EE 330
Lecture 32

Two-Port Amplifier Models

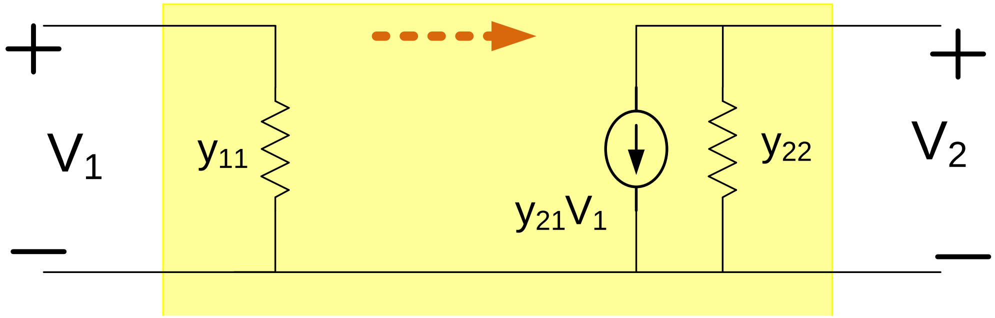
Basic amplifier architectures

- Common Emitter/Source
- Common Collector/Drain
- Common Base/Gate

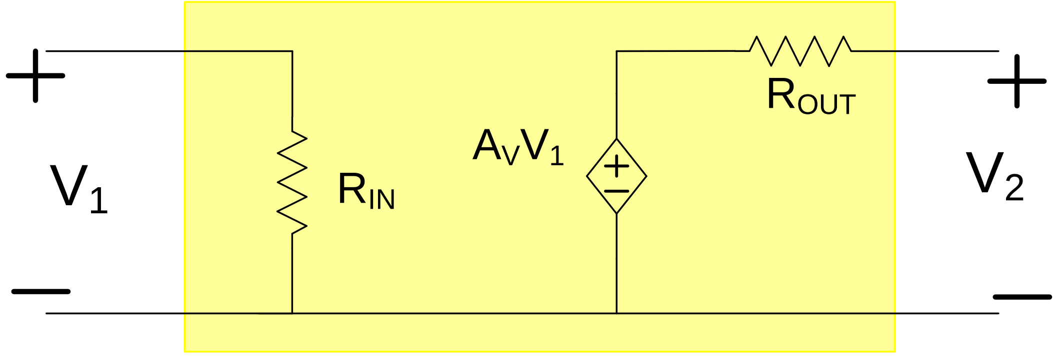
Exam 3
Friday November 22

Two-port representation of amplifiers

Unilateral amplifiers:



- Thevenin equivalent output port often more standard
- R_{IN}, A_V, and R_{OUT} often used to characterize the two-port of amplifiers

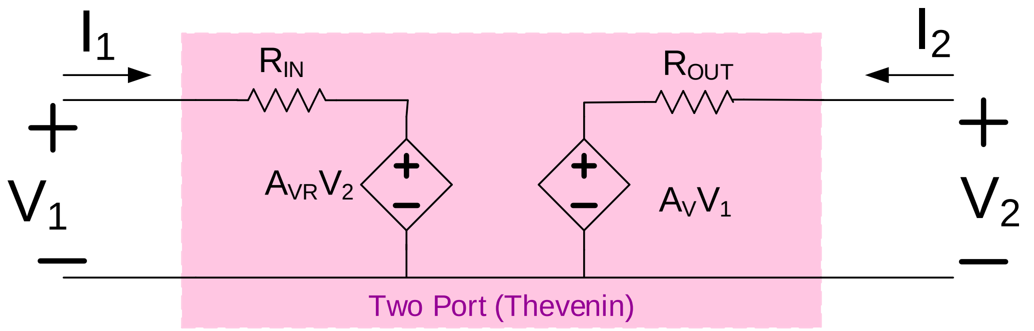


Unilateral amplifier in terms of “amplifier” parameters

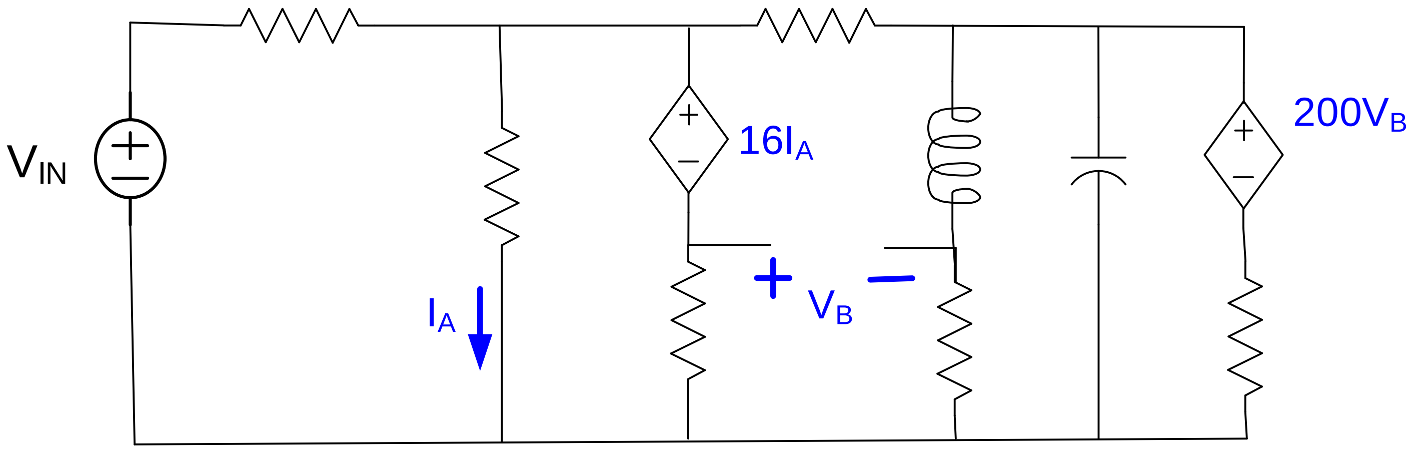
$$R_{IN} = \frac{1}{y_{11}} \qquad A_V = -\frac{y_{21}}{y_{22}} \qquad R_{OUT} = \frac{1}{y_{22}}$$

Review from Previous Lecture

Relationship with Dependent Sources ?

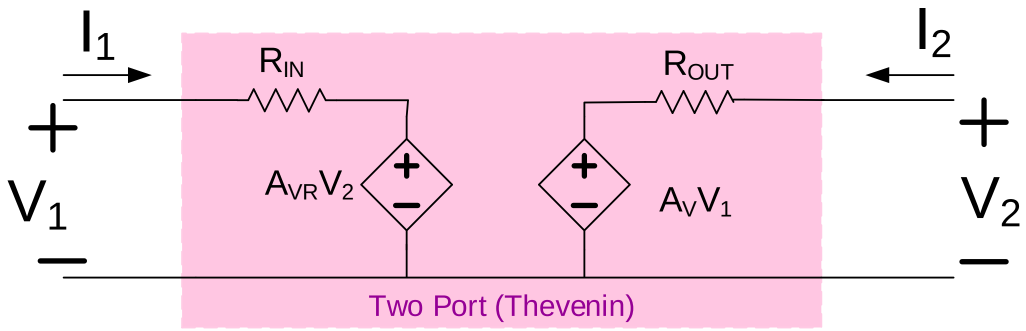


Dependent sources from EE 201



Example showing two dependent sources

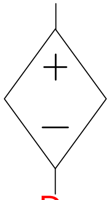
Relationship with Dependent Sources ?



Dependent sources from EE 201

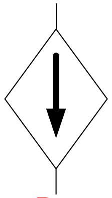
Voltage Amplifier

$v_s = \mu v_x$



Voltage Dependent Voltage Source

$I_s = \alpha v_x$

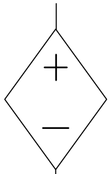


Voltage Dependent Current Source

Transconductance Amplifier

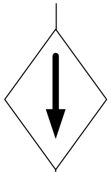
Transresistance Amplifier

$v_s = \rho I_x$



Current Dependent Voltage Source

$I_s = \beta I_x$

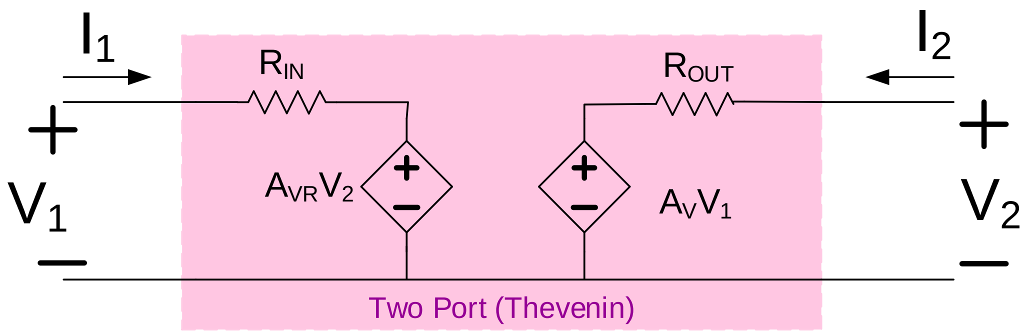


Current Dependent Current Source

Current Amplifier

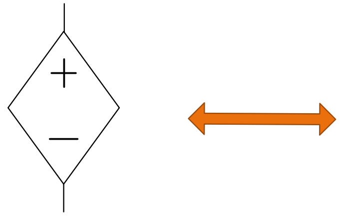
Review From Previous Lecture

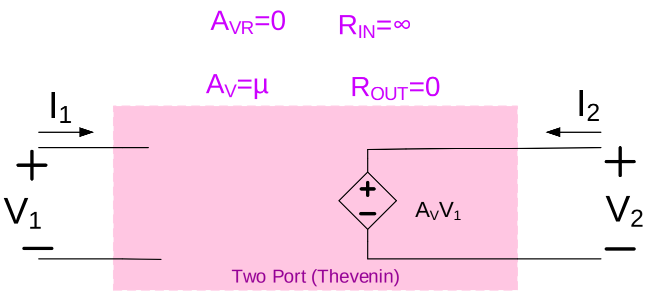
Relationship with Dependent Sources ?



It follows that

$v_S = \mu v_X$



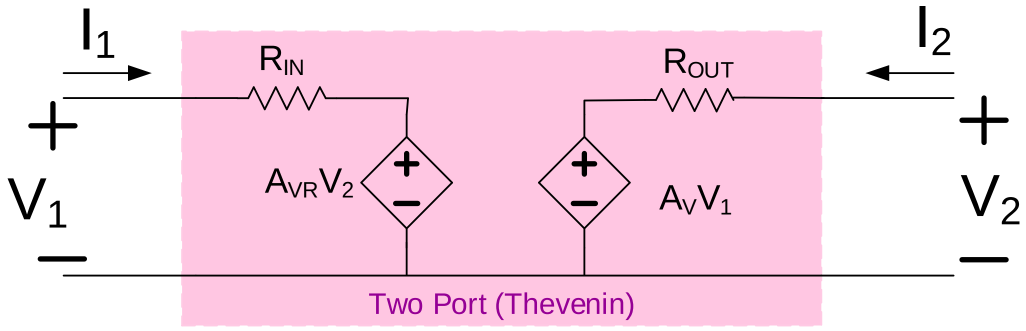


$V_2 = A_V V_1$

Voltage dependent voltage source is a unilateral floating two-port voltage amplifier with $R_{IN}=\infty$ and $R_{OUT}=0$

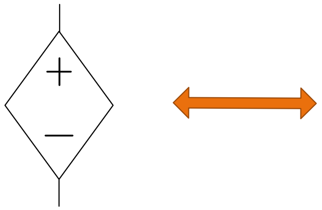
Review From Previous Lecture

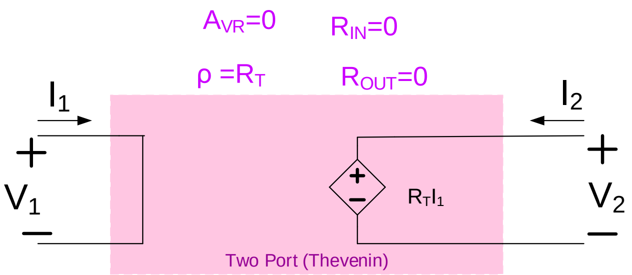
Relationship with Dependent Sources ?



It follows that

$\mathcal{v}_S = \rho I_x$

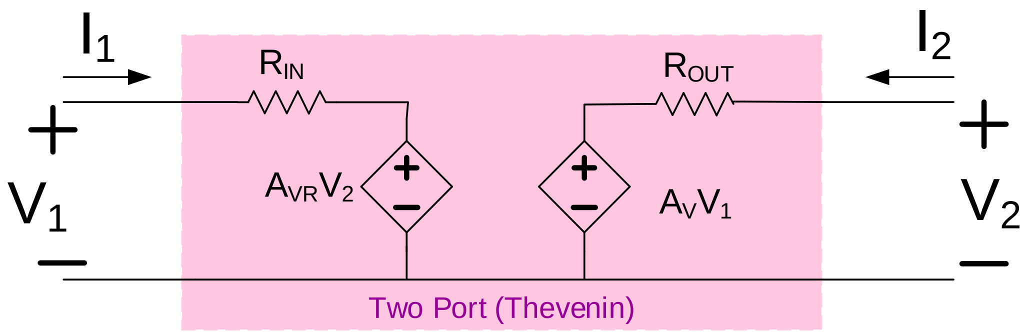




$V_2 = R_T I_1$

Current dependent voltage source is a unilateral floating two-port transresistance amplifier with $R_{IN}=0$ and $R_{OUT}=0$

Relationship with Dependent Sources ?



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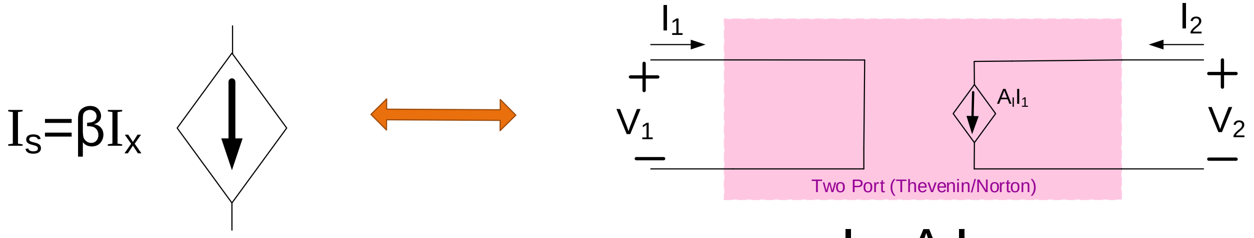
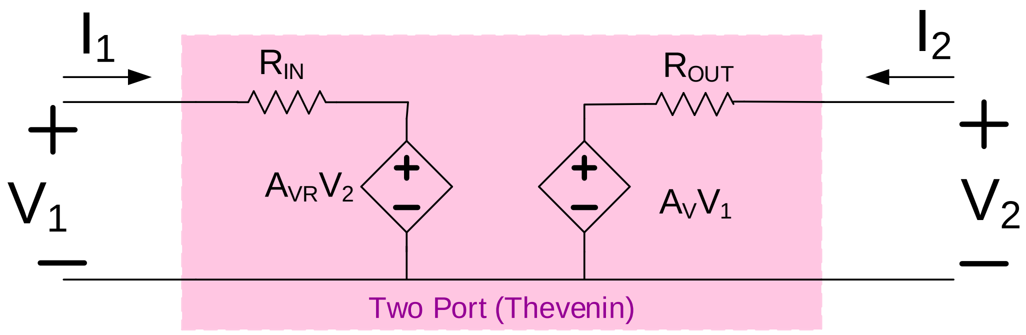


$I_2=A_II_1$

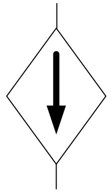
Current dependent current source is a floating unilateral two-port current amplifier with $R_{IN}=0$ and $R_{OUT}=\infty$

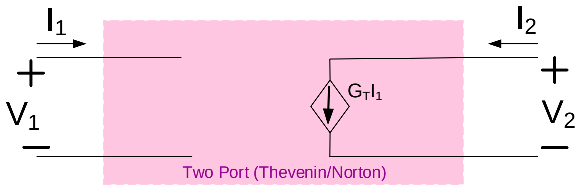
Relationship with Dependent Sources ?



It follows that

$I_S = \alpha \mathcal{V}_x$



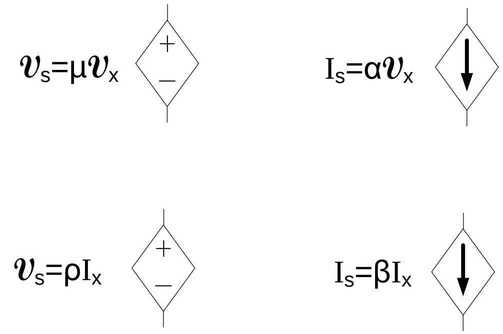


$I_2 = G_T V_1$

Voltage dependent current source is a floating unilateral two-port transconductance amplifier with $R_{IN}=\infty$ and $R_{OUT}=\infty$

Review From Previous Lecture

Dependent Sources



Dependent sources are unilateral two-port amplifiers with ideal input and output impedances

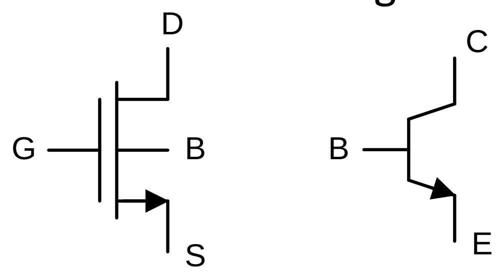
Dependent sources do not exist as basic circuit elements but amplifiers can be designed to perform approximately like a dependent source

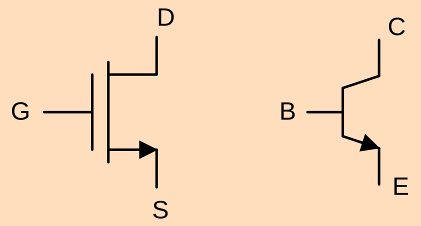
- Practical dependent sources typically are not floating on input or output
- One terminal is usually grounded
- Input and output impedances of realistic structures are usually not ideal

Why were “dependent sources” introduced as basic circuit elements instead of two-port amplifiers in the basic circuits courses???
Why was the concept of “dependent sources” not discussed in the basic electronics courses???

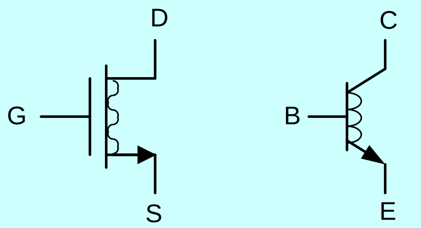
Basic Amplifier Structures

- MOS and Bipolar Transistors both have 3 primary terminals
- MOS transistor has a fourth terminal that is generally considered a parasitic terminal





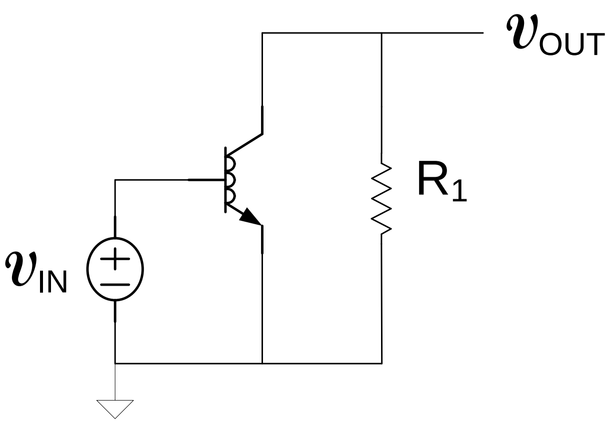
Transistors as 3-terminal Devices

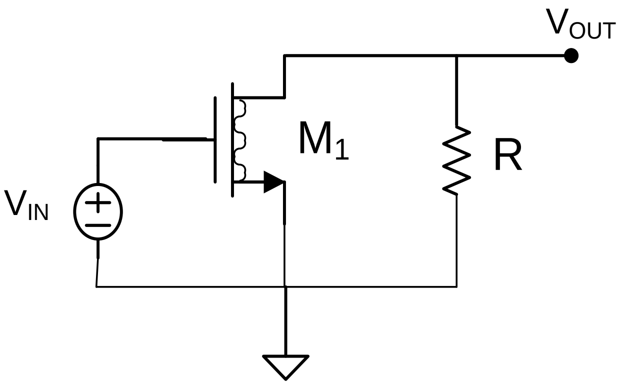


Small Signal Transistor Models
as 3-terminal Devices

Basic Amplifier Structures

Observation:



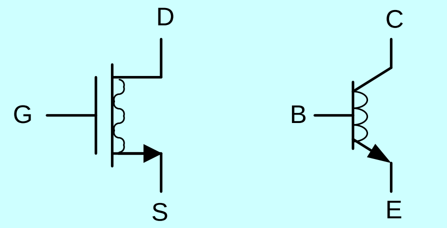


These circuits considered previously have a terminal (emitter or source) common to the input and output in the small-signal equivalent circuit

For BJT, E is common, input on B, output on C — Termed "Common Emitter"

For MOSFET, S is common, input on G, output on D — Termed "Common Source"

Basic Amplifier Structures



Small Signal Transistor Models
as 3-terminal Devices

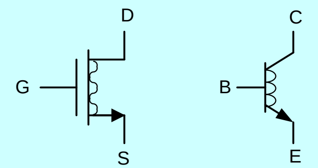
Amplifiers using these devices generally have one terminal common and use remaining terminals as input and output

Since devices are nearly unilateral, designation of input and output terminals is uniquely determined

Three different ways to designate the common terminal

Source or Emitter	termed Common Source or Common Emitter
Gate or Base	termed Common Gate or Common Base
Drain or Collector	termed Common Drain or Common Collector

Basic Amplifier Structures



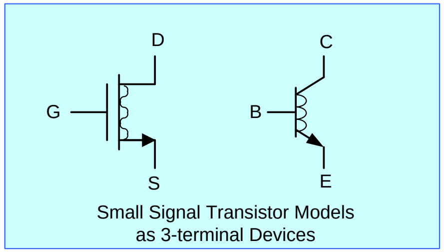
Small Signal Transistor Models
as 3-terminal Devices

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

Identification of Input and Output Terminals is not arbitrary

It will be shown that all 3 of the basic amplifiers are useful !

Basic Amplifier Structures



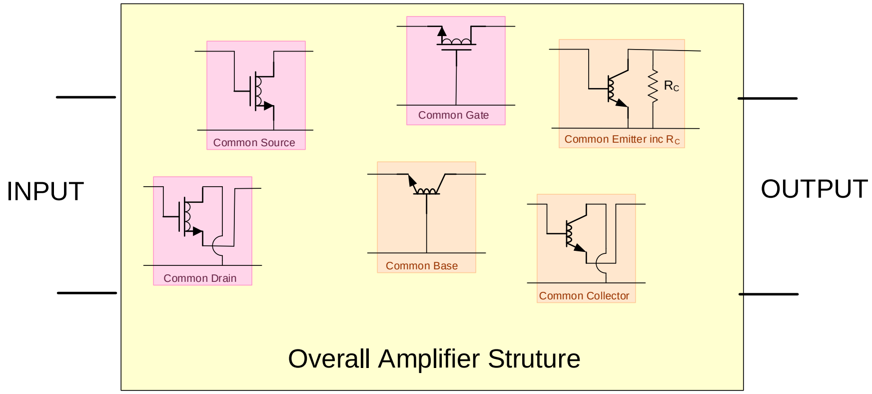
Common Source or Common Emitter

Common Gate or Common Base

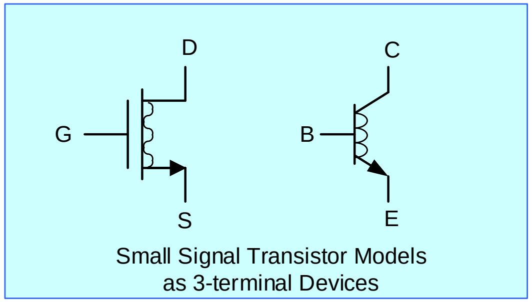
Common Drain or Common Collector

Objectives in Study of Basic Amplifier Structures

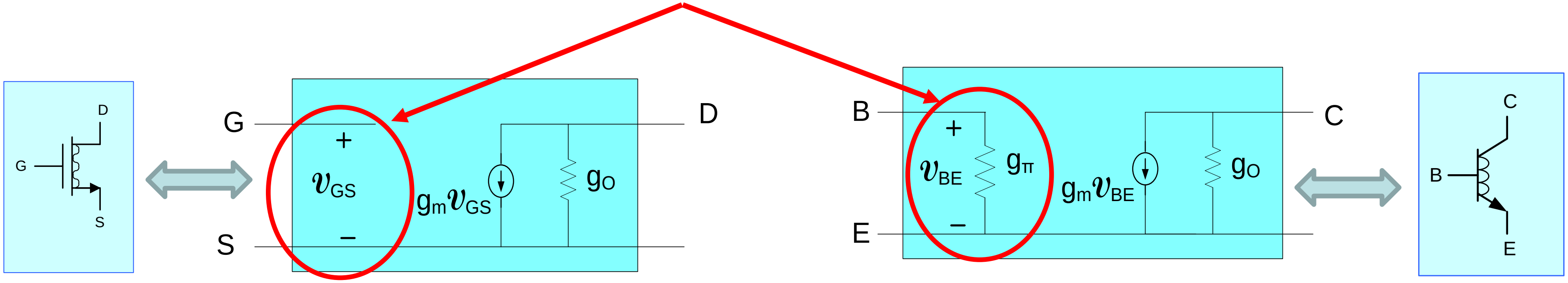
1. Obtain key properties of each basic amplifier
2. Develop method of designing amplifiers with specific characteristics using basic amplifier structures



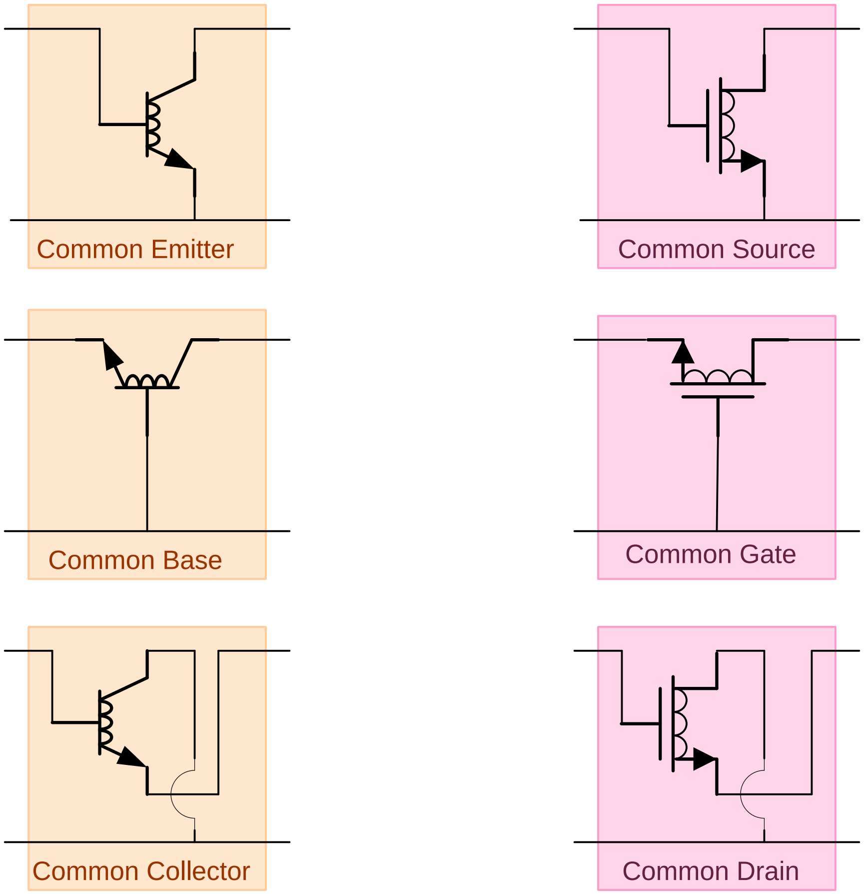
Characterization of Basic Amplifier Structures



- Observe that the small-signal equivalent of any 3-terminal network is a two-port
- Thus to characterize any of the 3 basic amplifier structures, it suffices to determine the two-port equivalent network
- Since small signal model when expressed in terms of small-signal parameters of BJT and MOSFET differ only in the presence/absence of g_π term, can analyze the BJT structures and then obtain characteristics of corresponding MOS structure by setting g_π=0

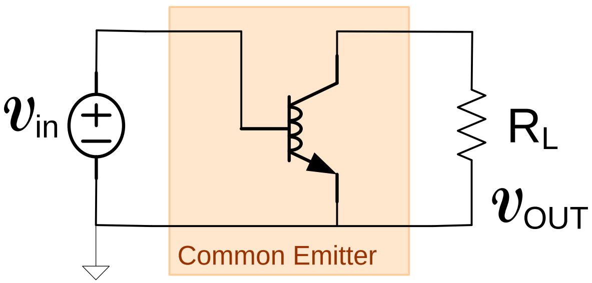


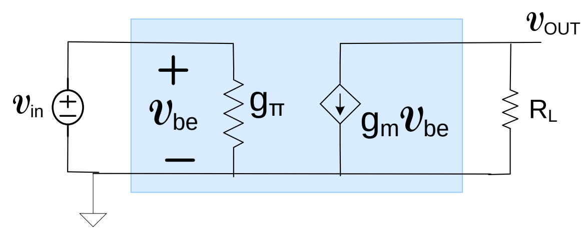
The three basic amplifier types for both MOS and bipolar processes



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

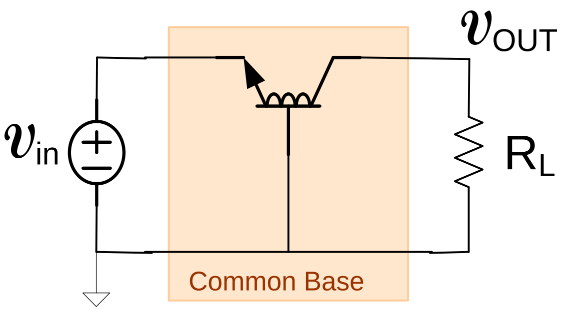
The three basic amplifier types for both MOS and bipolar processes

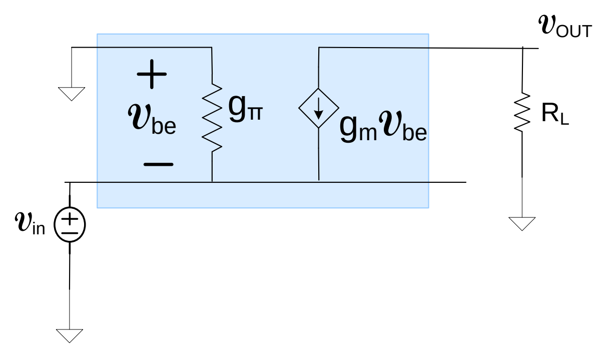




$$\left.\begin{aligned} v_{OUT} &= -g_m R_L v_{be} \\ v_{IN} &= v_{be} \end{aligned}\right\}$$

$$A_V = \frac{v_{OUT}}{v_{IN}} = -g_m R_L$$





$$\left.\begin{aligned} v_{OUT} &= -g_m R_L v_{be} \\ v_{IN} &= -v_{be} \end{aligned}\right\}$$

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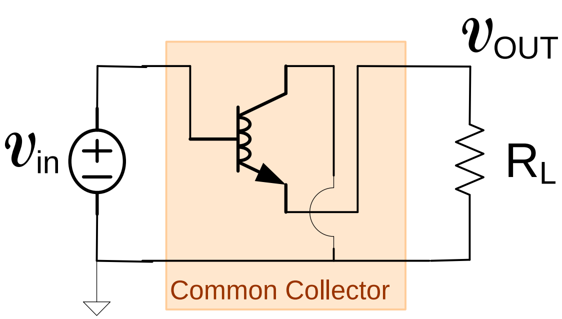
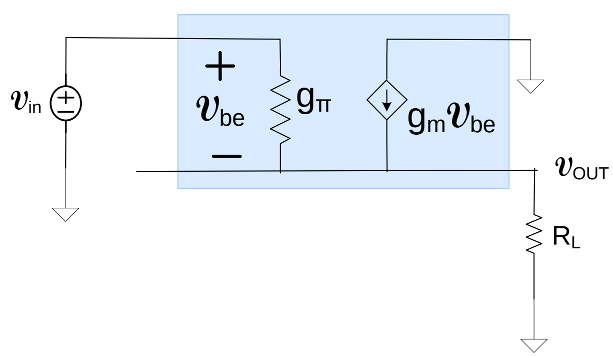


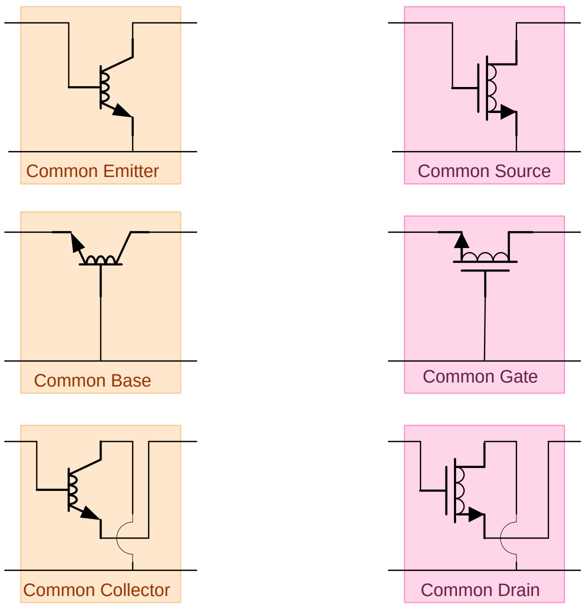


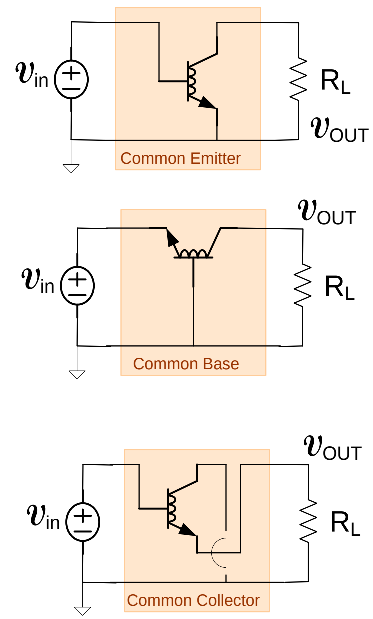
$$\left.\begin{aligned} v_{OUT} &= (g_m + g_\pi) v_{be} R_L \\ v_{IN} &= v_{be} + (g_m + g_\pi) v_{be} R_L \end{aligned}\right\}$$

$$A_V = \frac{v_{OUT}}{v_{IN}} = \frac{(g_m + g_\pi) R_L}{1 + (g_m + g_\pi) R_L} \cong 1$$

- Significantly different gain characteristics for the three basic amplifiers
- There are other significant differences too (R_{IN}, R_{OUT}, …) as well

The three basic amplifier types for both MOS and bipolar processes





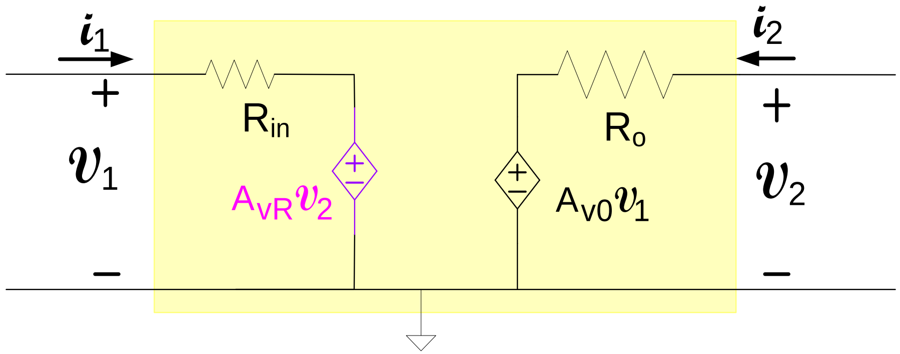
More general models are needed to accommodate biasing, understand performance capabilities, and include effects of loading of the basic structures

Two-port models are useful for characterizing the basic amplifier structures

How can the two-port parameters be obtained for these or any other linear two-port networks?

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 a previous lecture)

2. Write v_1 : v_2 equations in standard form

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

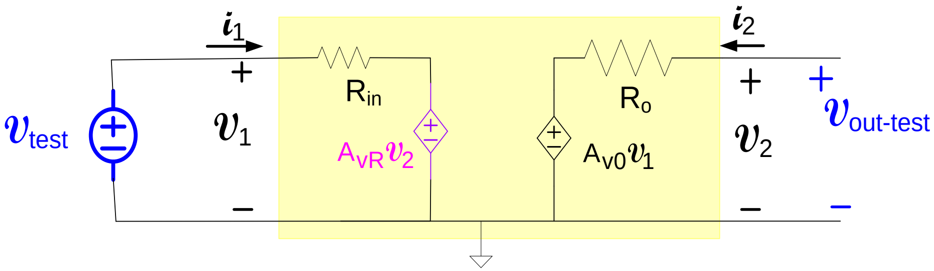
3. Thevenin-Norton Transformations

4. Ad Hoc Approaches

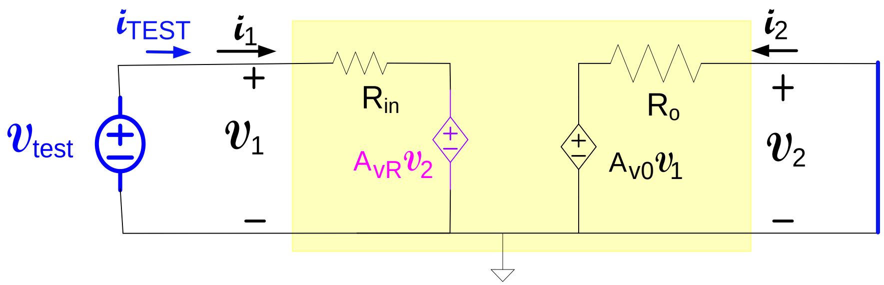
Any of these methods can be used to obtain the two-port model

$v_{test} : i_{test}$ Method for Obtaining Two-Port Amplifier Parameters

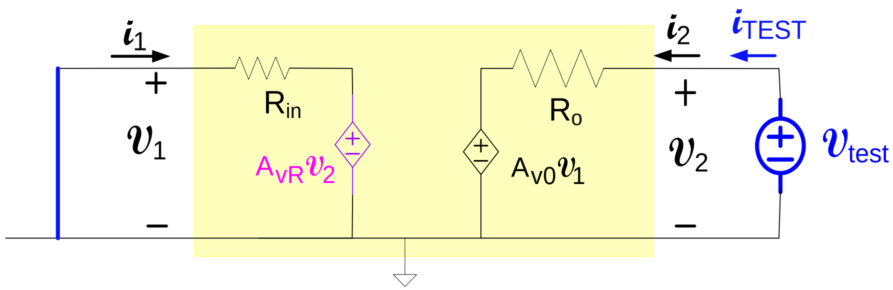
SUMMARY from PREVIOUS LECTURE



$$A_{V0} = \frac{v_{out\text{-}test}}{v_{test}}$$

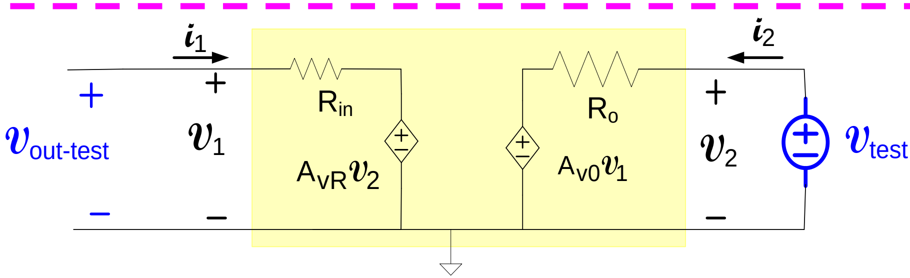


$$R_{in} = \frac{v_{test}}{i_{test}}$$



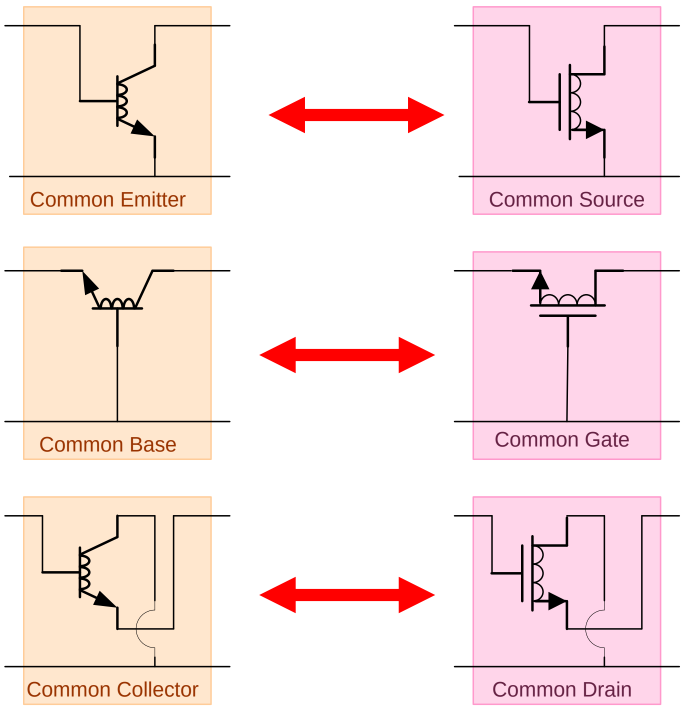
$$R_0 = \frac{v_{test}}{i_{test}}$$

If Unilateral $A_{VR} = 0$

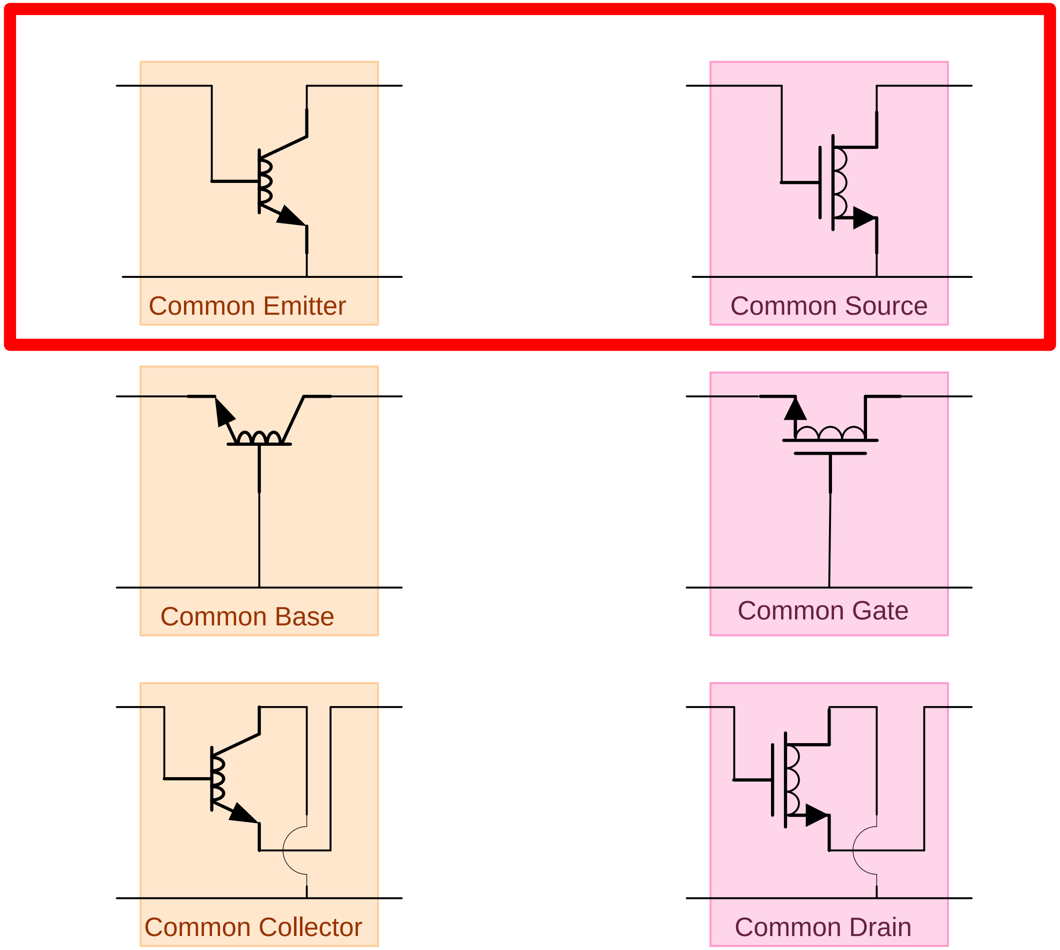


$$A_{VR} = \frac{v_{out\text{-}test}}{v_{test}}$$

Will now develop two-port model for each of the three basic amplifiers and look at one widely used application of each

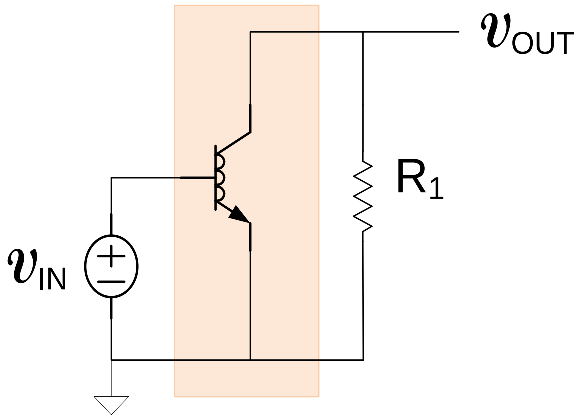


Consider Common Emitter/Common Source Two-port Models

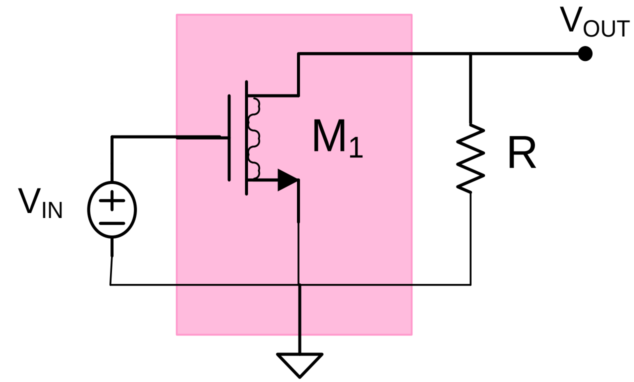


Will focus on Bipolar Circuit since MOS counterpart is a special case obtained by setting $g_\pi=0$

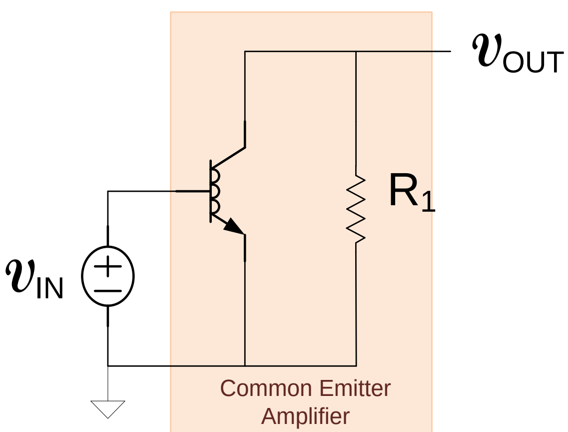
Basic CE/CS Amplifier Structures

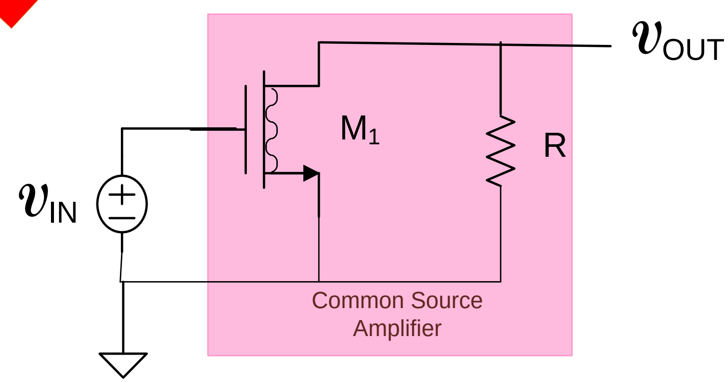


Common Emitter Amplifier



Common Source Amplifier

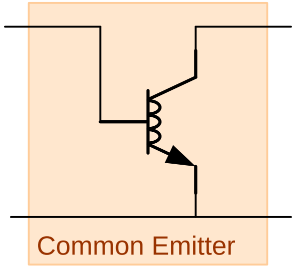


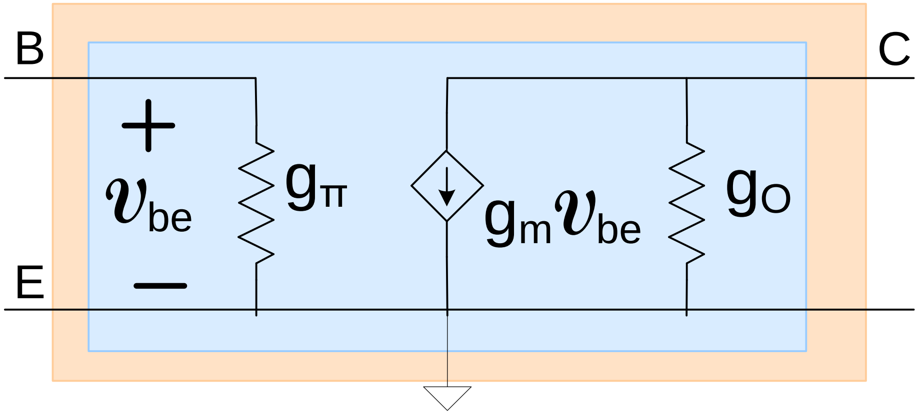


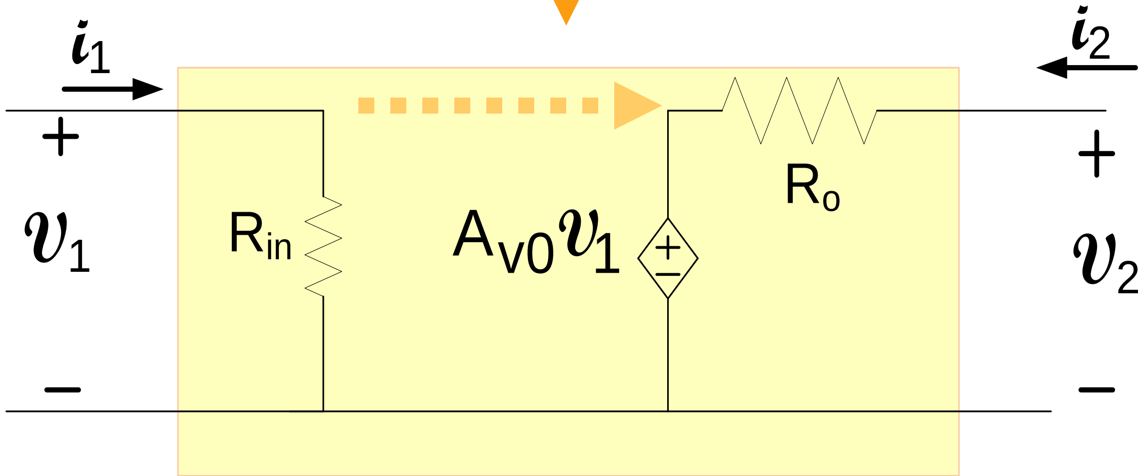
Can include or exclude R and R_1 in two-port models (of course they are different circuits)

The CE and CS amplifiers are themselves two-ports !

Two-port model for Common Emitter Configuration



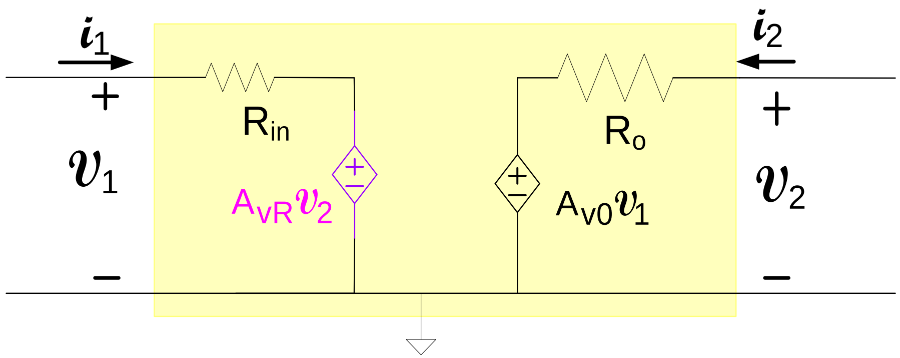




$\{R_i, A_{V0}$ and $R_0\}$

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

Methods of Obtaining Amplifier Two-Port Network



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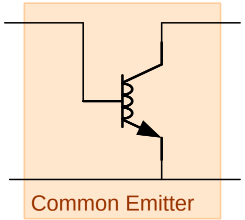
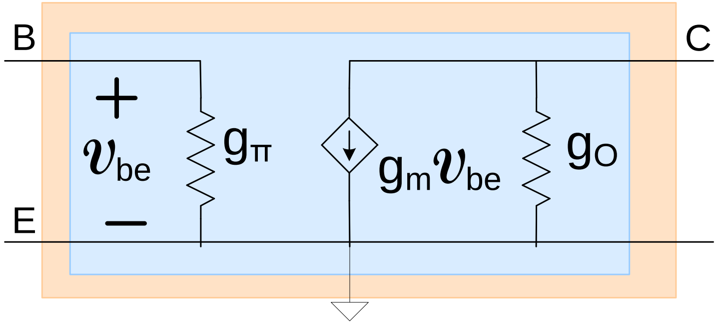
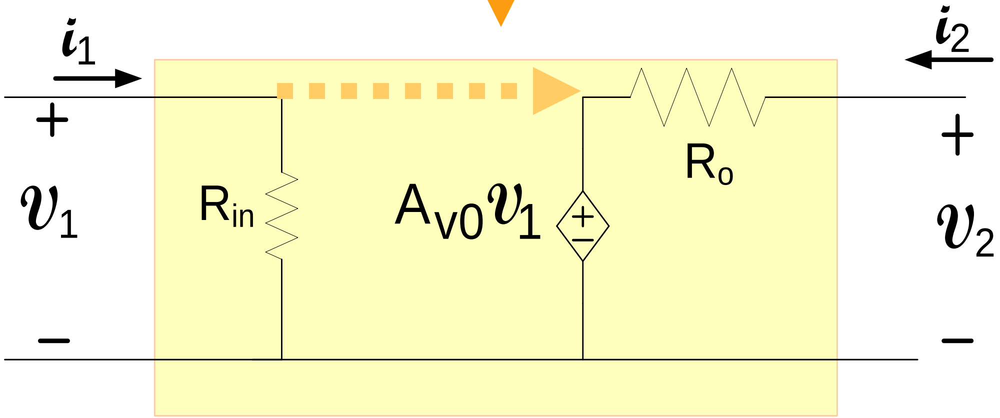
4. Ad Hoc Approaches

Two-port model for Common Emitter Configuration





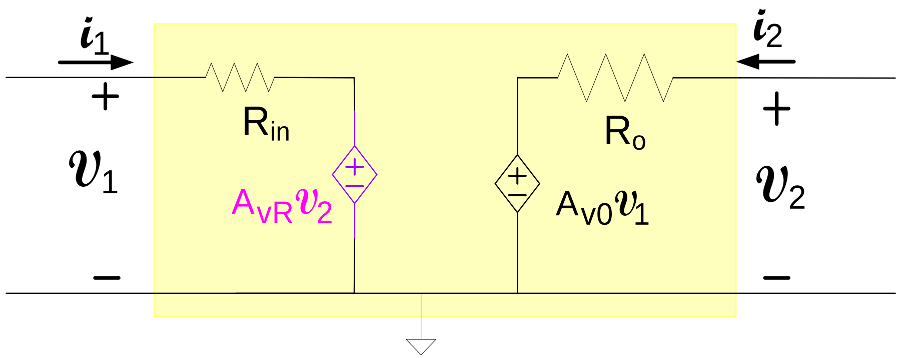


By Thevenin : Norton Transformations

$$R_{in} = \frac{1}{g_\pi} \qquad A_{V0} = -\frac{g_m}{g_0} \qquad R_0 = \frac{1}{g_0} \qquad A_{VR} = 0$$

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

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

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

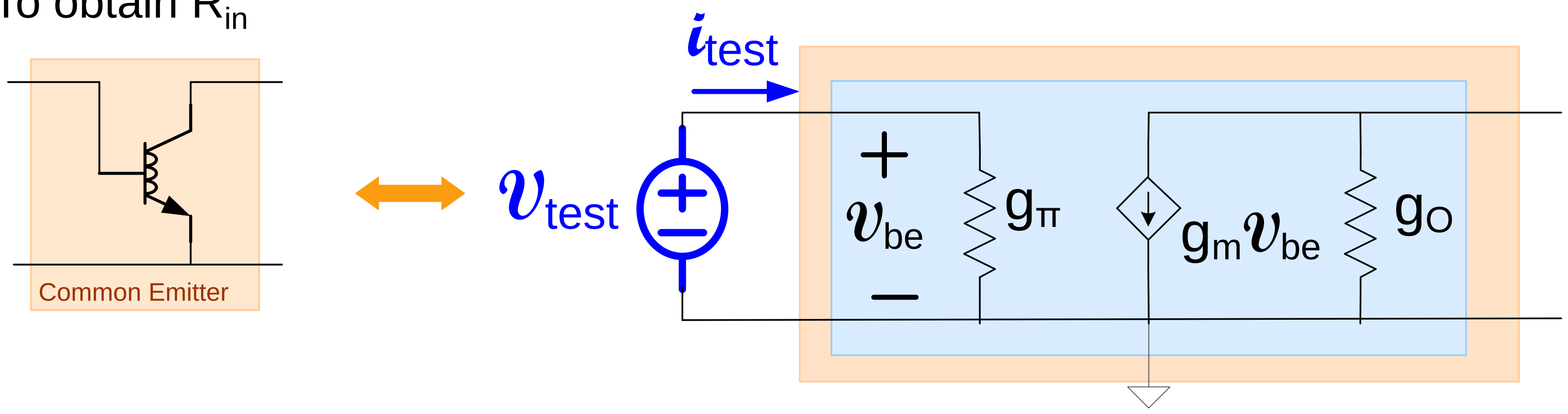
3. Thevenin-Norton Transformations

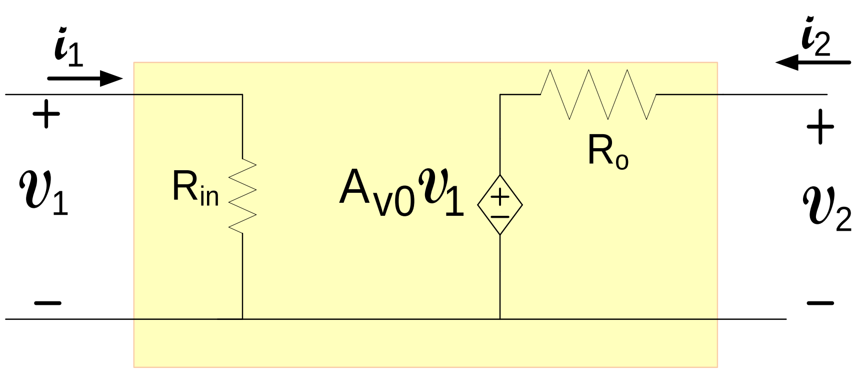
4. Ad Hoc Approaches

Two-port model for Common Emitter Configuration

Alternately, by v_{TEST} : i_{TEST} Method

To obtain R_{in}





$$R_{in} = \frac{v_{test}}{i_{test}}$$

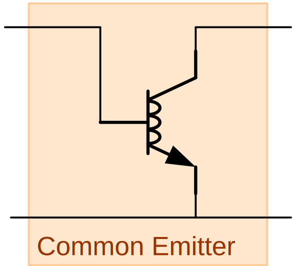
$$R_{in} = \frac{1}{g_\pi}$$

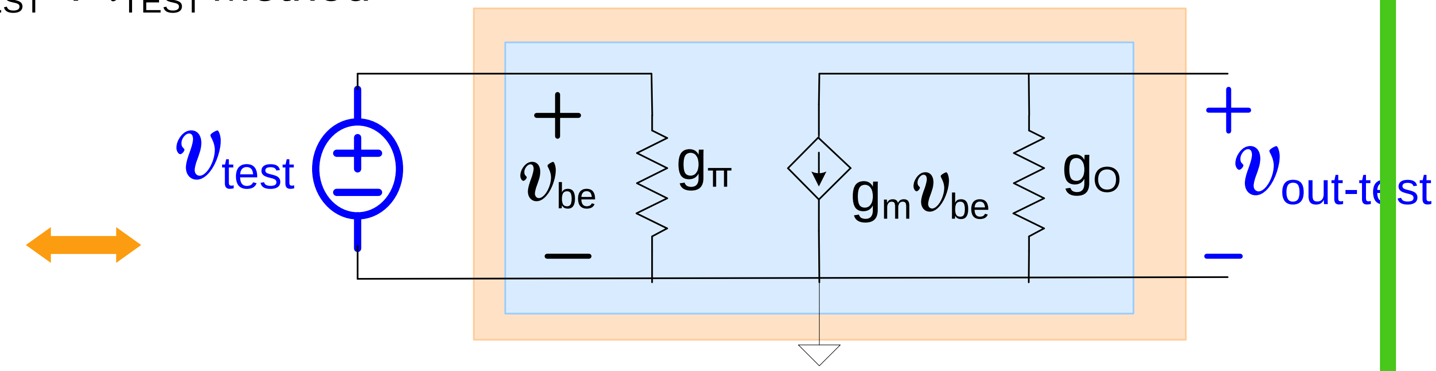
{R_{in}, A_{V0} and R_0}

Two-port model for Common Emitter Configuration

Alternately, by v_{TEST} : i_{TEST} Method

To obtain A_{V0}

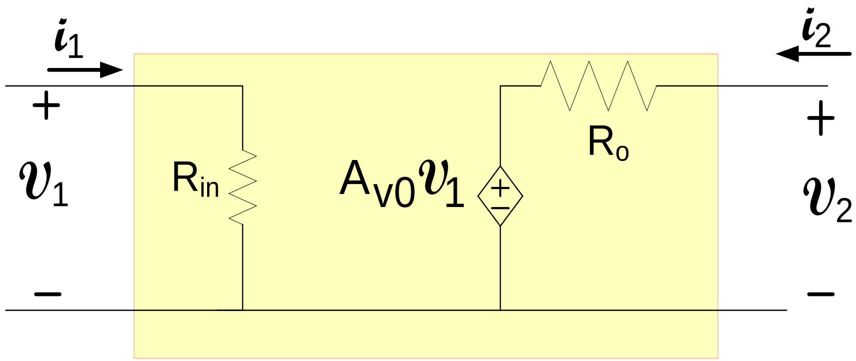




$$A_{V0} = \frac{v_{out\text{-}test}}{v_{test}}$$

$$v_{out-test} = v_{test}\left(-\frac{g_m}{g_0}\right)$$

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

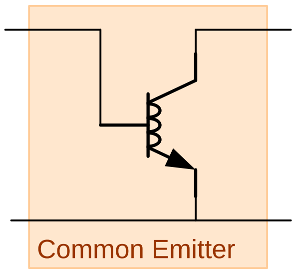


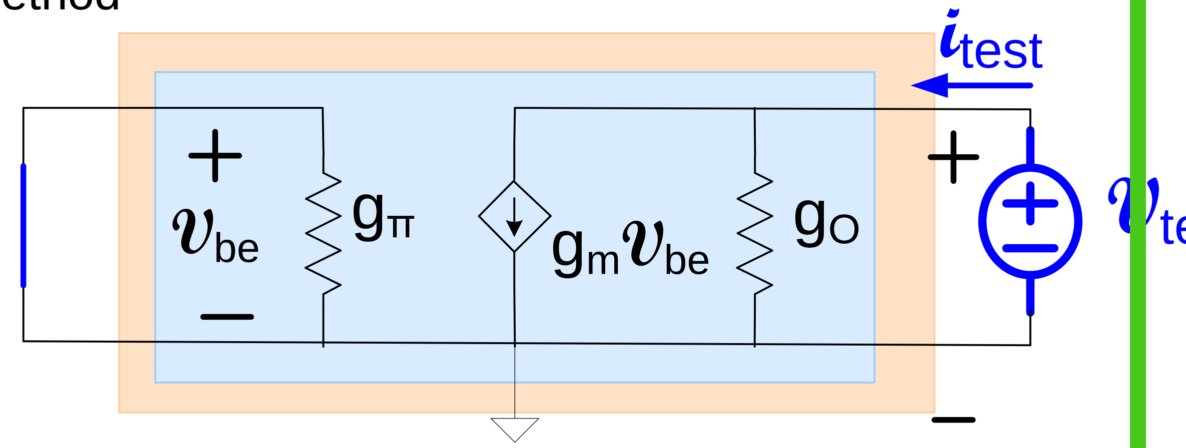
{R_{in}, A_{V0} and R_0}

Two-port model for Common Emitter Configuration

Alternately, by v_{TEST} : i_{TEST} Method

To obtain g_0

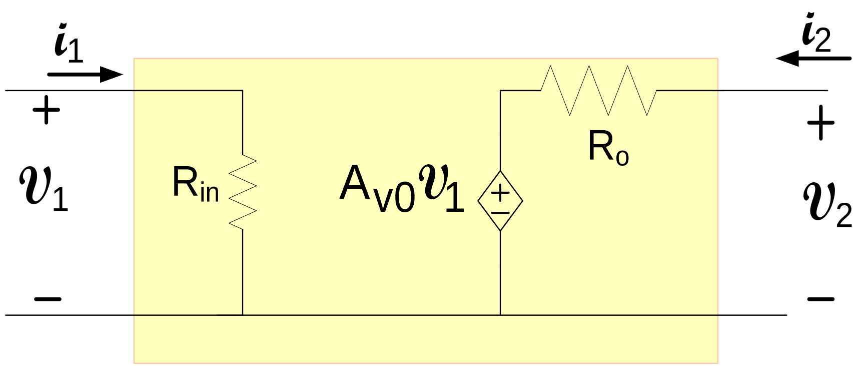




$$R_0 = \frac{v_{test}}{i_{test}}$$

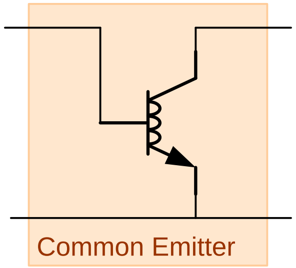
$$v_{test} = i_{test}\left(g_0\right)$$

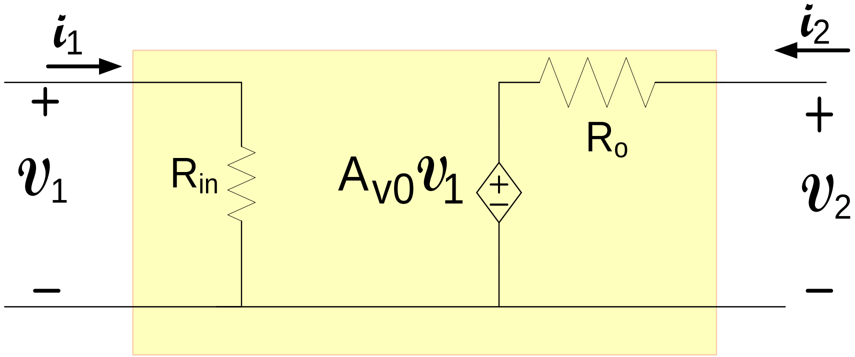
$$R_0 = \frac{1}{g_0}$$



{R_{in}, A_{V0} and R_0}

Two-port model for Common Emitter Configuration





In terms of small signal model parameters:

$$R_{in} = \frac{1}{g_\pi} \qquad A_{V0} = -\frac{g_m}{g_0} \qquad R_0 = \frac{1}{g_0} \qquad A_{VR} = 0$$

In terms of operating point and model parameters:

$$R_i = \frac{\beta V_t}{I_{CQ}} \qquad A_{V0} = -\frac{V_{AF}}{V_t} \qquad R_0 = \frac{V_{AF}}{I_{CQ}} \qquad A_{VR} = 0$$

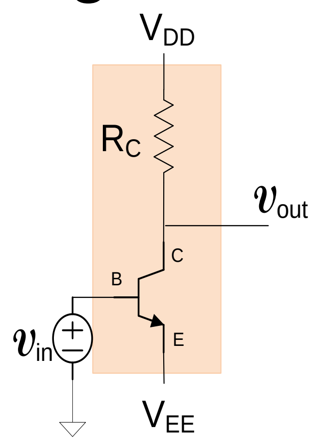
Characteristics:

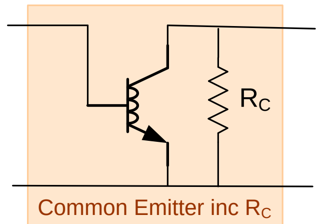
- Input impedance is mid-range
- Voltage Gain is Large and Inverting
- Output impedance is large
- Unilateral
- Widely used to build voltage amplifiers

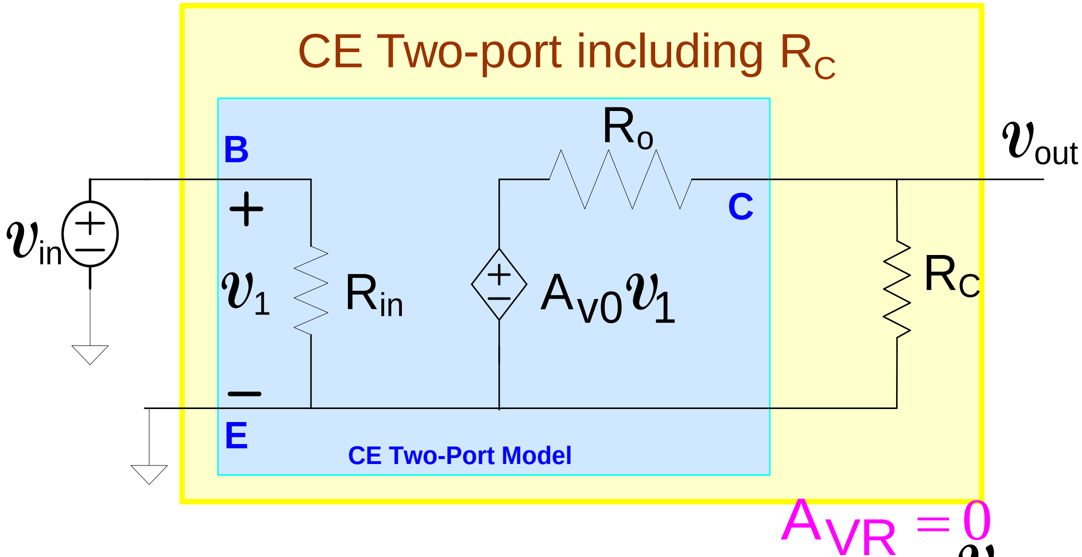
Common Emitter Configuration

Consider the following CE application

(this will also generate a two-port model for this CE application)







$$v_{out}\left(g_C + g_0\right) = g_0 A_{V0} v_{in} \rightarrow A_{VC} = \frac{v_{out}}{v_{in}} = \frac{g_0 A_{V0}}{g_0 + g_C} = \frac{-g_m}{g_0 + g_C} \overset{g_0 << g_C}{\cong} -g_m R_C$$

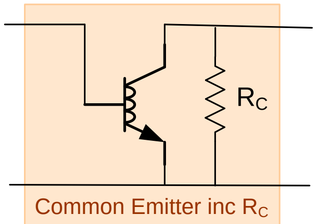
$$R_{inC} = R_{in} = r_\pi$$

$$R_{outC} = R_o // R_C \rightarrow R_{outC} = R_o // R_C = \frac{1}{g_0 + g_C} \overset{g_0 << g_C}{\cong} R_C$$

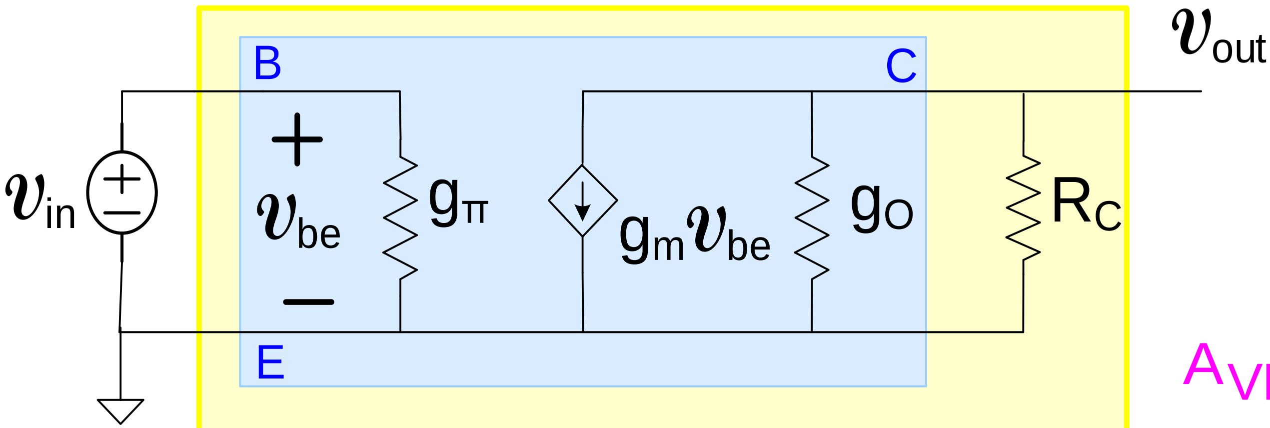
Common Emitter Configuration

Consider the following CE application

(this will also generate a two-port model for this CE application)



This circuit can also be analyzed directly without using 2-port model for CE configuration



$A_{VR} = 0$

$$v_{out} = -g_m v_{in}\left(\frac{1}{g_0 + g_C}\right)$$

$$A_v = \frac{v_{out}}{v_{in}} = -\left(\frac{g_m}{g_0 + g_C}\right) \overset{g_0 << g_C}{\cong} -g_m R_C$$

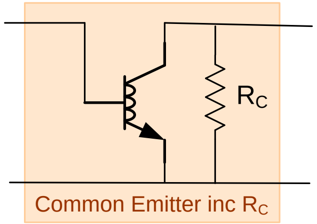
$$R_{in} = r_\pi$$

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

Common Emitter Configuration

Consider the following CE application

(this is also a two-port model for this CE application)



Small signal parameter domain

Operating point and model parameter domain

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

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

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

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

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

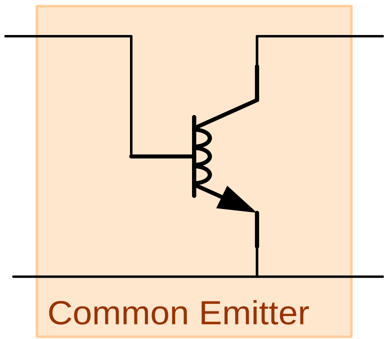
$$R_{in} = \frac{\beta V_t}{I_{CQ}}$$

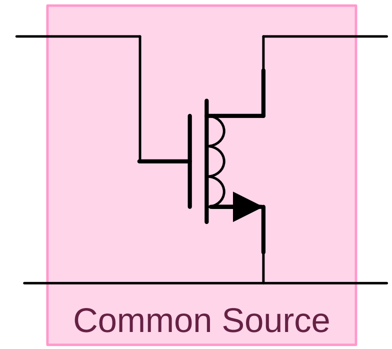
$$A_{VR} = 0$$

Characteristics:

- Input impedance is mid-range
- Voltage Gain is large and Inverting
- Output impedance is mid-range
- Unilateral
- Widely used as a voltage amplifier

Common Source/ Common Emitter Configurations





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

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

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

In terms of operating point and model parameters:

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

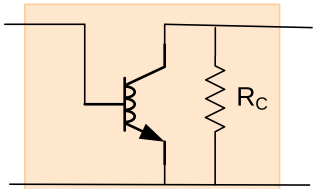
$$R_{in} = \infty \qquad R_0 = \frac{1}{\lambda I_{DQ}} = \frac{V_{AF}}{I_{DQ}}$$

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

Characteristics:

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

Common Source/Common Emitter Configuration



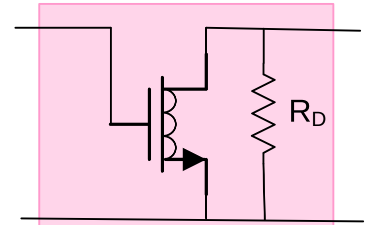
Common Emitter inc R$_C$

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

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

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

$$A_{VR} = 0$$



Common Source inc R$_D$

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

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

$$A_{VR} = 0$$

$$R_{in} = \infty$$

In terms of operating point and model parameters:

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

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

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

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

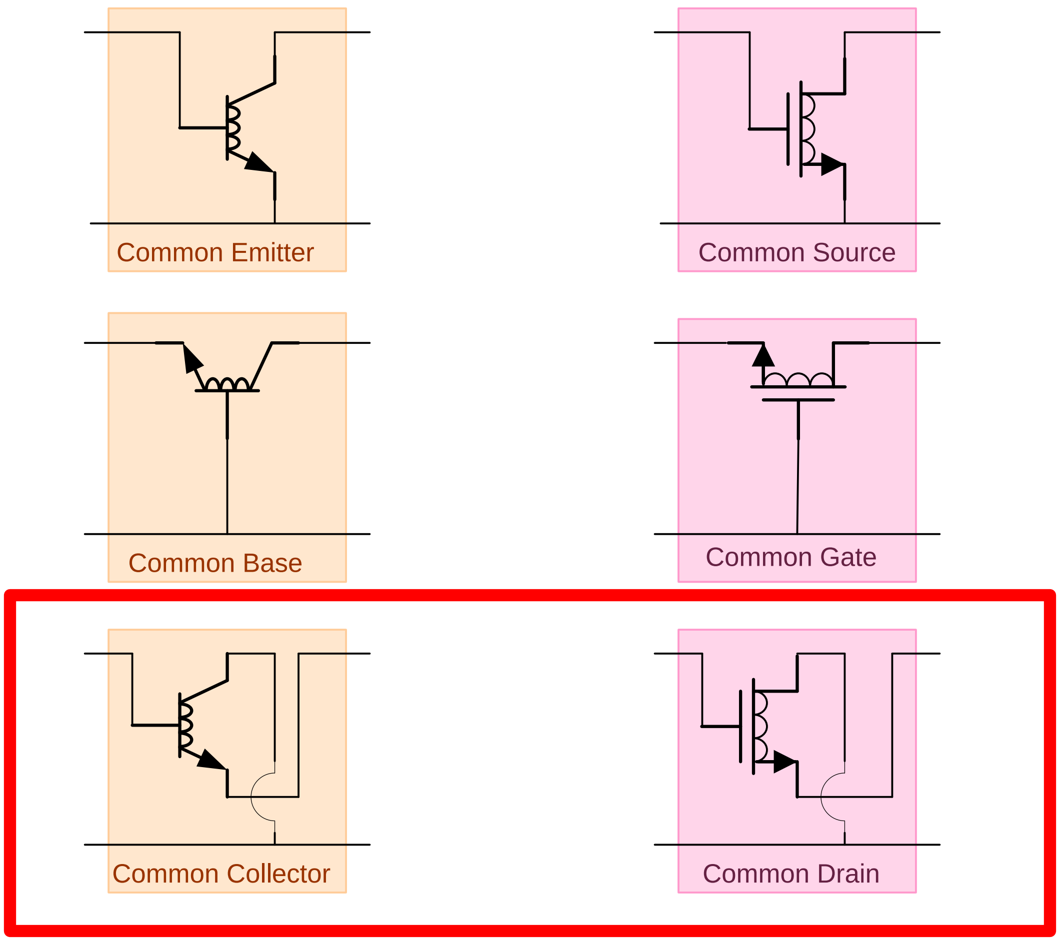
$$R_{in} = \infty$$

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

Characteristics:

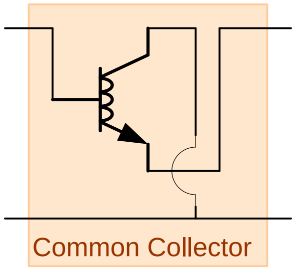
- Input impedance is mid-range (infinite for MOS)
- Voltage Gain is Large and Inverting
- Output impedance is mid-range
- Unilateral
- Widely used as a voltage amplifier

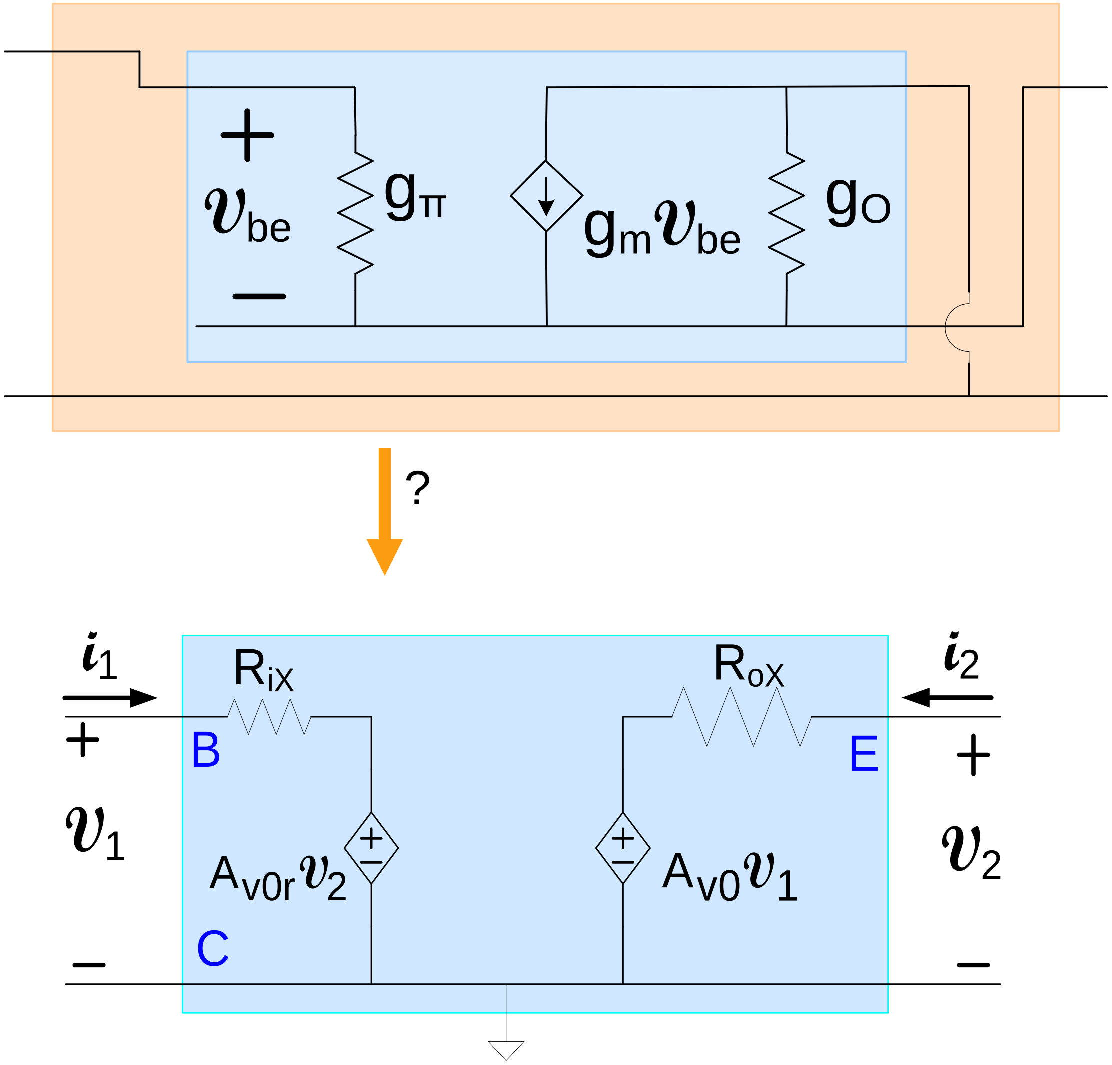
Consider Common Collector/Common Drain Two-port Models



Will focus on Bipolar Circuit since MOS counterpart is a special case obtained by setting $g_\pi=0$

Two-port model for Common Collector Configuration

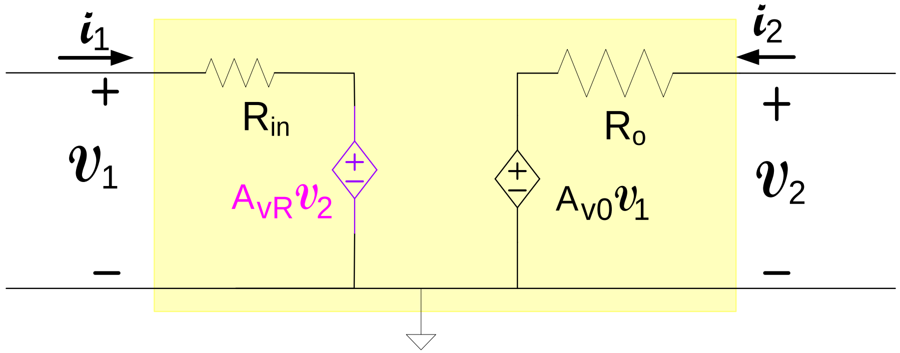




{R_{iX}, A_{V0}, A_{V0r} and R_{0X}}

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

Methods of Obtaining Amplifier Two-Port Network



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

2. Write v_1 : v_2 equations in standard form

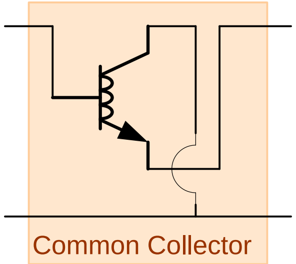
$$v_1 = i_1 R_{IN} + A_{VR} v_2$$

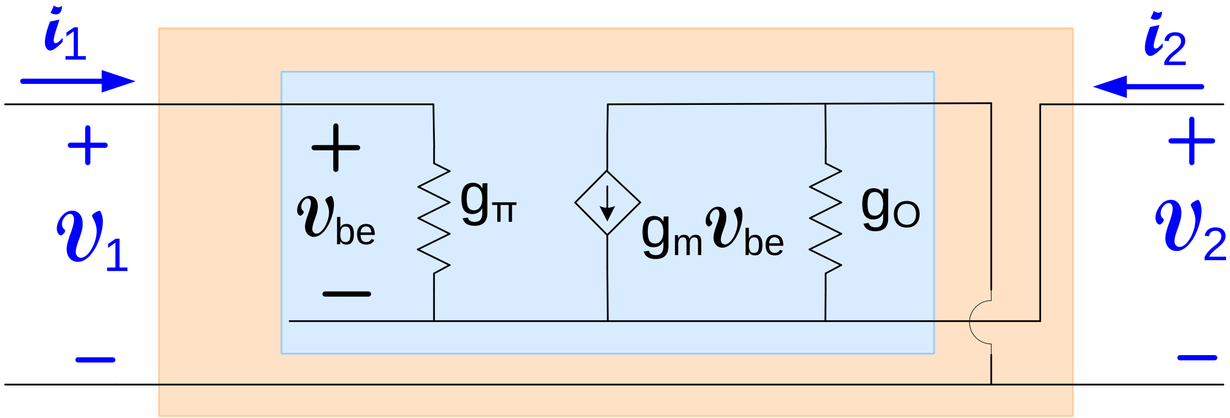
$$v_2 = i_2 R_O + A_{V0} v_1$$

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches

Two-port model for Common Collector Configuration





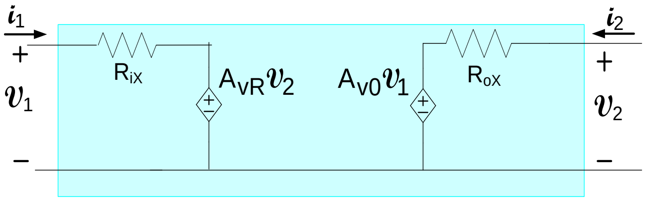
Applying KCL at the input and output node, obtain

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

These can be rewritten as

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

Standard Two-Port Amplifier Representation



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

$$v_2 = i_2 R_{oX} + A_V v_1$$

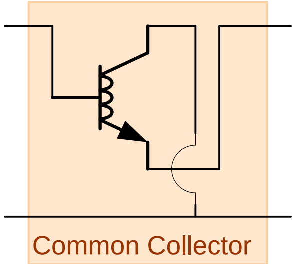
$v_1 : v_2$ equations in standard form

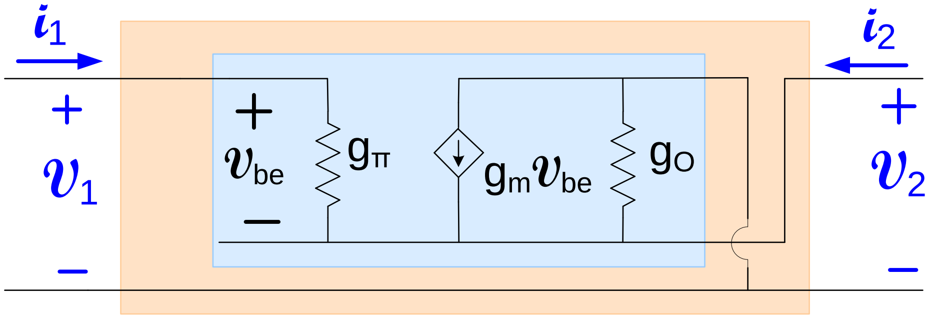
It thus follows that

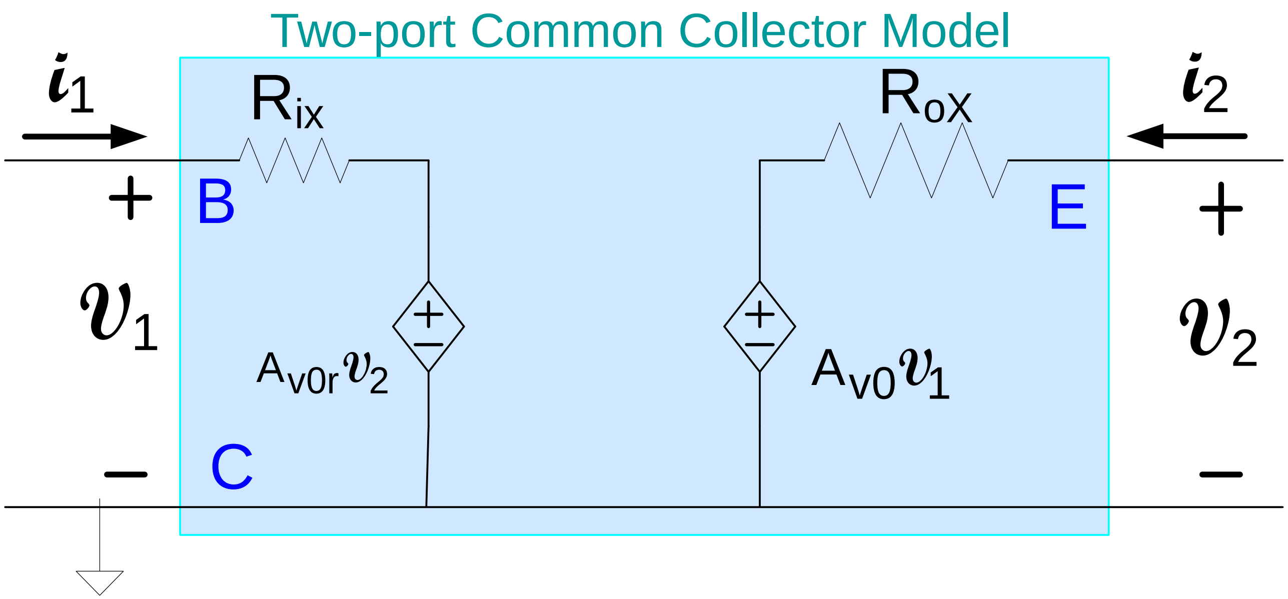
$R_{iX} = r_\pi$ $\qquad$ $A_{VOr} = 1$

$$R_{0X} = \left(\frac{1}{g_m + g_\pi + g_o}\right) \qquad A_{V0} = \left(\frac{g_m + g_\pi}{g_m + g_\pi + g_o}\right)$$

Two-port model for Common Collector Configuration







$R_{ix} = r_\pi$

$A_{V0r} = 1$

$$R_{0X} = \left(\frac{1}{g_m + g_\pi + g_o} \right) \cong \frac{1}{g_m}$$

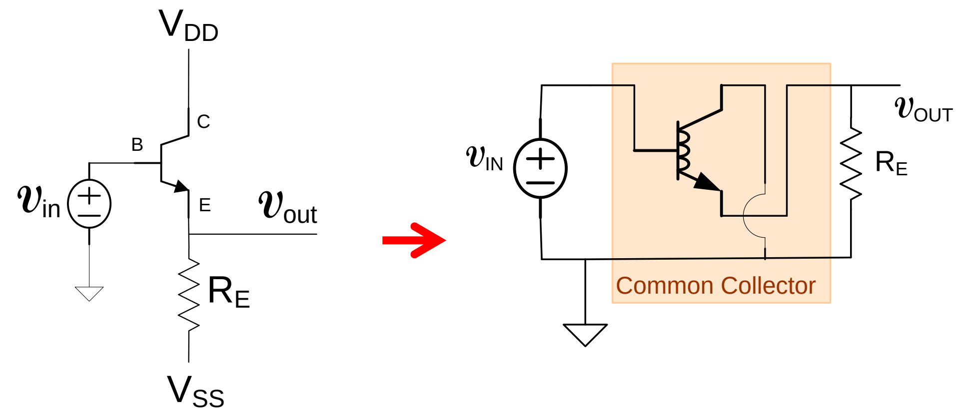
$$A_{V0} = \left(\frac{g_m + g_\pi}{g_m + g_\pi + g_o} \right) \cong 1$$

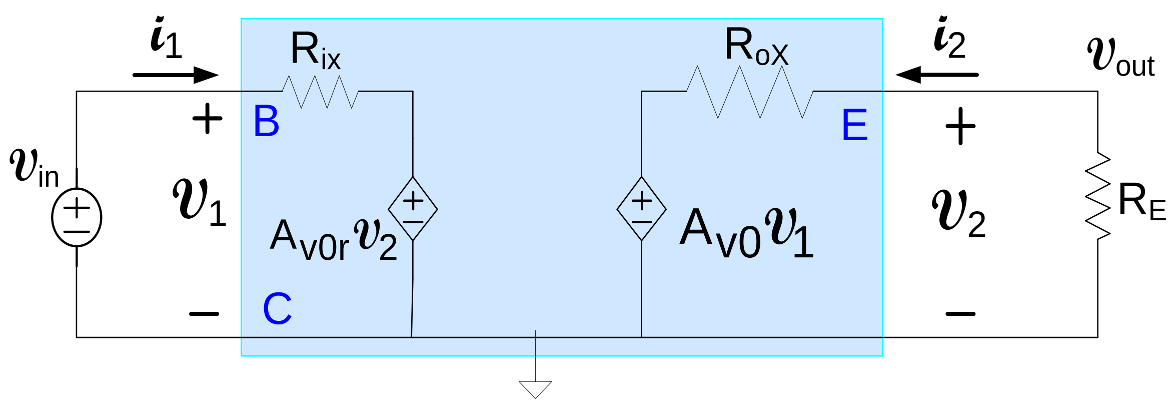
Common Collector Configuration

Consider the following CC application

Determine R_{in}, R_0, and A_V

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





$$A_V = A_{V0}\frac{g_{ox}}{g_{ox}+g_E} = \frac{g_m+g_\pi}{g_m+g_\pi+g_o}\left(\frac{g_m+g_\pi+g_o}{g_m+g_\pi+g_o+g_E}\right) = \frac{g_m+g_\pi}{g_m+g_\pi+g_o+g_E} \cong \frac{g_m}{g_m+g_E} \overset{if\ g_m>>g_E}{\cong} 1$$

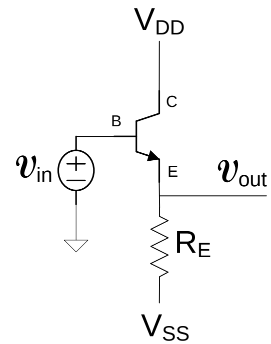
$$v_{in} = i_1 R_{ix} + A_{v0r}A_{v0}\frac{g_{0X}}{g_{0X}+g_E}v_{in} \rightarrow R_{in} = \frac{r_\pi}{1-\dfrac{g_m+g_\pi}{g_m+g_\pi+g_o+g_E}} = r_\pi\frac{g_m+g_\pi+g_o+g_E}{g_o+g_E} \overset{g_E>>g_o}{\cong} r_\pi+\beta R_E$$

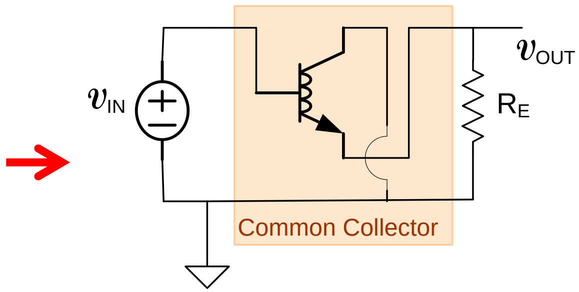
$$R_0 \cong \frac{1}{g_m+g_E+g_0+g_\pi} = \frac{1}{g_m+g_E} = \frac{R_E}{1+g_m R_E} \overset{g_m>>g_E}{\cong} \frac{1}{g_m}$$

Common Collector Configuration

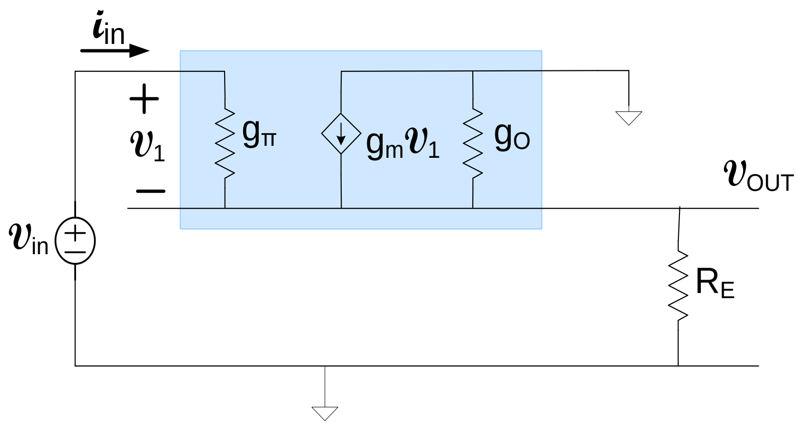
Consider the following CC application

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





Alternately, this circuit can also be analyzed directly



$$\left.\begin{aligned} v_{out}(g_E+g_0+g_\pi) &= v_{in}g_\pi + g_m v_1 \\ v_{in} &= v_1 + v_{out} \end{aligned}\right\}$$

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

$$A_V = \frac{g_\pi+g_m}{g_m+g_E+g_0+g_\pi} \cong \frac{g_m}{g_m+g_E} = \frac{I_{CQ}R_E}{I_{CQ}R_E+V_t}$$

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

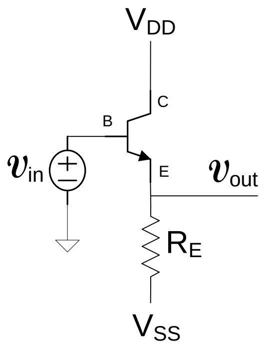
$$i_{in}(g_m+g_\pi+g_E+g_0) = g_\pi v_{in}(g_E+g_0)$$

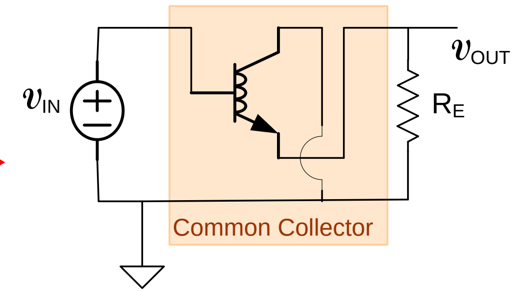
$$R_{in} = r_\pi \frac{g_m+g_\pi+g_o+g_E}{g_o+g_E} \overset{g_E \gg g_o}{\cong} r_\pi + \beta R_E$$

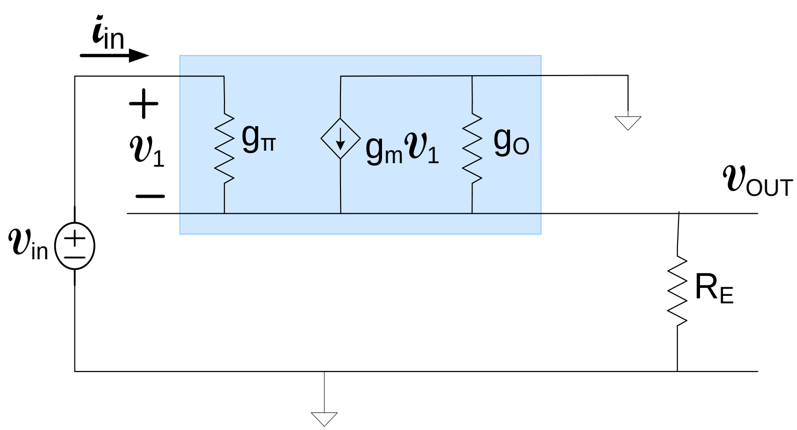
Common Collector Configuration

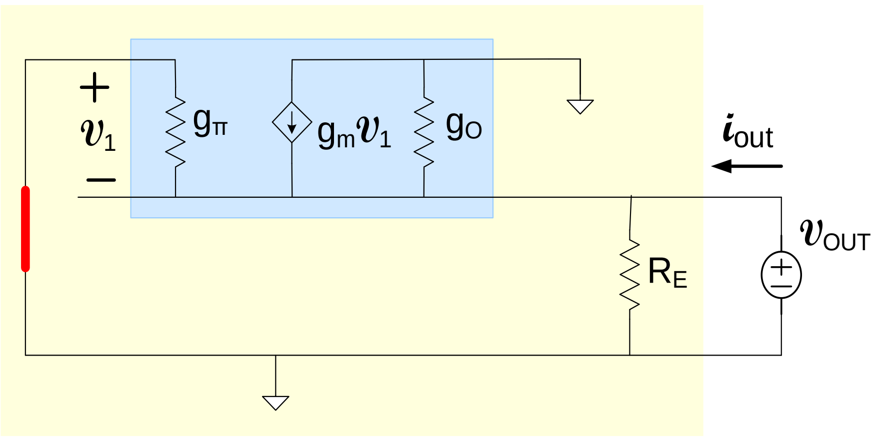
Consider the following CC application

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









To obtain R_0, set $v_{in} = 0$

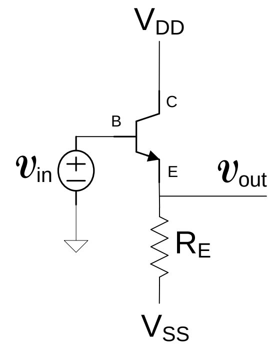
$$i_{out} = v_{out}\left(g_E + g_0 + g_\pi\right) - g_m\left(-v_{out}\right)$$

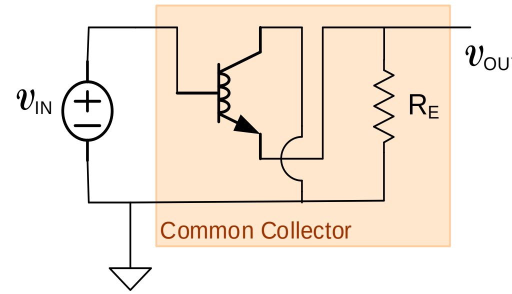
$$R_{out} = \frac{1}{g_m + g_\pi + g_o + g_E} \overset{g_E \ll g_o}{\cong} \frac{1}{g_m}$$

Common Collector Configuration

Consider the following CC application

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





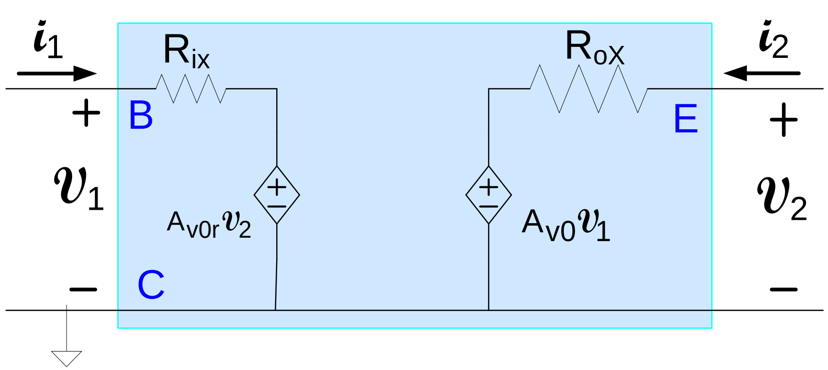
$$A_V = \frac{g_\pi + g_m}{g_m + g_E + g_0 + g_\pi} \cong \frac{g_m}{g_m + g_E} = \frac{I_{CQ}R_E}{I_{CQ}R_E + V_t} \cong 1$$

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

$$R_{out} = \frac{1}{g_m + g_\pi + g_o + g_E} \overset{g_E << g_o}{\cong} \frac{1}{g_m}$$

Question: Why are these not the two-port parameters of this circuit?

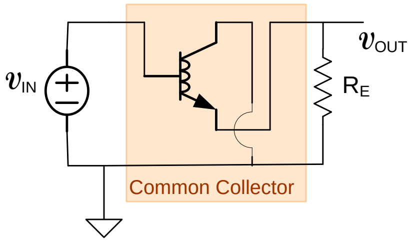
- R_{in} defined for open-circuit on output instead of short-circuit (see previous slide : -2 slides)
- $A_{V0r} \neq 0$

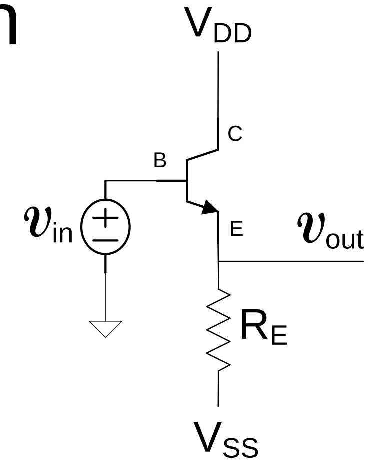


Common Collector Configuration

For this CC application

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





Small signal parameter domain

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

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

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

Operating point and model parameter domain

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

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

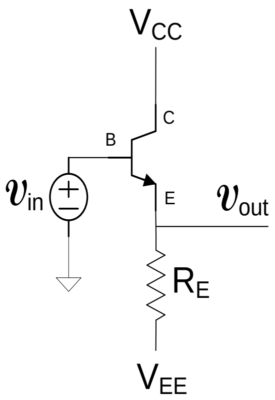
$$R_0 \overset{I_{CQ} R_E >> V_t}{\cong} \frac{V_t}{I_{CQ}}$$

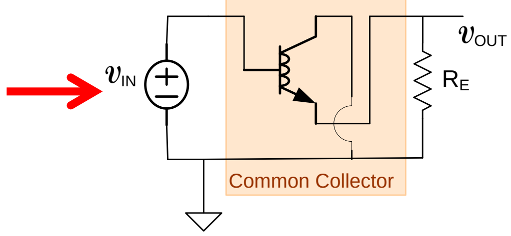
Characteristics:

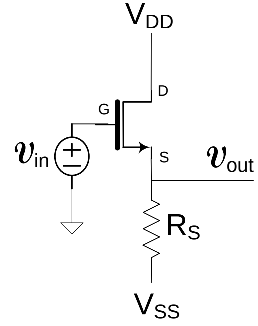
- Output impedance is low
- A_{V0} is positive and near 1
- Input impedance is very large
- Widely used as a buffer
- Not completely unilateral but output-input transconductance (or A_{Vr}) is small and effects are generally negligible though magnitude same as A_V

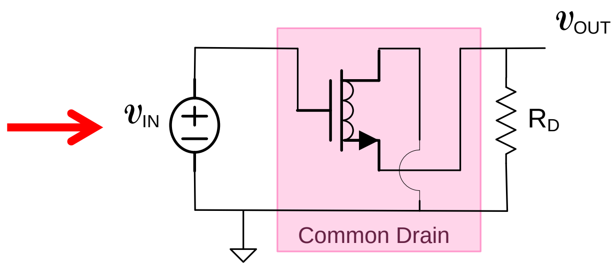
Common Collector/Common Drain Configurations

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









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

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

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

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

$$R_{in} = \infty$$

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

In terms of operating point and model parameters:

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

$$R_0 \overset{I_{CQ} R_E >> V_t}{\cong} \frac{V_t}{I_{CQ}}$$

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

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

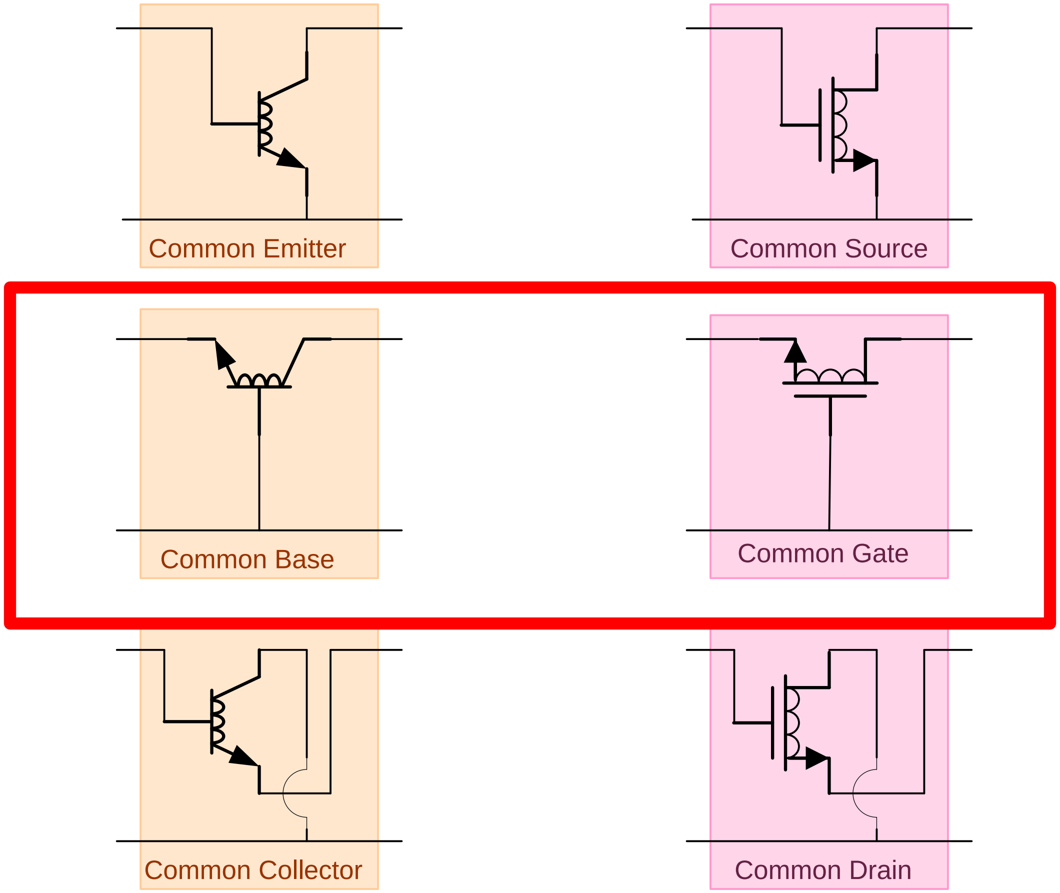
$$R_0 \cong \frac{V_{EBQ} R_S}{V_{EBQ} + 2 I_{DQ} R_S} \overset{2 I_{DQ} R_S >> V_{EBQ}}{\cong} \frac{V_{EBQ}}{2 I_{DQ}}$$

$$R_{in} = \infty$$

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

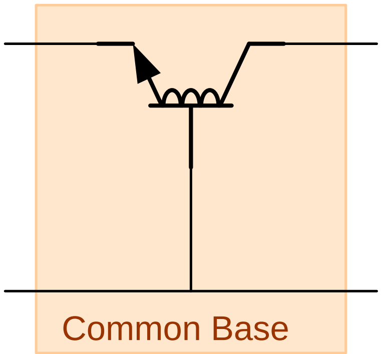
- Widely used as a buffer
- Not completely unilateral but output-input transconductance is small

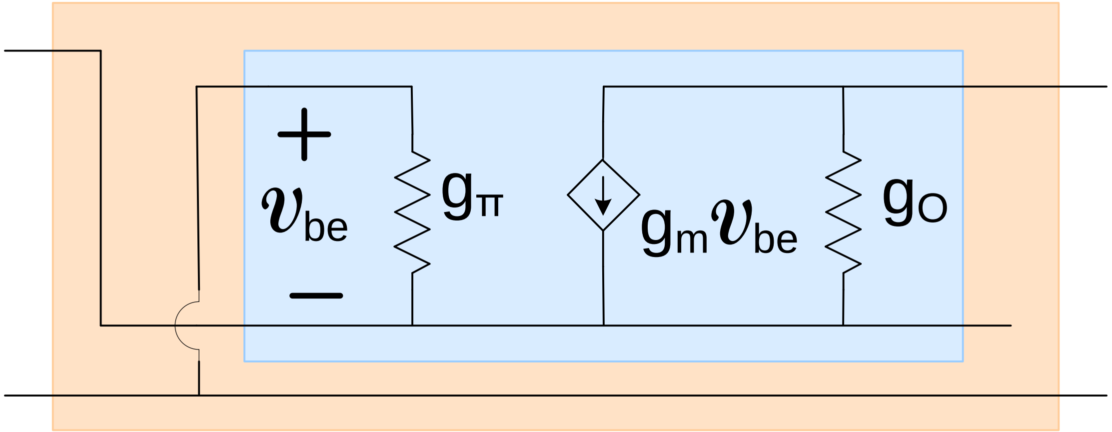
Consider Common Base/Common Gate Two-port Models

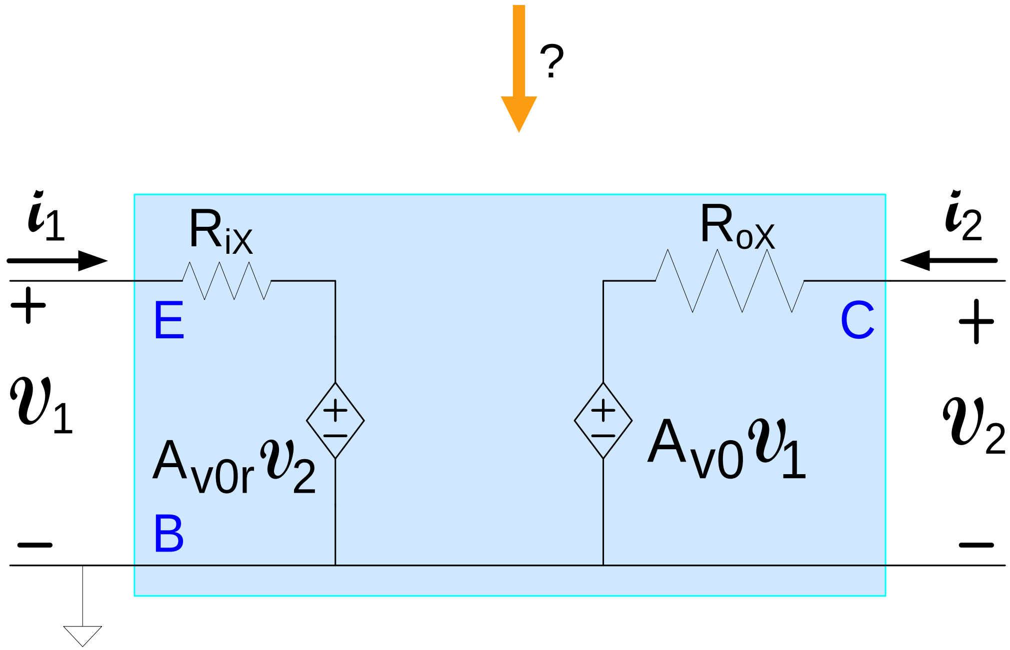


Will focus on Bipolar Circuit since MOS counterpart is a special case obtained by setting g_π=0

Two-port model for Common Base Configuration



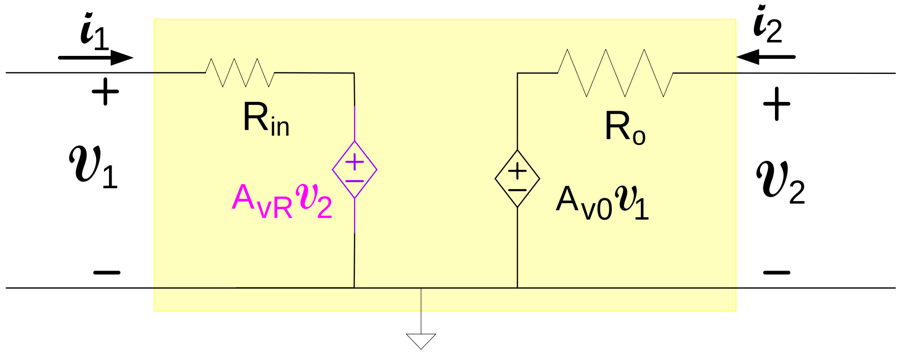




$\{R_{iX}, A_{V0}, A_{V0r}$ and $R_{0X}\}$

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

Methods of Obtaining Amplifier Two-Port Network



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

2. Write v_1 : v_2 equations in standard form

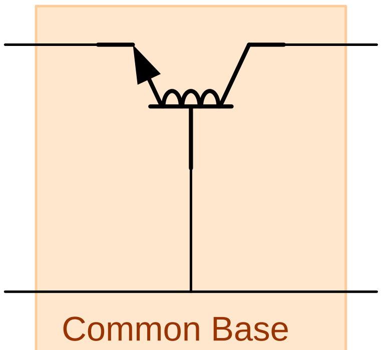
$$v_1 = i_1 R_{IN} + A_{VR} v_2$$

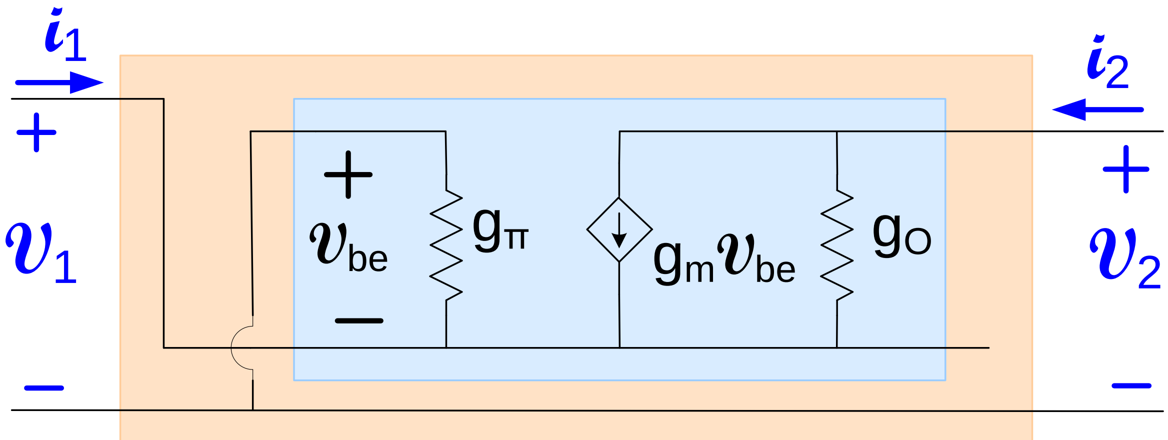
$$v_2 = i_2 R_O + A_{V0} v_1$$

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches

Two-port model for Common Base Configuration





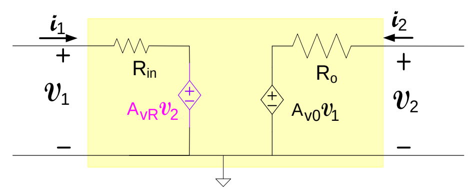
From KCL

$$i_1 = v_1 g_\pi + (v_1 - v_2) g_0 + g_m v_1$$
$$i_2 = (v_2 - v_1) g_0 - g_m v_1$$

These can be rewritten as

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

Standard Form for Amplifier Two-Port



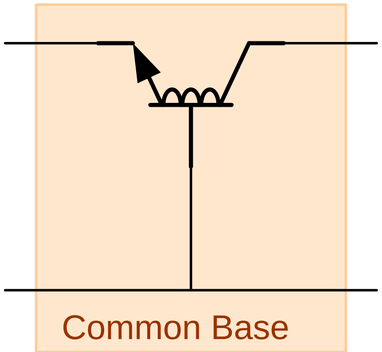
$$v_1 = i_1 R_{IN} + A_{VR} v_2$$
$$v_2 = i_2 R_O + A_{V0} v_1$$

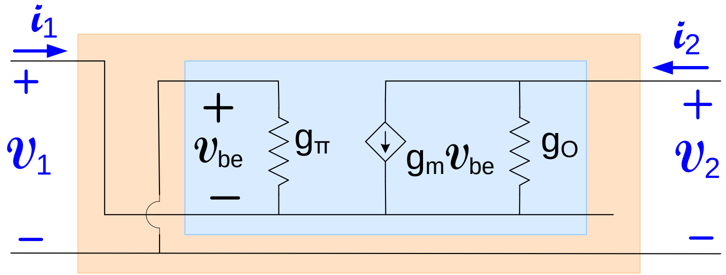
$v_1 : v_2$ equations in standard form

It thus follows that:

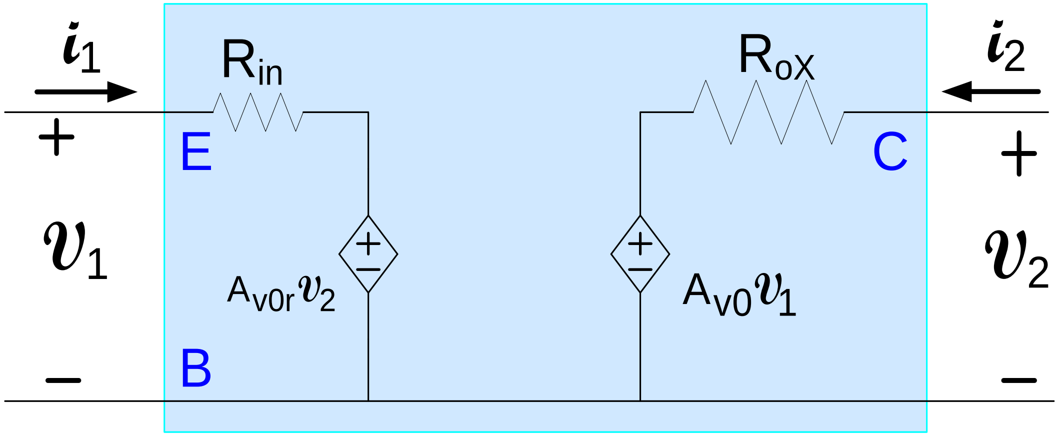
$$R_{iX} = \frac{1}{g_m + g_\pi + g_0} \cong \frac{1}{g_m} \qquad A_{VOr} = \frac{g_0}{g_m + g_\pi + g_0} \qquad A_{V0} = 1 + \frac{g_m}{g_0} \cong \frac{g_m}{g_0} \qquad R_{oX} = \frac{1}{g_0}$$

Two-port model for Common Base Configuration





Two-port Common Base Model



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

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

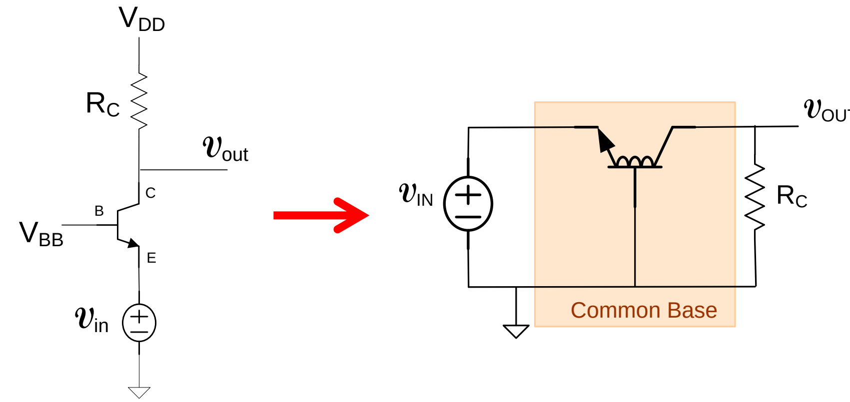
$$A_{VOr} = \frac{g_0}{g_m + g_\pi + g_0} \cong \frac{g_0}{g_m}$$

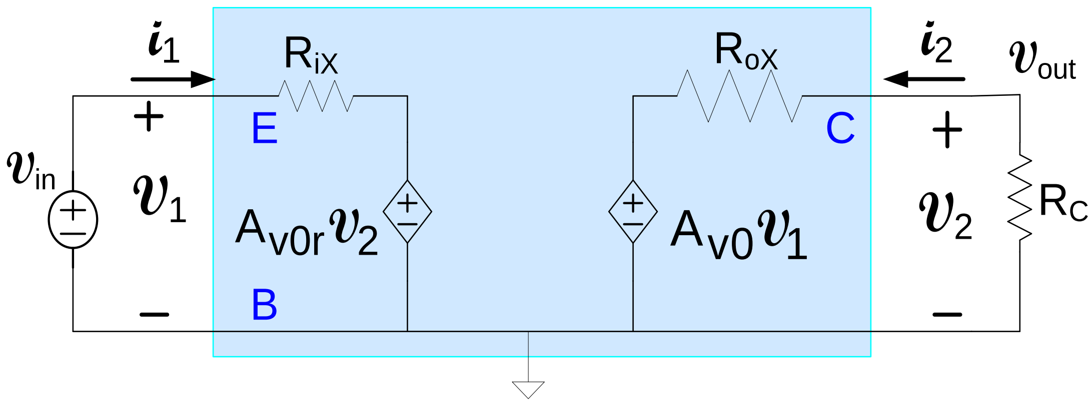
$$R_{oX} = \frac{1}{g_0}$$

Common Base Configuration

Consider the following CB application

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





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

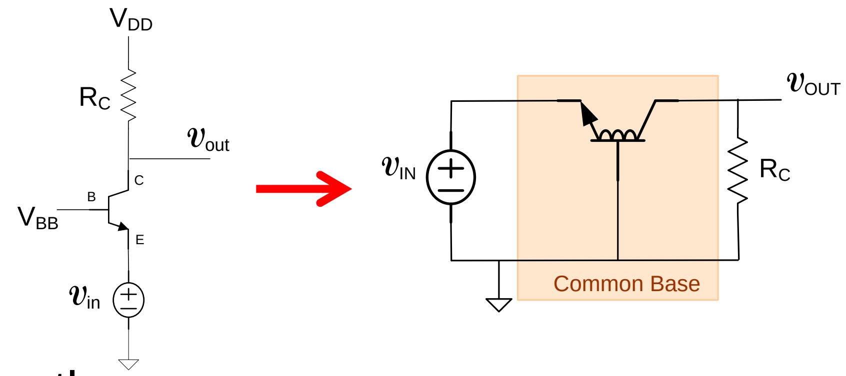
$$R_{in} = \frac{v_{in}}{i_1} = \frac{i_1 R_{iX} + A_{V0r} v_{out}}{i_1} \rightarrow R_{in} = \frac{R_{iX}}{1-A_{V0r}A_V} = \frac{g_0+g_C}{g_C\left(g_m+g_\pi+g_0\right)+g_\pi g_0} \cong \frac{1}{g_m}$$

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

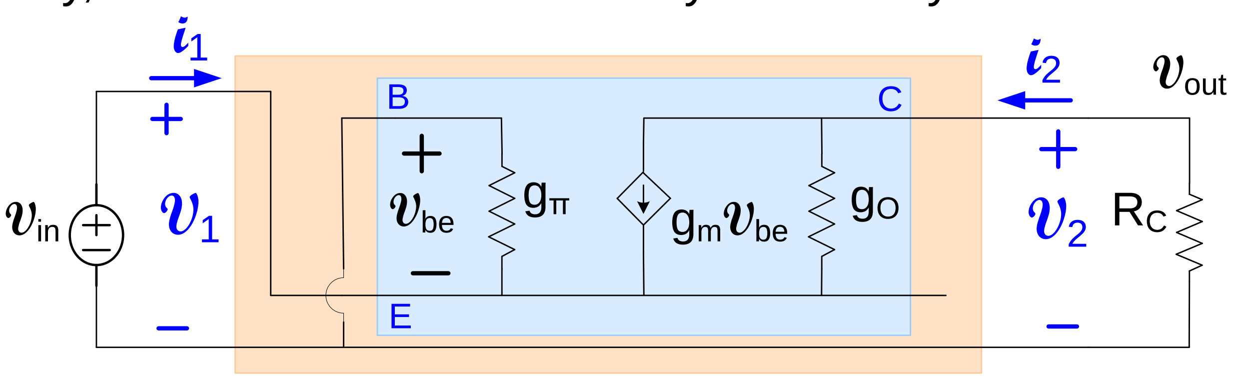
Common Base Configuration

Consider the following 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



By KCL at the output node, obtain

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

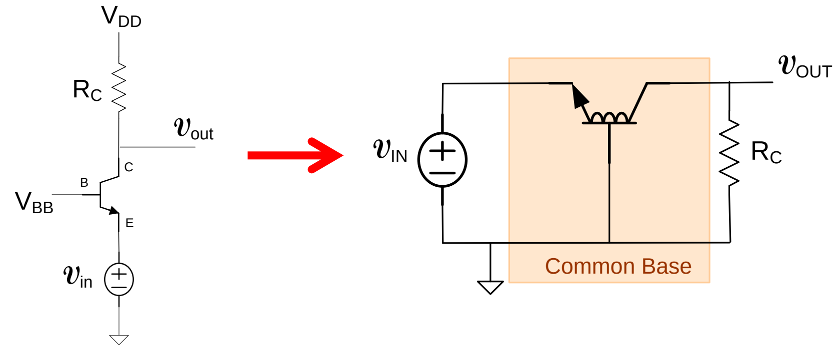
By KCL at the emitter node, obtain

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

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

Common Base Application

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



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

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

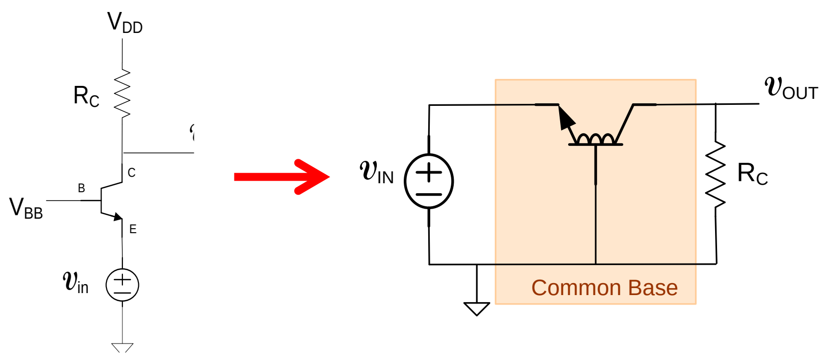
$$R_{out} \overset{R_C << r_0}{\cong} R_C \qquad R_{out} \overset{R_C << r_0}{\cong} R_C$$

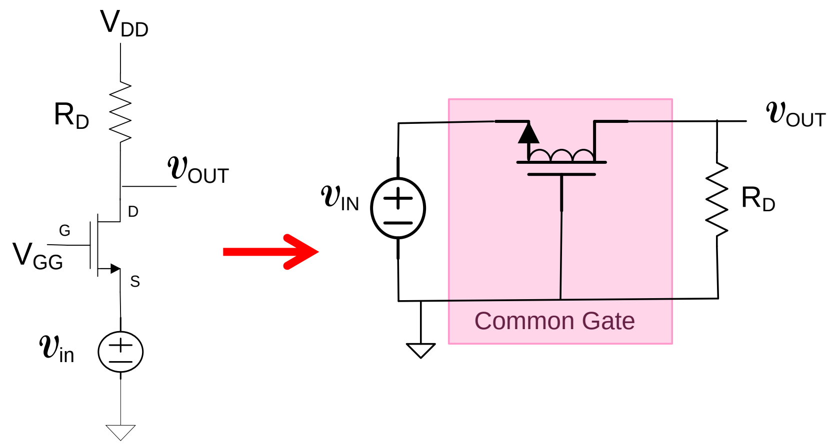
Characteristics:

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

Common Base/Common Gate Application

(these are not a two-port models)





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

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

In terms of operating point and model parameters:

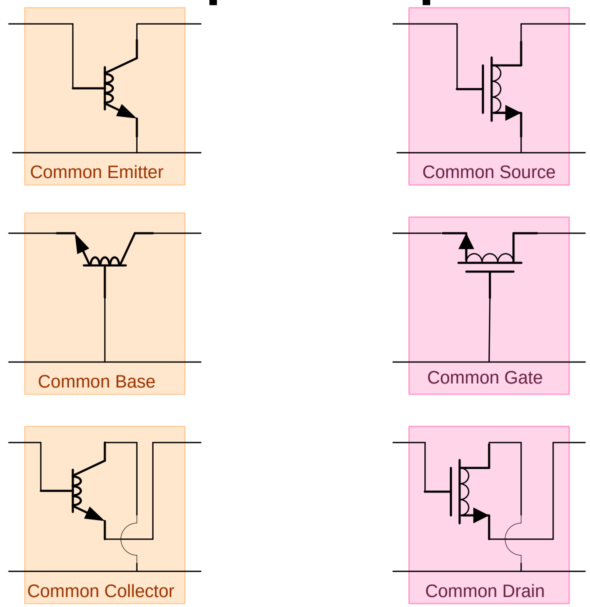
$$A_V \cong \frac{I_{CQ}R_C}{V_t} \qquad R_{in} \cong \frac{V_t}{I_{CQ}} \qquad R_{out} \overset{I_{CQ}R_C<<V_{AF}}{\cong} R_C$$

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

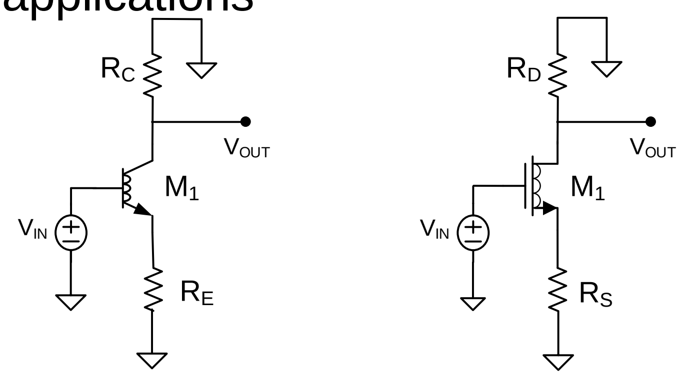
Characteristics:

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

The three basic amplifier types for both MOS and bipolar processes



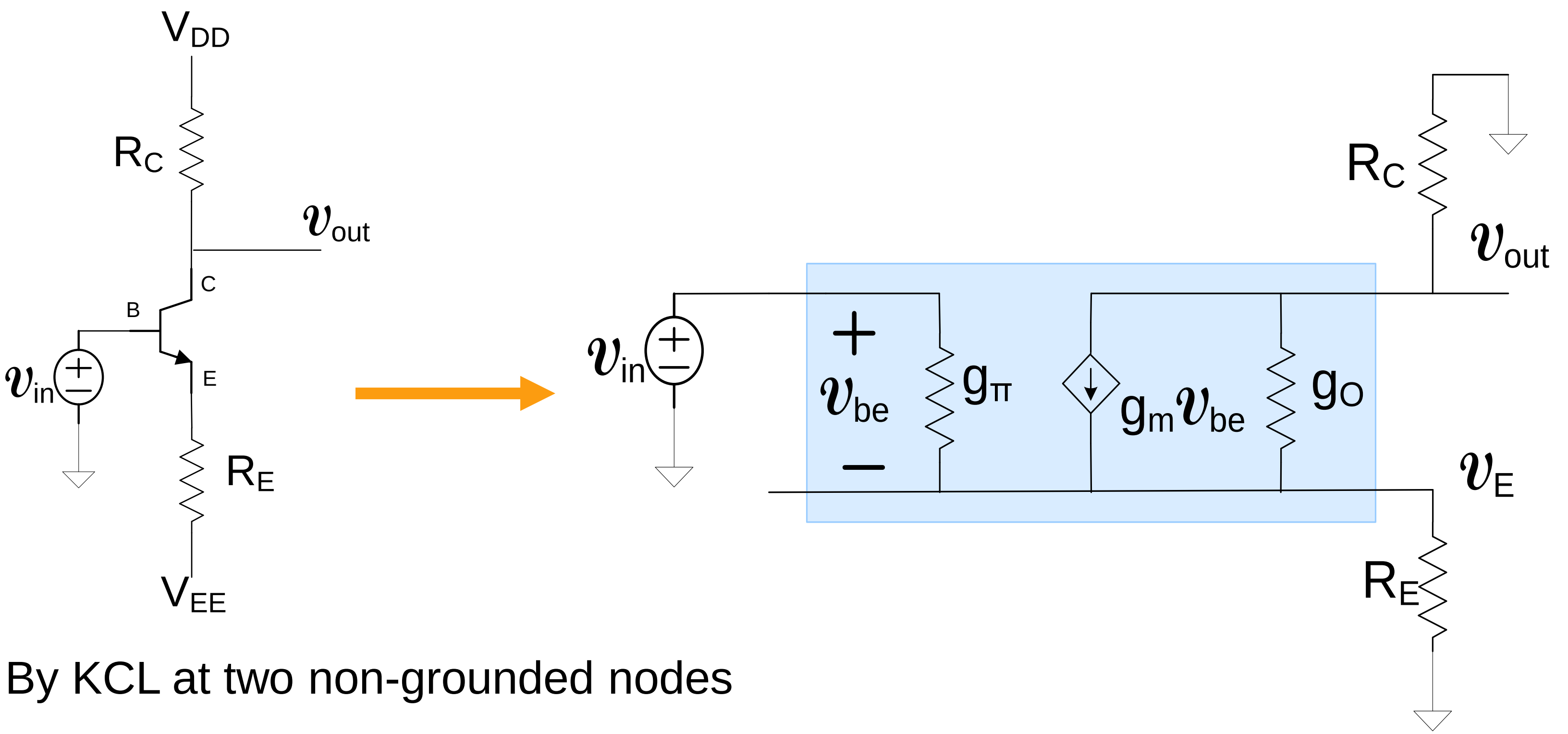
- Have developed both two-ports and a widely used application of all 6
- A fourth structure (two additional applications) is also quite common so will be added to list of basic applications



CE with R_E CS with R_S

Common Emitter with Emitter Resistor Configuration Application

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



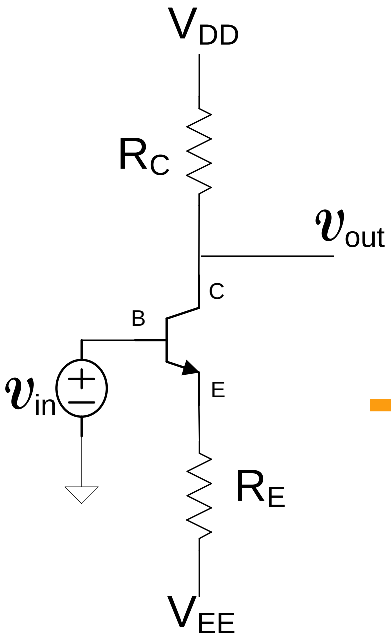
By KCL at two non-grounded nodes

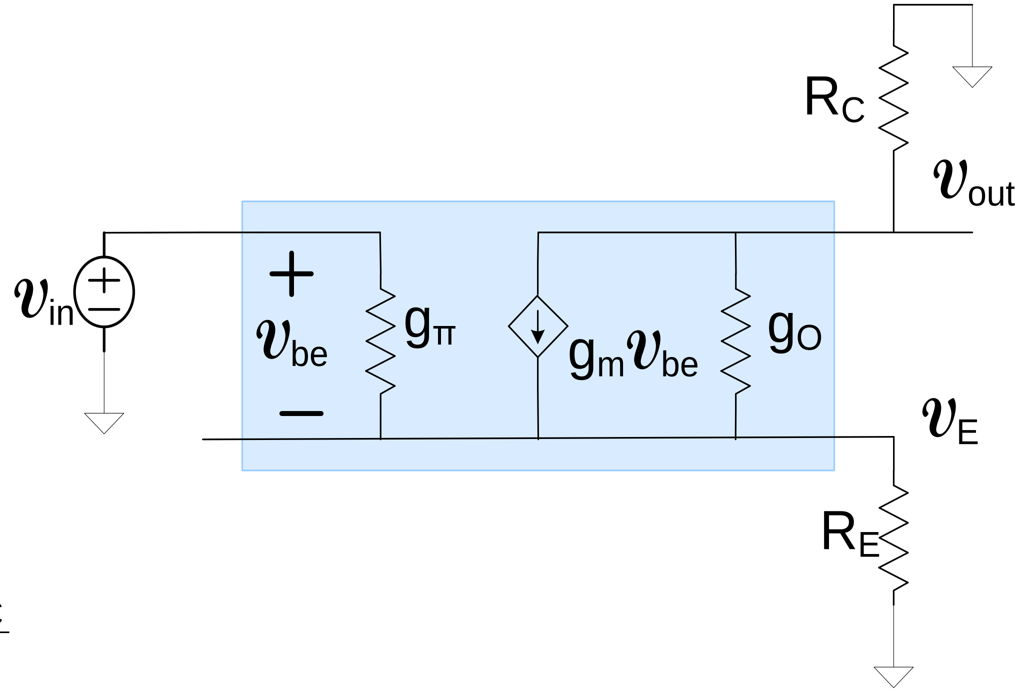
$$\left.\begin{aligned} v_{out}\left(g_C+g_0\right)+\left(v_{in}-v_E\right)g_m &= g_0 v_E \\ v_E\left(g_E+g_0+g_\pi\right)-\left(v_{in}-v_E\right)g_m &= g_0 v_{out}+g_\pi v_{in} \end{aligned}\right\}$$

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

Common Emitter with Emitter Resistor Configuration Application

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





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

It can also be shown that

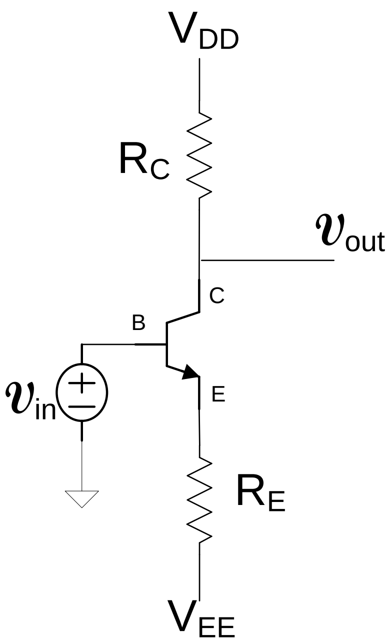
$$R_{in} \cong r_\pi + \beta R_E$$

$$R_{out} \cong R_C$$

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)



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

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

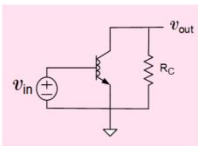
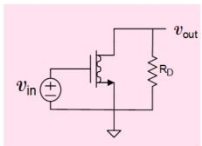
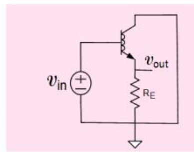
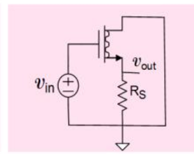
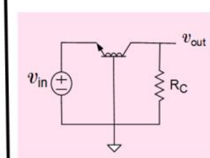
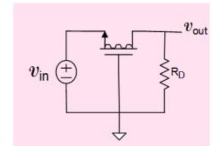
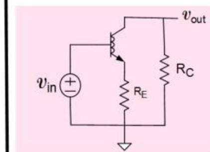
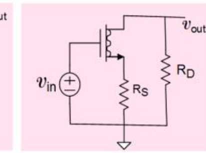
$$R_{out} \cong R_C$$

(this is not a two-port model)

Characteristics:

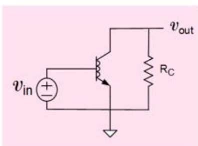
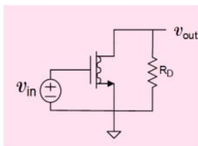
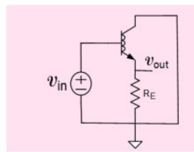
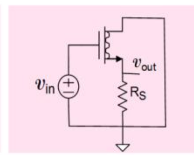
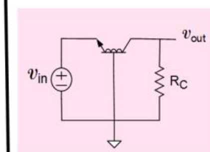
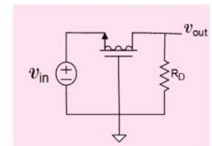
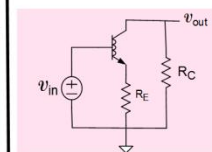
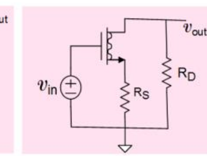
- Analysis would simplify if g_0 were set to 0 in model
- Gain can be accurately controlled with resistor ratios
- Useful for reasonably accurate low gains
- Input impedance is high

Basic Amplifier Gain Table

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

(not two-port models for the four structures)

Basic Amplifier Gain Table

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

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

End of Lecture 32