

# EE 330

## Lecture 32

### Basic Amplifiers

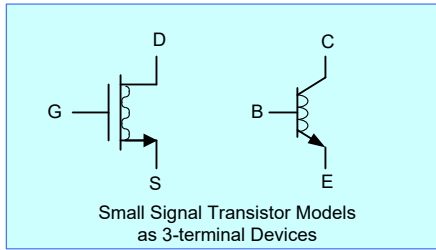
- Analysis, Operation, and Design

### Cascaded Amplifiers

# Fall 2023 Exam Schedule

Exam 1	Friday Sept 22	
Exam 2	Friday Oct 20	
Exam 3	Friday Nov. 17	
Final	Monday Dec 11	12:00 – 2:00 p.m.

# 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

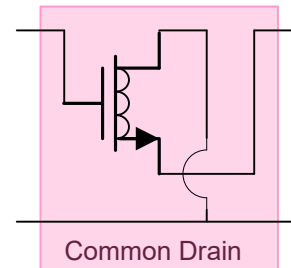
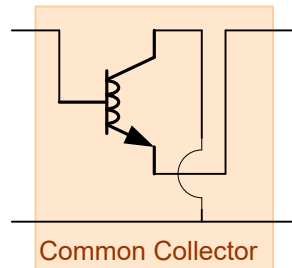
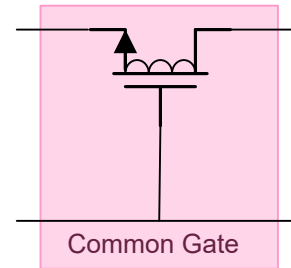
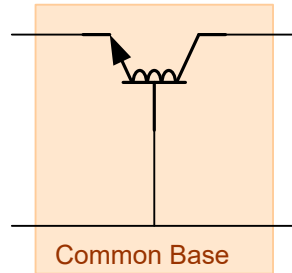
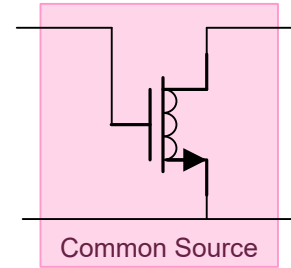
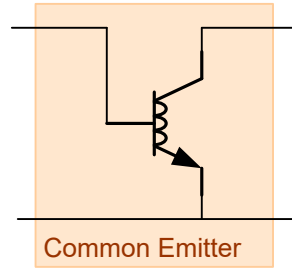
BJT		
Common	Input	Output
E	B	C
B	E	C
C	B	E

## 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

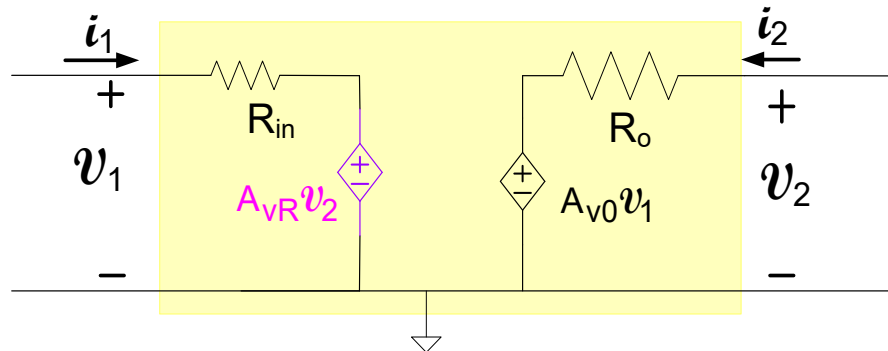
Review Previous Lecture



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.  $v_{\text{TEST}} : i_{\text{TEST}}$  Method (considered in last lecture)

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

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

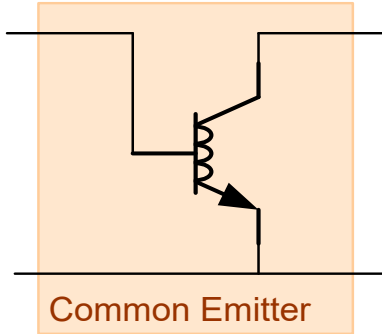
$$v_2 = i_2 R_{\text{O}} + A_{\text{V0}} v_1$$

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches

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

# Common Source/ Common Emitter Configurations



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

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

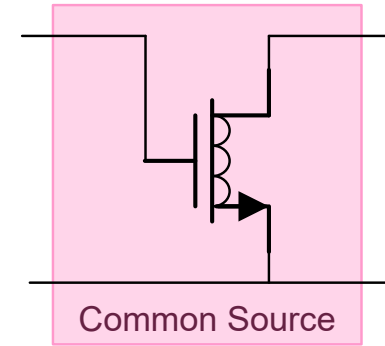
$$A_{VR} = 0$$

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



$$A_{VR} = 0$$

$$R_{in} = \infty$$



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

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

In terms of operating point and model parameters:

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

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

$$R_0 = \frac{V_{AF}}{I_{CQ}}$$



$$R_{in} = \infty$$

$$R_0 = \frac{1}{\lambda I_{DQ}} = \frac{V_{AF}}{I_{DQ}}$$

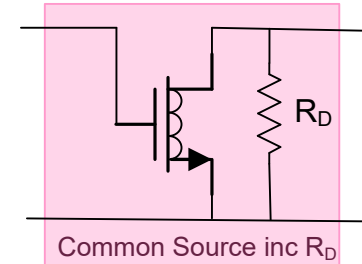
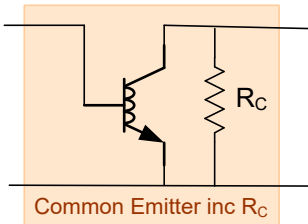
$$A_{V0} = -\frac{2}{\lambda V_{EBQ}} = -2 \frac{V_{AF}}{V_{EBQ}}$$

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)



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

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

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

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

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

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

$$R_{in} = \infty$$

In terms of operating point and model parameters:

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

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

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

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

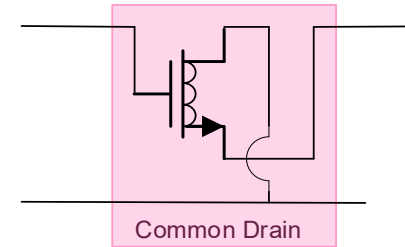
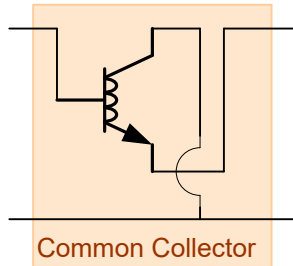
$$R_{in} = \infty$$

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

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:

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

$$A_{V0} = 1$$

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

$$R_{in} = \infty$$

$$A_{V0} = 1$$

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

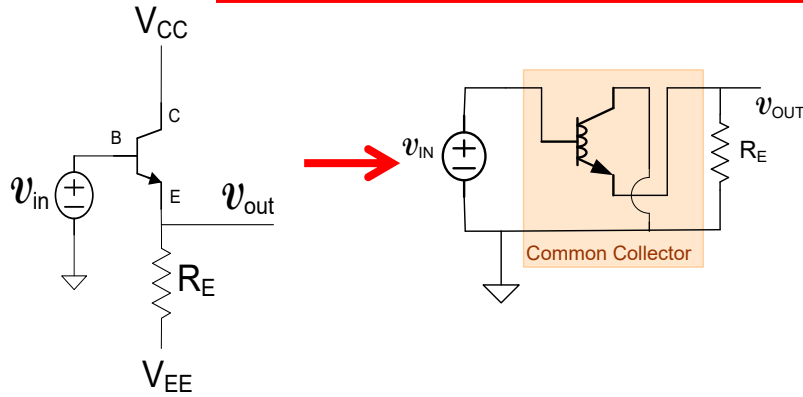
Characteristics:

- 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)



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

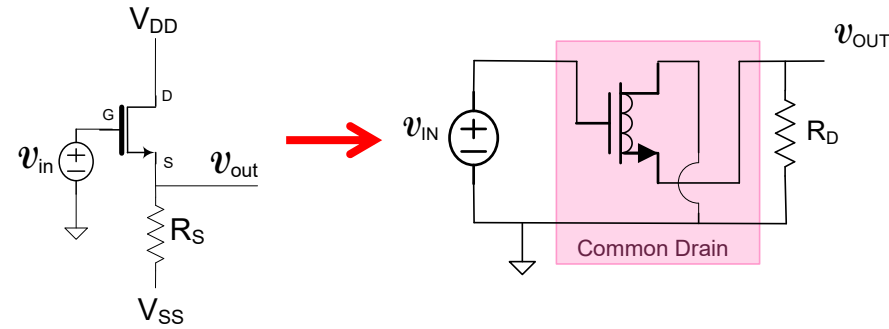
$$R_{in} \stackrel{g_E \gg g_0}{\cong} r_\pi + \beta R_E$$

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

In terms of operating point and model parameters:

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

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



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

$$R_{in} = \infty$$

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

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

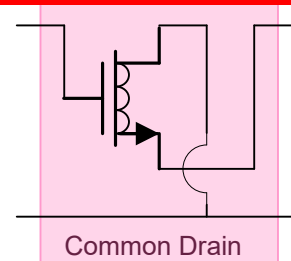
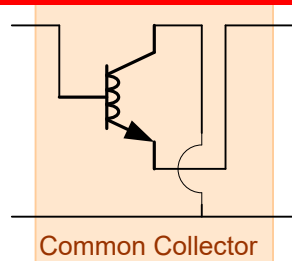
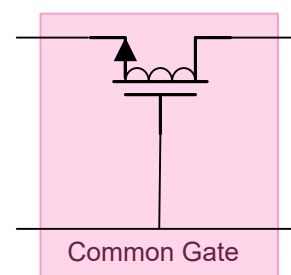
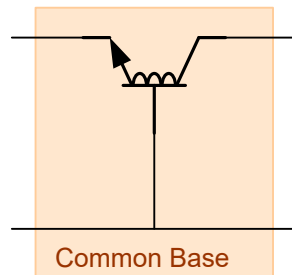
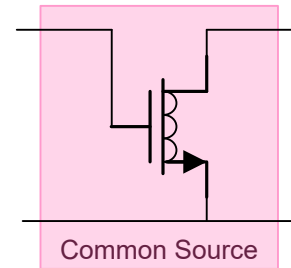
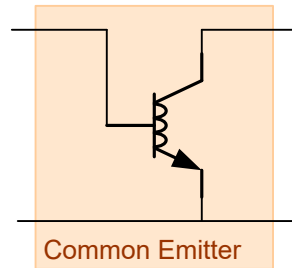
$$R_0 \cong \frac{V_{EBQ} R_S}{V_{EBQ} + 2I_{DQ} R_S} \stackrel{2I_{DQ} R_S \gg V_{EBQ}}{\cong} \frac{V_{EBQ}}{2I_{DQ}}$$

$$R_{in} = \infty$$

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

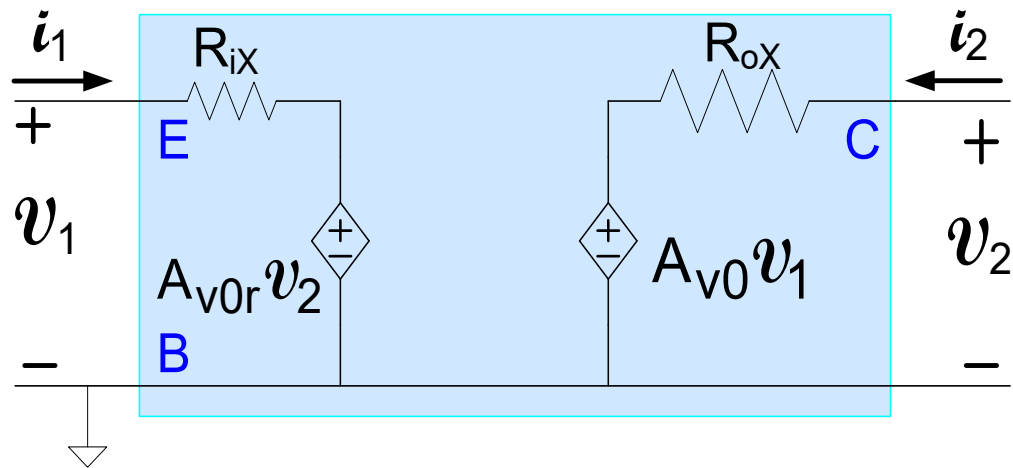
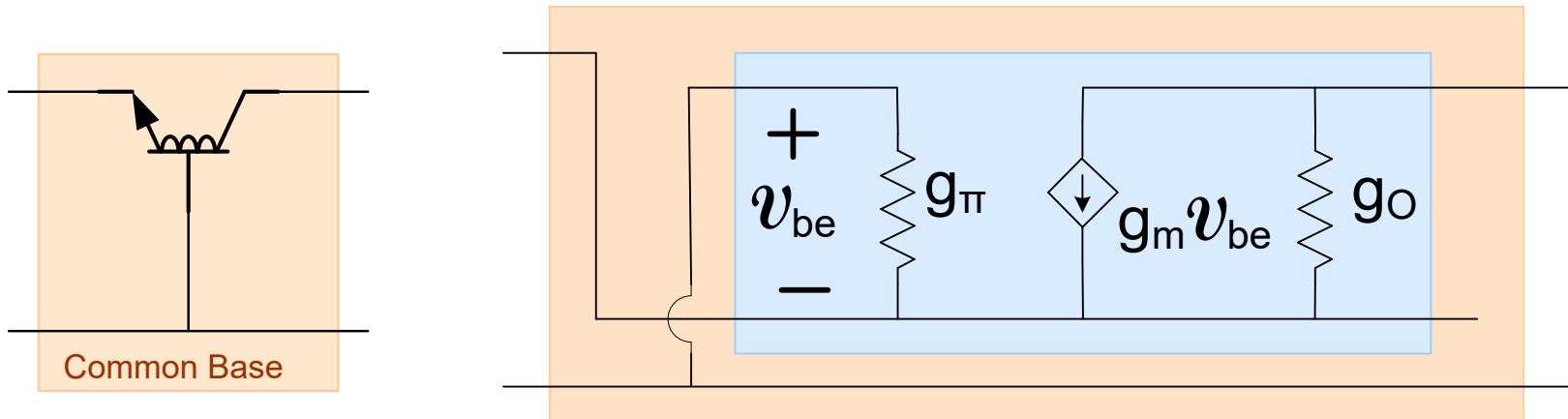
- Widely used as a buffer
- Not completely unilateral but output-input transconductance is small

# 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

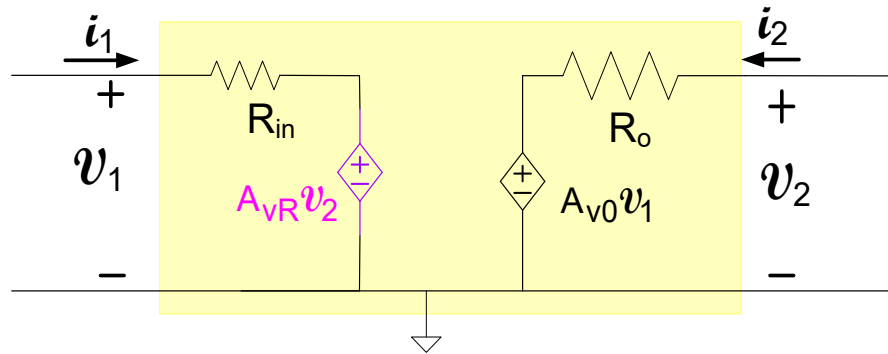
# Two-port model for Common Base Configuration



$\{R_{ix}, A_{v0}, A_{v0r} \text{ and } R_{ox}\}$

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

## Methods of Obtaining Amplifier Two-Port Network



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



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

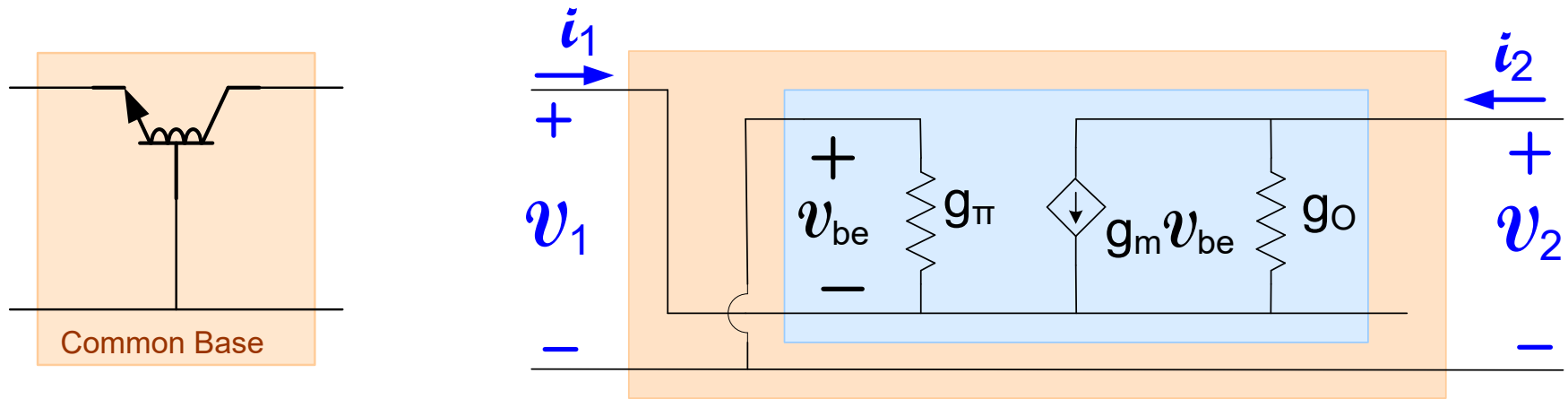
$$v_1 = i_1 R_{IN} + A_{VR} v_2$$

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

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches

# Two-port model for Common Base Configuration



From KCL

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

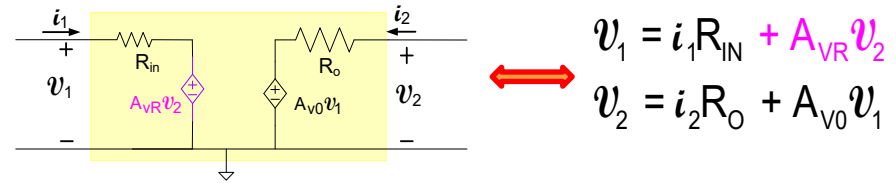
These can be rewritten as

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

It thus follows that:

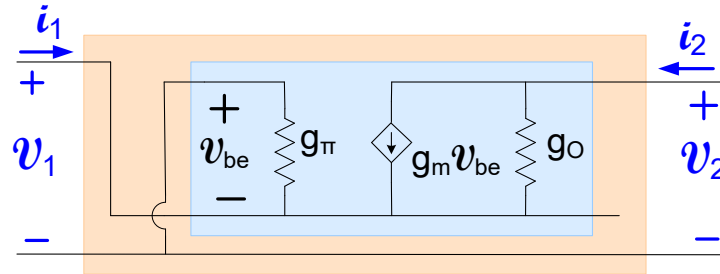
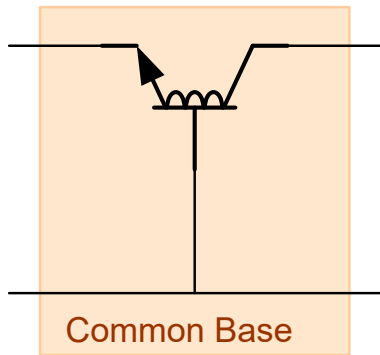
$$R_{iX} = \frac{1}{g_m + g_\pi + g_o} \cong \frac{1}{g_m} \quad A_{VOr} = \frac{g_o}{g_m + g_\pi + g_o} \quad A_{V0} = 1 + \frac{g_m}{g_o} \cong \frac{g_m}{g_o} \quad R_{oX} = \frac{1}{g_o}$$

Standard Form for Amplifier Two-Port

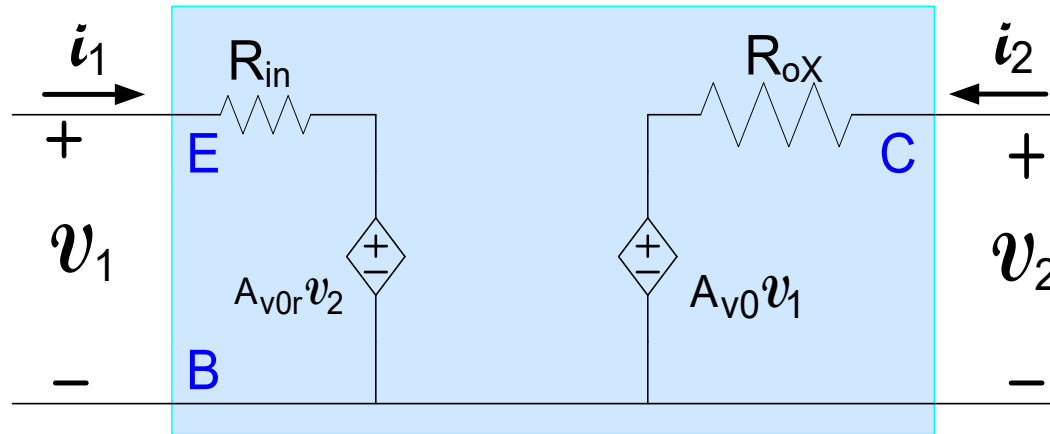


$v_1 : v_2$  equations in standard form

# Two-port model for Common Base Configuration



Two-port Common Base Model



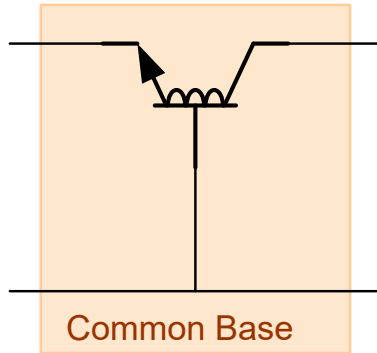
$$R_{iX} = \frac{1}{g_m + g_\pi + g_o} \cong \frac{1}{g_m}$$

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

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

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

# Two-port model for Common Base Configuration



Common Base

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

$$A_{V0} = \frac{g_m}{g_0}$$

$$R_0 = \frac{1}{g_0}$$

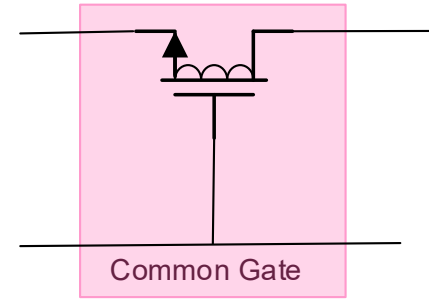
$$A_{VR} \cong \frac{g_0}{g_m}$$

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

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

$$A_{V0} = \frac{g_m}{g_0}$$

$$R_0 = \frac{1}{g_0}$$



Common Gate

In terms of operating point and model parameters:

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

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

$$R_0 = \frac{V_{AF}}{I_{CQ}}$$

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

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

$$R_0 = \frac{1}{\lambda I_{DQ}}$$

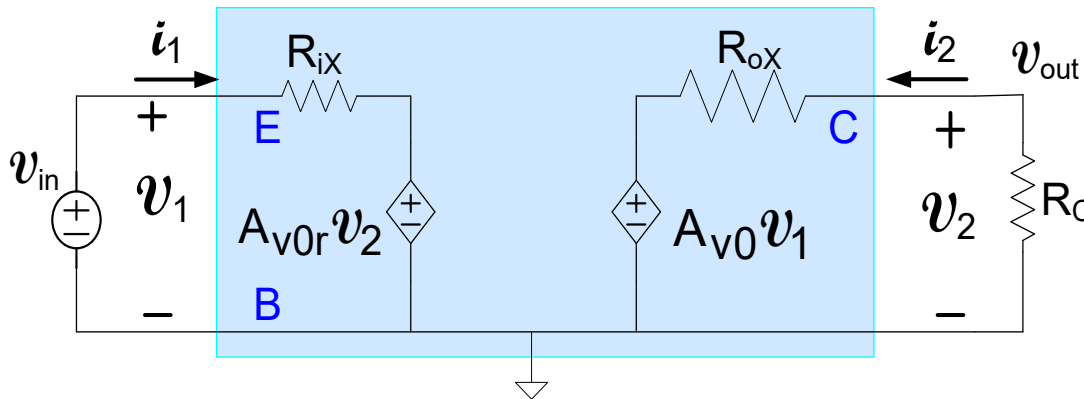
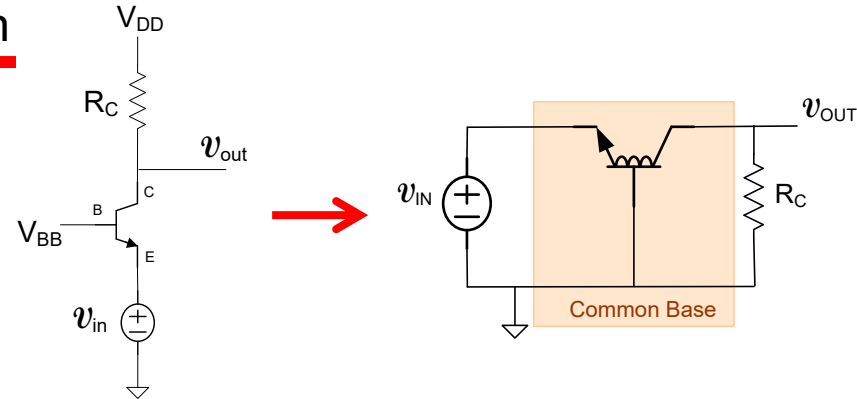
Characteristics:

- 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 )



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

$$R_{in} = \frac{v_{in}}{i_1} = \frac{i_1 R_{iX} + A_{V0} v_{out}}{i_1} \longrightarrow R_{in} = \frac{R_{iX}}{1 - A_{V0} A_V} = \frac{R_{iX}}{g_C (g_m + g_\pi + g_0) + g_\pi g_0} \cong \frac{1}{g_m}$$

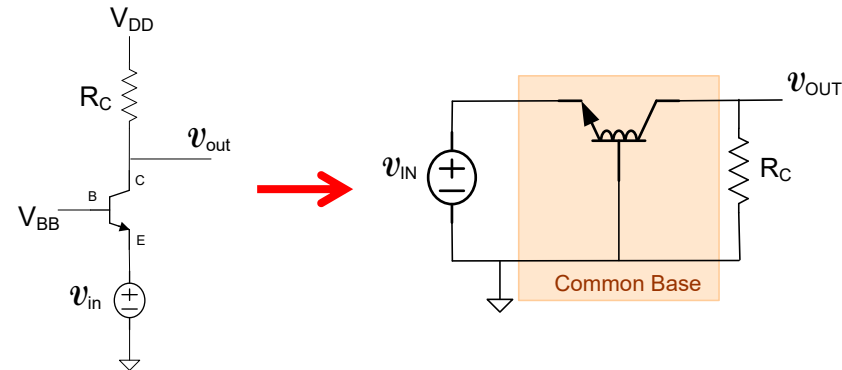
$$R_{out} = R_C // R_{0X} \longrightarrow R_{out} = \frac{R_C}{1 + g_0 R_C}$$



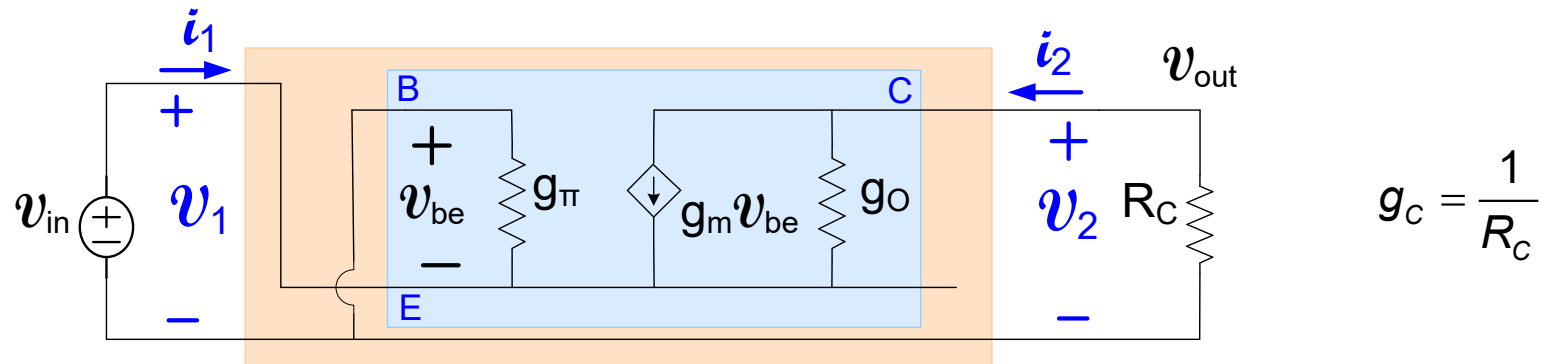
# Common Base Configuration

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



By KCL at the output node, obtain

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

By KCL at the emitter node, obtain

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

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

# Popular Common Base Application

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

$$A_V \cong g_m R_C$$

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

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

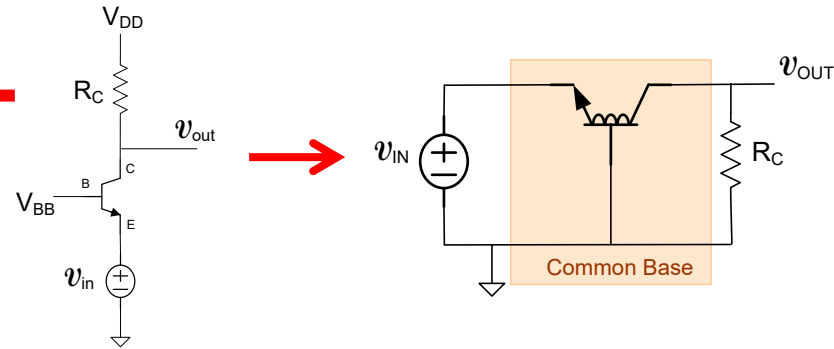
$$R_{in} \cong \frac{V_t}{I_{CQ}}$$

$$R_{out} \stackrel{R_C \ll r_o}{\cong} R_C$$

$$R_{out} \stackrel{R_C \ll r_o}{\cong} R_C$$

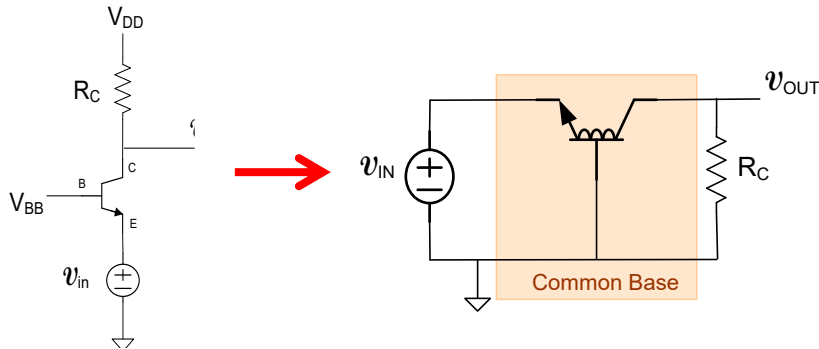
## Characteristics:

- 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

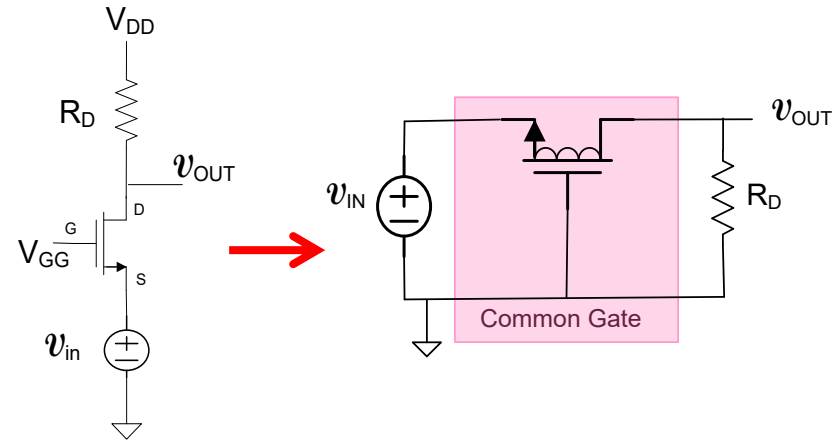


# Common Base/Common Gate Application

(these are not a two-port models)



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



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

In terms of operating point and model parameters:

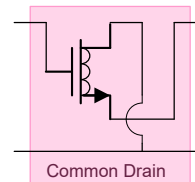
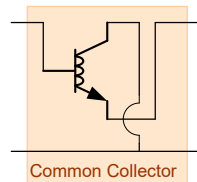
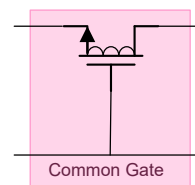
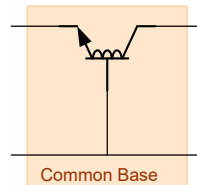
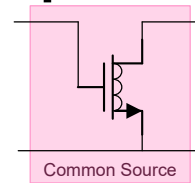
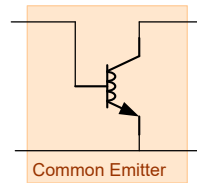
$$A_V \cong \frac{I_{CQ} R_C}{V_t} \quad R_{in} \cong \frac{V_t}{I_{CQ}} \quad R_{out} \cong R_C \quad I_{CQ} R_C \ll V_{AF}$$

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

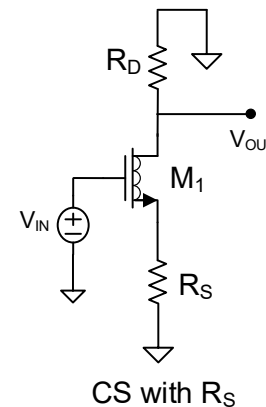
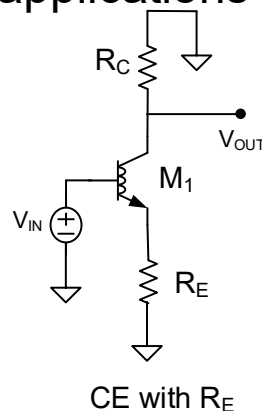
Characteristics:

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- $A_{V0}$  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

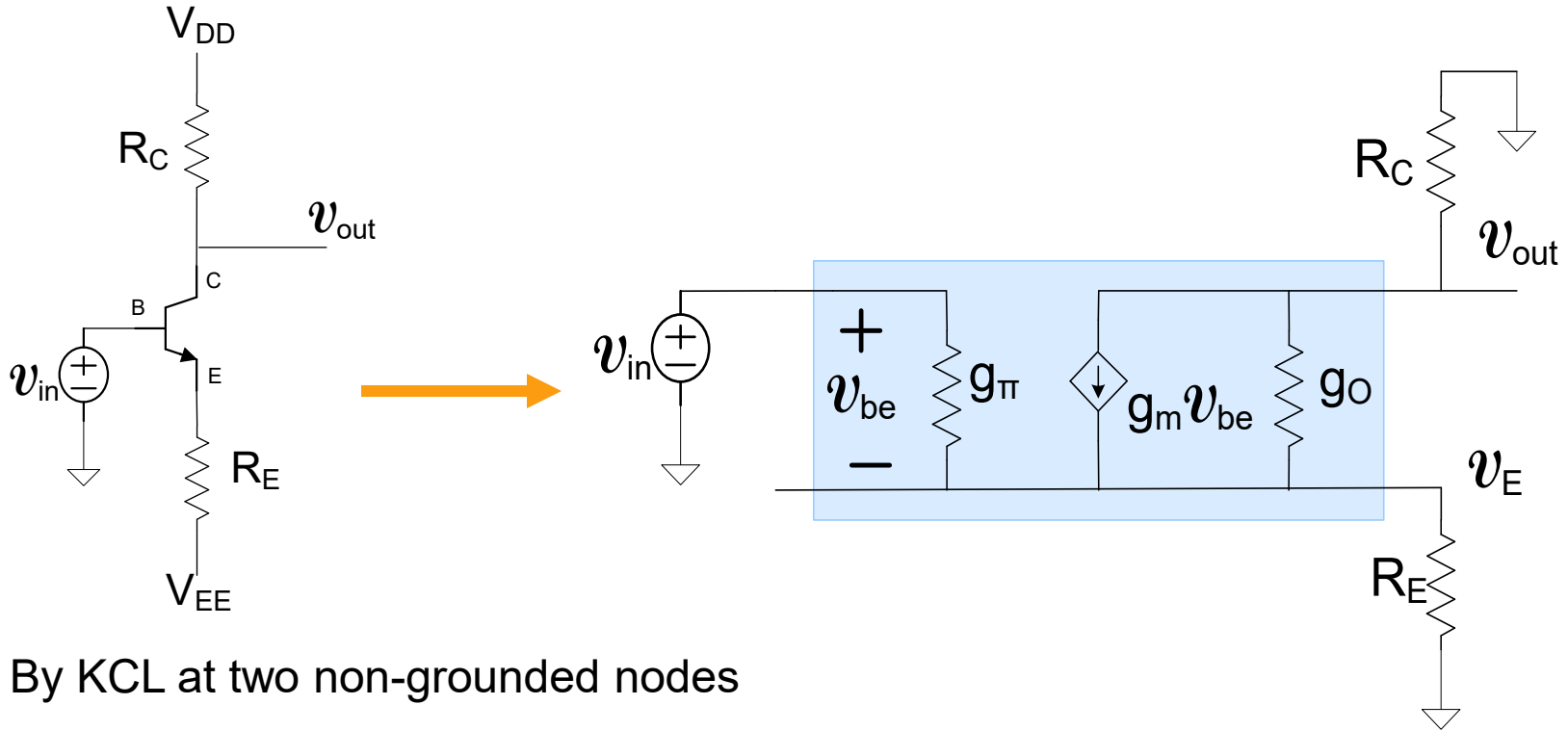


- Have developed both two-ports and a widely used application of all 6
- A fourth structure (two additional applications) is also quite common so will be added to list of basic applications



# 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

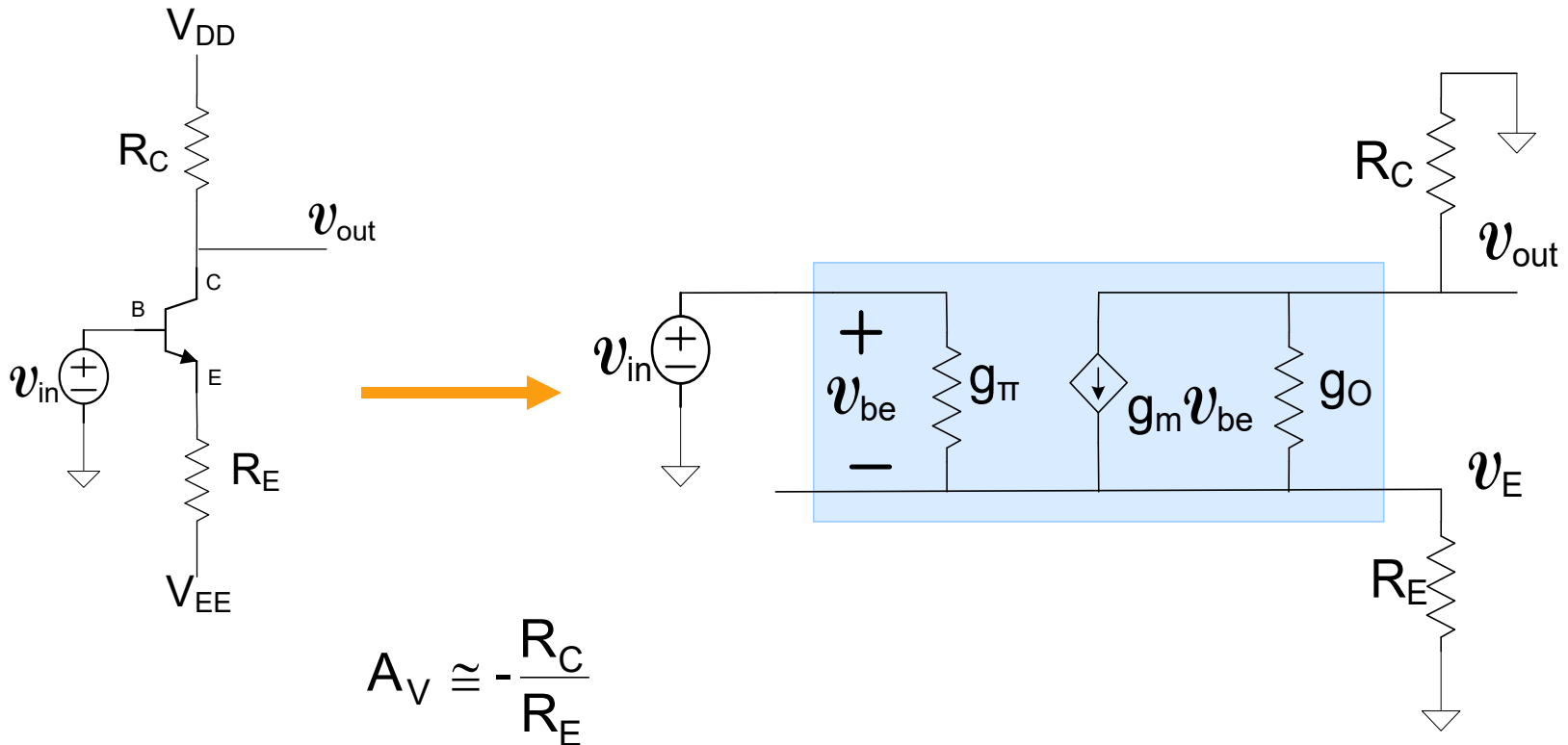
$$v_{out} (g_C + g_0) + (v_{in} - v_E) g_m = g_0 v_E$$

$$v_E (g_E + g_0 + g_{\pi}) - (v_{in} - v_E) g_m = g_0 v_{out} + g_{\pi} v_{in}$$

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

# 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

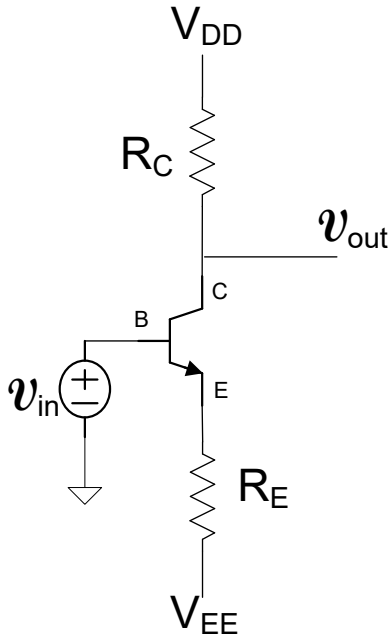
$$R_{in} \cong r_{\pi} + \beta R_E \cong \beta R_E$$

$$R_{out} \cong R_C$$

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:

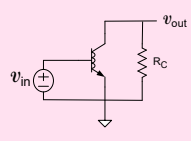
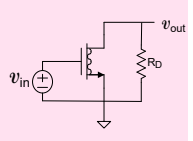
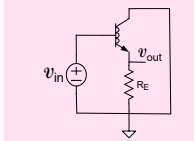
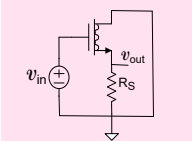
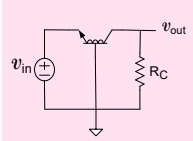
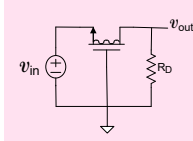
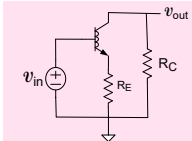
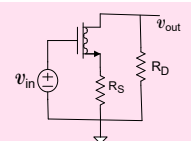
- Analysis would simplify if  $g_0$  were set to 0 in model
- Gain can be accurately controlled with resistor ratios
- Useful for reasonably accurate low gains
- Input impedance is high

# Basic Two-Port Amplifier Gain Table

	CE/CS		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	$\frac{V_{AF}}{V_t}$	$\frac{2}{\lambda V_{EB}}$
$R_{in}$	$\frac{r_{\pi}}{\beta} = \frac{V_t}{I_{CQ}}$	$\infty$	$r_{\pi} = \beta \left( \frac{V_t}{I_{CQ}} \right)$	$\infty$	$\frac{1}{g_m + g_{\pi} + g_o} = g_m^{-1} = \frac{V_t}{I_{CQ}}$	$\frac{1}{g_m + g_o} = g_m^{-1} = \frac{V_{EB}}{2I_{DQ}}$
$R_{out}$	$\frac{1}{g_o}$	$\frac{1}{g_o}$	$\frac{1}{g_m + g_{\pi} + g_o} = g_m^{-1} = \frac{V_t}{I_{CQ}}$	$\frac{1}{g_m + g_o} = g_m^{-1} = \frac{V_{EB}}{2I_{DQ}}$	$\frac{1}{g_o}$	$\frac{1}{\lambda I_{DQ}}$
$A_{VR}$	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
$A_V$	 $-g_m R_C$ $\frac{I_{CQ} R_C}{V_t}$	 $-\frac{2I_{DQ} R_D}{V_{EB}}$	 $\frac{g_m}{g_m + g_E}$ $\frac{I_{CQ} R_E}{I_{CQ} R_E + V_t}$	 $\frac{2I_{DQ} R_E}{2I_{DQ} R_E + V_{EB}}$	 $g_m R_C$ $\frac{I_{CQ} R_C}{V_t}$	 $\frac{2I_{DQ} R_C}{V_{EB}}$	 $-\frac{R_C}{R_E}$	 $\infty$
$R_{in}$	$r_{\pi}$ $\frac{\beta V_t}{I_{CQ}}$	$\infty$	$r_{\pi} + \beta R_E$ $r_{\pi} + \beta R_E$	$\infty$	$g_m^{-1}$ $\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$	$r_{\pi} + \beta R_E$ $\beta \left( \frac{V_t}{I_{CQ}} + R_E \right)$	$\infty$
$R_{out}$	$R_C$	$R_C$	$g_m^{-1}$ $\frac{V_t}{I_{CQ}}$	$\frac{V_{EB}}{2I_{DQ}}$	$R_C$	$R_C$	$R_C$	$R_C$

(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?

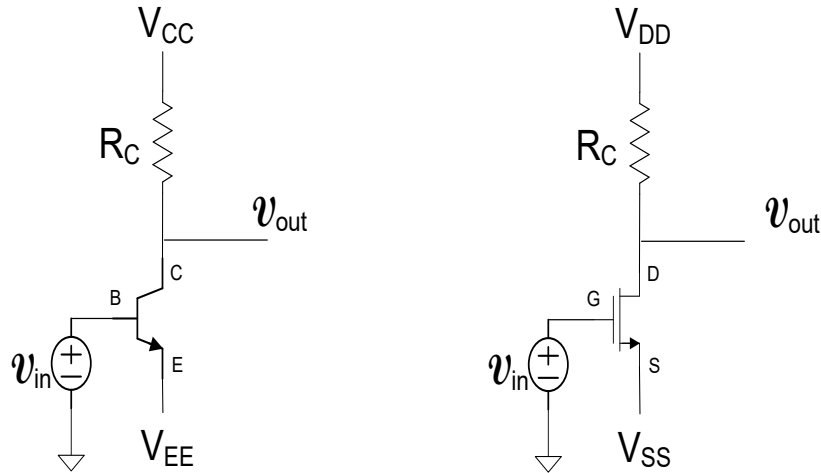
1. So that we can develop analytical skills
2. So that we can design a circuit
3. So that we can get the insight needed to design a circuit

## 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

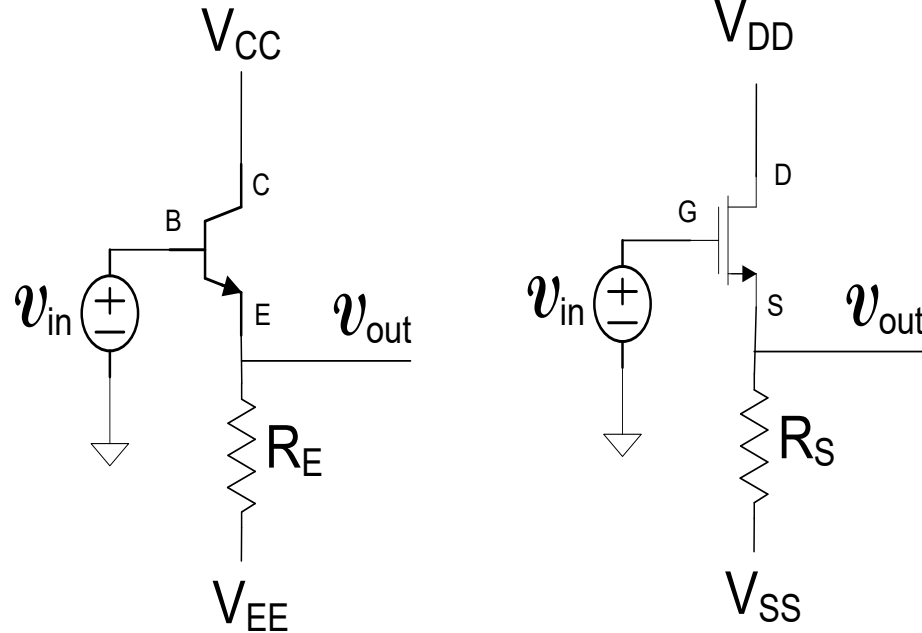
$R_C$  or  $R_D$  may (or may not) be load

- 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)



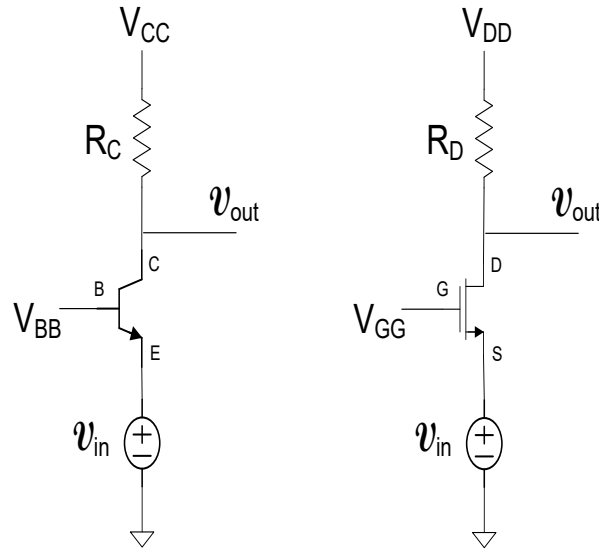
More practical biasing circuits usually used

$R_E$  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



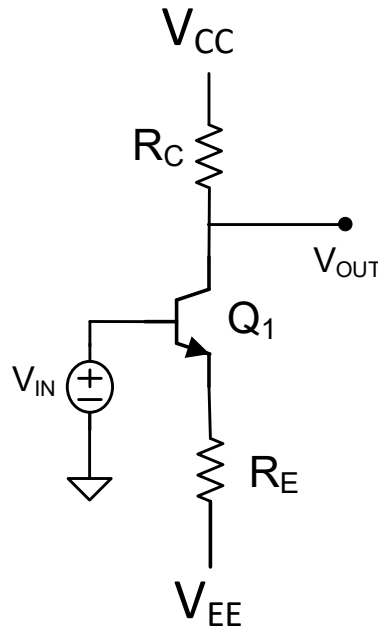
More practical biasing circuits usually used

$R_C$  or  $R_D$  may (or may not) be load

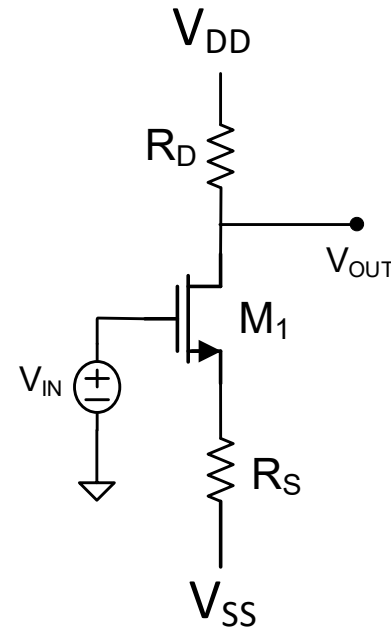
- Large noninverting gain
- Low input impedance
- Moderate (or high) output impedance
- Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode

# Properties/Use of Basic Amplifiers

## CEwRE and CSwRS



CE with  $R_E$



CS with  $R_S$

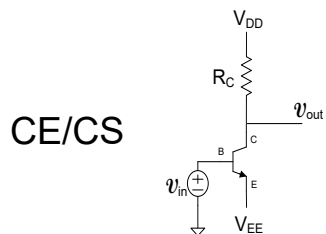
More practical biasing circuits usually used

$R_C$  or  $R_D$  may (or may not) be load

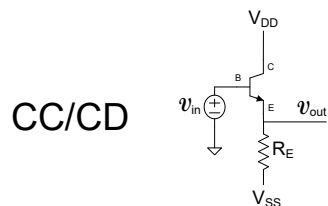
- **Gain can be accurately controlled with resistor ratios**
- **Useful for reasonably accurate low gains**
- **Input impedance is high**



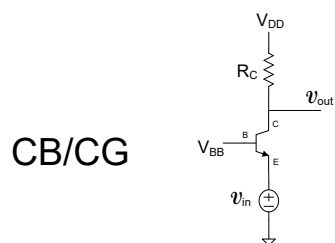
# Basic Amplifier Characteristics Summary



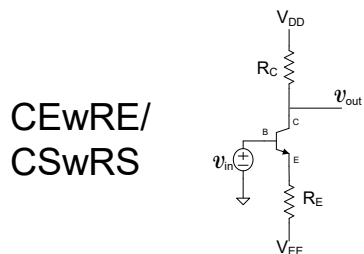
- Large inverting gain
  - Moderate input impedance
  - Moderate (or high) output impedance
  - Widely used as the basic high gain inverting amplifier
- 



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

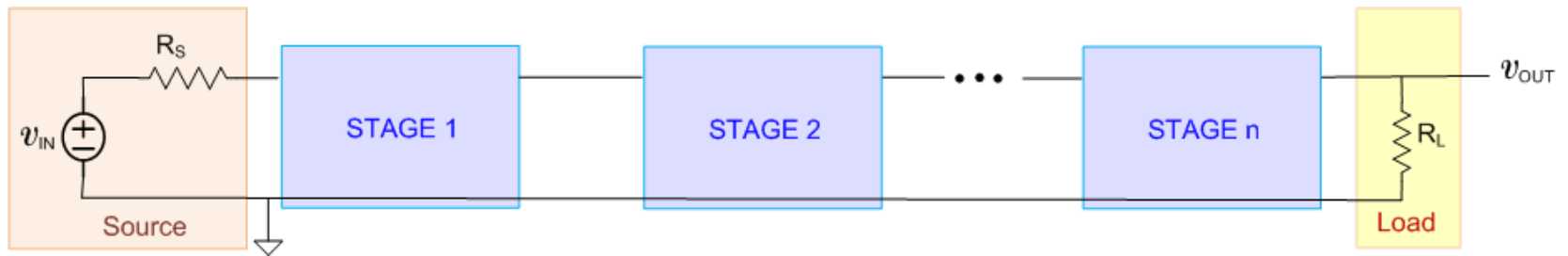


- Large noninverting gain
  - Low input impedance
  - Moderate (or high) output impedance
  - Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode
- 



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

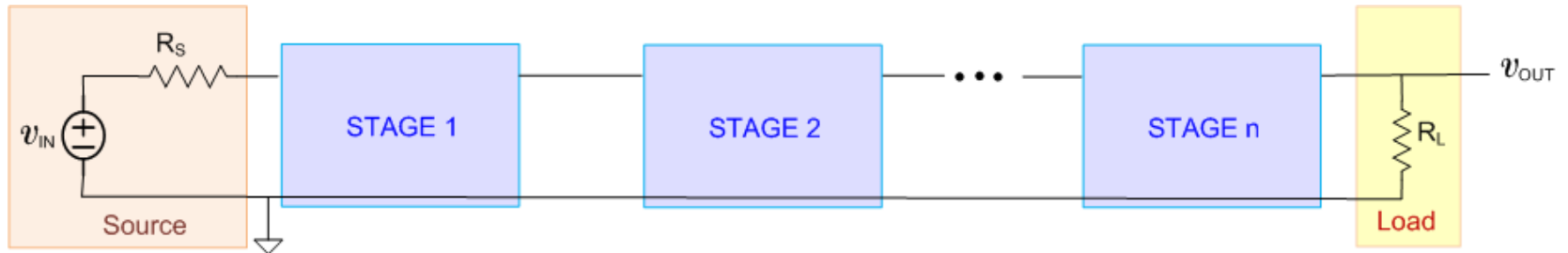
# Cascaded Amplifiers



- 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.. )

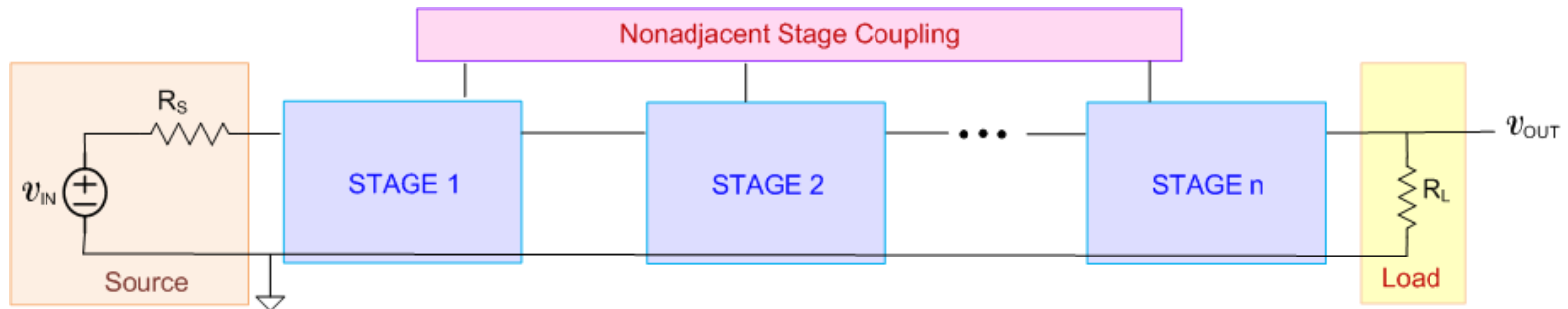
# Cascaded Amplifier Analysis and Operation

## Adjacent Stage Coupling Only



- Systematic Methods of Analysis/Design will be Developed

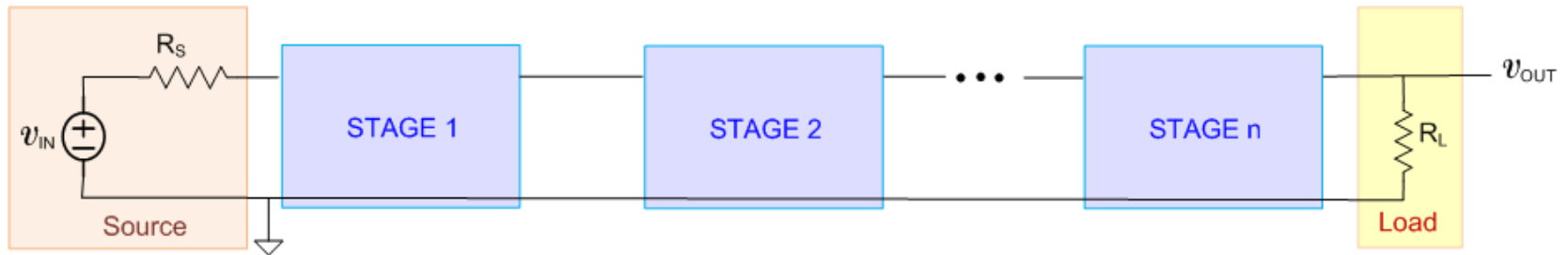
## One or more couplings of nonadjacent stages



- 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

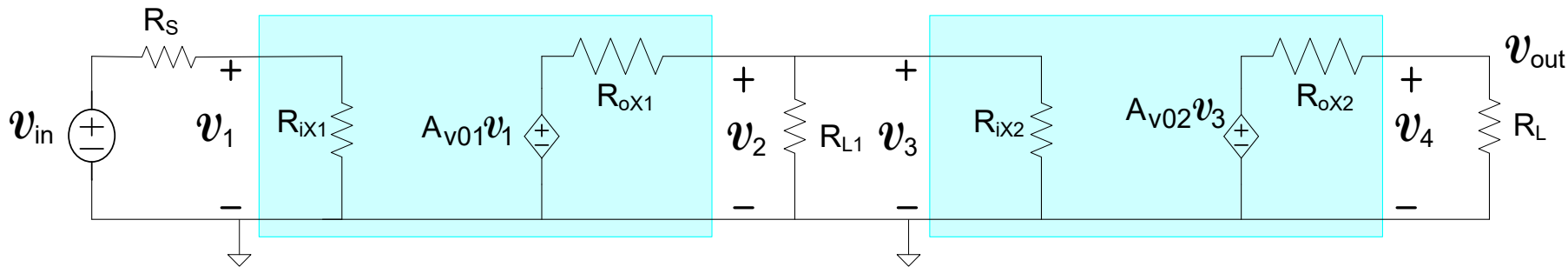
Case 1: All stages Unilateral

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



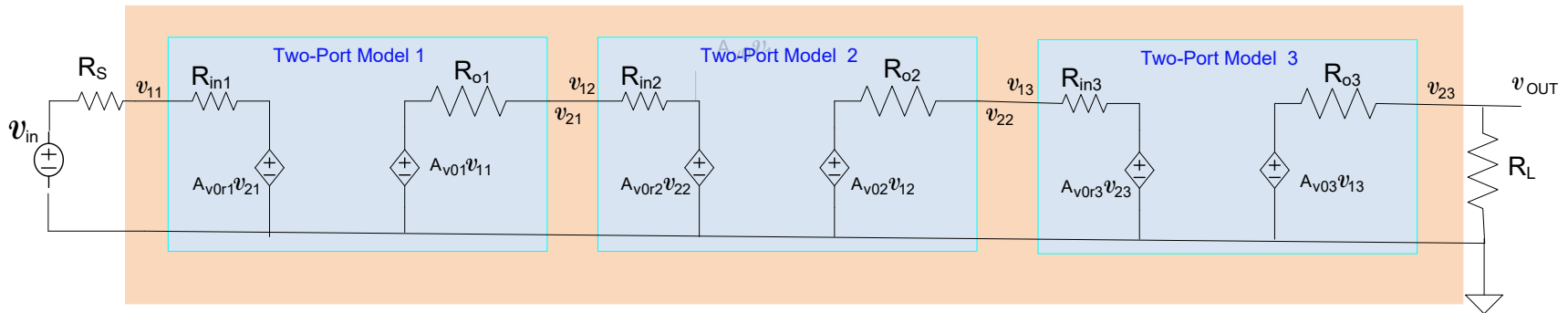
$$A_V = \frac{v_{out}}{v_{in}} = \left( \frac{R_{iX1}}{R_{iX1} + R_S} \right) A_{V01} \left( \frac{R_{L1} // R_{iX2}}{R_{L1} // R_{iX2} + R_{oX1}} \right) A_{V02} \left( \frac{R_L}{R_L + R_{oX2}} \right)$$

**Accounts for all loading between stages !**

# Cascaded Amplifier Analysis and Operation

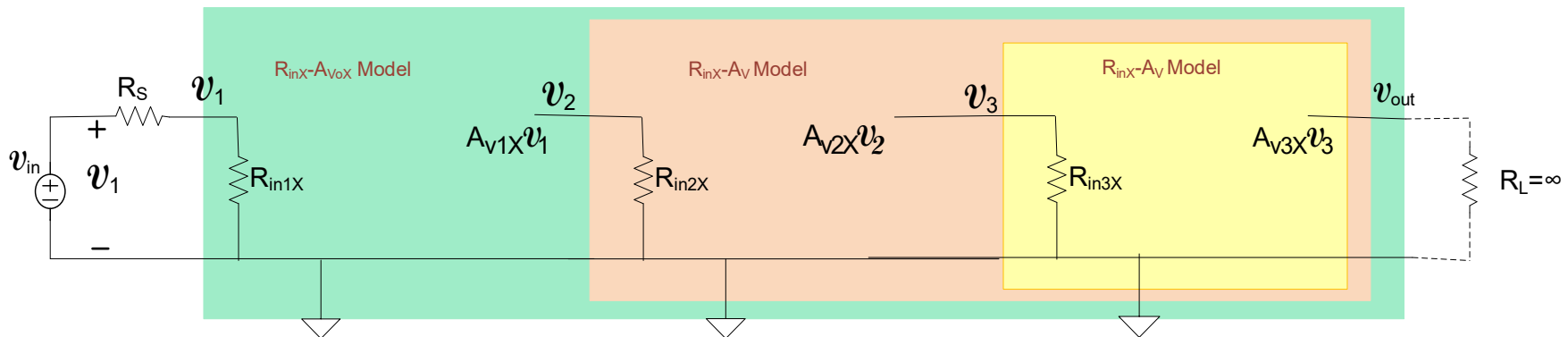
Case 2: One or more stages are not unilateral

## ➤ Standard two-port cascade



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

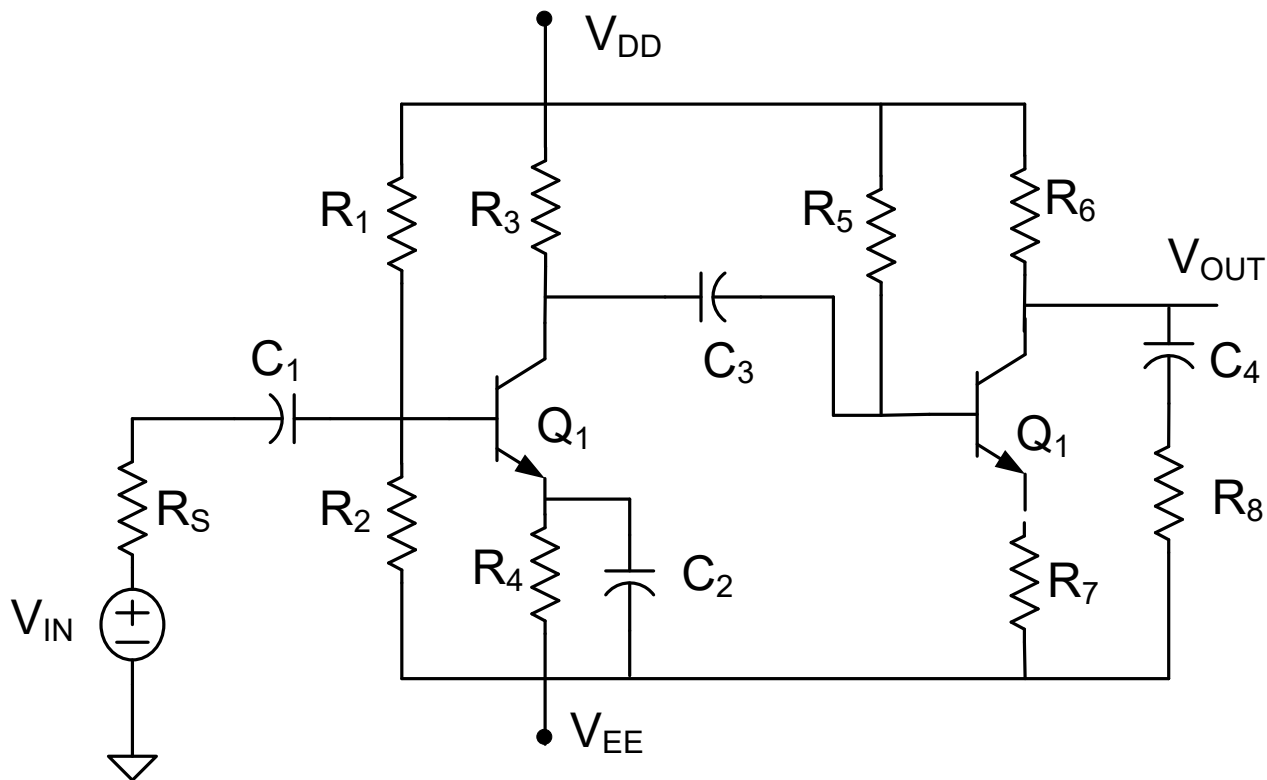
## ➤ Right-to-left nested $R_{inx}, A_{VKX}$ approach



- $R_{inx}$  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 everything!

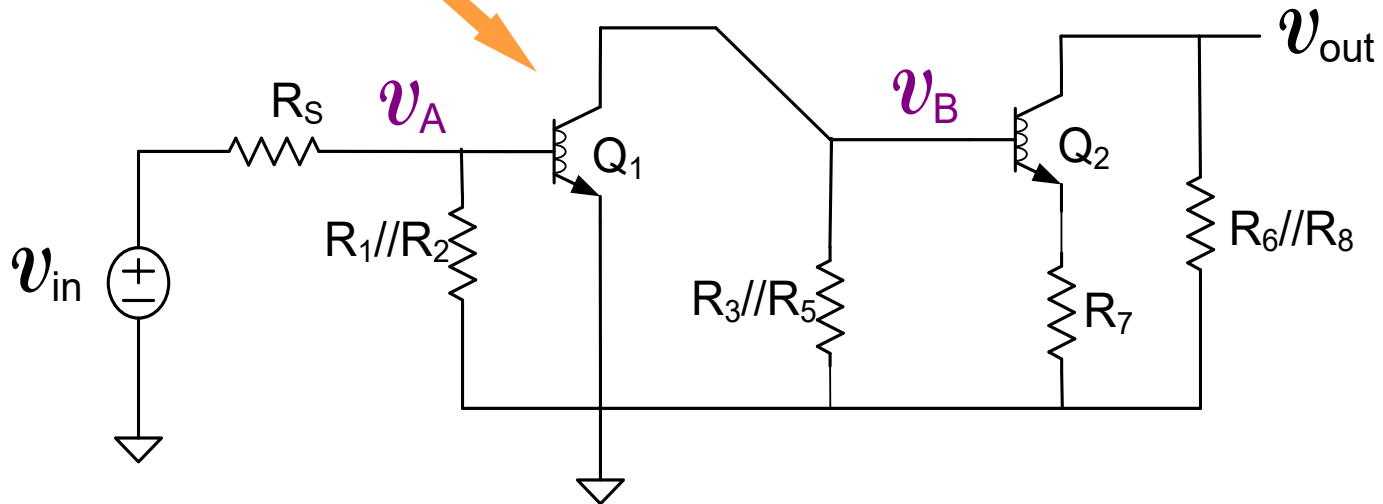
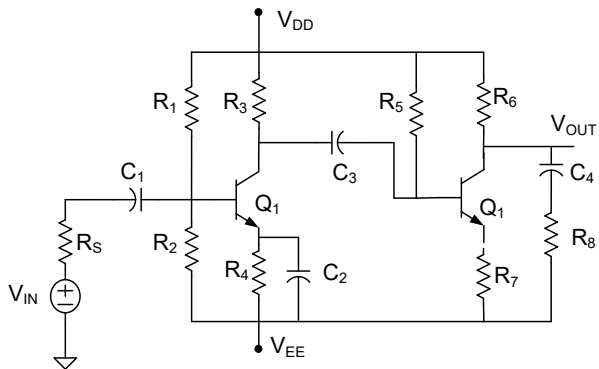
# Example 1:

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:

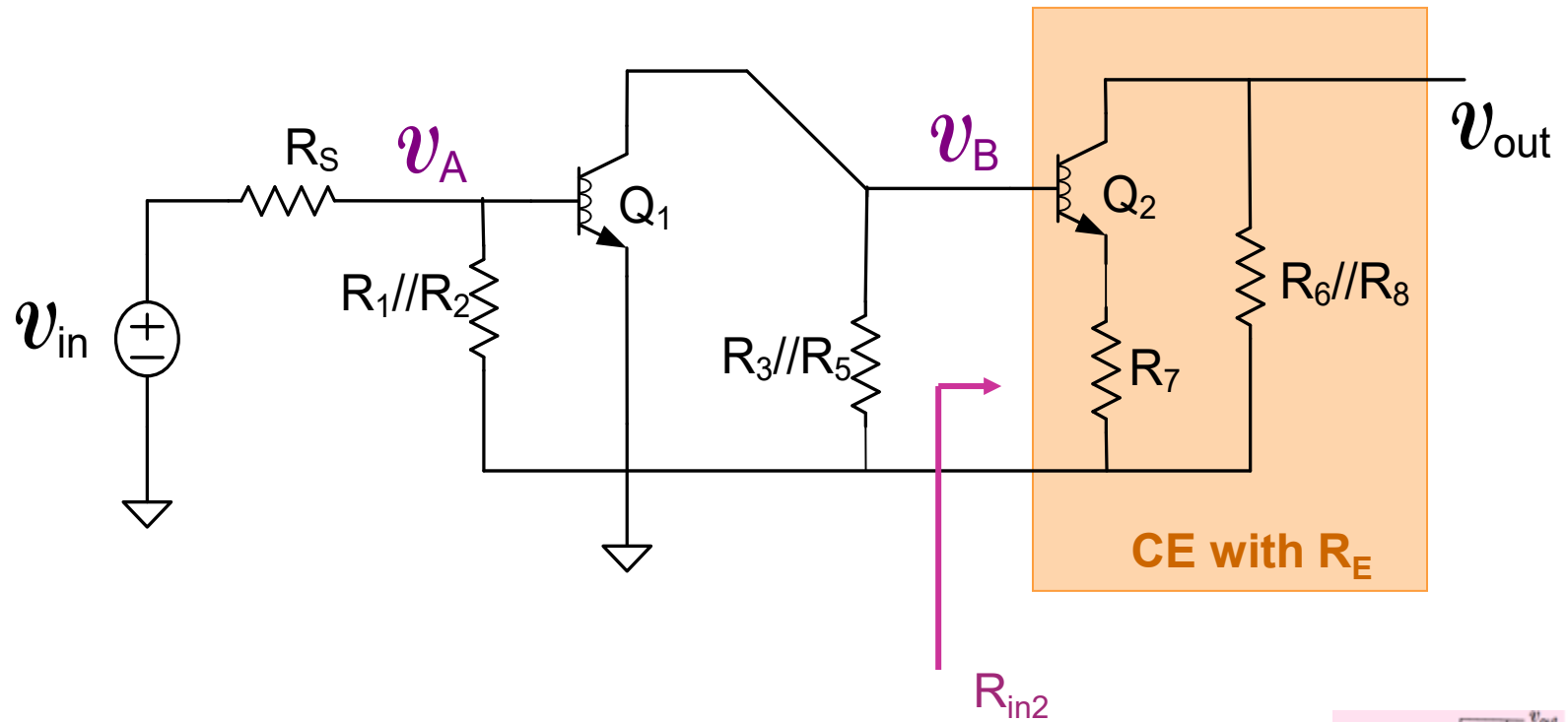


Will calculate  $A_V$  by determining the three ratios (not voltage gains of dependent source):

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

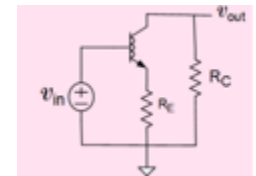


# Example 1:

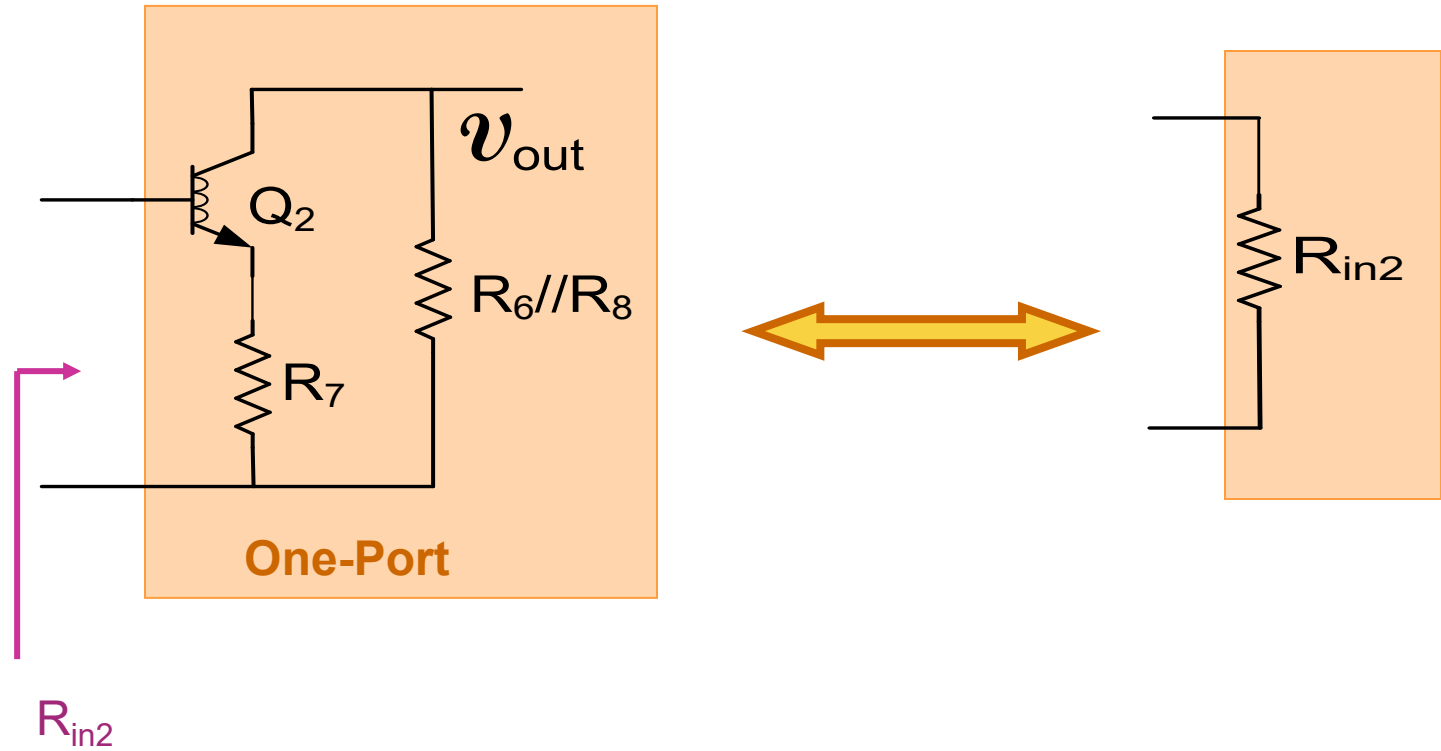


$$A_{V2} = \frac{v_{out}}{v_B} \cong -\frac{R_6 // R_8}{R_7}$$

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

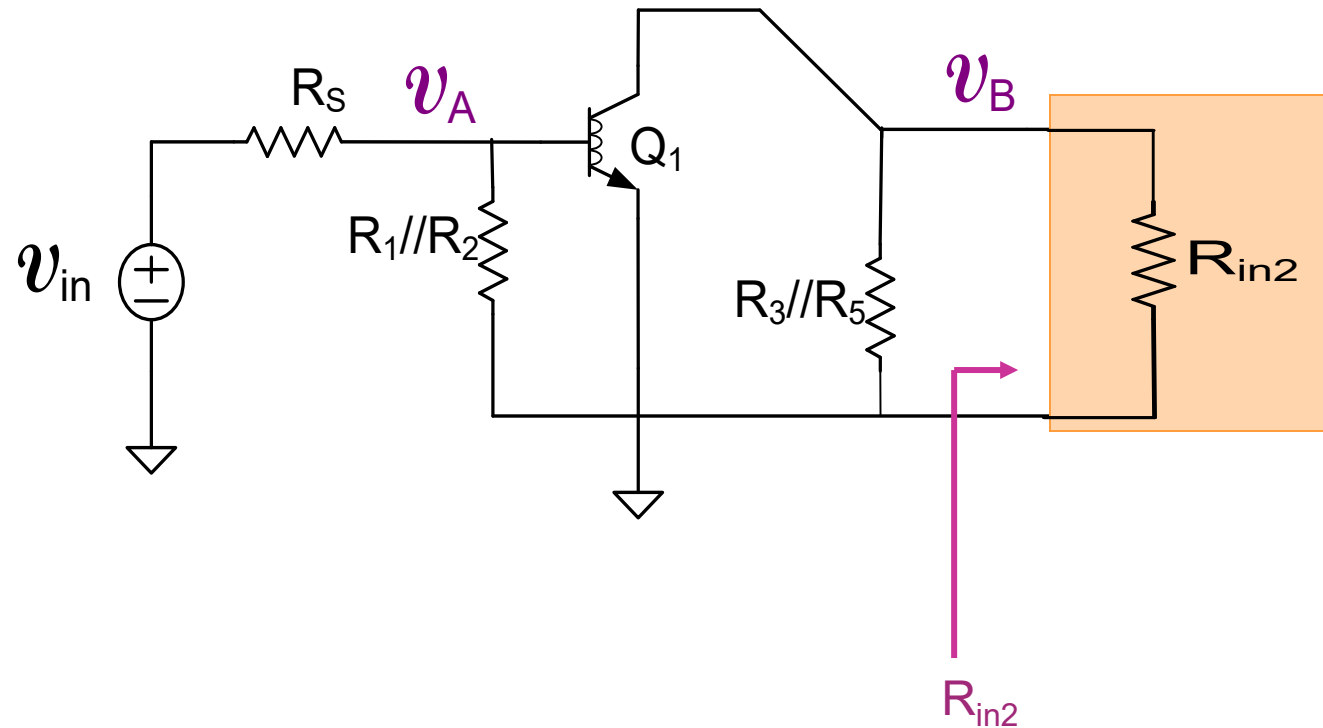


# Example 1:



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

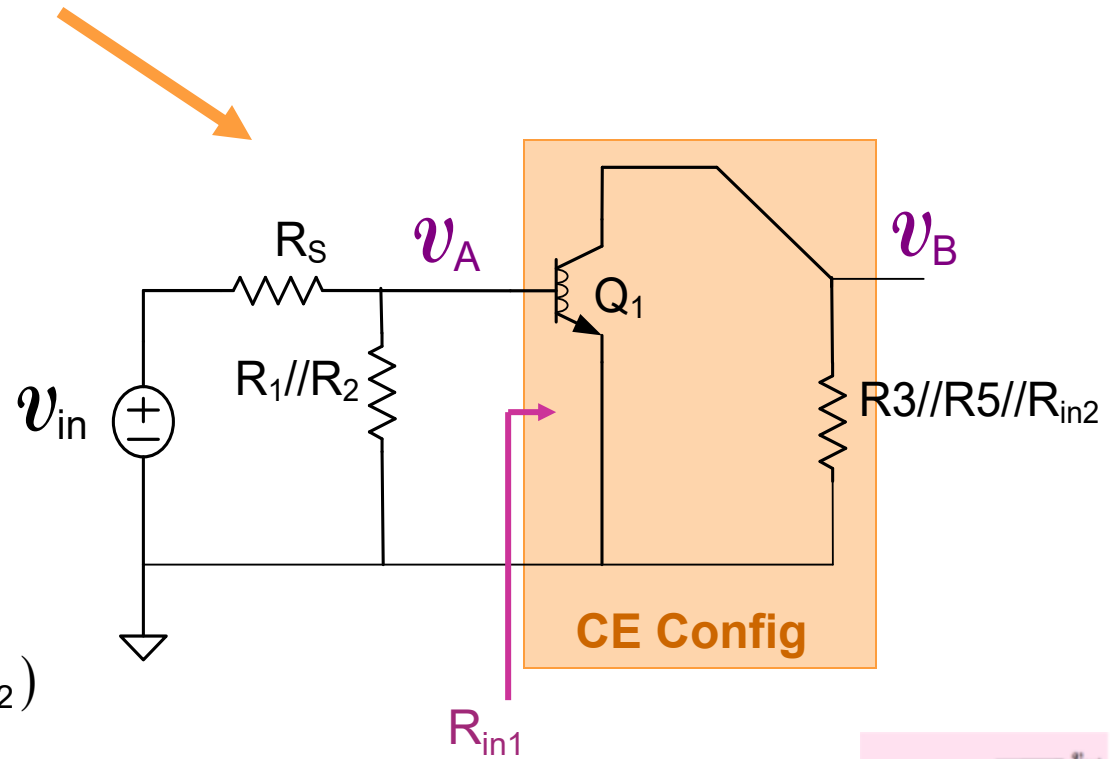
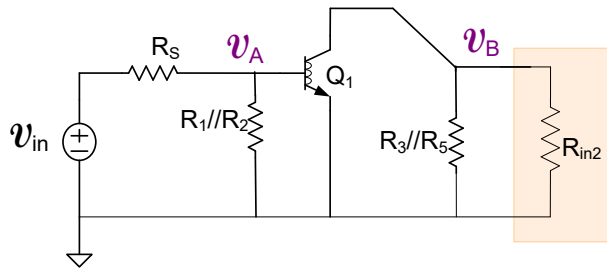
# Example 1:



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

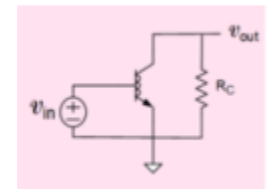
$$R_{in2} \cong \beta R_7$$

# Example 1:

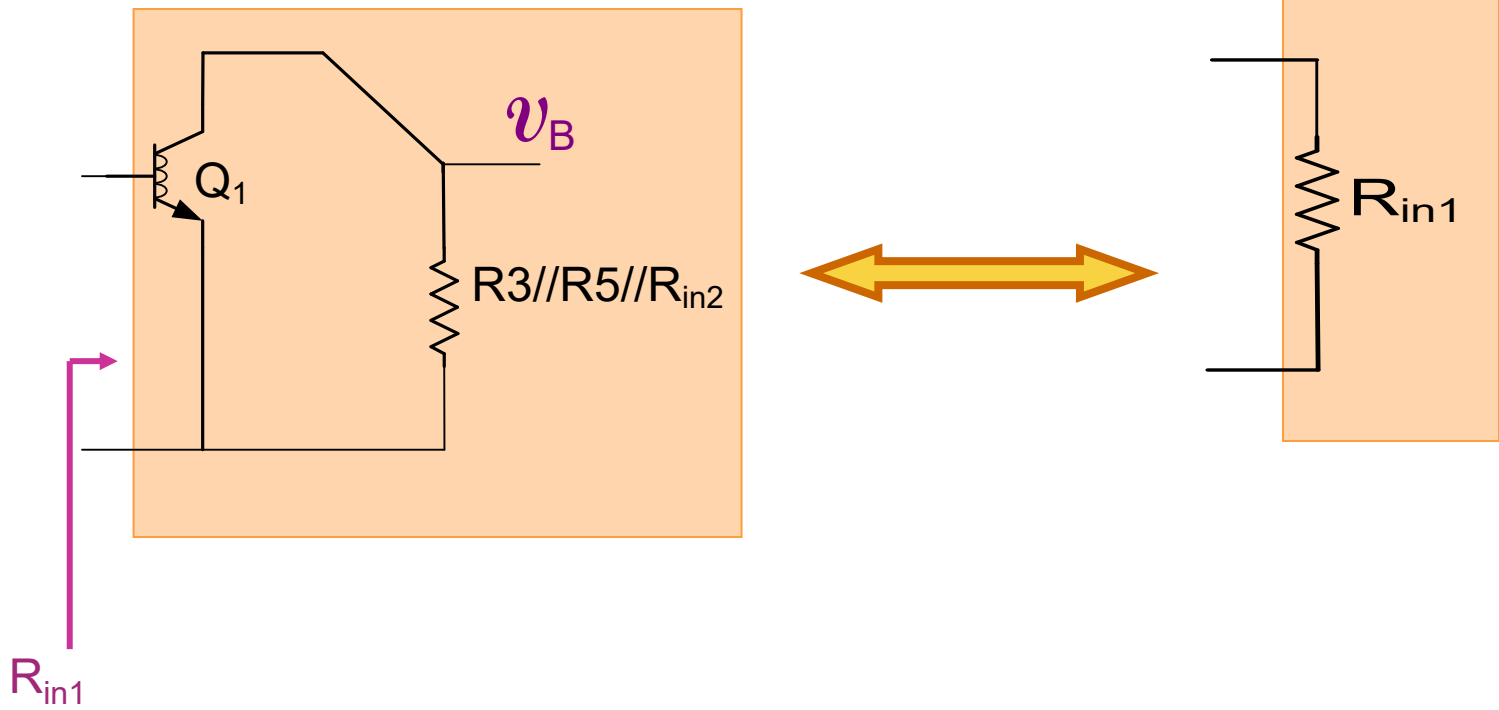


$$A_{V1} = \frac{v_B}{v_A} \cong -g_{m1} (R_3 // R_5 // R_{in2})$$

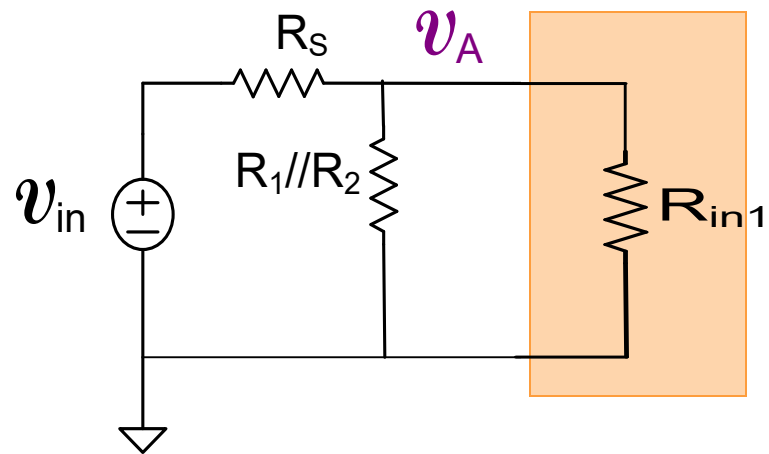
$$R_{in1} \cong r_{\pi 1}$$



# Example 1:

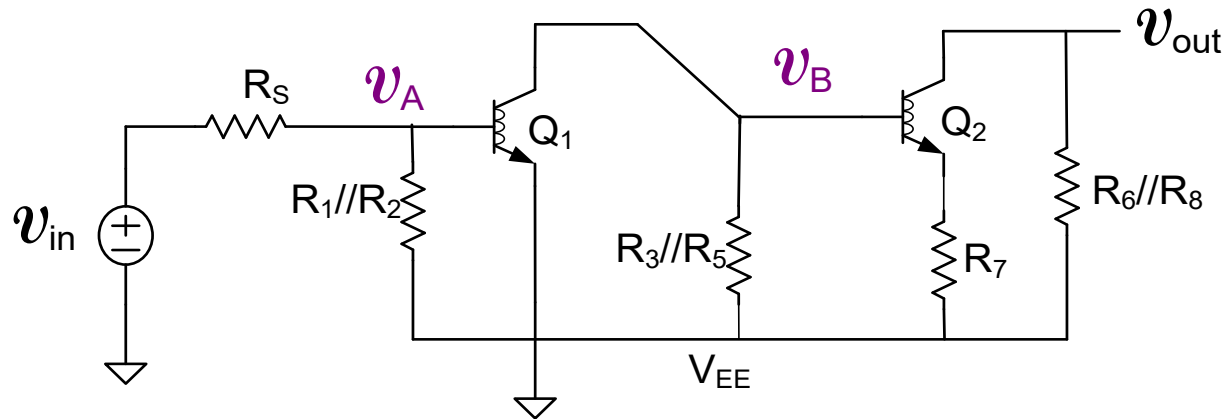


# Example 1:



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

# 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

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

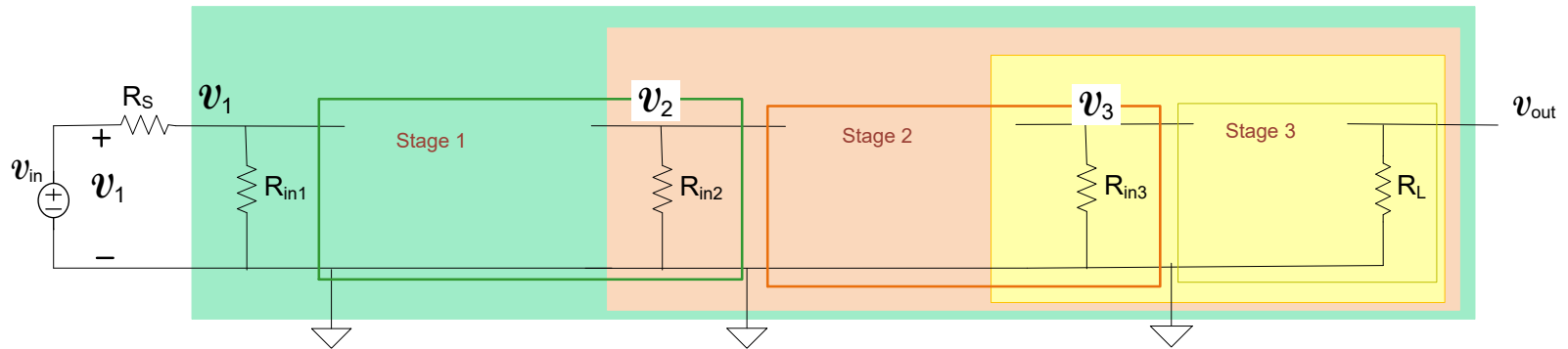
$$\frac{v_B}{v_A} \cong -g_{m1} (R_3 // R_5 // R_{in2})$$

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

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

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

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



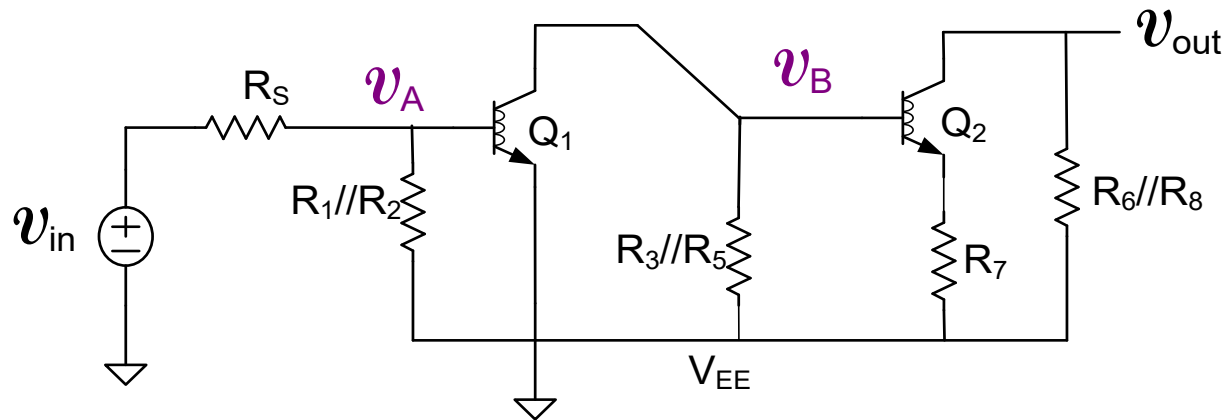
$R_{in_k}$  includes effects of all loading  
 Must recalculate if any change in loading  
 Analysis systematic and rather simple

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

This was the approach used in analyzing the previous cascaded amplifier



## Example 1:

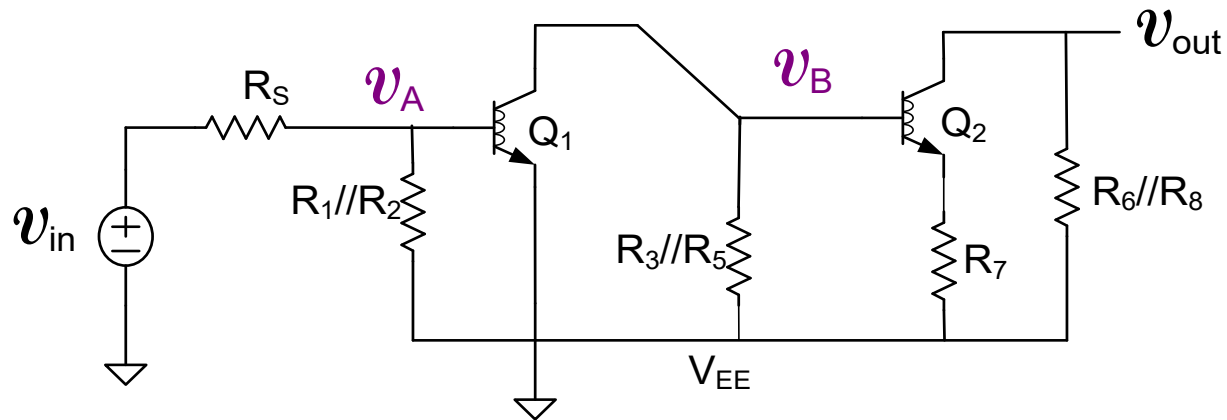


Observation: By working from the output back to the input we were able to create a sequence of steps where the circuit at each step looked EXACTLY like one of the four basic amplifiers. Engineers often follow a design approach that uses a cascade of the basic amplifiers and that is why it is often possible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

Two other methods could have been used to analyze this circuit

What are they?

# Example 1:

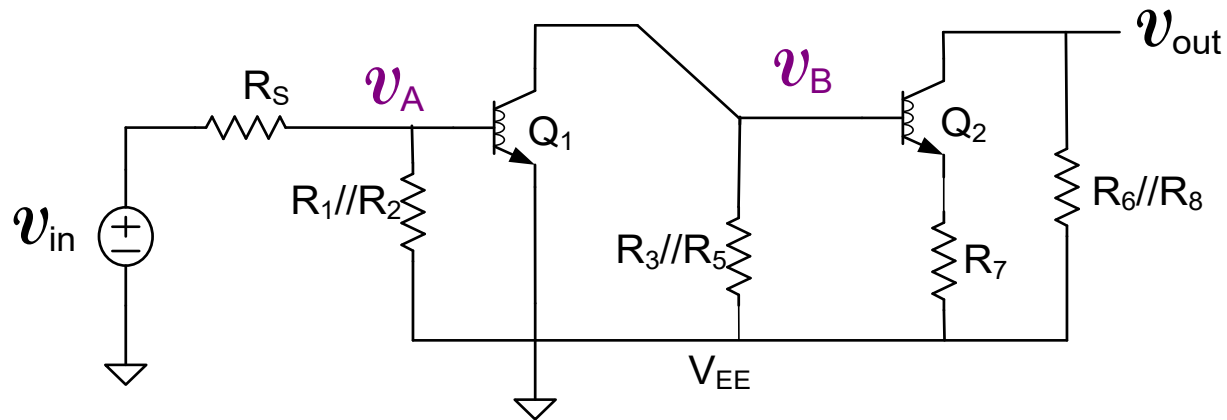


Two other methods could have been used to analyze this small-signal circuit

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:

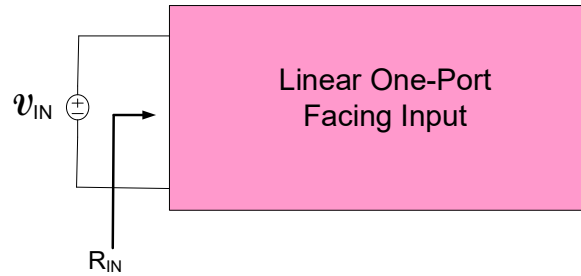


Two other methods could have been used to analyze this circuit

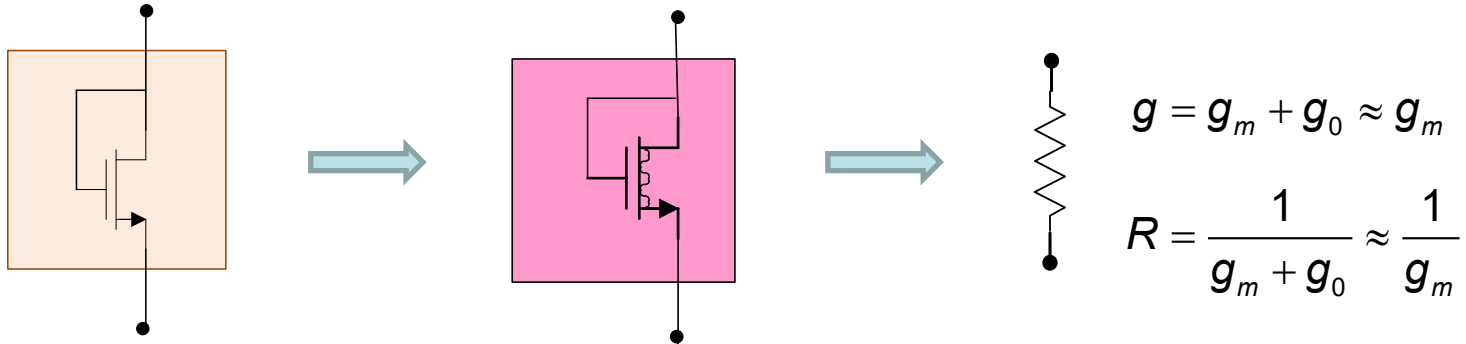
2. Put in small-signal model for  $Q_1$  and  $Q_2$  and solve resultant circuit

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

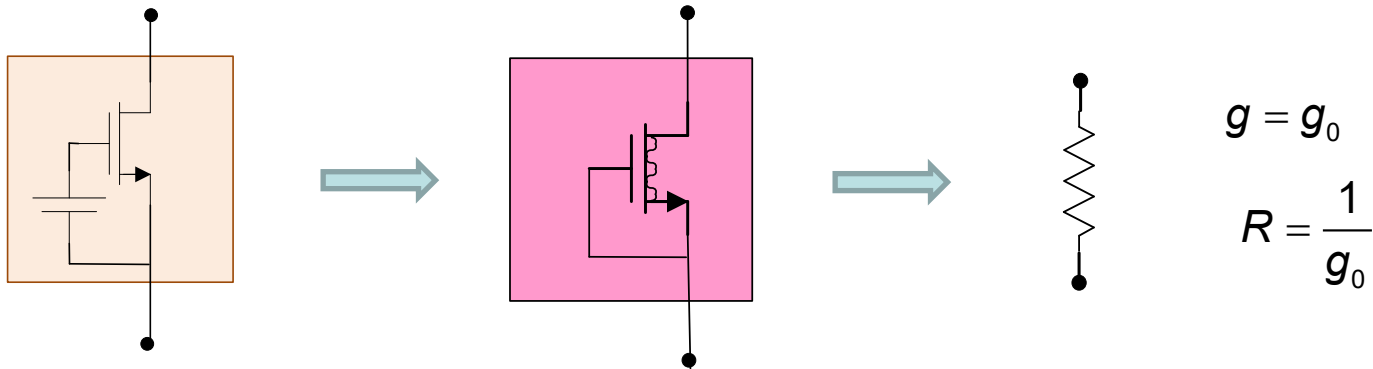
# Review: Small-signal equivalent of a one-port



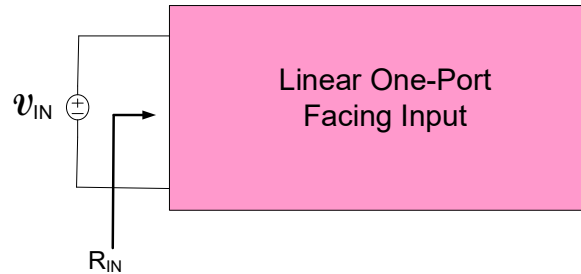
“Diode-connected transistor”



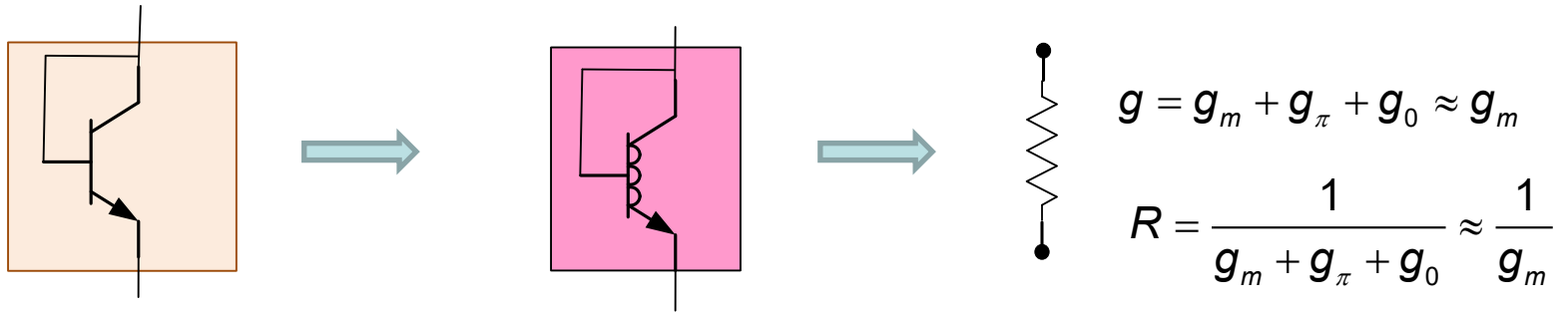
“GS - connected transistor”



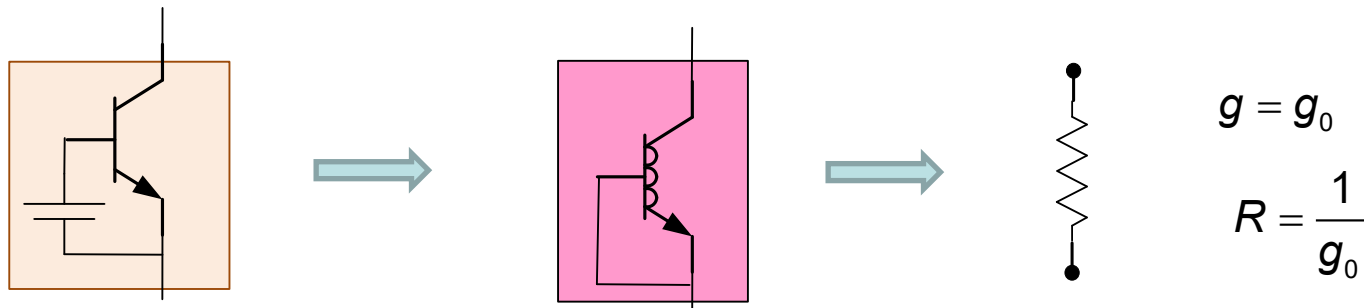
# Review: Small-signal equivalent of a one-port



“Diode-connected transistor”

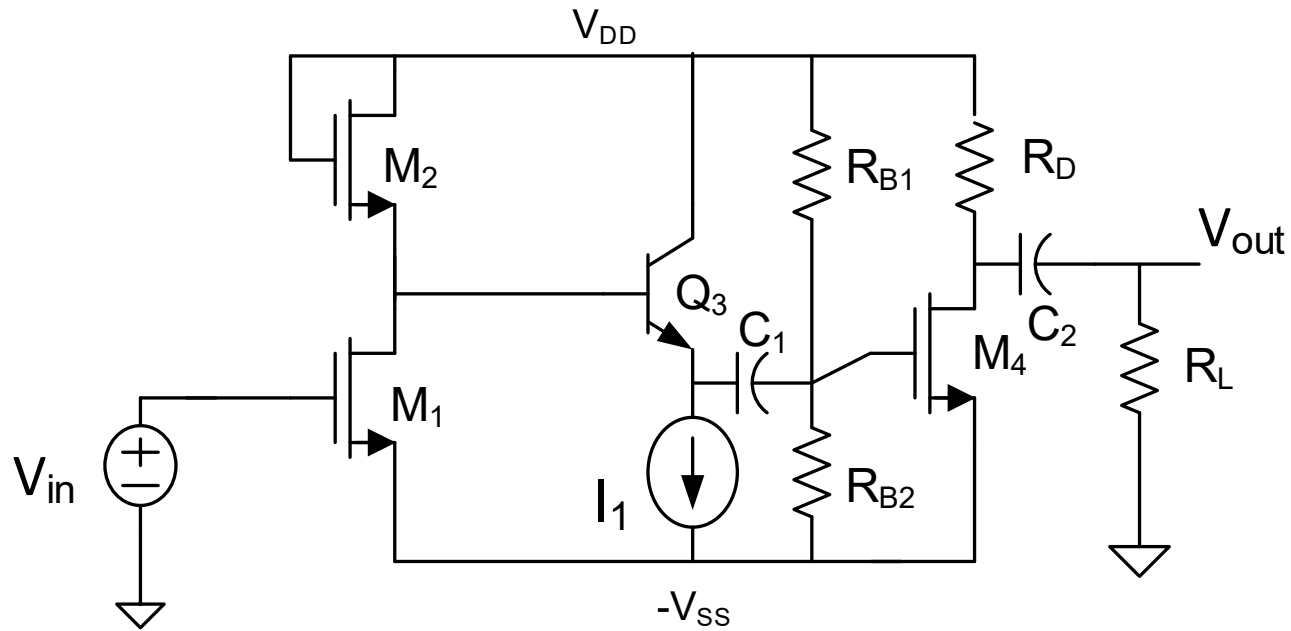


“BE - connected transistor”



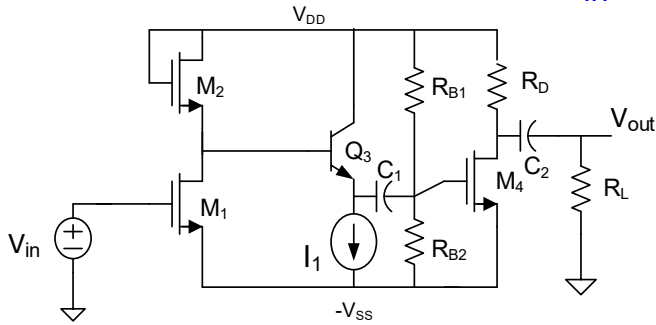
Example 2:  $A_V = \frac{v_{out}}{v_{in}} = ?$

Express in terms of small-signal parameters

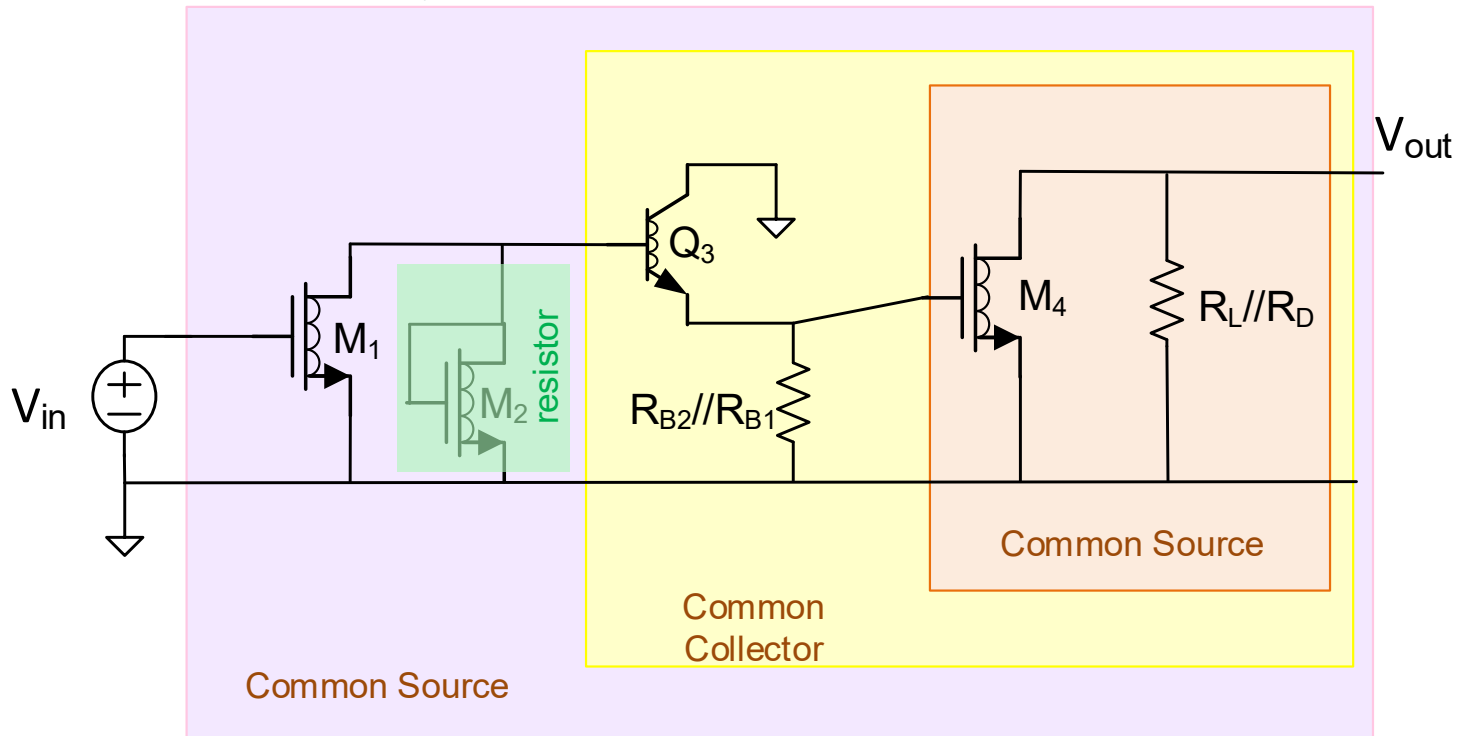


Example 2:  $A_V = \frac{v_{out}}{v_{in}} = ?$

Express in terms of small-signal parameters



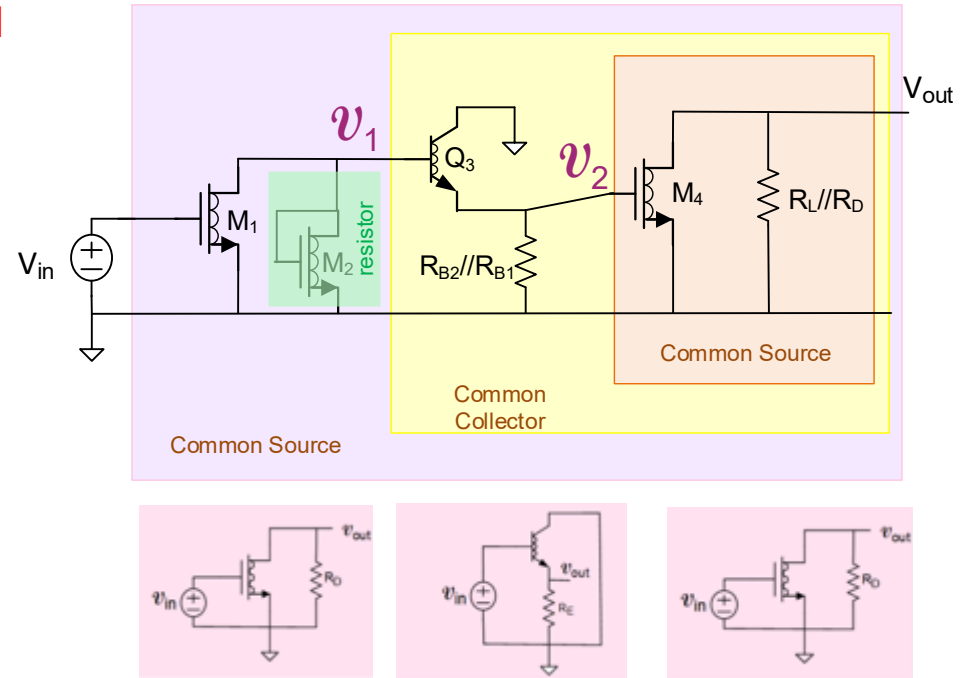
visualize



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

Express in terms of small-signal parameters

Gain Calculation in terms of Small-Signal Parameters



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

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

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

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

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



# Example 3:

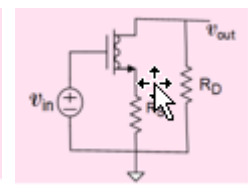
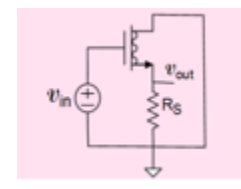
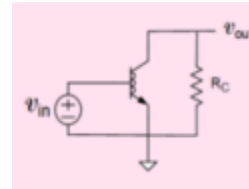
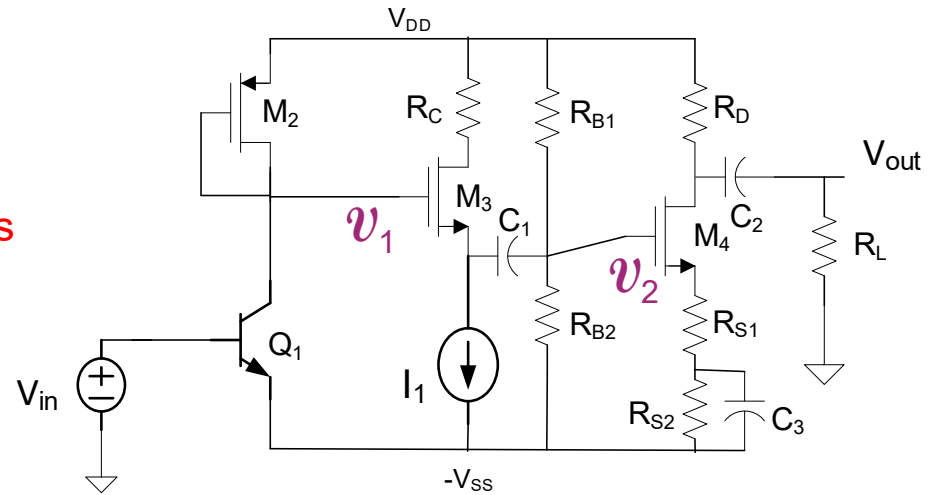
Visualize small-signal circuit  
(Draw small-signal circuit if necessary)

Gain Calculation in Small-Signal Parameters

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

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

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

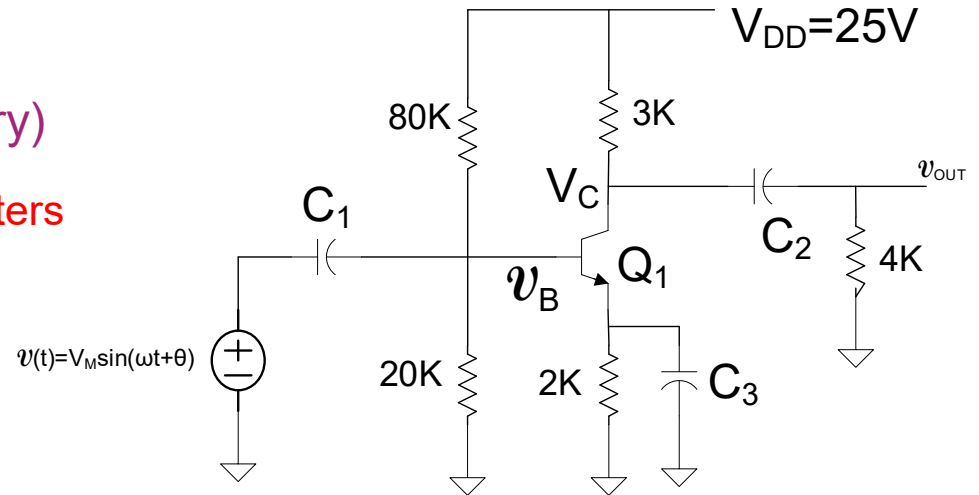


$$A_V = \frac{v_{out}}{v_2} \frac{v_2}{v_1} \frac{v_1}{v_{in}} \cong \left[ -g_{m4} (R_D // R_L) / R_{S1} \right] [1] \left[ \frac{-g_{m1}}{g_{m2}} \right]$$

# Example 5:

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

Gain Calculation in Small-Signal Parameters



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



Stay Safe and Stay Healthy !

End of Lecture 32