EE 330
Lecture 31

Two-Port Amplifier Models

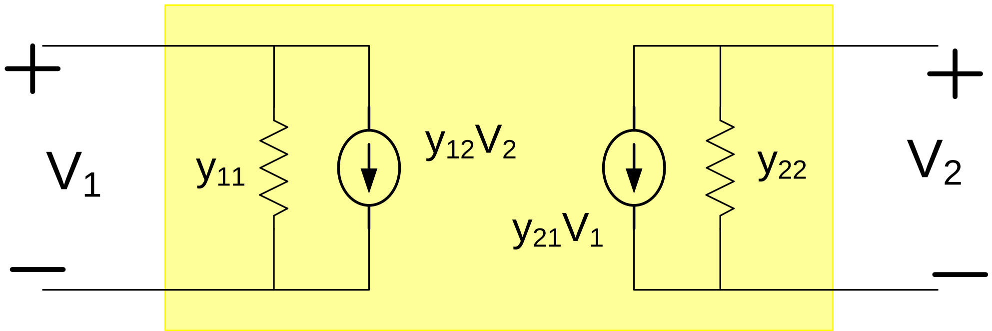
Basic amplifier architectures

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

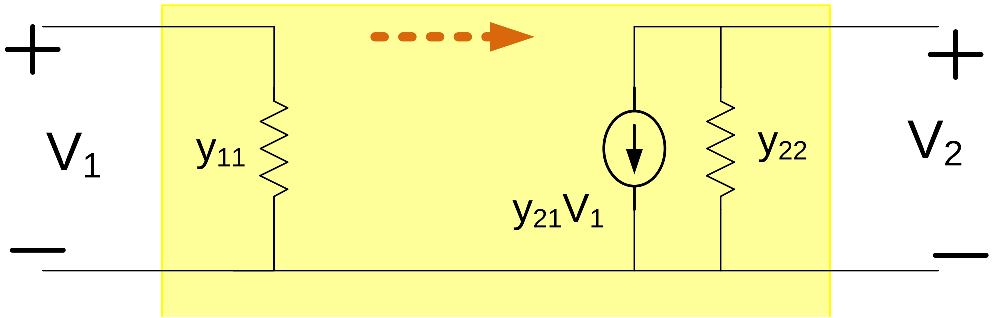
Review From Previous Lecture

Two-port representation of amplifiers

Amplifiers can be modeled as a two-port



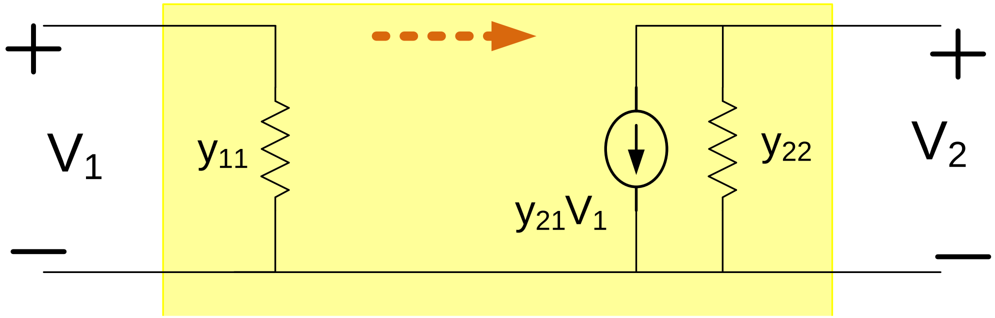
- Amplifier often **unilateral** (signal propagates in only one direction: wlog y_{12}=0)
- One terminal is often common



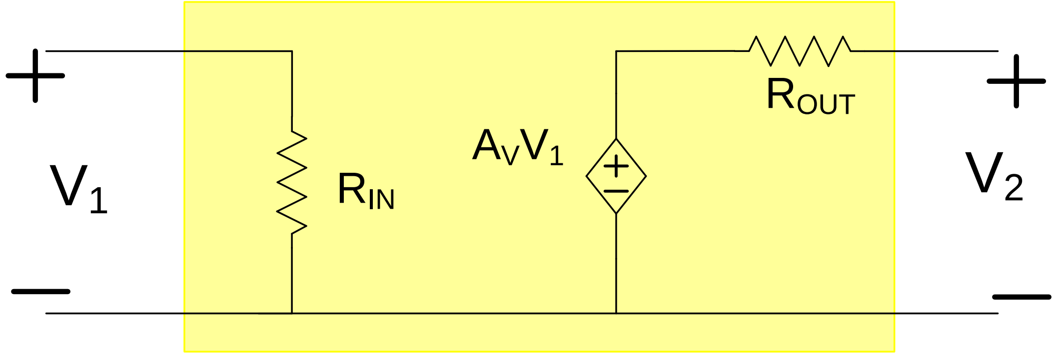
Review from Previous Lecture

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

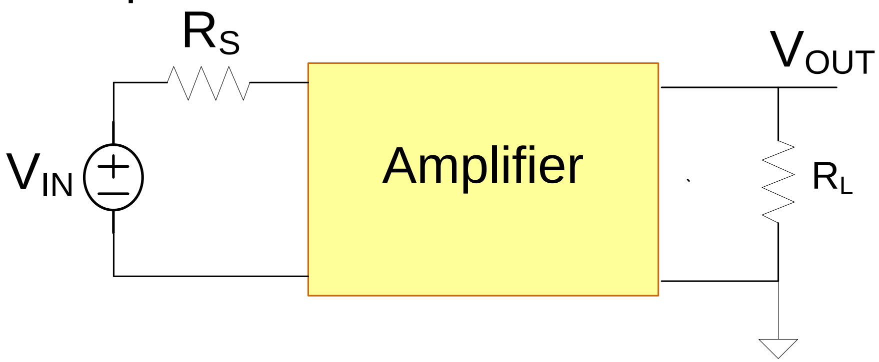
$$R_{IN} = \frac{1}{y_{11}} \qquad A_V = -\frac{y_{21}}{y_{22}} \qquad R_{OUT} = \frac{1}{y_{22}}$$

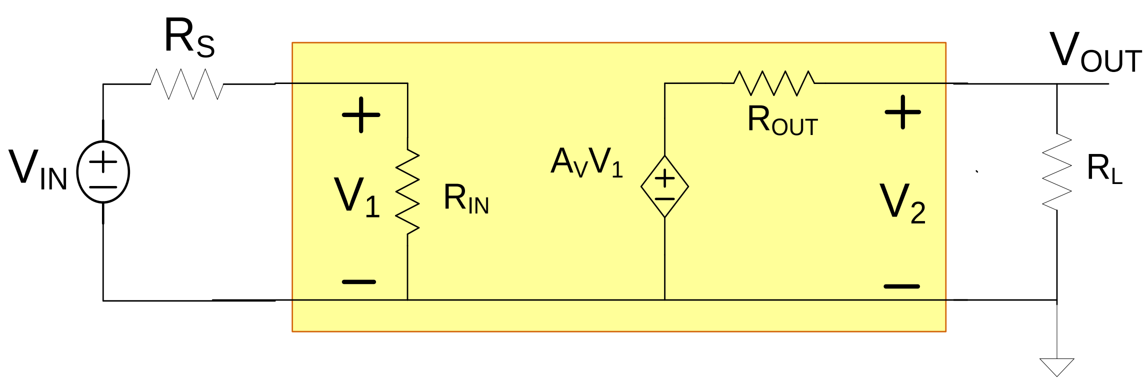
Review from Previous Lecture

Amplifier input impedance, output impedance and gain are usually of interest

Why?

Example 1: Assume amplifier is <u>unilateral</u>





$$V_{OUT} = \left(\frac{R_L}{R_L + R_{OUT}}\right) A_V \left(\frac{R_{IN}}{R_S + R_{IN}}\right) V_{IN}$$

$$A_{VAMP} = \frac{V_{OUT}}{V_{IN}} = \left(\frac{R_L}{R_L + R_{OUT}}\right)\left(\frac{R_{IN}}{R_S + R_{IN}}\right) A_V$$

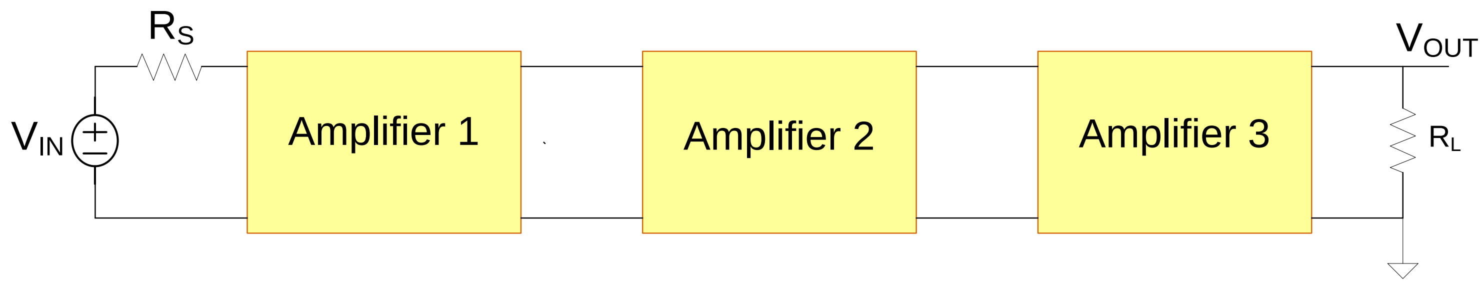
- Can get gain without reconsidering details about components internal to the Amplifier !!!
  - Analysis more involved when not unilateral

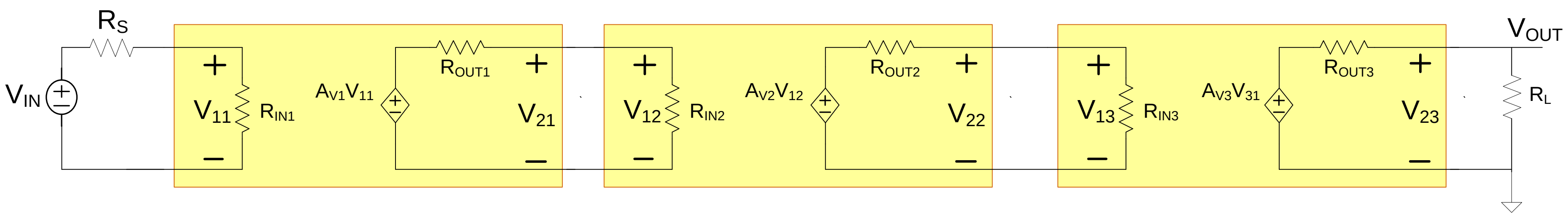
Review from Previous Lecture

Amplifier input impedance, output impedance and gain are usually of interest

Why?

Example 2: Assume amplifiers are unilateral





$$V_{OUT} = \left(\frac{R_L}{R_L + R_{OUT3}}\right) A_{V3} \left(\frac{R_{IN3}}{R_{OUT2} + R_{IN3}}\right) A_{V2} \left(\frac{R_{IN2}}{R_{OUT1} + R_{IN2}}\right) A_{V1} \left(\frac{R_{IN1}}{R_S + R_{IN1}}\right) V_{IN}$$

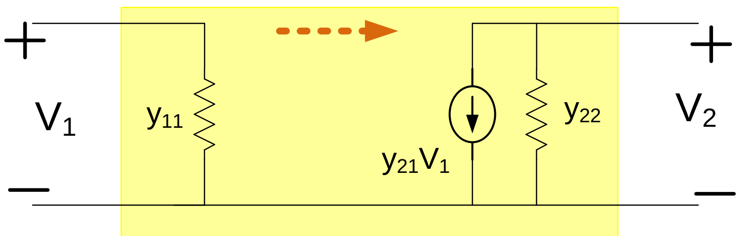
$$A_{VAMP} = \frac{V_{OUT}}{V_{IN}} = \left(\frac{R_L}{R_L + R_{OUT3}}\right) A_{V3} \left(\frac{R_{IN3}}{R_{OUT2} + R_{IN3}}\right) A_{V2} \left(\frac{R_{IN2}}{R_{OUT1} + R_{IN2}}\right) A_{V1} \left(\frac{R_{IN1}}{R_S + R_{IN1}}\right)$$

- Can get gain without reconsidering details about components internal to the Amplifier !!!
- Analysis more involved when not unilateral

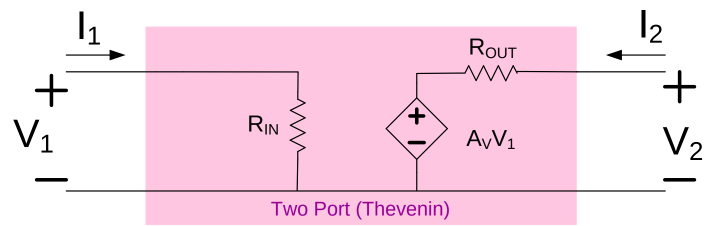
Review from Previous Lecture

Two-port representation of amplifiers

- Amplifier usually **unilateral** (signal propagates in only one direction: wlog y_{12}=0)
- One terminal is often common
- “Amplifier” parameters often used

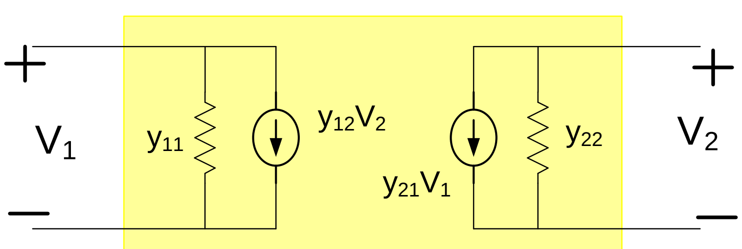


y parameters

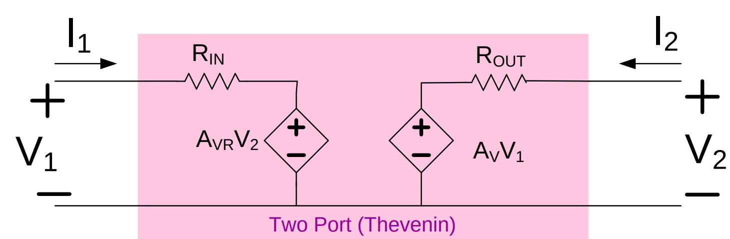


Amplifier parameters

- Amplifier parameters can also be used if not **unilateral**
- One terminal is often common



y parameters

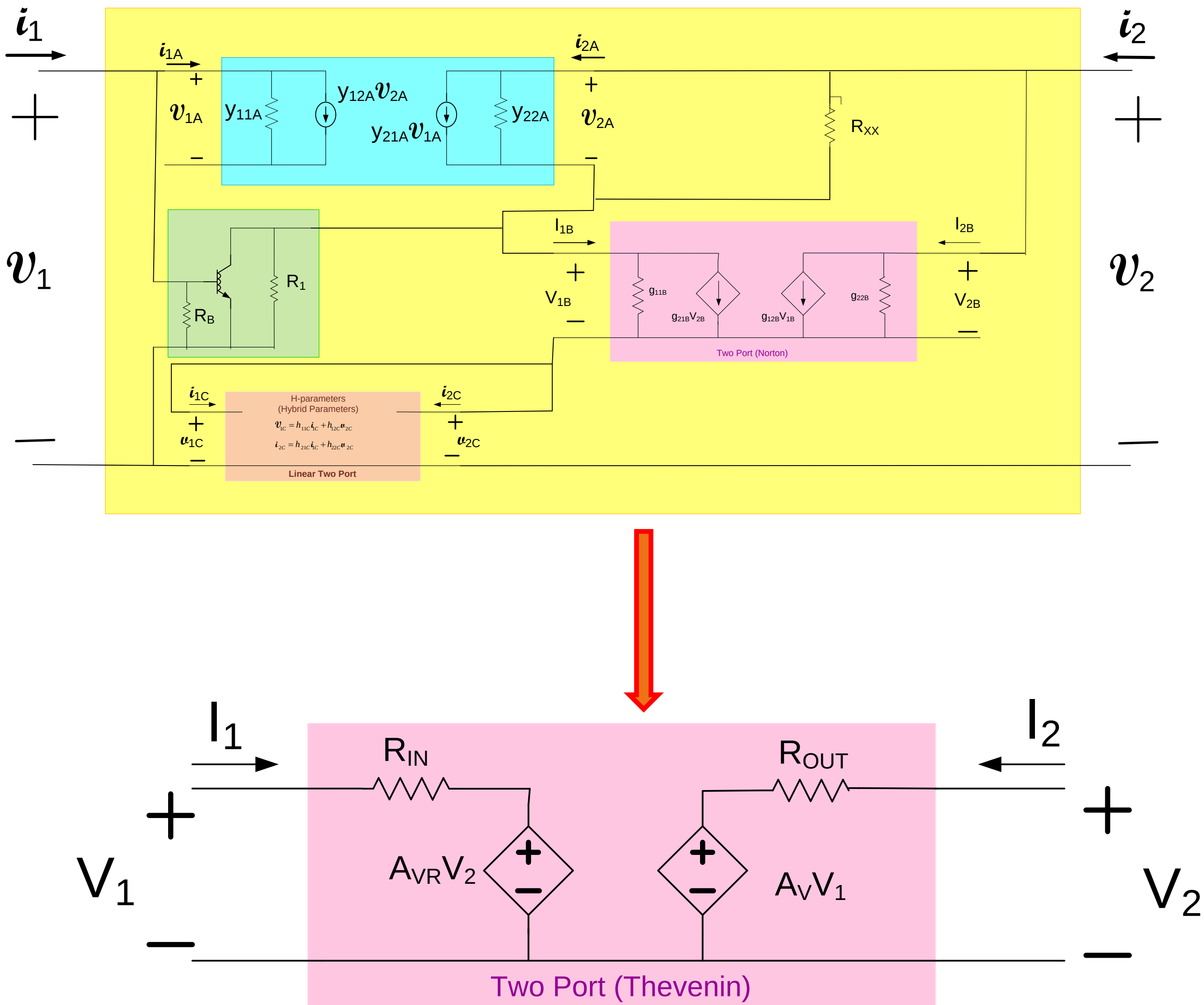


Amplifier parameters

Review from Previous Lecture

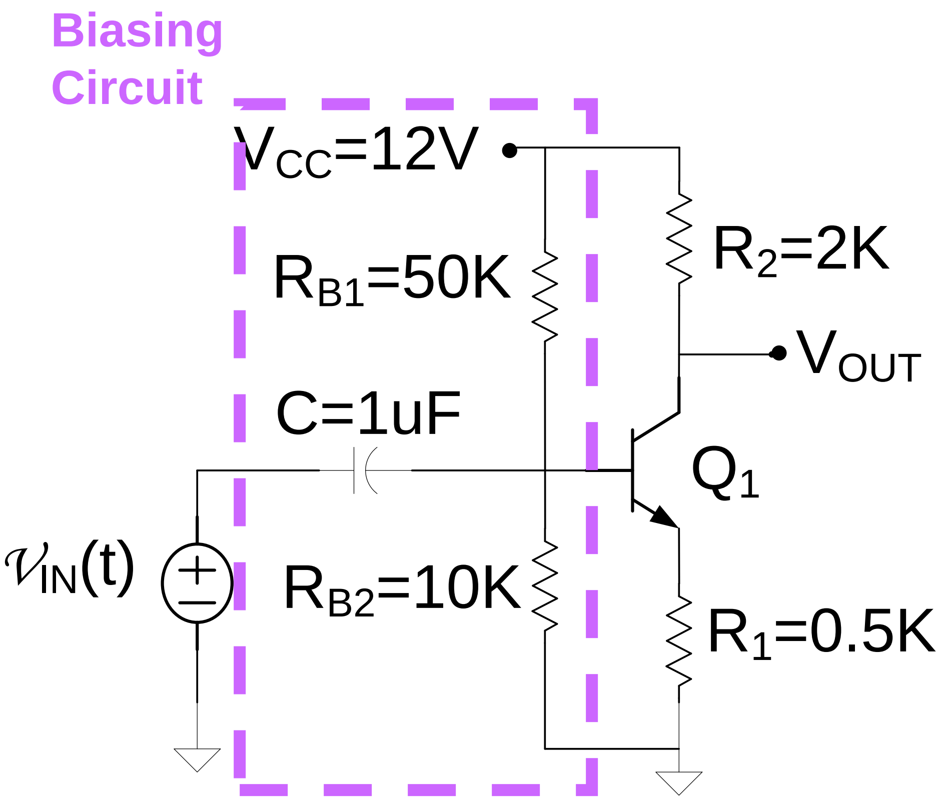
Two-Port Equivalents of Interconnected Two-ports

Example:



Review from Previous Lecture

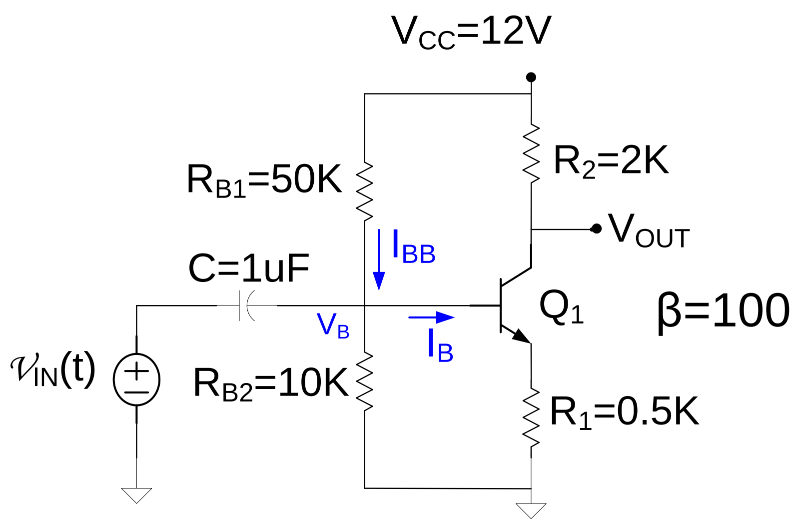
Examples

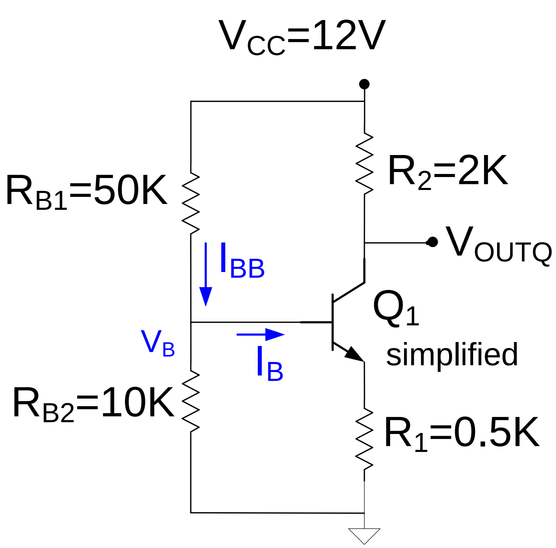


Determine V_{OUTQ} and the SS voltage gain (A_V), assume β=100

(A_V is one of the small-signal model parameters for this circuit)

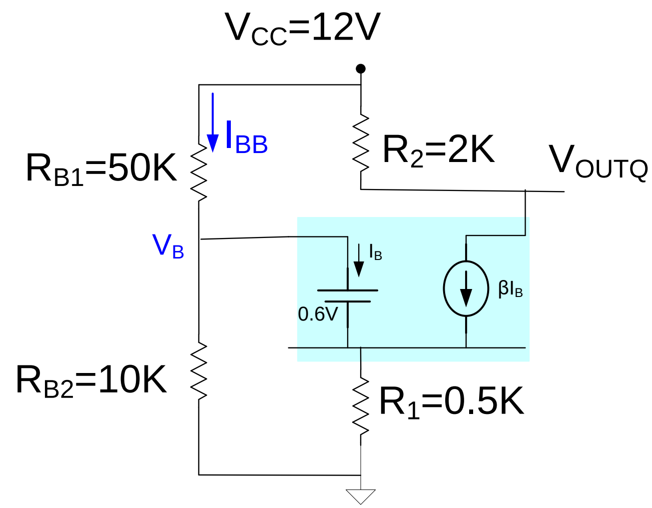
Examples





dc equivalent circuit

Determine V_{OUTQ}



dc equivalent circuit

This circuit is most practical when $I_B \ll I_{BB}$

With this assumption,

$$V_B = \left(\frac{R_{B2}}{R_{B1}+R_{B2}}\right)12V$$

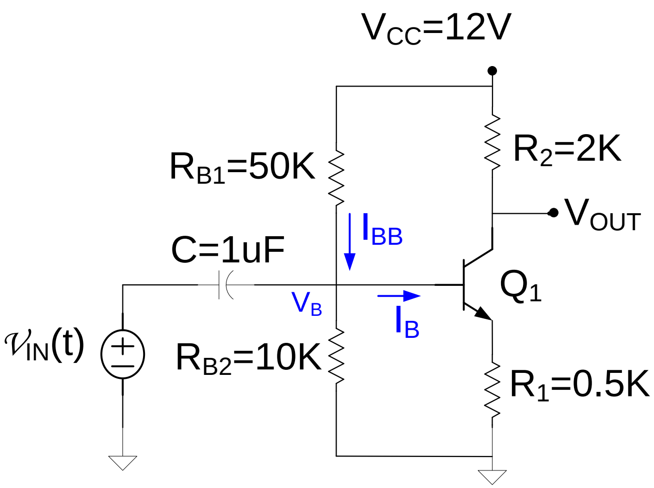
$$I_{CQ} = I_{EQ} = \left(\frac{V_B - 0.6V}{R_1}\right) = \frac{1.4V}{.5K} = 2.8mA$$

$$V_{OUTQ} = 12V - I_{CQ}R_1 = 6.4V$$

Note: This Q-point is nearly independent of the characteristics of the nonlinear BJT !

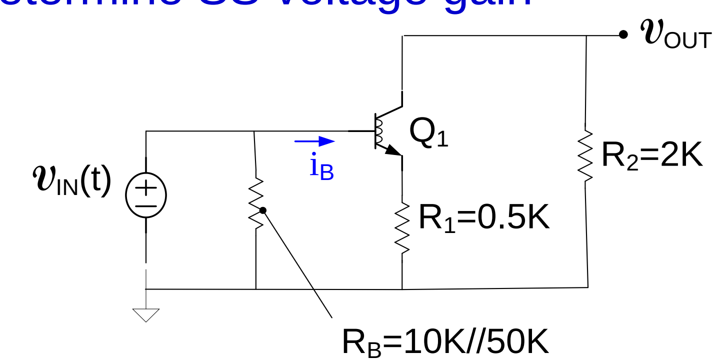
Review from Previous Lecture

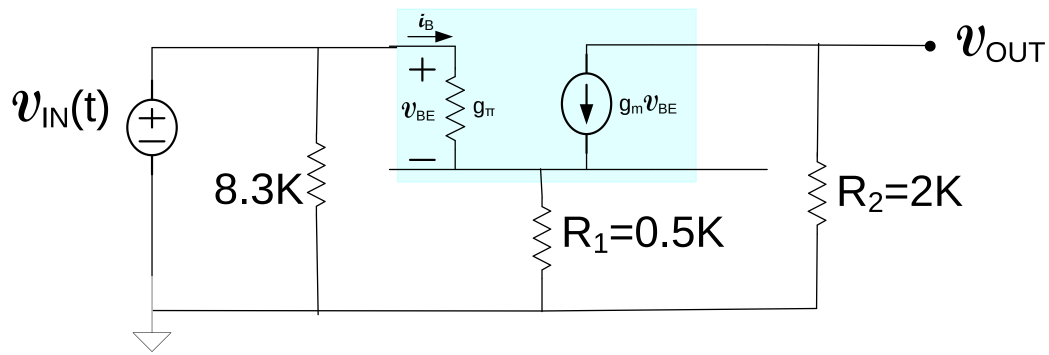
Examples



β=100

Determine SS voltage gain





This voltage gain is nearly independent of the characteristics of the nonlinear BJT !

This is a fundamentally different amplifier structure

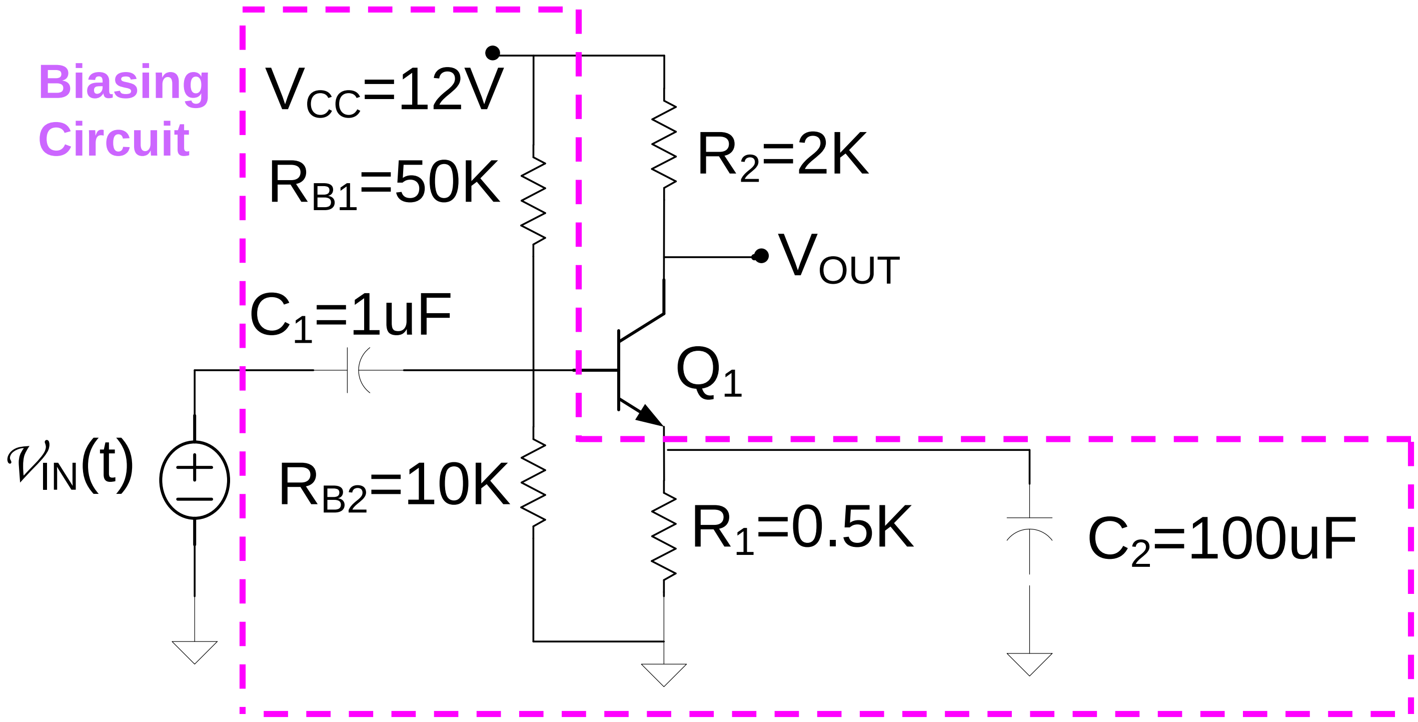
It can be shown that this is slightly non-unilateral

$$\left.\begin{aligned} v_{OUT} &= -g_m v_{BE} R_2 \\ v_{IN} &= v_{BE} + R_1\left(v_{BE}\left[g_\pi + g_m\right]\right) \end{aligned}\right\}$$

$$A_V = \frac{-R_2 g_m v_{BE}}{v_{BE} + R_1\left(v_{BE}\left[g_\pi + g_m\right]\right)} = \frac{-R_2 g_m}{1 + R_1\left(\left[g_\pi + g_m\right]\right)}$$

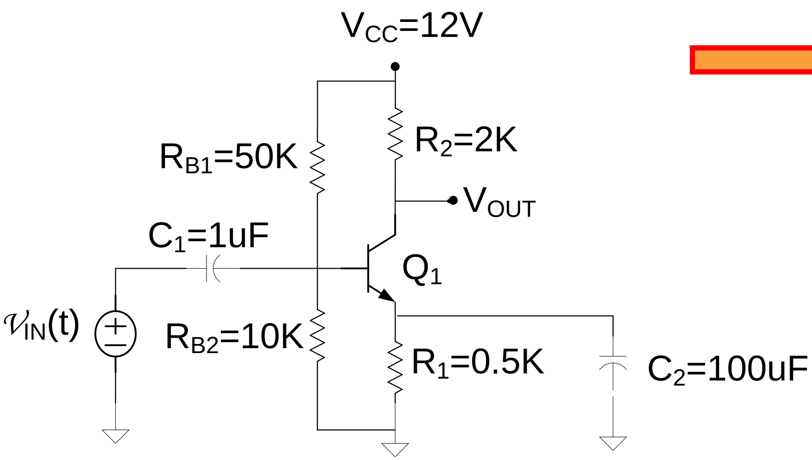
$$A_V \cong \frac{-R_2 g_m}{R_1 g_m} = \frac{-R_2}{R_1} = -4$$

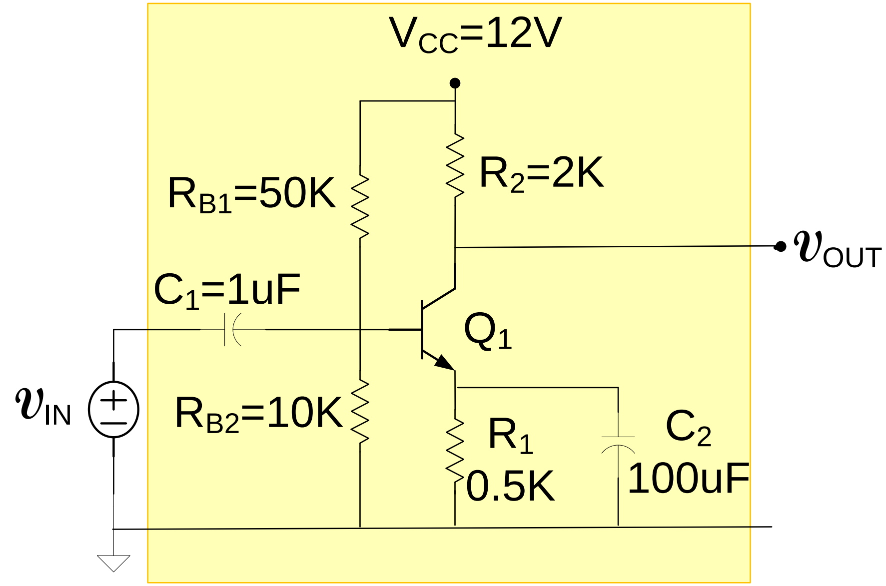
Examples

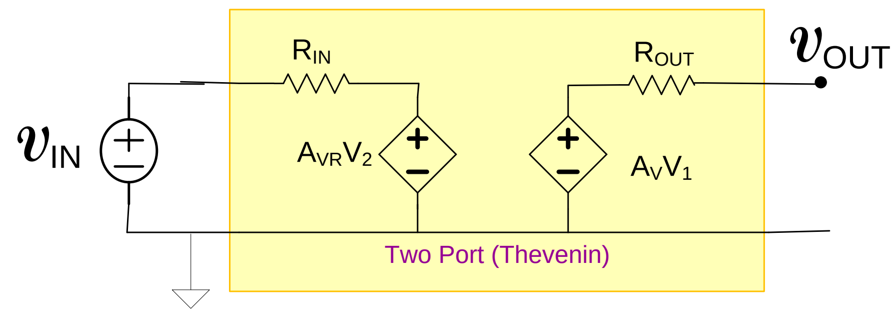


Determine V_{OUTQ} , R_{IN}, R_{OUT},and the SS voltage gain, and A_{VR} assume β=100

Examples





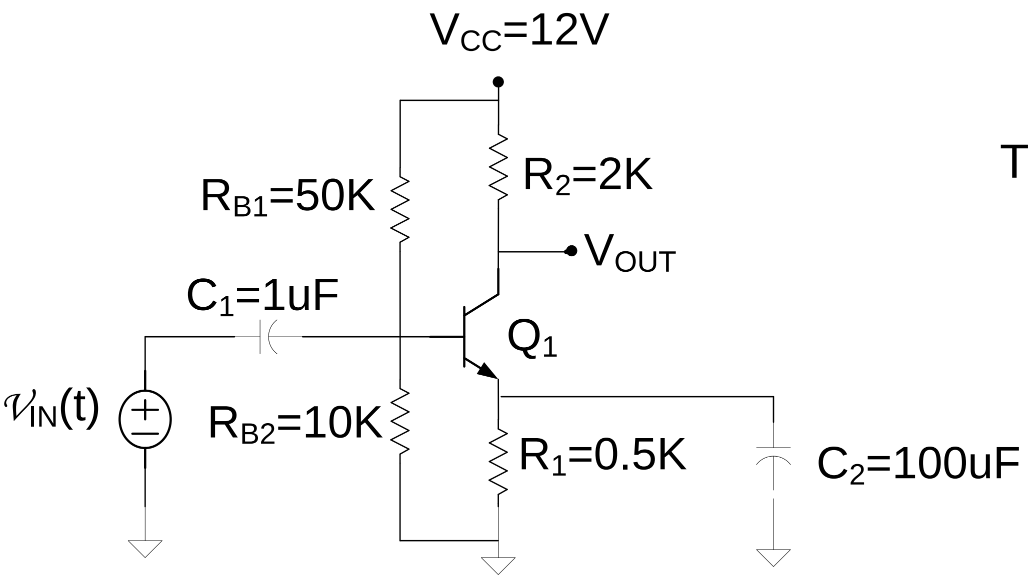


Determine V_{OUTQ} , R_{IN}, R_{OUT}, A_V, and A_{VR}; assume β=100

(A_V , R_{IN}, R_{OUT} , and A_{VR} are the small-signal model parameters for this circuit)

Examples

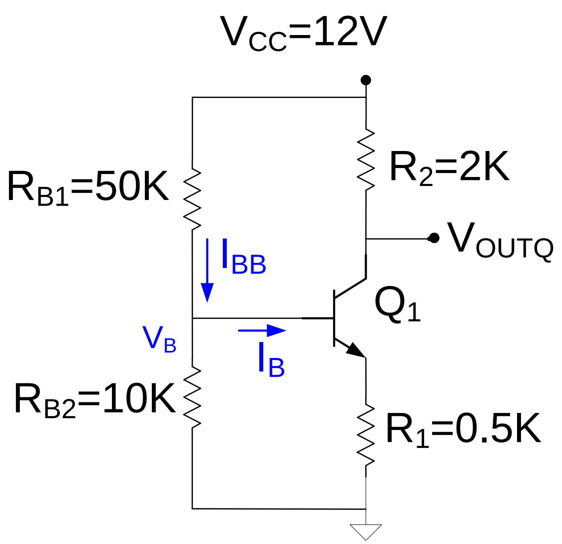
Determine V_{OUTQ}



This is the same as the previous circuit !

$$V_{OUTQ} = 6.4V$$

$$I_{CQ} = \frac{5.6V}{2K} = 2.8mA$$

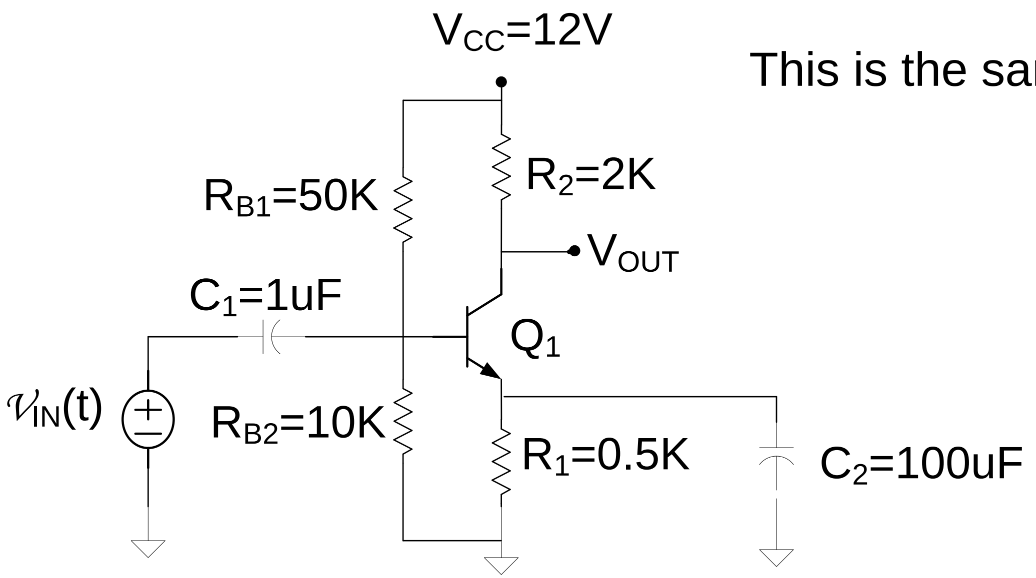


The dc equivalent circuit

Note: This Q-point is nearly independent of the characteristics of the nonlinear BJT !

Examples

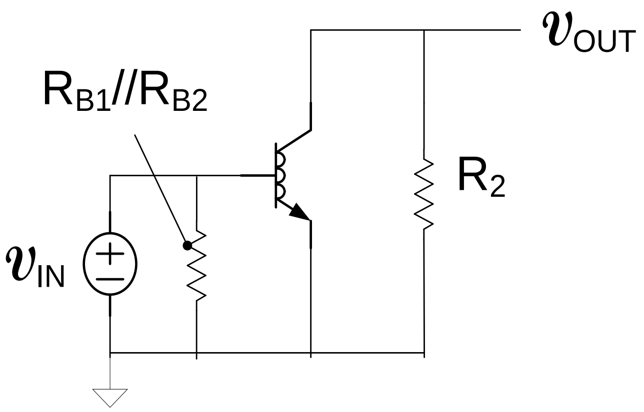
Determine the SS voltage gain A_V



This is the same as another previous-previous circuit !

$$A_V \cong -g_m R_2$$

$$A_V \cong -\frac{I_{CQ} R_2}{V_t}$$



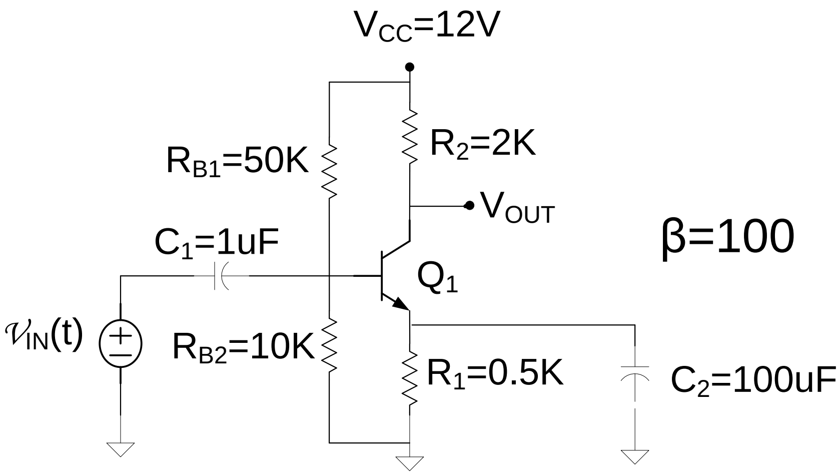
The SS equivalent circuit

$$A_V \cong -\frac{5.6V}{26mV} = -215$$

Note: This Gain is nearly independent of the characteristics of the nonlinear BJT !

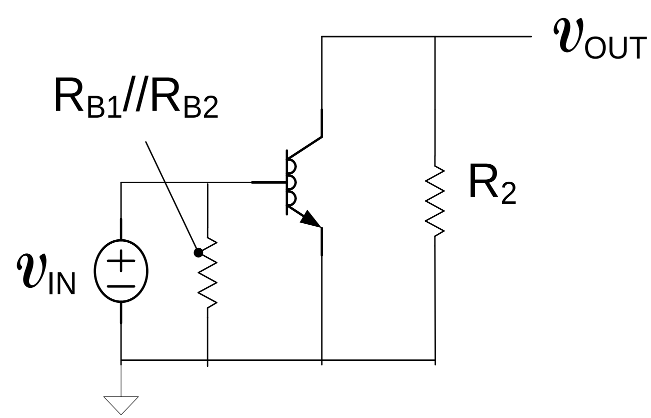
Examples

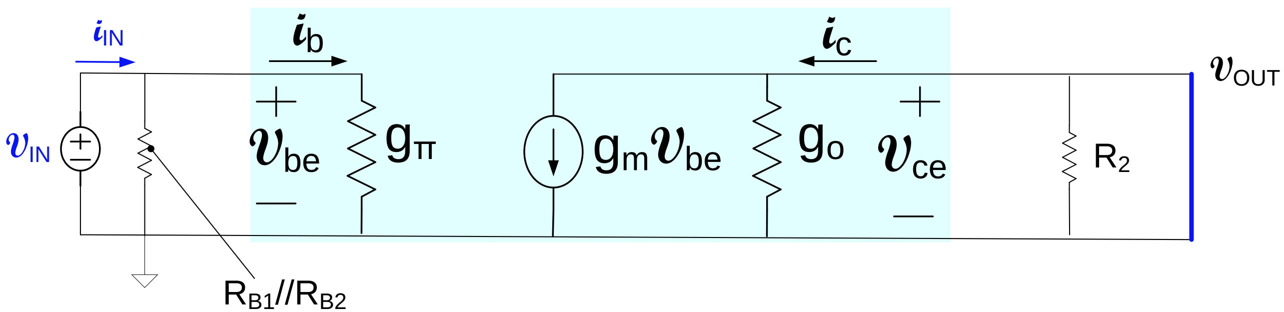
Determination of R_{IN}



$\beta=100$

The SS equivalent circuit





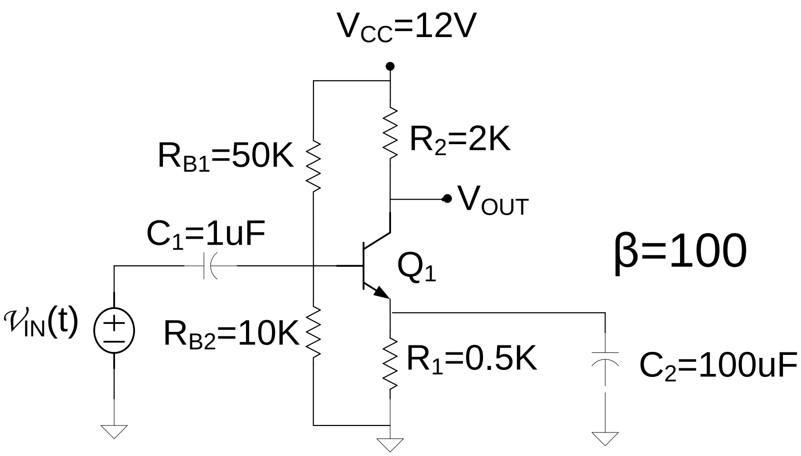
$$R_{IN} = R_{B1}//R_{B2}//r_\pi \cong r_\pi$$

$$r_\pi = \left(\frac{I_{CQ}}{\beta V_t}\right)^{-1} = \left(\frac{2.8\text{mA}}{100 \bullet 26\text{mV}}\right)^{-1} = 928\Omega$$

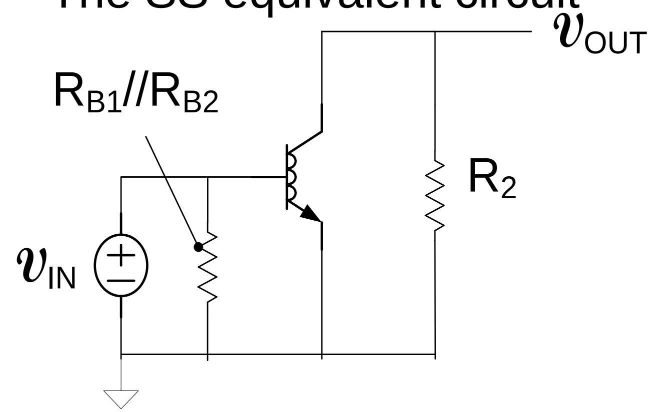
$$R_{IN} = R_{B1}//R_{B2}//r_\pi \cong r_\pi = 930\Omega$$

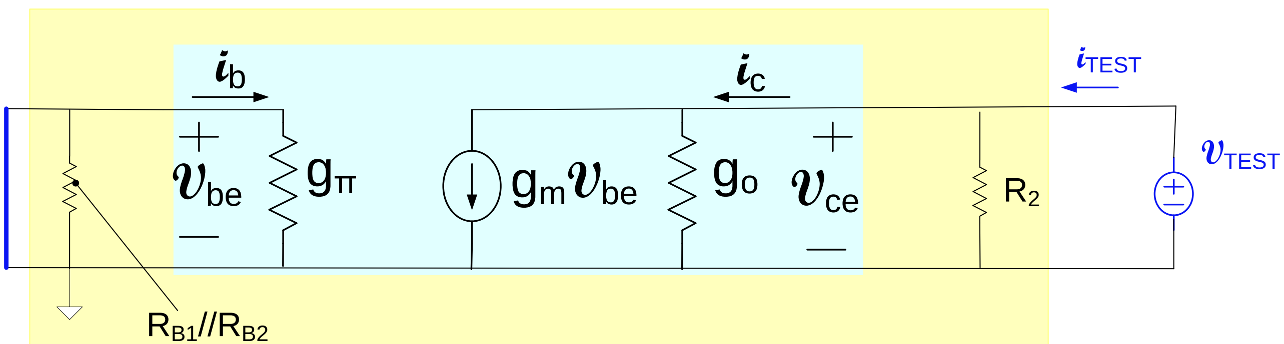
Examples

Determination of R_{OUT}



The SS equivalent circuit





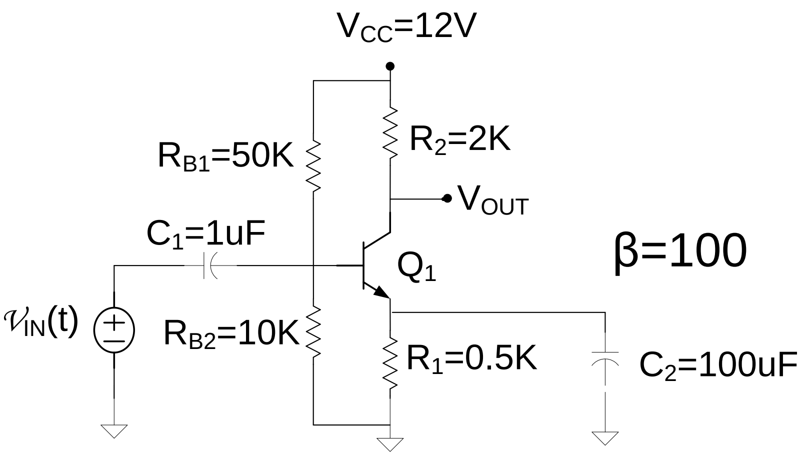
$$R_{OUT} = \frac{v_{TEST}}{i_{TEST}} = R_2 // r_o$$

$$r_o = \left(\frac{I_{CQ}}{V_{AF}}\right)^{-1} = \left(\frac{2.8\text{mA}}{200\text{V}}\right)^{-1} = (1.4\text{E-}5)^{-1} = 71\text{K}\Omega$$

$$R_{OUT} = R_2 // r_o \cong R_2 = 2K$$

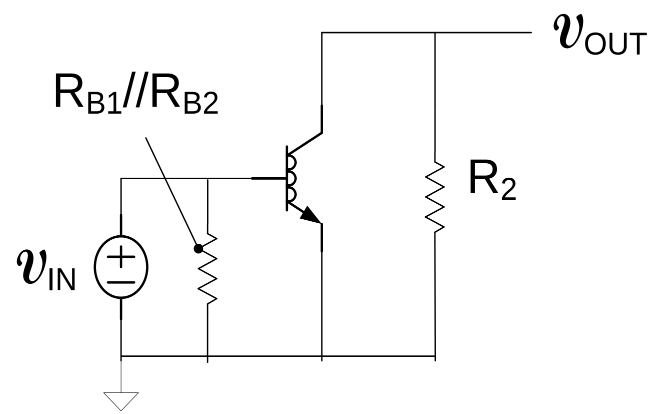
Examples

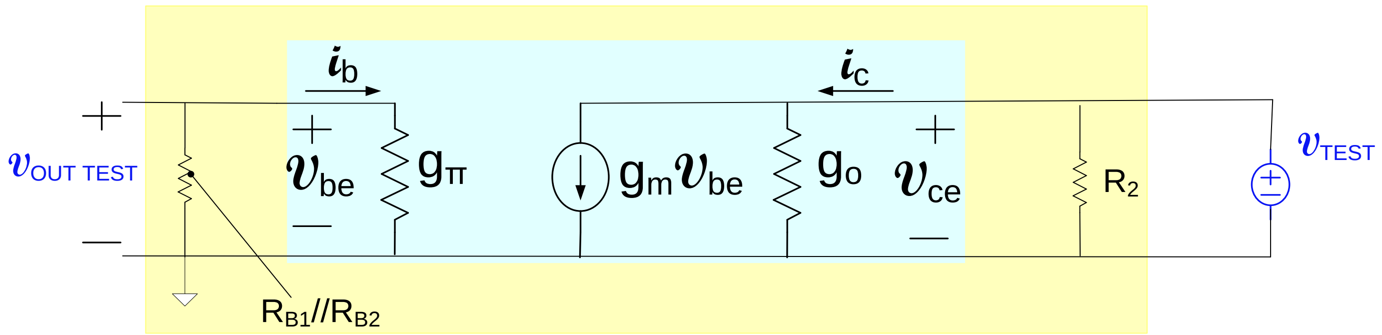
Determine A_{VR}



β=100

The SS equivalent circuit

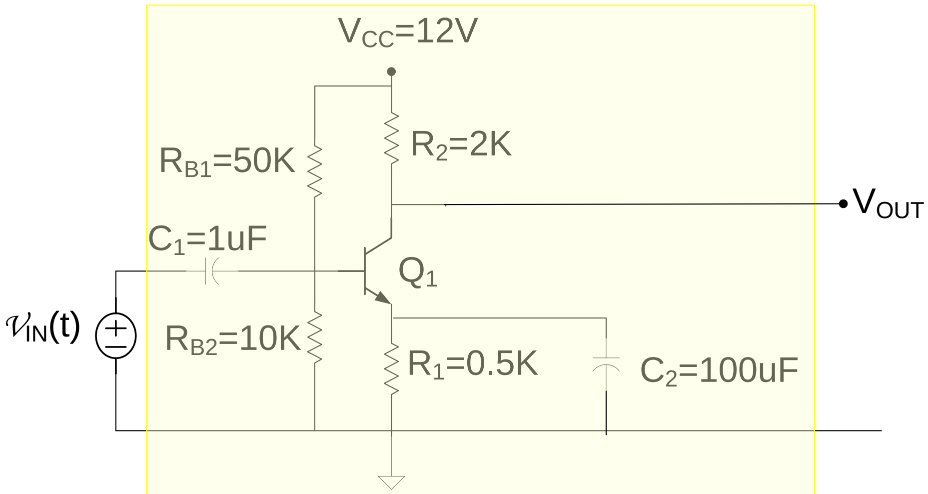


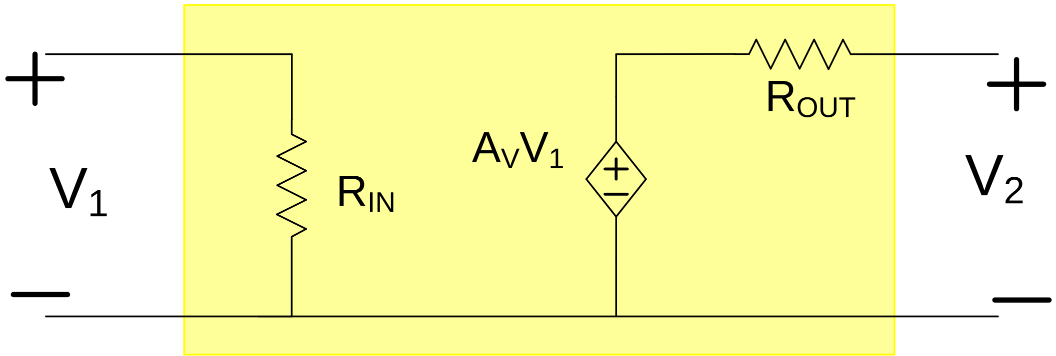


$$v_{OUT\ TEST}=0$$

$$A_{VR}=0$$

Determination of small-signal two-port representation

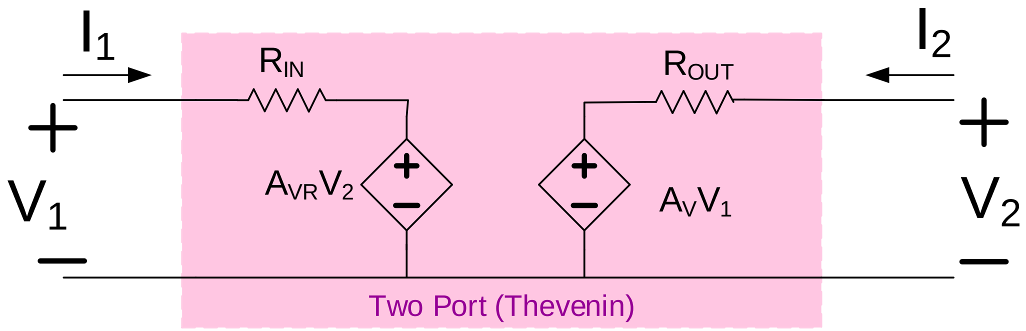




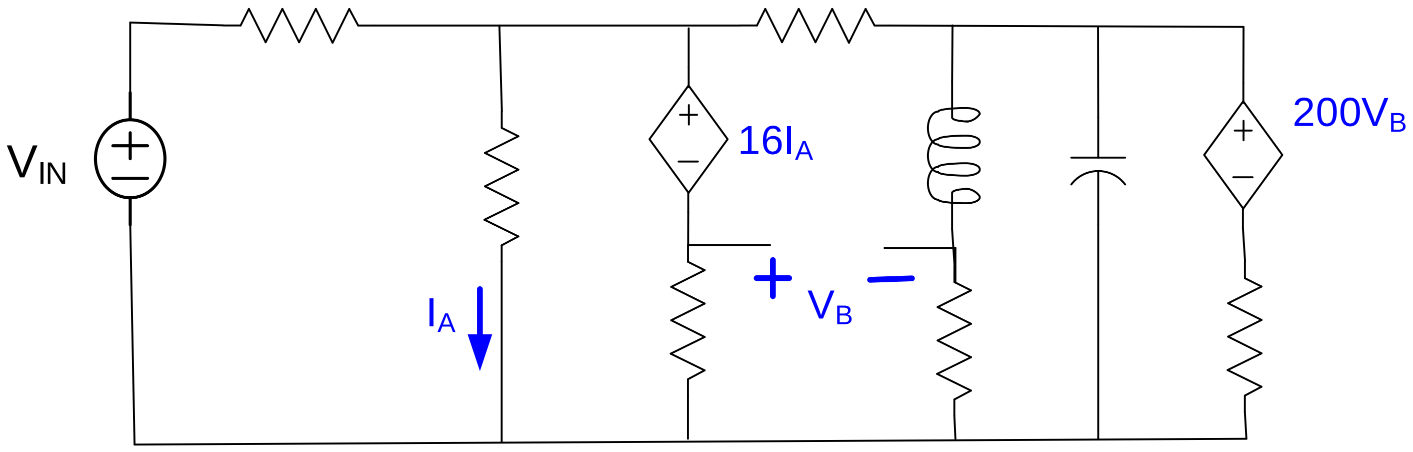
$A_V \cong -215$ $\quad R_{IN} \cong r_\pi = 930\Omega$ $\quad R_{OUT} \cong R_2 = 2K$

This is the same basic amplifier that was considered many times

Relationship with Dependent Sources ?

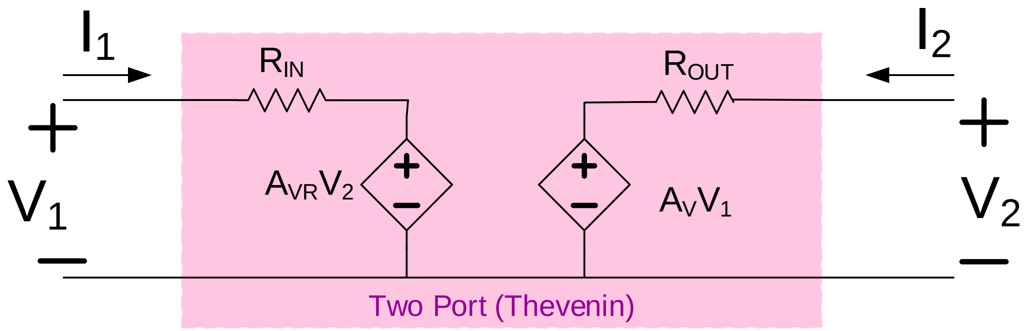


Dependent sources from EE 201



Example showing two dependent sources

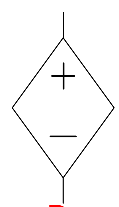
Relationship with Dependent Sources ?



Dependent sources from EE 201

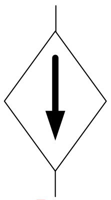
Voltage Amplifier

$v_s = \mu v_x$



Voltage Dependent Voltage Source

$I_s = \alpha v_x$

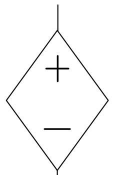


Voltage Dependent Current Source

Transconductance Amplifier

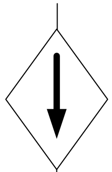
Transresistance Amplifier

$v_s = \rho I_x$



Current Dependent Voltage Source

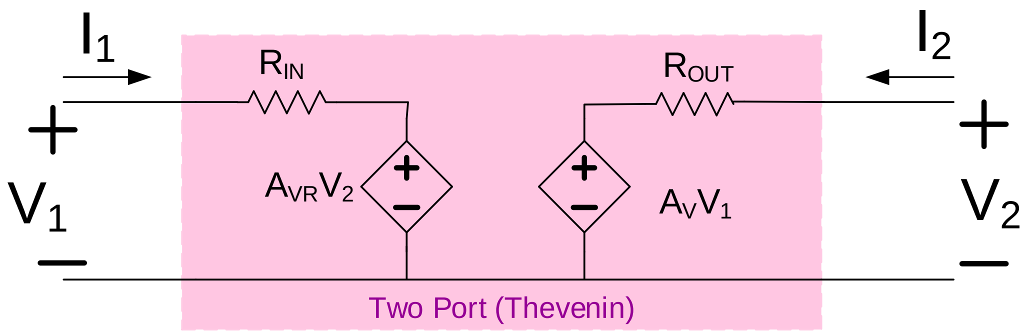
$I_s = \beta I_x$



Current Dependent Current Source

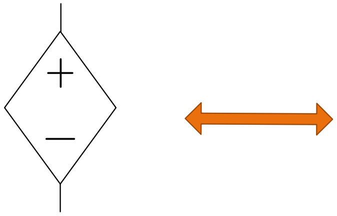
Current Amplifier

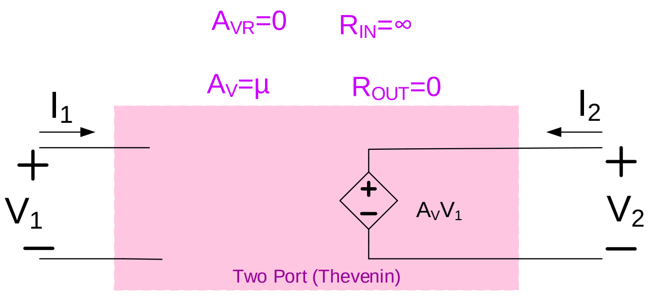
Relationship with Dependent Sources ?



It follows that

$\mathcal{v}_s=\mu\mathcal{v}_x$

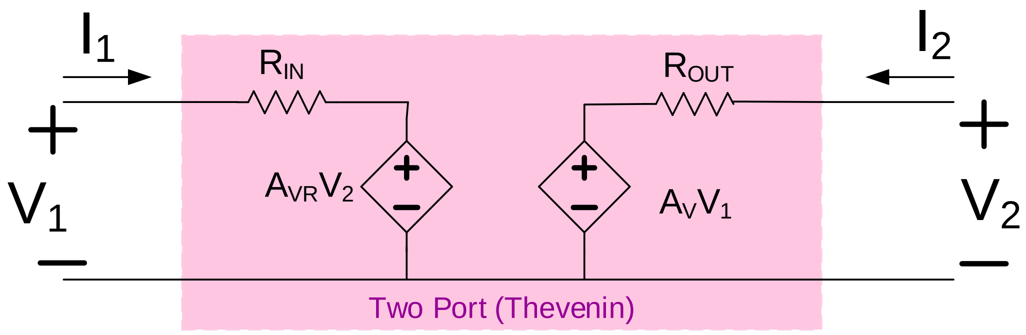




$V_2=A_VV_1$

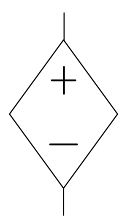
Voltage dependent voltage source is a unilateral floating two-port voltage amplifier with $R_{IN}=\infty$ and $R_{OUT}=0$

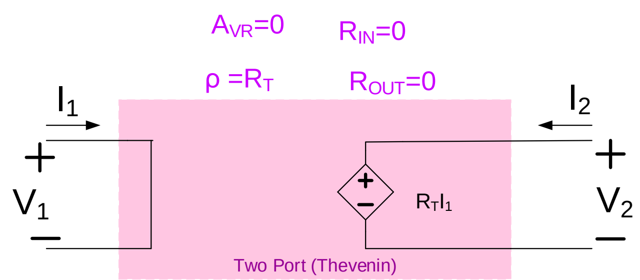
Relationship with Dependent Sources ?



It follows that

$v_s = \rho I_x$

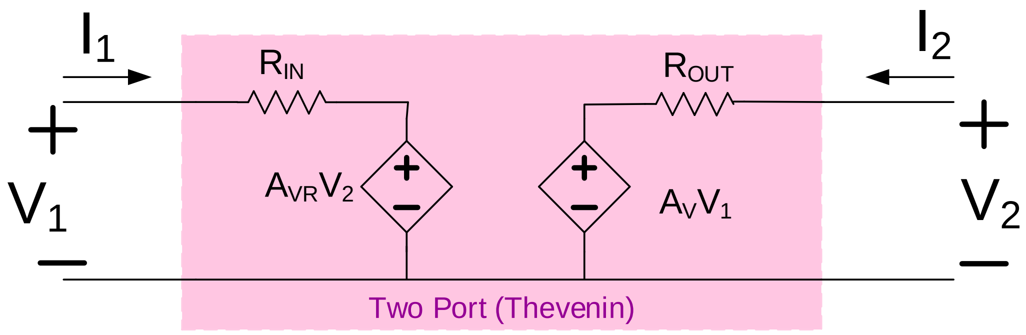




$V_2 = R_T I_1$

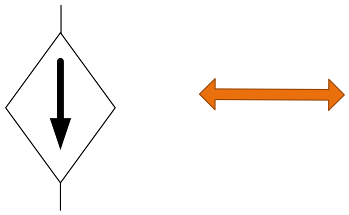
Current dependent voltage source is a unilateral floating two-port transresistance amplifier with $R_{IN}=0$ and $R_{OUT}=0$

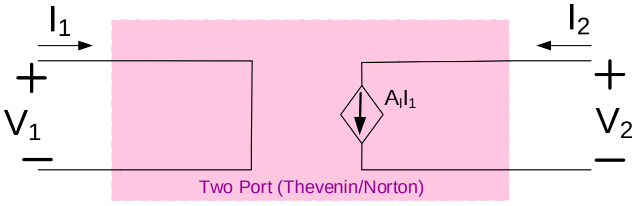
Relationship with Dependent Sources ?



It follows that

$I_S=\beta I_X$

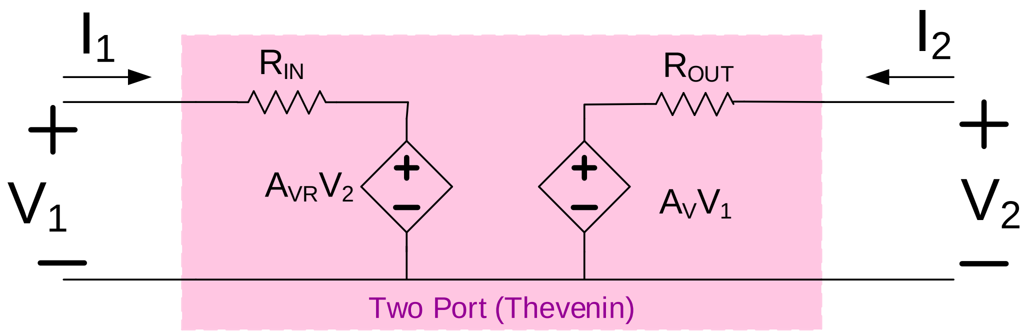




$I_2=A_II_1$

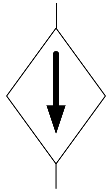
Current dependent current source is a floating unilateral two-port current amplifier with $R_{IN}=0$ and $R_{OUT}=\infty$

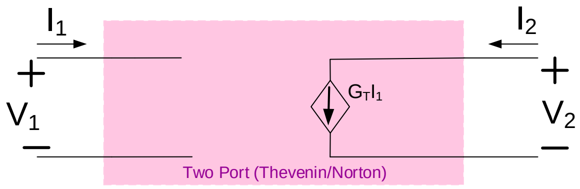
Relationship with Dependent Sources ?



It follows that

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

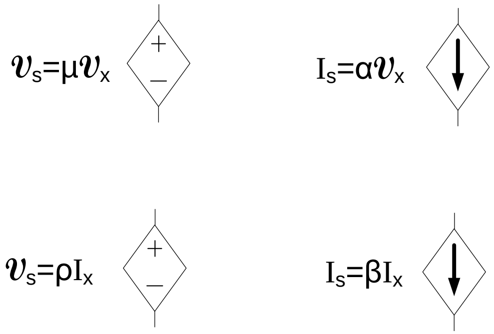




$I_2 = G_TV_1$

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

Dependent Sources



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

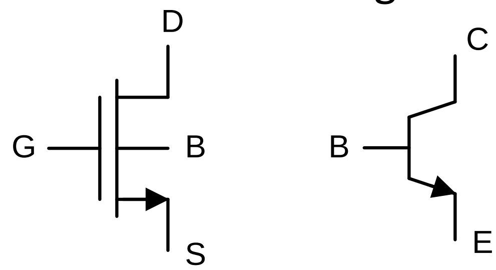
Dependent sources do not exist as basic circuit elements but amplifiers can be designed to perform approximately like a dependent source

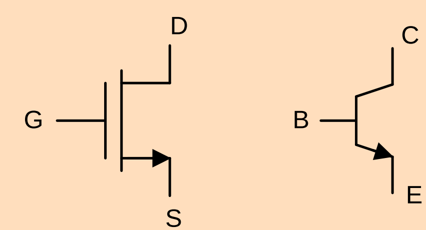
- Practical dependent sources typically are not floating on input or output
- One terminal is usually grounded
- Input and output impedances of realistic structures are usually not ideal

Why were “dependent sources” introduced as basic circuit elements instead of two-port amplifiers???

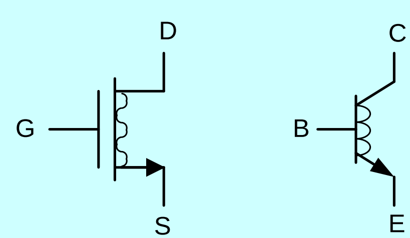
Basic Amplifier Structures

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





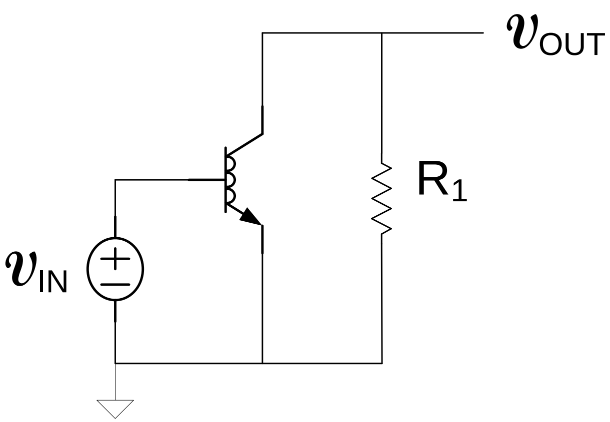
Transistors as 3-terminal Devices

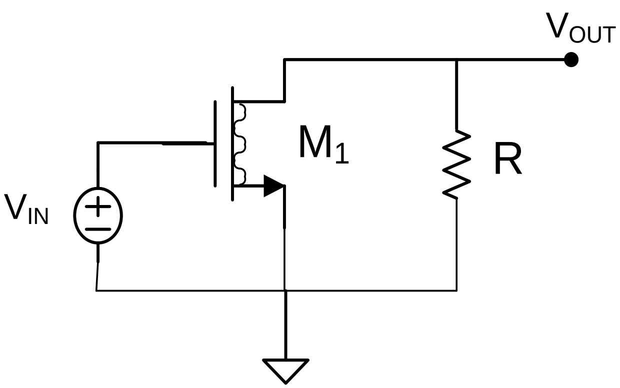


Small Signal Transistor Models
as 3-terminal Devices

Basic Amplifier Structures

Observation:



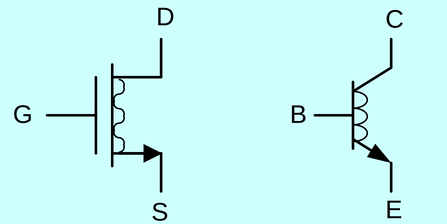


These circuits considered previously have a terminal (emitter or source) common to the input and output in the small-signal equivalent circuit

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

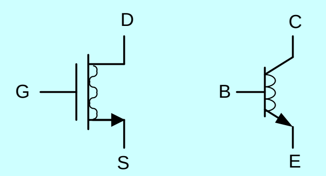
Amplifiers using these devices generally have one terminal common and use remaining terminals as input and output

Since devices are 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



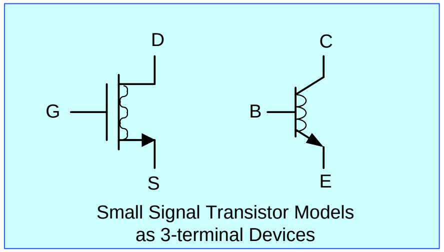
Small Signal Transistor Models
as 3-terminal Devices

	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



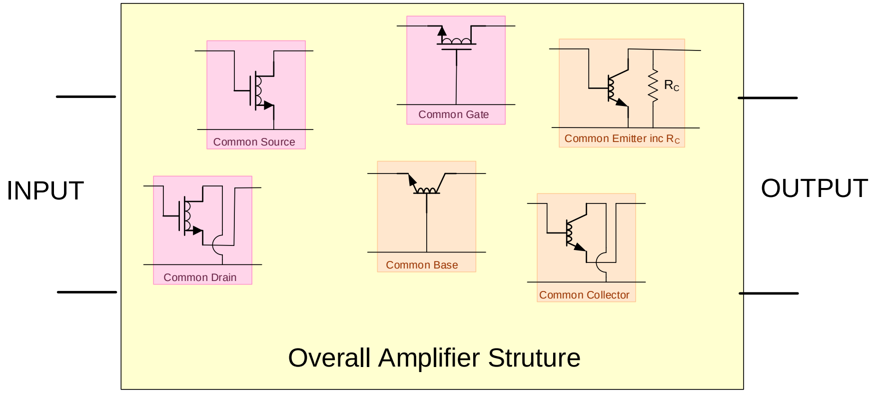
Common Source or Common Emitter

Common Gate or Common Base

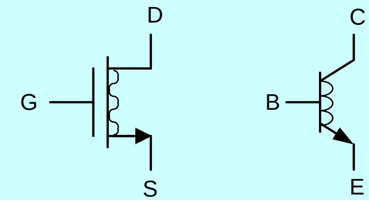
Common Drain or Common Collector

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

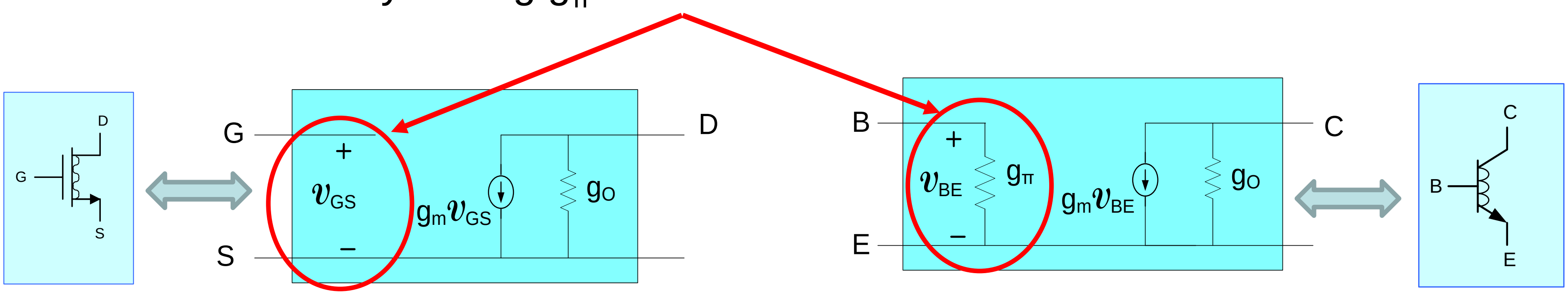


Small Signal Transistor Models
as 3-terminal Devices

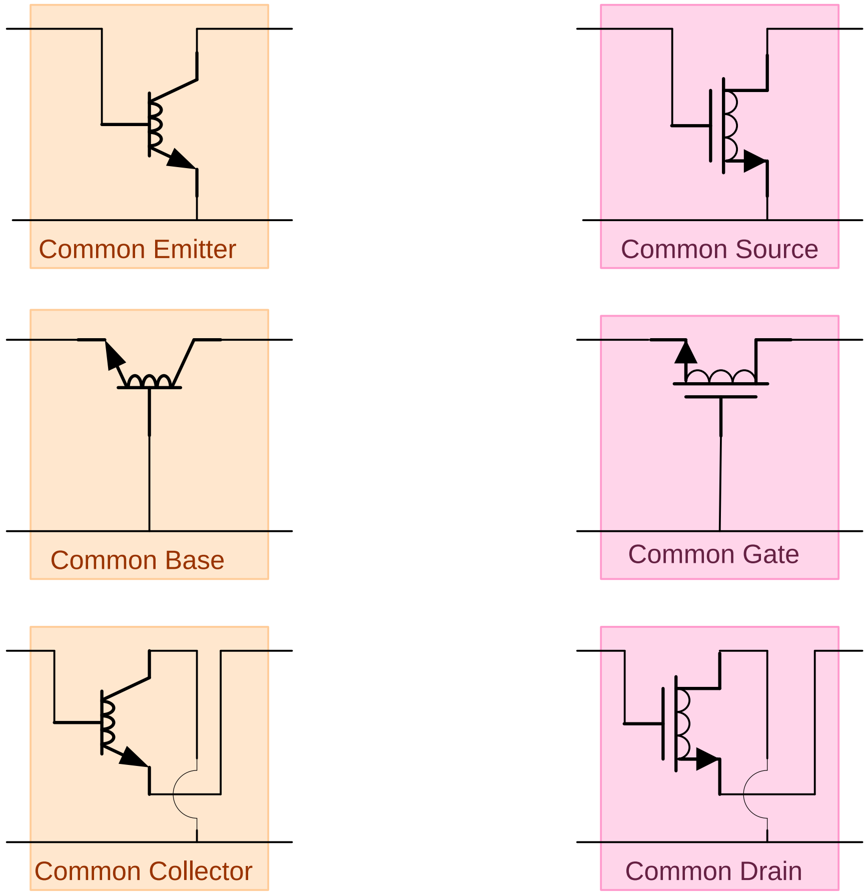
- Observe that the small-signal equivalent of any 3-terminal network is a two-port

- 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 $g_\pi=0$

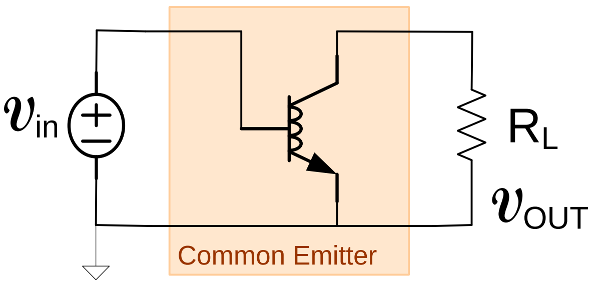


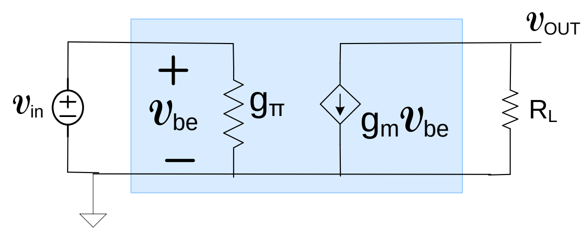
The three basic amplifier types for both MOS and bipolar processes



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

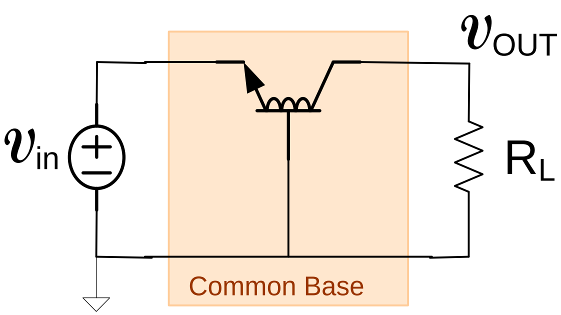
The three basic amplifier types for both MOS and bipolar processes

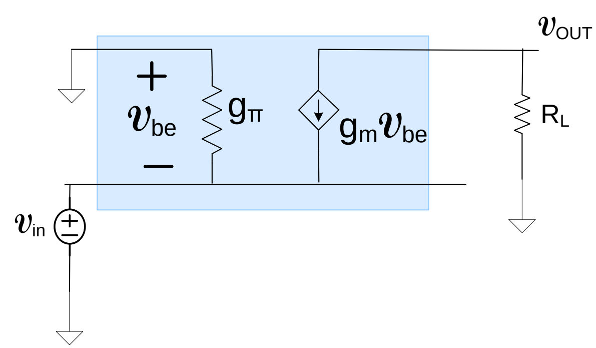




$$\left.\begin{aligned} v_{OUT} &= -g_m R_L v_{be} \\ v_{IN} &= v_{be} \end{aligned}\right\}$$

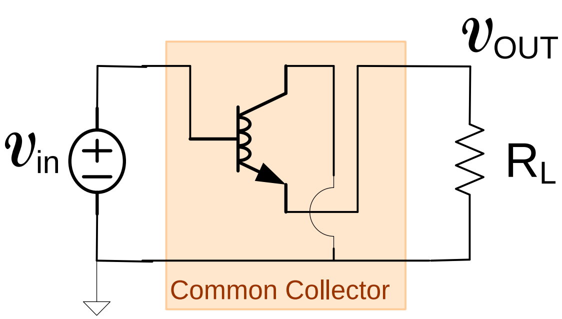
$$A_V = \frac{v_{OUT}}{v_{IN}} = -g_m R_L$$

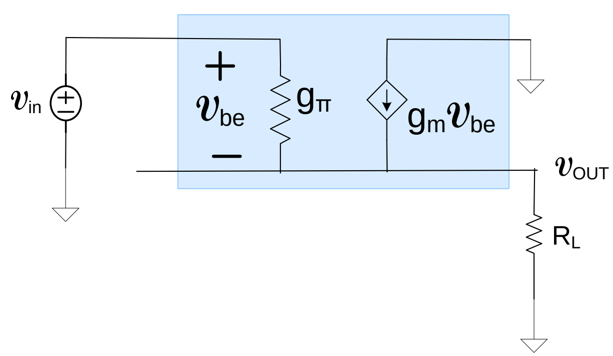




$$\left.\begin{aligned} v_{OUT} &= -g_m R_L v_{be} \\ v_{IN} &= -v_{be} \end{aligned}\right\}$$

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



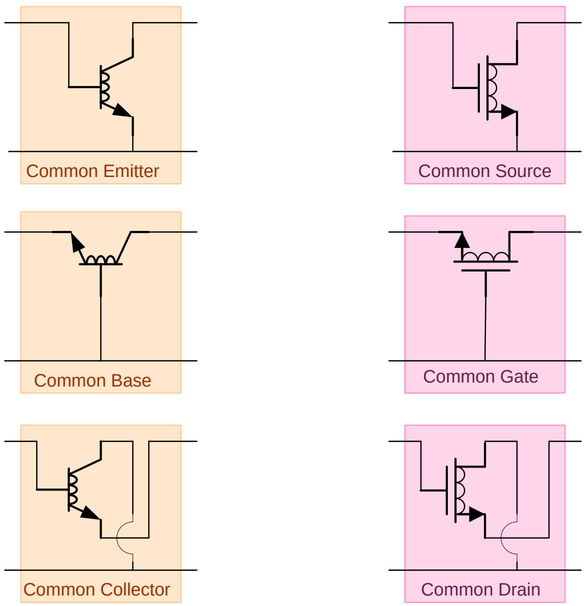


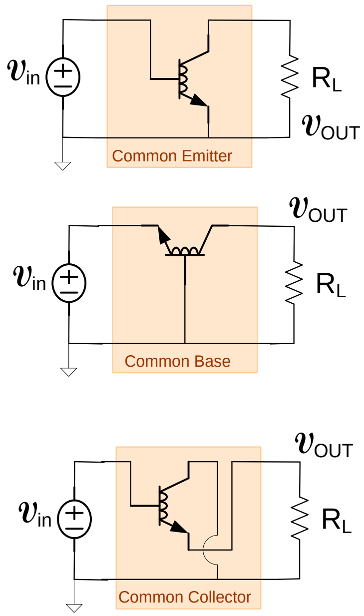
$$\left.\begin{aligned} v_{OUT} &= (g_m + g_\pi) v_{be} R_L \\ v_{IN} &= v_{be} + (g_m + g_\pi) v_{be} R_L \end{aligned}\right\}$$

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

- 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





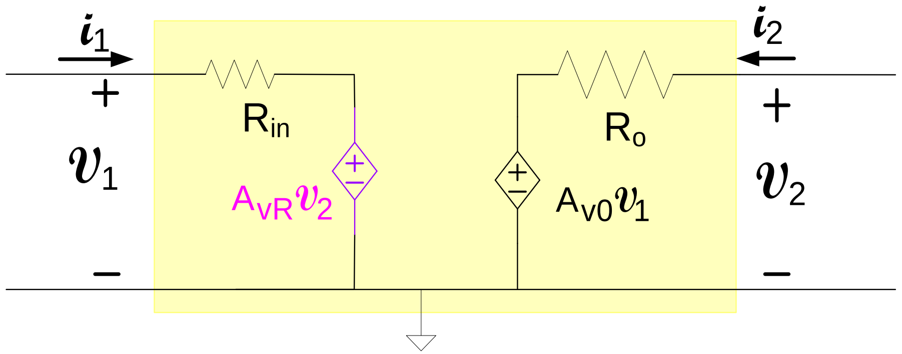
More general models are needed to accommodate biasing, understand performance capabilities, and include effects of loading of the basic structures

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 last lecture)

2. Write v_1 : v_2 equations in standard form

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

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

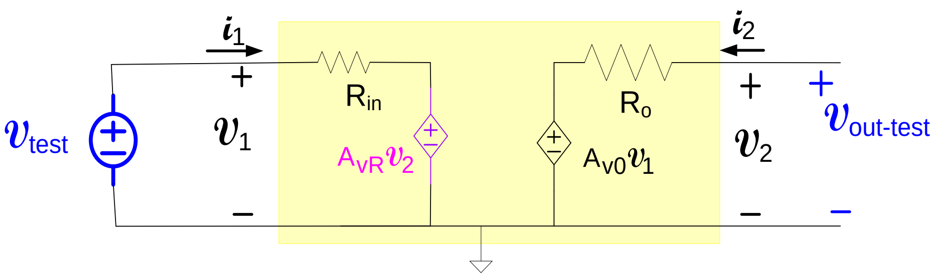
3. Thevenin-Norton Transformations

4. Ad Hoc Approaches

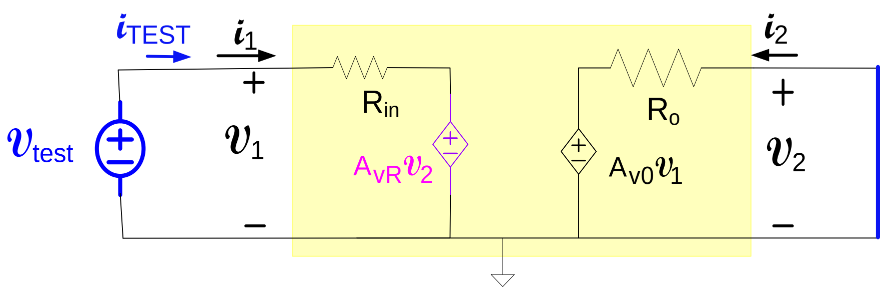
Any of these methods can be used to obtain the two-port model

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

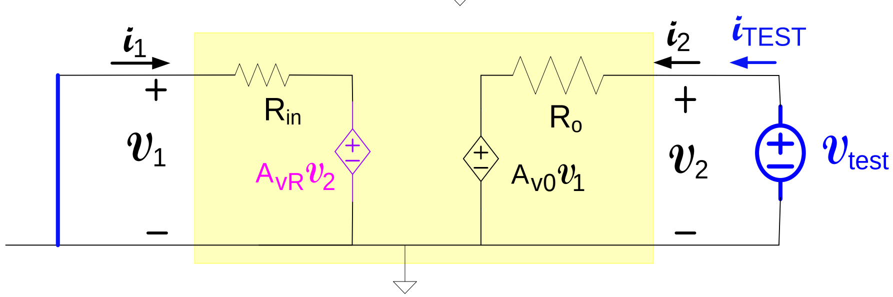
SUMMARY from PREVIOUS LECTURE



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

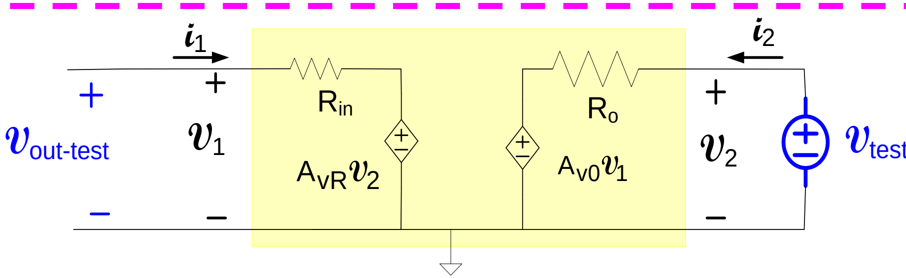


$$R_{in} = \frac{v_{\text{test}}}{i_{\text{test}}}$$



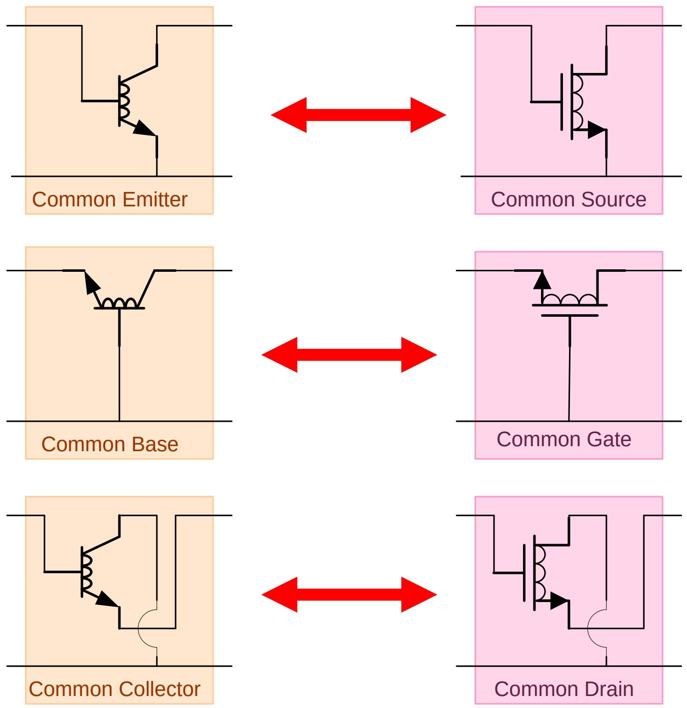
$$R_0 = \frac{v_{\text{test}}}{i_{\text{test}}}$$

If Unilateral $A_{VR} = 0$

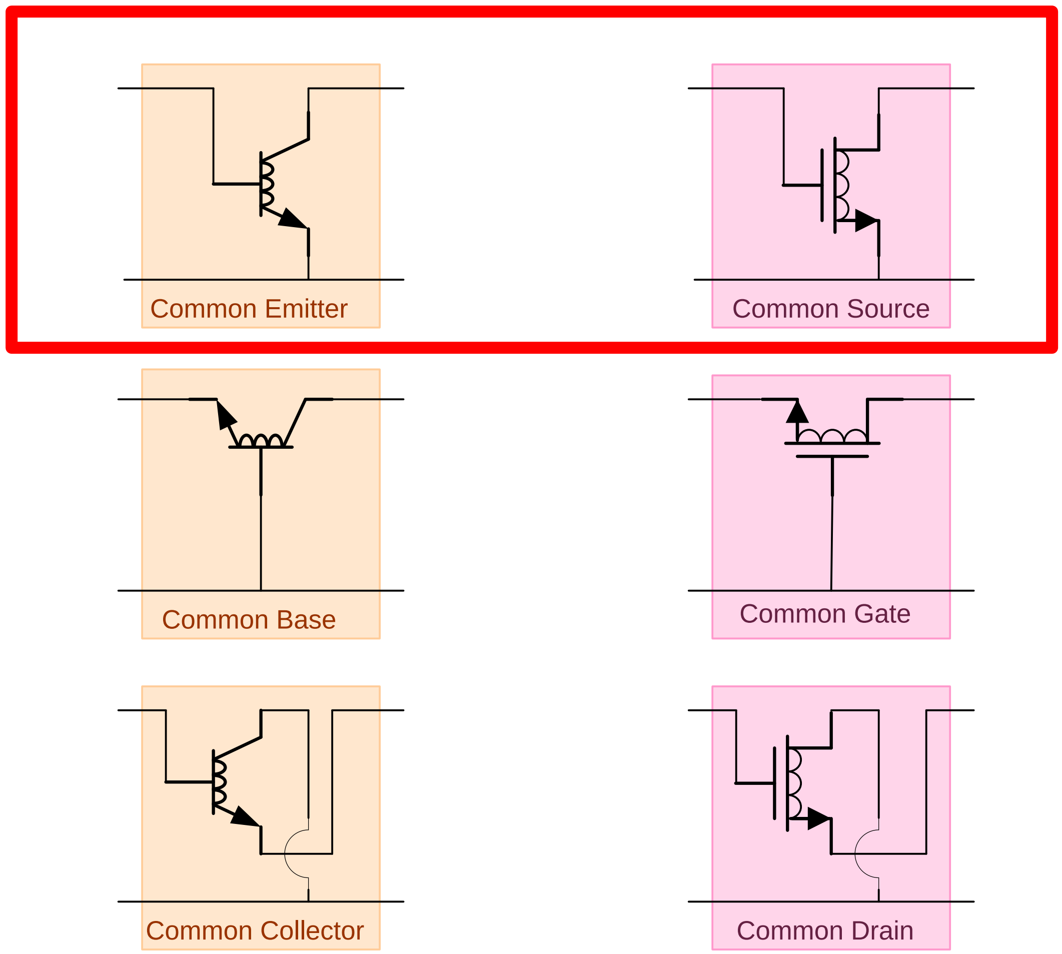


$$A_{VR} = \frac{v_{\text{out-test}}}{v_{\text{test}}}$$

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

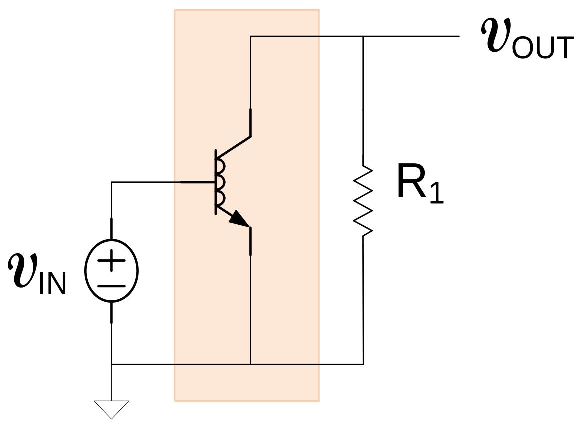


Consider Common Emitter/Common Source Two-port Models

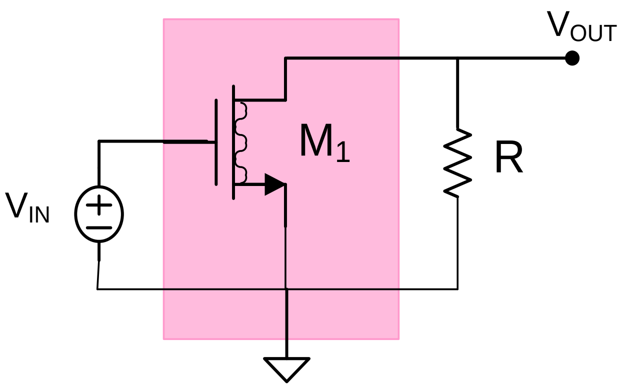


Will focus on Bipolar Circuit since MOS counterpart is a special case obtained by setting $g_{\pi}=0$

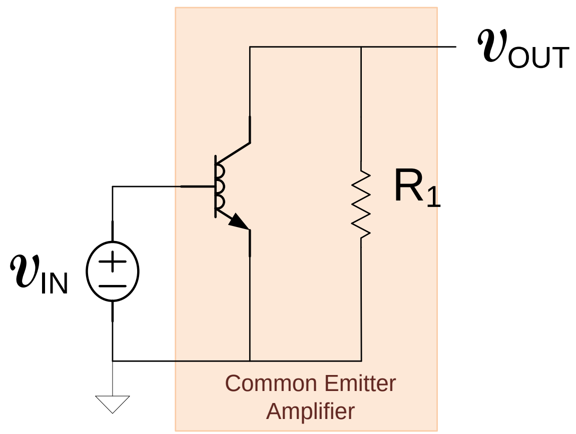
Basic CE/CS Amplifier Structures

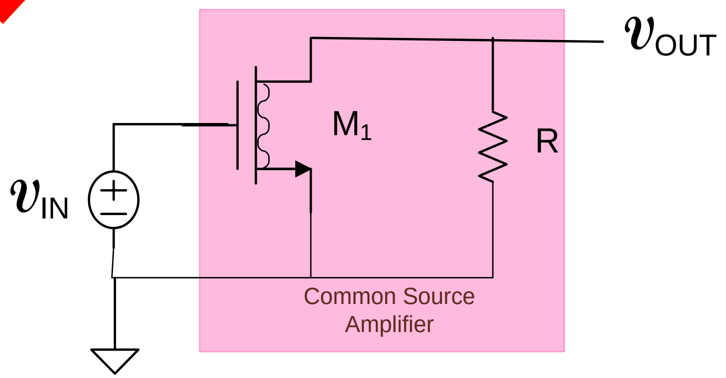


Common Emitter Amplifier



Common Source Amplifier

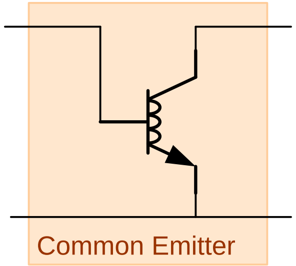


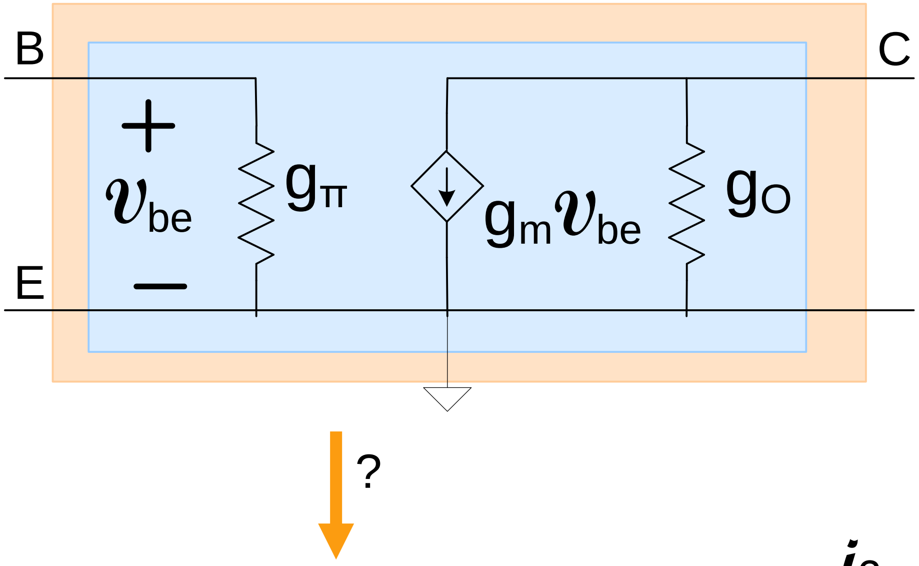


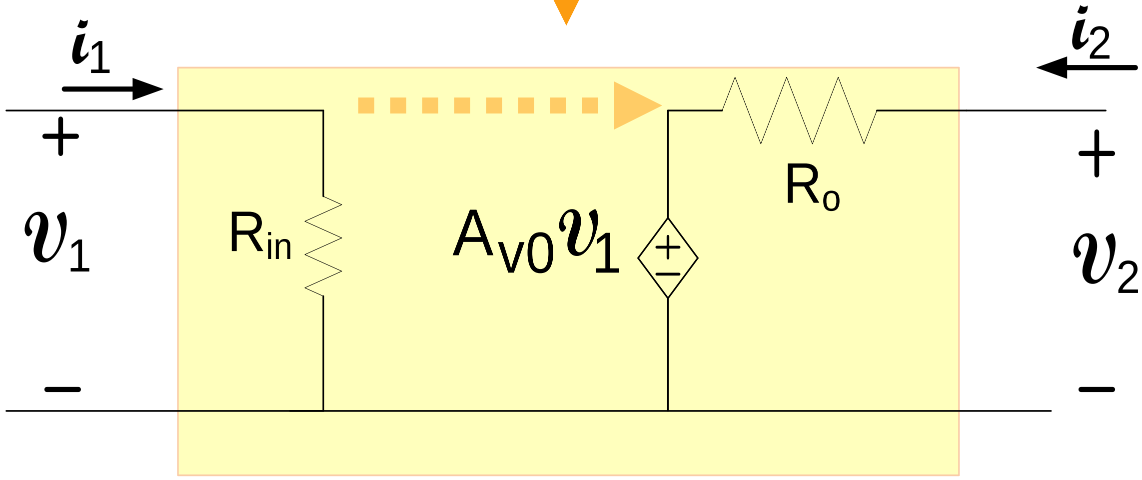
Can include or exclude R and R_1 in two-port models (of course they are different circuits)

The CE and CS amplifiers are themselves two-ports !

Two-port model for Common Emitter Configuration



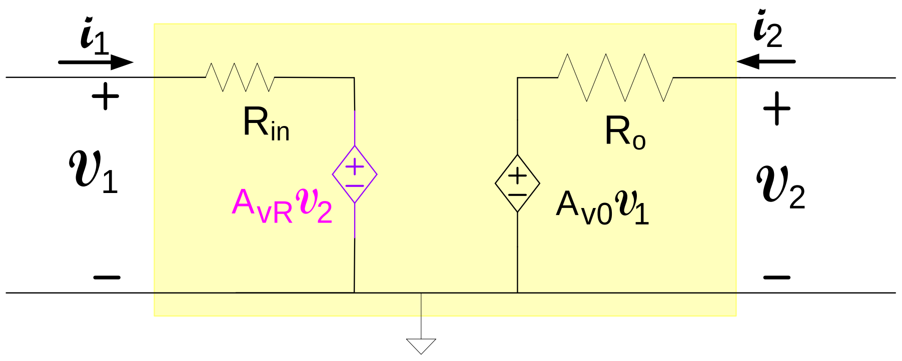




$\{R_i, A_{V0}$ and $R_0\}$

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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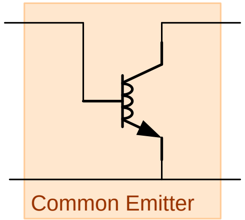
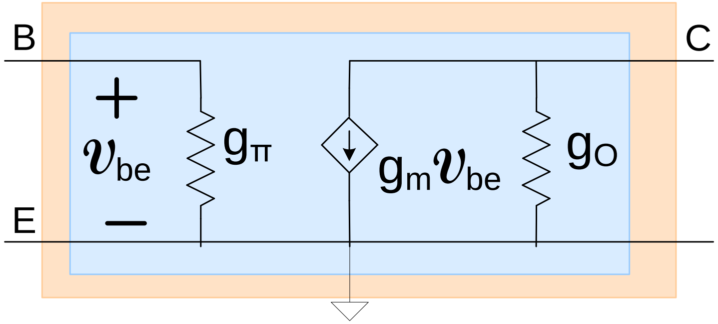
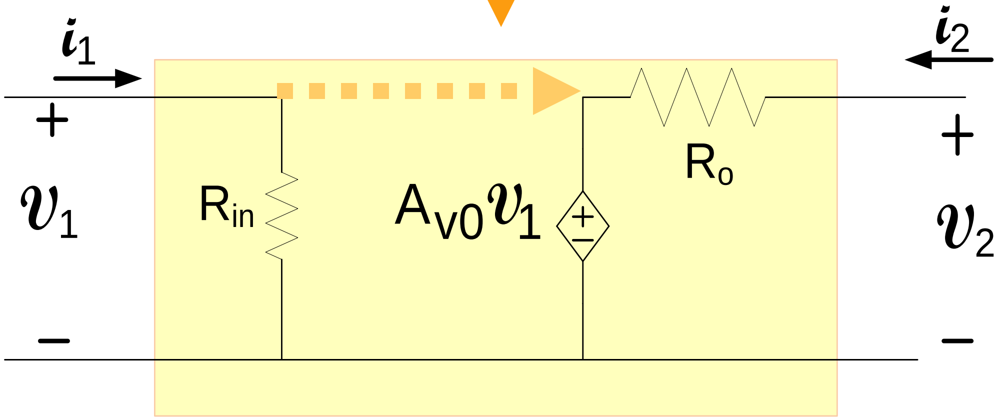
4. Ad Hoc Approaches

Two-port model for Common Emitter Configuration







By Thevenin : Norton Transformations

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

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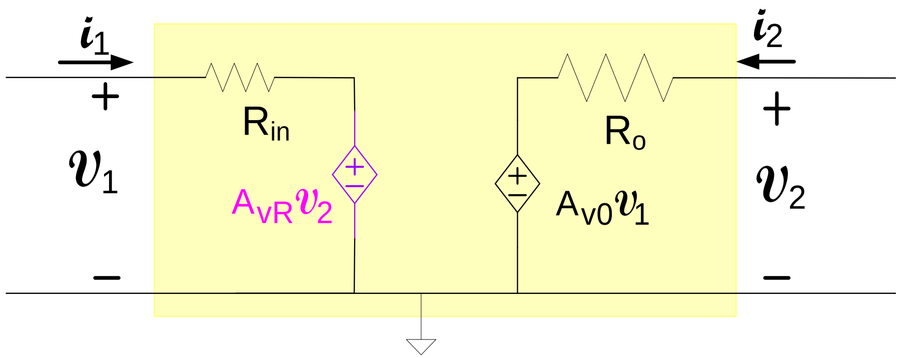

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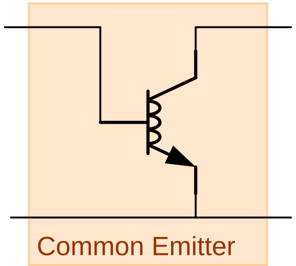
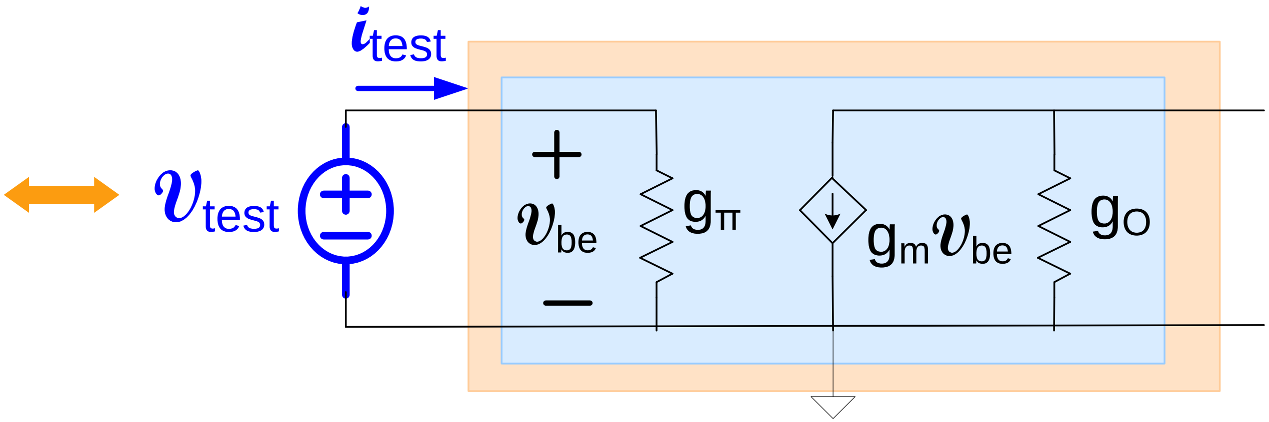
4. Ad Hoc Approaches

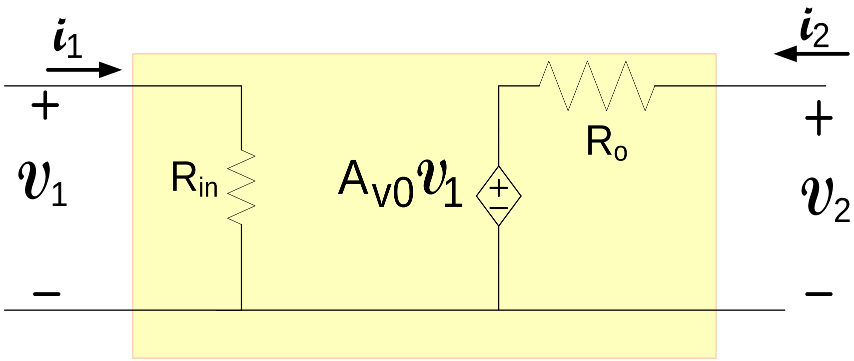
Two-port model for Common Emitter Configuration

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

To obtain R_{in}







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

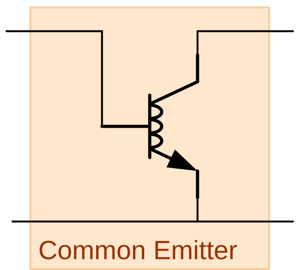
$$R_{in} = \frac{1}{g_\pi}$$

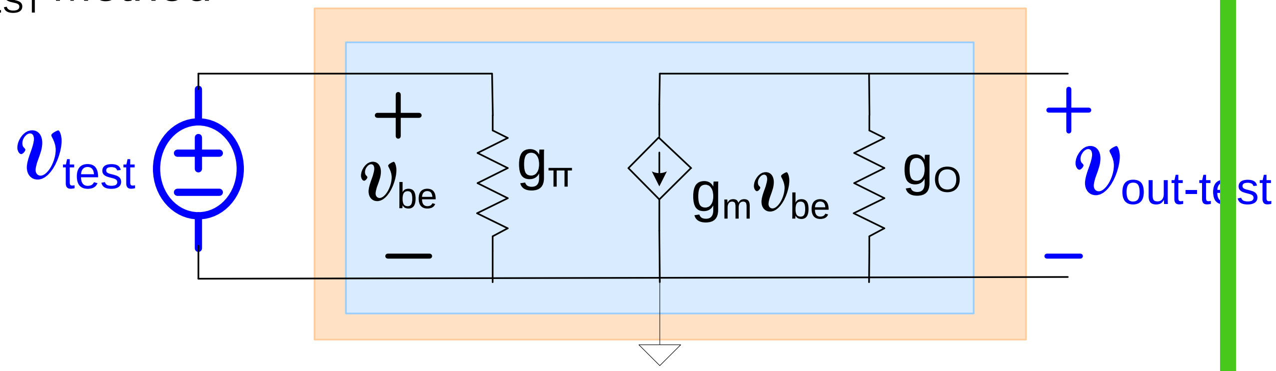
{R_{in}, A_{V0} and R_0}

Two-port model for Common Emitter Configuration

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

To obtain A_{V0}

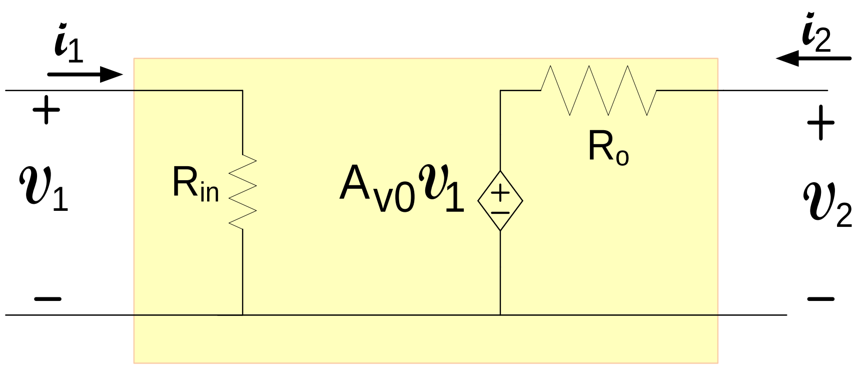




$$A_{V0} = \frac{v_{out\text{-}test}}{v_{test}}$$

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

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

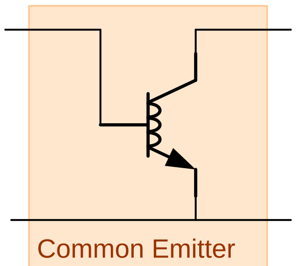


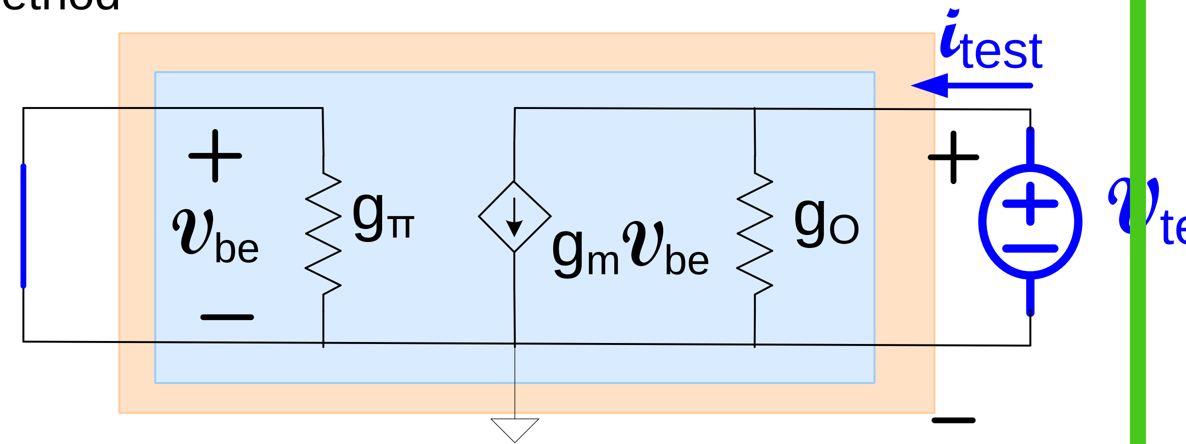
{R_{in}, A_{V0} and R_0}

Two-port model for Common Emitter Configuration

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

To obtain g_0

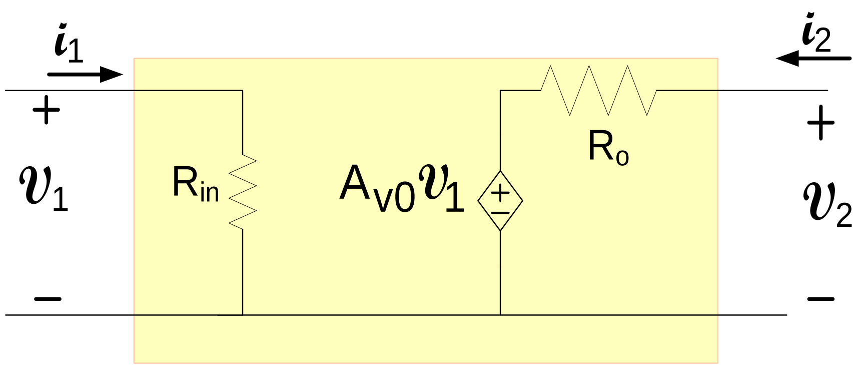




$$R_0 = \frac{v_{test}}{i_{test}}$$

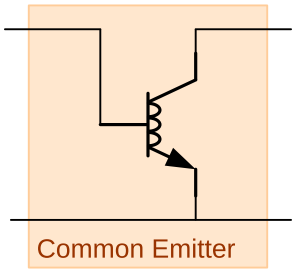
$$v_{test} = i_{test}\left(g_0\right)$$

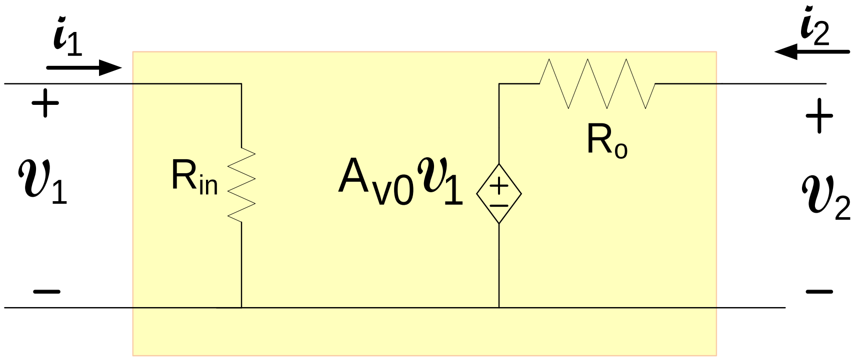
$$R_0 = \frac{1}{g_0}$$



{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

End of Lecture 31