

EE 330

Lecture 32

Basic Amplifiers

- Analysis, Operation, and Design

Cascaded Amplifiers

High Gain Amplifiers

Exam Schedule

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

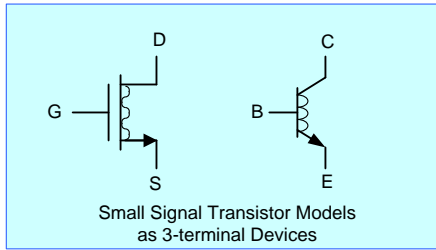
Photo courtesy of the director of the National Institute of Health (NIH)



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

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

Basic Amplifier Structures



Common Source or Common Emitter

Common Gate or Common Base

Common Drain or Common Collector

MOS		
Common	Input	Output
S	G	D
G	S	D
D	G	S

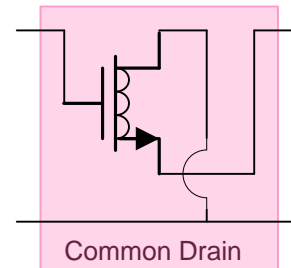
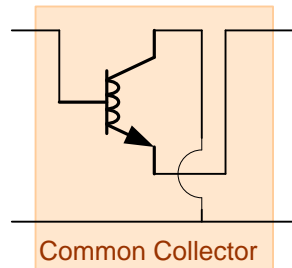
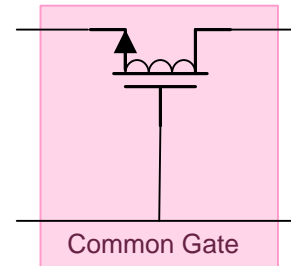
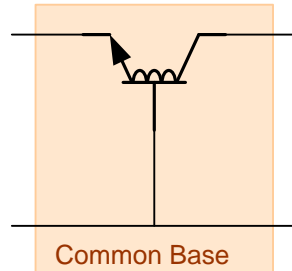
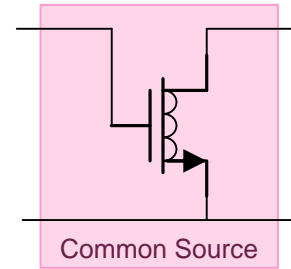
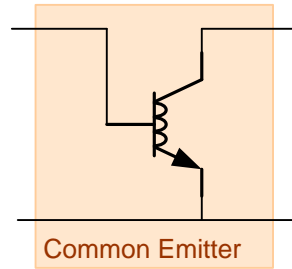
BJT		
Common	Input	Output
E	B	C
B	E	C
C	B	E

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

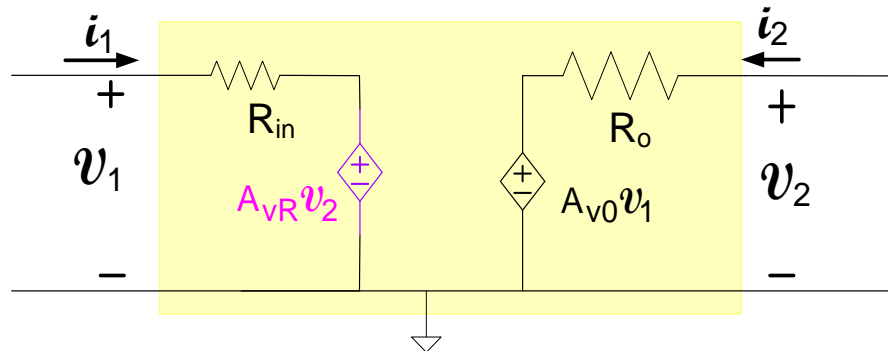
Review Previous Lecture



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

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

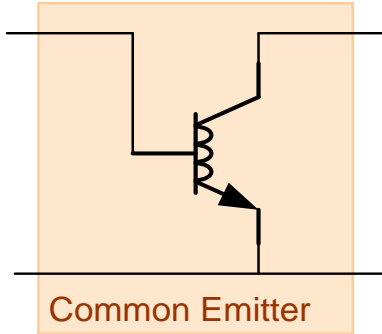
$$v_1 = i_1 R_{IN} + A_{VR} v_2$$

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

3. Thevenin-Norton Transformations
4. Ad Hoc Approaches

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

Common Source/ Common Emitter Configurations



$$R_{in} = \frac{1}{g_{\pi}}$$

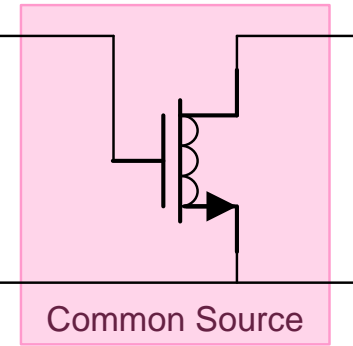
$$A_{V0} = -\frac{g_m}{g_o}$$

$$R_o = \frac{1}{g_o}$$

$$A_{VR} = 0$$

$$A_{VR} = 0$$

$$R_{in} = \infty$$



$$A_{V0} = -\frac{g_m}{g_o}$$

$$R_o = \frac{1}{g_o}$$

In terms of operating point and model parameters:

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

$$A_{V0} = -\frac{V_{AF}}{V_t}$$

$$R_o = \frac{V_{AF}}{I_{CQ}}$$

$$R_{in} = \infty$$

$$R_o = \frac{1}{\lambda I_{DQ}} = \frac{V_{AF}}{I_{DQ}}$$

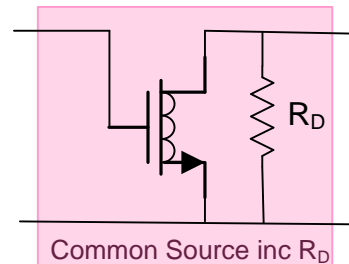
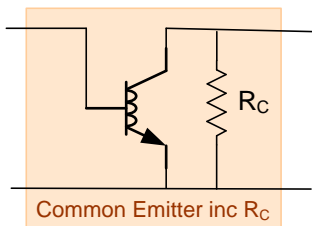
$$A_{V0} = -\frac{2}{\lambda V_{EBQ}} = -2 \frac{V_{AF}}{V_{EBQ}}$$

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)



$$R_{out} = \frac{1}{g_0 + g_C} \stackrel{g_0 \ll g_C}{\cong} R_C$$

$$A_v \stackrel{g_0 \ll g_C}{\cong} -g_m R_C$$

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

$$A_{VR} = 0 \quad | \quad A_{VR} = 0$$

$$R_{out} = \frac{1}{g_0 + g_D} \stackrel{g_0 \ll g_D}{\cong} R_D$$

$$A_v \stackrel{g_0 \ll g_D}{\cong} -g_m R_D$$

$$R_{in} = \infty$$

In terms of operating point and model parameters:

$$A_v \stackrel{g_0 \ll g_C}{\cong} -\frac{I_{CQ} R_C}{V_t}$$

$$R_{out} \stackrel{g_0 \ll g_C}{\cong} R_C$$

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

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

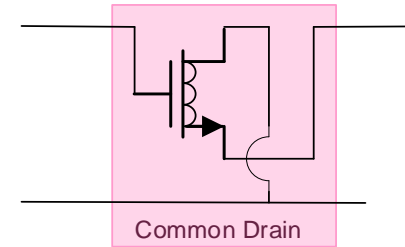
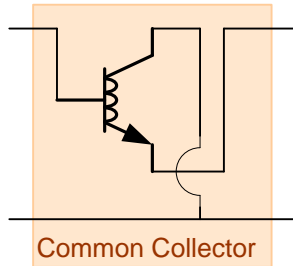
$$R_{in} = \infty$$

$$R_{out} \stackrel{g_0 \ll g_D}{\cong} R_D$$

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

Two-port model for Common Collector Configuration



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

$$A_{V0} = 1$$

$$R_0 = \frac{1}{g_m}$$

$$A_{VR} = 1$$

$$A_{VR} = 1$$

$$R_{in} = \infty$$

$$A_{V0} = 1$$

$$R_0 = \frac{1}{g_m}$$

In terms of operating point and model parameters:

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

$$A_{V0} = 1$$

$$R_0 = \frac{V_t}{I_{CQ}}$$

$$R_{in} = \infty$$

$$A_{V0} = 1$$

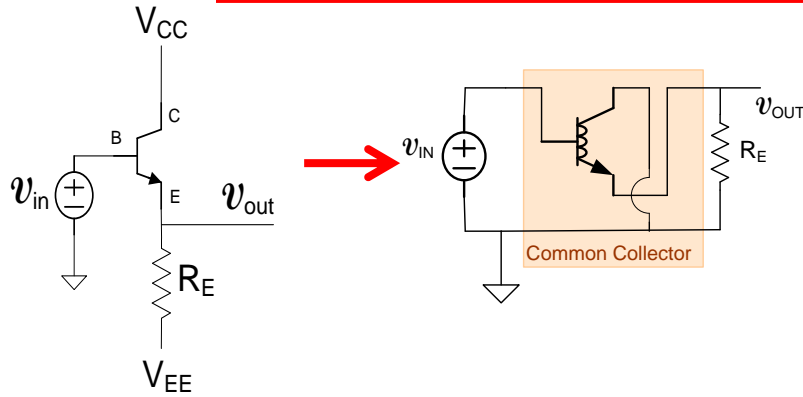
$$R_0 = \frac{V_{EB}}{2I_{DQ}}$$

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

Common Collector/Common Drain Configurations

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



$$A_V = \frac{g_\pi + g_m}{g_m + g_E + g_0 + g_\pi} \quad \text{if } g_m \gg g_E \cong 1$$

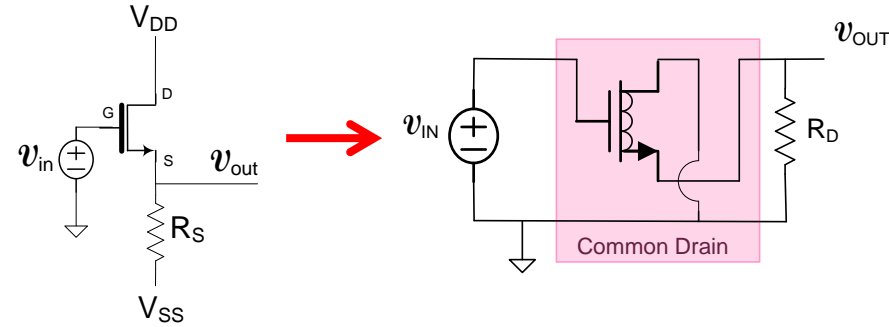
$$R_{in} \stackrel{g_E \gg g_o}{\cong} r_\pi + \beta R_E$$

$$R_0 \cong \frac{R_E}{1 + g_m R_E} \stackrel{g_m R_E \gg 1}{\cong} \frac{1}{g_m}$$

In terms of operating point and model parameters:

$$A_V \cong \frac{I_{CQ} R_E}{I_{CQ} R_E + V_t} \stackrel{I_{CQ} R_E \gg V_t}{\cong} 1 \quad R_0 \cong \frac{V_t}{I_{CQ}}$$

$$R_{in} \stackrel{I_{CQ} R_E \gg V_t}{\cong} r_\pi + \beta R_E$$



$$A_V = \frac{g_m}{g_m + g_S + g_0} \quad \text{if } g_m \gg g_S \cong 1$$

$$R_{in} = \infty$$

$$R_0 \cong \frac{R_S}{1 + g_m R_S} \stackrel{g_m R_S \gg 1}{\cong} \frac{1}{g_m}$$

$$A_V \cong \frac{2I_{DQ} R_S}{2I_{DQ} R_S + V_{EBQ}} \stackrel{\text{if } 2I_{DQ} R_S \gg V_{EBQ}}{\cong} 1$$

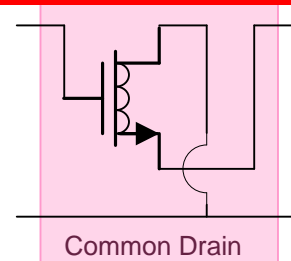
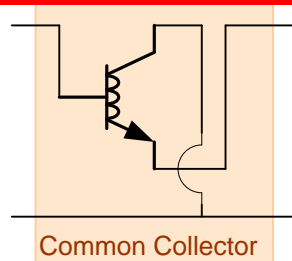
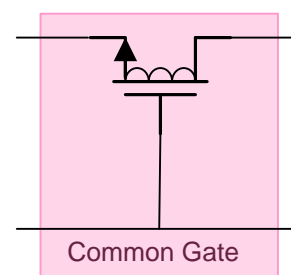
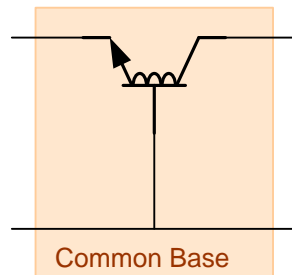
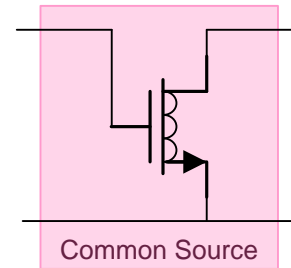
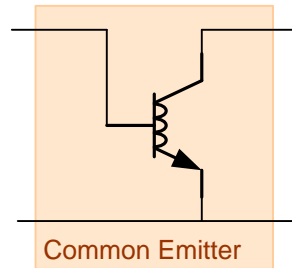
$$R_0 \cong \frac{V_{EBQ} R_S}{V_{EBQ} + 2I_{DQ} R_S} \stackrel{2I_{DQ} R_S \gg V_{EBQ}}{\cong} \frac{V_{EBQ}}{2I_{DQ}}$$

$$R_{in} = \infty$$

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

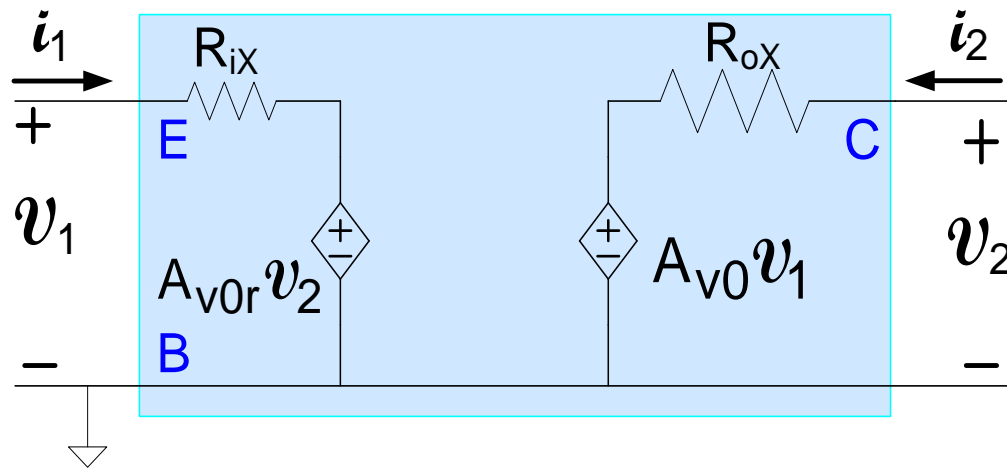
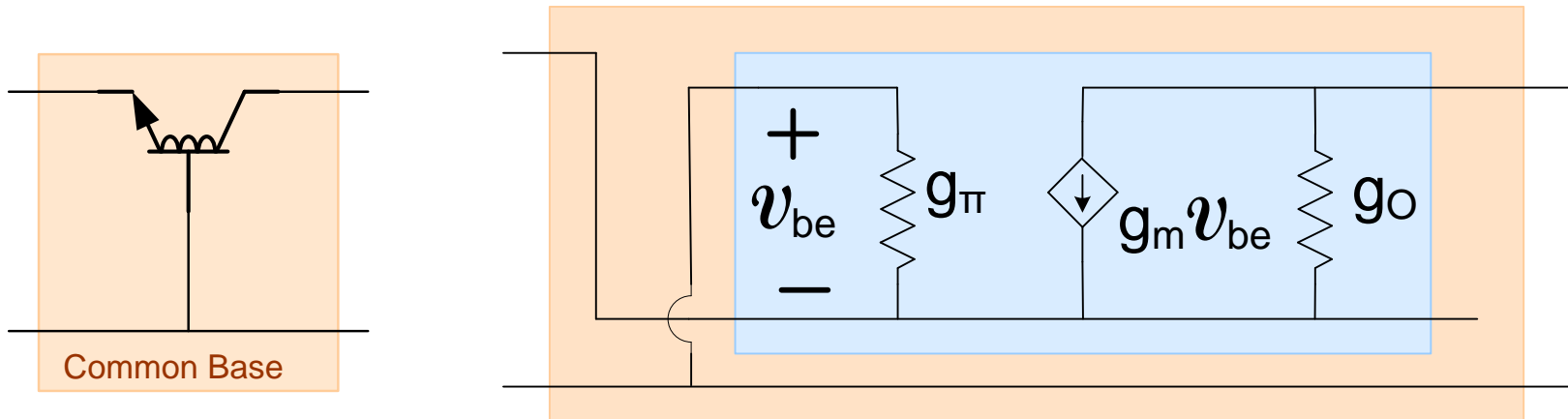
- Widely used as a buffer
- Not completely unilateral but output-input transconductance is small

Consider Common Base/Common Gate Two-port Models



- Will focus on Bipolar Circuit since MOS counterpart is a special case obtained by setting $g_{\pi}=0$
- Will consider both two-port model and a widely used application

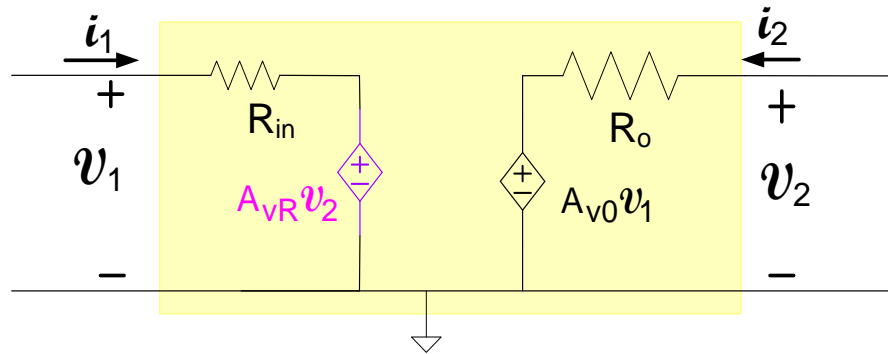
Two-port model for Common Base Configuration



$\{R_{iX}, A_{v0}, A_{v0r} \text{ and } R_{oX}\}$

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

Methods of Obtaining Amplifier Two-Port Network



1. $v_{\text{TEST}} : i_{\text{TEST}}$ Method



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

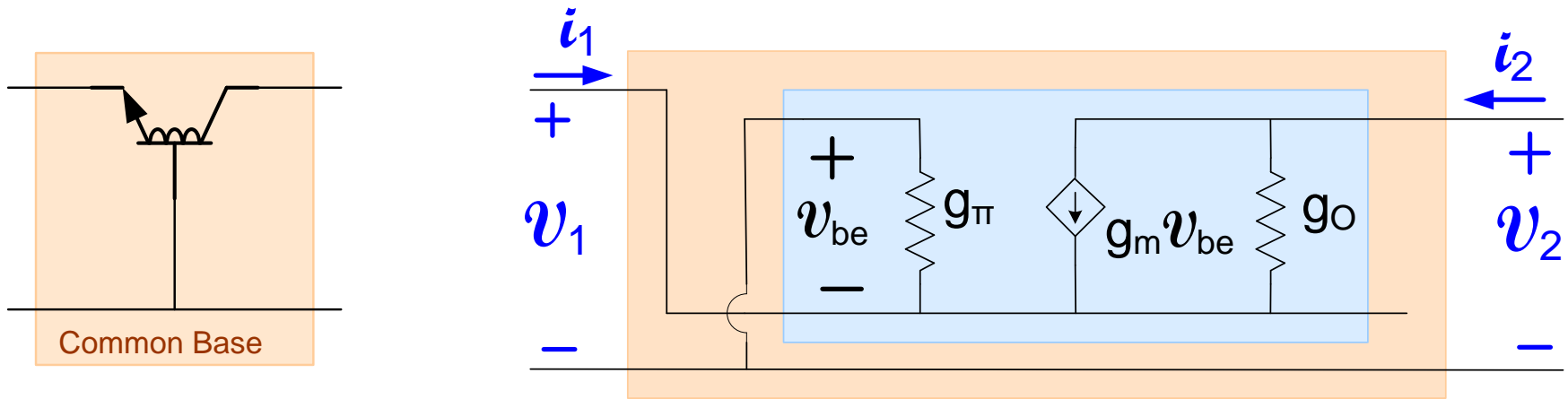
$$v_1 = i_1 R_{\text{IN}} + A_{\text{VR}} v_2$$

$$v_2 = i_2 R_{\text{O}} + A_{\text{V0}} v_1$$

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches

Two-port model for Common Base Configuration



From KCL

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

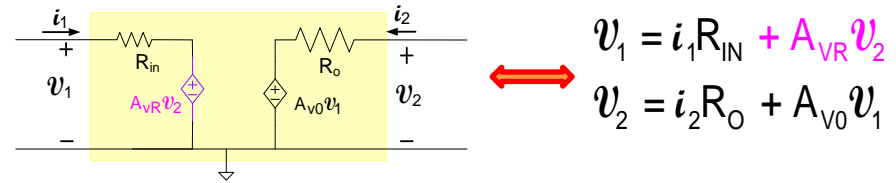
These can be rewritten as

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

It thus follows that:

$$R_{iX} = \frac{1}{g_m + g_\pi + g_o} \cong \frac{1}{g_m} \quad A_{vOr} = \frac{g_o}{g_m + g_\pi + g_o} \quad A_{vO} = 1 + \frac{g_m}{g_o} \cong \frac{g_m}{g_o} \quad R_{oX} = \frac{1}{g_o}$$

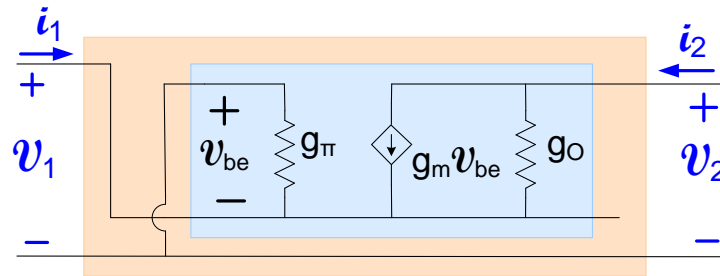
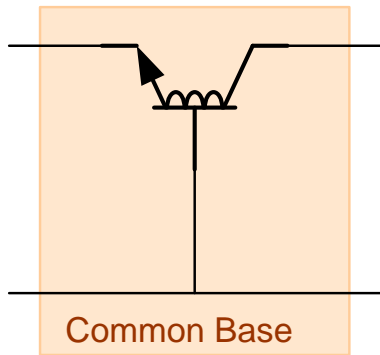
Standard Form for Amplifier Two-Port



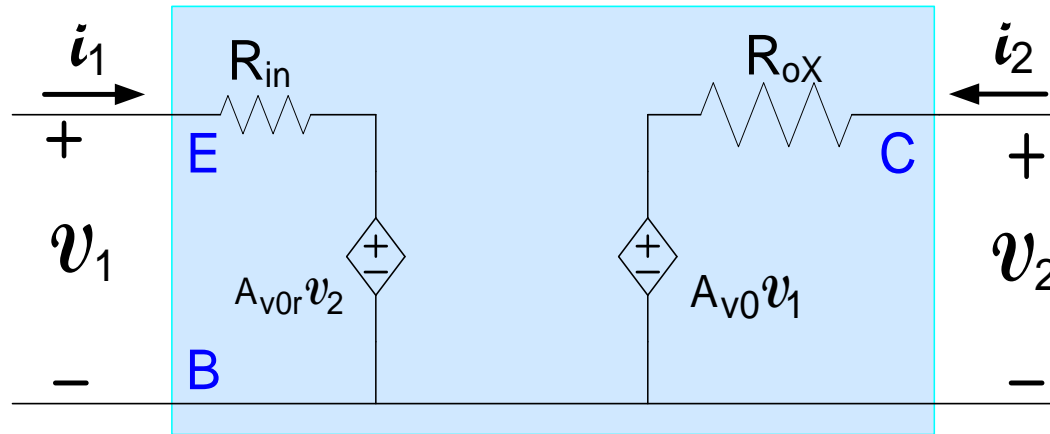
$$\begin{aligned} v_1 &= i_1 R_{iN} + A_{vR} v_2 \\ v_2 &= i_2 R_{o} + A_{vO} v_1 \end{aligned}$$

$v_1 : v_2$ equations in standard form

Two-port model for Common Base Configuration



Two-port Common Base Model



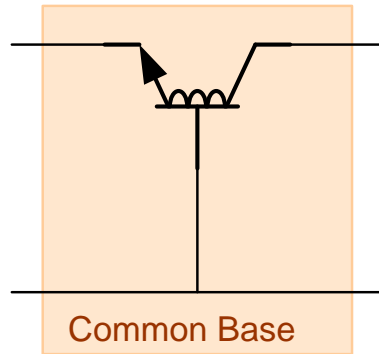
$$R_{iX} = \frac{1}{g_m + g_\pi + g_o} \cong \frac{1}{g_m}$$

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

$$A_{V0r} = \frac{g_o}{g_m + g_\pi + g_o} \cong \frac{g_o}{g_m}$$

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

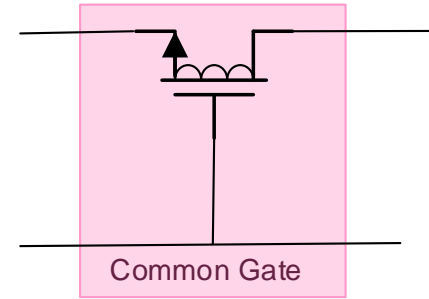
Two-port model for Common Base Configuration



Common Base

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

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



Common Gate

$$R_{in} \cong \frac{1}{g_m}$$

$$A_{V0} = \frac{g_m}{g_o}$$

$$R_o = \frac{1}{g_o}$$

$$R_{in} \cong \frac{1}{g_m}$$

$$A_{V0} = \frac{g_m}{g_o}$$

$$R_o = \frac{1}{g_o}$$

In terms of operating point and model parameters:

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

$$A_{V0} = \frac{V_{AF}}{V_t}$$

$$R_o = \frac{V_{AF}}{I_{CQ}}$$

$$R_{in} = \frac{V_{EB}}{2I_{DQ}}$$

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

$$R_o = \frac{1}{\lambda I_{DQ}}$$

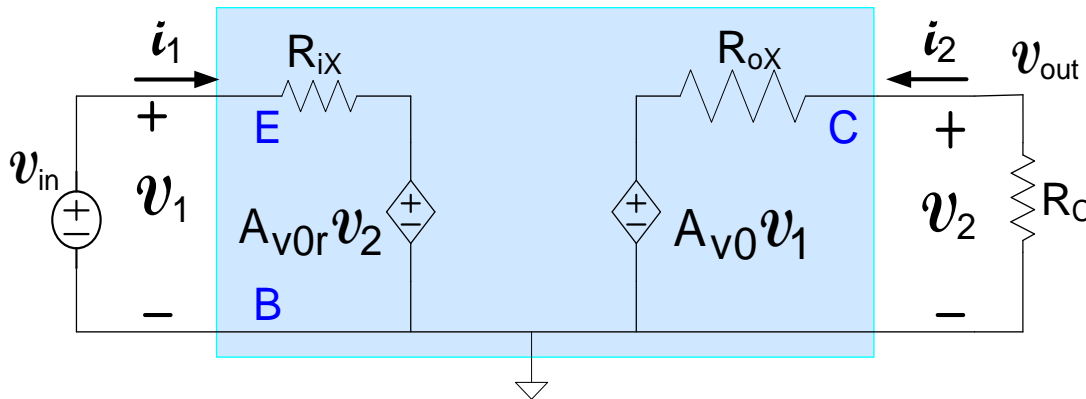
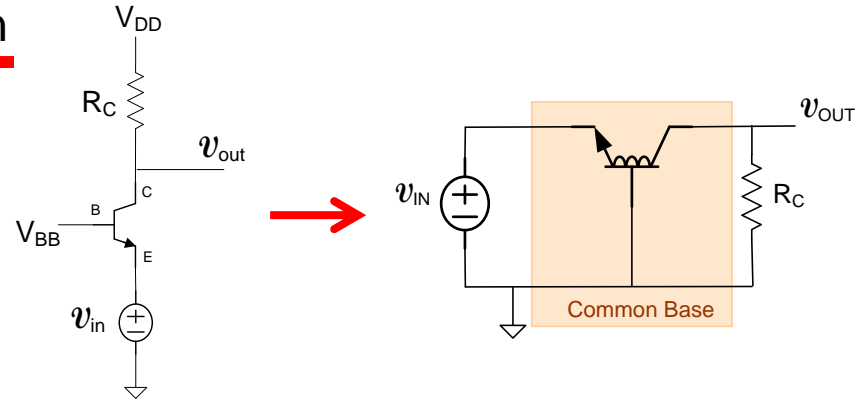
Characteristics:

- 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)



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

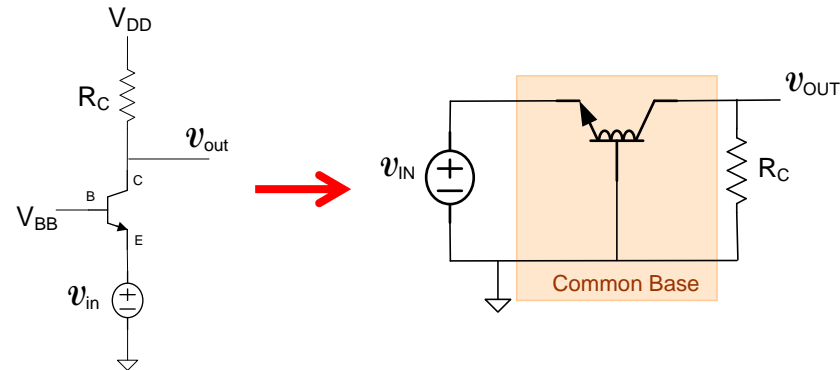
$$R_{in} = \frac{v_{in}}{i_1} = \frac{i_1 R_{iX} + A_{V0r} v_{out}}{i_1} \longrightarrow R_{in} = \frac{R_{iX}}{1 - A_{V0r} A_V} = \frac{g_0 + g_C}{g_C (g_m + g_\pi + g_0) + g_\pi g_0} \cong \frac{1}{g_m}$$

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

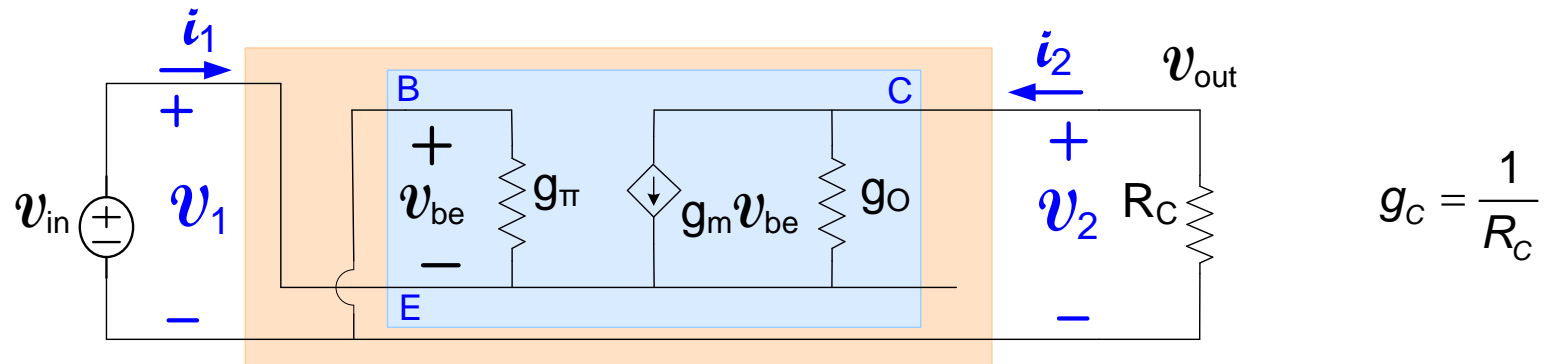
Common Base Configuration

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



By KCL at the output node, obtain

$$(g_C + g_0)v_o = (g_m + g_0)v_{in} \quad \longrightarrow \quad A_V = \frac{g_m + g_0}{g_C + g_0} \cong g_m R_C$$

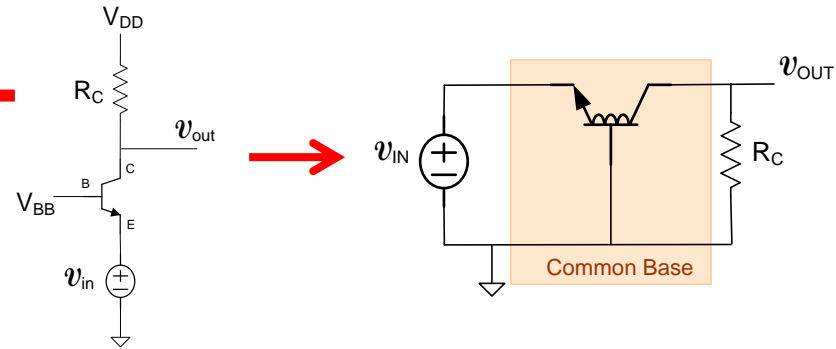
By KCL at the emitter node, obtain

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

$$R_{out} = R_C // r_o \quad \longrightarrow \quad R_{out} = \frac{R_C}{1 + g_0 R_C} \cong R_C$$

Popular Common Base Application

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



$$A_V \cong g_m R_C$$
$$R_{in} \cong \frac{1}{g_m}$$
$$R_{out} \cong R_C$$

$R_c \ll r_o$

$$A_V \cong \frac{I_{CQ} R_C}{V_t}$$
$$R_{in} \cong \frac{V_t}{I_{CQ}}$$
$$R_{out} \cong R_C$$

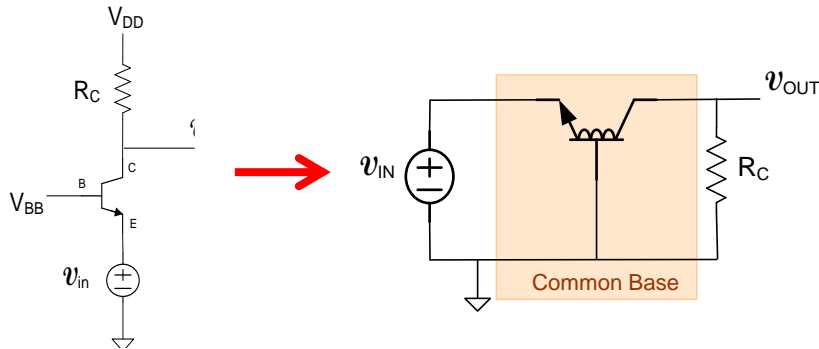
$R_c \ll r_o$

Characteristics:

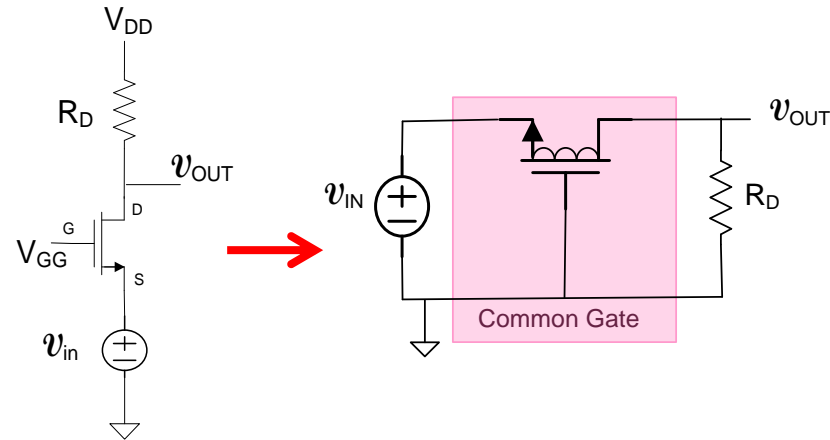
- Output impedance is mid-range
- A_{V0} is large and positive (equal in mag to that to CE)
- Input impedance is very low
- Not completely unilateral but output-input transconductance is small

Common Base/Common Gate Application

(these are not a two-port models)



$$A_V \cong g_m R_C \quad R_{in} \cong \frac{1}{g_m} \quad R_{out} \stackrel{R_c \ll r_o}{\cong} R_C$$



$$A_V \cong g_m R_D \quad R_{in} \cong \frac{1}{g_m} \quad R_{out} \stackrel{R_b \ll r_o}{\cong} R_D$$

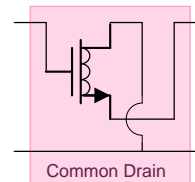
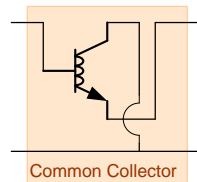
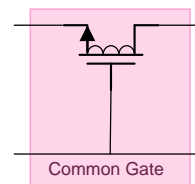
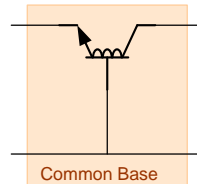
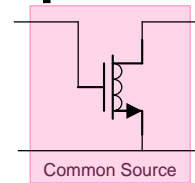
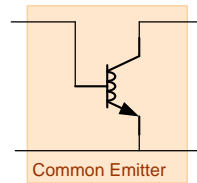
In terms of operating point and model parameters:

$$A_V \cong \frac{I_{CQ} R_C}{V_t} \quad R_{in} \cong \frac{V_t}{I_{CQ}} \quad R_{out} \stackrel{I_{CQ} R_C \ll V_{AF}}{\cong} R_C \quad A_V \cong \frac{2I_{DQ} R_D}{V_{EBQ}} \quad R_{in} \cong \frac{V_{EBQ}}{2I_{DQ}} \quad R_{out} \stackrel{I_{DQ} R_D \ll 1/\lambda}{\cong} R_D$$

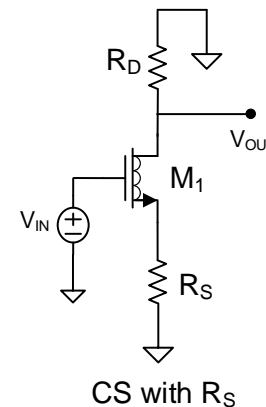
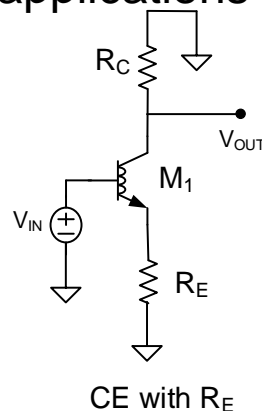
Characteristics:

- 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

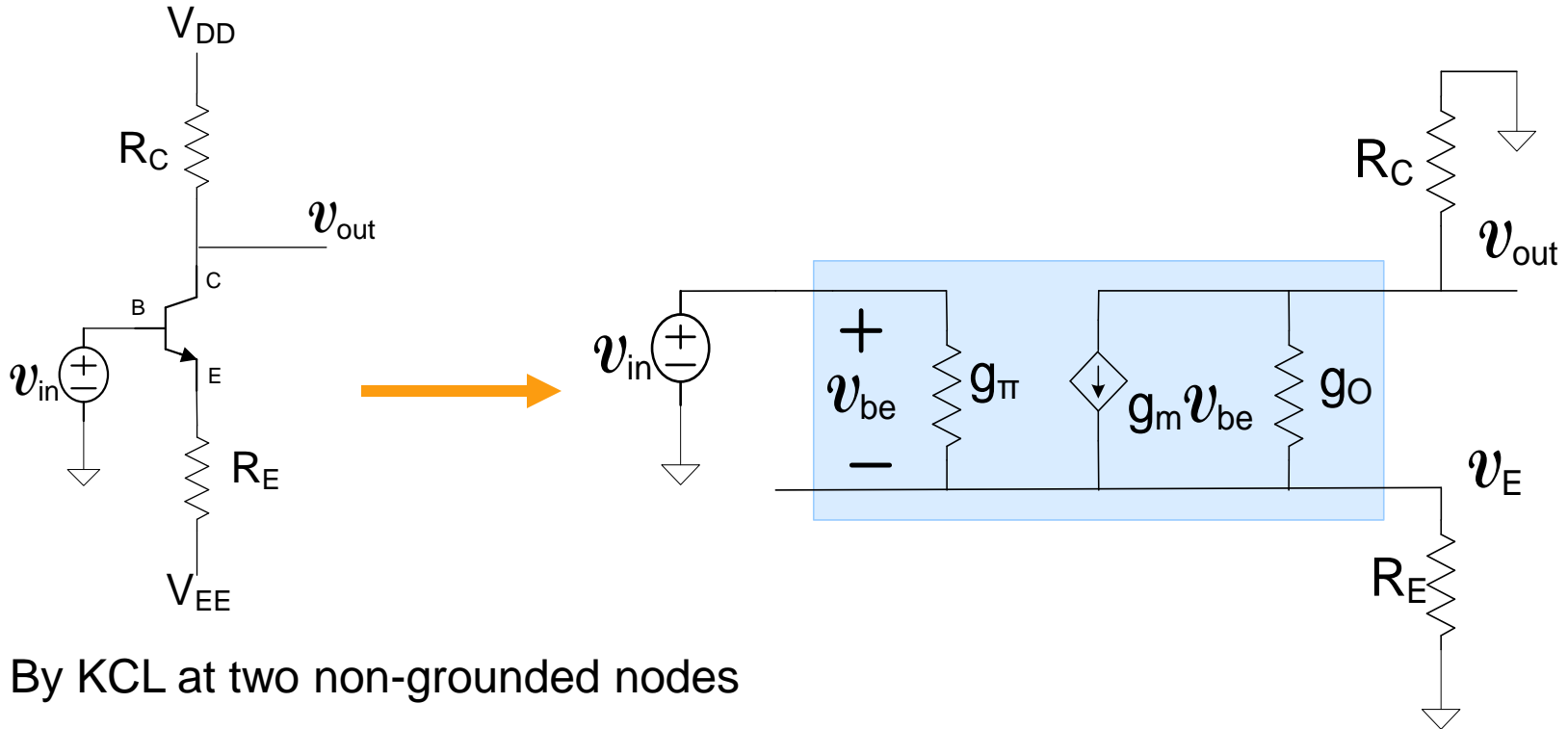


- Have developed both two-ports and a widely used application of all 6
- A fourth structure (two additional applications) is also quite common so will be added to list of basic applications



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

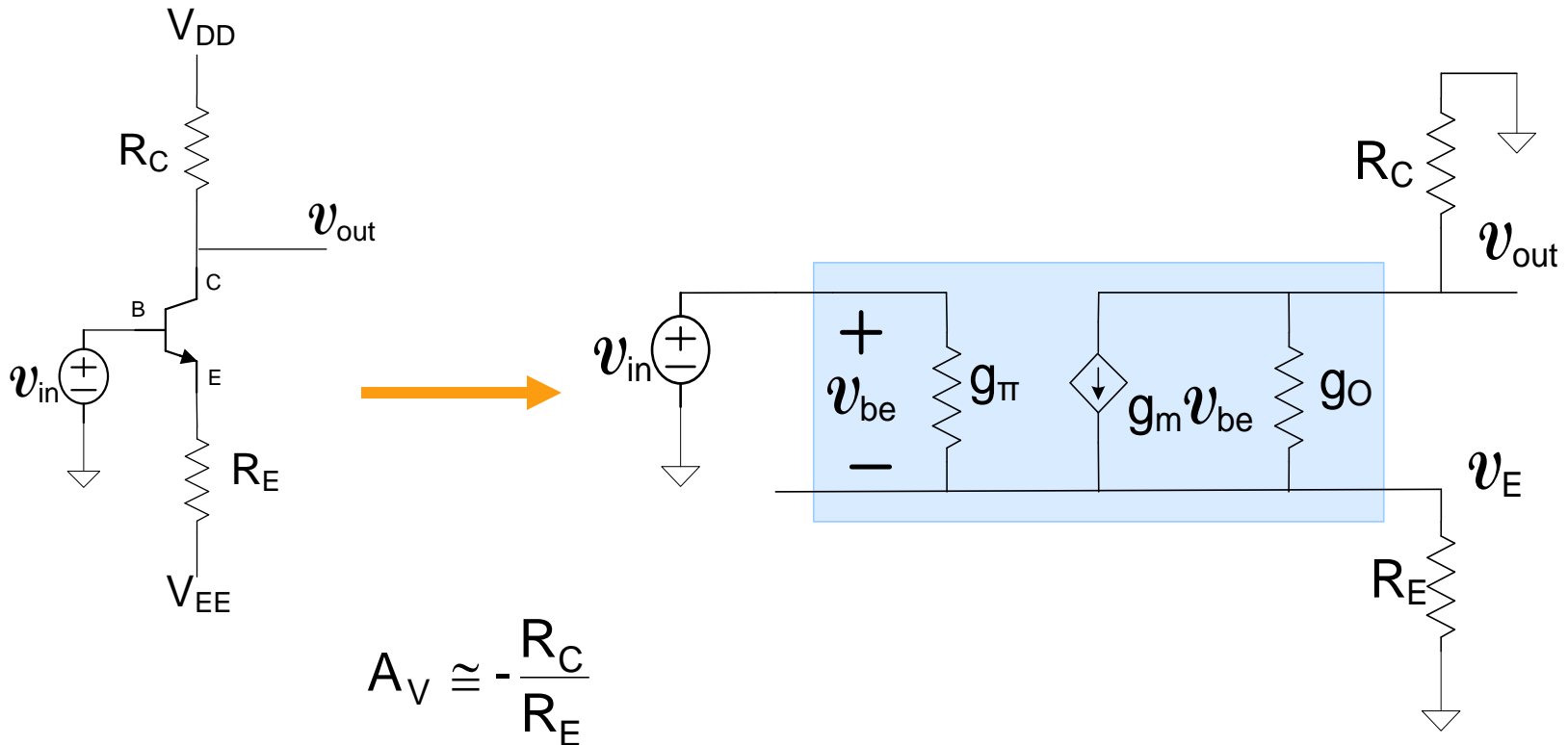
$$v_{out} (g_C + g_o) + (v_{in} - v_E) g_m = g_o v_E$$

$$v_E (g_E + g_o + g_{\pi}) - (v_{in} - v_E) g_m = g_o v_{out} + g_{\pi} v_{in}$$

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

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

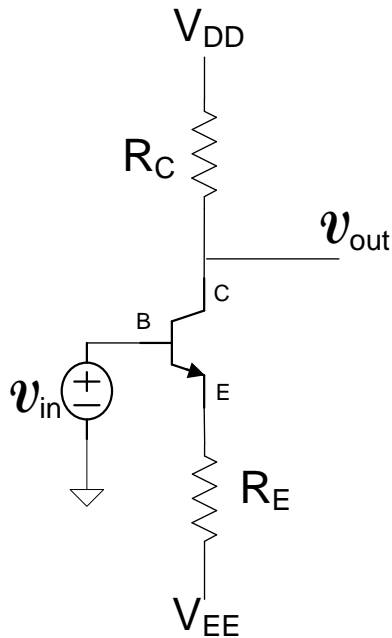
$$R_{in} \cong r_{\pi} + \beta R_E$$

$$R_{out} \cong R_C$$

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)



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

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

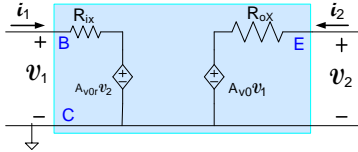
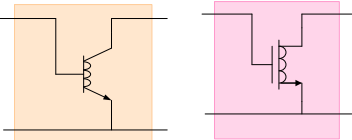
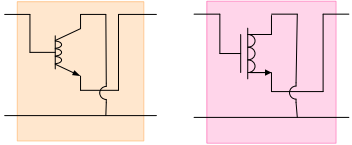
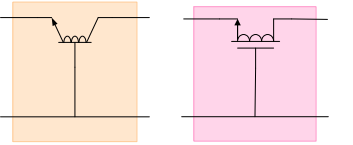
$$R_{out} \cong R_C$$

(this is not a two-port model)

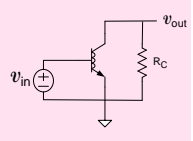
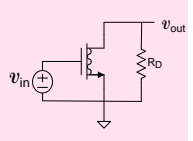
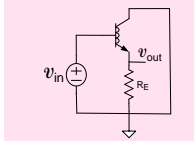
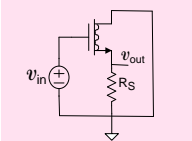
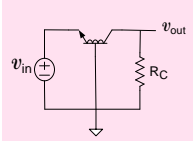
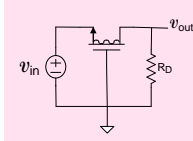
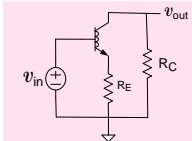
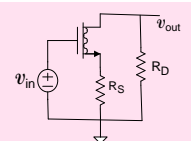
Characteristics:

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


Basic Amplifier Application Gain Table

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

(not 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?

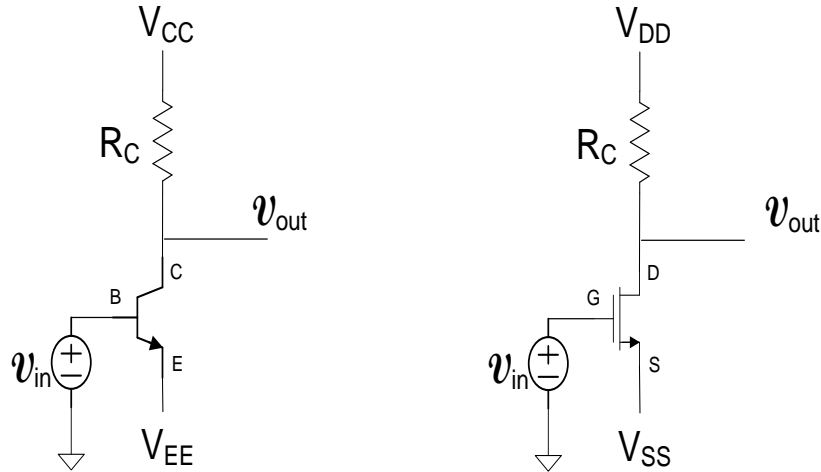
1. So that we can develop analytical skills
2. So that we can design a circuit
3. So that we can get the insight needed to design a circuit

Which is the most important?

- 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

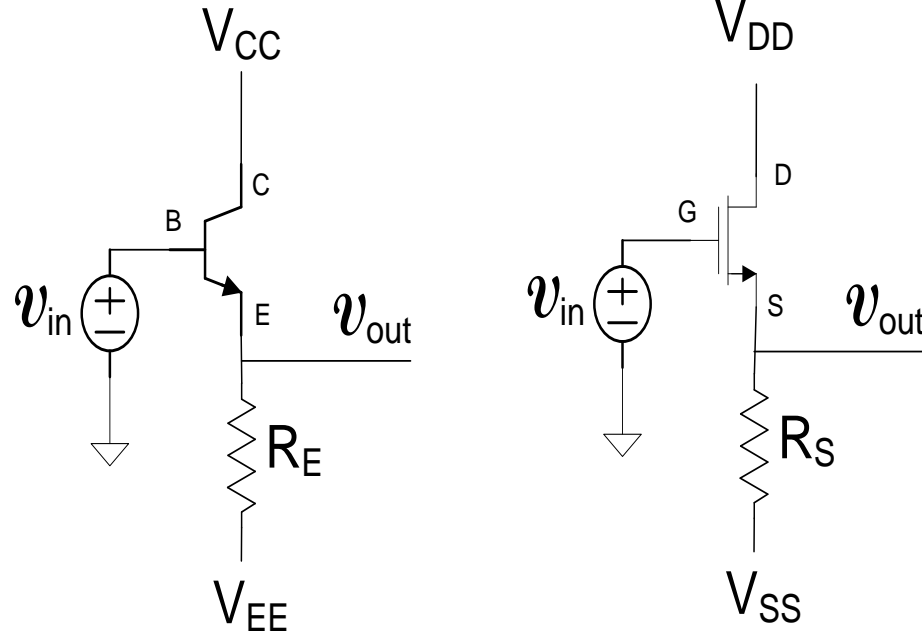
R_C or R_D may (or may not) be load

- 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)



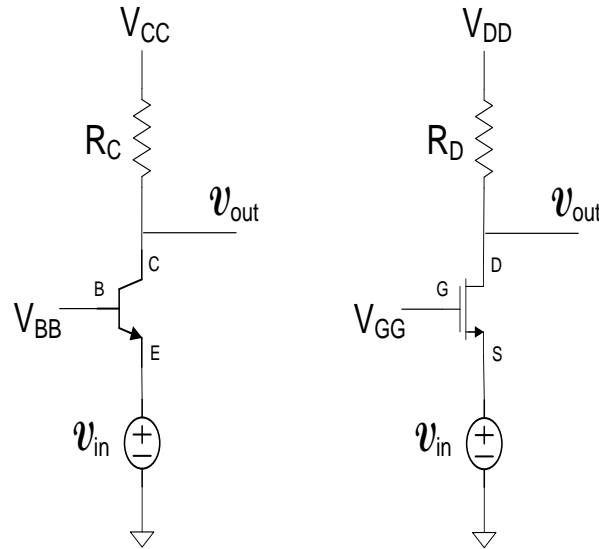
More practical biasing circuits usually used

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



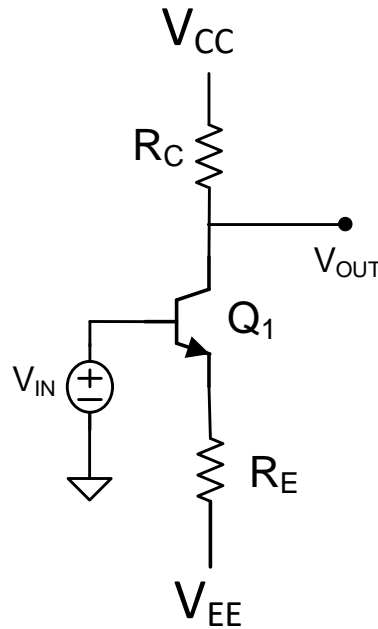
More practical biasing circuits usually used

R_C or R_D may (or may not) be load

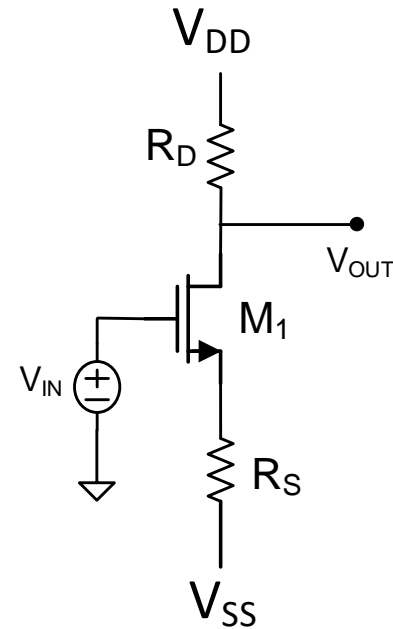
- Large noninverting gain
- Low input impedance
- Moderate (or high) output impedance
- Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode

Properties/Use of Basic Amplifiers

CEwRE and CSwRS



CE with R_E



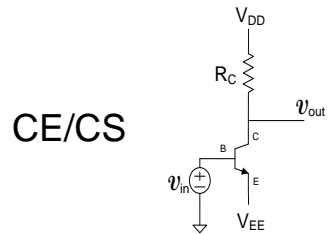
CS with R_S

More practical biasing circuits usually used

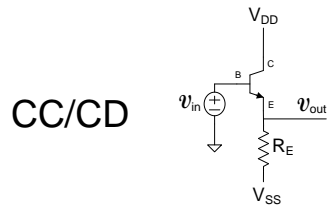
R_C or R_D may (or may not) be load

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

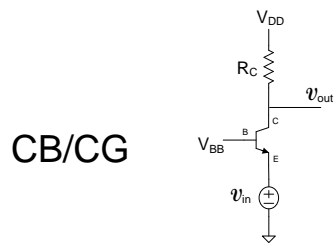
Basic Amplifier Characteristics Summary



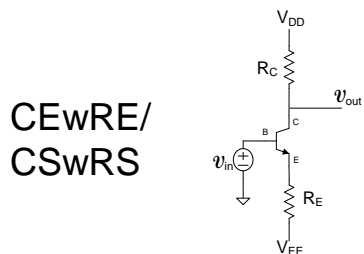
- Large inverting gain
 - Moderate input impedance
 - Moderate (or high) output impedance
 - Widely used as the basic high gain inverting amplifier
-



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

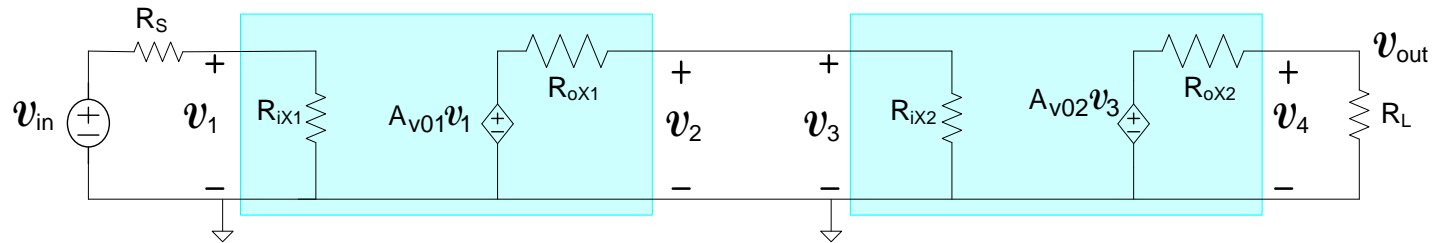


- Large noninverting gain
 - Low input impedance
 - Moderate (or high) output impedance
 - Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode
-



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

Cascaded Amplifiers



$$A_V = \frac{v_{out}}{v_{in}} = \left(\frac{R_{iX1}}{R_{iX1} + R_S} \right) A_{V01} \left(\frac{R_{iX2}}{R_{iX2} + R_{oX1}} \right) A_{V02} \left(\frac{R_L}{R_L + R_{oX2}} \right)$$

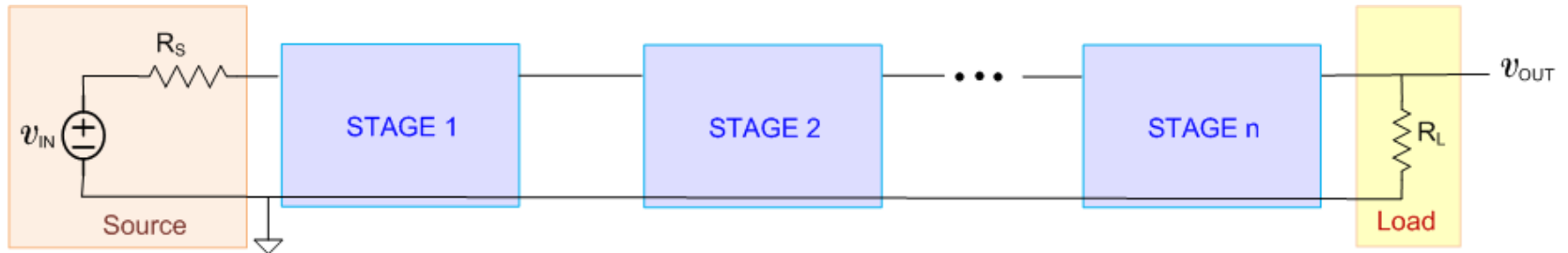
$$\text{If } R_o \ll R_i \quad R_S \ll R_i \quad R_o \ll R_L$$

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

- 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..)

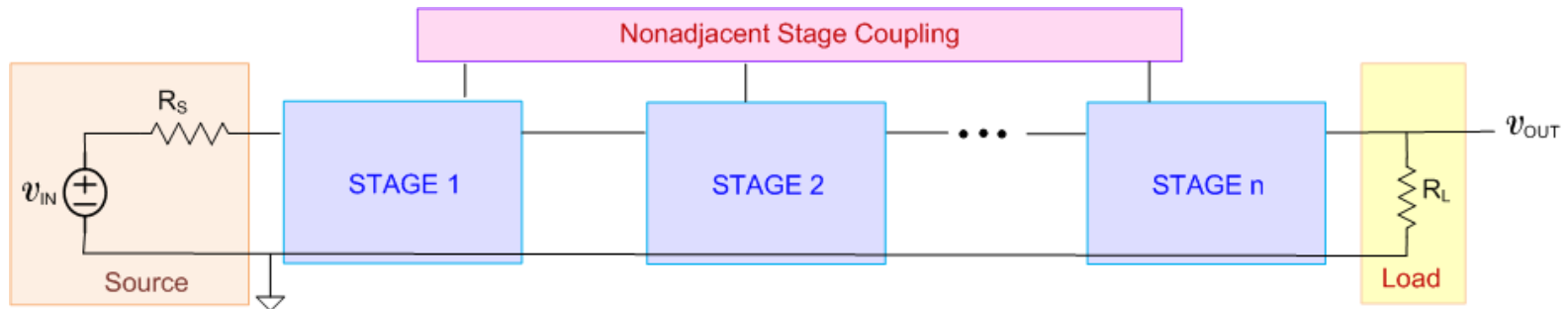
Cascaded Amplifier Analysis and Operation

Adjacent Stage Coupling Only



- Systematic Methods of Analysis/Design will be Developed

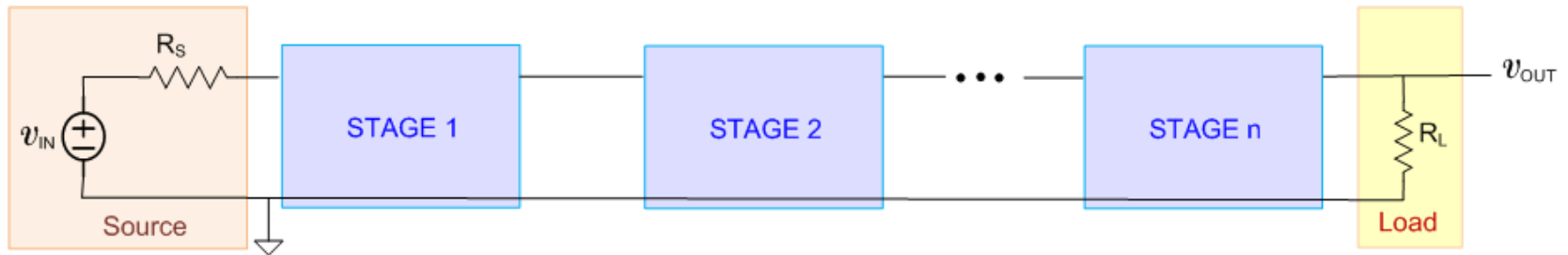
One or more couplings of nonadjacent stages



- 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

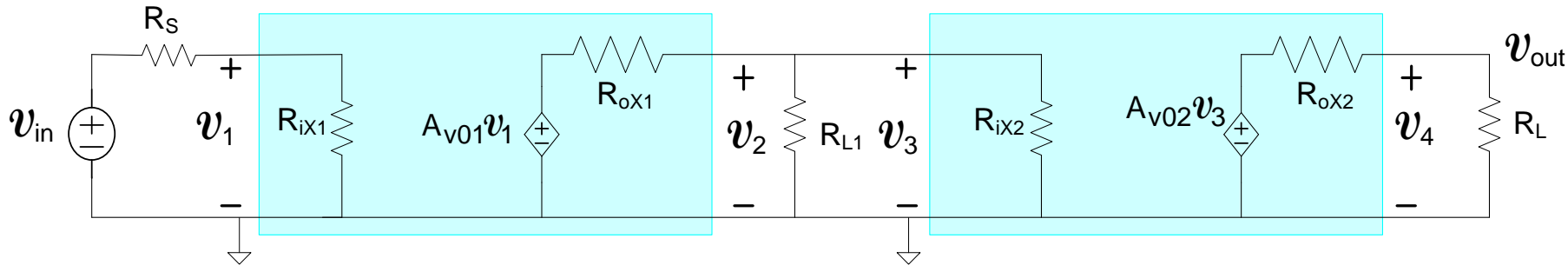
Case 1: All stages Unilateral

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



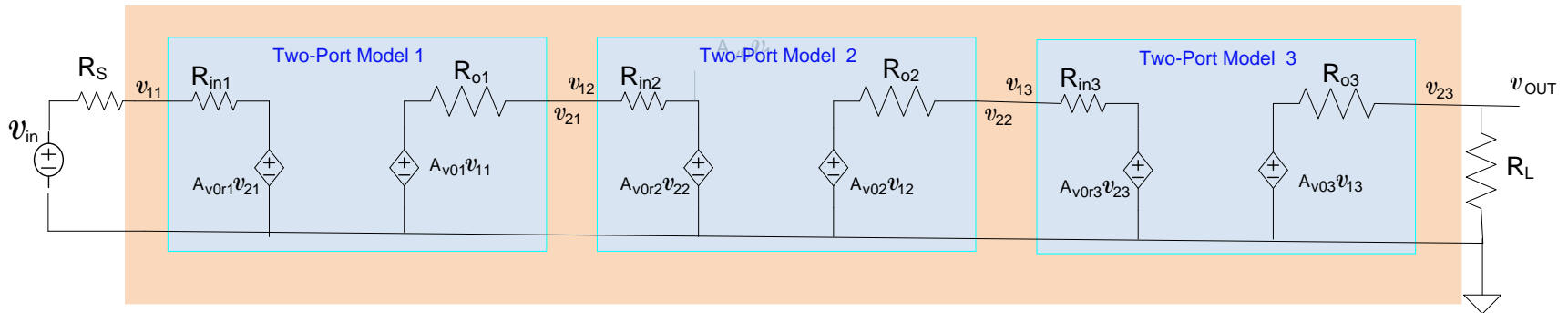
$$A_V = \frac{v_{out}}{v_{in}} = \left(\frac{R_{iX1}}{R_{iX1} + R_S} \right) A_{V01} \left(\frac{R_{L1} // R_{iX2}}{R_{L1} // R_{iX2} + R_{oX1}} \right) A_{V02} \left(\frac{R_L}{R_L + R_{oX2}} \right)$$

Accounts for all loading between stages !

Cascaded Amplifier Analysis and Operation

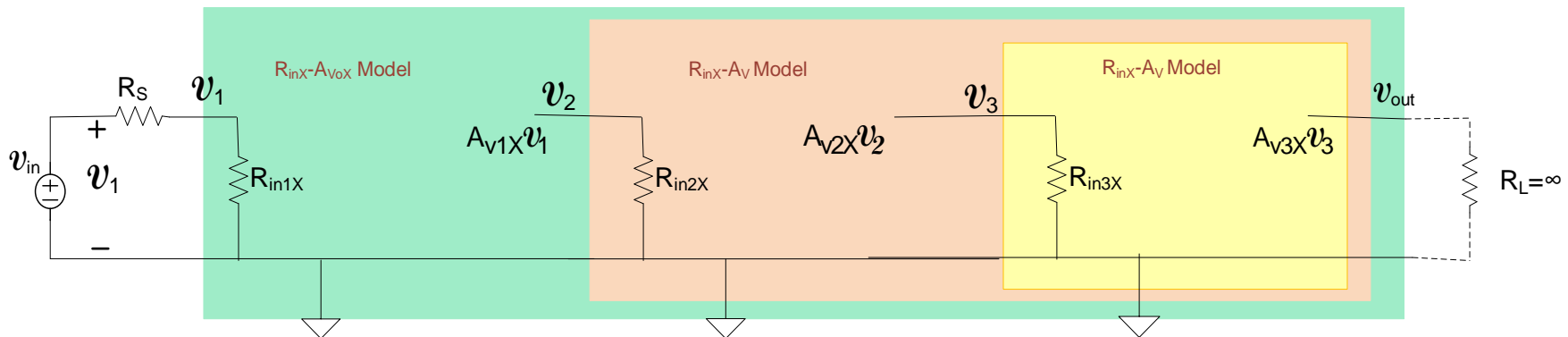
Case 2: One or more stages are not unilateral

➤ Standard two-port cascade



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

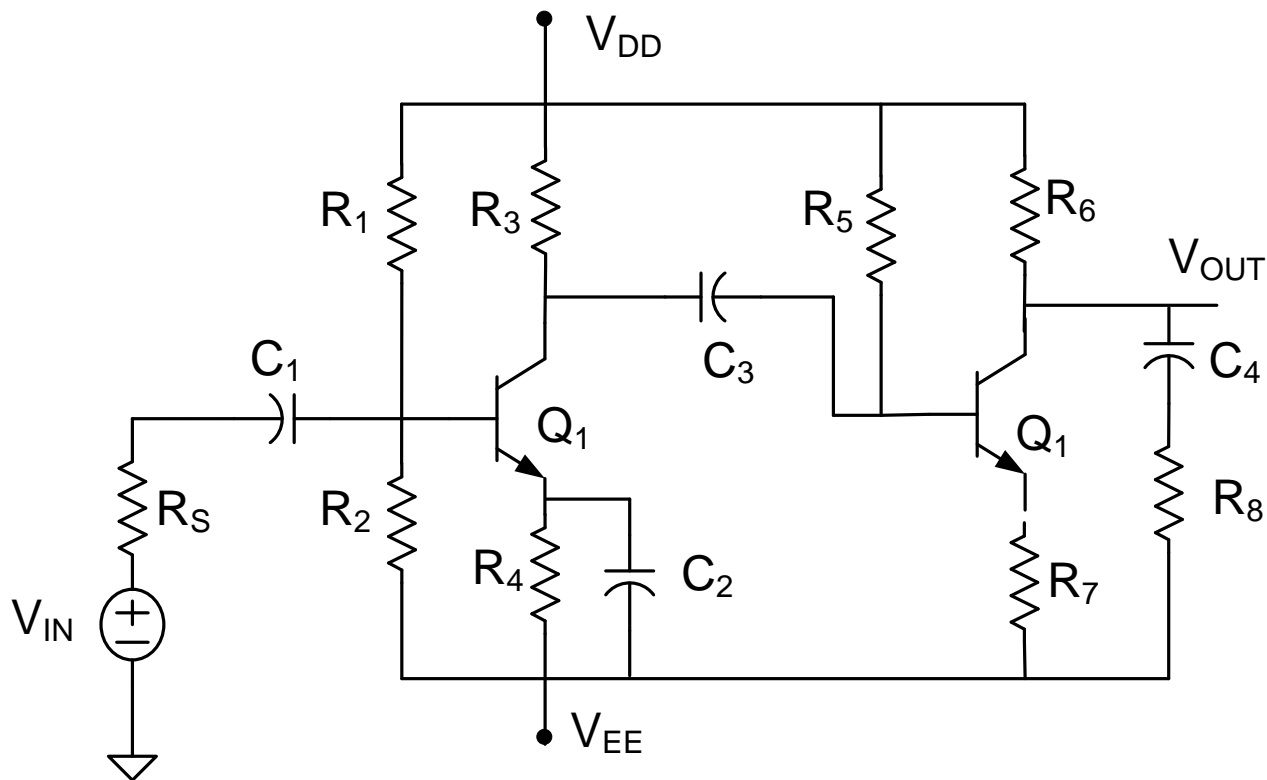
➤ Right-to-left nested R_{inx}, A_{VKX} approach



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

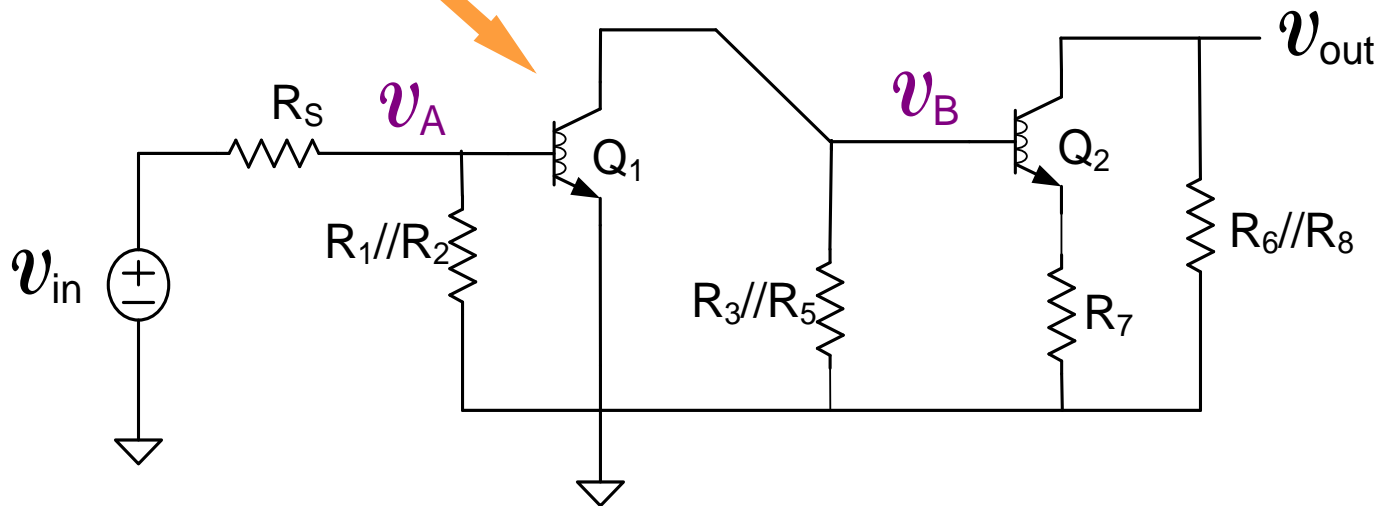
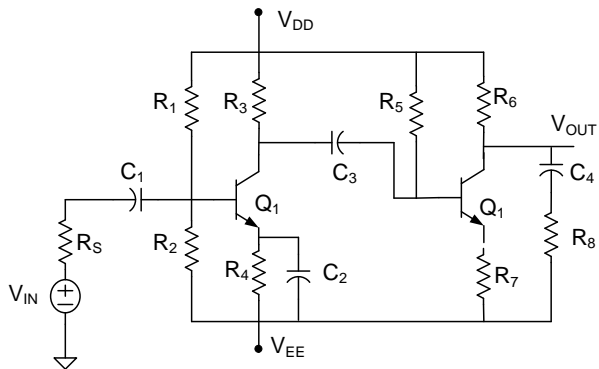
Example 1:

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



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

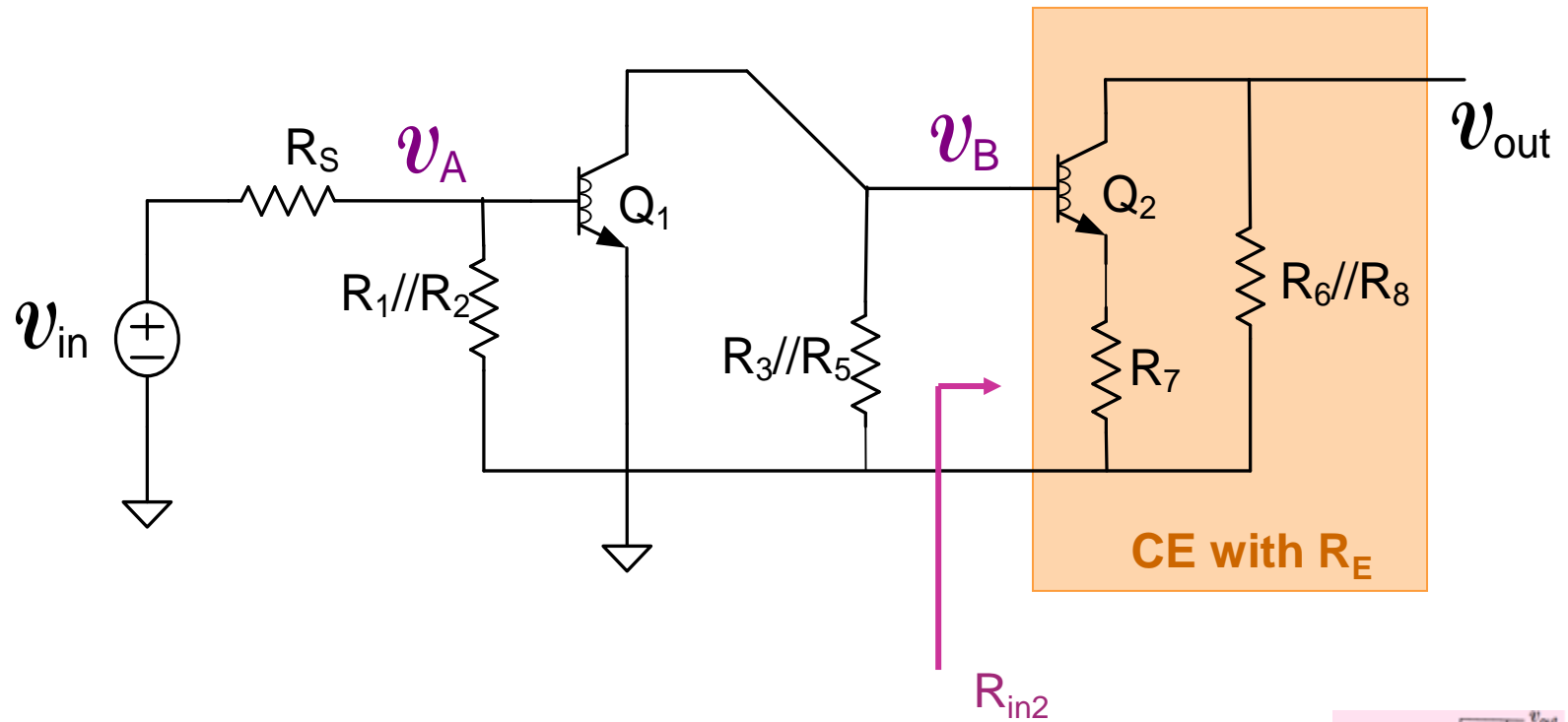
Example 1:



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

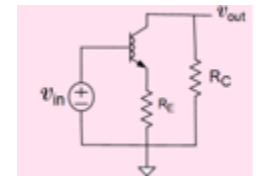
$$A_V = \frac{v_{out}}{v_{in}} = \frac{v_{out}}{v_B} \frac{v_B}{v_A} \frac{v_A}{v_{in}} = A_{V2} A_{V1} A_{V0}$$

Example 1:

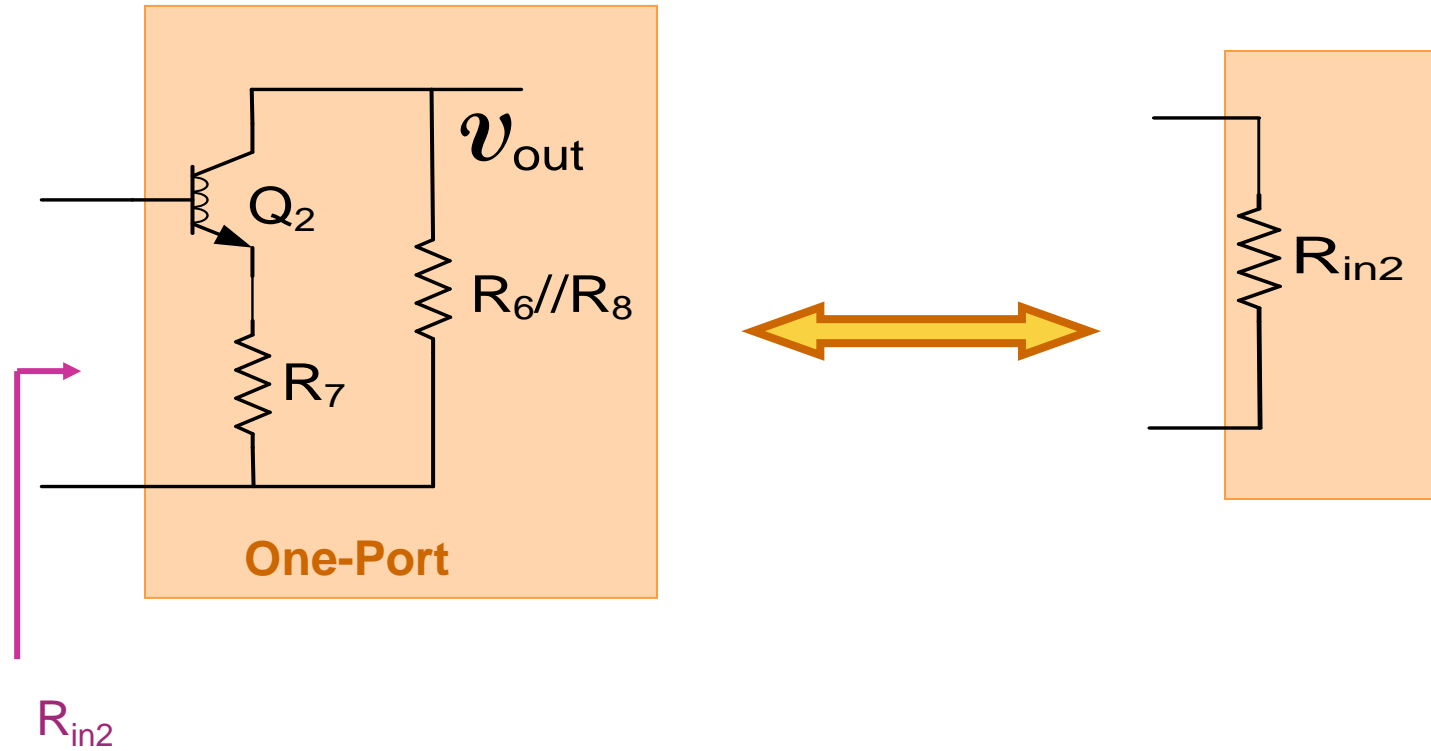


$$A_{V2} = \frac{v_{out}}{v_B} \cong -\frac{R_6 // R_8}{R_7}$$

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

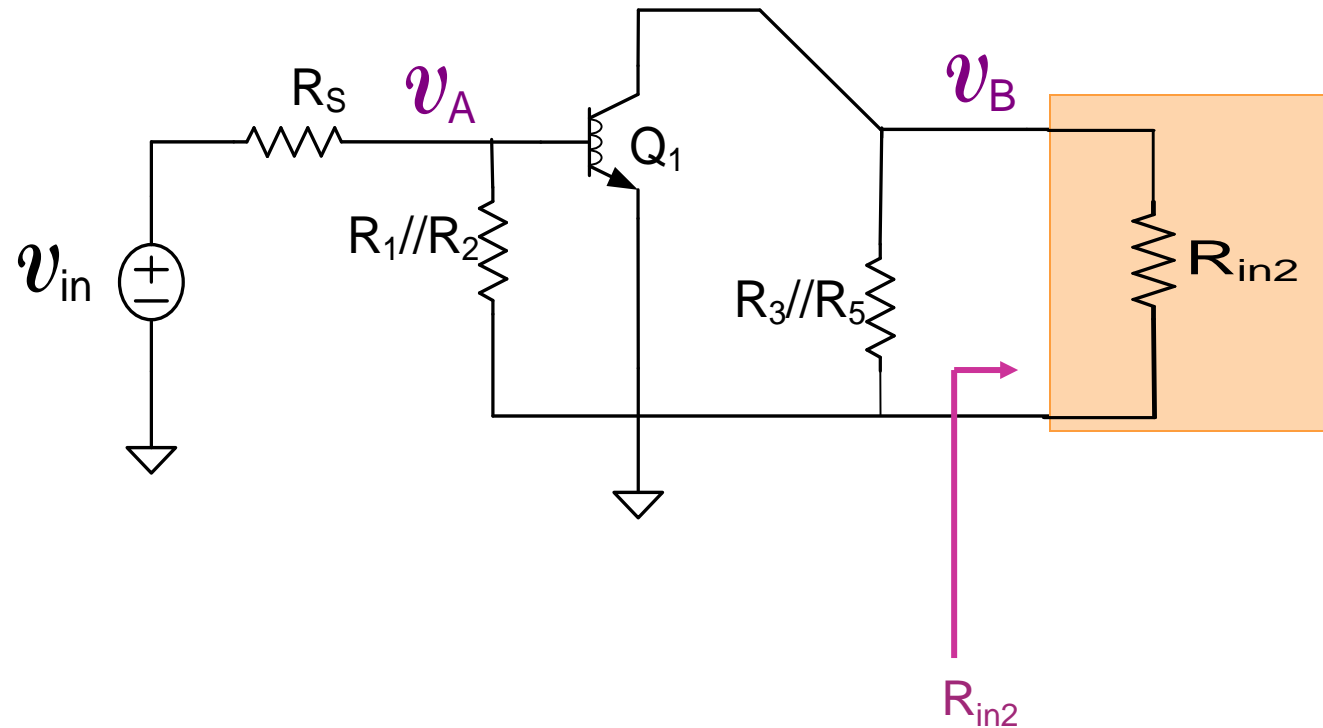


Example 1:



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

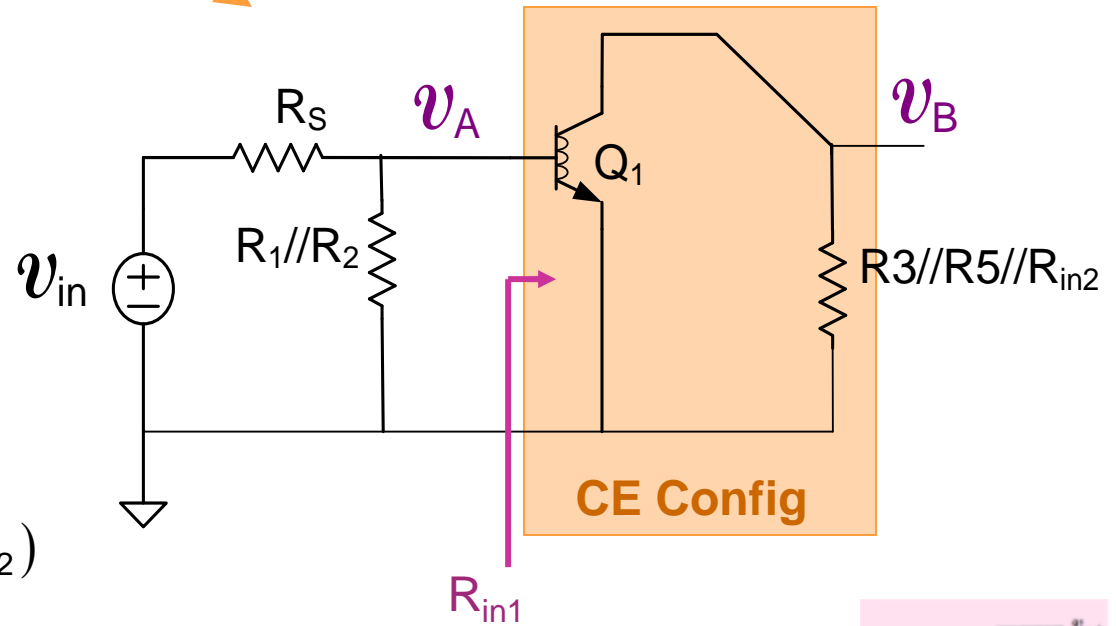
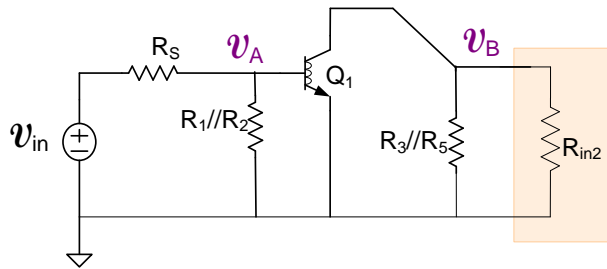
Example 1:



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

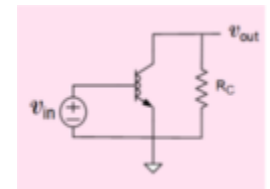
$$R_{in2} \cong \beta R_7$$

Example 1:

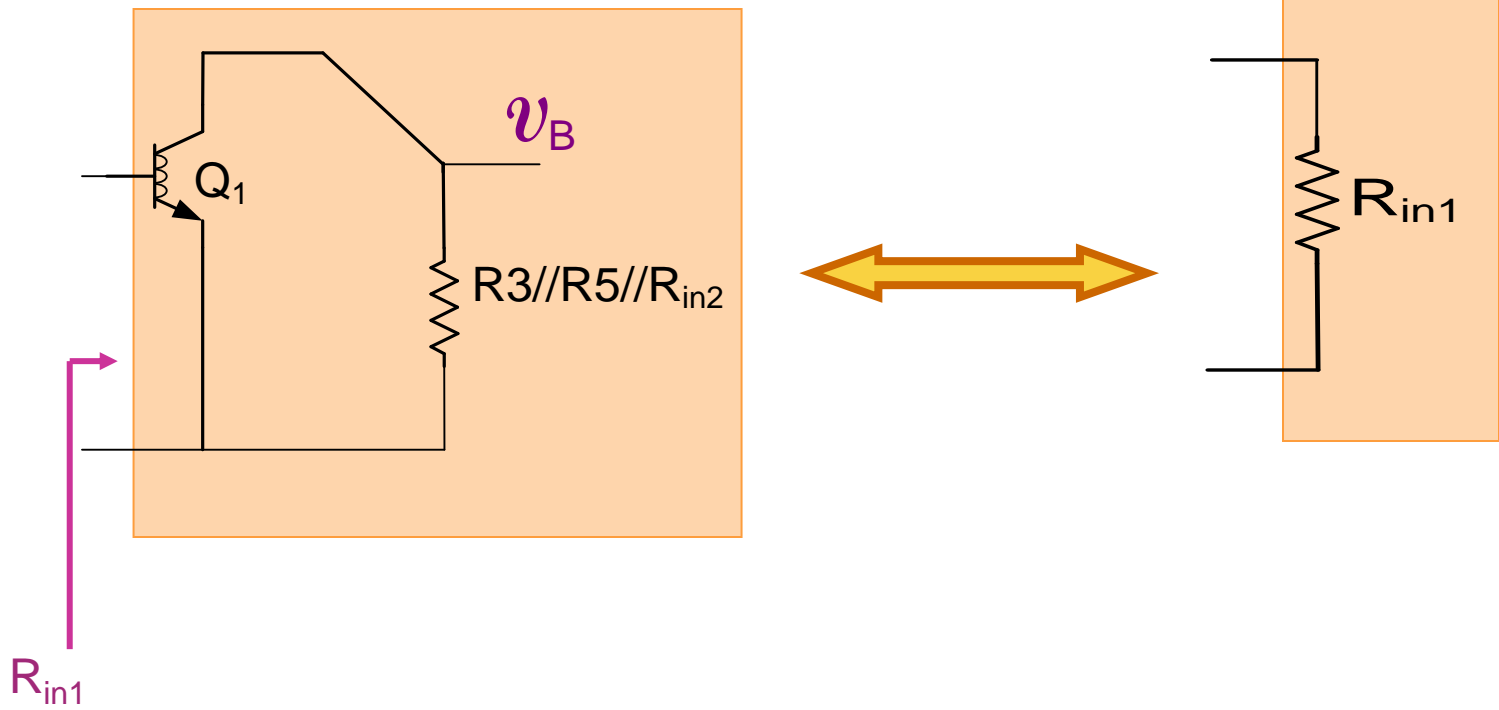


$$A_{V1} = \frac{v_B}{v_A} \cong -g_{m1} (R_3 // R_5 // R_{in2})$$

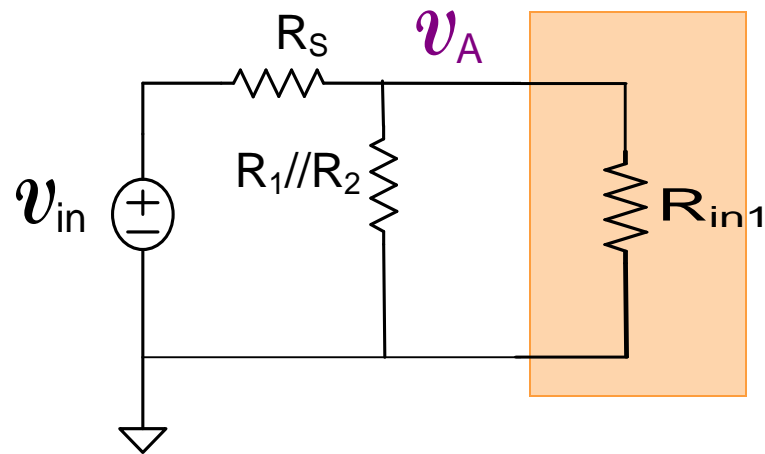
$$R_{in1} \cong r_{\pi 1}$$



Example 1:

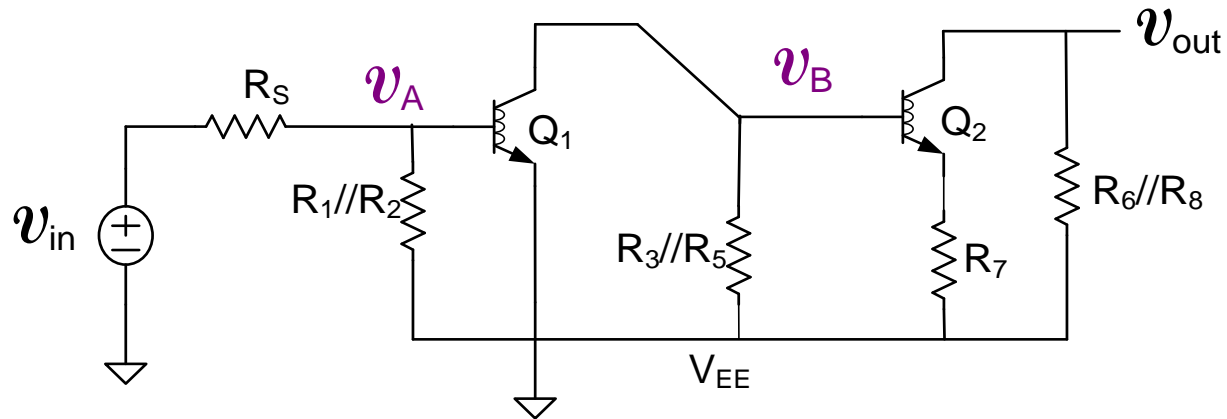


Example 1:



$$A_{v0} = \frac{v_A}{v_{in}} \cong \frac{R_1 // R_2 // R_{in1}}{R_s + R_1 // R_2 // R_{in1}}$$

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

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

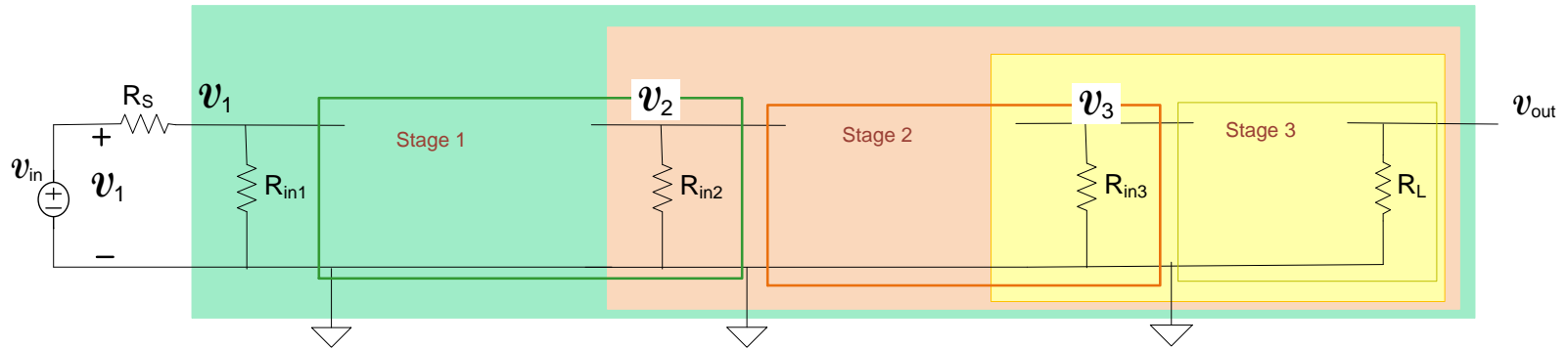
$$\frac{v_B}{v_A} \cong -g_{m1} (R_3 // R_5 // R_{in2})$$

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

$$\frac{v_A}{v_{in}} \cong \frac{R_1 // R_2 // R_{in1}}{R_s + R_1 // R_2 // R_{in1}}$$

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

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

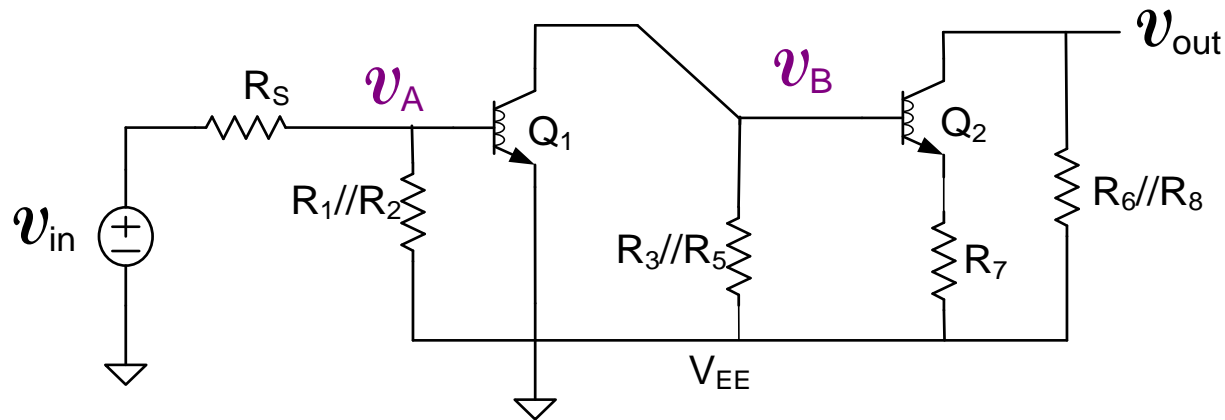


R_{in_k} includes effects of all loading
 Must recalculate if any change in loading
 Analysis systematic and rather simple

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

This was the approach used in analyzing the previous cascaded amplifier

Example 1:

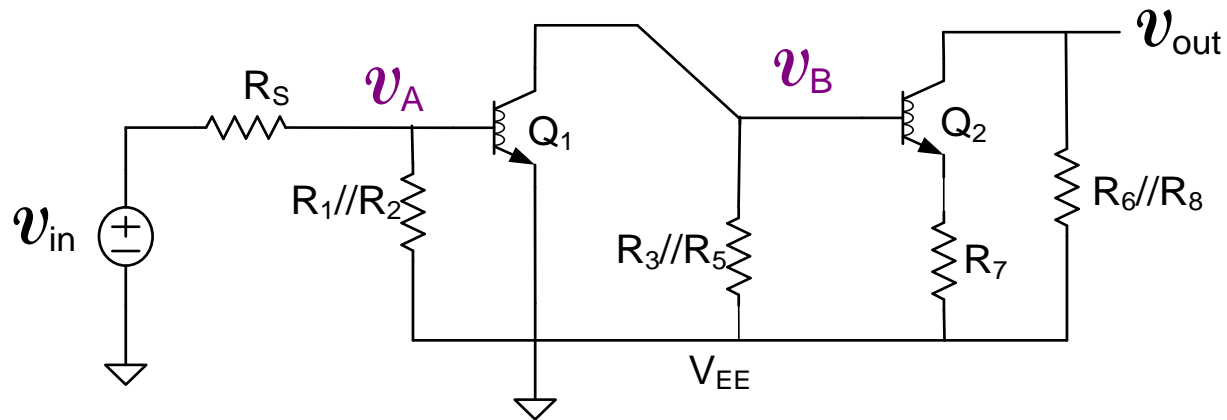


Observation: By working from the output back to the input we were able to create a sequence of steps where the circuit at each step looked EXACTLY like one of the four basic amplifiers. Engineers often follow a design approach that uses a cascade of the basic amplifiers and that is why it is often possible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

Two other methods could have been used to analyze this circuit

What are they?

Example 1:

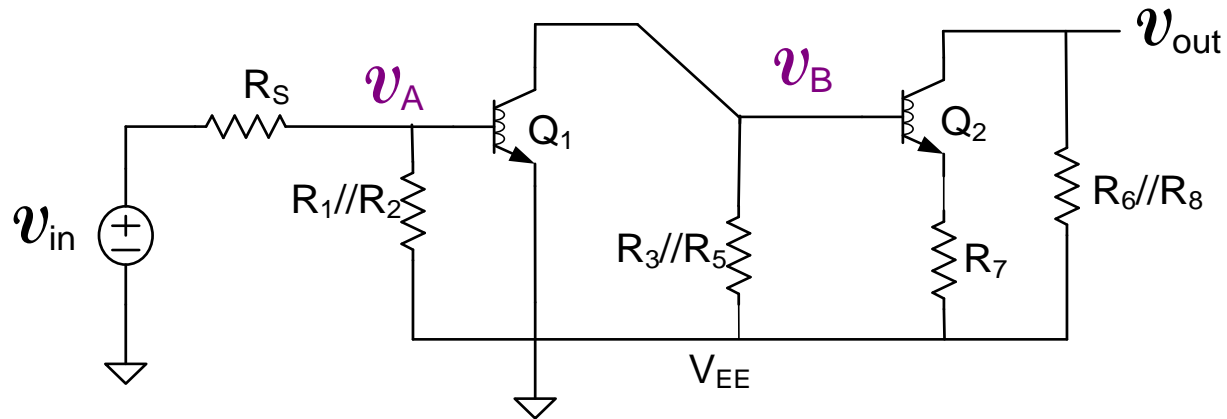


Two other methods could have been used to analyze this small-signal circuit

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:

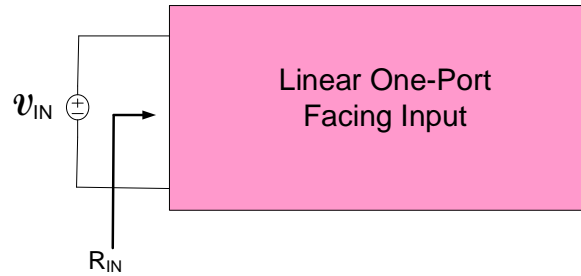


Two other methods could have been used to analyze this circuit

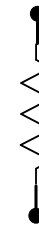
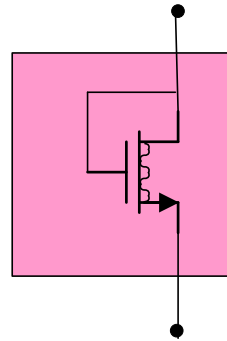
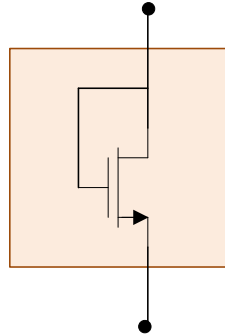
2. Put in small-signal model for Q_1 and Q_2 and solve resultant circuit

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

Review: Small-signal equivalent of a one-port

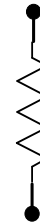
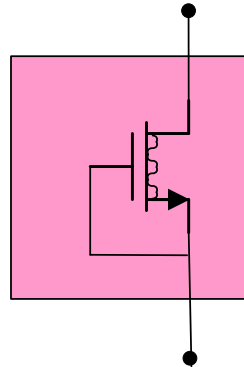
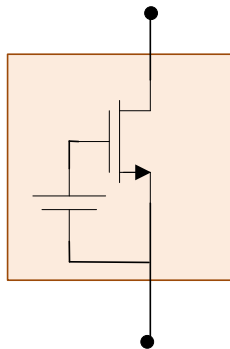


“Diode-connected transistor”



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

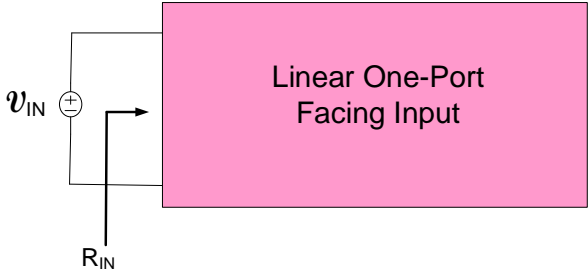
$$R = \frac{1}{g_m + g_0} \approx \frac{1}{g_m}$$



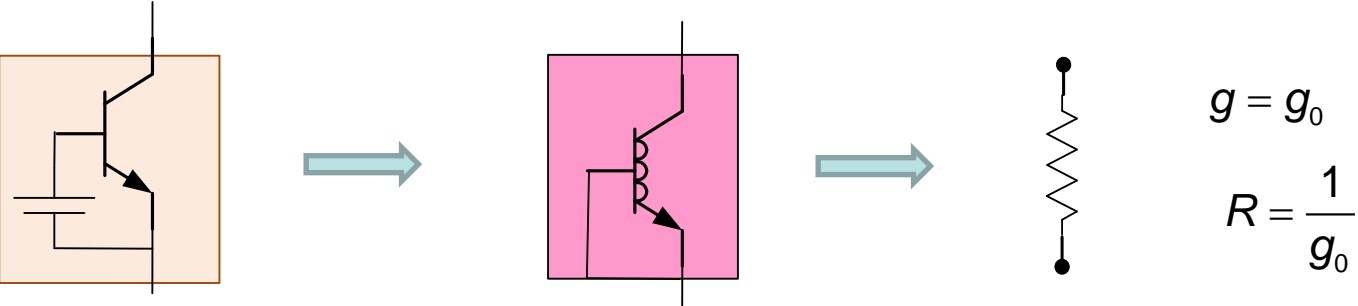
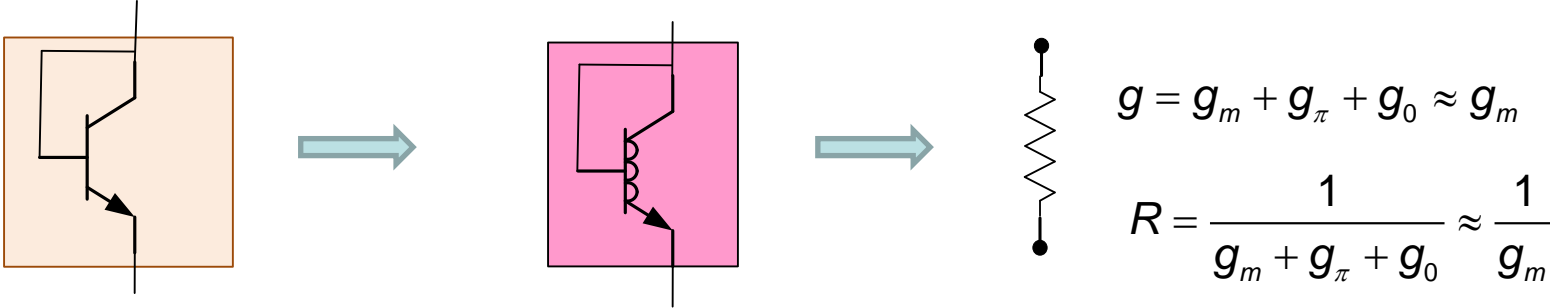
$$g = g_0$$

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

Review: Small-signal equivalent of a one-port

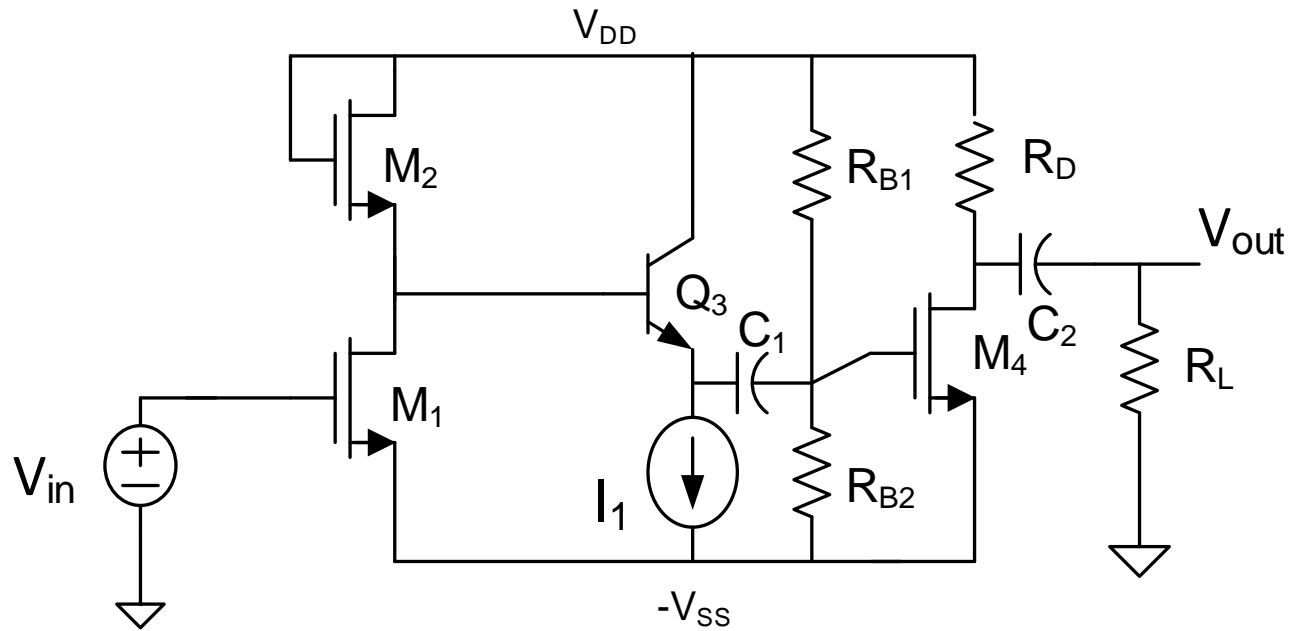


“Diode-connected transistor”



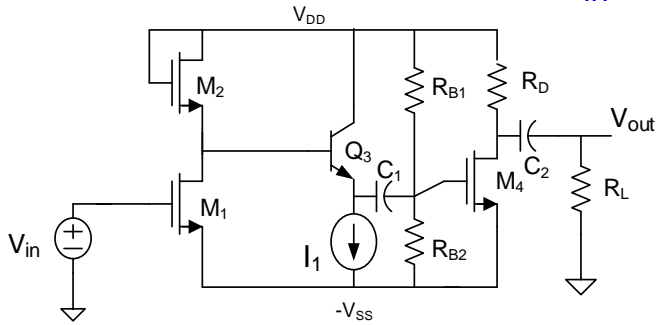
Example 2: $A_V = \frac{v_{out}}{v_{in}} = ?$

Express in terms of small-signal parameters

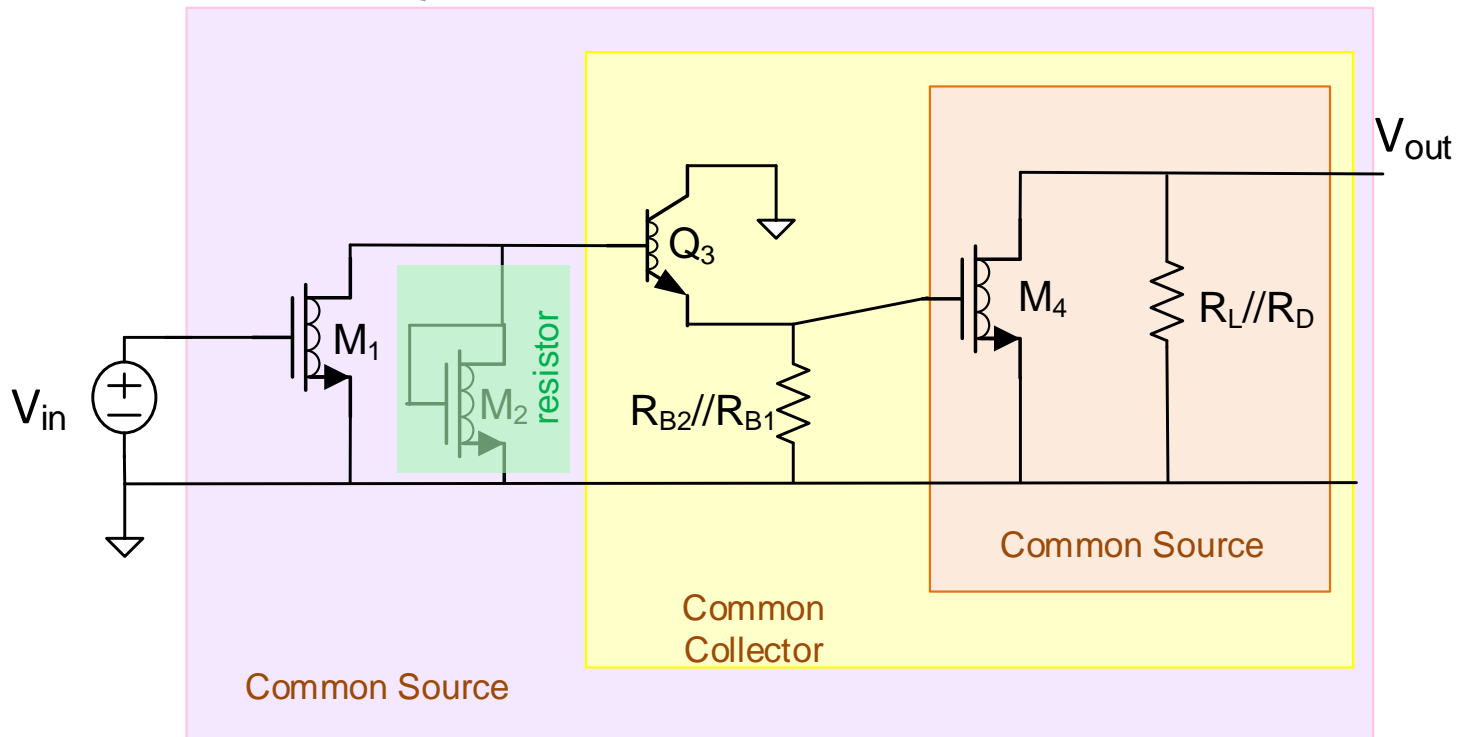


Example 2: $A_V = \frac{v_{out}}{v_{in}} = ?$

Express in terms of small-signal parameters

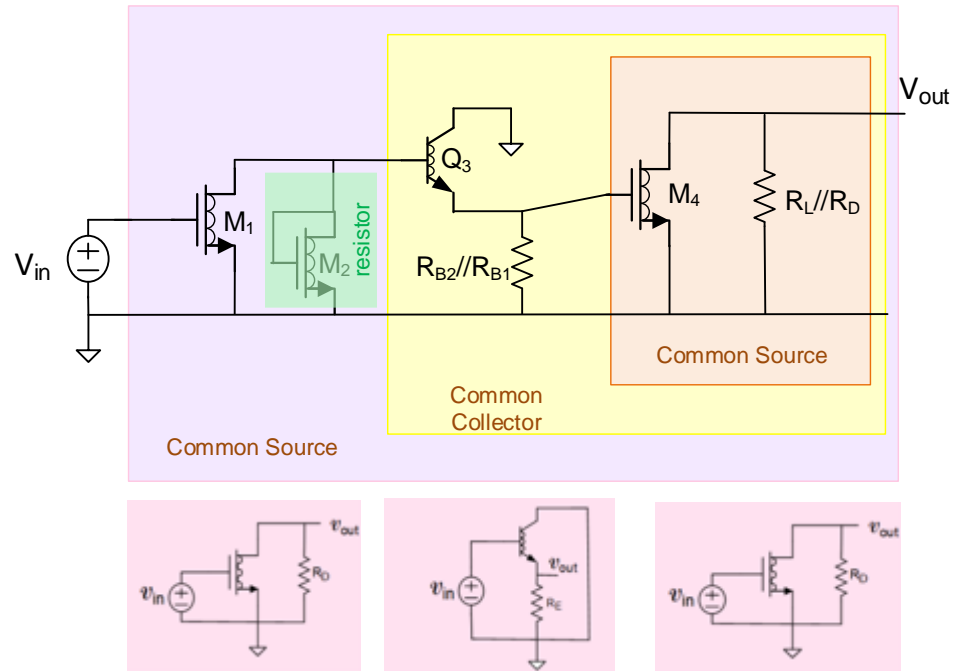


visualize

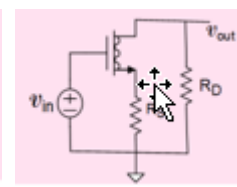
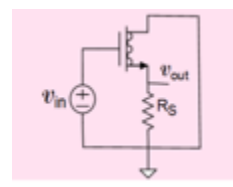
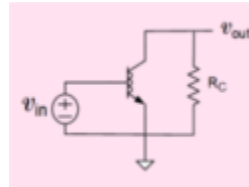
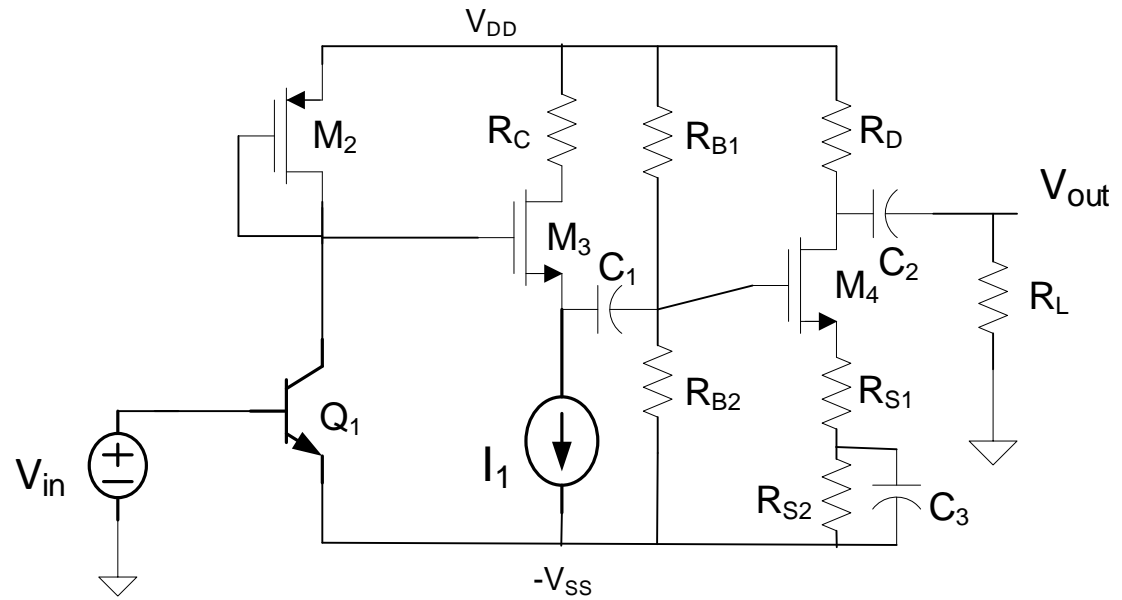


Example 2: $A_V = \frac{v_{out}}{v_{in}} = ?$

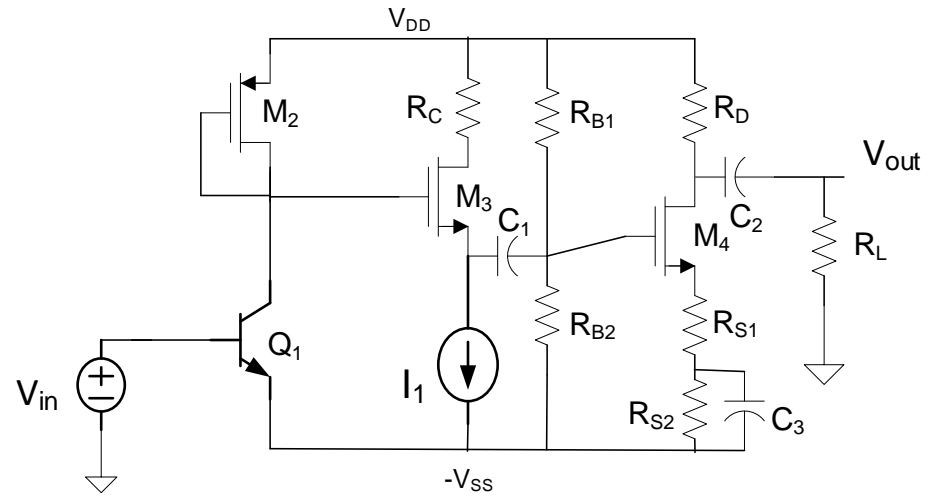
Express in terms of small-signal parameters



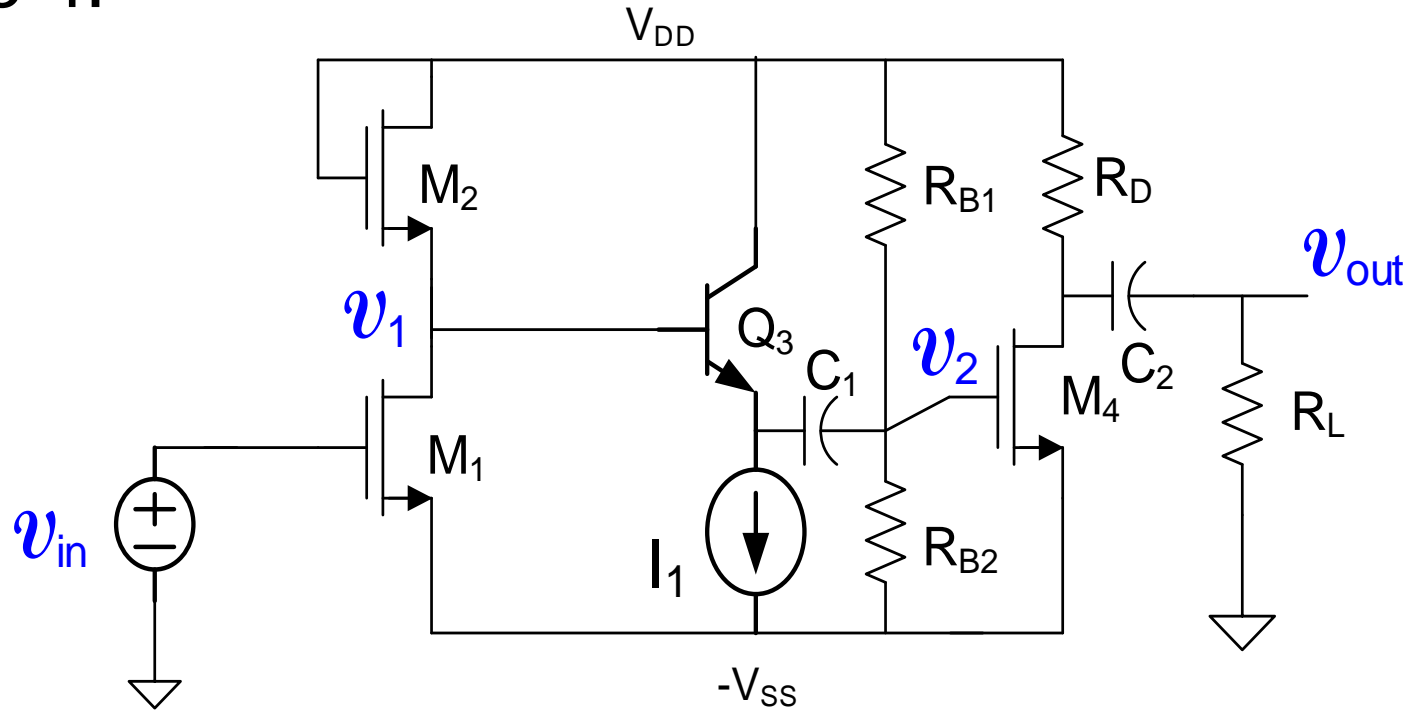
Example 3:



Example 3:

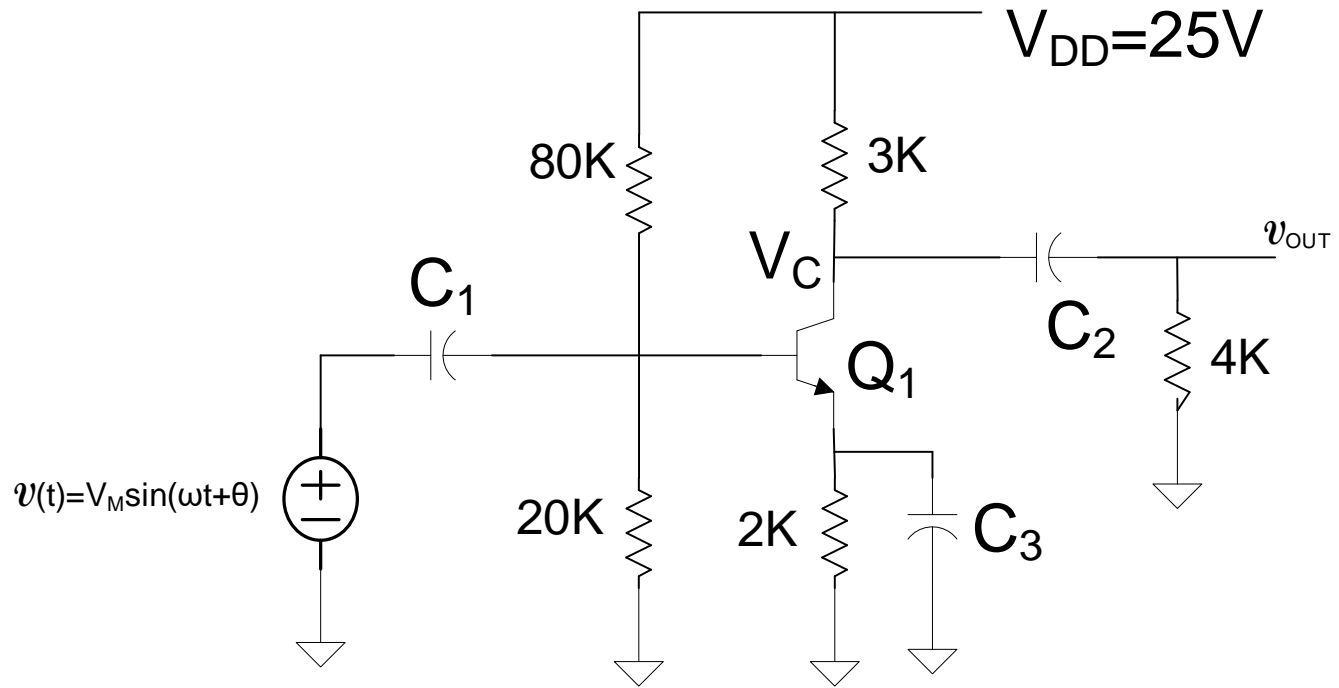


Example 4:



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

Example 5:





Stay Safe and Stay Healthy !

End of Lecture 32