EE 330
Lecture 32

Basic Amplifiers

- Analysis, Operation, and Design

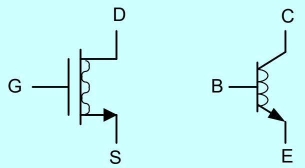
Cascaded Amplifiers

Spring 2024 Exam Schedule

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

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

Basic Amplifier Structures



Small Signal Transistor Models
as 3-terminal Devices

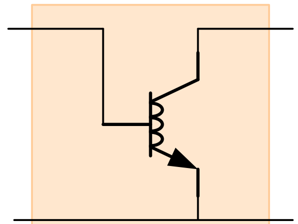
	MOS Common	MOS Input	MOS Output	BJT Common	BJT Input	BJT Output
Common Source or Common Emitter	S	G	D	E	B	C
Common Gate or Common Base	G	S	D	B	E	C
Common Drain or Common Collector	D	G	S	C	B	E

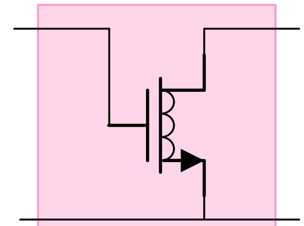
Objectives in Study of Basic Amplifier Structures

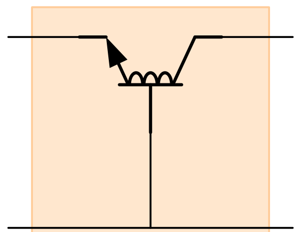
1. Obtain key properties of each basic amplifier
2. Develop method of designing amplifiers with specific characteristics using basic amplifier structures

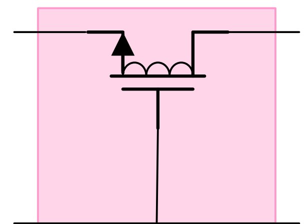
The three basic amplifier types for both MOS and bipolar processes

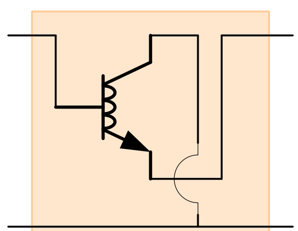
Review Previous Lecture

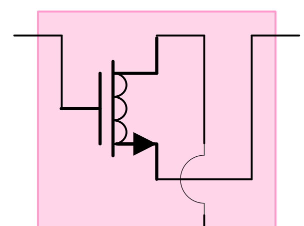

Common Emitter


Common Source


Common Base


Common Gate


Common Collector

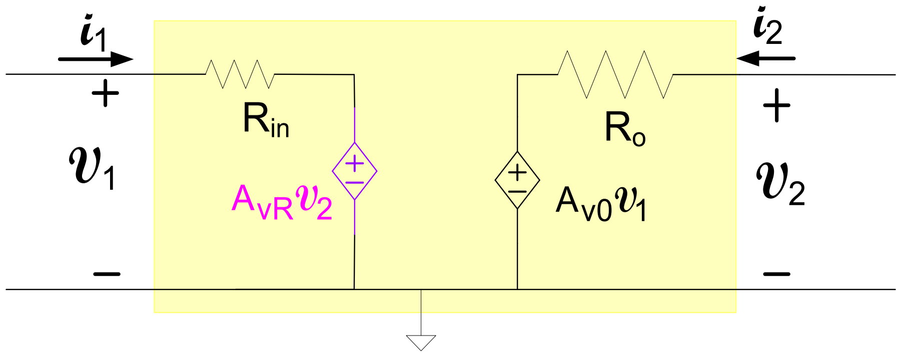

Common Drain

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

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

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

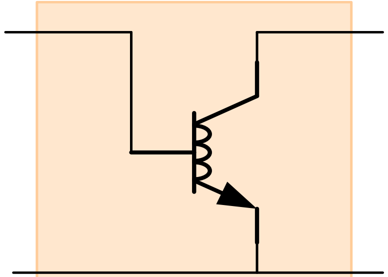
3. Thevenin-Norton Transformations

4. Ad Hoc Approaches

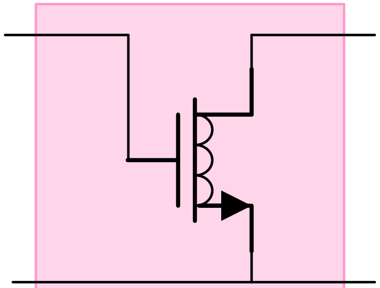
Any of these methods can be used to obtain the two-port model

Review From Previous Lecture

Common Source/ Common Emitter Configurations



Common Emitter



Common Source

$A_{VR} = 0$ $\qquad$ $A_{VR} = 0$

$$R_{in} = \frac{1}{g_\pi} \qquad A_{V0} = -\frac{g_m}{g_0} \qquad R_0 = \frac{1}{g_0}$$

$$R_{in} = \infty \qquad A_{V0} = -\frac{g_m}{g_0} \qquad R_0 = \frac{1}{g_0}$$

In terms of operating point and model parameters:

$$R_{in} = \frac{\beta V_t}{I_{CQ}} \qquad A_{V0} = -\frac{V_{AF}}{V_t} \qquad R_0 = \frac{V_{AF}}{I_{CQ}}$$

$$R_{in} = \infty \qquad R_0 = \frac{1}{\lambda I_{DQ}} = \frac{V_{AF}}{I_{DQ}}$$

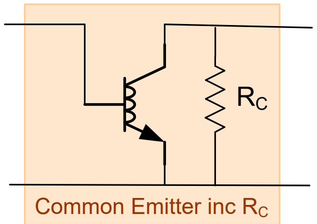
$$A_{V0} = -\frac{2}{\lambda V_{EBQ}} = -2\frac{V_{AF}}{V_{EBQ}}$$

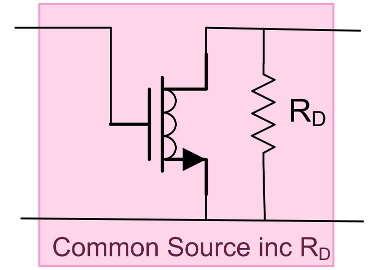
Characteristics:

- Input impedance is mid-range (infinite for MOS)
- Voltage Gain is Large and Inverting
- Output impedance is large
- Unilateral
- Widely used to build voltage amplifiers

Common Source/Common Emitter Configuration

Widely used CE application (but also a two-port)





$$R_{out} = \frac{1}{g_0 + g_C} \overset{g_0 << g_C}{\cong} R_C$$

$$A_v \overset{g_0 << g_C}{\cong} -g_m R_C$$

$$R_{in} = r_\pi$$

$$A_{VR} = 0$$

$$R_{out} = \frac{1}{g_0 + g_D} \overset{g_0 << g_D}{\cong} R_D$$

$$A_v \overset{g_0 << g_D}{\cong} -g_m R_D$$

$$R_{in} = \infty$$

$$A_{VR} = 0$$

In terms of operating point and model parameters:

$$A_v \overset{g_0 << g_C}{\cong} -\frac{I_{CQ} R_C}{V_t}$$

$$R_{out} \overset{g_0 << g_C}{\cong} R_C$$

$$R_{in} = \frac{\beta V_t}{I_{CQ}}$$

$$A_v \overset{g_0 << g_D}{\cong} -\frac{2I_{DQ} R_D}{V_{EBQ}}$$

$$R_{in} = \infty$$

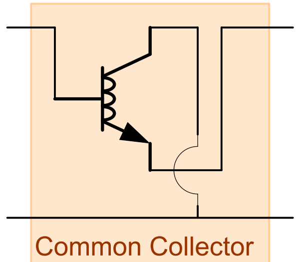
$$R_{out} \overset{g_0 << g_D}{\cong} R_D$$

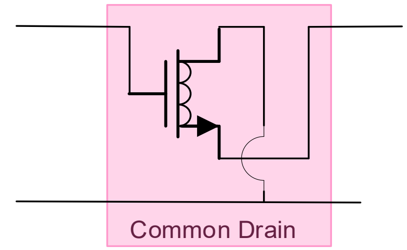
Characteristics:

- Input impedance is mid-range (infinite for MOS)
- Voltage Gain is Large and Inverting
- Output impedance is mid-range
- Unilateral
- Widely used as a voltage amplifier

Review From Previous Lecture

Two-port model for Common Collector Configuration





$A_{VR} = 1$ $\quad$ $A_{VR} = 1$

$R_{in} = r_\pi \qquad A_{V0} = 1 \qquad R_0 = \dfrac{1}{g_m}$ $\quad$ | $\quad$ $R_{in} = \infty \qquad A_{V0} = 1 \qquad R_0 = \dfrac{1}{g_m}$

In terms of operating point and model parameters:

$R_{in} = \dfrac{\beta V_t}{I_{CQ}} \qquad A_{V0} = 1 \qquad R_0 = \dfrac{V_t}{I_{CQ}}$ $\quad$ | $\quad$ $R_{in} = \infty \qquad A_{V0} = 1 \qquad R_0 = \dfrac{V_{EB}}{2I_{DQ}}$

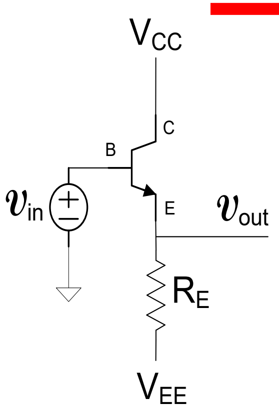
Characteristics:

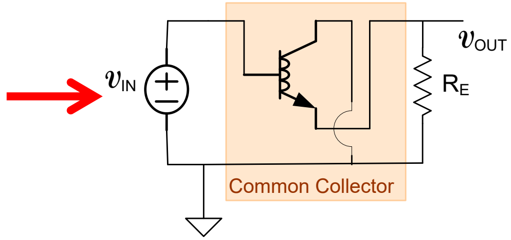
- Input impedance is mid-range (infinite for MOS)
- Voltage Gain is nearly 1
- Output impedance is very low
- Slightly non-unilateral (critical though in increasing input impedance when R_E added)
- Widely used as a buffer

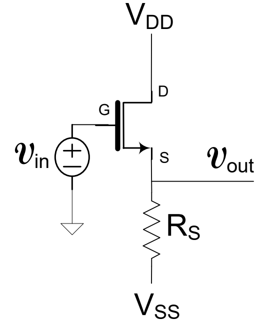
Review From Previous Lecture

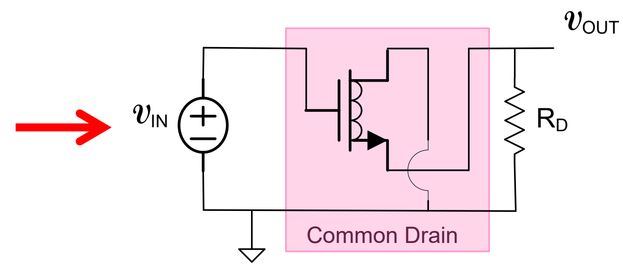
Common Collector/Common Drain Configurations

For these popular CC/CD applications (not two-port models for these applications)









$$A_V = \frac{g_\pi + g_m}{g_m + g_E + g_0 + g_\pi} \overset{if\ g_m >> g_E}{\cong} 1$$

$$R_{in} \overset{g_E >> g_o}{\cong} r_\pi + \beta R_E$$

$$R_0 \cong \frac{R_E}{1+g_m R_E} \overset{g_m R_E >> 1}{\cong} \frac{1}{g_m}$$

$$A_V = \frac{g_m}{g_m + g_S + g_0} \overset{if\ g_m >> g_S}{\cong} 1$$

$$R_{in} = \infty$$

$$R_0 \cong \frac{R_S}{1+g_m R_S} \overset{g_m R_S >> 1}{\cong} \frac{1}{g_m}$$

In terms of operating point and model parameters:

$$A_V \cong \frac{I_{CQ} R_E}{I_{CQ} R_E + V_t} \overset{I_{CQ} R_E >> V_t}{\cong} 1 \qquad R_0 \overset{I_{CQ} R_E >> V_t}{\cong} \frac{V_t}{I_{CQ}}$$

$$R_{in} \overset{I_{CQ} R_E >> V_t}{\cong} r_\pi + \beta R_E$$

$$A_V \cong \frac{2I_{DQ} R_S}{2I_{DQ} R_S + V_{EBQ}} \overset{if\ 2I_{DQ} R_S >> V_{EBQ}}{\cong} 1$$

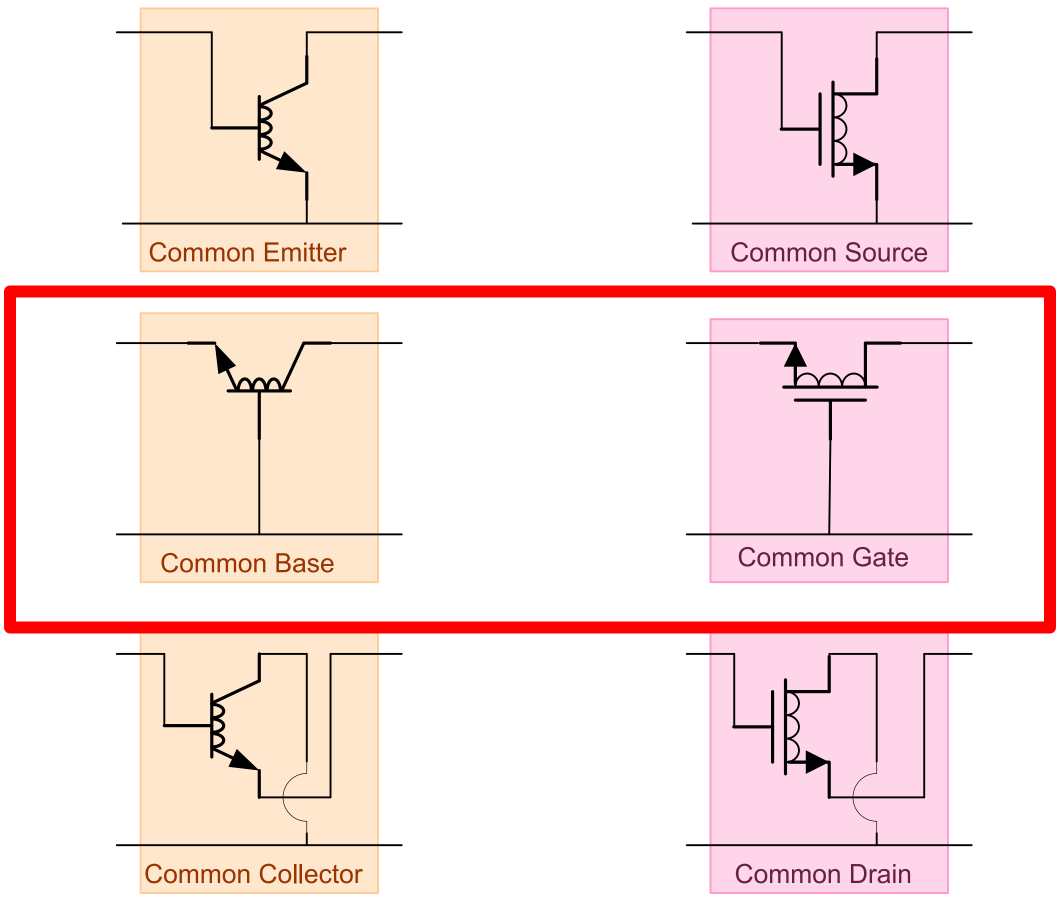
$$R_0 \cong \frac{V_{EBQ} R_S}{V_{EBQ} + 2I_{DQ} R_S} \overset{2I_{DQ} R_S >> V_{EBQ}}{\cong} \frac{V_{EBQ}}{2I_{DQ}}$$

$$R_{in} = \infty$$

- Output impedance is low
- A_{V0} is positive and near 1
- Input impedance is very large

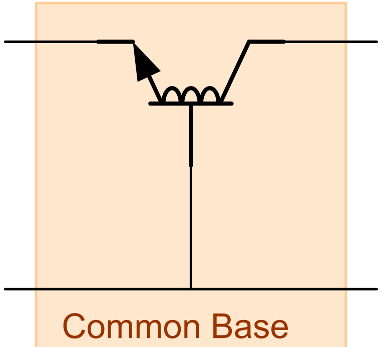
- Widely used as a buffer
- Not completely unilateral but output-input transconductance is small

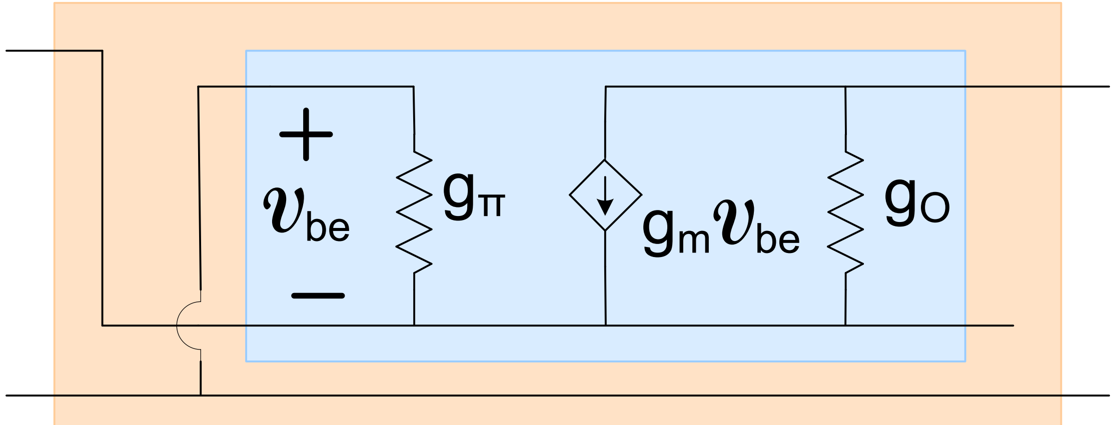
Consider Common Base/Common Gate Two-port Models



- Will focus on Bipolar Circuit since MOS counterpart is a special case obtained by setting g_π=0
- Will consider both two-port model and a widely used application

Two-port model for Common Base Configuration





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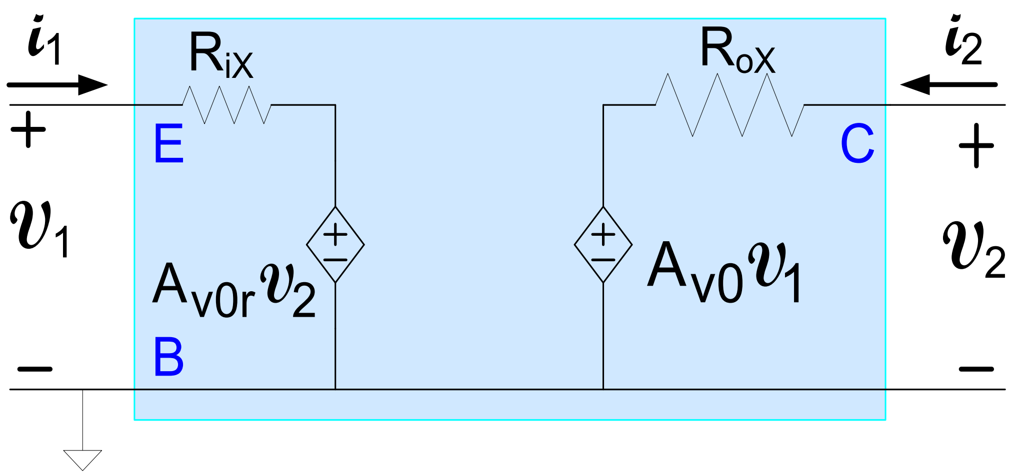
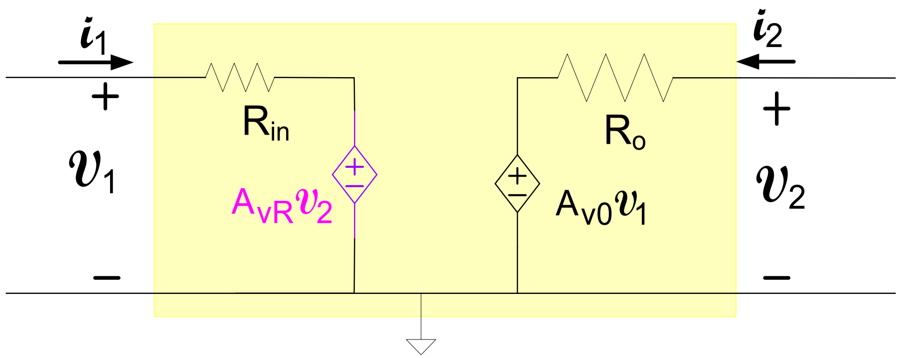


$\{R_{iX}, A_{V0}, A_{V0r}$ and $R_{0X}\}$

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

2. Write $v_1 : v_2$ equations in standard form

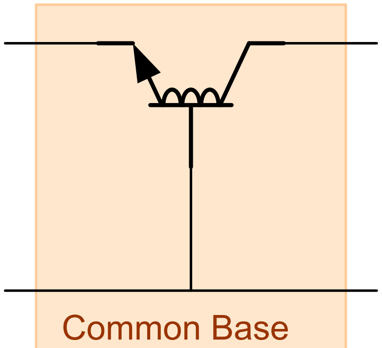
$$v_1 = i_1 R_{IN} + A_{VR} v_2$$

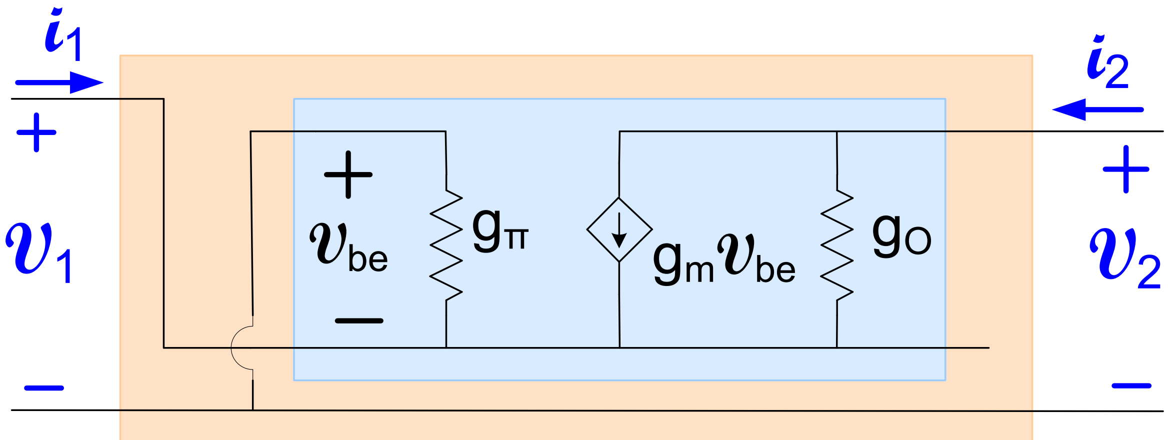
$$v_2 = i_2 R_O + A_{V0} v_1$$

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches

Two-port model for Common Base Configuration





From KCL

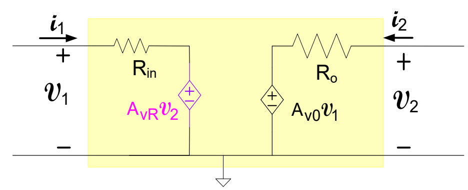
$$\left.\begin{aligned} i_1 &= v_1 g_\pi + \left(v_1 - v_2\right) g_0 + g_m v_1 \\ i_2 &= \left(v_2 - v_1\right) g_0 - g_m v_1 \end{aligned}\right\}$$

These can be rewritten as

$$\left.\begin{aligned} v_1 &= \left(\frac{1}{g_m + g_\pi + g_0}\right) i_1 + \left(\frac{g_0}{g_m + g_\pi + g_0}\right) v_2 \\ v_2 &= \left(\frac{1}{g_0}\right) i_2 + \left(1 + \frac{g_m}{g_0}\right) v_1 \end{aligned}\right\}$$

$v_1 : v_2$ equations in standard form

Standard Form for Amplifier Two-Port



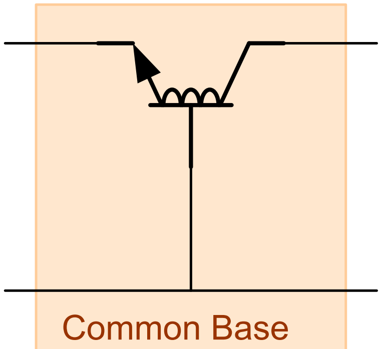
$v_1 = i_1 R_{IN} + A_{VR} v_2$

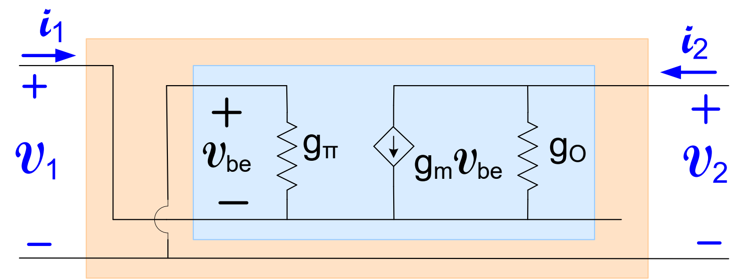
$v_2 = i_2 R_O + A_{V0} v_1$

It thus follows that:

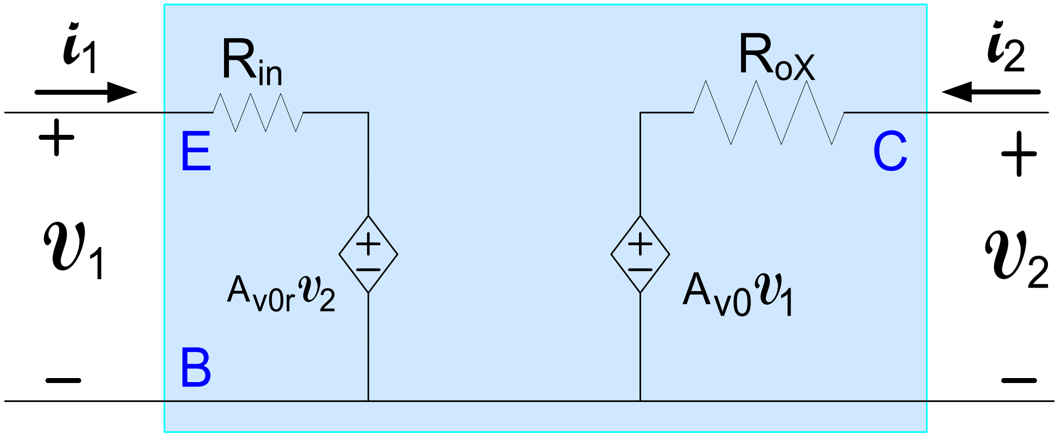
$$R_{iX} = \frac{1}{g_m + g_\pi + g_0} \cong \frac{1}{g_m} \qquad A_{VOr} = \frac{g_0}{g_m + g_\pi + g_0} \qquad A_{V0} = 1 + \frac{g_m}{g_0} \cong \frac{g_m}{g_0} \qquad R_{oX} = \frac{1}{g_0}$$

Two-port model for Common Base Configuration





Two-port Common Base Model



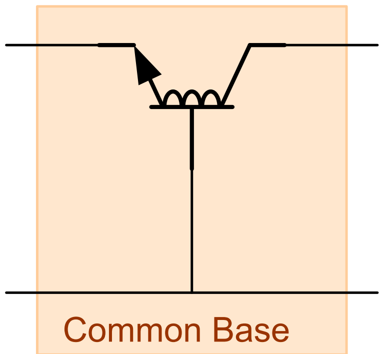
$$R_{iX} = \frac{1}{g_m + g_\pi + g_0} \cong \frac{1}{g_m}$$

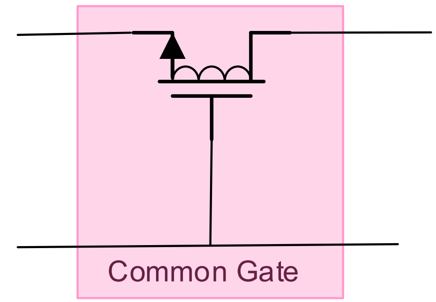
$$A_{V0} = 1 + \frac{g_m}{g_0} \cong \frac{g_m}{g_0}$$

$$A_{VOr} = \frac{g_0}{g_m + g_\pi + g_0} \cong \frac{g_0}{g_m}$$

$$R_{oX} = \frac{1}{g_0}$$

Two-port model for Common Base Configuration





$$A_{VR} \cong \frac{g_0}{g_m}$$

$$A_{VR} \cong \frac{g_0}{g_m}$$

$$R_{in} \cong \frac{1}{g_m} \qquad A_{V0} = \frac{g_m}{g_0} \qquad R_0 = \frac{1}{g_0}$$

$$R_{in} \cong \frac{1}{g_m} \qquad A_{V0} = \frac{g_m}{g_0} \qquad R_0 = \frac{1}{g_0}$$

In terms of operating point and model parameters:

$$R_{in} = \frac{V_t}{I_{CQ}} \qquad A_{V0} = \frac{V_{AF}}{V_t} \qquad R_0 = \frac{V_{AF}}{I_{CQ}}$$

$$R_{in} = \frac{V_{EB}}{2I_{DQ}} \qquad A_{V0} = \frac{2}{\lambda V_{EBQ}} \qquad R_0 = \frac{1}{\lambda I_{DQ}}$$

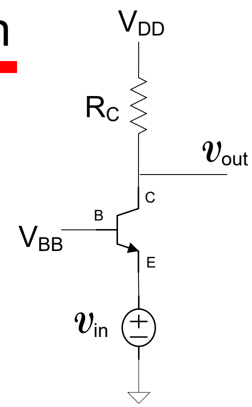
Characteristics:

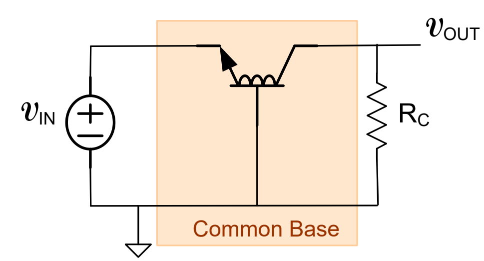
- Input impedance is low
- Voltage Gain is Large and noninverting
- Output impedance is large
- Slightly nonunilateral
- Widely used to build voltage amplifiers

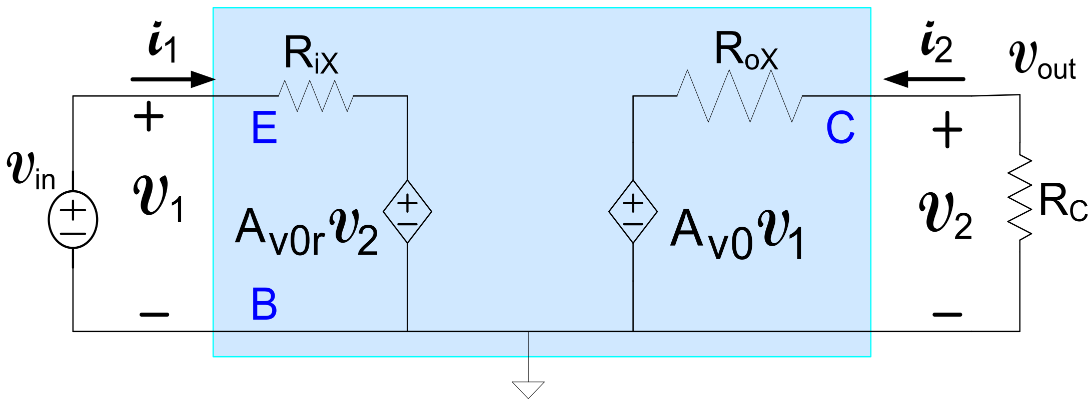
Common Base Configuration

Consider the following popular CB application

(this is not asking for a two-port model for this CB application - – R_{in} and A_V defined for no load on output, R_o defined for short-circuit input)







$$A_V = A_{V0}\frac{R_C}{R_C+R_{0X}} = \left(\frac{g_m+g_0}{g_0}\right)\left(\frac{g_0}{g_C+g_0}\right) = \frac{g_m+g_0}{g_C+g_0} \cong g_m R_C$$

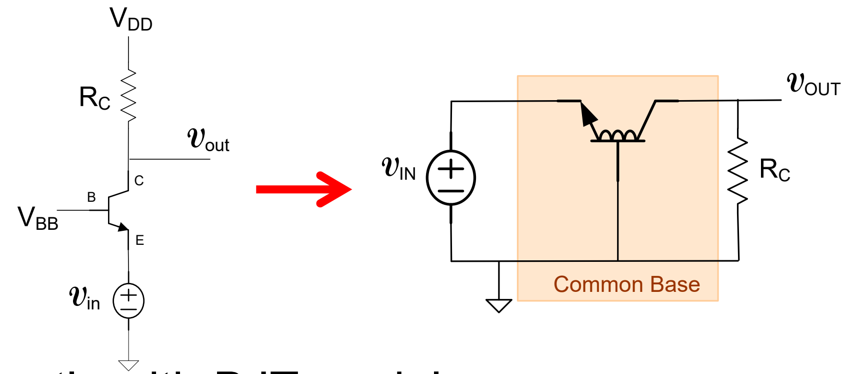
$$R_{in} = \frac{v_{in}}{i_1} = \frac{i_1 R_{iX} + A_{V0r} v_{out}}{i_1} \longrightarrow R_{in} = \frac{R_{iX}}{1-A_{V0r}A_V} = \frac{g_0+g_C}{g_C\left(g_m+g_\pi+g_0\right)+g_\pi g_0} \cong \frac{1}{g_m}$$

$$R_{out} = R_C // R_{0X} \longrightarrow R_{out} = \frac{R_C}{1+g_0 R_C}$$

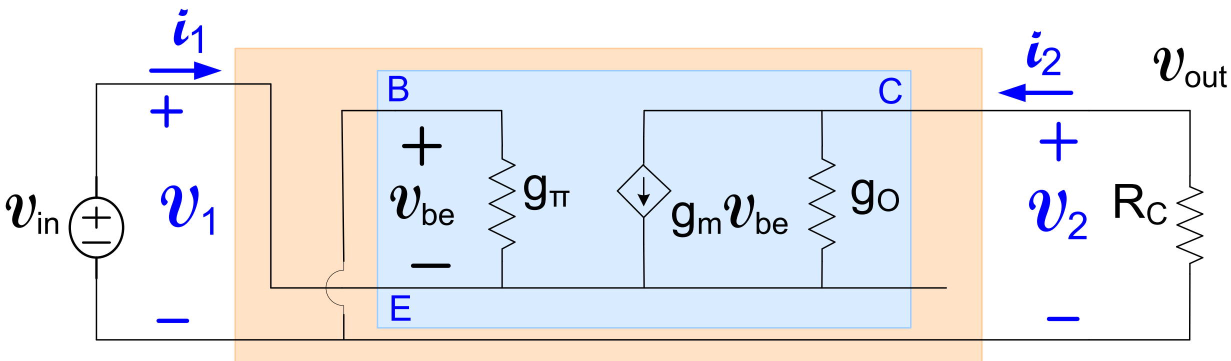
Common Base Configuration

Consider the following popular CB application

(this is not asking for a two-port model for this CB application – R_{in} and A_V defined for no load on output, R_o defined for short-circuit input)



Alternately, this circuit can also be analyzed directly with BJT model



$$g_C = \frac{1}{R_C}$$

By KCL at the output node, obtain

$$(g_C + g_0)v_0 = (g_m + g_0)v_{in} \rightarrow A_V = \frac{g_m + g_0}{g_C + g_0} \cong g_m R_C$$

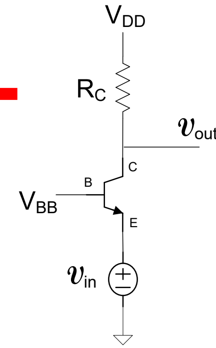
By KCL at the emitter node, obtain

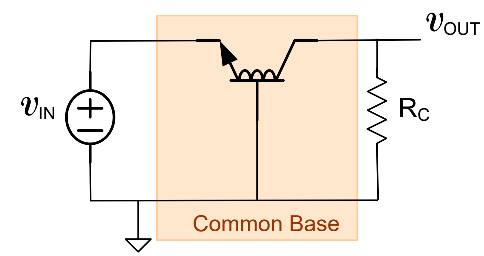
$$i_1 = (g_m + g_\pi + g_0)v_{in} - g_0 v_{out} \rightarrow R_{in} = \frac{g_0 + g_C}{g_C(g_m + g_\pi + g_0) + g_\pi g_0} \cong \frac{1}{g_m}$$

$$R_{out} = R_C // r_0 \rightarrow R_{out} = \frac{R_C}{1 + g_0 R_C} \cong R_C$$

Popular Common Base Application

(this is not a two-port model for this CB application)





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

$$R_{in} \cong \frac{1}{g_m} \qquad R_{in} \cong \frac{V_t}{I_{CQ}}$$

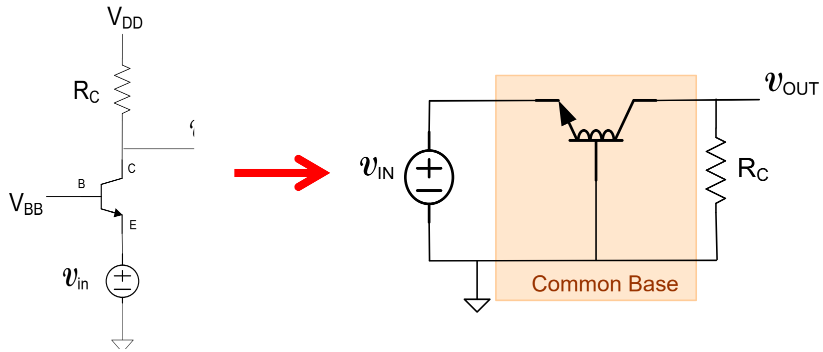
$$R_{out} \overset{R_c<<r_0}{\cong} R_C \qquad R_{out} \overset{R_c<<r_0}{\cong} R_C$$

Characteristics:

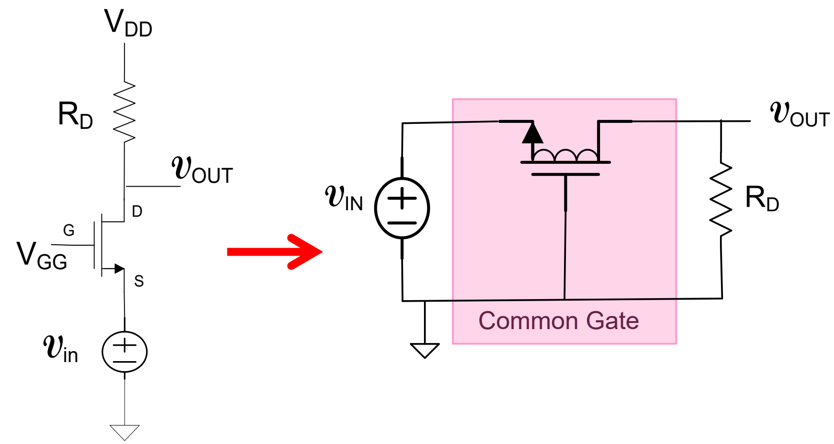
- Output impedance is mid-range
- A_{V0} is large and positive (equal in mag to that to CE)
- Input impedance is very low
- Not completely unilateral but output-input transconductance is small

Common Base/Common Gate Application

(these are not a two-port models)



$$A_V \cong g_m R_C \qquad R_{in} \cong \frac{1}{g_m} \qquad R_{out} \overset{R_C \ll r_0}{\cong} R_C$$



$$A_V \cong g_m R_D \qquad R_{in} \cong \frac{1}{g_m} \qquad R_{out} \overset{R_D \ll r_0}{\cong} R_D$$

In terms of operating point and model parameters:

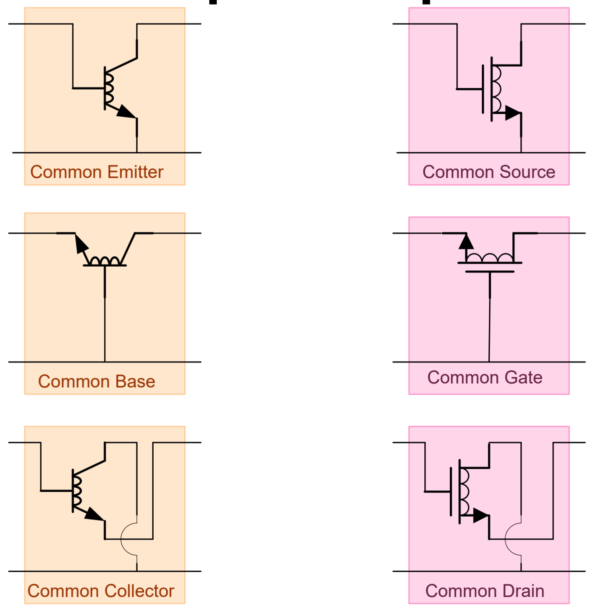
$$A_V \cong \frac{I_{CQ} R_C}{V_t} \qquad R_{in} \cong \frac{V_t}{I_{CQ}} \qquad R_{out} \overset{I_{CQ} R_C \ll V_{AF}}{\cong} R_C$$

$$A_V \cong \frac{2 I_{DQ} R_D}{V_{EBQ}} \qquad R_{in} \cong \frac{V_{EBQ}}{2 I_{DQ}} \qquad R_{out} \overset{I_{DQ} R_D \ll 1/\lambda}{\cong} R_D$$

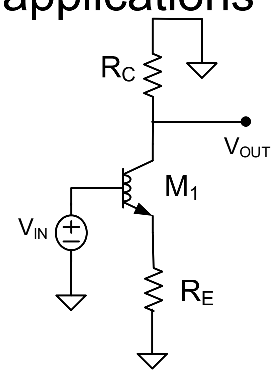
Characteristics:

- Output impedance is mid-range
- A_{V0} is large and positive (equal in mag to that to CE)
- Input impedance is very low
- Not completely unilateral but output-input transconductance is small

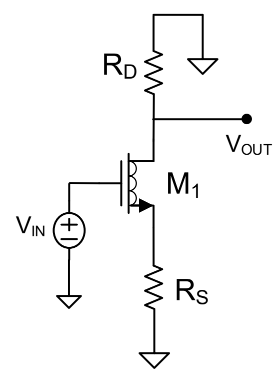
The three basic amplifier types for both MOS and bipolar processes



- Have developed both two-ports and a widely used application of all 6
- A fourth structure (two additional applications) is also quite common so will be added to list of basic applications



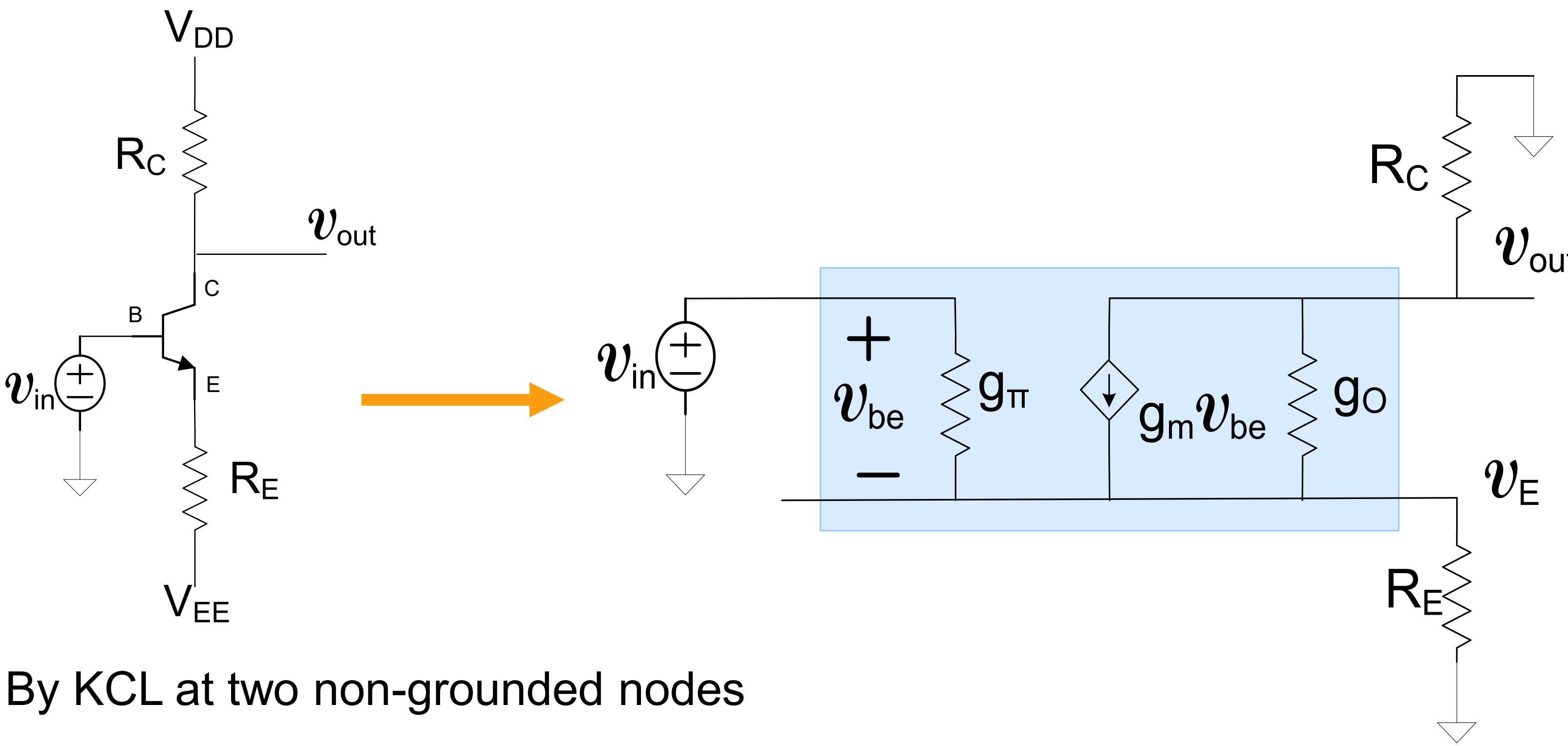
CE with R_E



CS with R_S

Common Emitter with Emitter Resistor Configuration Application

(this is not a two-port model for this CE with R_E application)



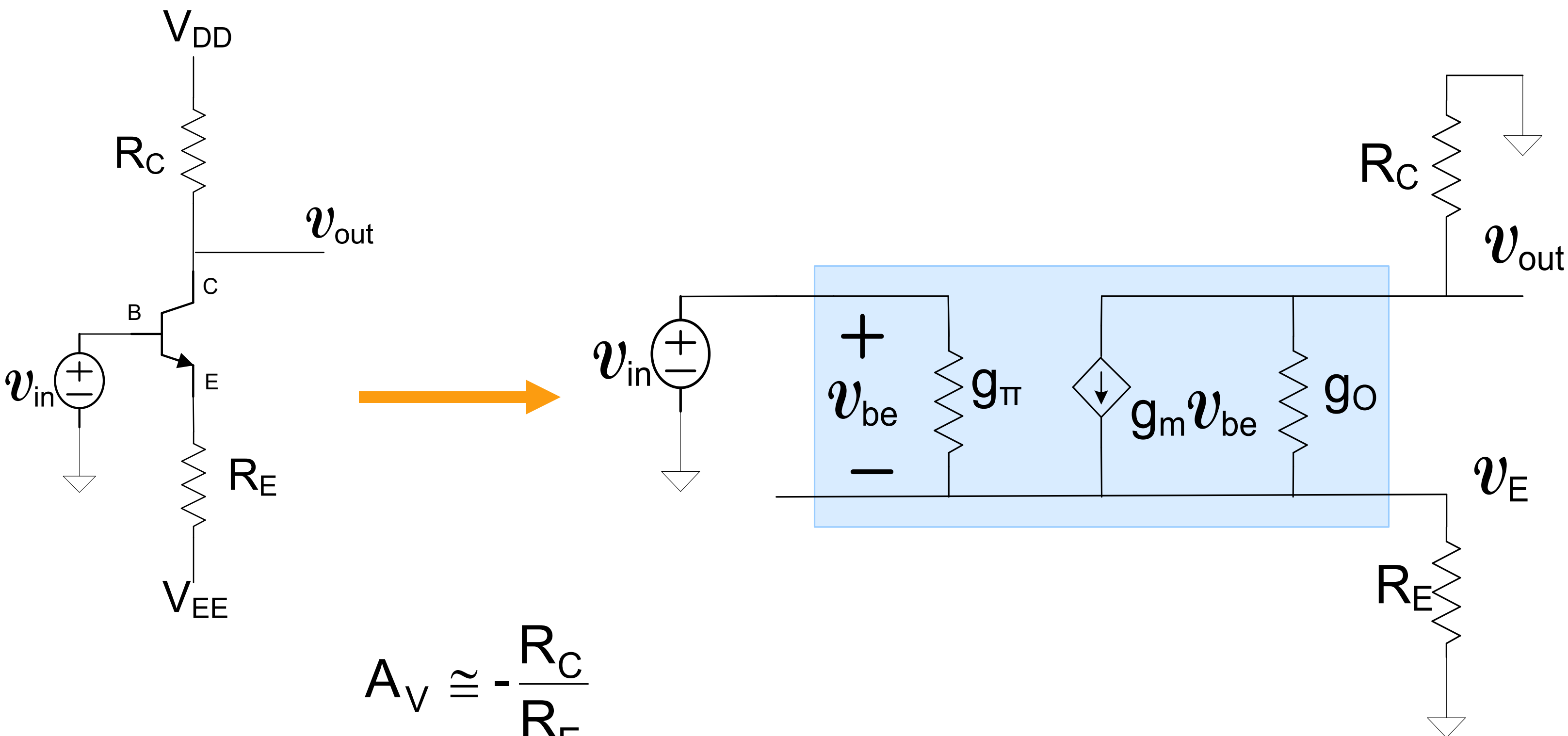
By KCL at two non-grounded nodes

$$\left.\begin{aligned} v_{out}\left(g_C+g_0\right)+\left(v_{in}-v_E\right)g_m &= g_0 v_E \\ v_E\left(g_E+g_0+g_\pi\right)-\left(v_{in}-v_E\right)g_m &= g_0 v_{out}+g_\pi v_{in} \end{aligned}\right\}$$

$$A_V=\frac{v_{out}}{v_{in}}=\frac{-g_m g_E+g_0 g_\pi}{g_C g_m+g_C\left(g_0+g_\pi+g_E\right)+g_0\left(g_\pi+g_E\right)}\cong -\frac{R_C}{R_E}$$

Common Emitter with Emitter Resistor Configuration Application

(this is not a two-port model for this CE with R_E application)



$$A_V \cong -\frac{R_C}{R_E}$$

It can also be shown that

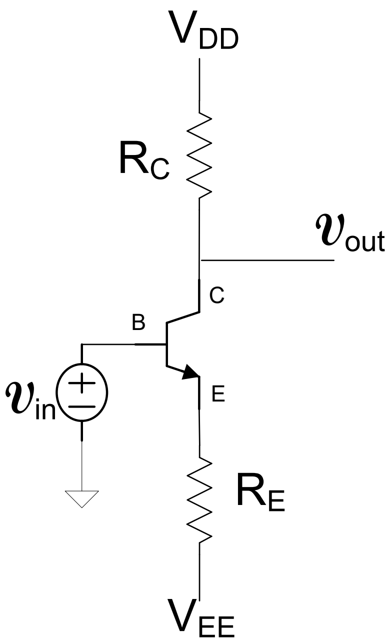
$$R_{in} \cong r_\pi + \beta R_E \cong \beta R_E$$

$$R_{out} \cong R_C$$

Nearly unilateral (is unilateral if g_o=0)

Common Emitter with Emitter Resistor Configuration Application

(this is not a two-port model for this CE with R_E application)



$$A_V \cong -\frac{R_C}{R_E}$$

$$R_{in} \cong \beta R_E$$

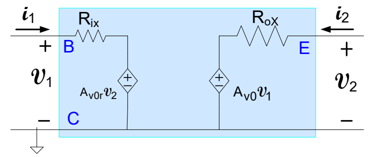
$$R_{out} \cong R_C$$

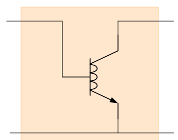
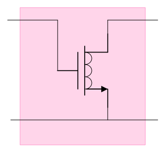
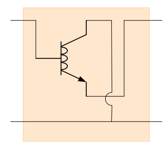
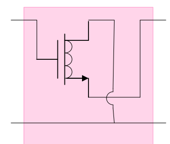
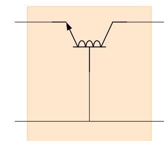
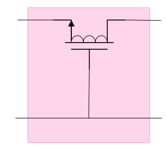
(this is not a two-port model)

Characteristics:

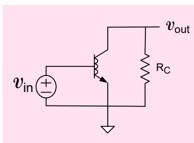
- Analysis would simplify if g_0 were set to 0 in model
- Gain can be accurately controlled with resistor ratios
- Useful for reasonably accurate low gains
- Input impedance is high

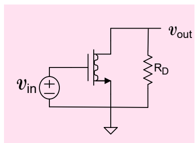
Basic Two-Port Amplifier Gain Table

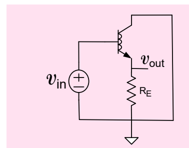


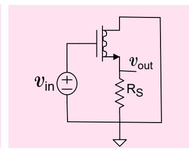
	CE/CS BJT	CE/CS MOS	CC/CD BJT	CC/CD MOS	CB/CG BJT	CB/CG MOS
						
A_V	$-\frac{g_m}{g_o}$		$\frac{g_m+g_\pi}{g_m+g_\pi+g_o}\simeq 1$	$\frac{g_m}{g_m+g_o}\simeq 1$	$1+\frac{g_m}{g_o}\simeq\frac{g_m}{g_o}$	
	$-\frac{I_{CQ}R_C}{V_t}$	$-\frac{2I_{DQ}R_D}{V_{EB}}$	1	1	$\frac{V_{AF}}{V_t}$	$\frac{2}{\lambda V_{EB}}$
R_{in}	r_π	∞	r_π	∞	$\frac{1}{g_m+g_\pi+g_o}\simeq g_m^{-1}$	$\frac{1}{g_m+g_o}\simeq g_m^{-1}$
	$\frac{\beta V_t}{I_{CQ}}$	∞	$\beta\left(\frac{V_t}{I_{CQ}}\right)$	∞	$\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$
R_{out}	$\frac{1}{g_o}$		$\frac{1}{g_m+g_\pi+g_o}\simeq g_m^{-1}$	$\frac{1}{g_m+g_o}\simeq g_m^{-1}$	$\frac{1}{g_o}$	
			$\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$	$\frac{V_{AF}}{I_{CQ}}$	$\frac{1}{\lambda I_{DQ}}$
A_{VR}	0		1		$\frac{g_o}{g_m+g_\pi+g_o}\simeq\frac{g_o}{g_m}$	$\frac{g_o}{g_m+g_o}\simeq\frac{g_o}{g_m}$
	0	0	1	1	$\frac{V_t}{V_{AF}}$	$\frac{\lambda V_{EB}}{2}$

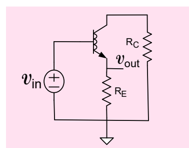
Basic Amplifier Application Gain Table

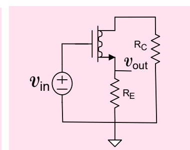


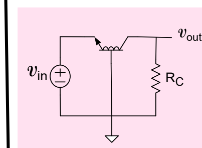


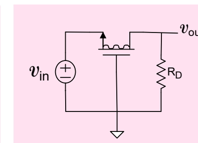


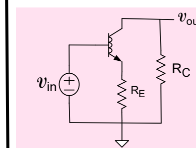


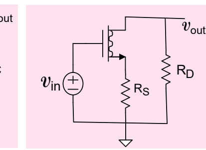












	CE/CS	CC/CD	CB/CG	CEwRE/CSwRS
	BJT / MOS	BJT / MOS	BJT / MOS	BJT / MOS
A_V	$-g_m R_C$ BJT: $-\frac{I_{CQ}R_C}{V_t}$ MOS: $-\frac{2I_{DQ}R_D}{V_{EB}}$	$\frac{g_m}{g_m+g_E}$ BJT: $\frac{I_{CQ}R_E}{I_{CQ}R_E+V_t}$ MOS: $\frac{2I_{DQ}R_E}{2I_{DQ}R_E+V_{EB}}$	$g_m R_C$ BJT: $\frac{I_{CQ}R_C}{V_t}$ MOS: $\frac{2I_{DQ}R_C}{V_{EB}}$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

(<u>not</u> two-port models for the four structures)

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?

Why are we focusing on these basic circuits?

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Which is the most important?

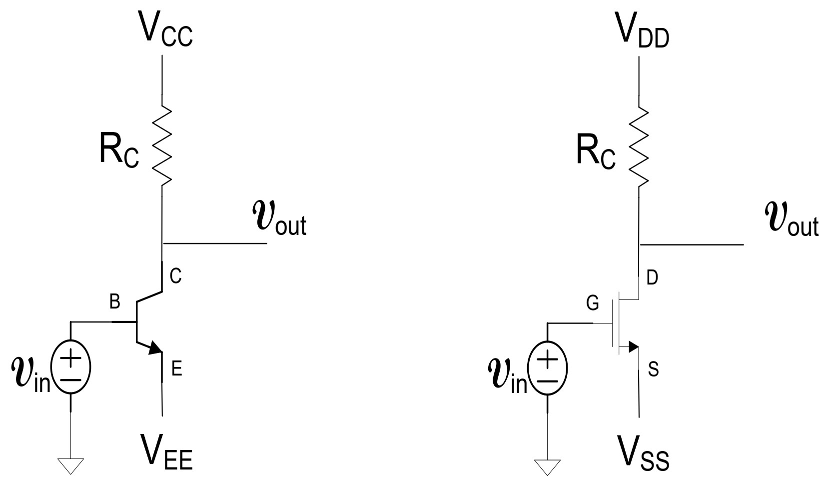
1. So that we can get the insight needed to design a circuit

2. So that we can design a circuit

3. So that we can develop analytical skills

Properties/Use of Basic Amplifiers

CE and CS



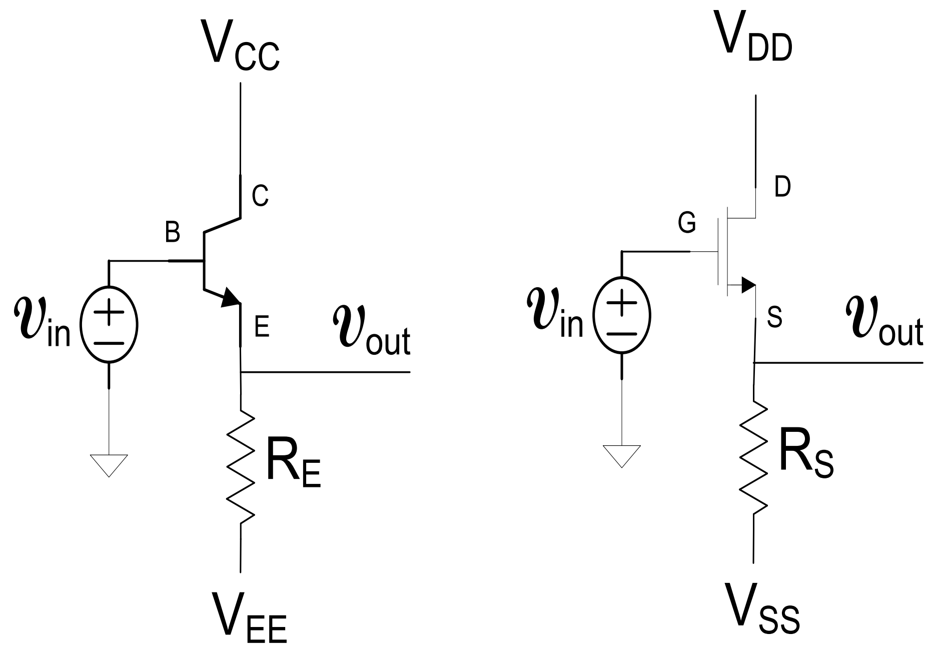
More practical biasing circuits usually used

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)



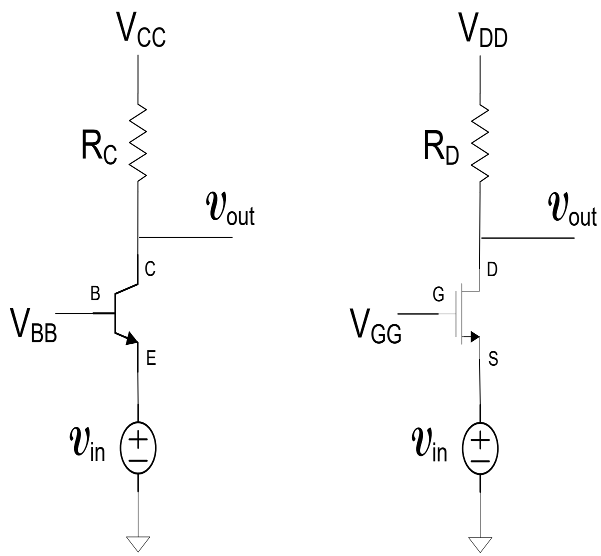
More practical biasing circuits usually used

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



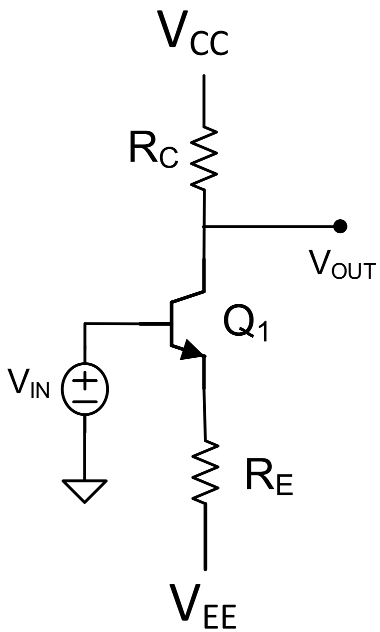
More practical biasing circuits usually used

R_C or R_D may (or may not) be load

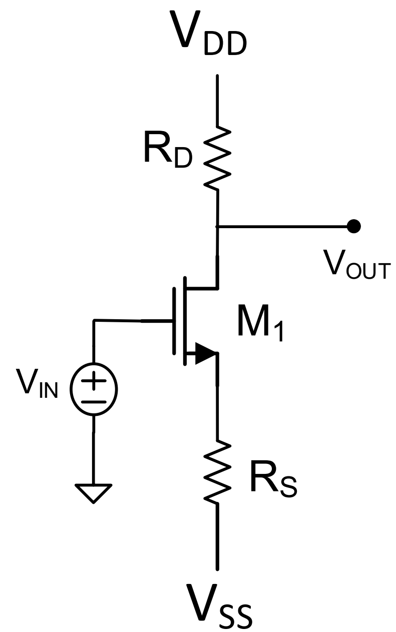
- **Large noninverting gain**
- **Low input impedance**
- **Moderate (or high) output impedance**
- **Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode**

Properties/Use of Basic Amplifiers

CEwRE and CSwRS



CE with R_E



CS with R_S

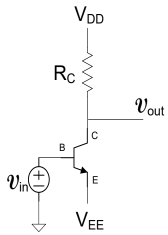
More practical biasing circuits usually used

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**

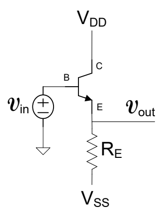
Basic Amplifier Characteristics Summary

CE/CS



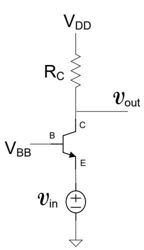
- **Large inverting gain**
- **Moderate input impedance**
- **Moderate (or high) output impedance**
- **Widely used as the basic high gain inverting amplifier**

CC/CD



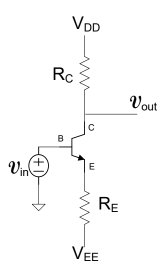
- **Gain very close to +1 (little less)**
- **High input impedance for BJT (high for MOS)**
- **Low output impedance**
- **Widely used as a buffer**

CB/CG



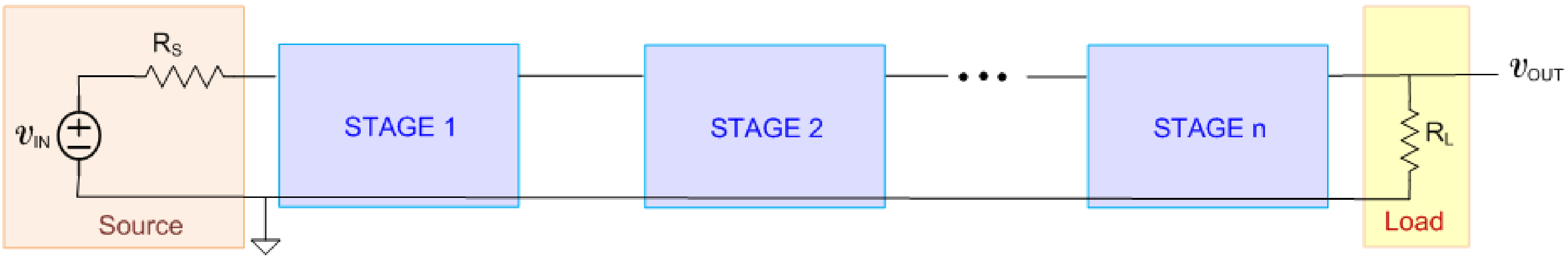
- **Large noninverting gain**
- **Low input impedance**
- **Moderate (or high) output impedance**
- **Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode**

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

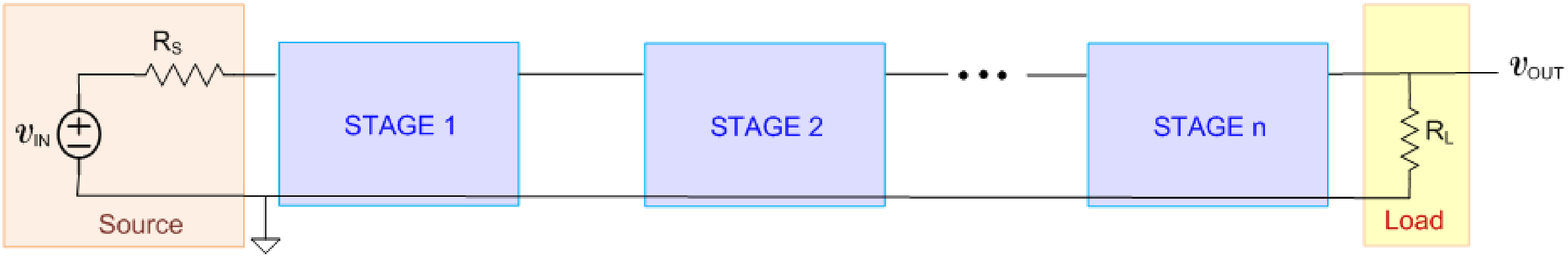


- Amplifier cascading widely used to enhance gain
- Amplifier cascading widely used to enhance other characteristics and/or alter functionality as well

  e.g. (R_{IN}, BW, Power, R_O, Linearity, Impedance Conversion..)

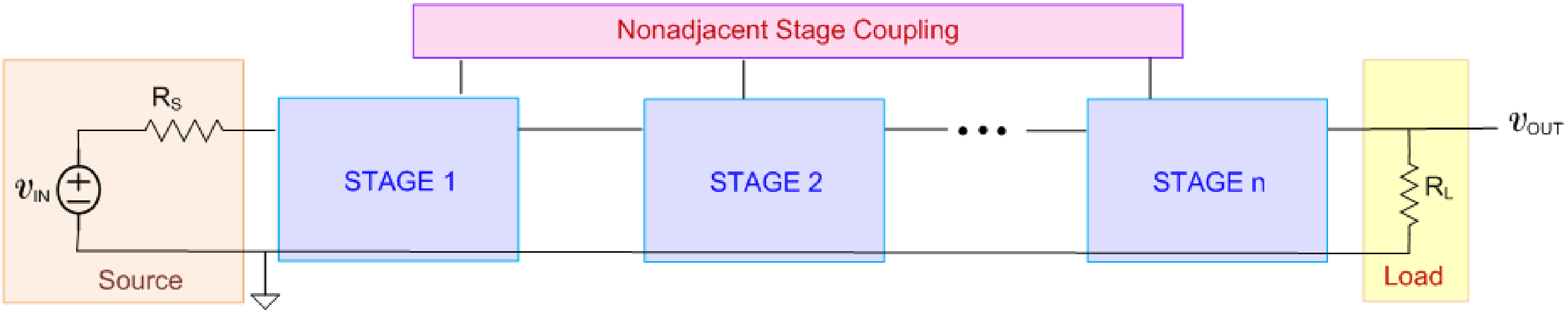
Cascaded Amplifier Analysis and Operation

Adjacent Stage Coupling Only



- Systematic Methods of Analysis/Design will be Developed

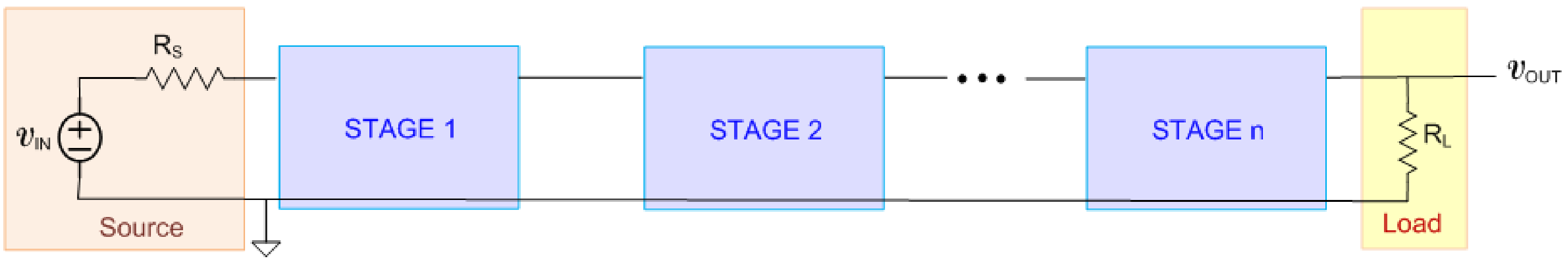
One or more couplings of nonadjacent stages



- 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

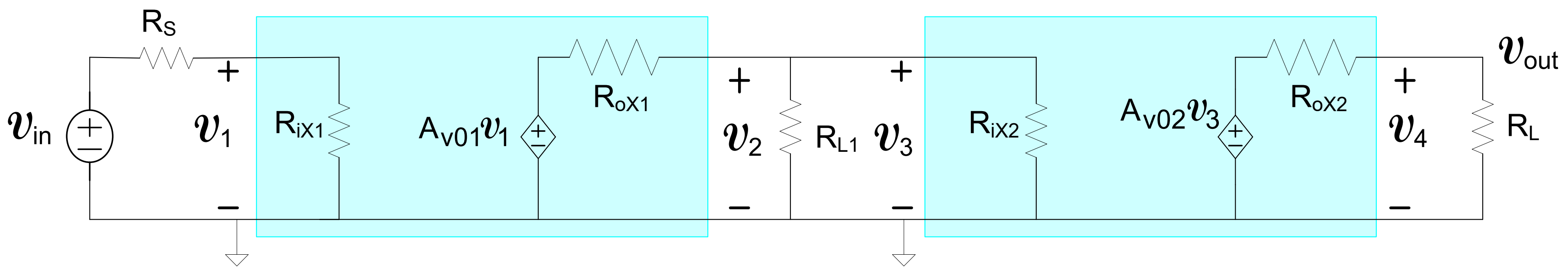
Case 1: All stages Unilateral

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



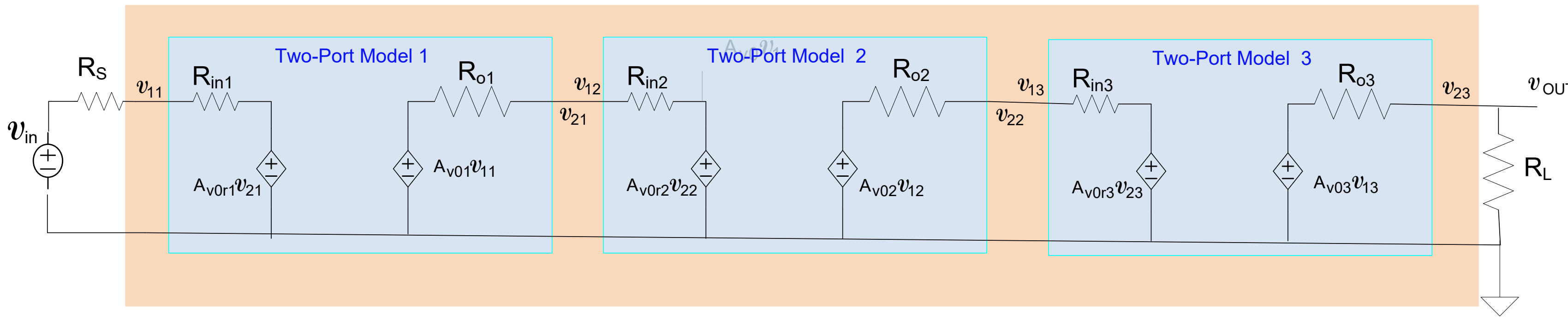
$$A_V = \frac{v_{out}}{v_{in}} = \left(\frac{R_{iX1}}{R_{iX1}+R_S}\right) A_{V01} \left(\frac{R_{L1}//R_{iX2}}{R_{L1}//R_{iX2}+R_{0X1}}\right) A_{V02} \left(\frac{R_L}{R_L+R_{0X2}}\right)$$

Accounts for all loading between stages !

Cascaded Amplifier Analysis and Operation

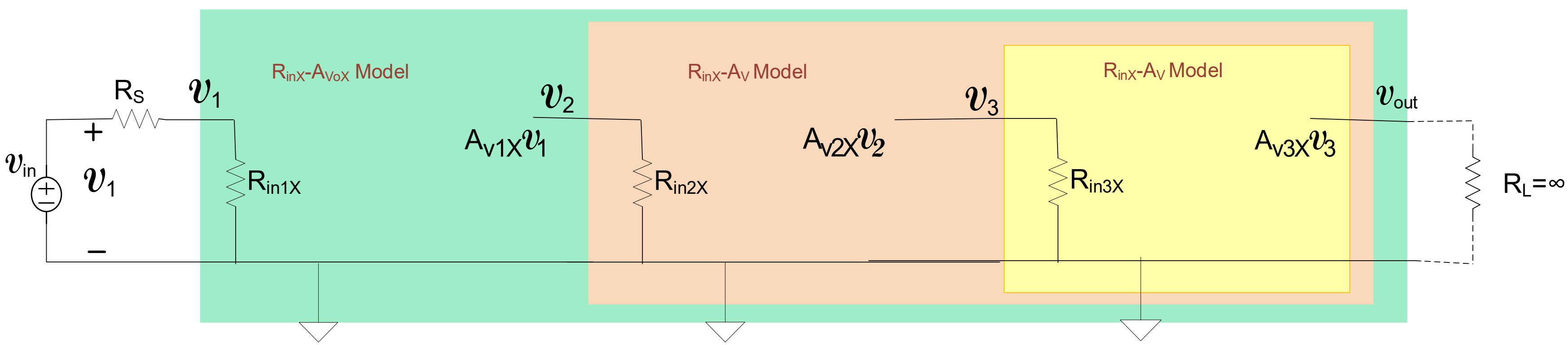
Case 2: One or more stages are not unilateral

- Standard two-port cascade



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

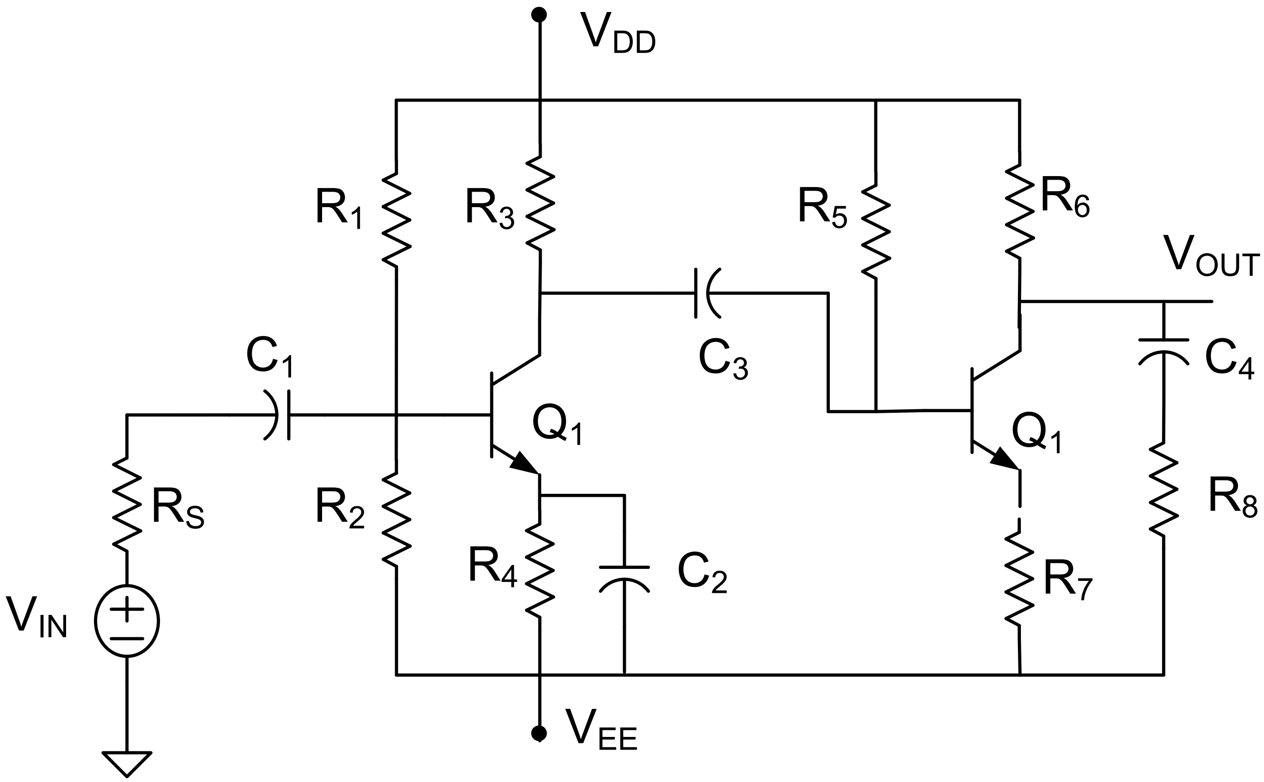
- Right-to-left nested R_{inx},A_{VKX} approach



- 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>

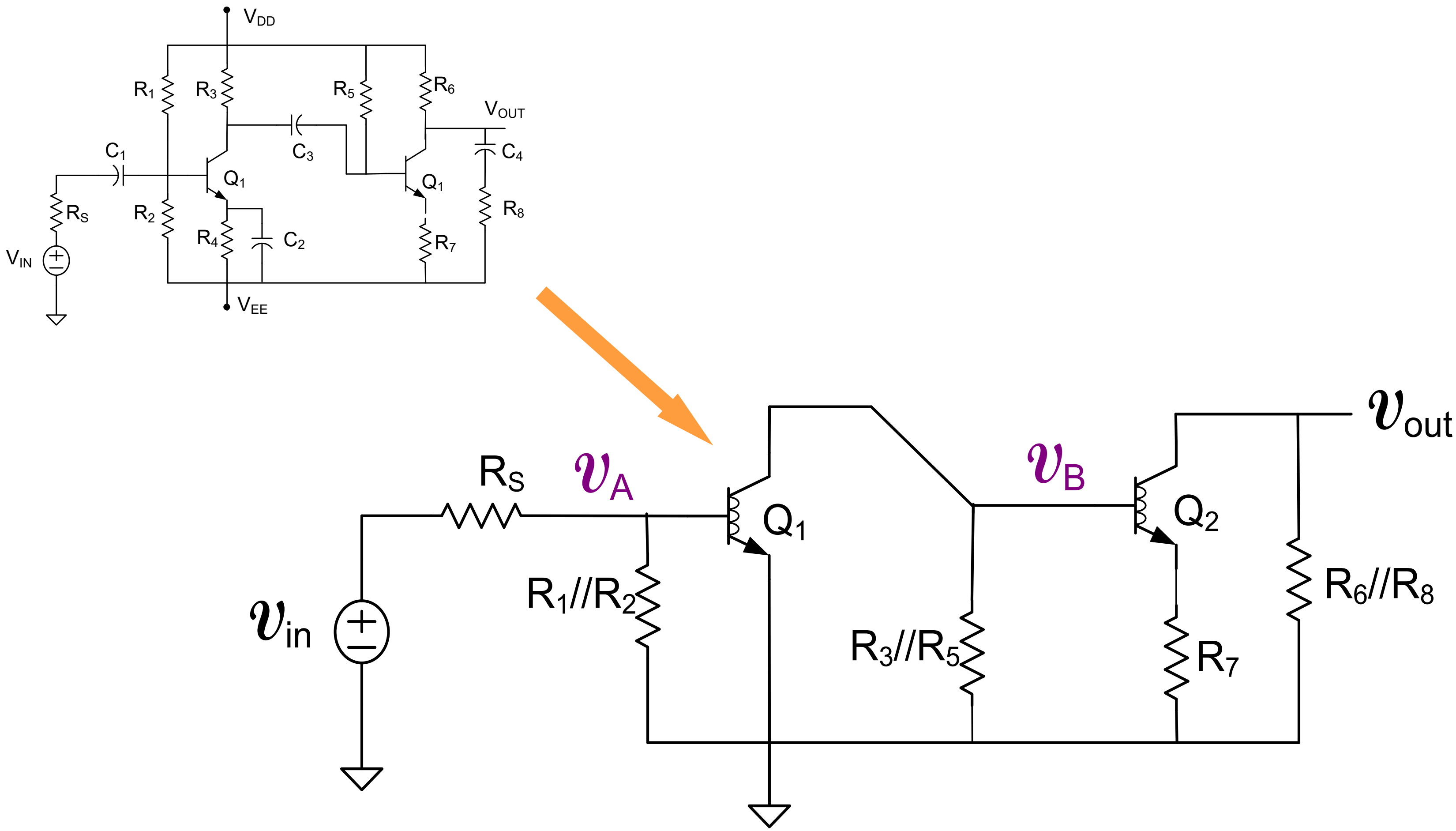
Example 1:

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 !

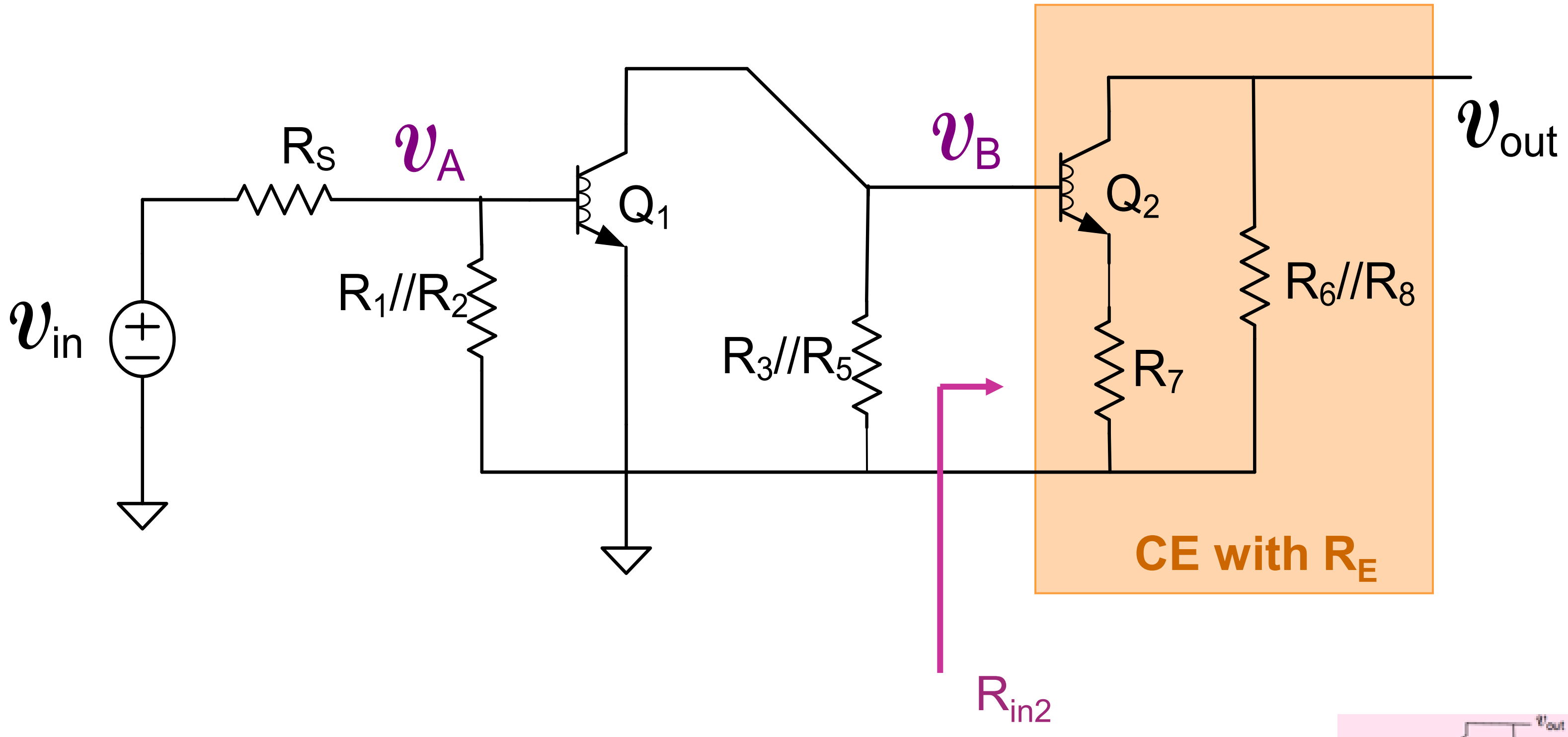
Example 1:

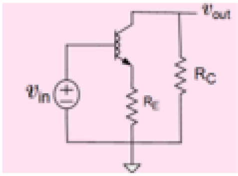


Will calculate A_V by determining the three ratios (not voltage gains of dependent source):

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

Example 1:

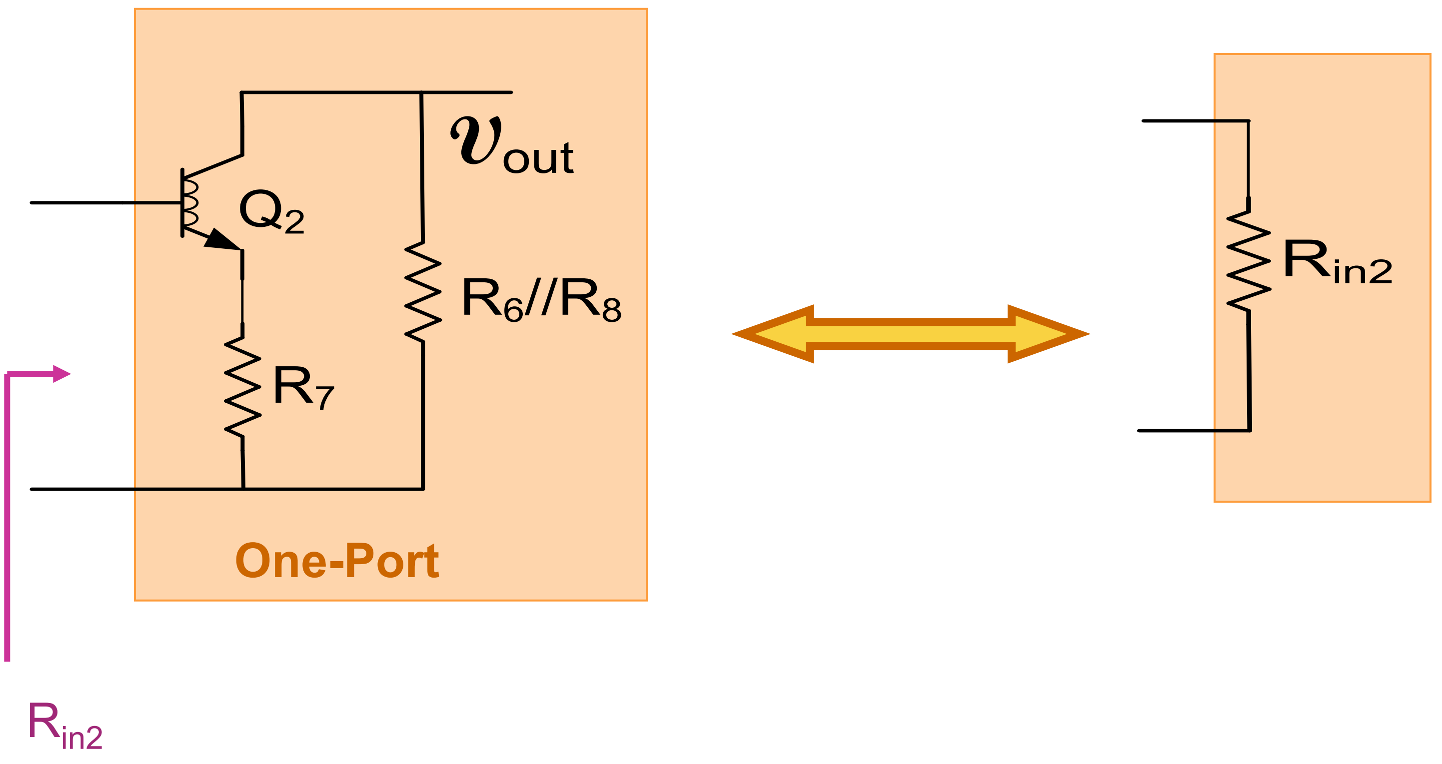




$$A_{V2} = \frac{v_{out}}{v_B} \cong -\frac{R_6//R_8}{R_7}$$

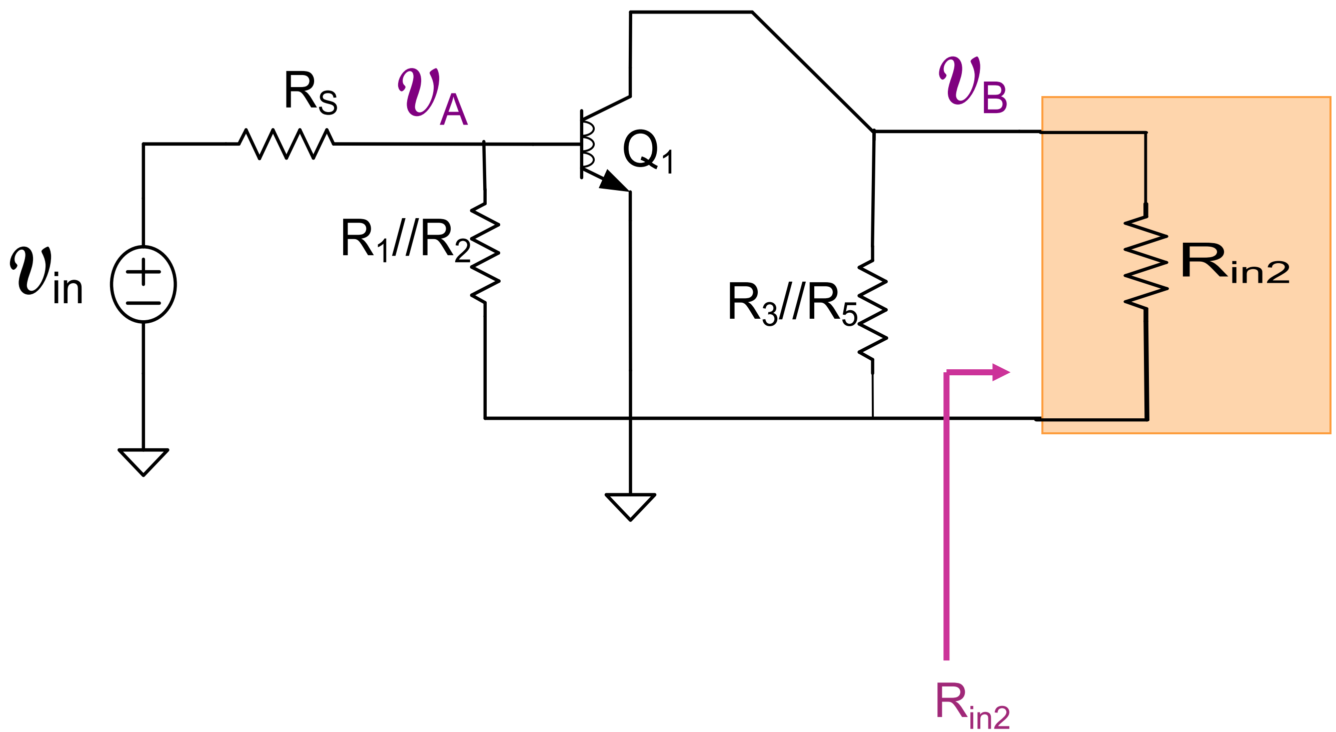
$$R_{in2} \cong \beta R_7$$

Example 1:



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

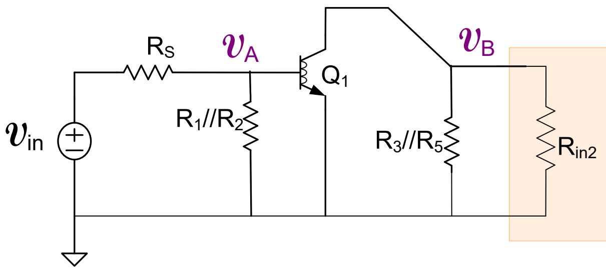
Example 1:

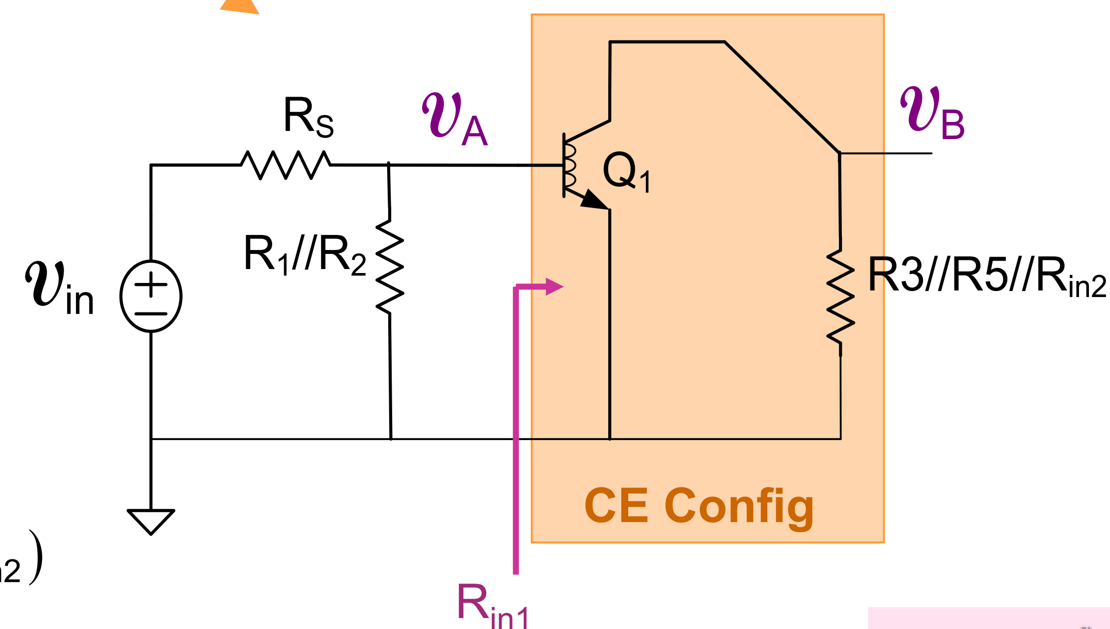


$$A_{V2} = \frac{v_{out}}{v_B} \cong -\frac{R_6//R_8}{R_7}$$

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

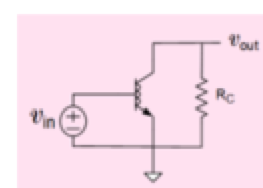
Example 1:



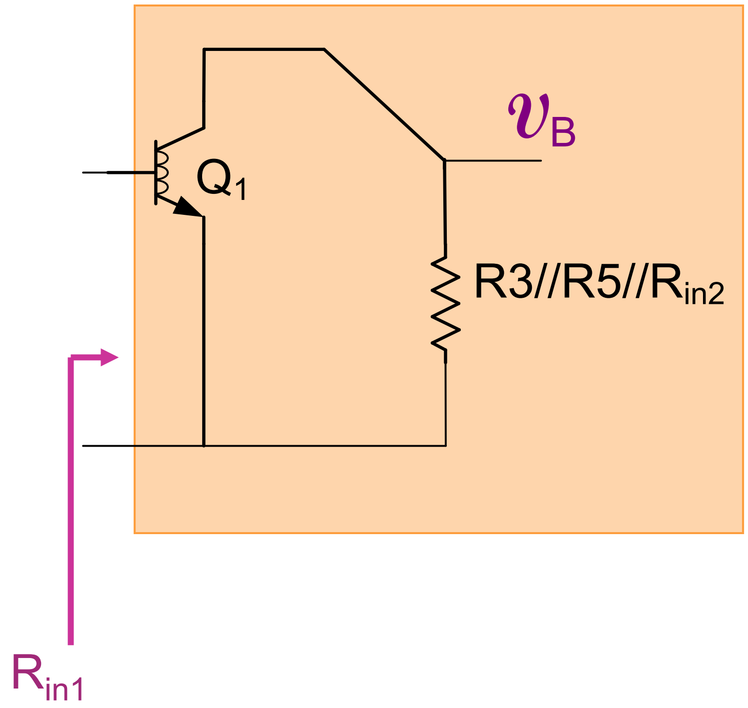


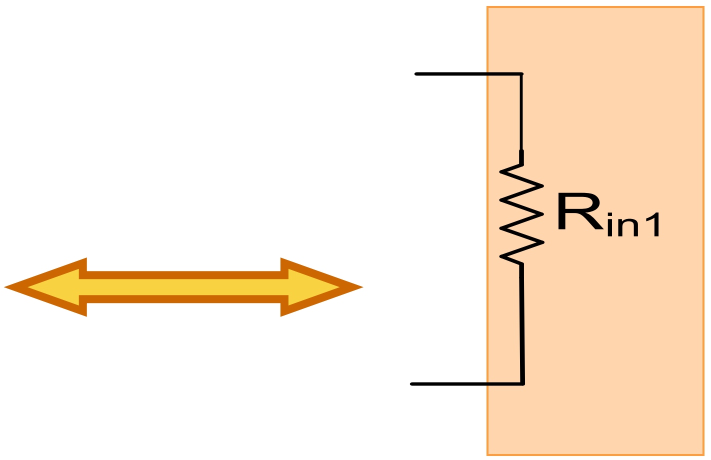
$$A_{V1}=\frac{v_B}{v_A}\cong -g_{m1}\left(R_3//R_5//R_{in2}\right)$$

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

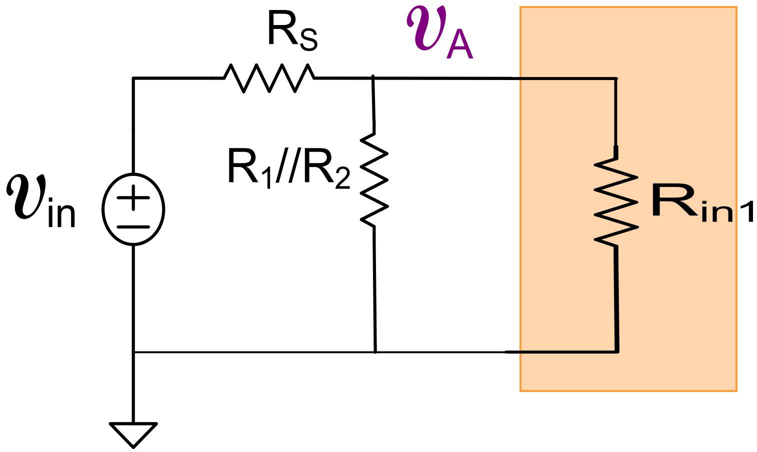


Example 1:



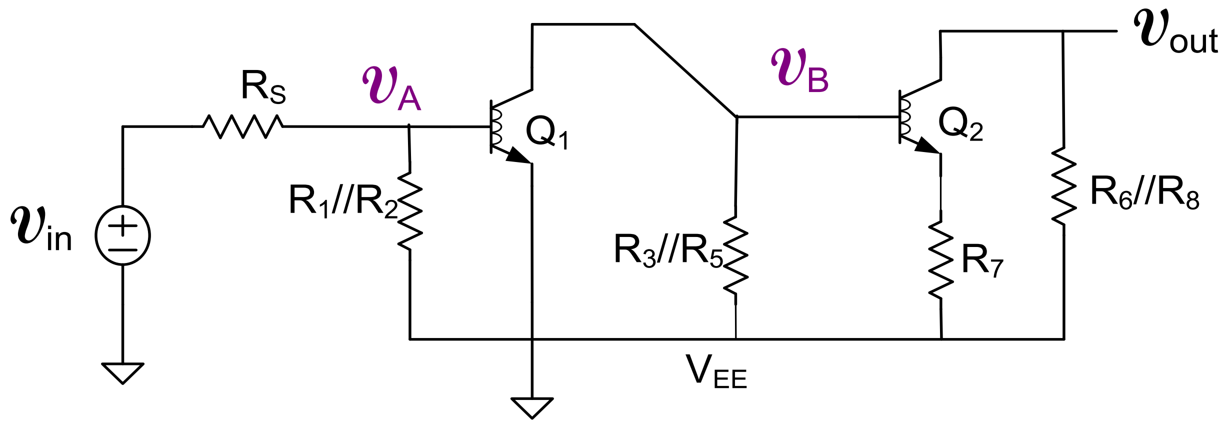


Example 1:



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

Example 1:



Thus we have

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

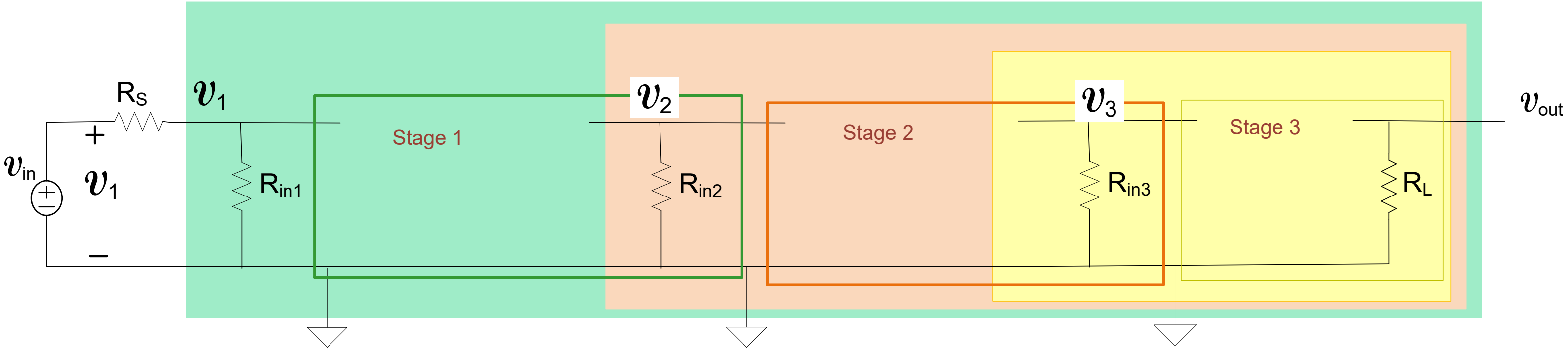
where

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

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

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

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

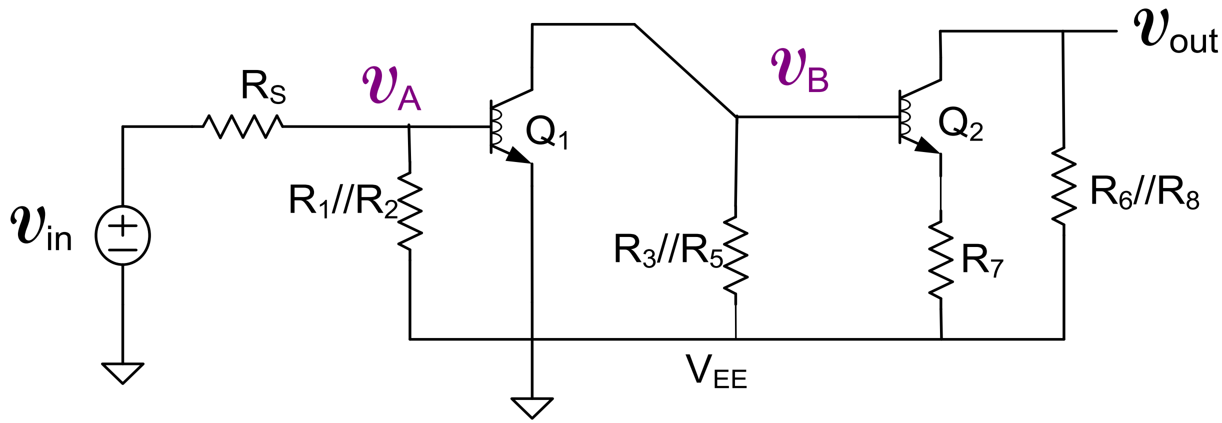


R_{ink} includes effects of all loading
Must recalculate if any change in loading
Analysis systematic and rather simple

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

This was the approach used in analyzing the previous cascaded amplifier

Example 1:

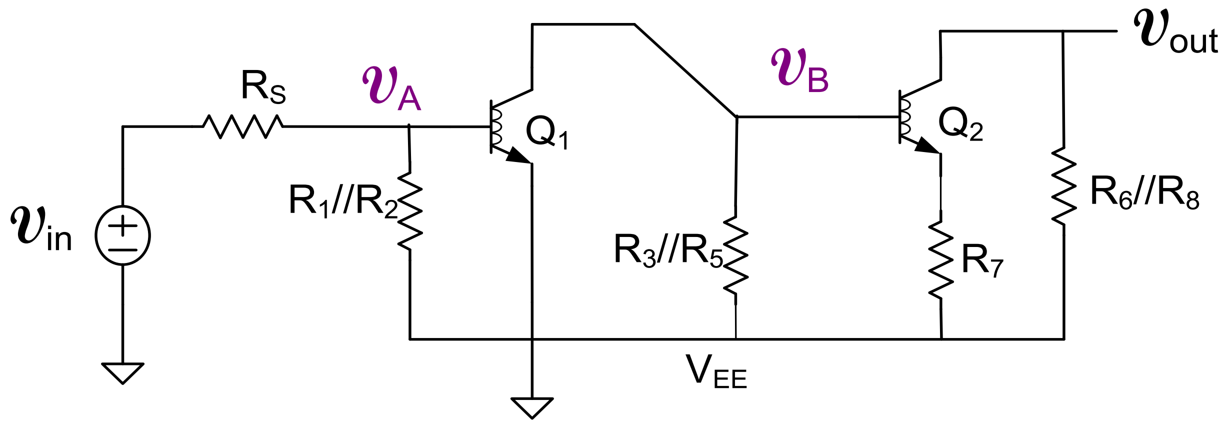


Observation: By working from the output back to the input we were able to create a sequence of steps where the circuit at each step looked EXACTLY like one of the four basic amplifiers. Engineers often follow a design approach that uses a cascade of the basic amplifiers and that is why it is often possible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

Two other methods could have been used to analyze this circuit

What are they?

Example 1:

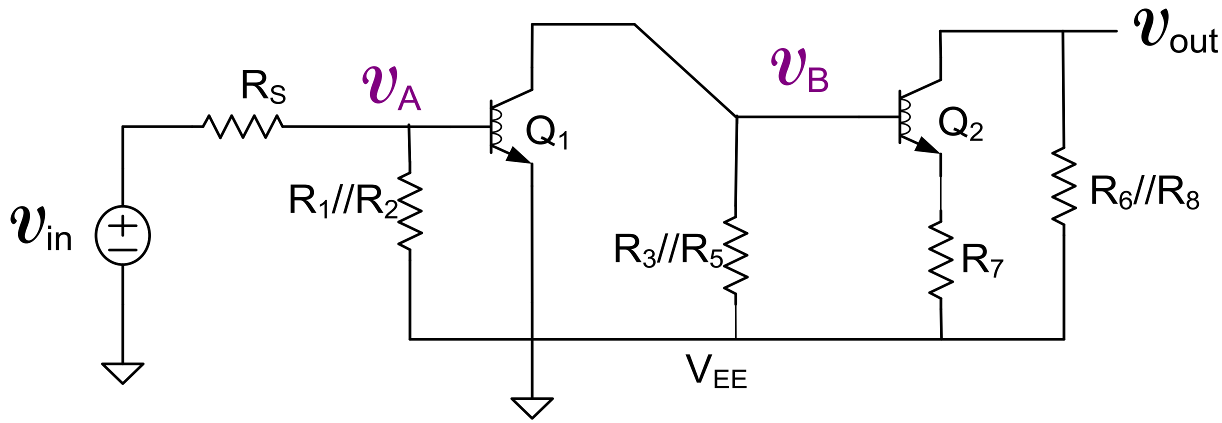


Two other methods could have been used to analyze this small-signal circuit

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

(for this example, since the first-stage is unilateral, the two-port cascade analysis is rather easy)

Example 1:

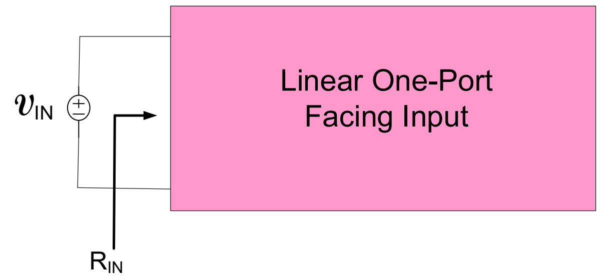


Two other methods could have been used to analyze this circuit

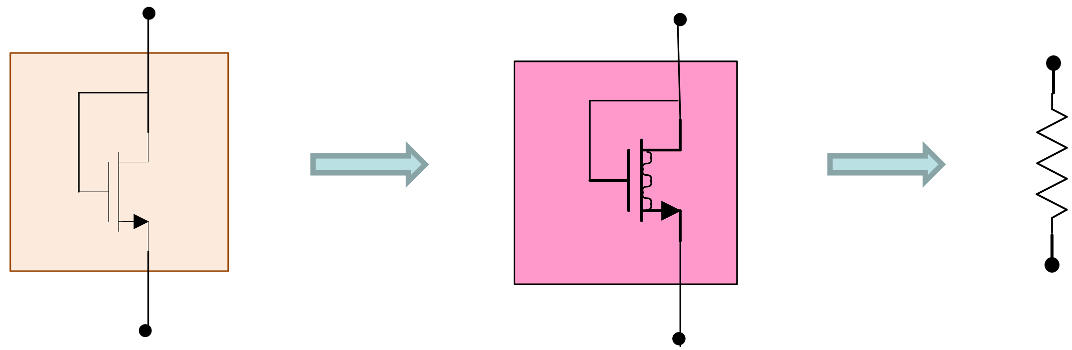
2. Put in small-signal model for Q_1 and Q_2 and solve resultant circuit

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

Review: Small-signal equivalent of a one-port



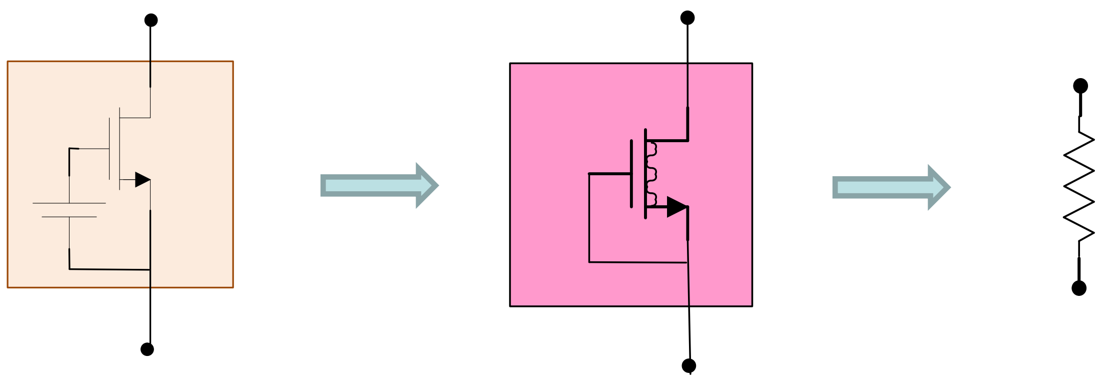
"Diode-connected transistor"



$$g = g_m + g_0 \approx g_m$$

$$R = \frac{1}{g_m + g_0} \approx \frac{1}{g_m}$$

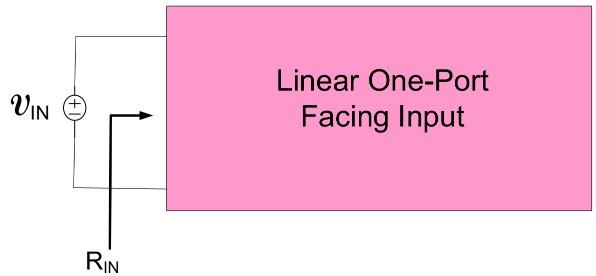
"GS - connected transistor"



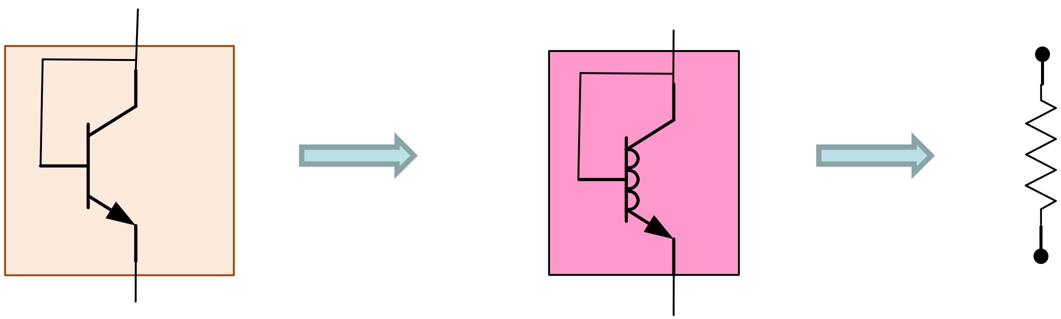
$$g = g_0$$

$$R = \frac{1}{g_0}$$

Review: Small-signal equivalent of a one-port



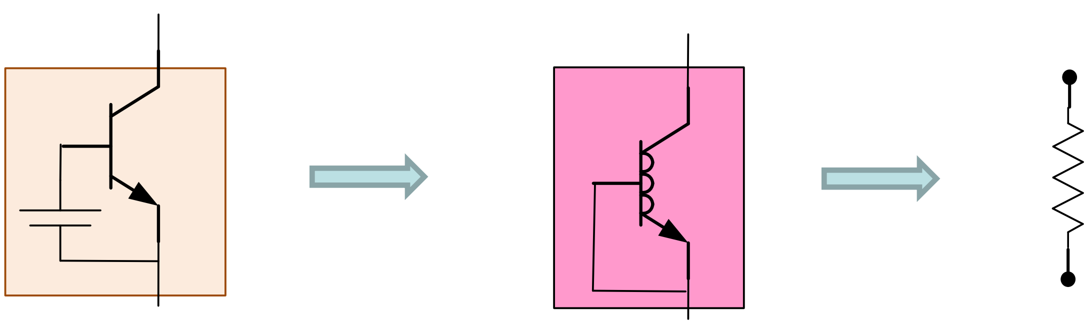
“Diode-connected transistor”



$$g = g_m + g_\pi + g_0 \approx g_m$$

$$R = \frac{1}{g_m + g_\pi + g_0} \approx \frac{1}{g_m}$$

“BE - connected transistor”

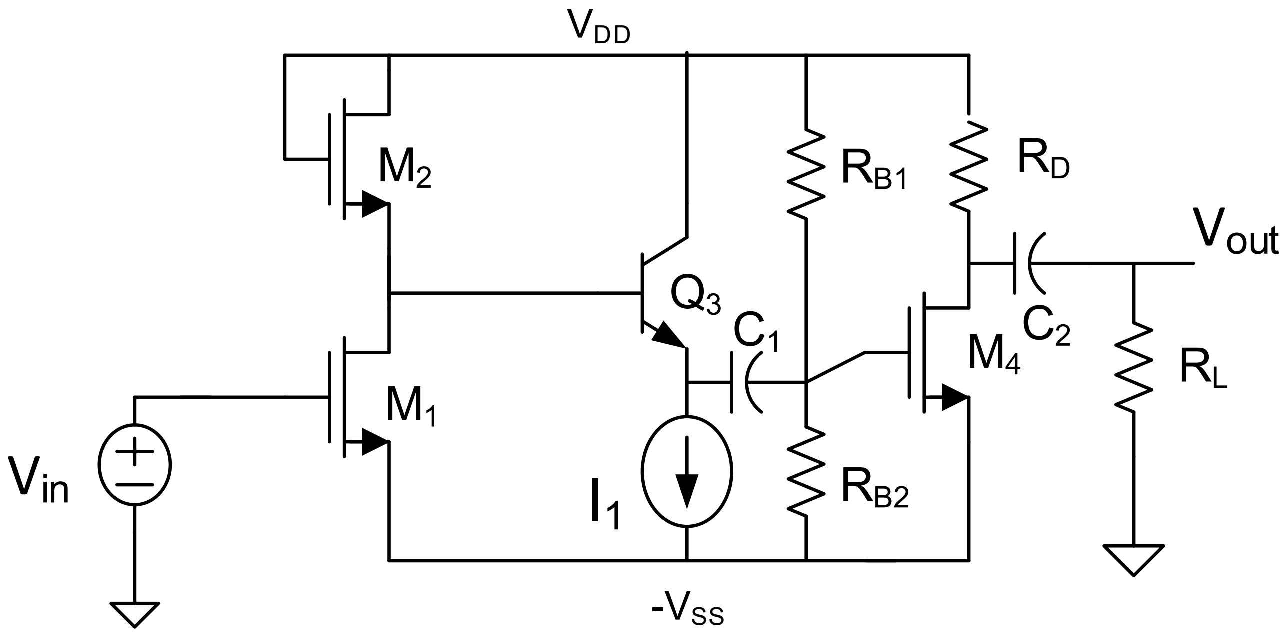


$$g = g_0$$

$$R = \frac{1}{g_0}$$

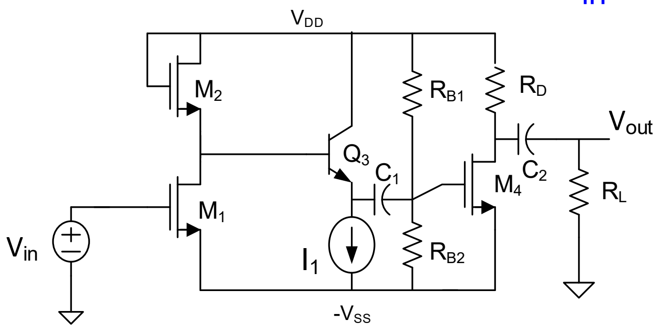
Example 2: $A_V = \dfrac{v_{out}}{v_{in}} = ?$

Express in terms of small-signal parameters

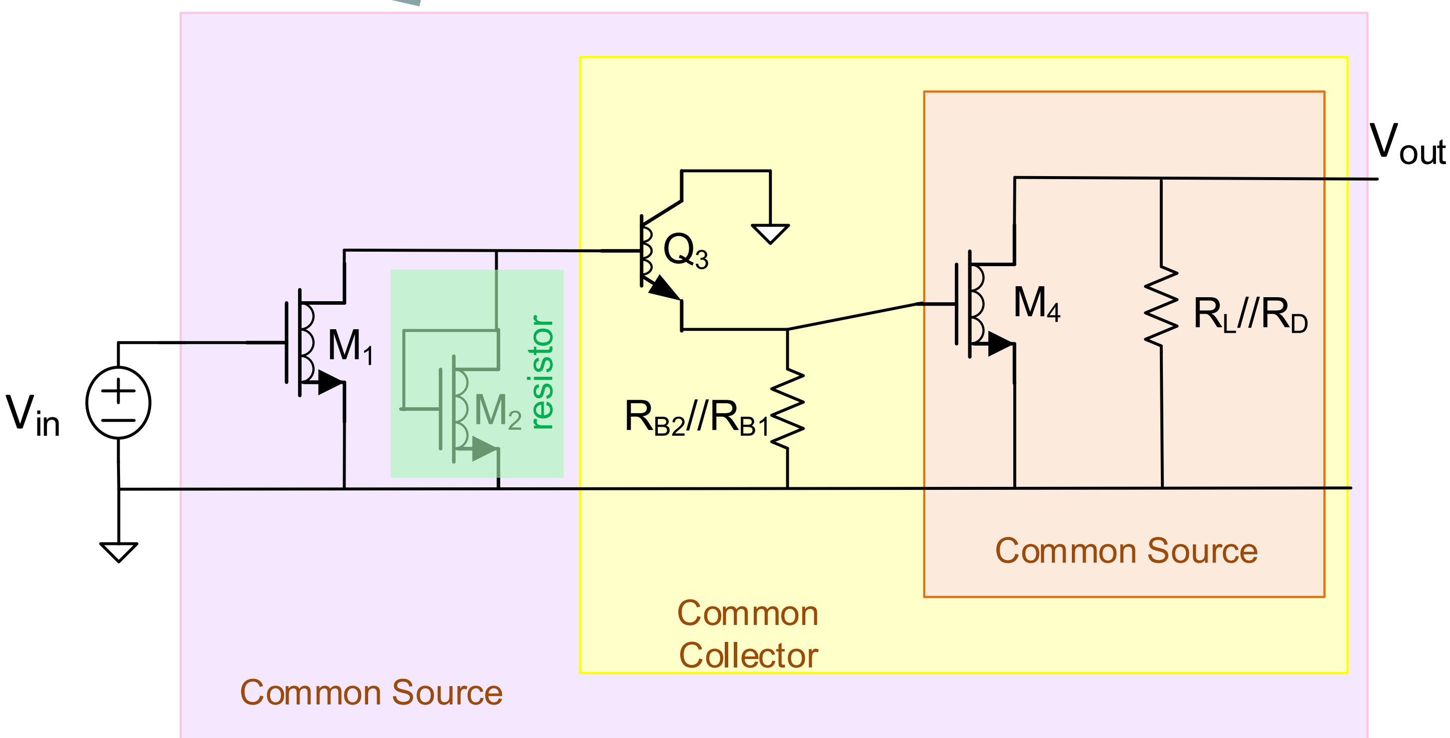


Example 2: $A_V = \frac{v_{out}}{v_{in}} = ?$

Express in terms of small-signal parameters



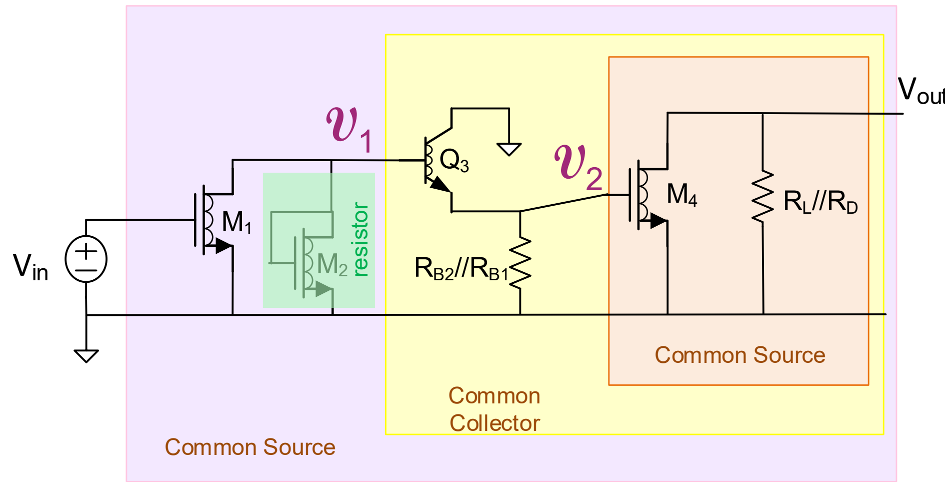
visualize

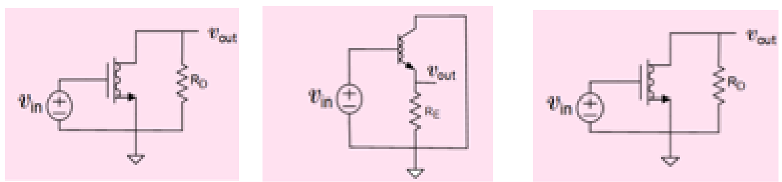


Example 2: $A_V = \frac{v_{out}}{v_{in}} = ?$

Express in terms of small-signal parameters

Gain Calculation in terms of Small-Signal Parameters





$$\frac{v_{OUT}}{v_2} =$$

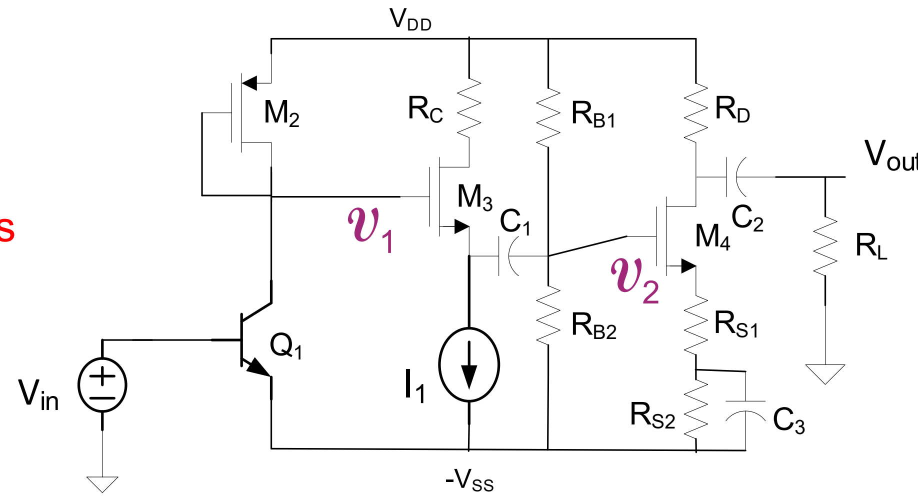
$$\frac{v_2}{v_1} =$$

$$\frac{v_1}{v_{in}} =$$

If $r_\pi + \beta(R_{B1}//R_{B2}) >> 1/g_{m2}$

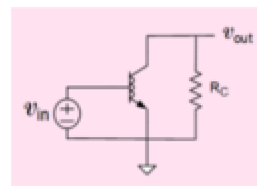
$$A_V = \frac{v_{out}}{v_2}\frac{v_2}{v_1}\frac{v_1}{v_{in}} \cong \left[-g_{m4}\left(R_D//R_L\right)\right]\left[1\right]\left[\frac{-g_{m1}}{g_{m2}}\right]$$

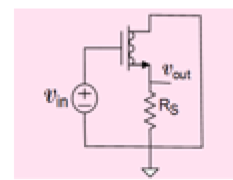
Example 3:

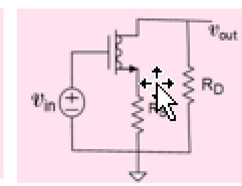


Visualize small-signal circuit
(Draw small-signal circuit if necessary)

Gain Calculation in Small-Signal Parameters







$$\frac{v_{OUT}}{v_2} =$$

$$\frac{v_2}{v_1} =$$

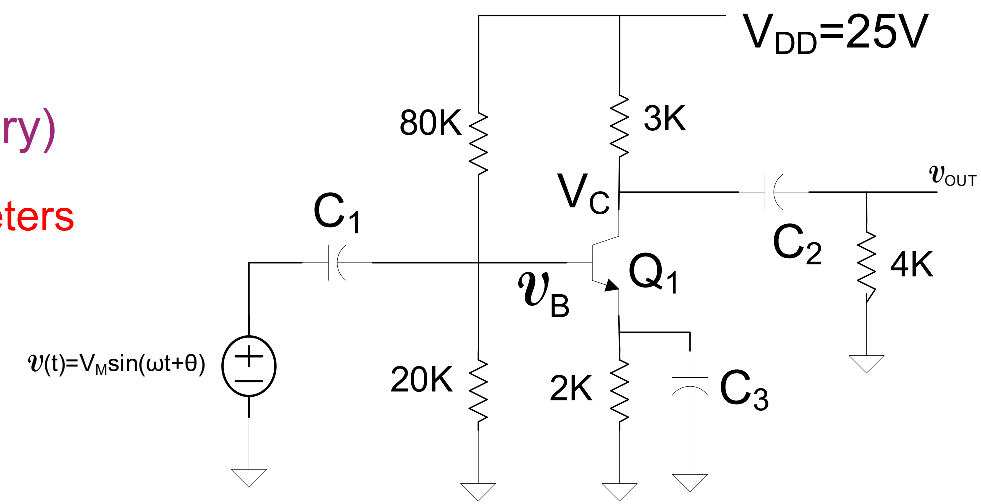
$$\frac{v_1}{v_{in}} =$$

$$A_V = \frac{v_{out}}{v_2}\frac{v_2}{v_1}\frac{v_1}{v_{in}} \cong \left[-g_{m4}\left(R_D//R_L\right)/R_{S1}\right][1]\left[\frac{-g_{m1}}{g_{m2}}\right]$$

Example 5:

Visualize small-signal circuit
(Draw small-signal circuit if necessary)

Gain Calculation in Small-Signal Parameters



$$A_V = \frac{v_{out}}{v_B} \cong -g_{m1}\left(3K//4K\right)$$

Stay Safe and Stay Healthy !

End of Lecture 32