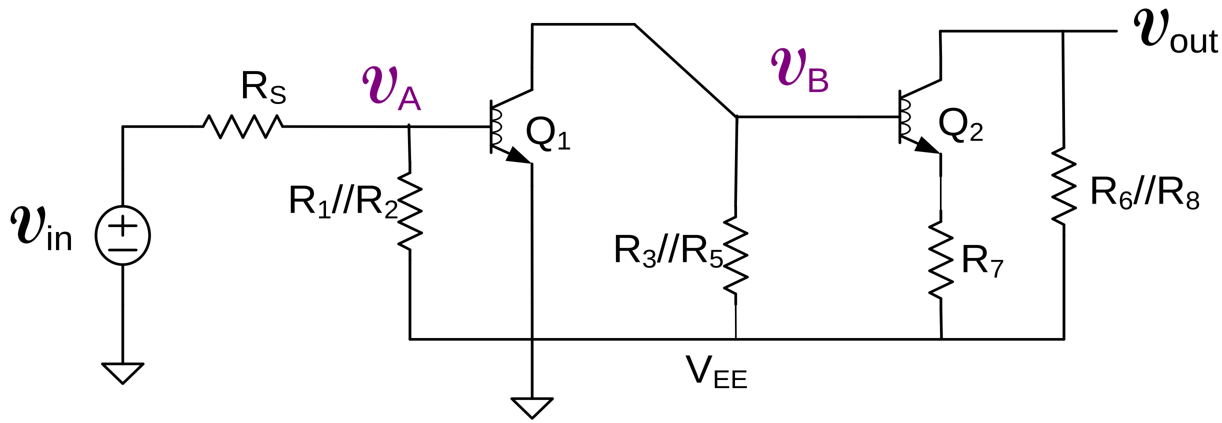


Example:



$$A_{V0} = \frac{v_A}{v_{in}} \cong \frac{R_1//R_2 // R_{in1}}{R_S + R_1//R_2 // R_{in1}}$$

Example:



Thus we have

$$A_V = \frac{v_{out}}{v_{in}} = \frac{v_{out}}{v_B}\frac{v_B}{v_A}\frac{v_A}{v_{in}}$$

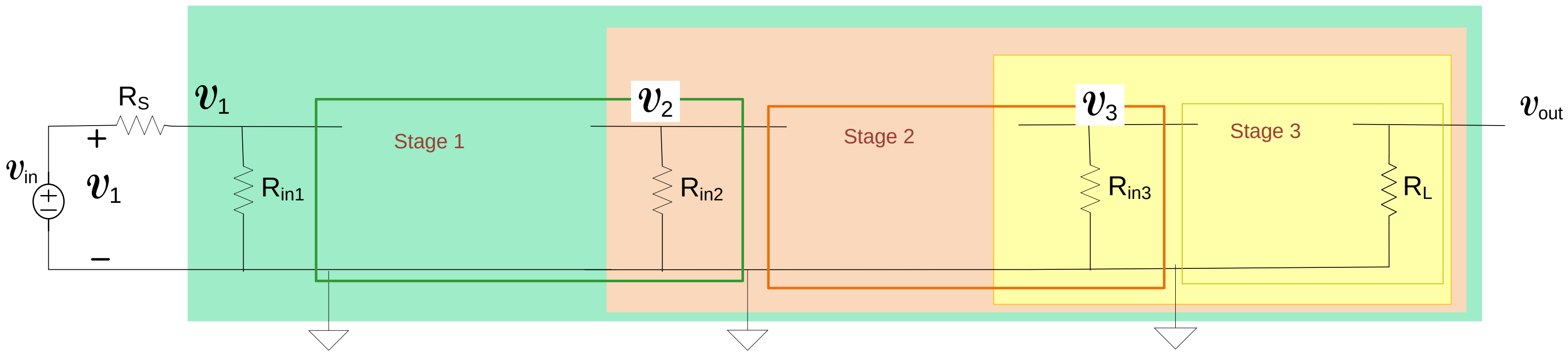
where

$$\frac{v_{out}}{v_B} \cong -\frac{R_6//R_8}{R_7}$$

$$\frac{v_B}{v_A} \cong -g_{m1}\left(R_3//R_5//R_{in2}\right) \qquad R_{in2} \cong \beta R_7$$

$$\frac{v_A}{v_{in}} \cong \frac{R_1//R_2//R_{in1}}{R_S + R_1//R_2//R_{in1}} \qquad R_{in1} \cong r_{\pi 1}$$

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

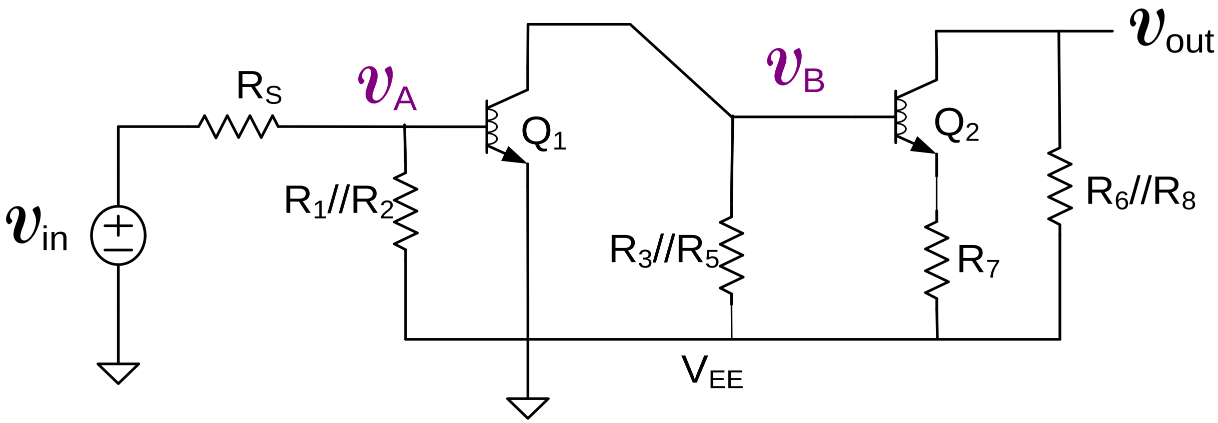


R_{ink} includes effects of all loading
Must recalculate if any change in loading
Analysis systematic and rather simple

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

This was the approach used in analyzing the previous cascaded amplifier

Example:

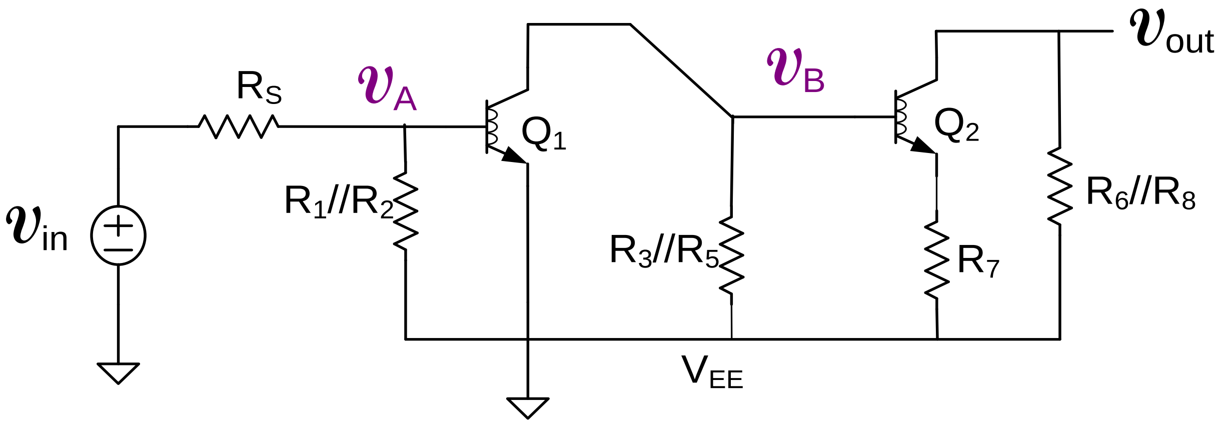


Observation: By working from the output back to the input we were able to create a sequence of steps where the circuit at each step looked EXACTLY like one of the four basic amplifiers. Engineers often follow a design approach that uses a cascade of the basic amplifiers and that is why it is often possible to follow this approach to analysis.

Two other methods could have been used to analyze this circuit

What are they?

Example:



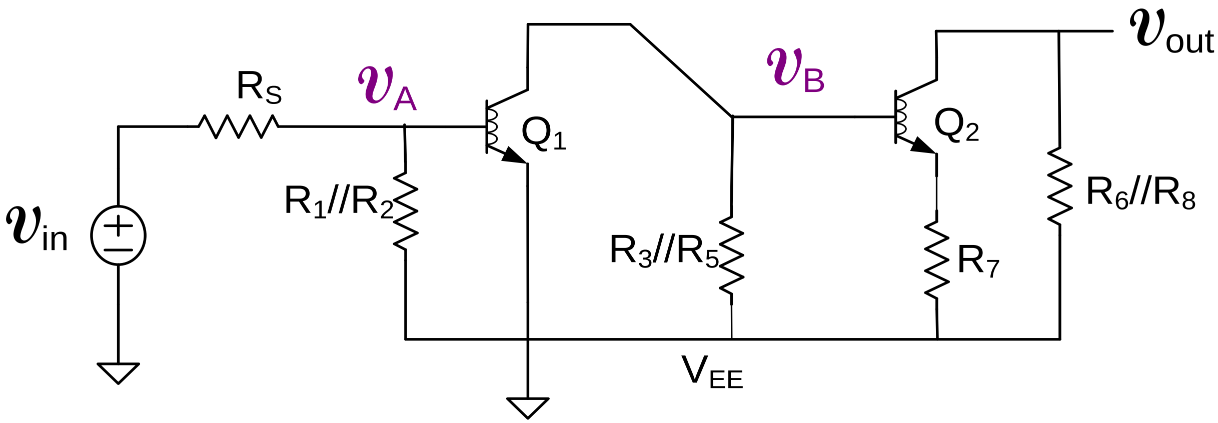
Two other methods could have been used to analyze this circuit

1. Create a two-port model of the two stages

(for this example, since the first-stage is unilateral, it can be shown that)

$$A_V = \frac{v_{out}}{v_{in}} = \frac{v_A}{v_{in}} \frac{v_B}{v_A} \frac{v_{out}}{v_B}$$

Example:

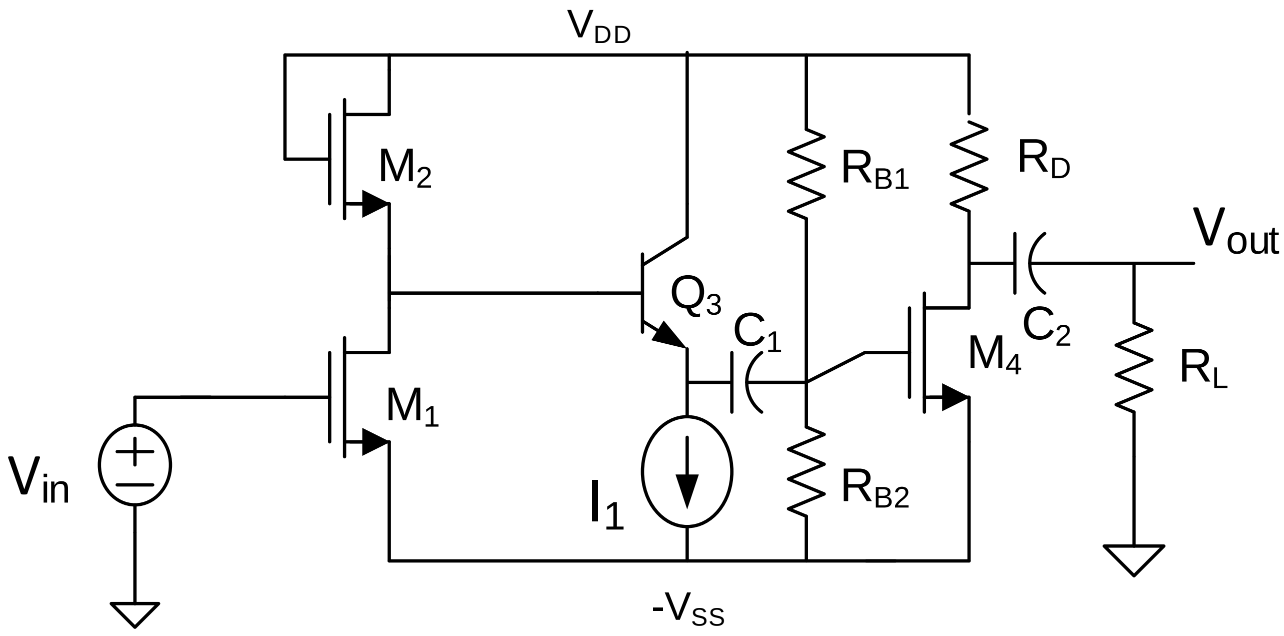


Two other methods could have been used to analyze this circuit

2. Put in small-signal model for Q_1 and Q_2 and solve resultant circuit

(not too difficult for this specific example but time consuming)

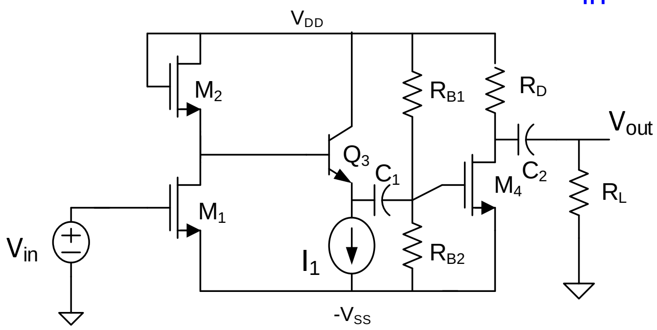
Example: $A_V = \dfrac{v_{out}}{v_{in}} = ?$ Express in terms of small-signal parameters



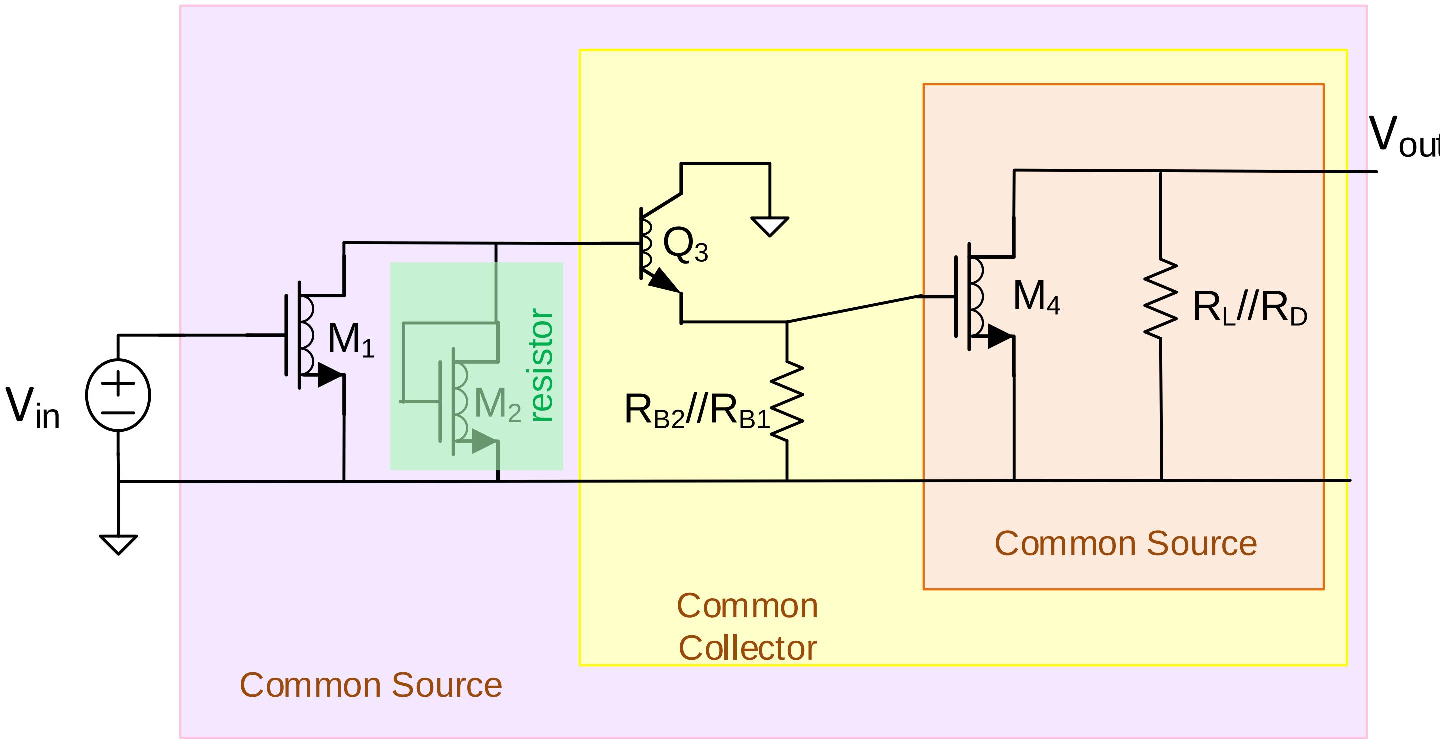
Example:

$$A_V = \frac{v_{out}}{v_{in}} = ?$$

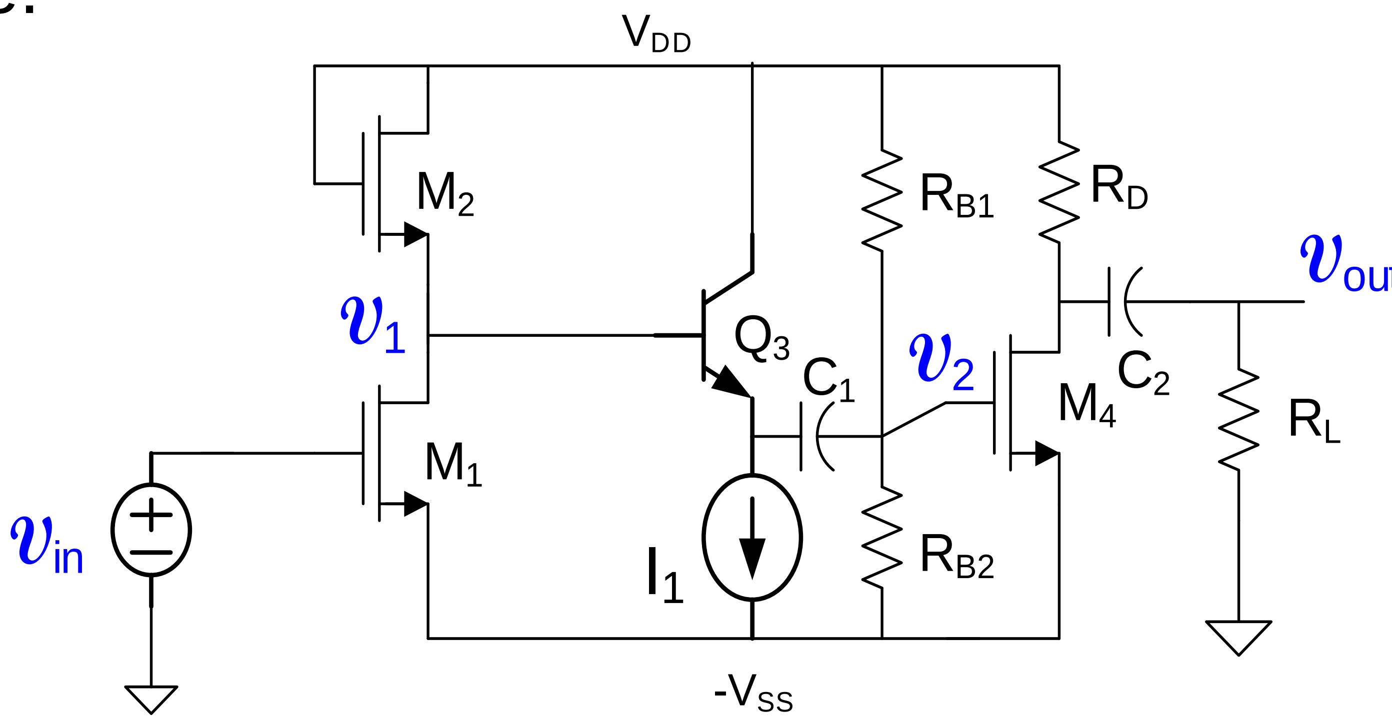
Express in terms of small-signal parameters



visualize

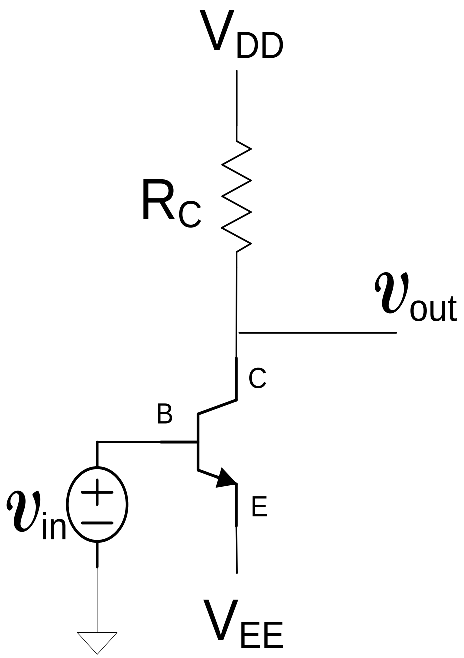


Example:



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

High-gain BJT amplifier



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

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

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

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

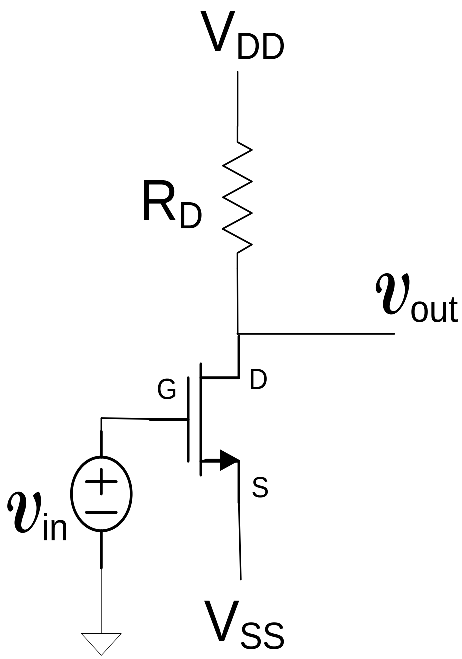
$$|A_V| < \frac{V_{DD} - V_{EE}}{2V_t}$$

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

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

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

High-gain MOS amplifier



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

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

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

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

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

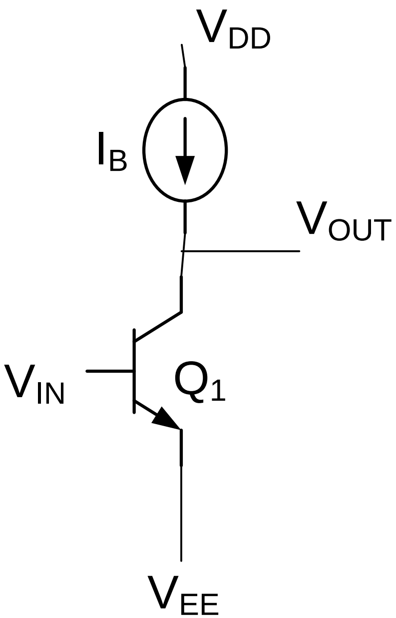
If V_{DD} -V_{SS}=5V and V_{EB}=100mV,

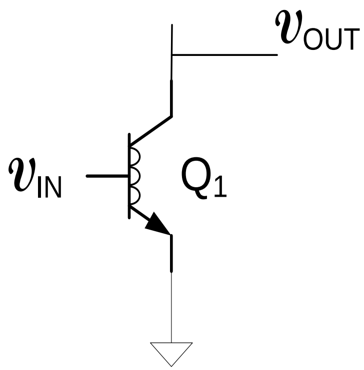
$$|A_V| < \frac{5V}{100mV} = 50$$

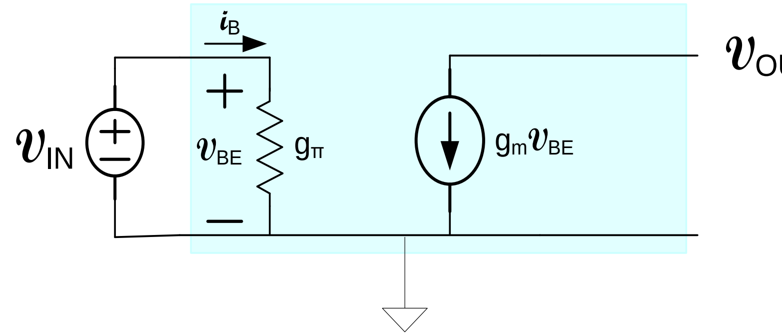
Gain is practically limited with this supply voltage to around 50

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

High-gain amplifier







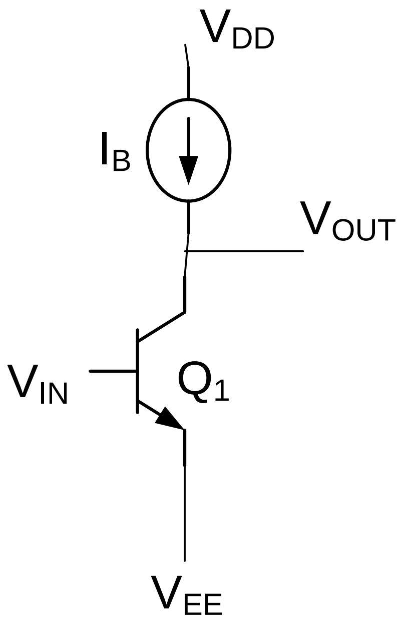
$$A_V = \frac{-g_m}{0} = -\infty$$

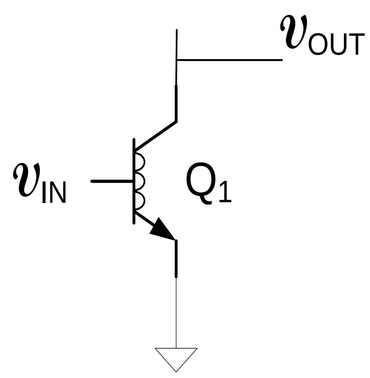
This gain is very large !

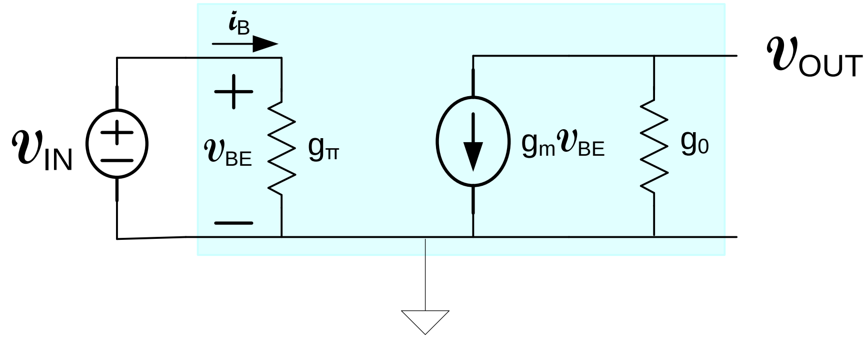
Too good to be true !

Need better model of MOS device!

High-gain amplifier







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

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

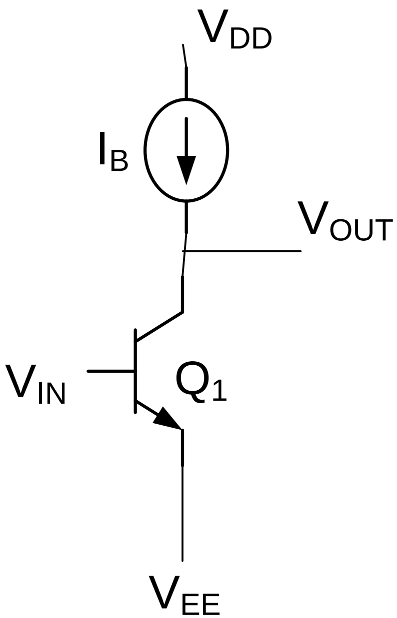
$$A_V = -\frac{V_{AF}}{V_t} \cong \frac{200\text{V}}{25\text{mV}} = -8000$$

This gain is very large (but realistic) !

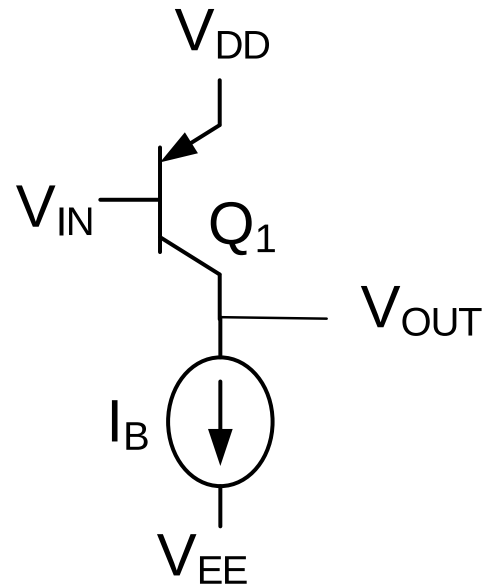
And no design parameters affect the gain

But how can we make a current source?

High-gain amplifier



$$A_V \cong -8000$$



Same gain with both npn and pnp transistors

How can we build the ideal current source?

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

End of Lecture 33