ESc201 : Introduction to Electronics

Amplifiers

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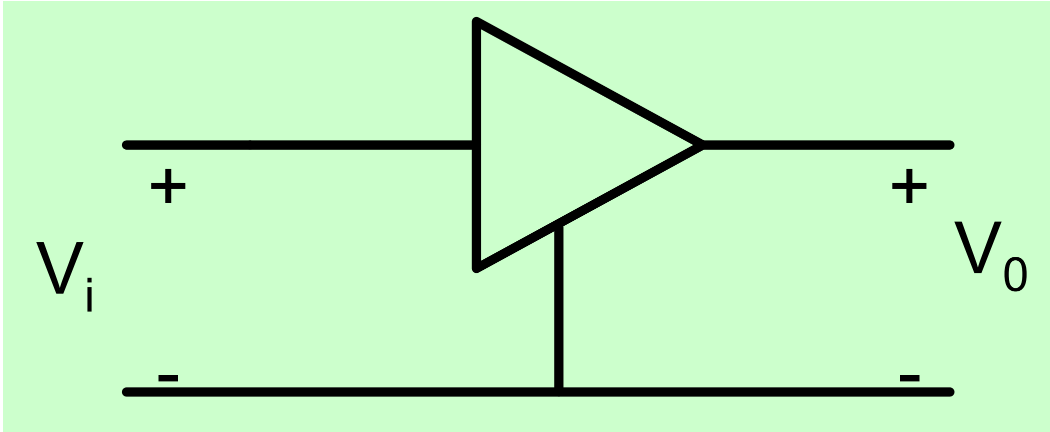
Objective

1. Learn ideal Transistor characteristics required for Voltage Amplification

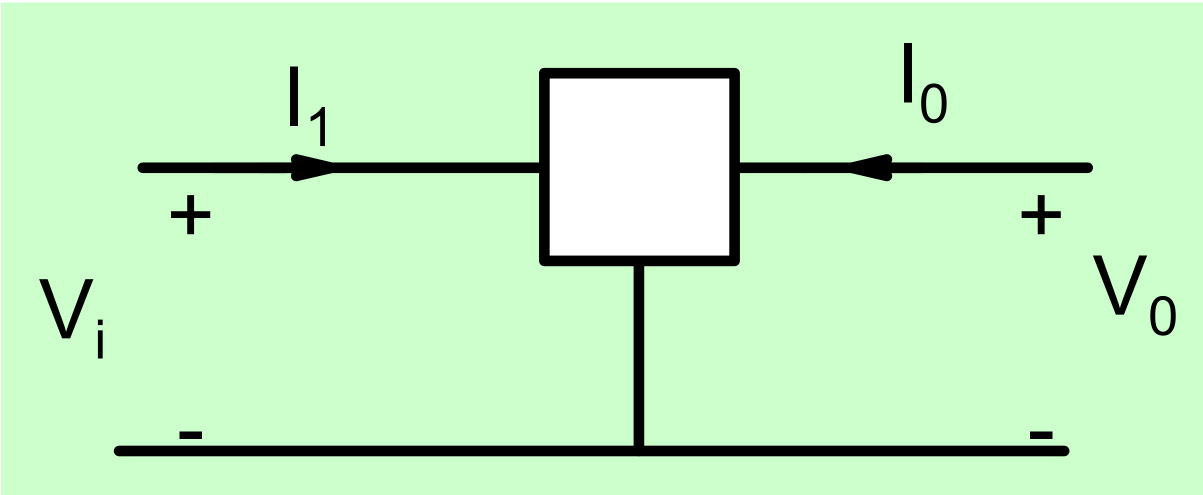
2. Learn to build amplifiers using elements which have non-ideal characteristics.

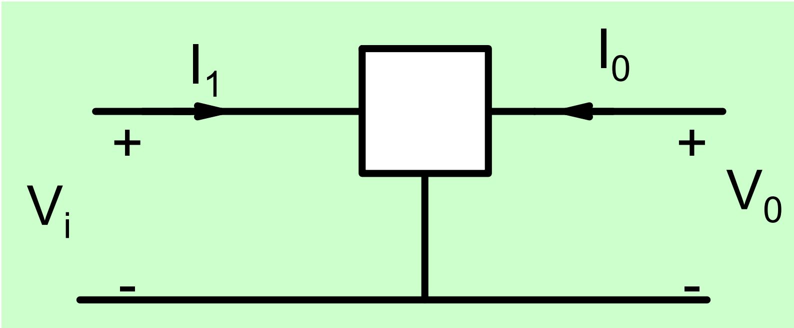
Voltage Amplification

$$V_o = G \times V_i$$
$$G > 1$$



3-terminal unilateral linear device





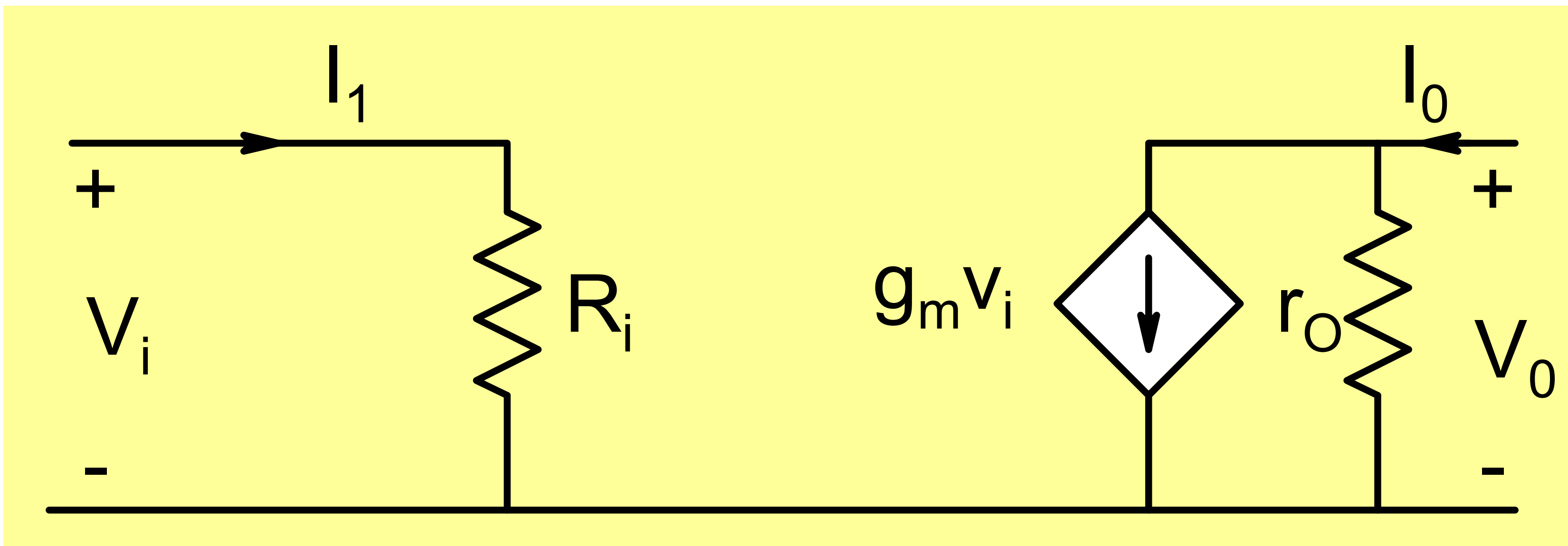
Input resistance $R_i = V_i / I_i$

(Ideally large)

Trans conductance

$$g_m = \left.\frac{I_o}{V_i}\right|_{V_0=0}$$

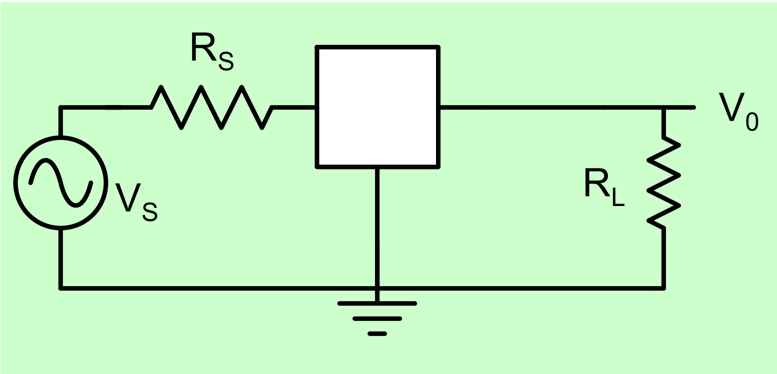
(Ideally large)

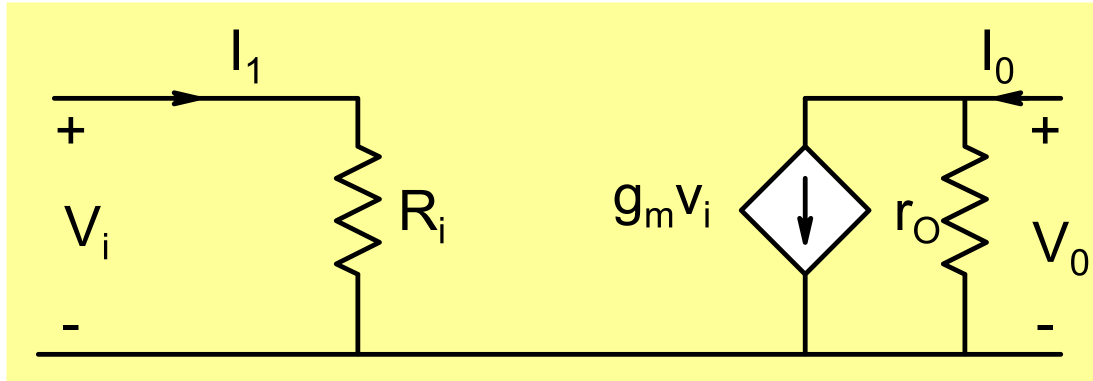


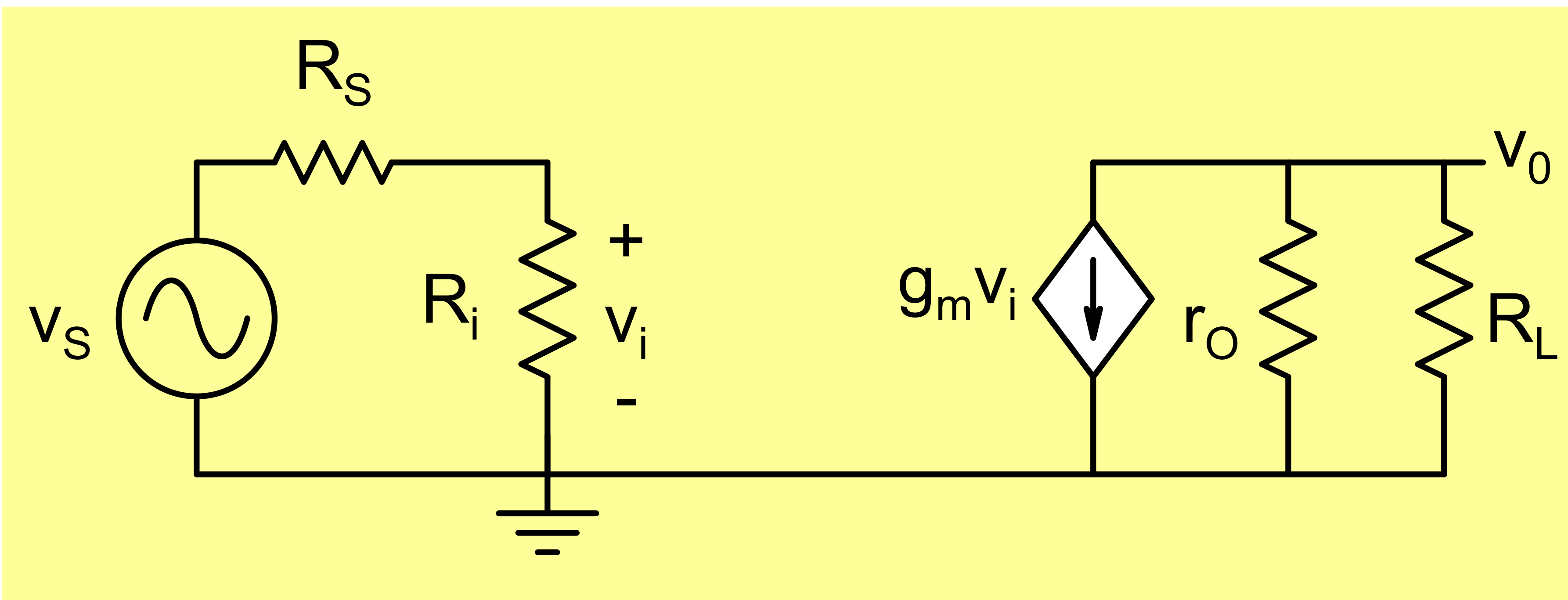
Output conductance: $g_o = 1/r_o = \left.\frac{I_o}{V_o}\right|_{V_i=0}$

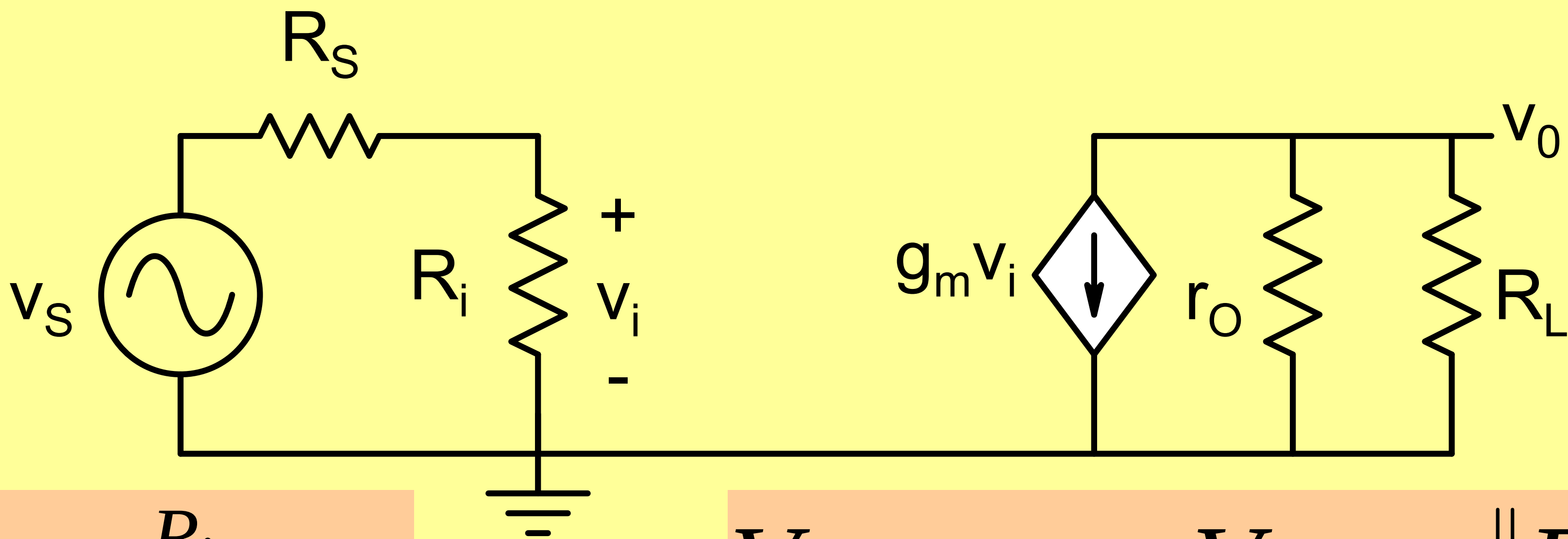
(Ideally small)

Voltage Amplifier









$$V_i = \frac{R_i}{R_i + R_S} V_S$$

$$V_o = -g_m V_i \times r_o \| R_L$$

$$A_V = \frac{V_o}{V_s} = -g_m r_o \times \frac{R_L}{r_o + R_L} \times \frac{R_i}{R_i + R_S}$$

$$\left| A_V \right| \le g_m \times r_o$$

Necessary Condition for Voltage Amplifications $g_m \times r_o > 1$

Voltage Amplification

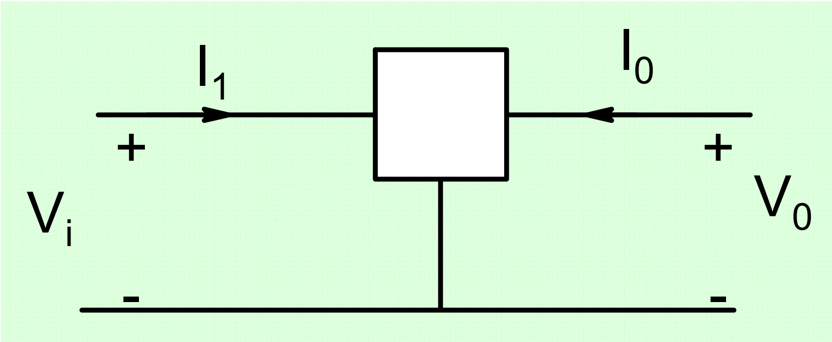
$$g_m r_o >> 1$$

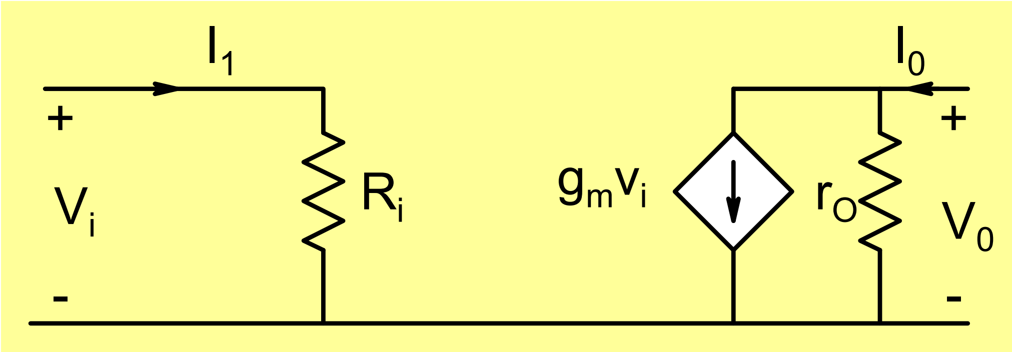
$$g_m >> g_o$$

Trans-conductance >> Output Conductance

$$g_m = \left.\frac{I_o}{V_i}\right|_{V_0=0}$$

$$g_o = \left.\frac{I_o}{V_o}\right|_{V_i=0}$$





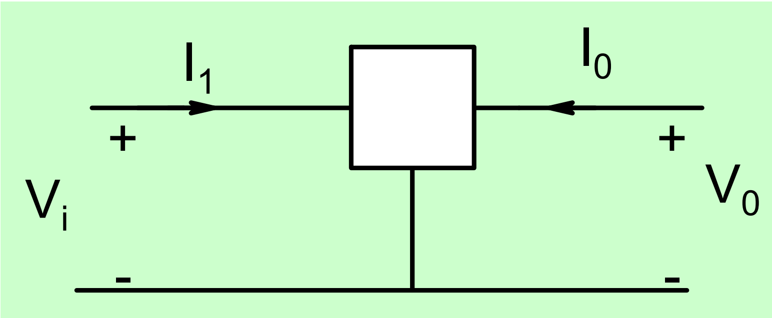
Transistor

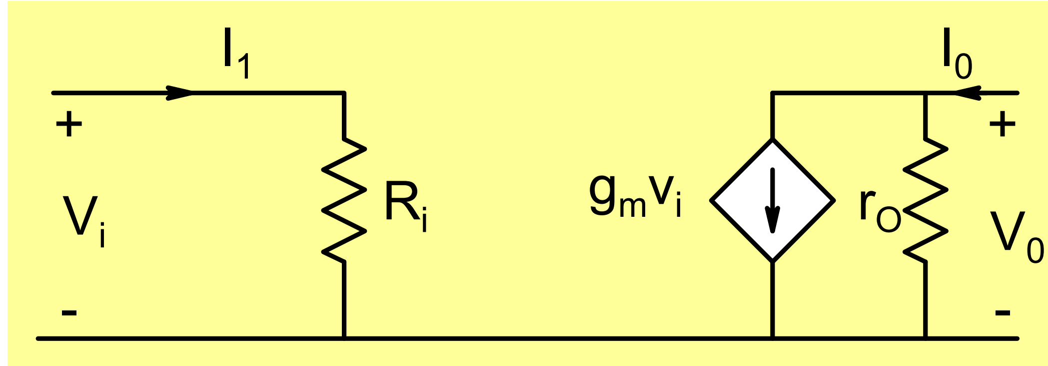
Transistor

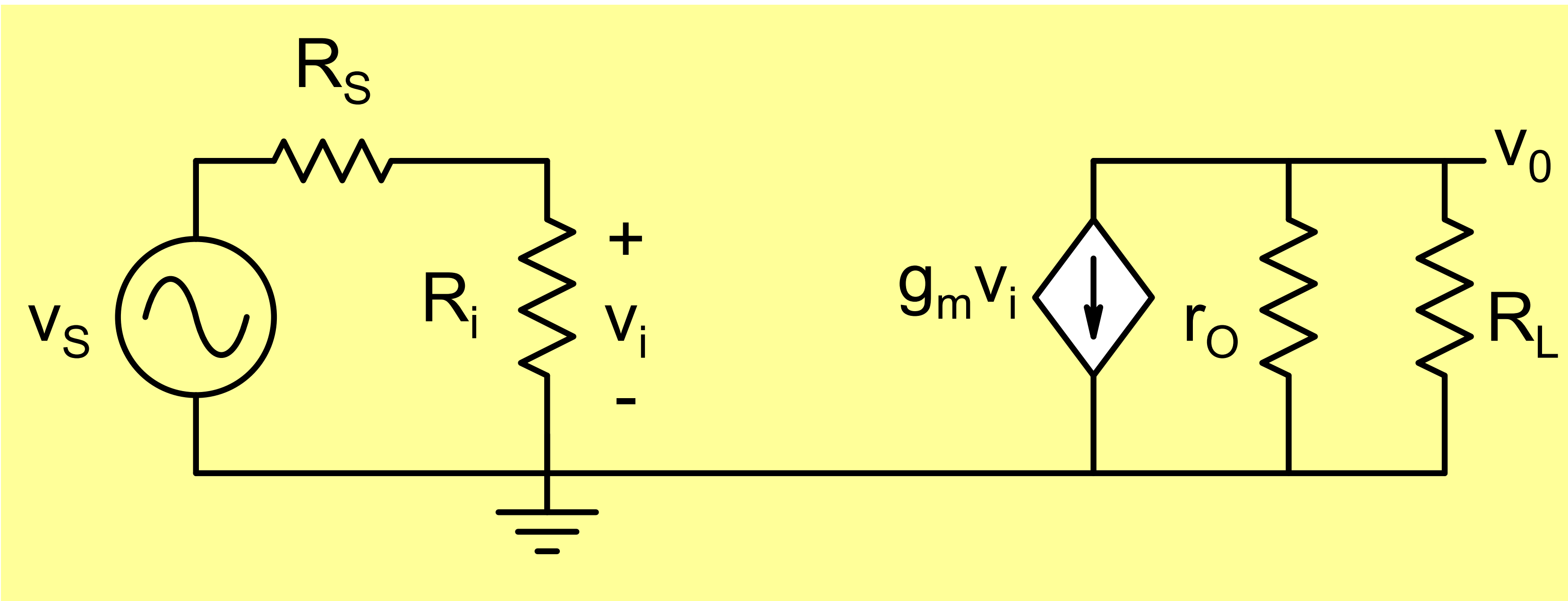
Trans-resistor

Current I_O is much more sensitive to V_{IN} than V_O

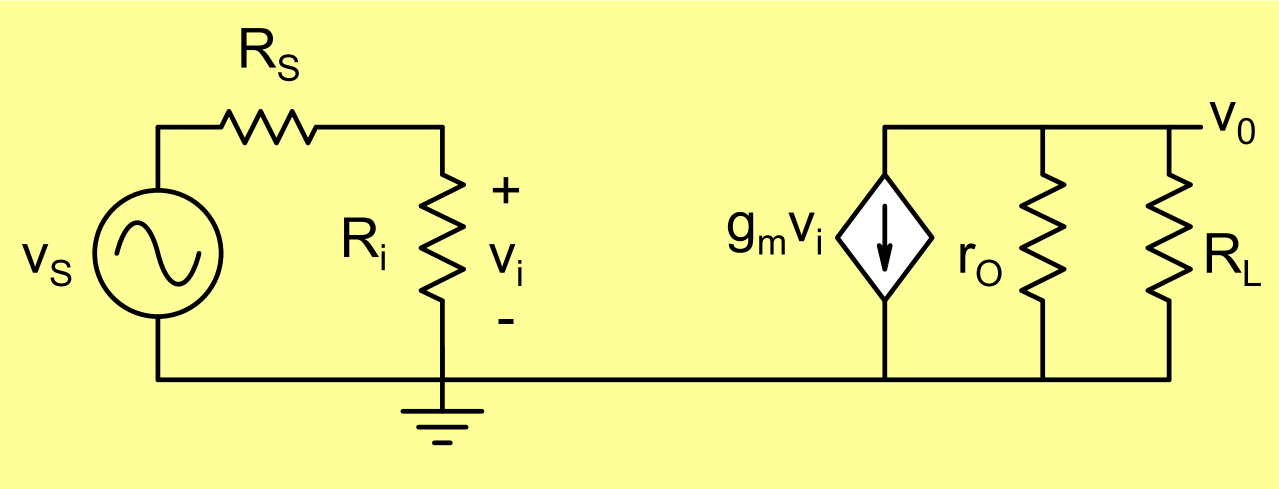
- Can be used for voltage amplification
- Can be used as a switch
- Implement logic
- …







$$A_V = \frac{V_o}{V_S} = -g_m r_o \times \frac{R_L}{r_o + R_L} \times \frac{R_i}{R_i + R_S}$$



$$A_V = \frac{V_o}{V_s} = -g_m r_o \times \frac{R_L}{r_o + R_L} \times \frac{R_i}{R_i + R_S}$$

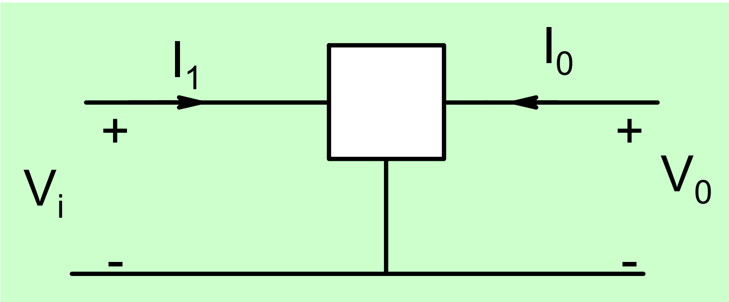
In the ideal case r_o is infinite

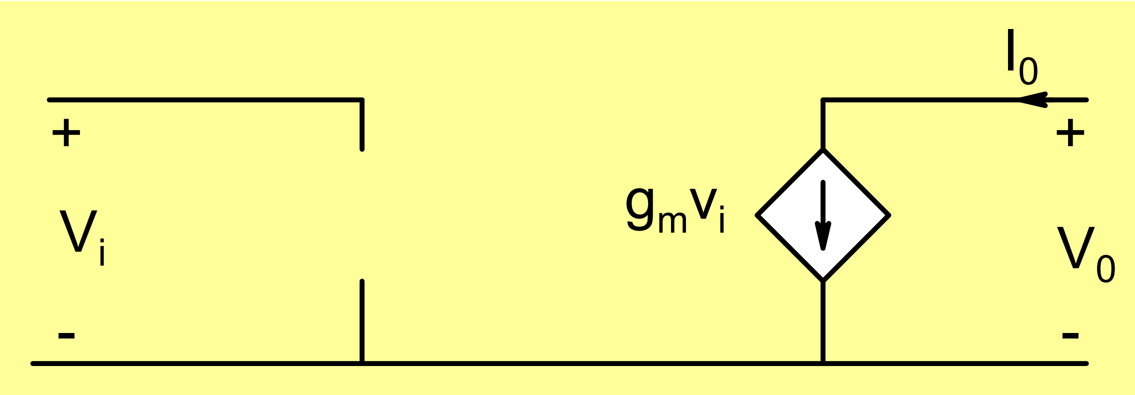
$$A_V = \frac{V_o}{V_s} = -g_m R_L \times \frac{R_i}{R_i + R_S}$$

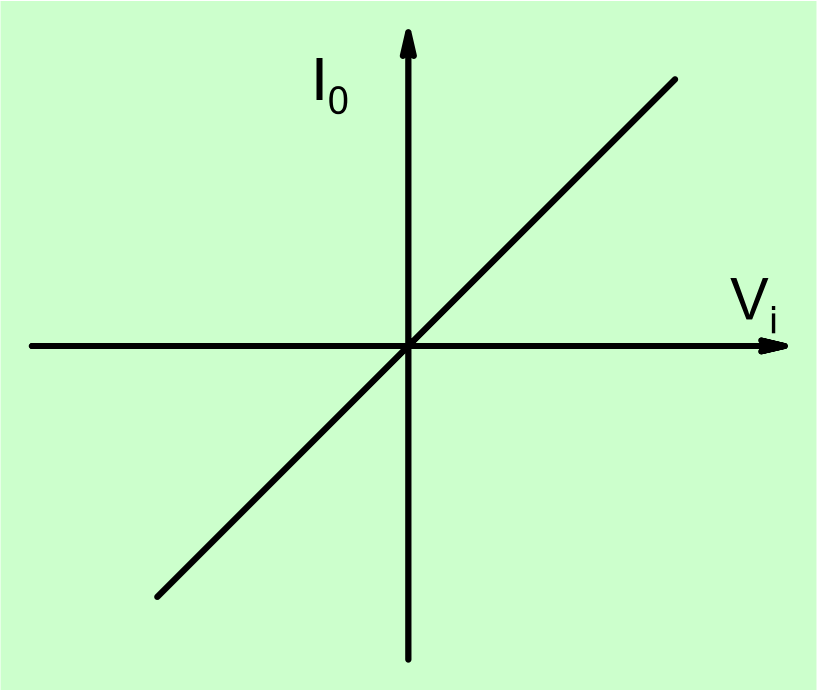
We would ideally like input resistance R_i to be infinite as well !

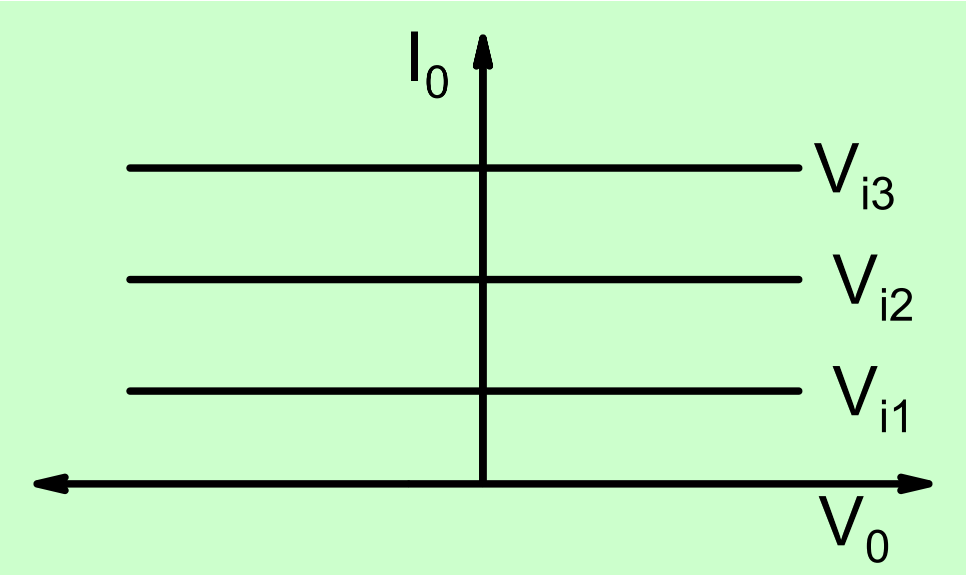
$$A_V = -g_m R_L$$

An ideal 3-terminal device for Voltage Amplification





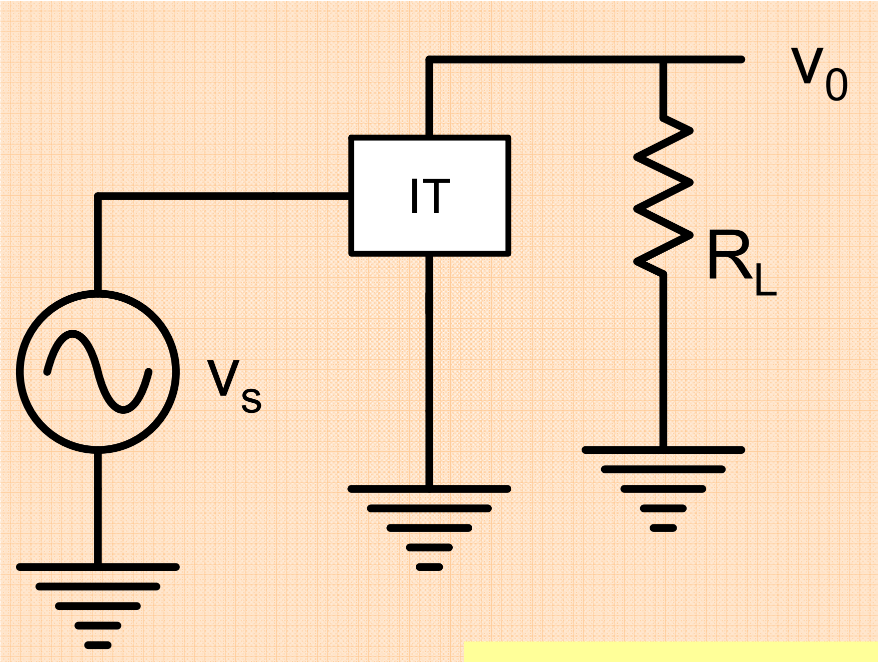


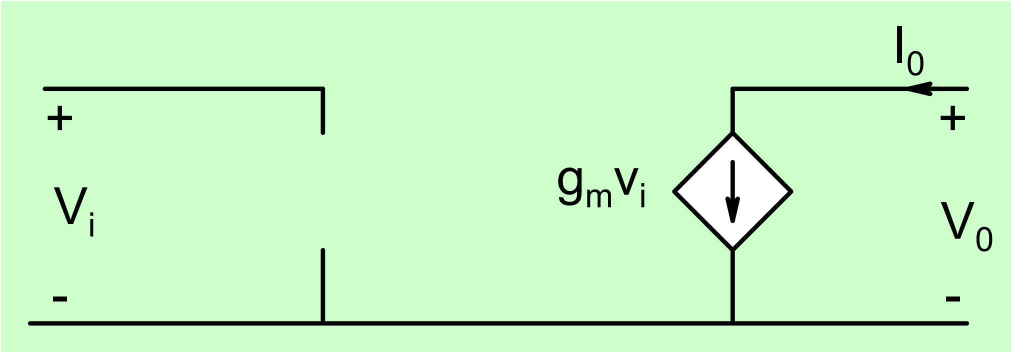


Ideal Transistor Characteristics

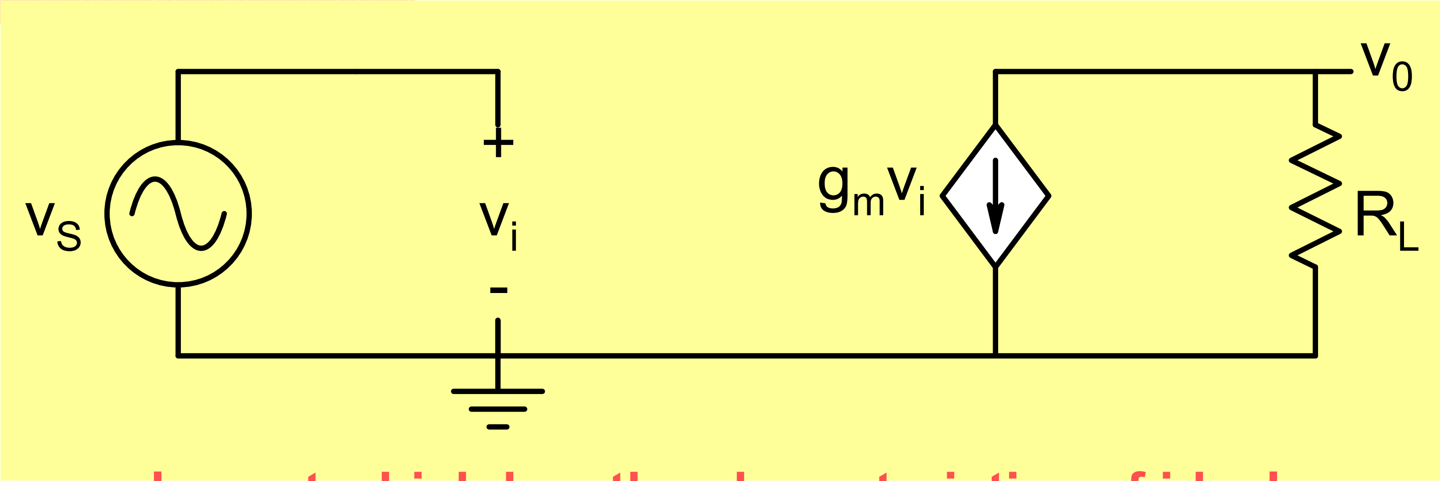
Ideal Transistor (IT)

Making a voltage amplifier with an ideal transistor is straightforward



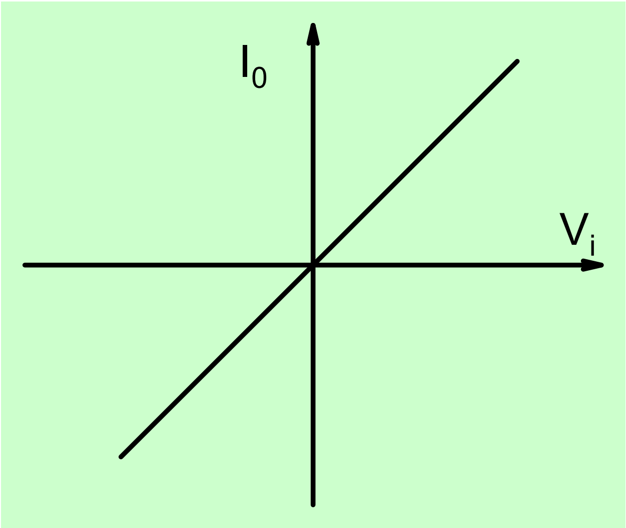


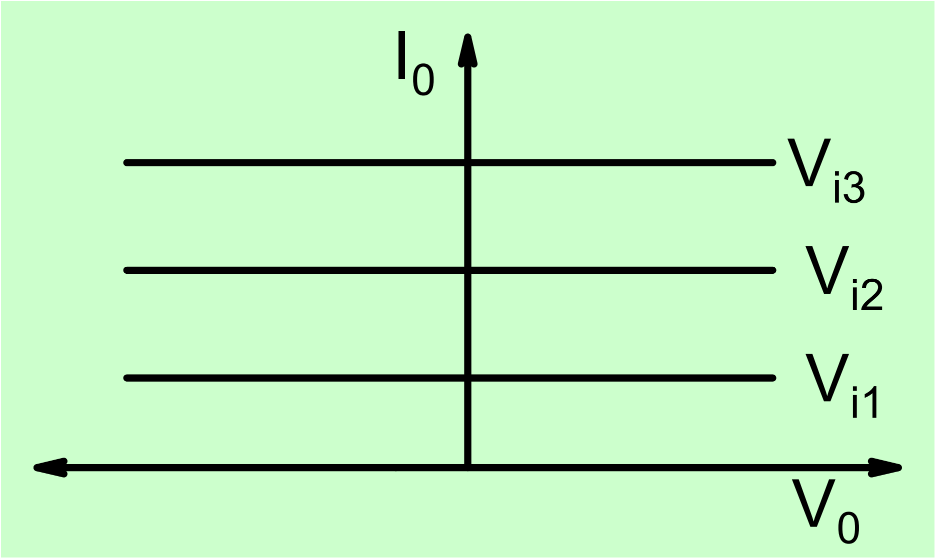
$$A_V = \frac{v_o}{v_s} = -g_m R_L$$



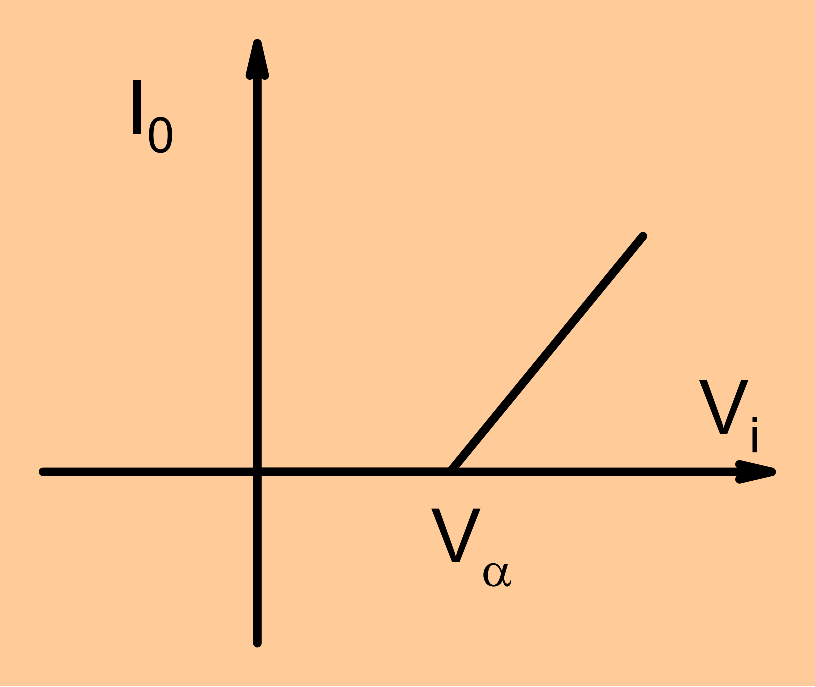
In practice there is no element which has the characteristics of ideal transistor !

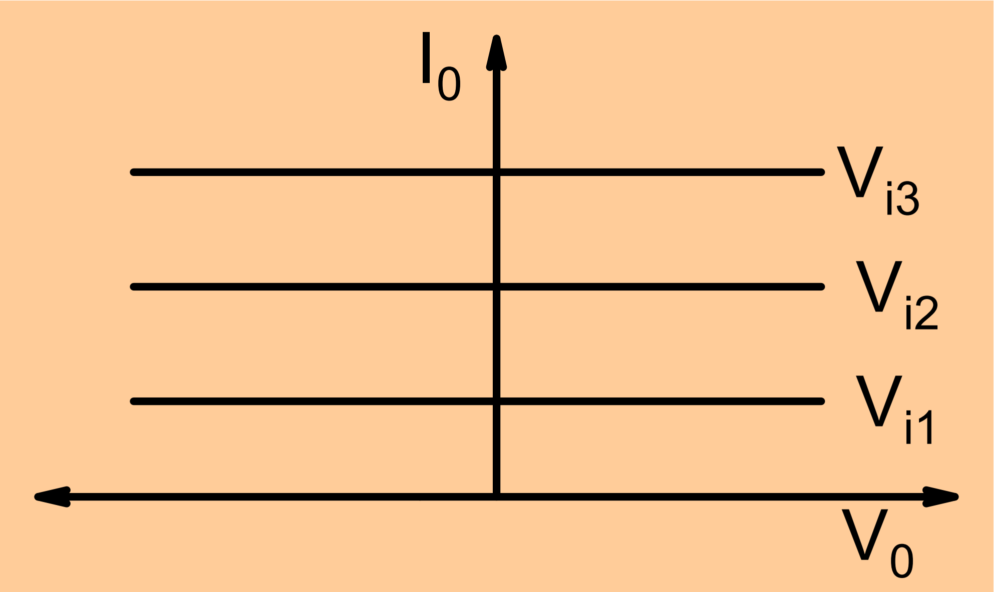
Ideal transistor



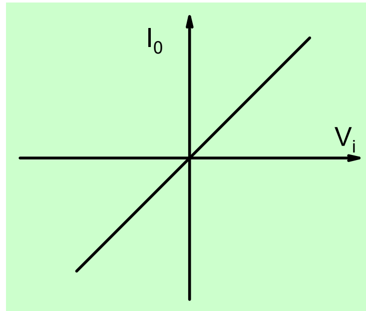


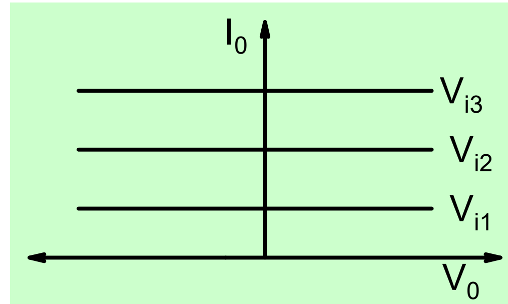
Device X



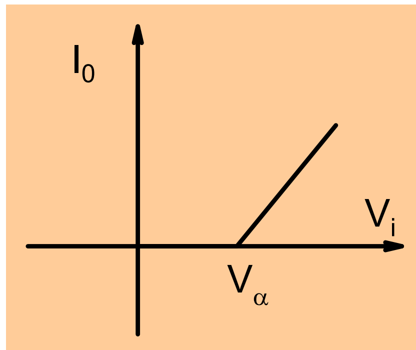


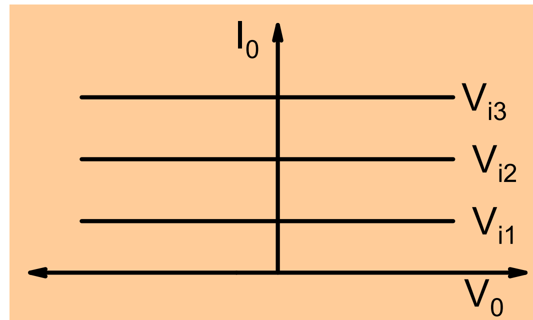
Ideal transistor



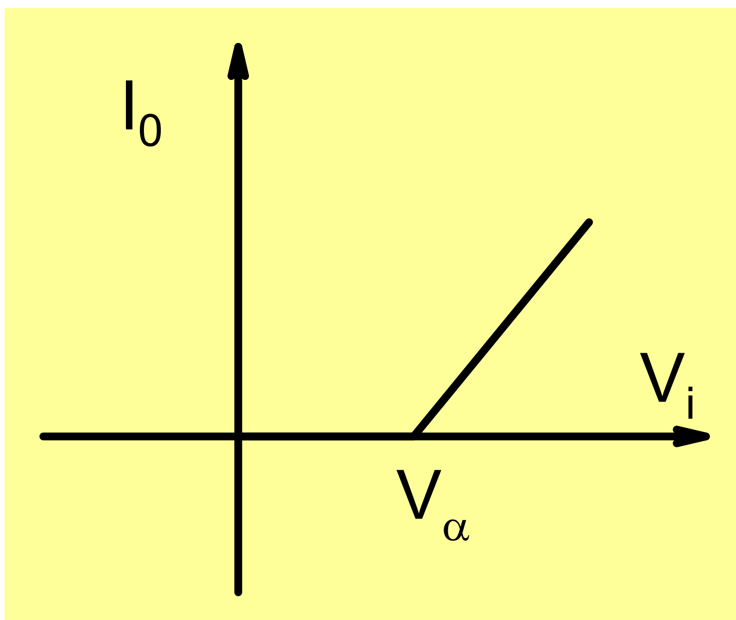


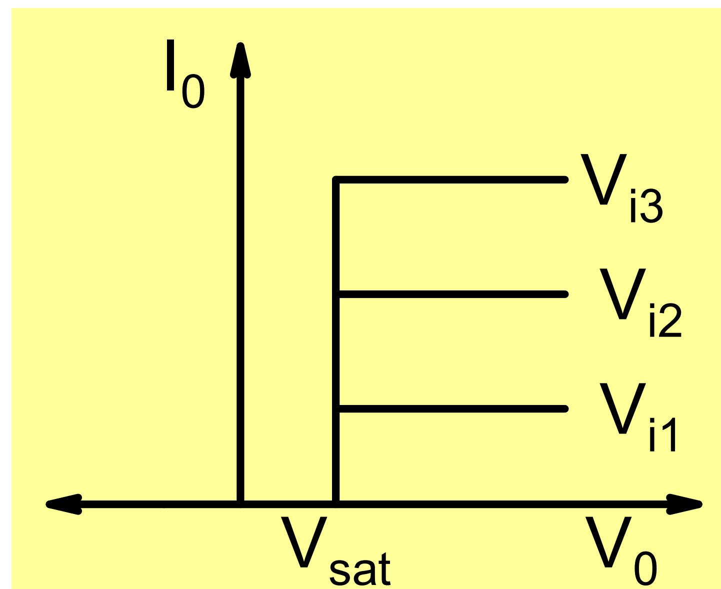
Device X





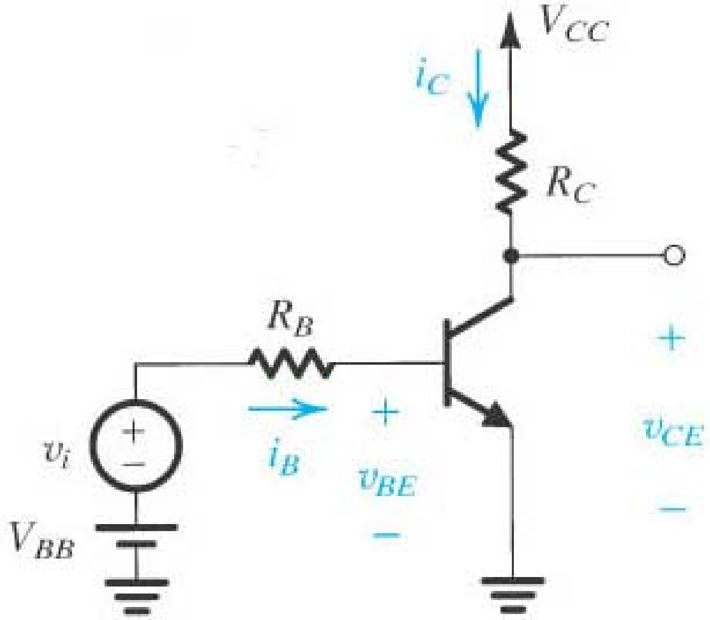
Device Y

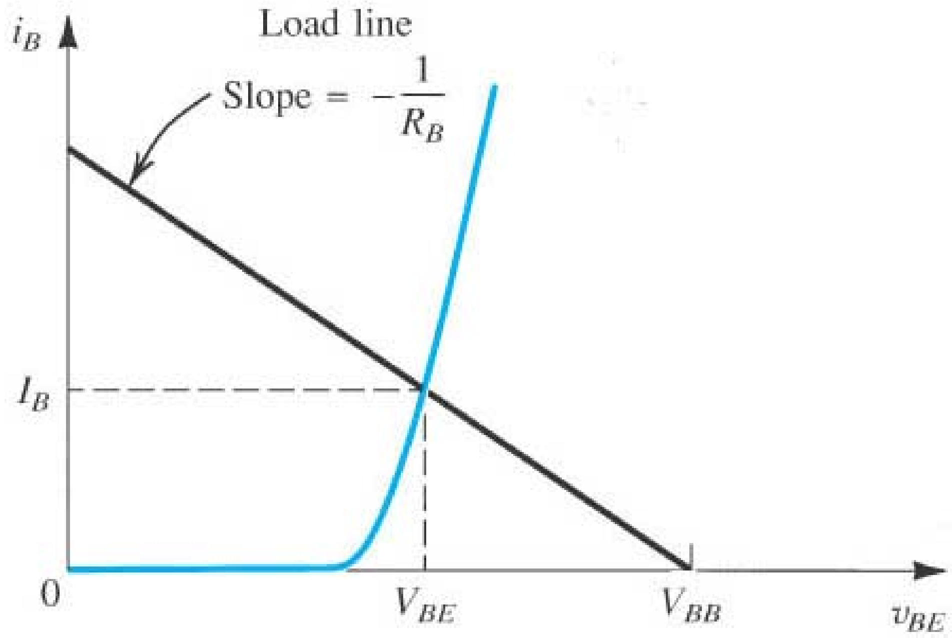




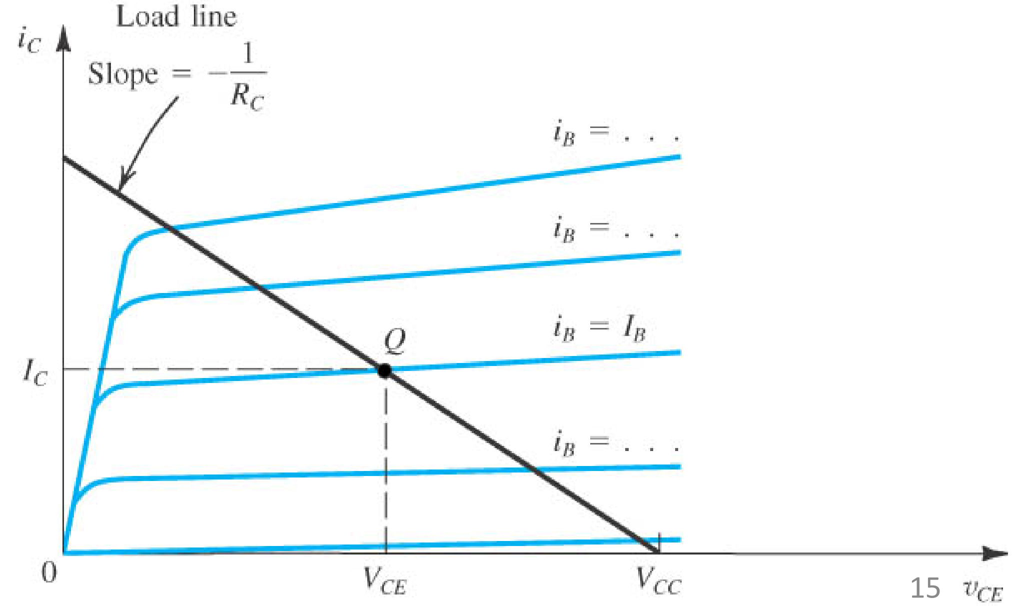
How do we use elements such as X, Y etc to make amplifiers?

Bipolar Junction Transistor: BJT



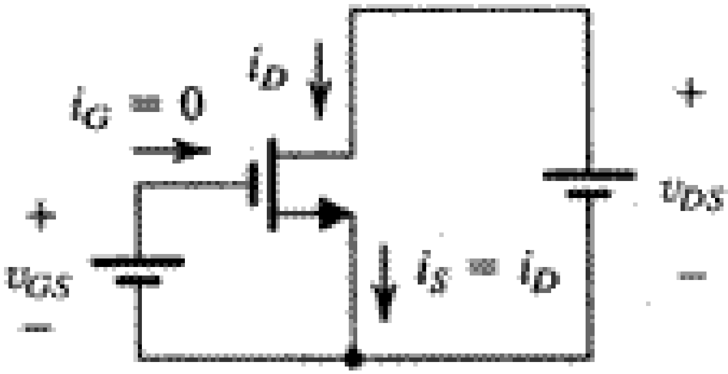


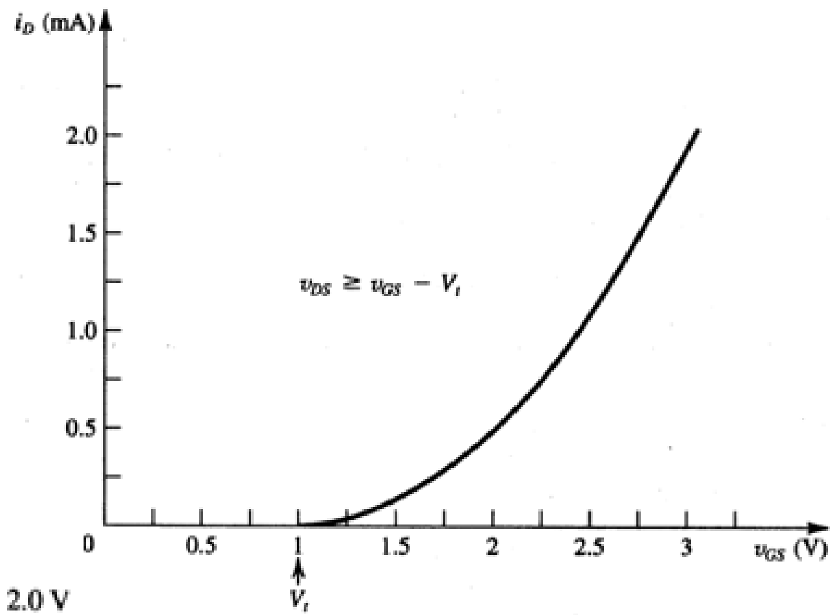
$$I_C = \beta_F I_B$$

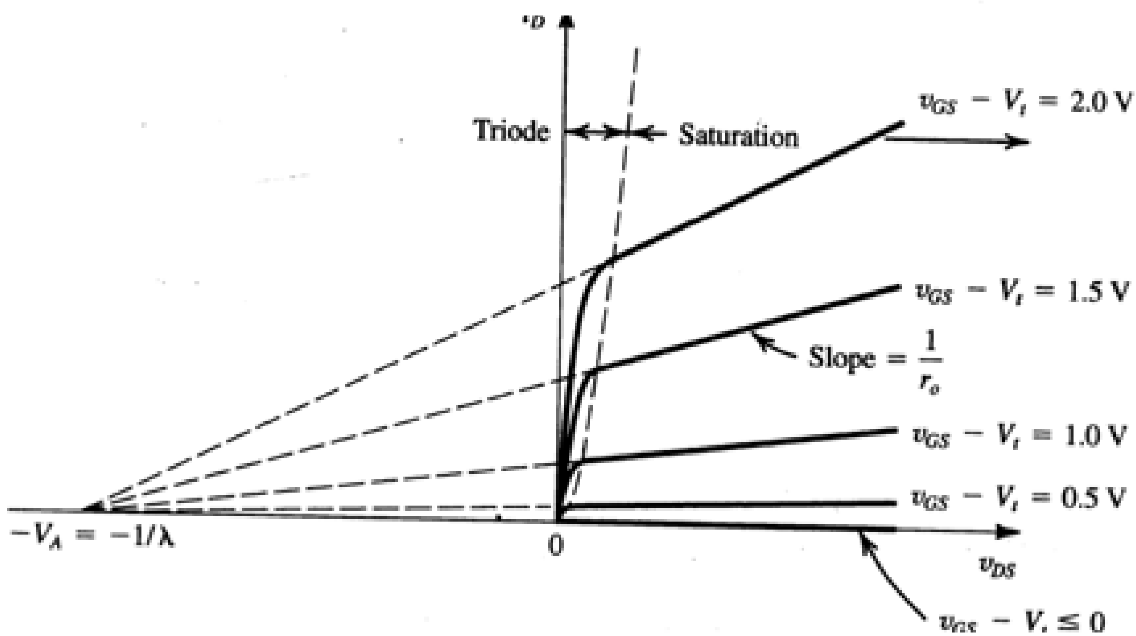


Metal Oxide Semiconductor Field Effect Transistor

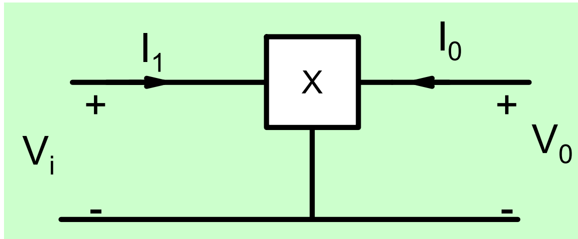
MOSFET



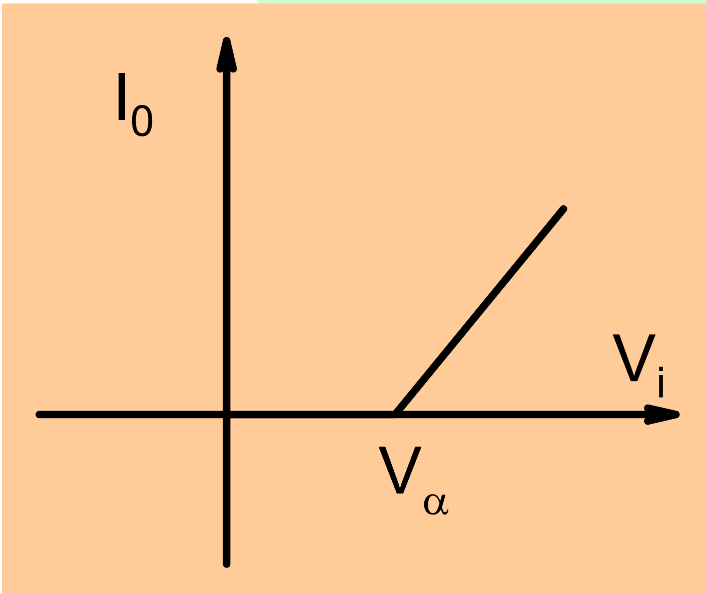


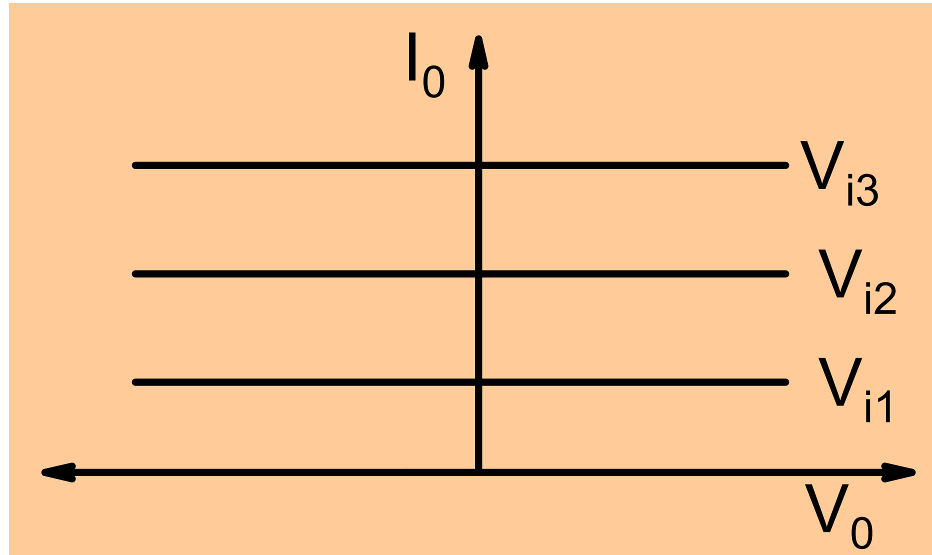


Device X

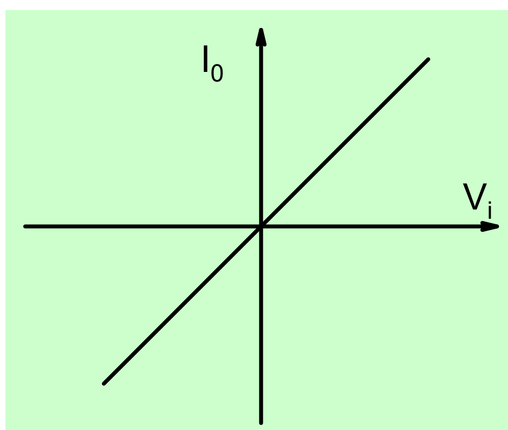


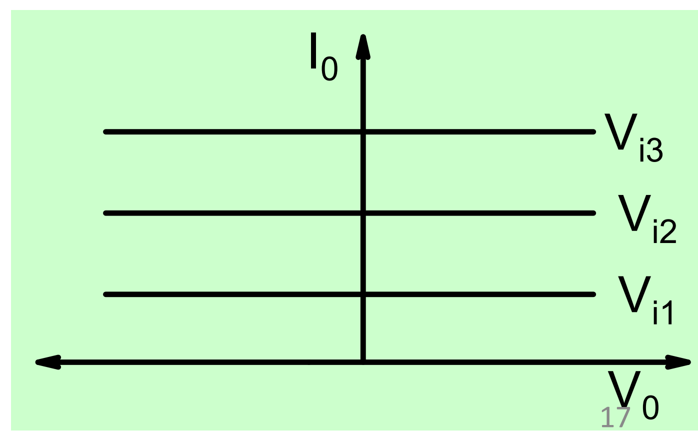
$$
\begin{aligned}
I_o &= 0 && \text{for } V_i \le V_\alpha \\
&= g_m \times (V_i - V_\alpha) && \text{for } V_i > V_\alpha
\end{aligned}
$$



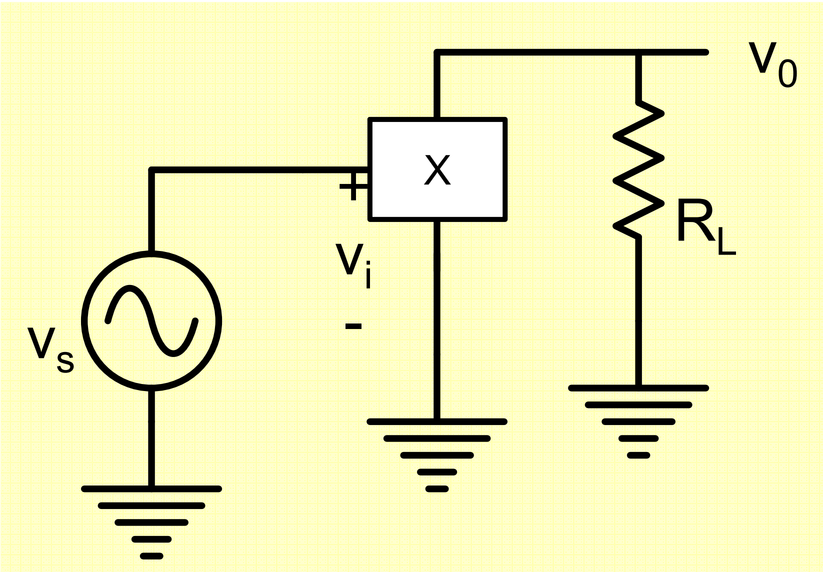


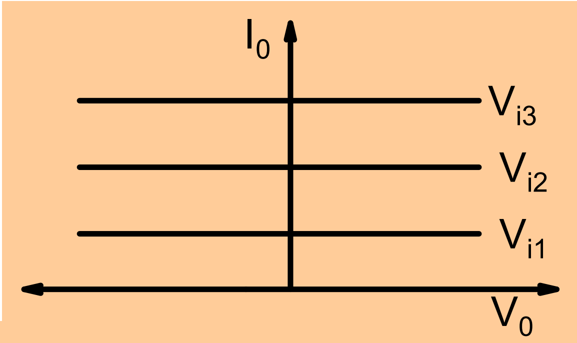
Ideal Characteristics

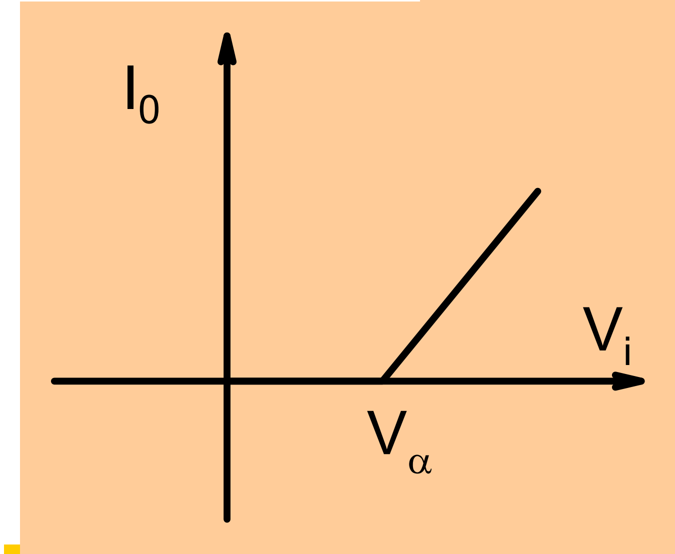


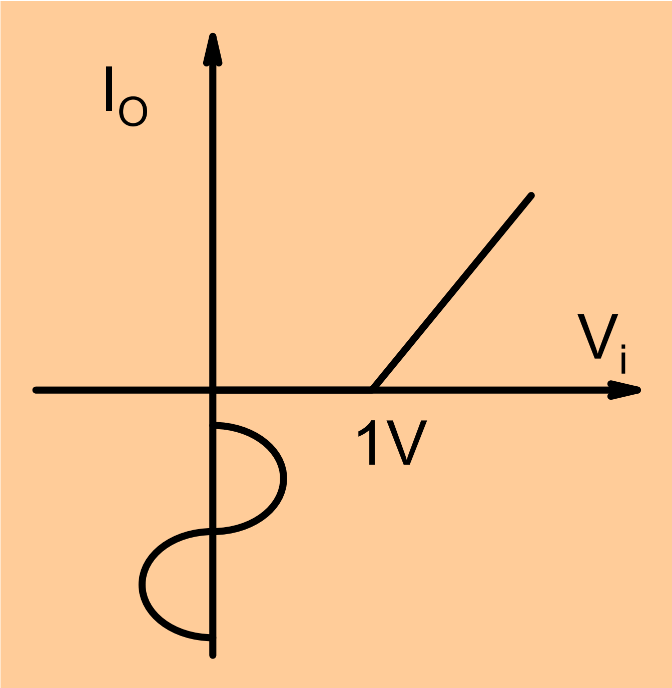


How do we use device X to make an amplifier?









$$V_\alpha = 1V;\ g_m = 0.01\Omega^{-1}$$

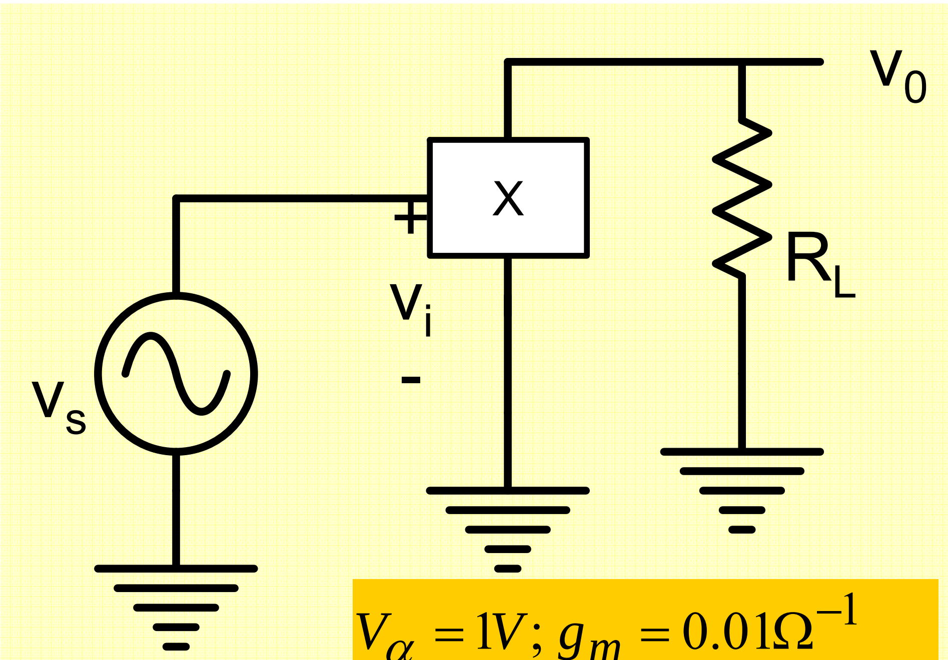
$$R_L = 1K\ ;\ v_s = 0.5V\ Sin\ \omega t$$

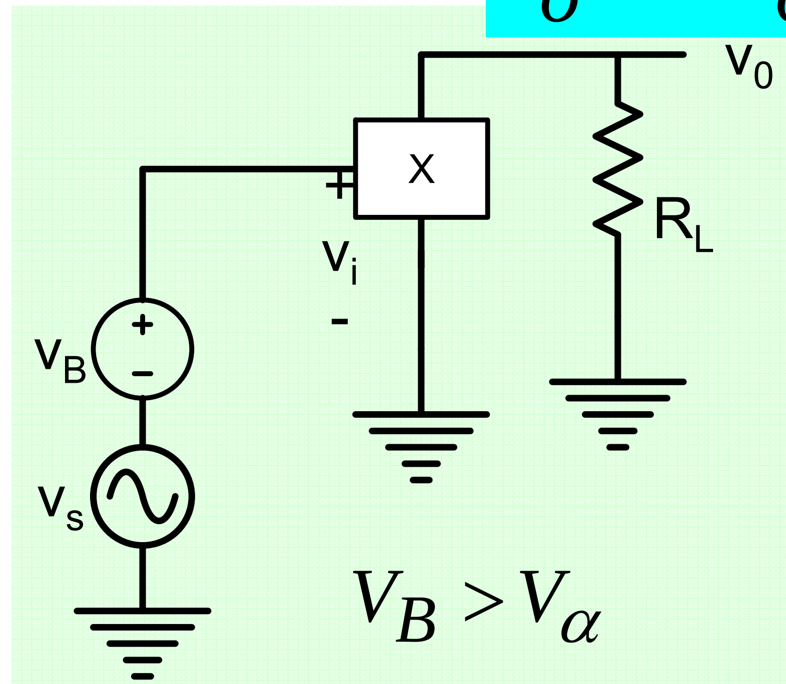
$$I_O = 0 \Rightarrow V_O = 0$$

No Amplification

How do we use device X to make an amplifier?

$$V_o = -I_o R_L$$

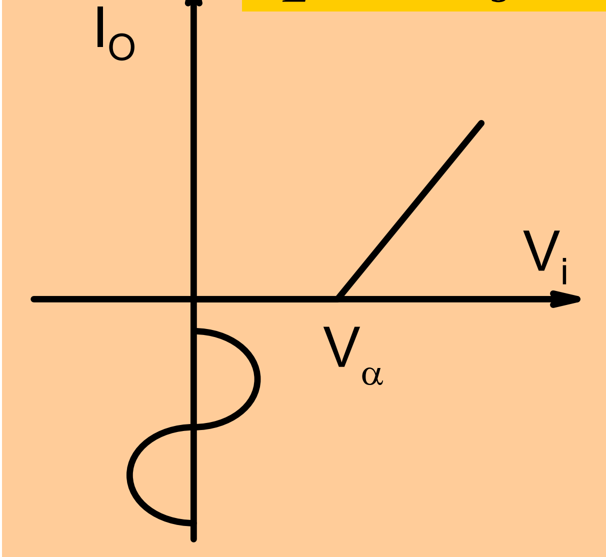


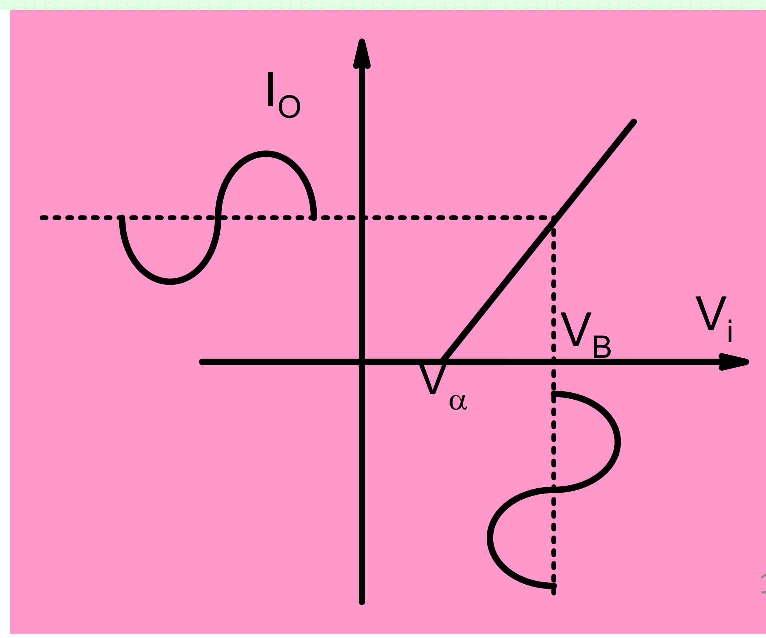


$$V_B > V_\alpha$$

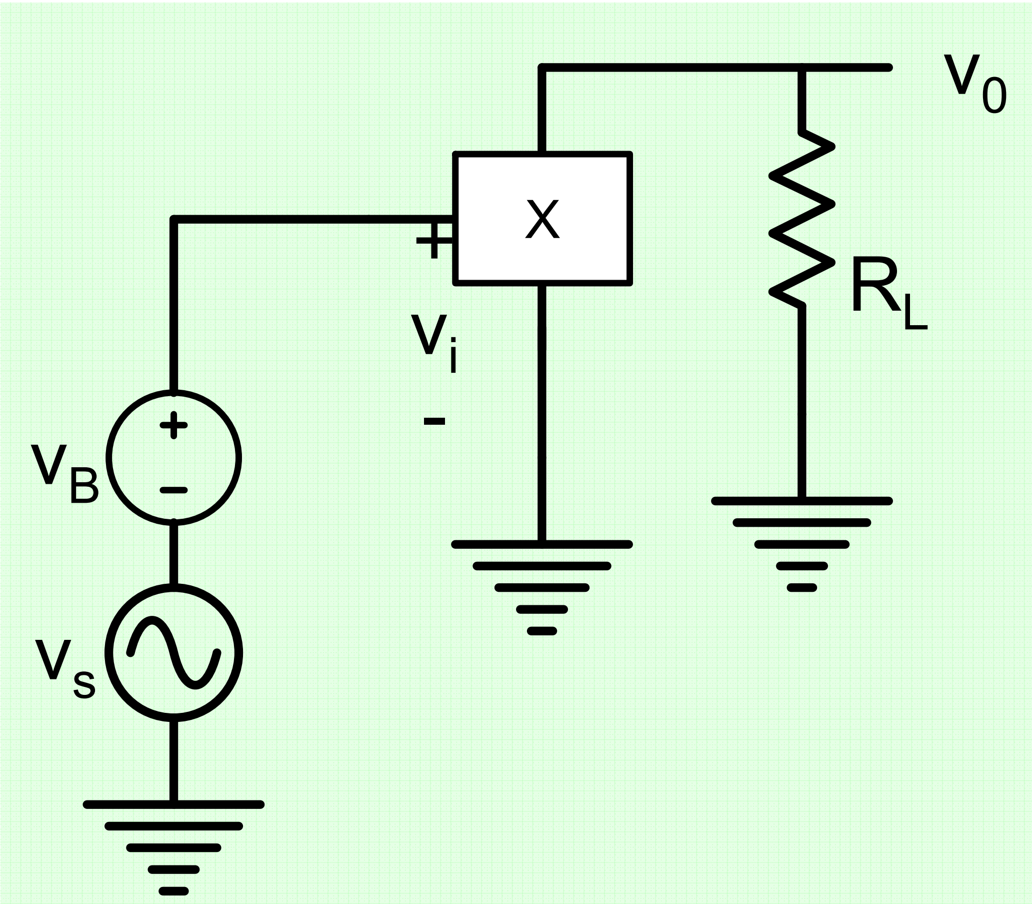
$$V_\alpha = 1V;\ g_m = 0.01\Omega^{-1}$$

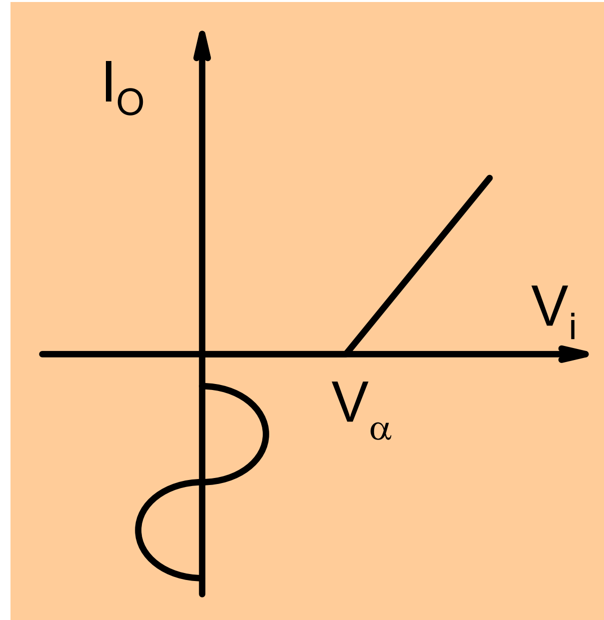
$$R_L = 1K\ ;\ v_s = 0.5V\ Sin\ \omega t$$

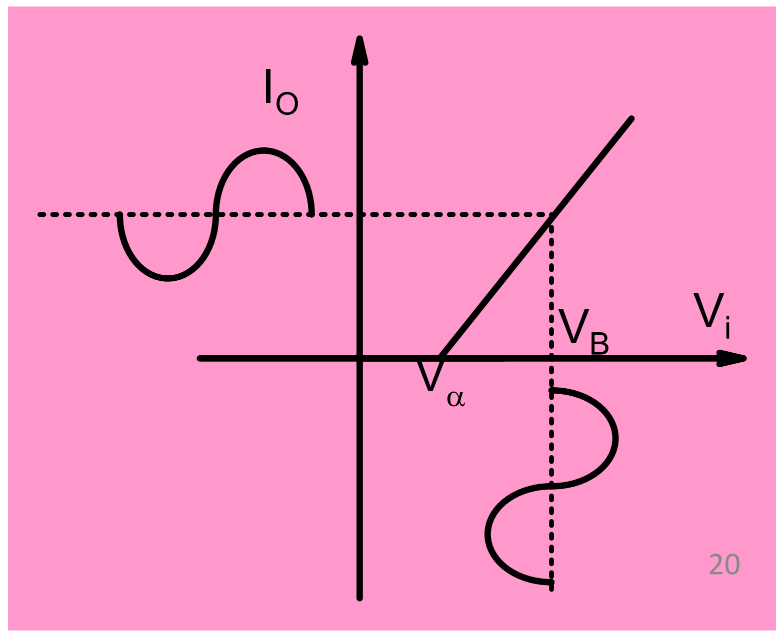




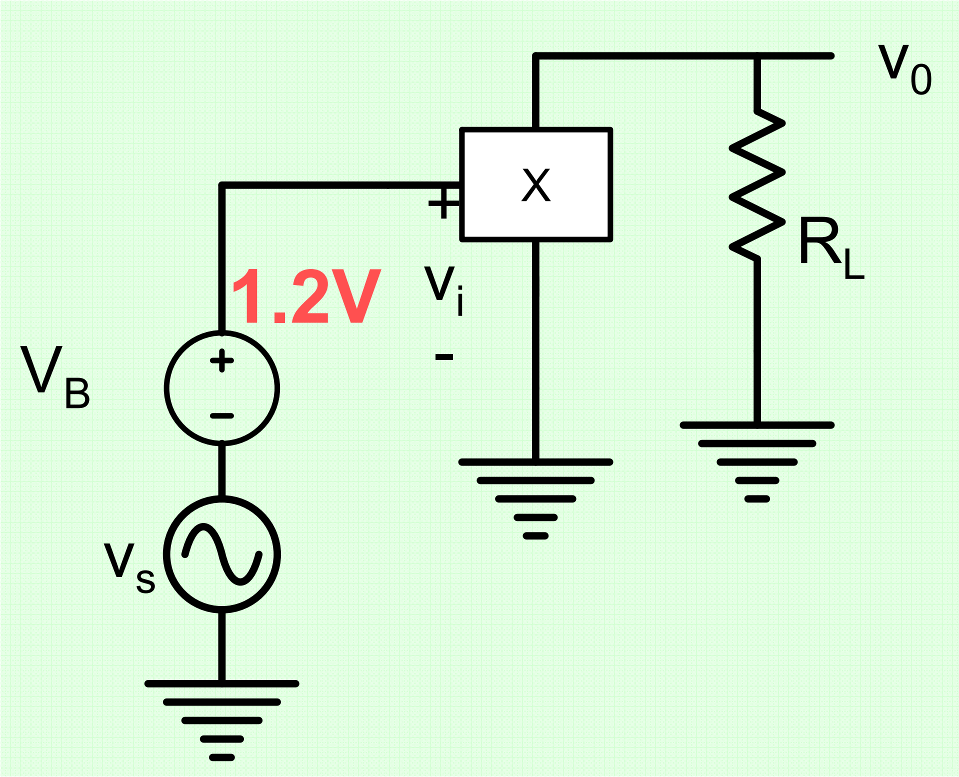
When only a part of device characteristics is suitable for amplification, then we need to push the device into that region by applying suitable bias voltages. This process is called **BIASING**



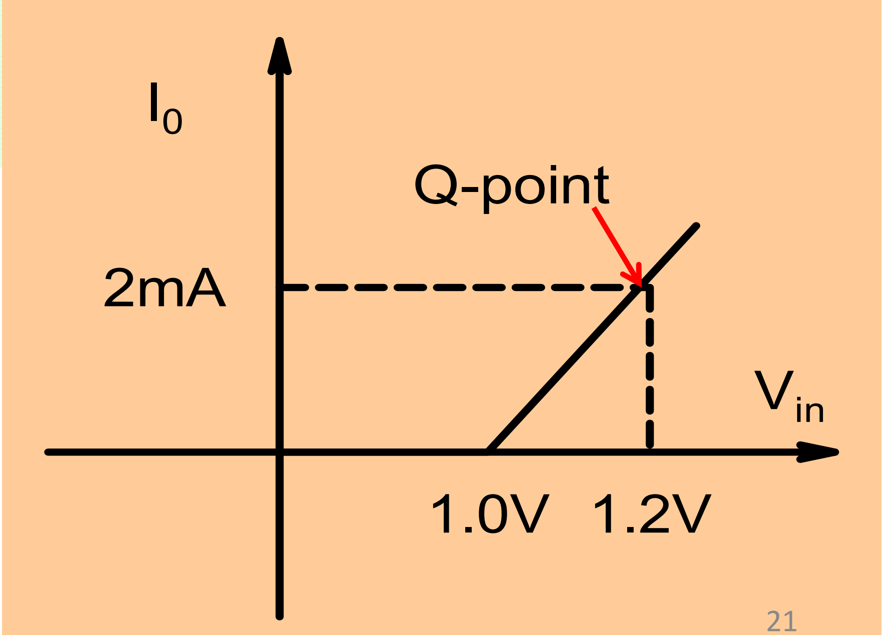




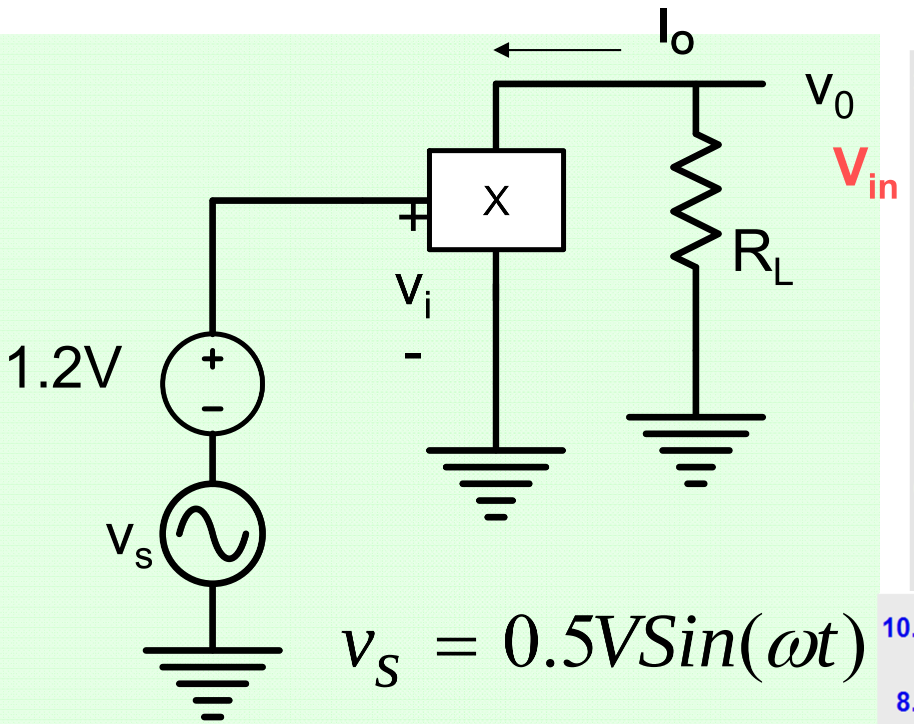
How should one choose the bias voltage V_B ?



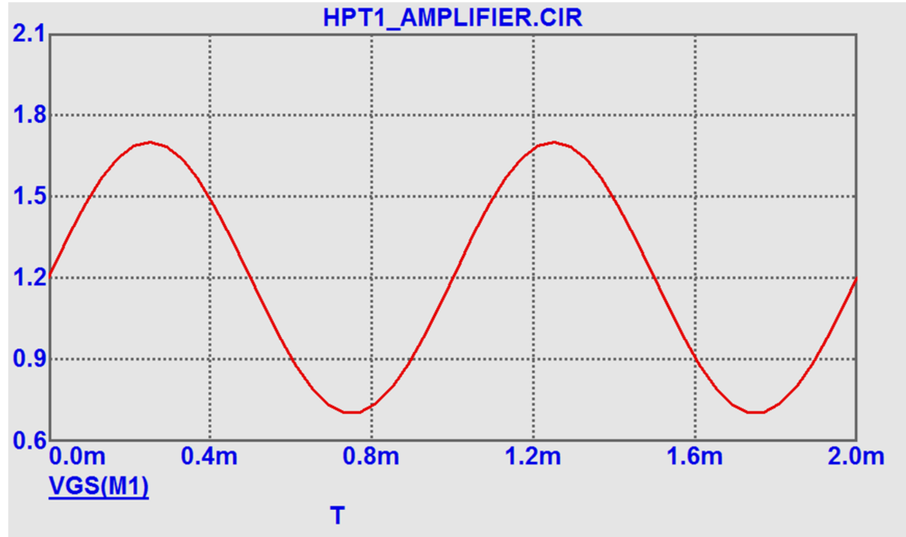
$$v_S = 0.5V\ Sin\ \omega t$$

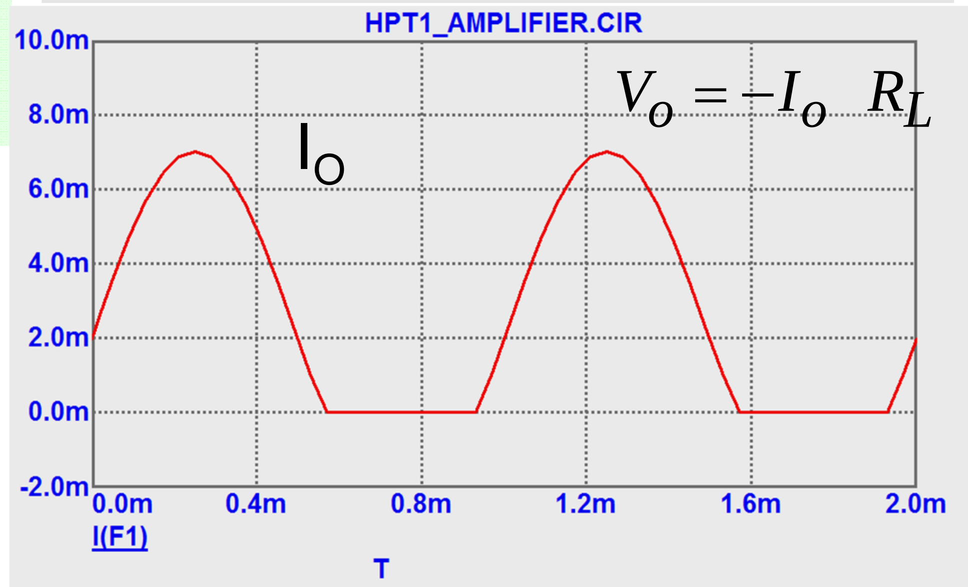


Quiescent point or Bias point

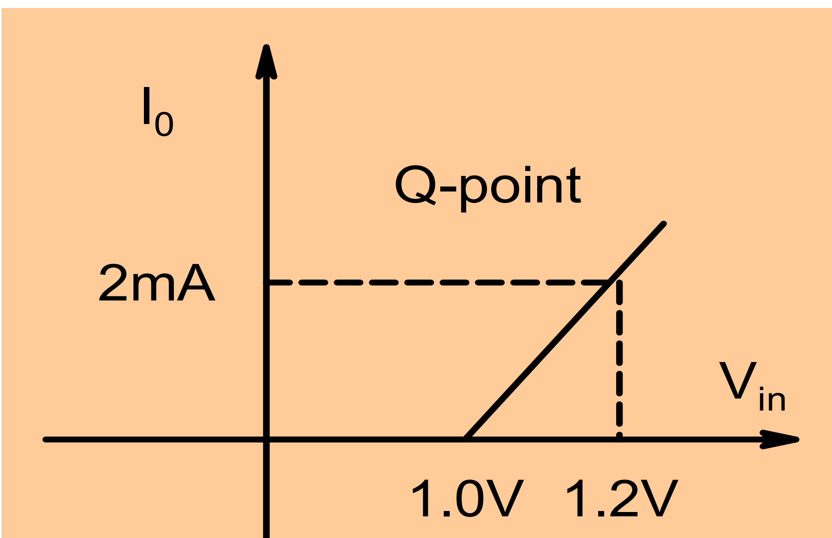


$$v_s = 0.5V Sin(\omega t)$$





$$V_o = -I_o \; R_L$$



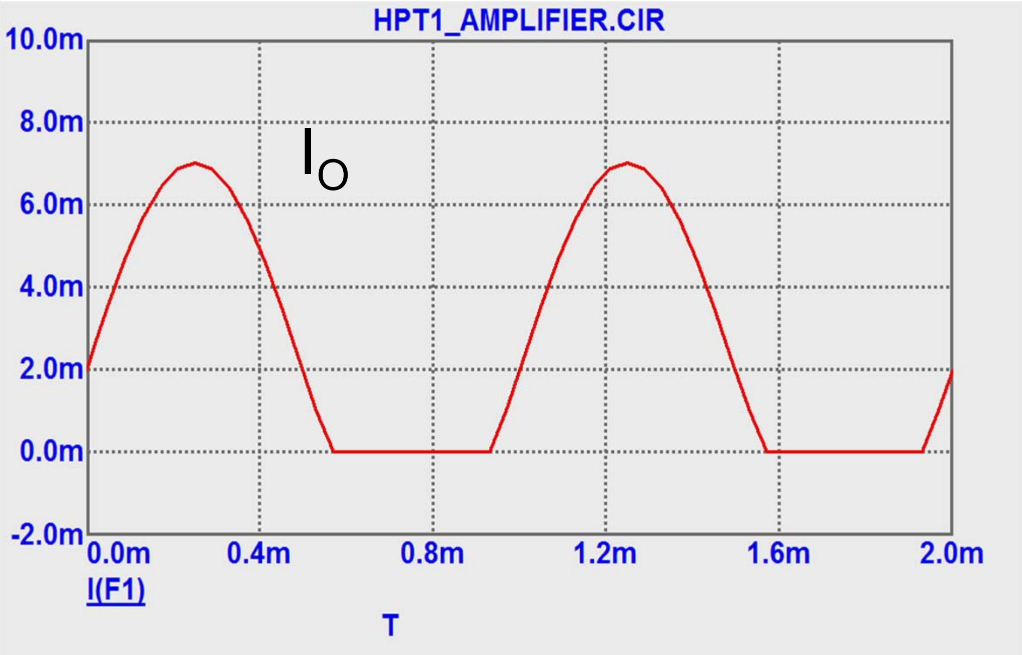
$$V_\alpha = 1V; \; g_m = 0.01\Omega^{-1}$$

$$\begin{aligned} I_o &= 0 && \text{for } V_i \le V_\alpha \\ &= g_m \times (V_i - V_\alpha) && \text{for } V_i > V_\alpha \end{aligned}$$

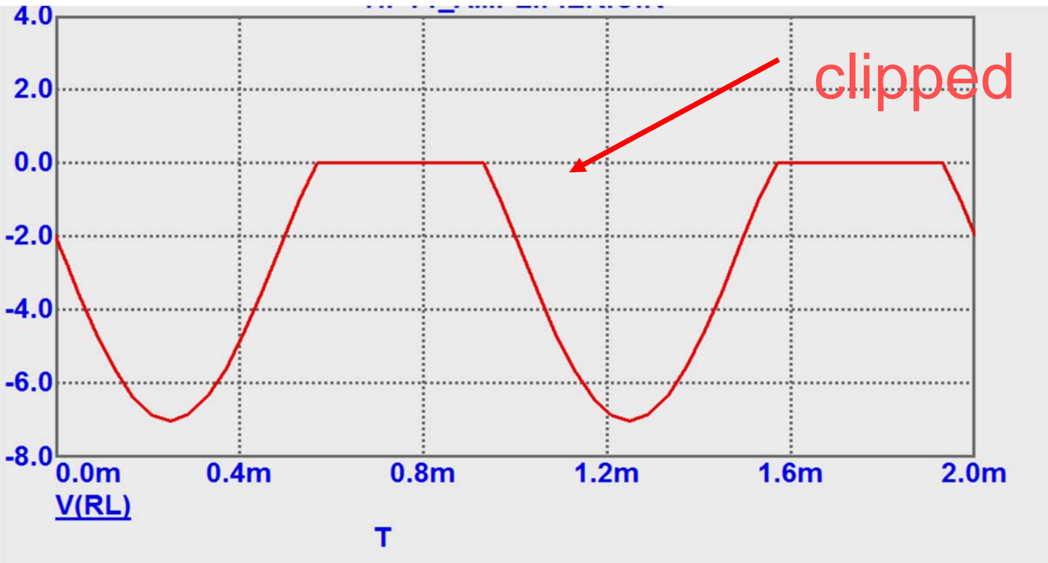
Output voltage is distorted !

RL=1kΩ

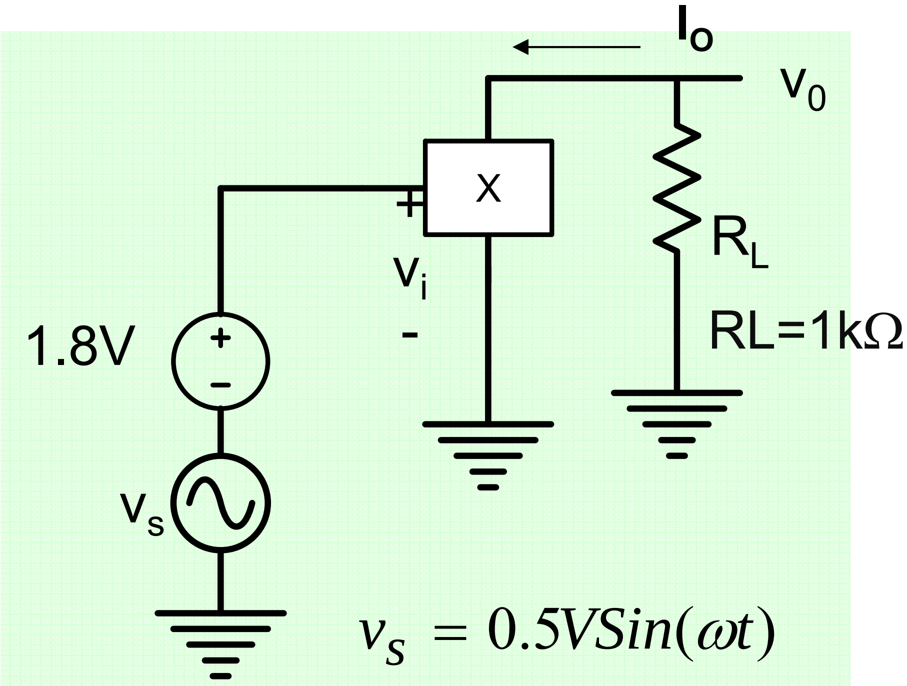
$$V_O = -I_O \ R_L$$



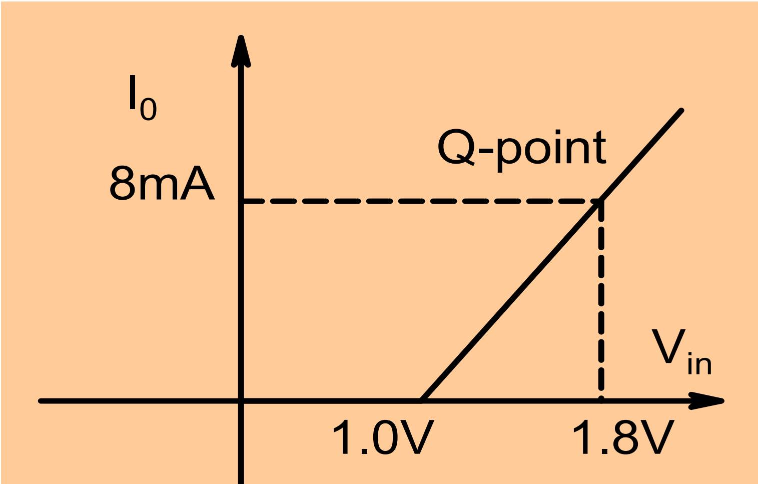
Need to choose a proper value of biasing Voltage



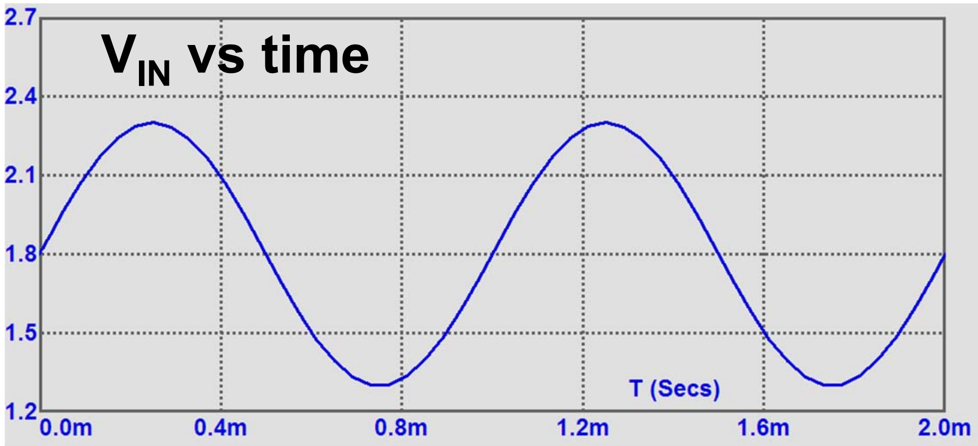
Unnecessary Power Dissipation

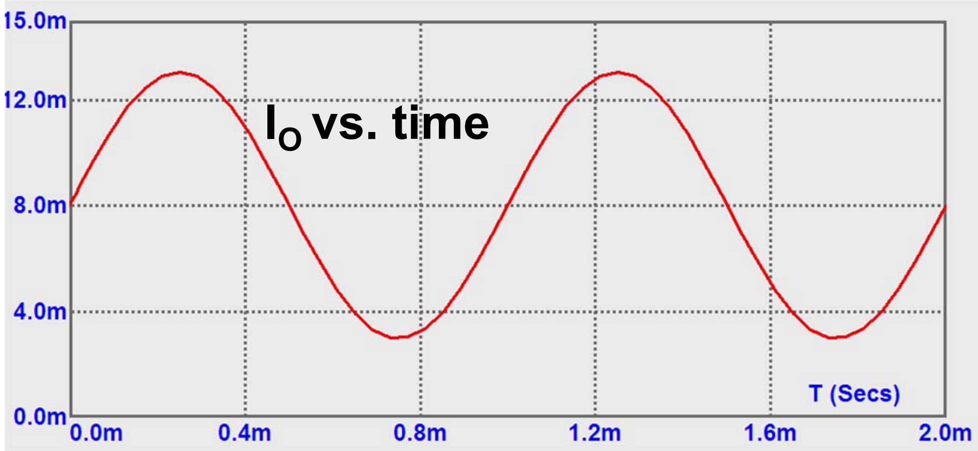


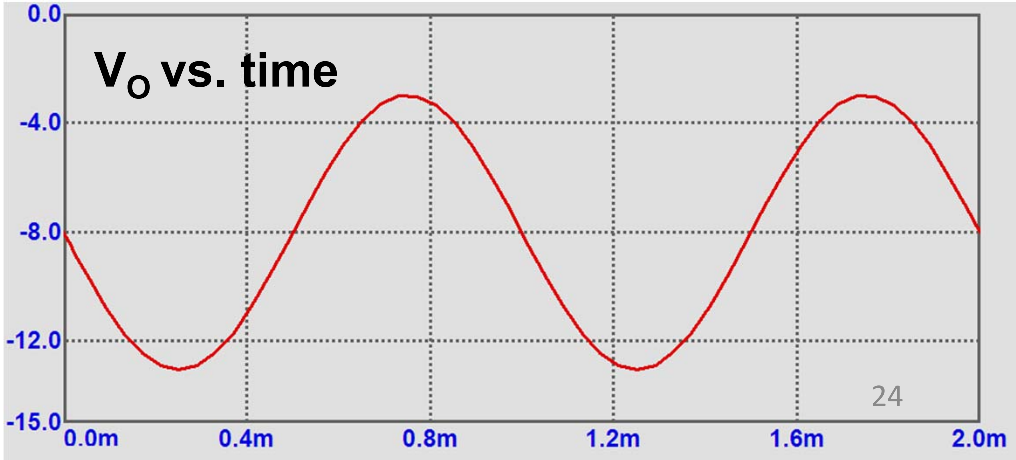
$$v_S = 0.5VSin(\omega t)$$



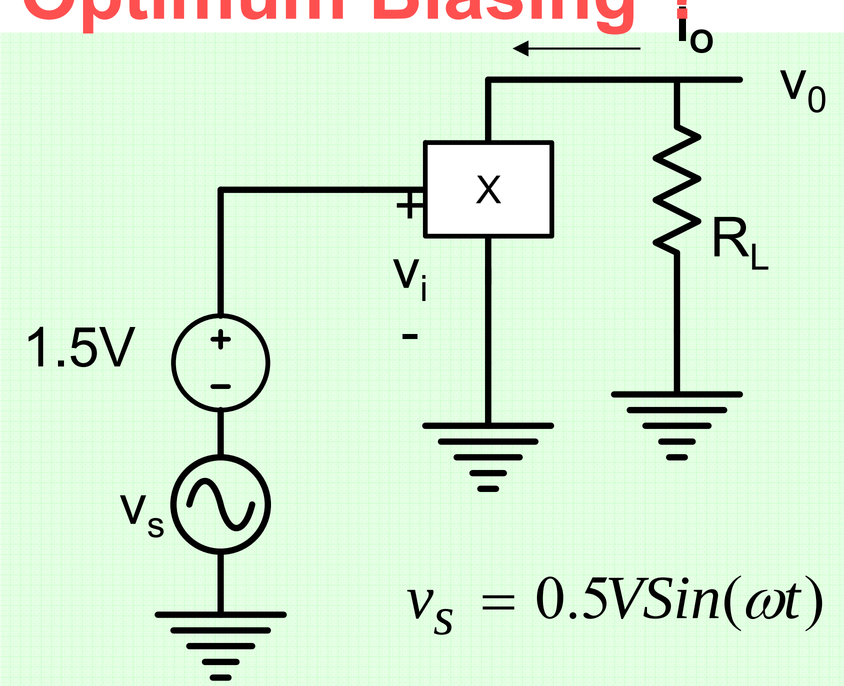
$$V_\alpha = 1V;\ g_m = 0.01\Omega^{-1}$$

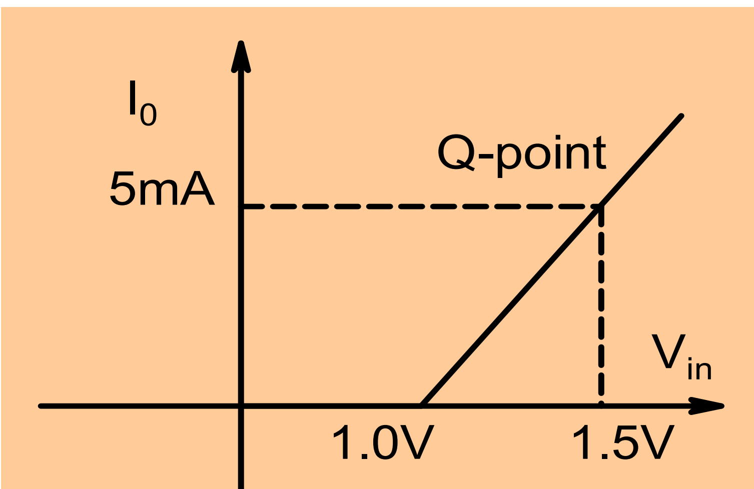




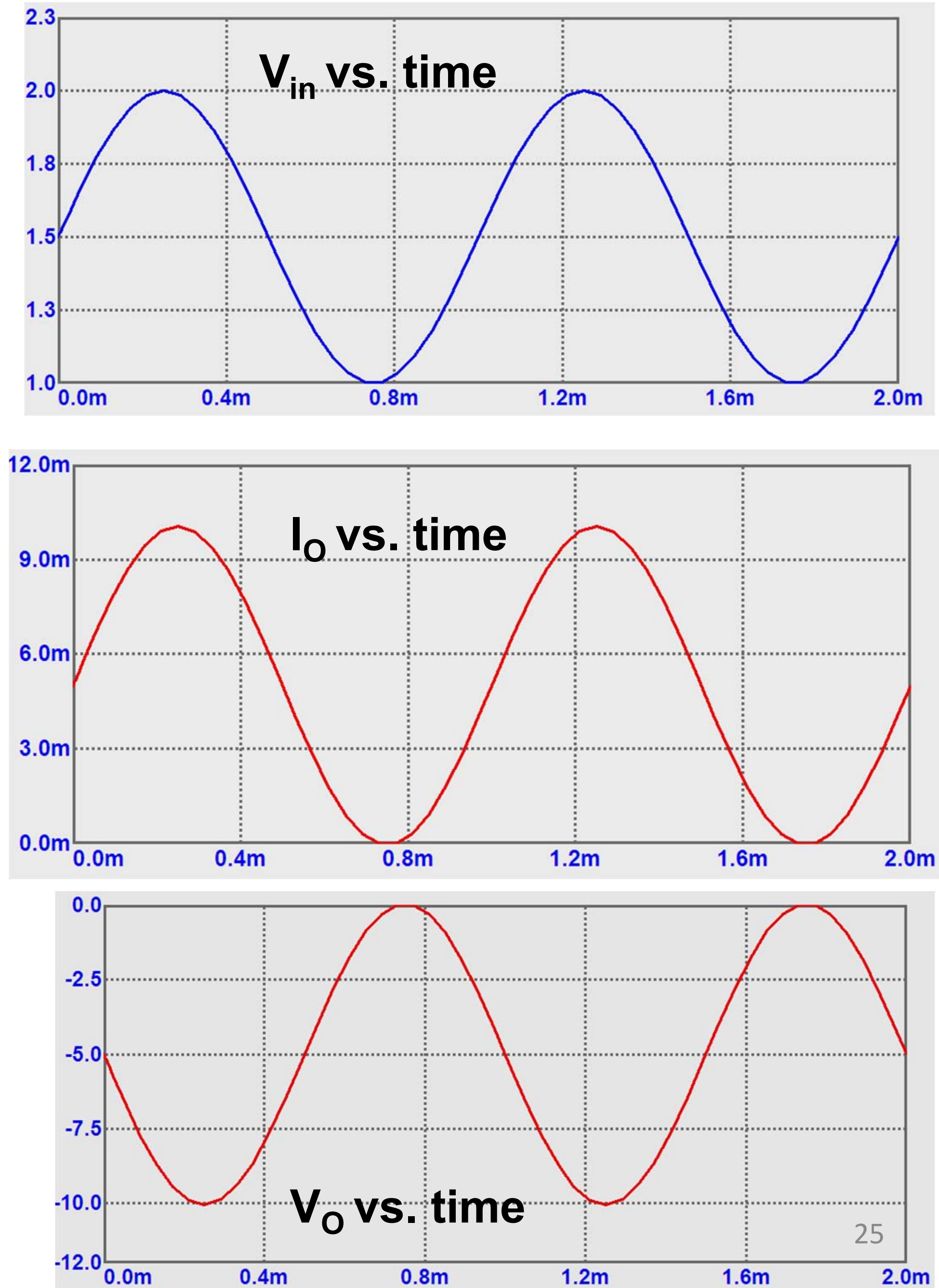


Optimum Biasing ?

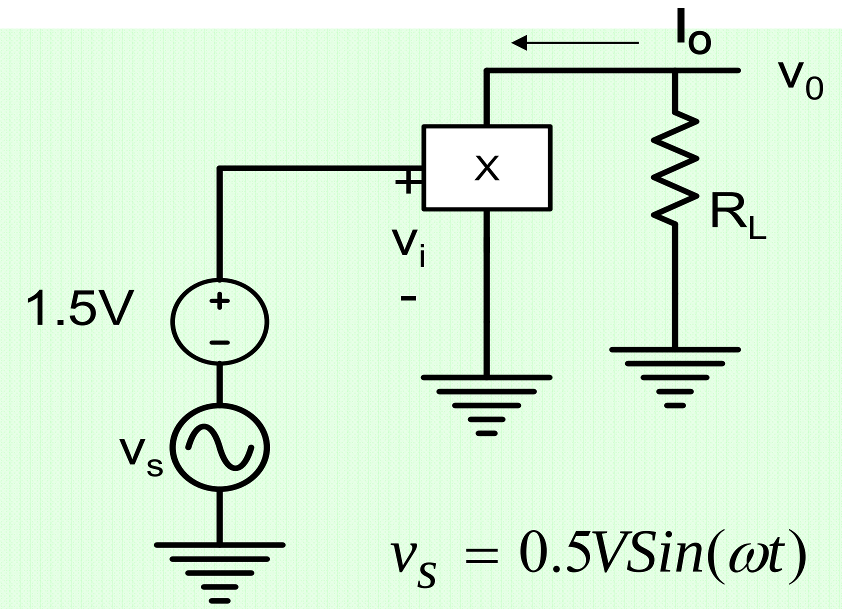




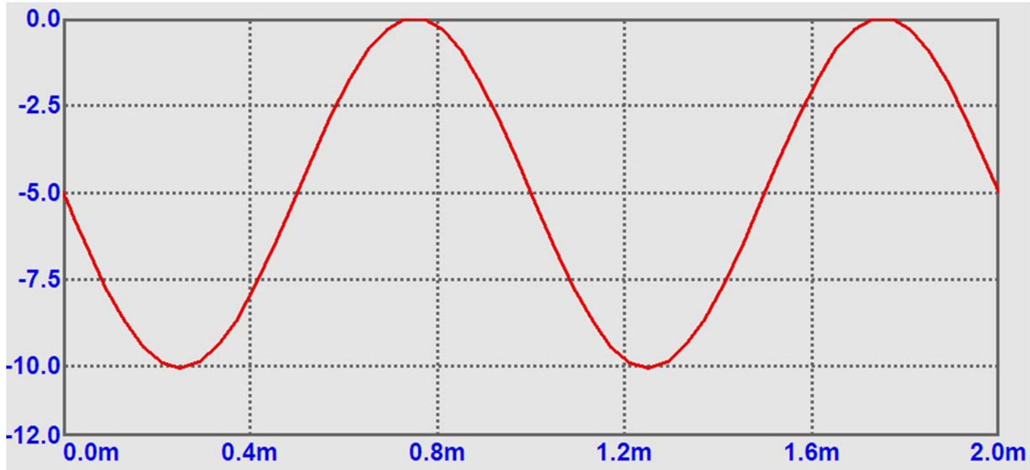
$V_\alpha = 1V;\ g_m = 0.01\Omega^{-1}$

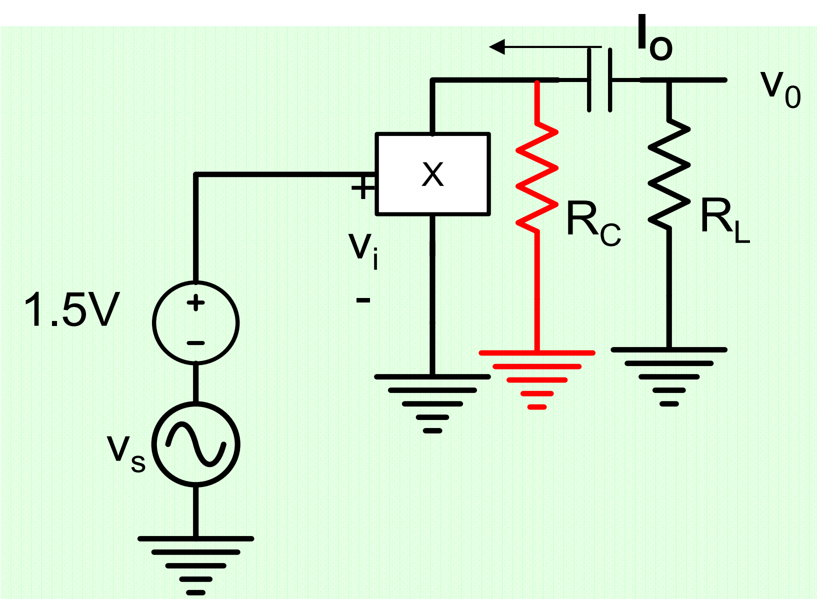


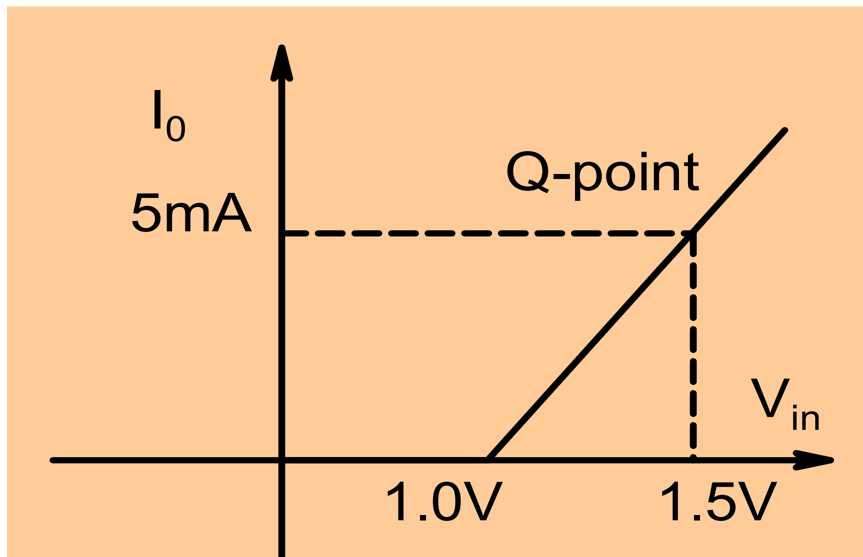
How do we get rid of unwanted dc voltage at the output ?



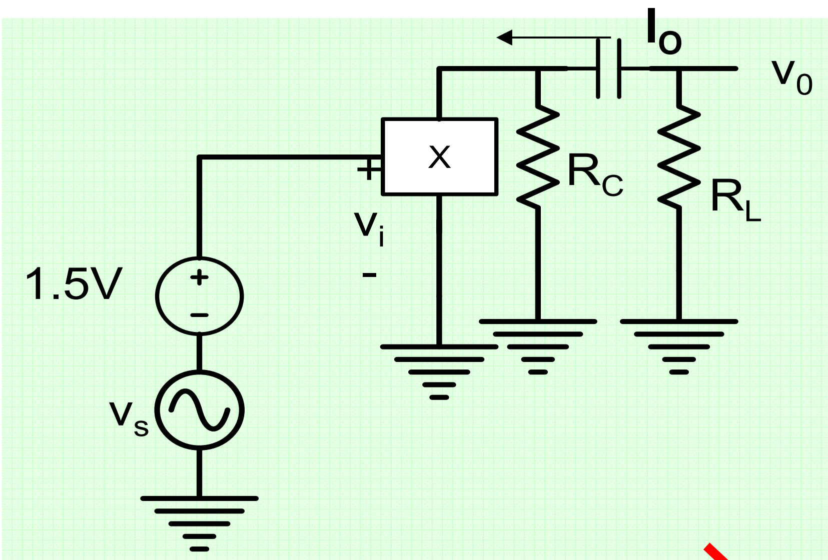
$$v_S = 0.5VSin(\omega t)$$

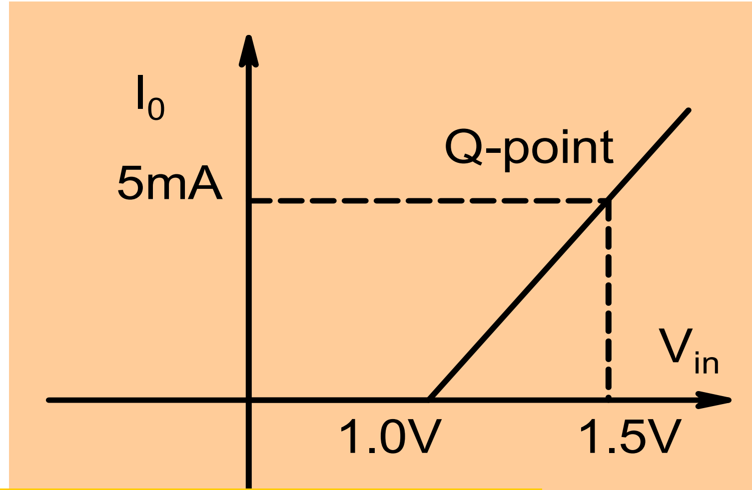






$$V_\alpha = 1V;\ g_m = 0.01\Omega^{-1}$$

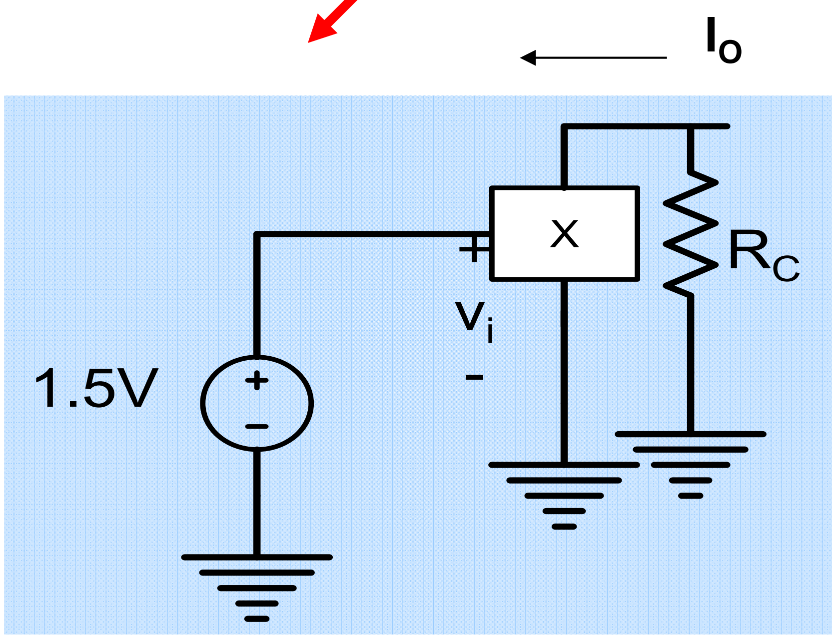


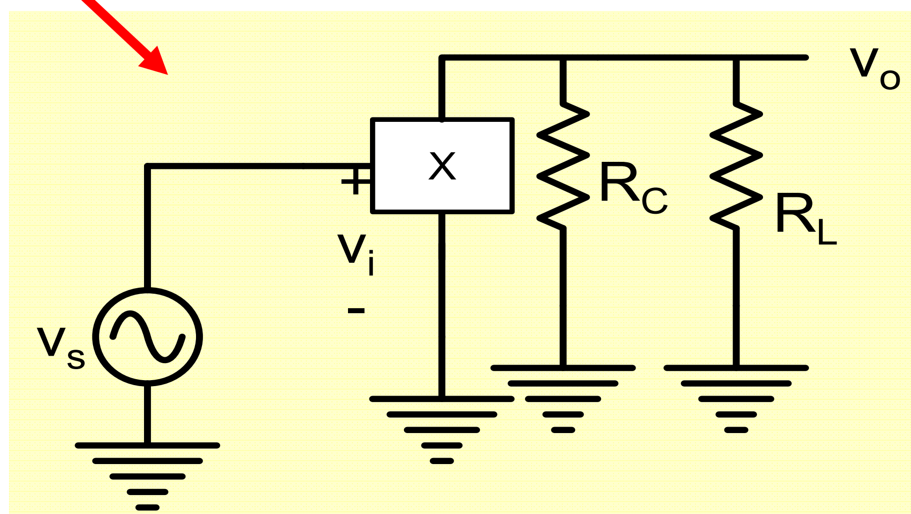


$$V_\alpha = 1V;\ g_m = 0.01\Omega^{-1}$$

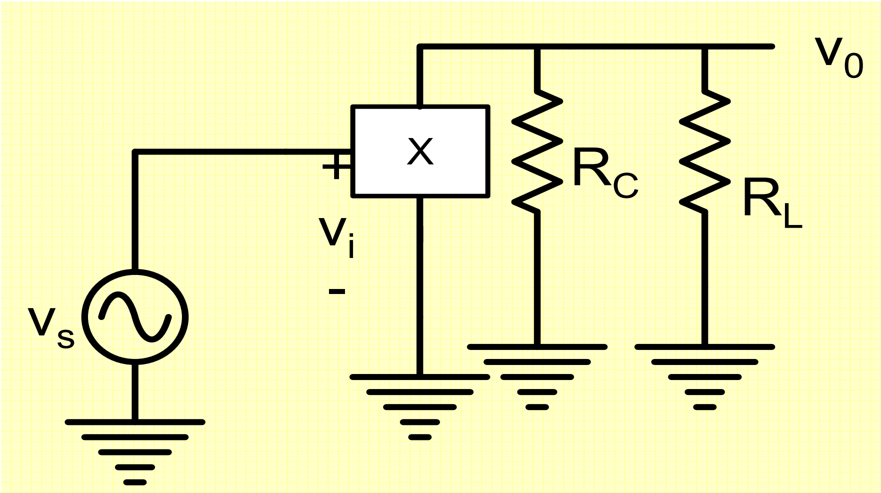
dc

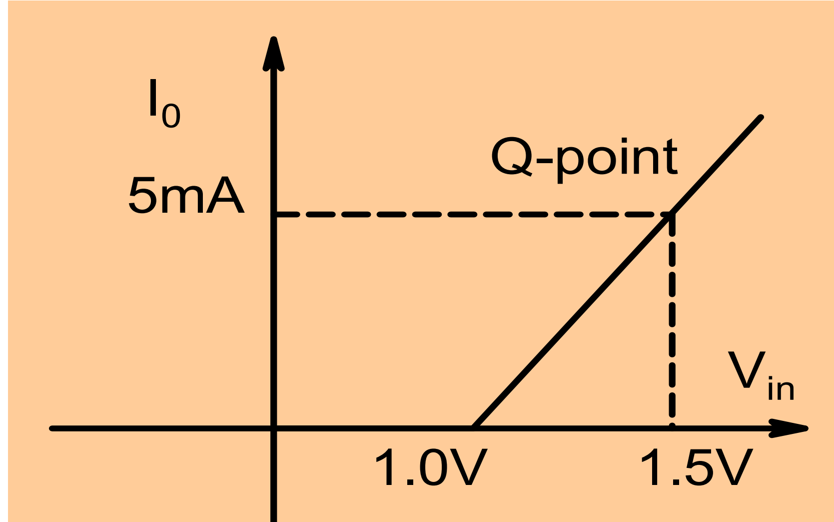
ac (signal)





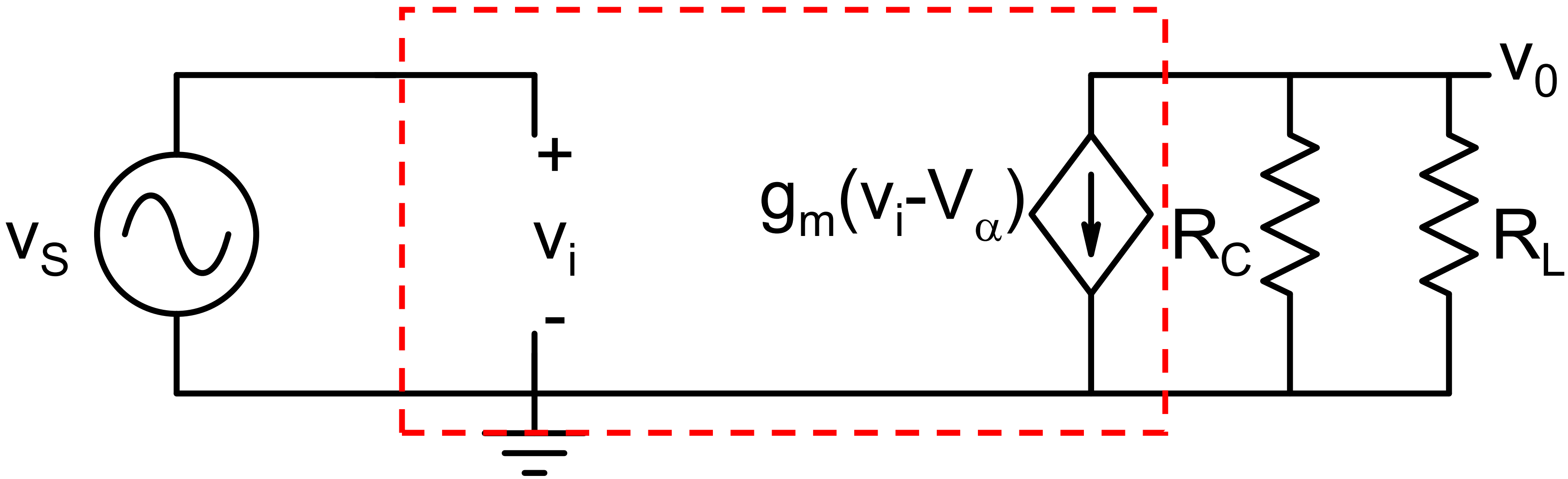
Capacitor is chosen large enough so that at the signal frequency $1/j\omega C \sim 0$.



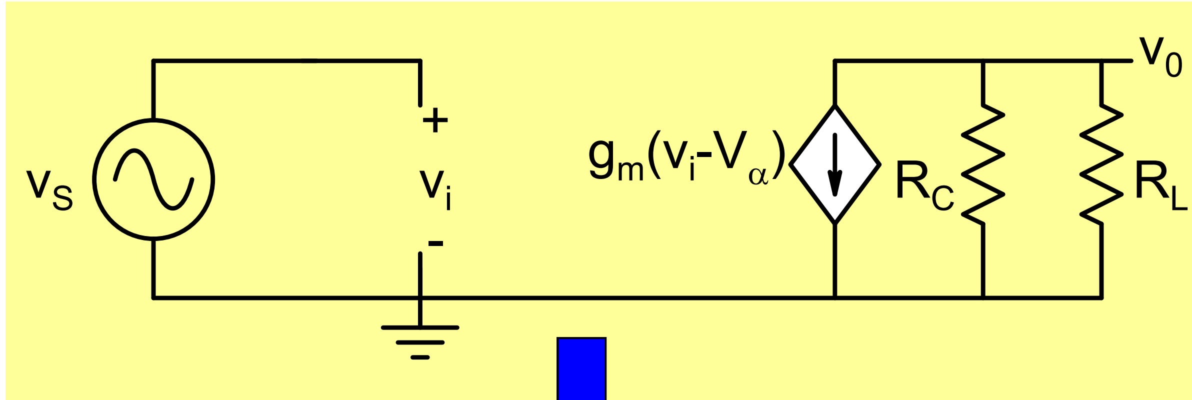


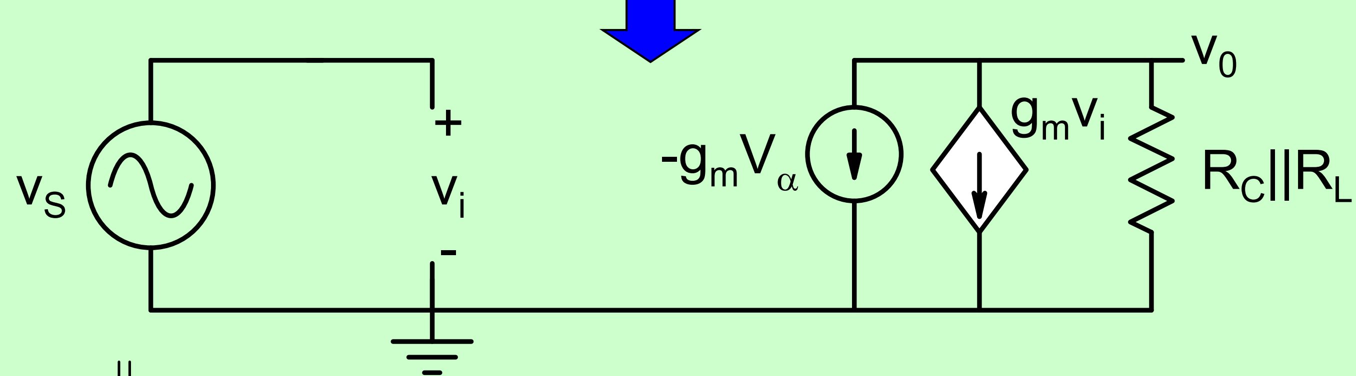
$V_{\alpha} = 1V;\ g_m = 0.01\Omega^{-1}$

$$I_o = g_m \times (V_i - V_{\alpha}) \text{ for } V_i > V_{\alpha}$$

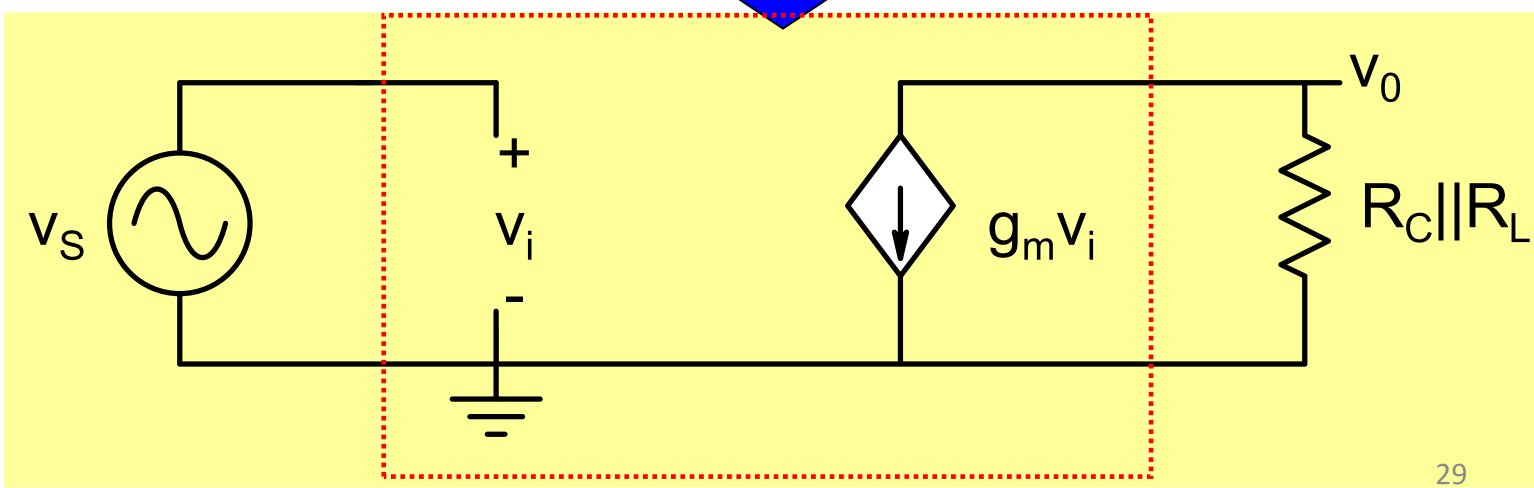


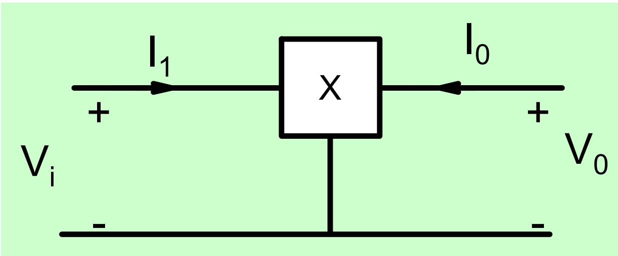
AC Analysis

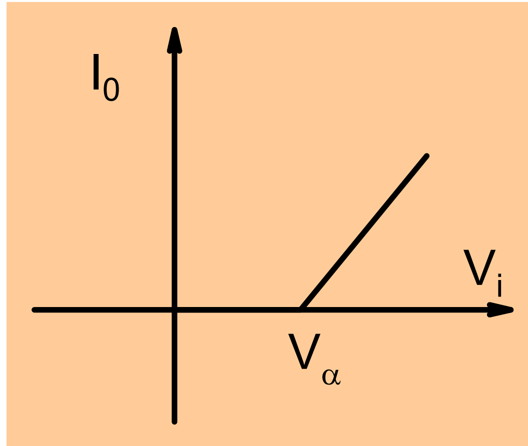


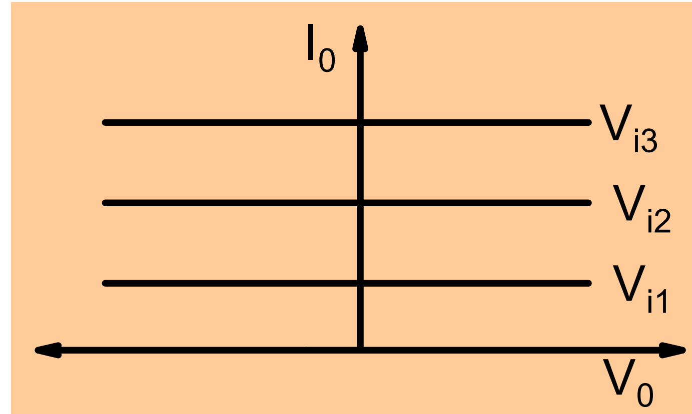


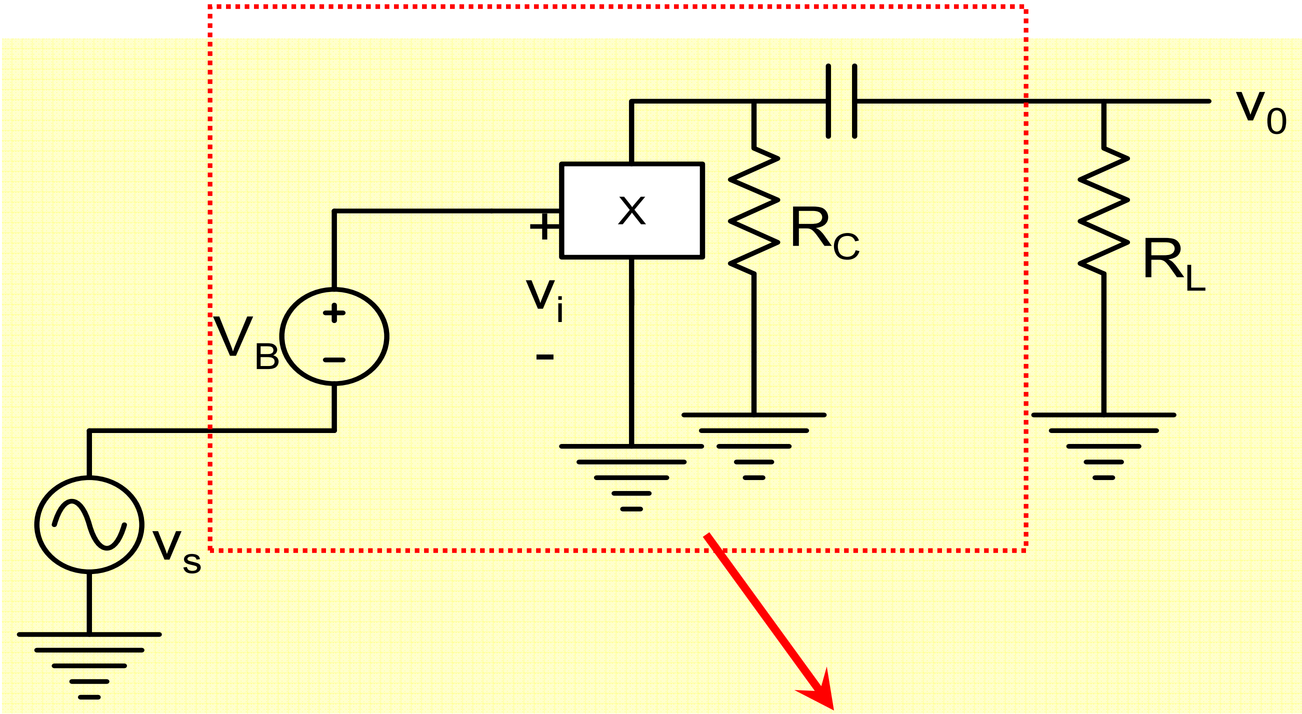
$$A_V = \frac{v_o}{v_s} = -g_m R_C \| R_L$$





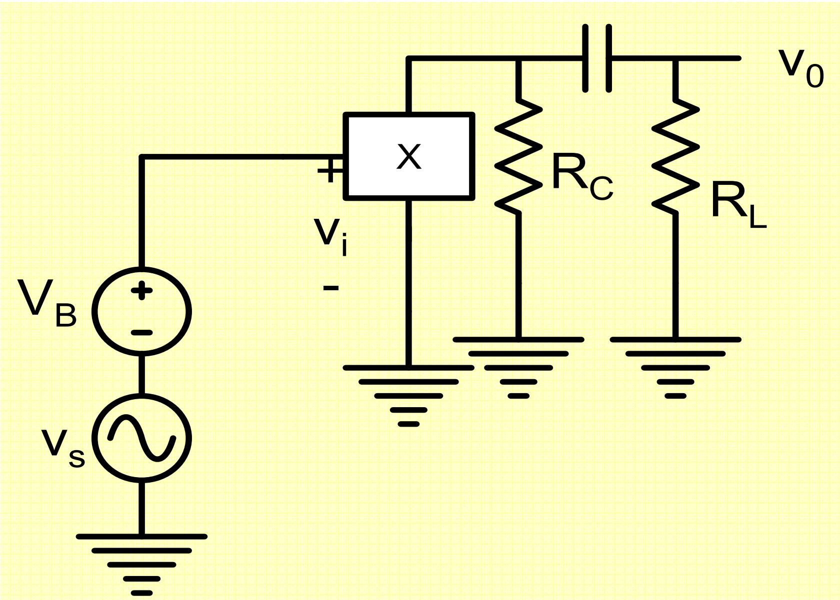


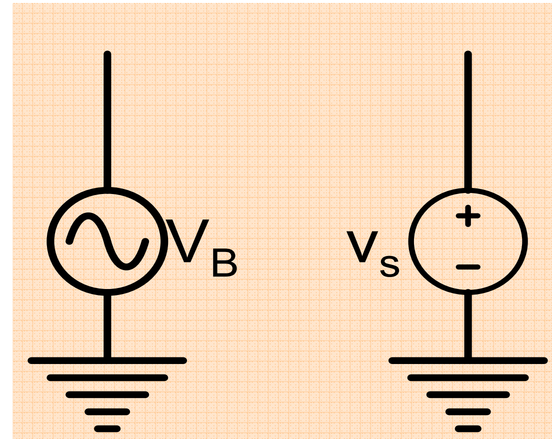


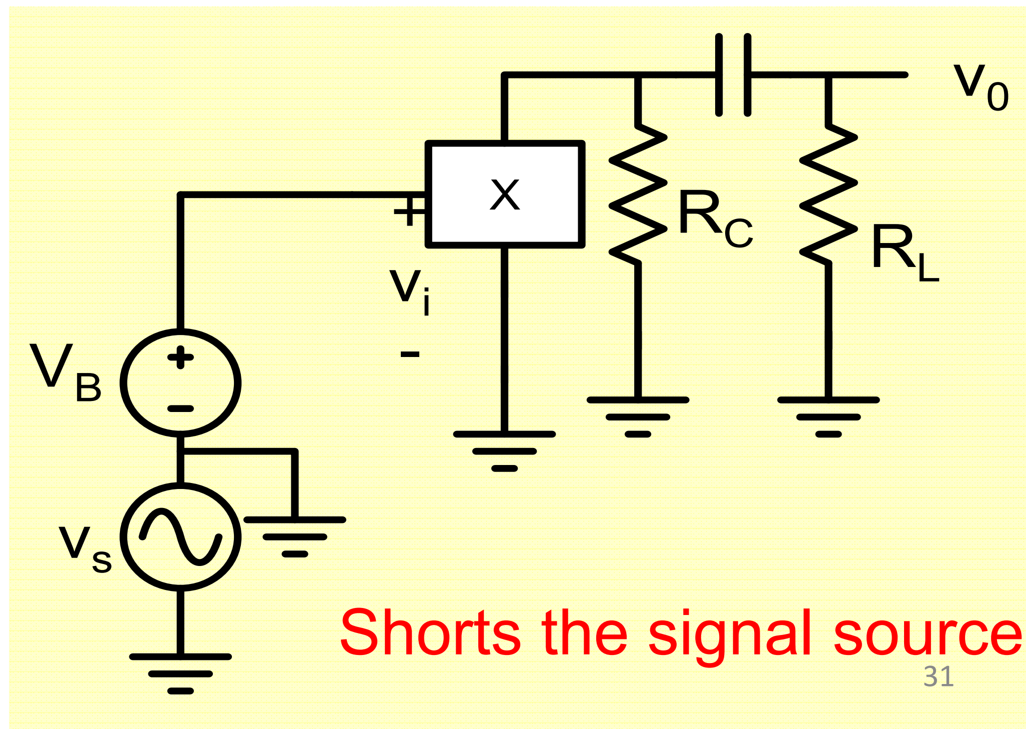


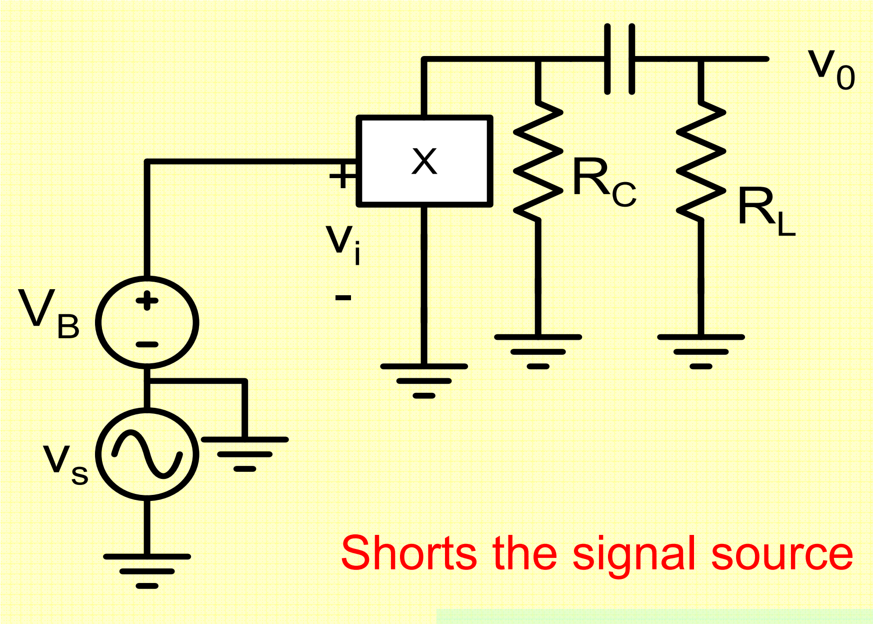
The addition of biasing network allows element X to appear as an ideal transistor to the signal source

What happens if both dc voltage source and signal source have one terminal as ground?

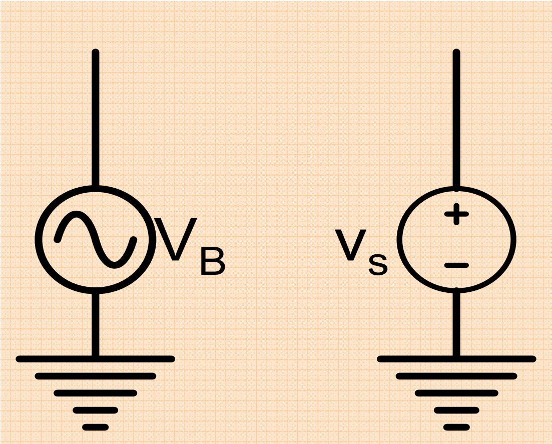






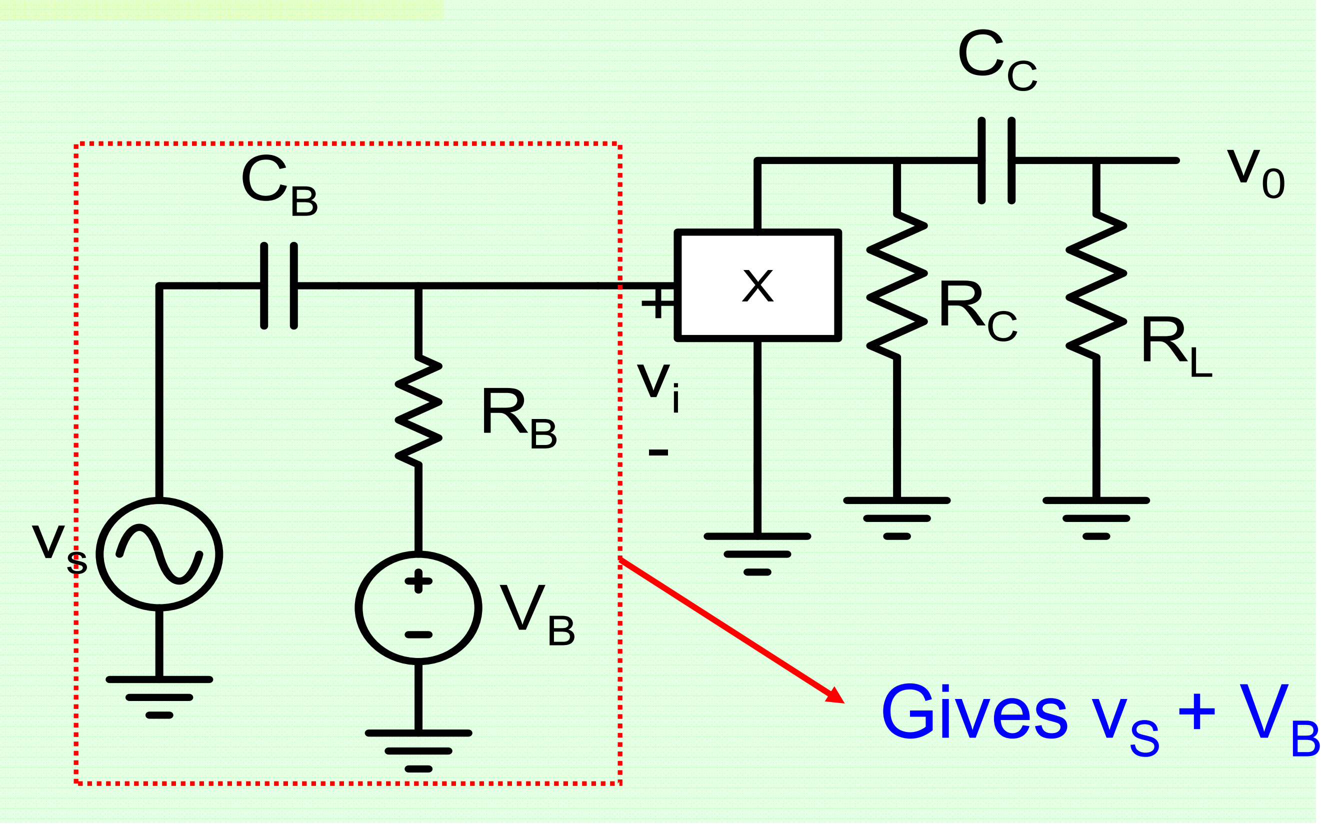


v0
X
RC
RL
+
vi
-
VB
vs
Shorts the signal source

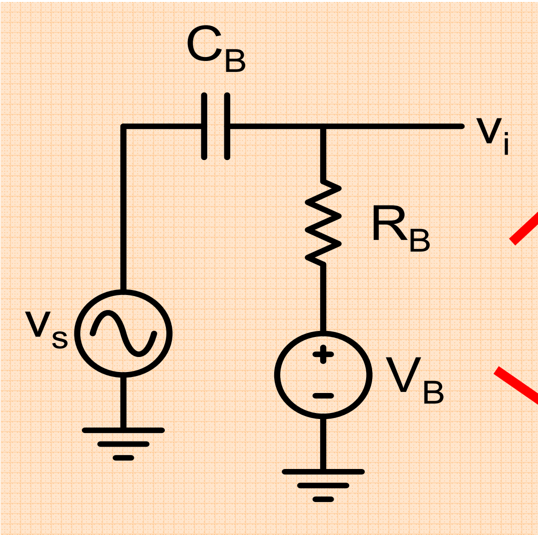


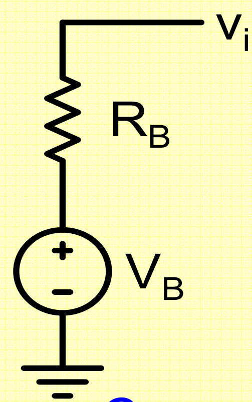
VB
vs

Solution



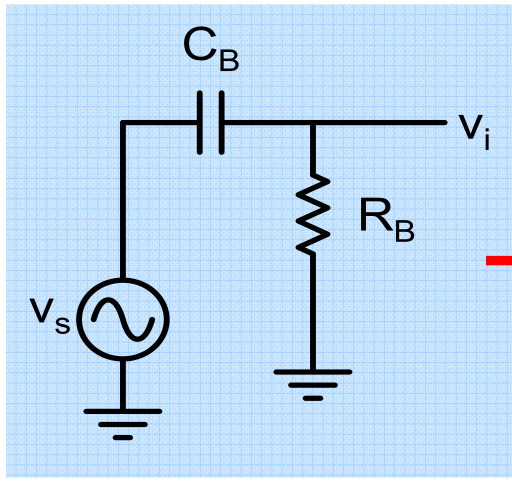
CC
v0
CB
X
RC
RL
+
vi
-
RB
vs
VB
Gives vS + VB

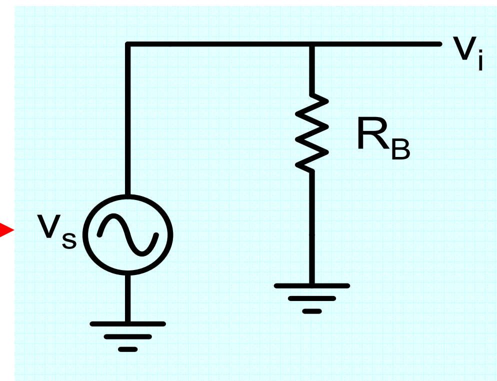




$$v_i = V_B$$

Capacitor is chosen large enough so that at the signal frequency $1/j\omega C \sim 0$.



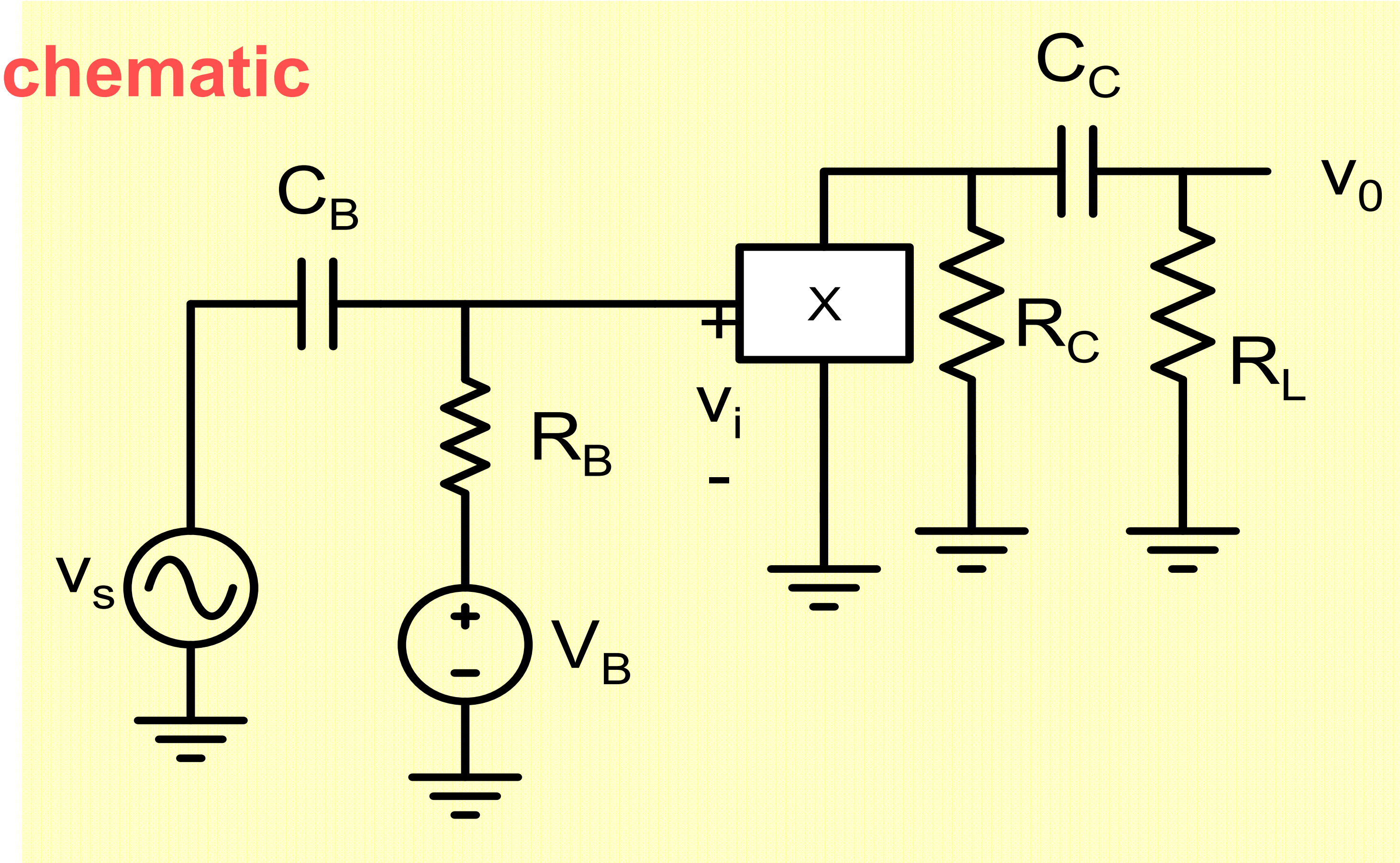


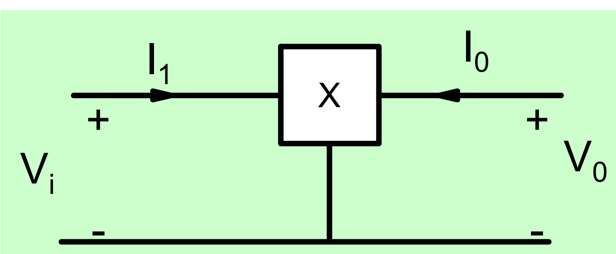
$$v_i = v_s$$

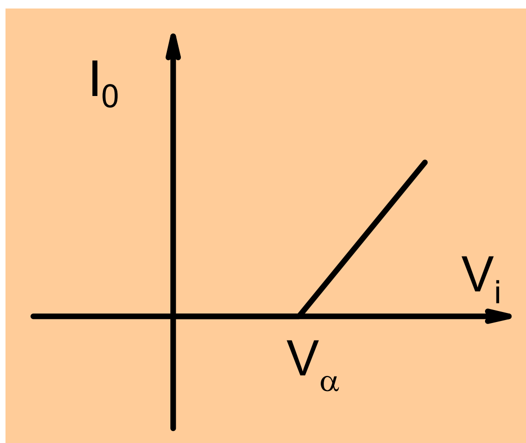
$$v_i(total) = v_s + V_B$$

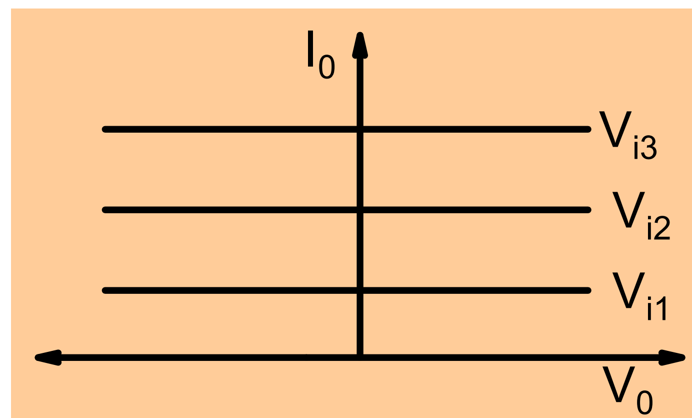
Note the role of R_B

Amplifier Schematic

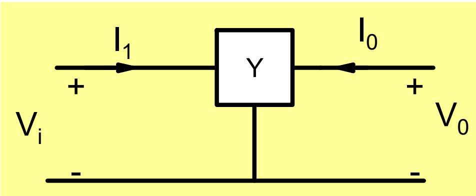


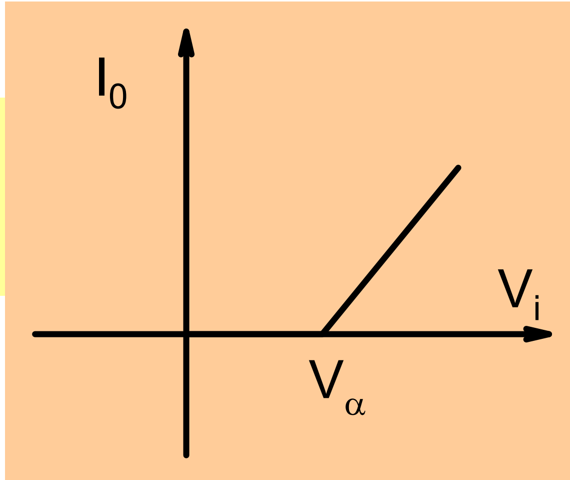


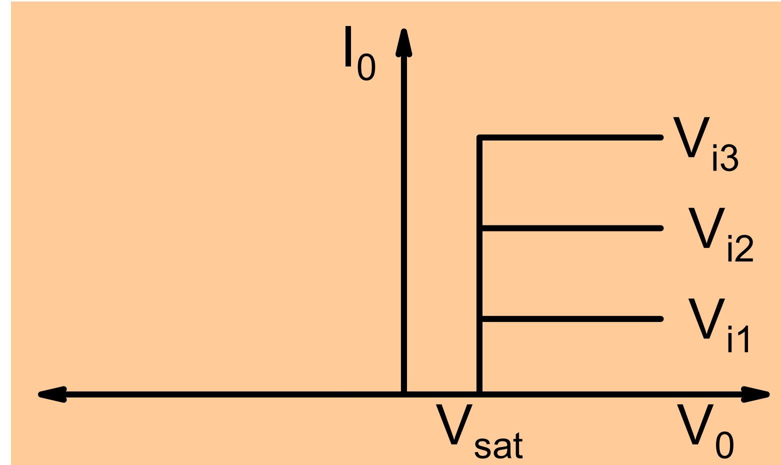




Device Y





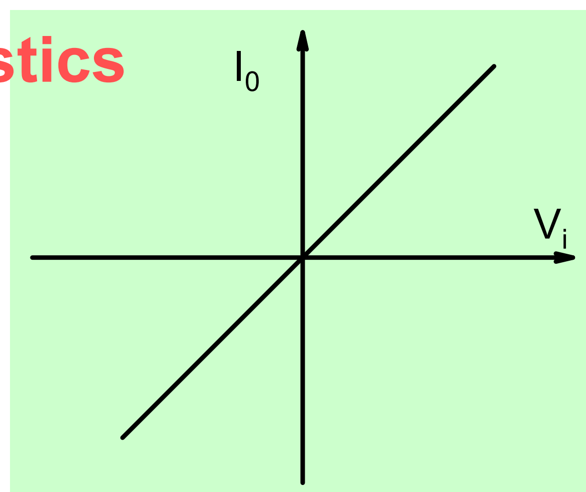


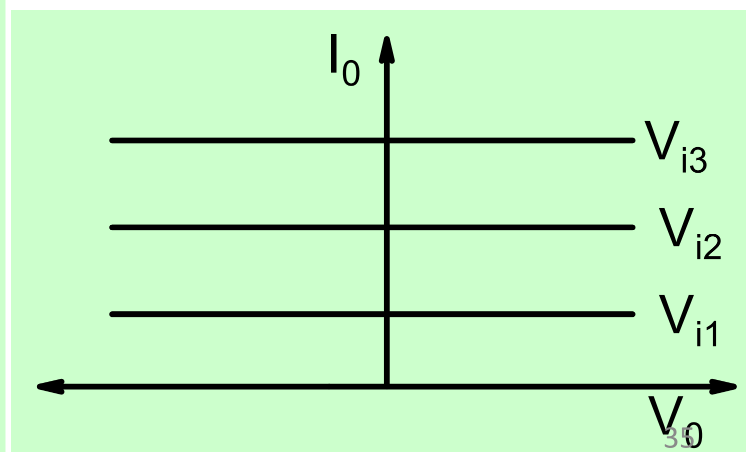
$I_o = 0$ for $V_0 < V_{sat}$

$$
\begin{aligned}
I_o &= 0 && \text{for } V_i \le V_\alpha \\
&= g_m \times (V_i - V_\alpha) && \text{for } V_i > V_\alpha
\end{aligned}
$$

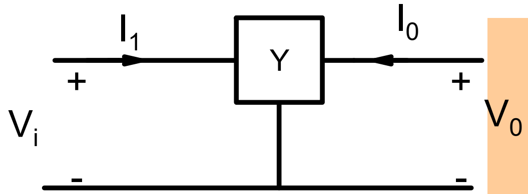
for $V_0 > V_{sat}$

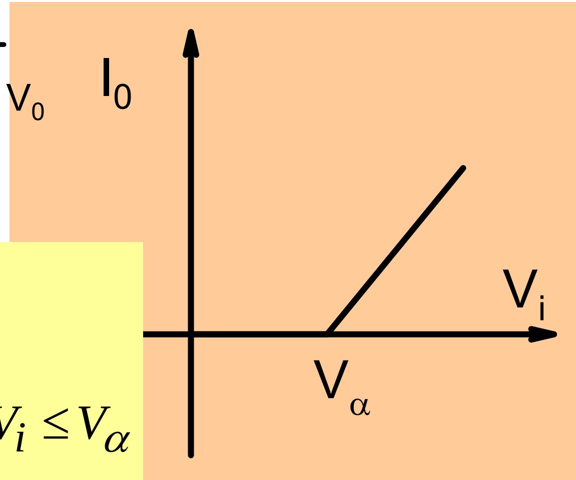
Ideal Characteristics

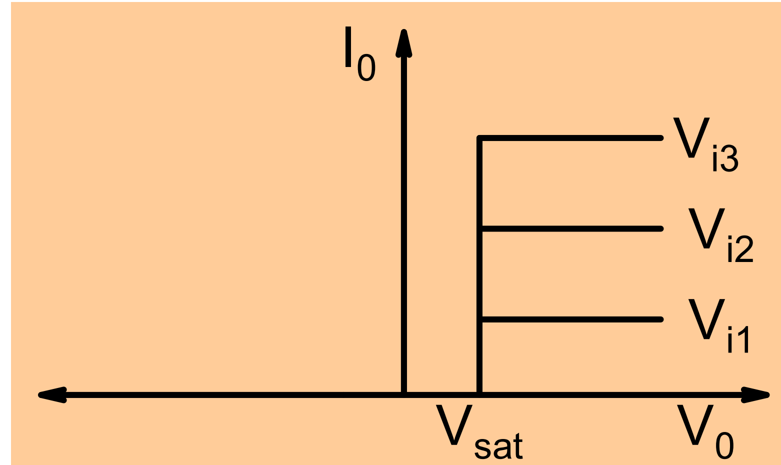




How do we use device Y to make an amplifier?







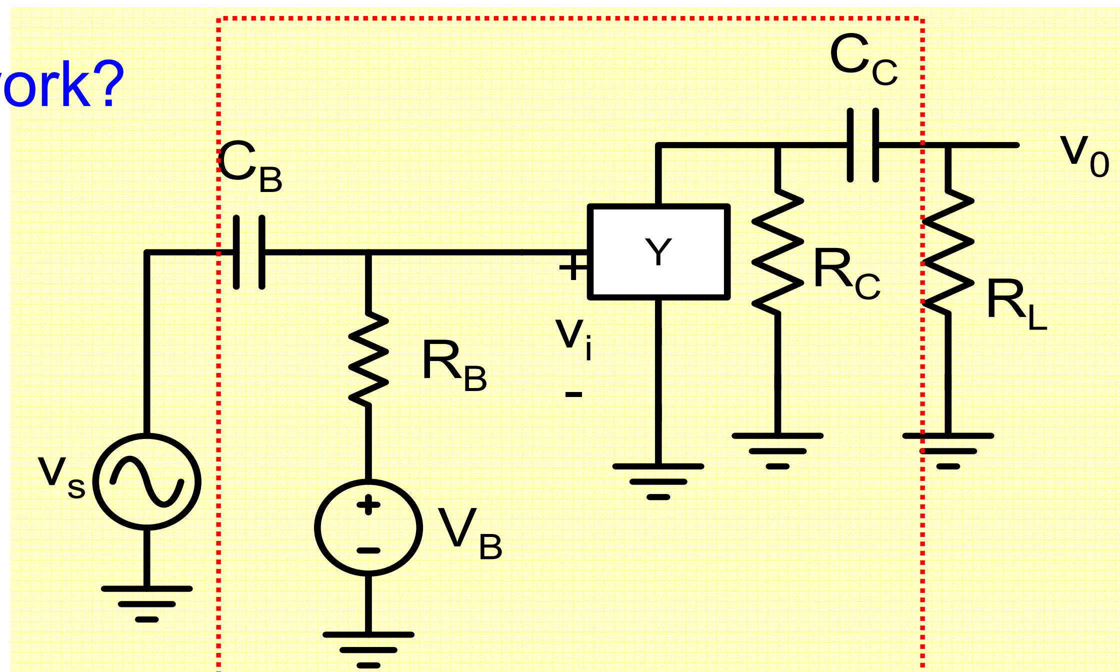
for $V_O < V_{sat} : I_o = 0$

for $V_O \ge V_{sat}$:

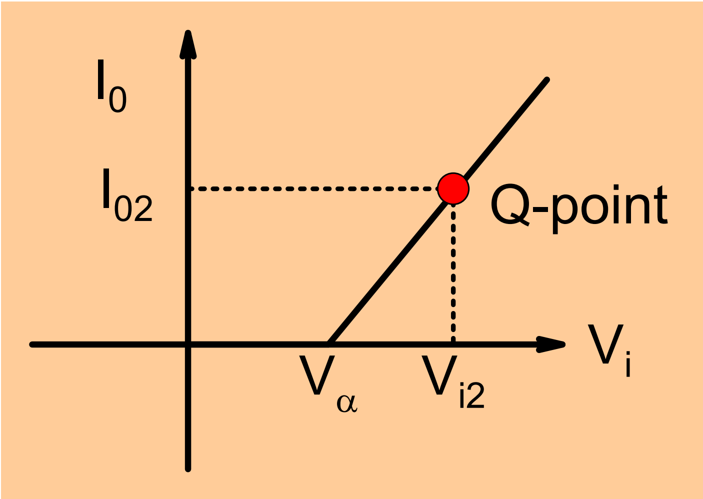
$I_o = 0$ for $V_i \le V_\alpha$

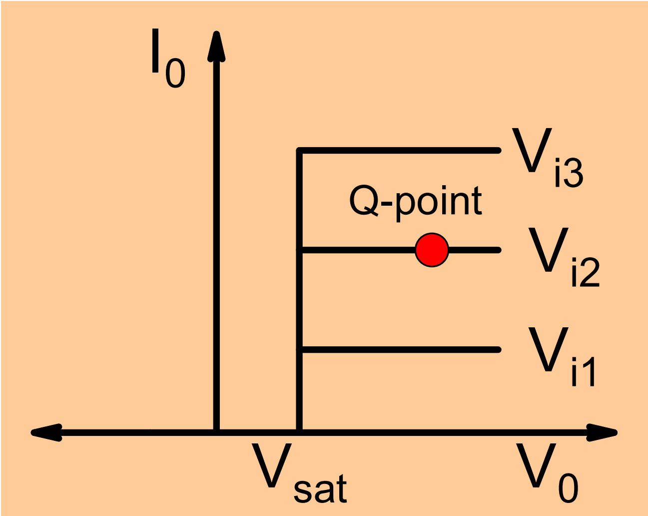
$= g_m \times (V_i - V_\alpha)$ for $V_i > V_\alpha$

Will the earlier solution work?

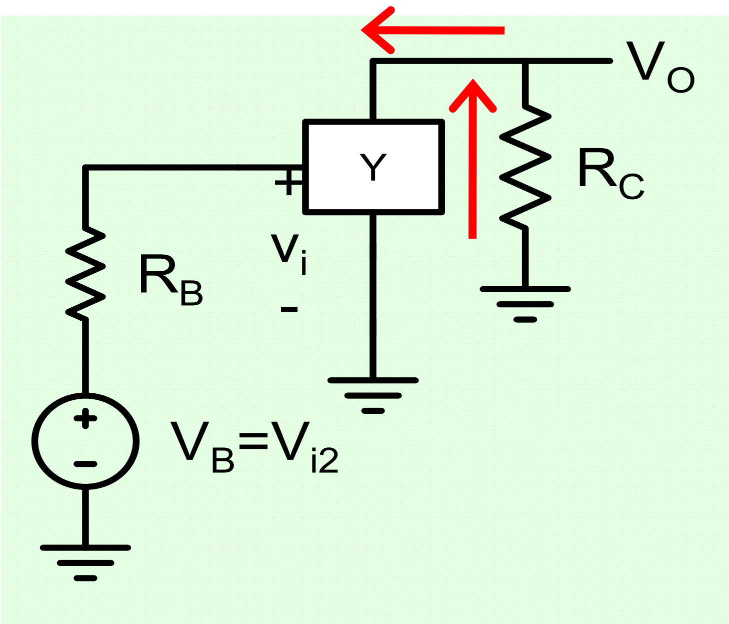


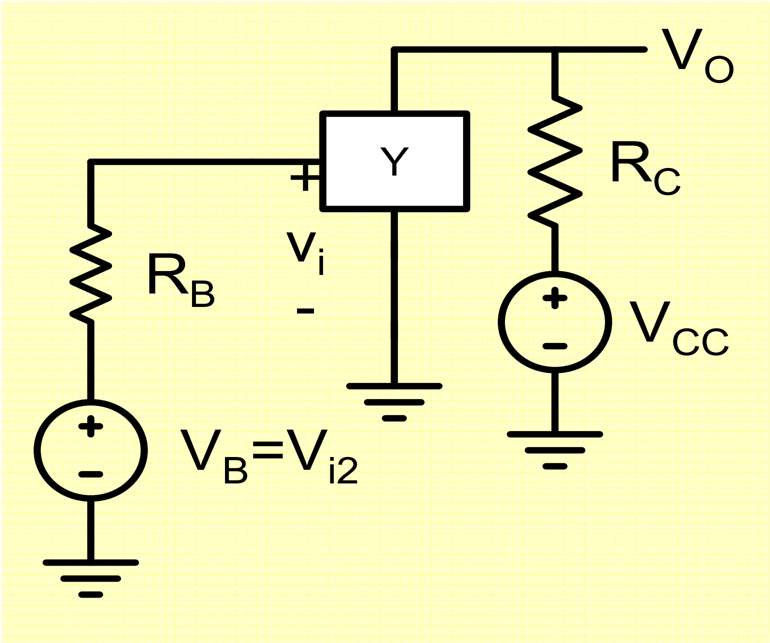
The purpose of biasing network is to operate the device in a region which resembles ideal transistor



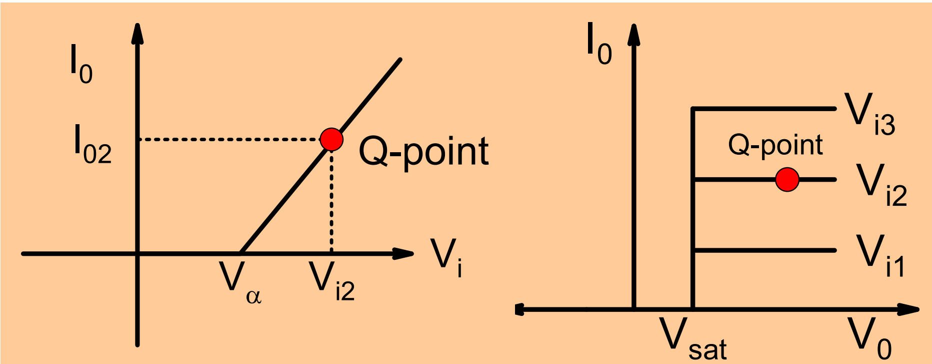


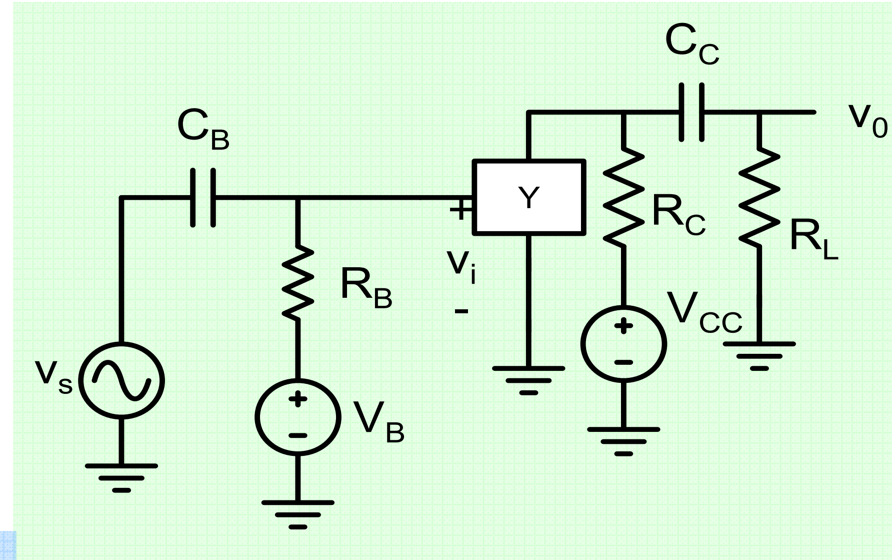
V_O = -ve which is not possible for device Y

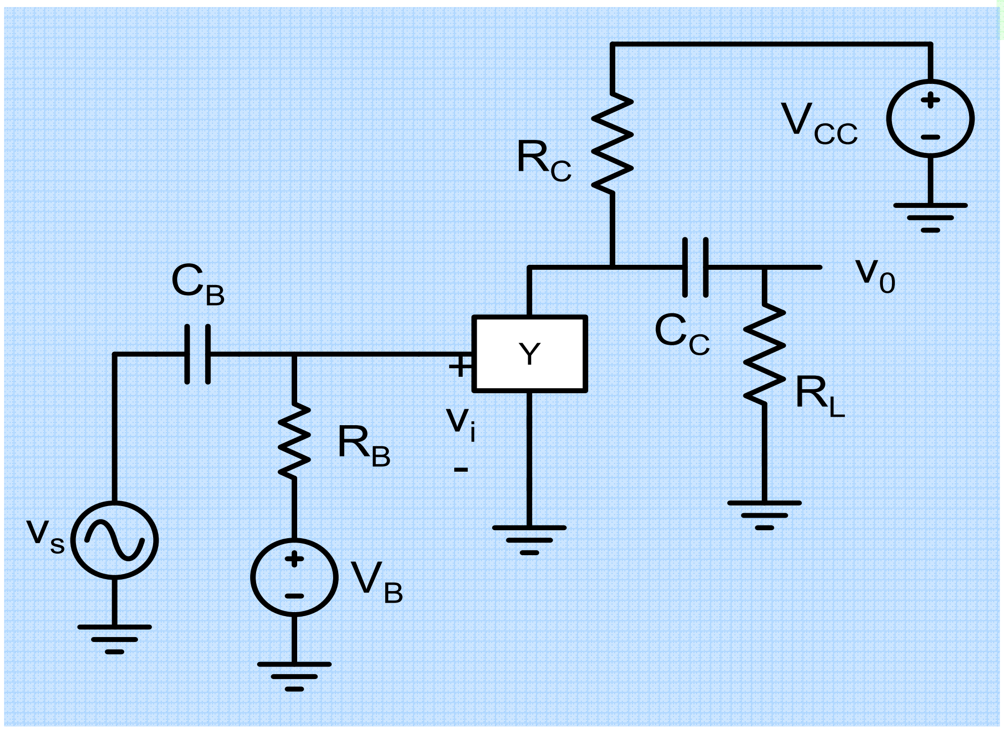


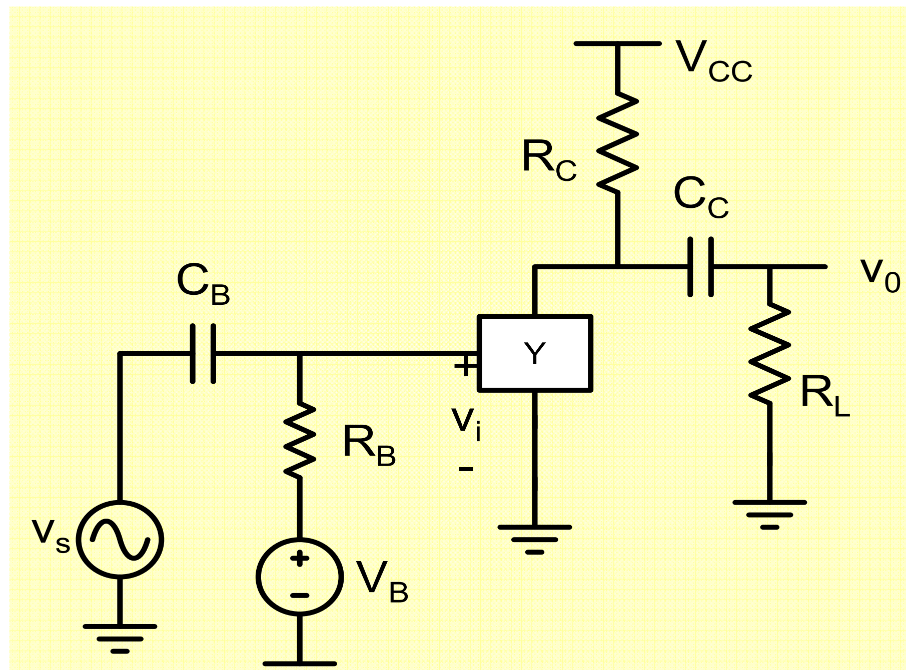


Revised Amplifier Schematic

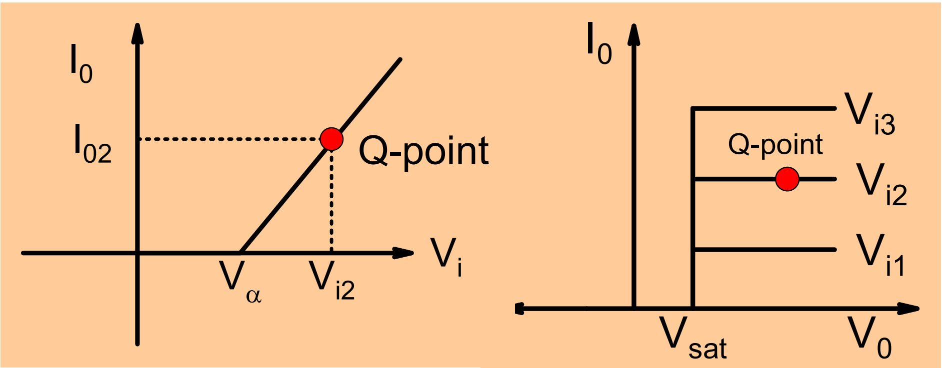


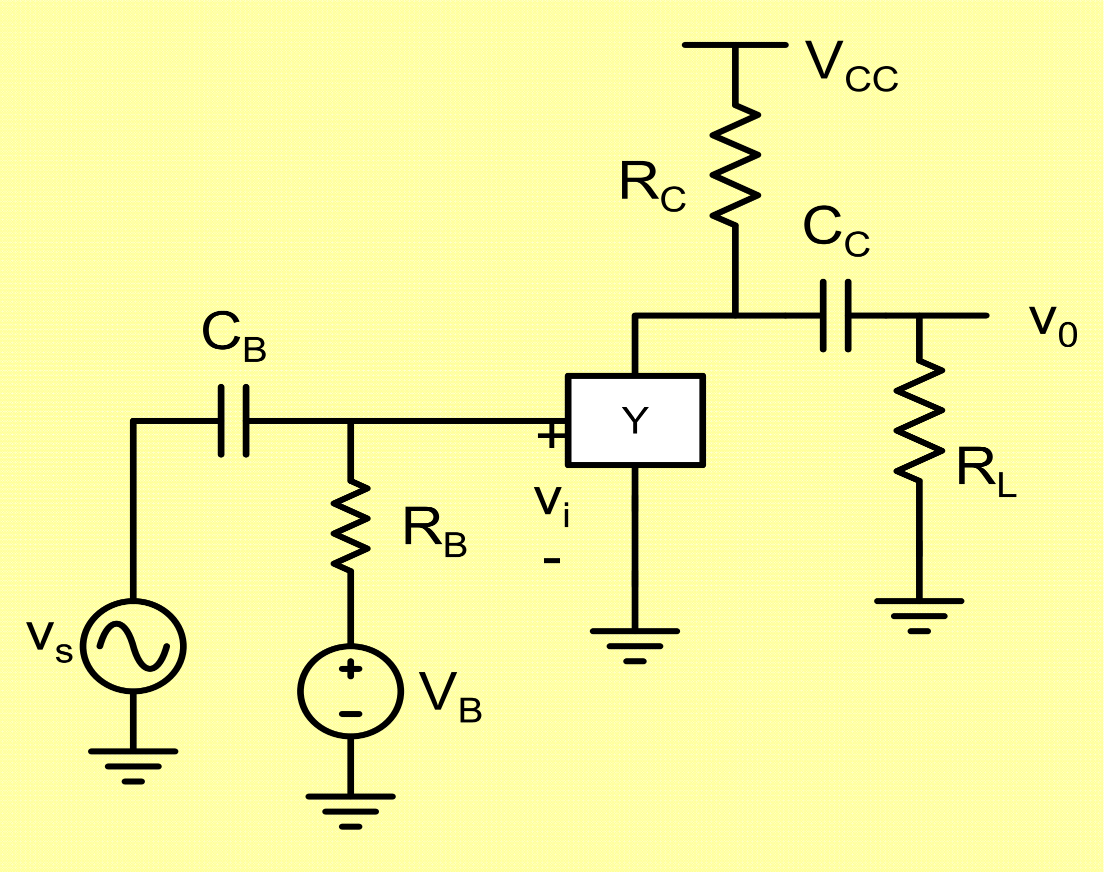




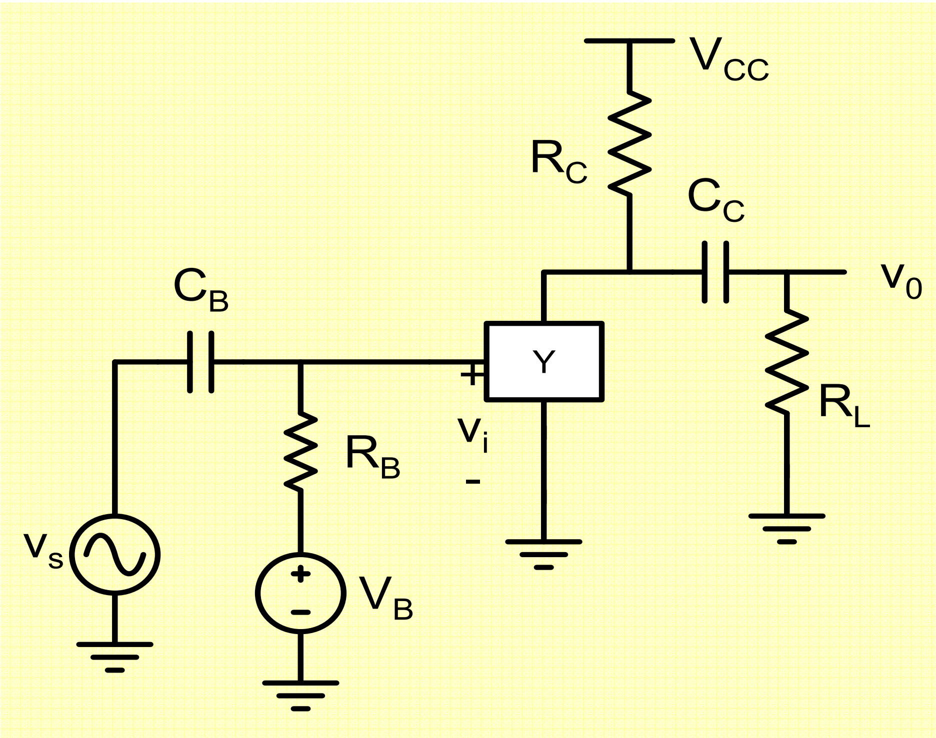


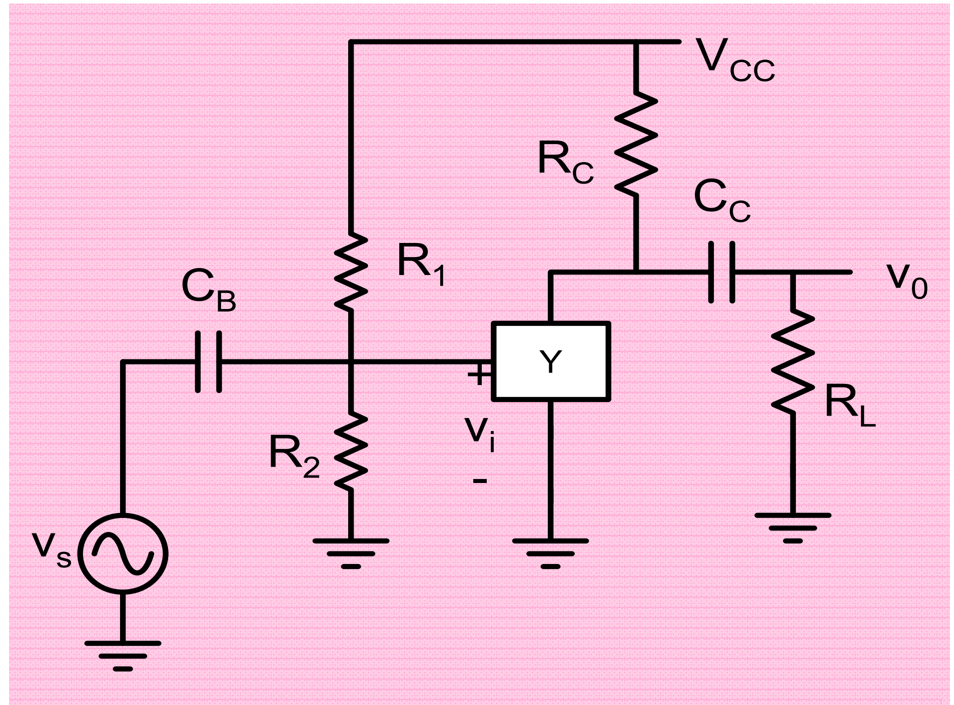
Revised Amplifier Schematic





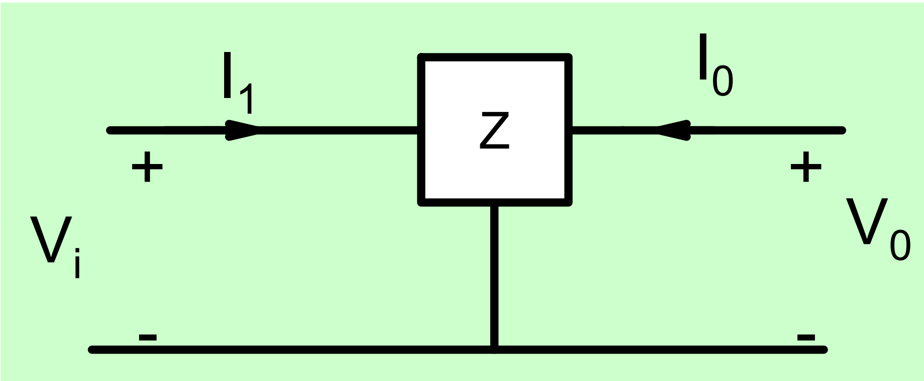
Can we amplify using one dc voltage source only?





$$V_B = V_{CC} \times \frac{R_2}{R_1 + R_2}$$

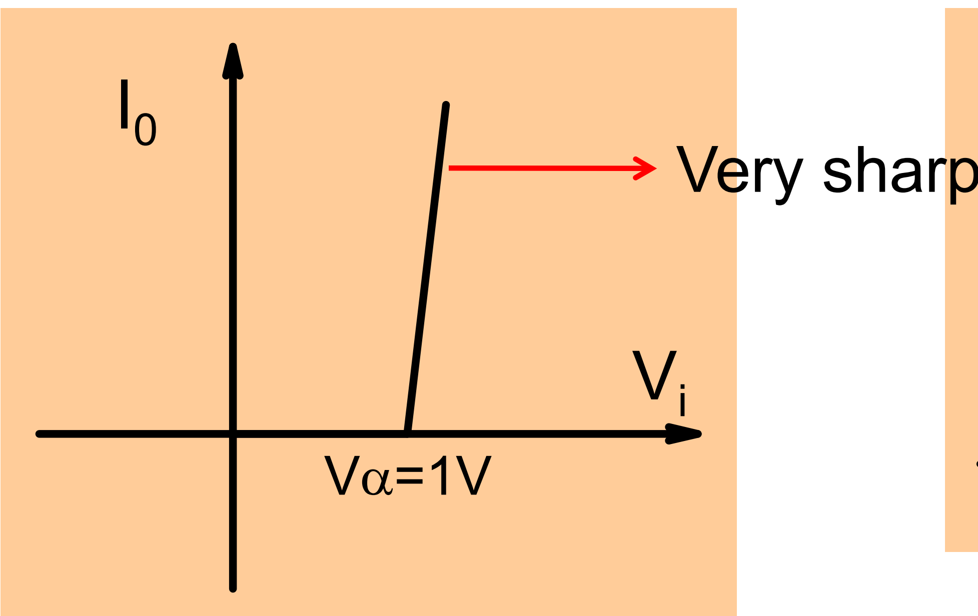
Device Z

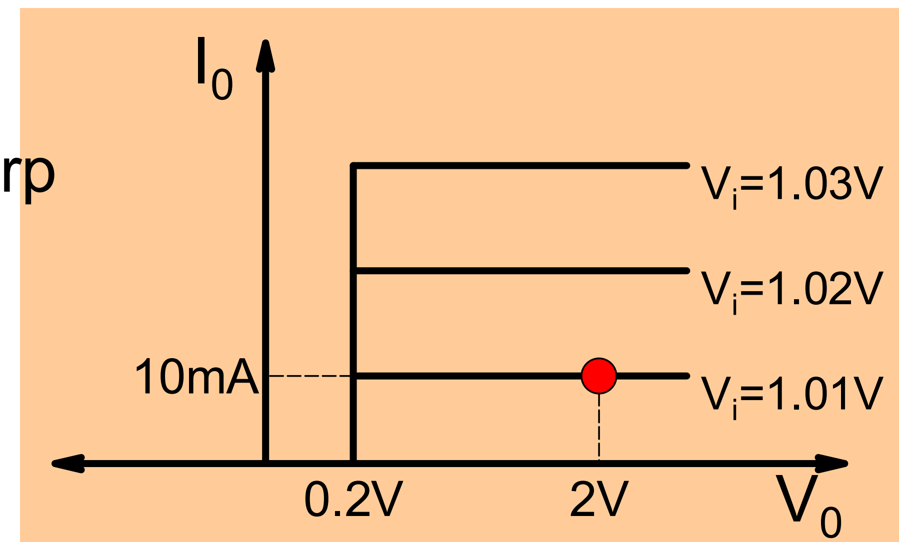


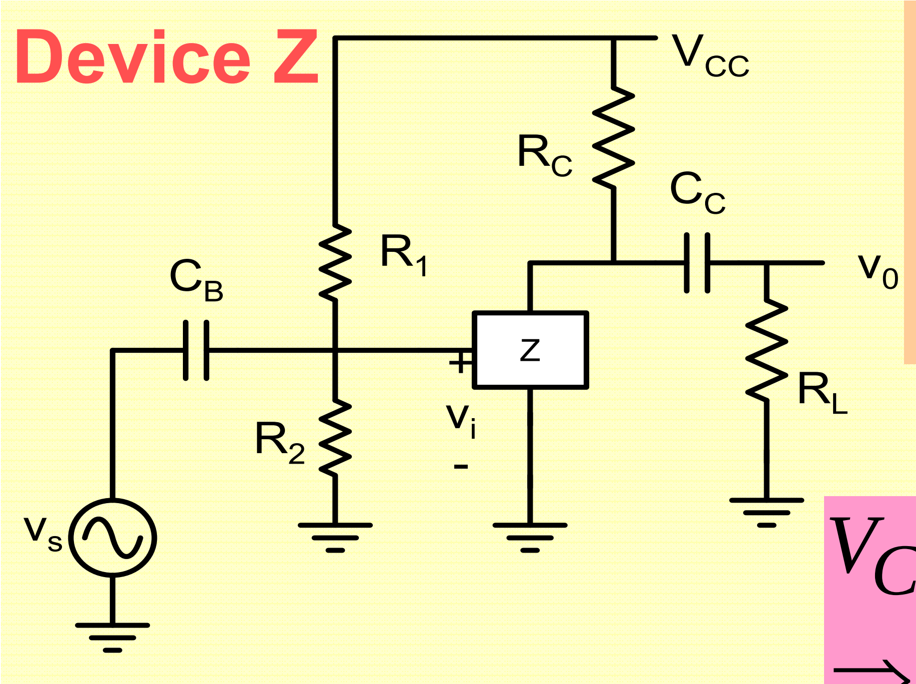
$$\text{for } V_o < 0.2V : I_o = 0$$

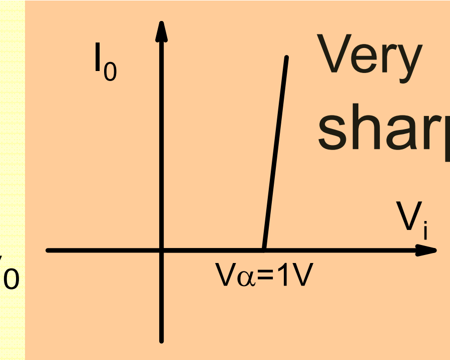
$$\text{for } V_o \geq 0.2 :$$

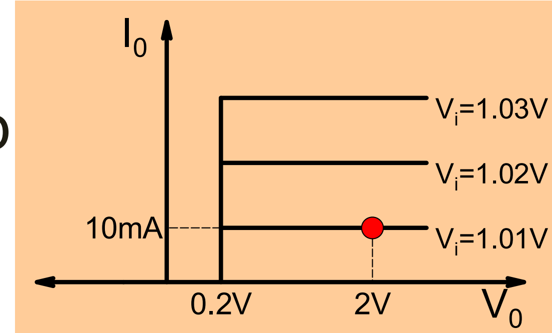
$$\begin{aligned} I_o &= 0 && \text{for } V_i \leq 1V \\ &= 1 \times (V_i - 1V) && \text{for } V_i > 1V \end{aligned}$$











$$V_{CC} = 5V; R_2 = 1K; R_1 = 3.95K$$
$$\Rightarrow V_i = 1.01 \Rightarrow I_o = 10mA$$

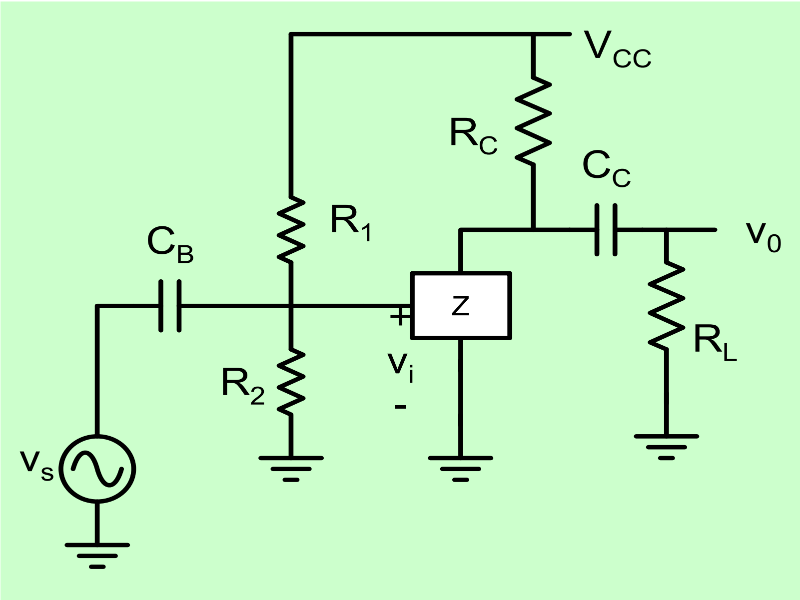
$$\text{for } V_o < 0.2V : I_o = 0$$
$$\text{for } V_o \geq 0.2 :$$
$$I_o = 0 \qquad \text{for } V_i \leq 1V$$
$$= 1 \times (V_i - 1V) \quad \text{for } V_i > 1V$$

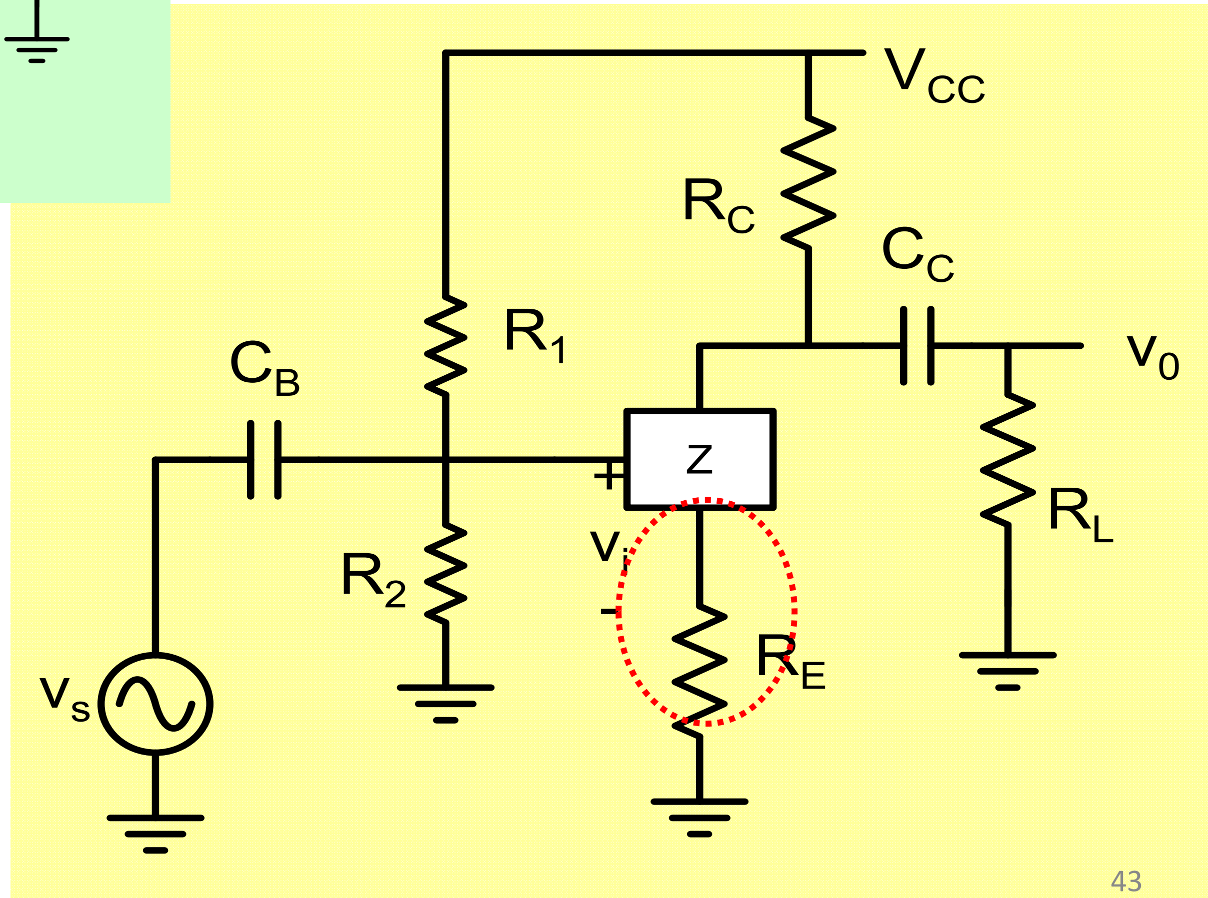
$$V_{CC} = 5V; R_2 = 0.99K; R_1 = 3.95K$$
$$\Rightarrow V_i = 1.002 \Rightarrow I_o = 2mA$$

$$V_{CC} = 5V; R_2 = 0.98K; R_1 = 3.95K$$
$$\Rightarrow V_i = 0.994V \Rightarrow I_o = 0$$

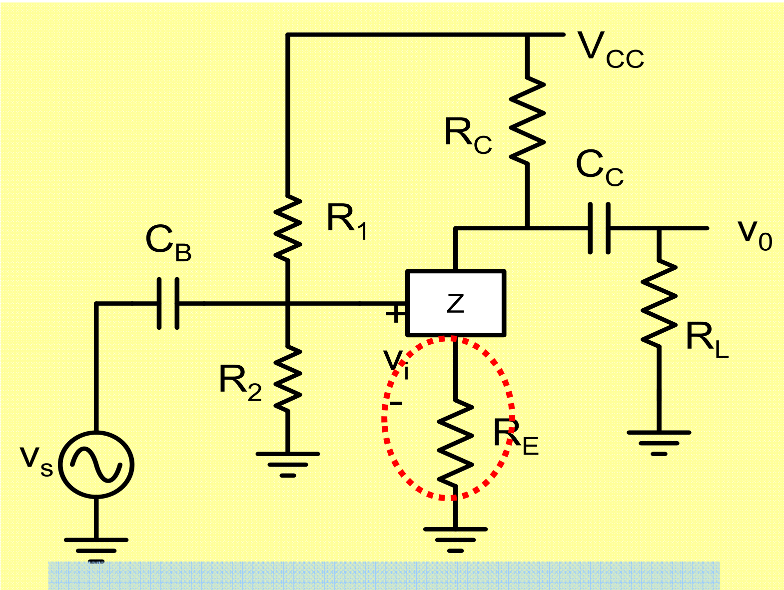
Circuit is very sensitive to variations in resistor values, power supply, device parameters such as Vα

Solution

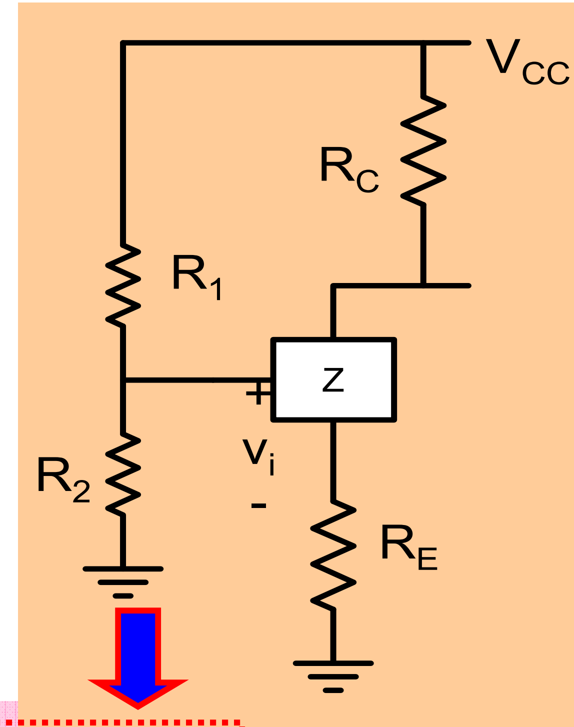


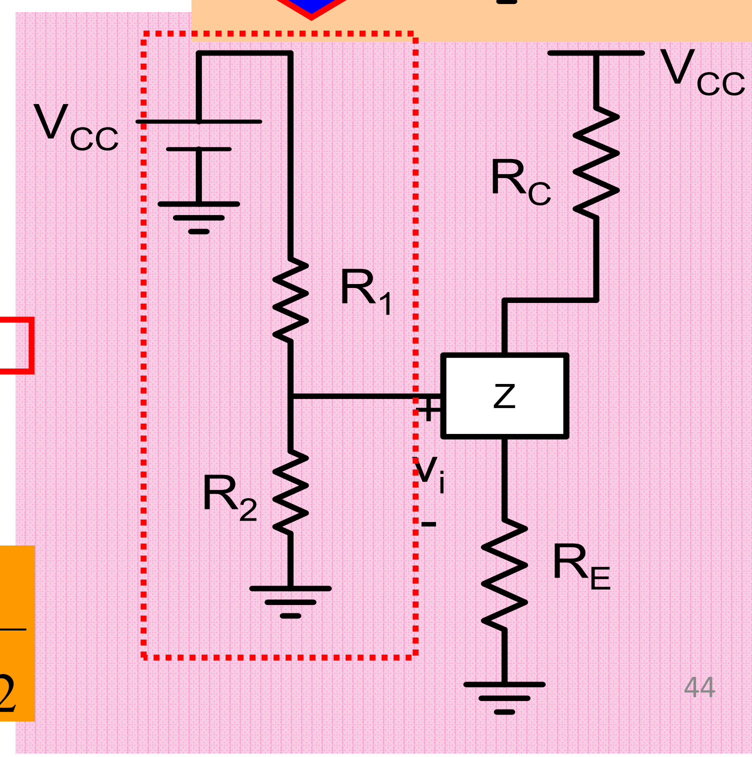


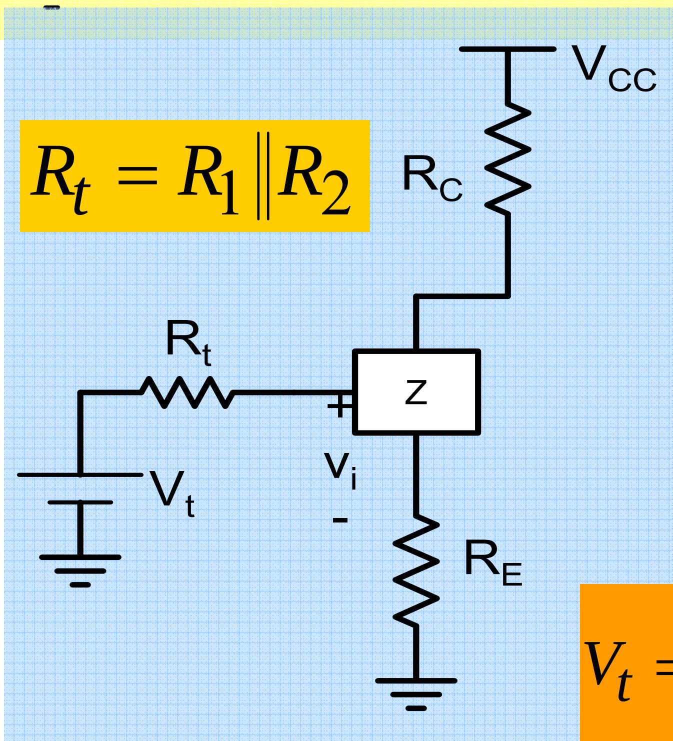
Solution



DC Analysis

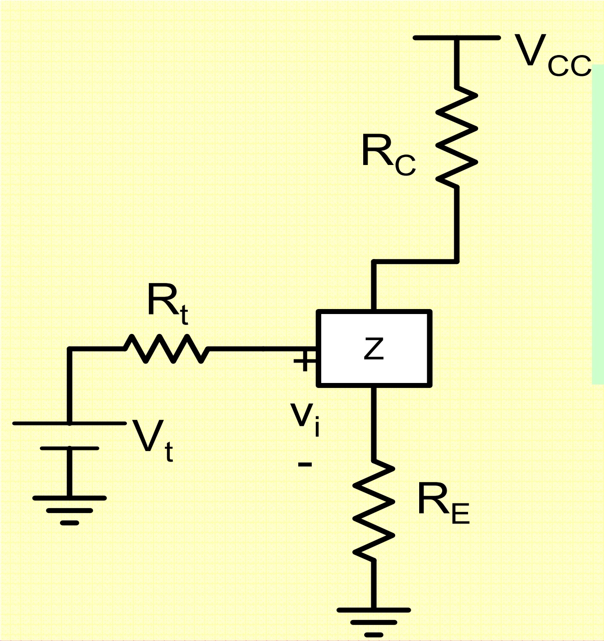


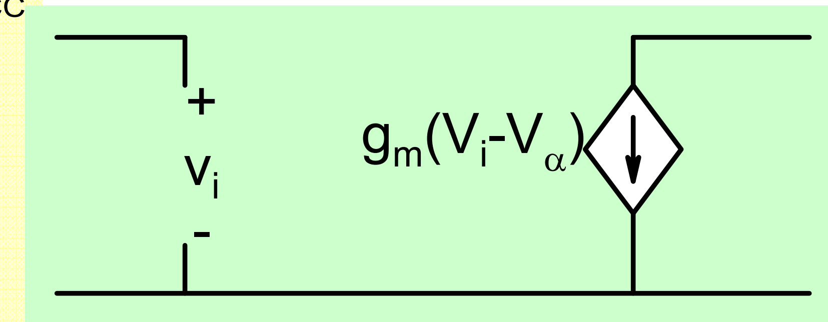


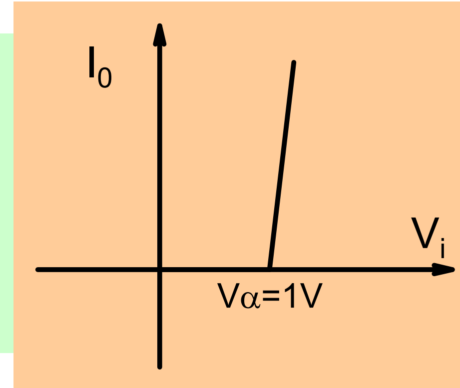


$$R_t = R_1 \| R_2$$

$$V_t = V_{CC} \times \frac{R_2}{R_1 + R_2}$$



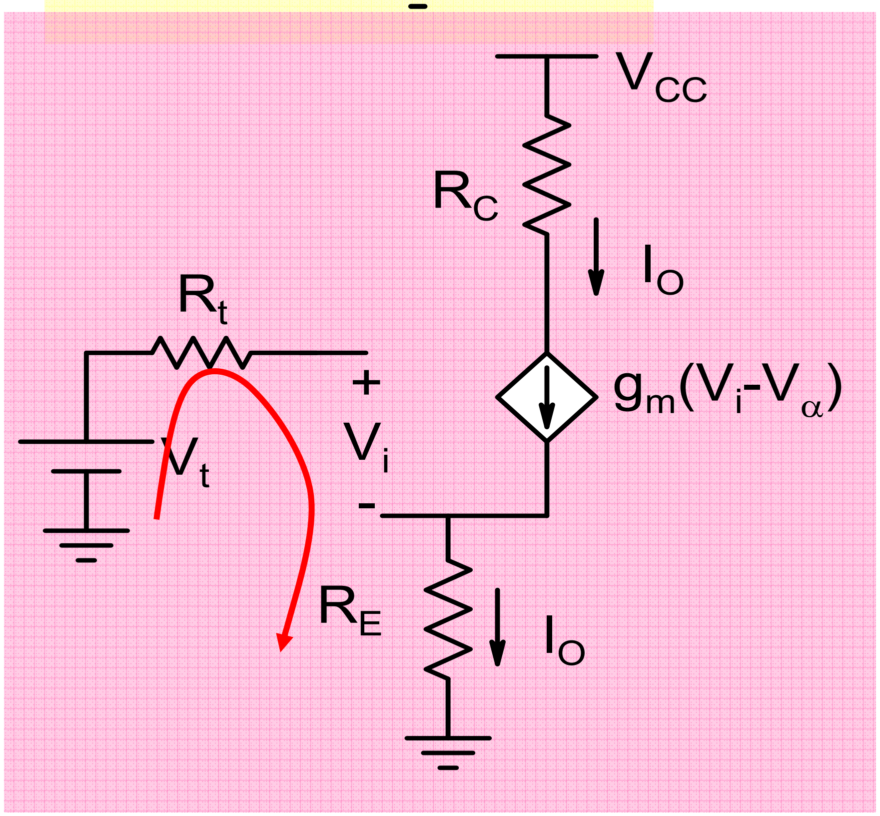




$$-V_t + 0 \times R_t + V_i + I_o R_E = 0$$

Since I_o vs. V_i characteristics is very sharp, $V_i \sim V_\alpha = 1V$

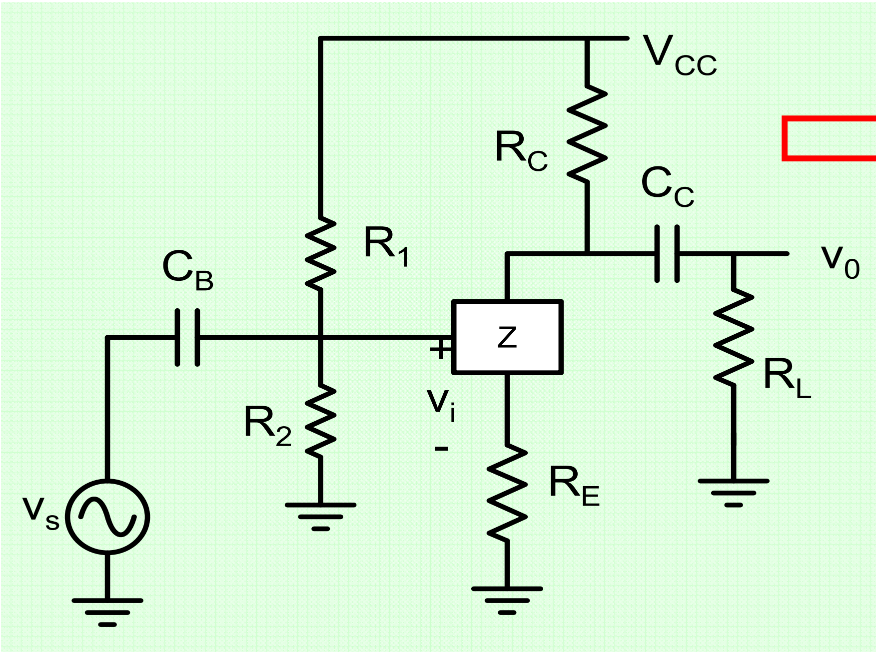
$$I_o \cong \frac{V_t - V_\alpha}{R_E}$$



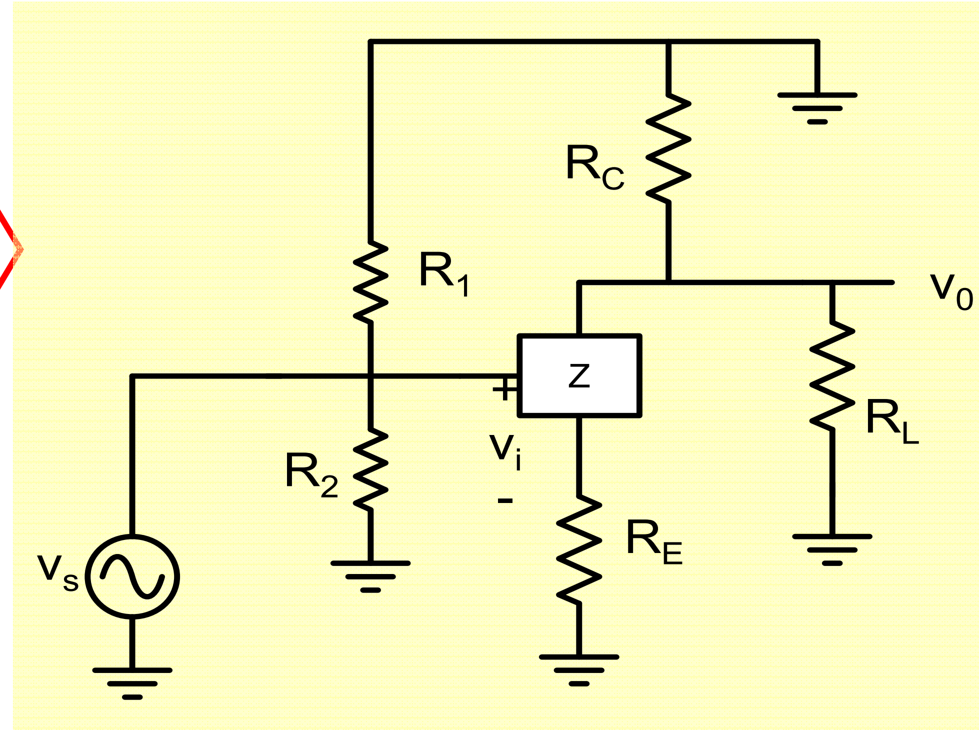
If V_t changes by 1% due to variation in resistor values then the change in output current is proportional.

But circuit is much less sensitive to variations in circuit parameters

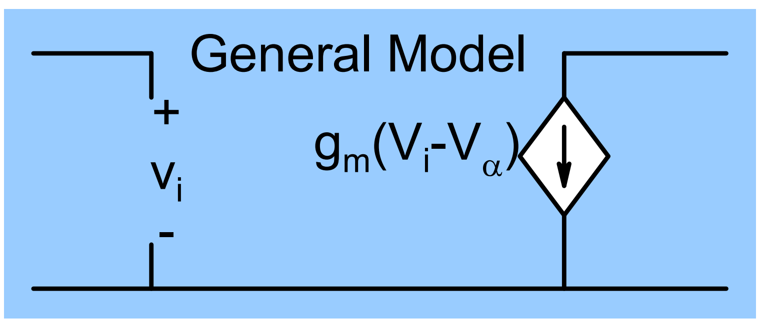
AC analysis



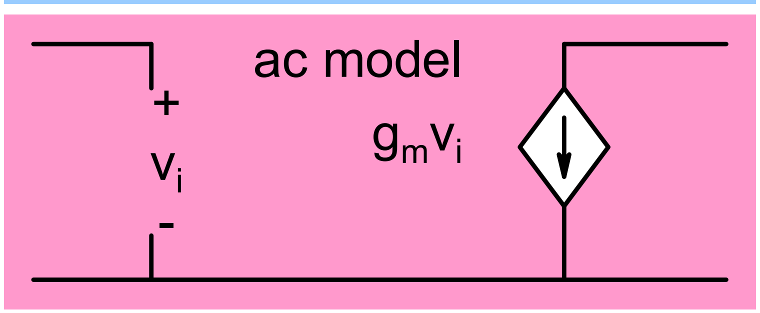
V_{CC}
R_C
C_C
R_1
C_B
v_0
z
+
v_i
-
R_L
R_2
R_E
v_s



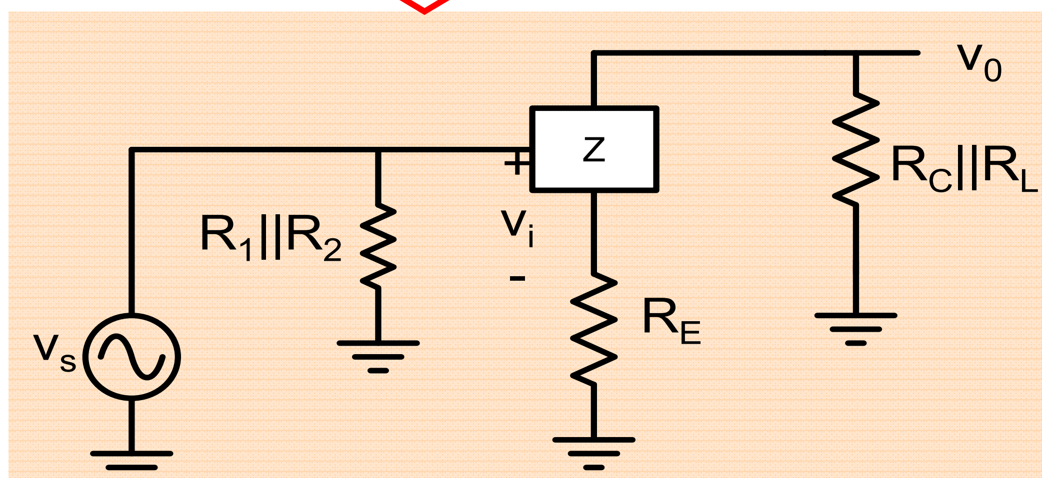
R_C
R_1
v_0
z
+
v_i
-
R_L
R_2
R_E
v_s



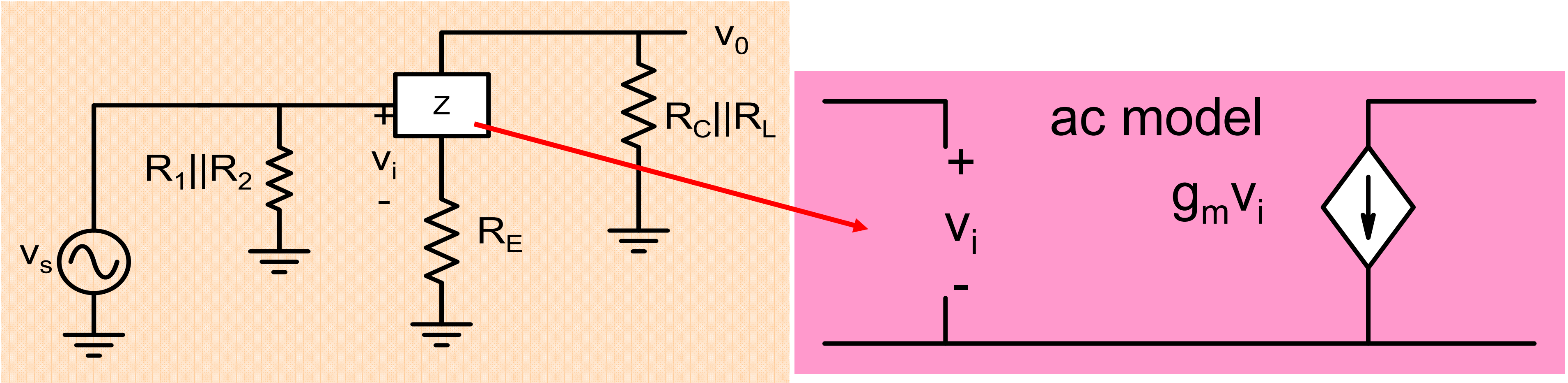
General Model
+
v_i
-
$g_m(V_i\text{-}V_\alpha)$

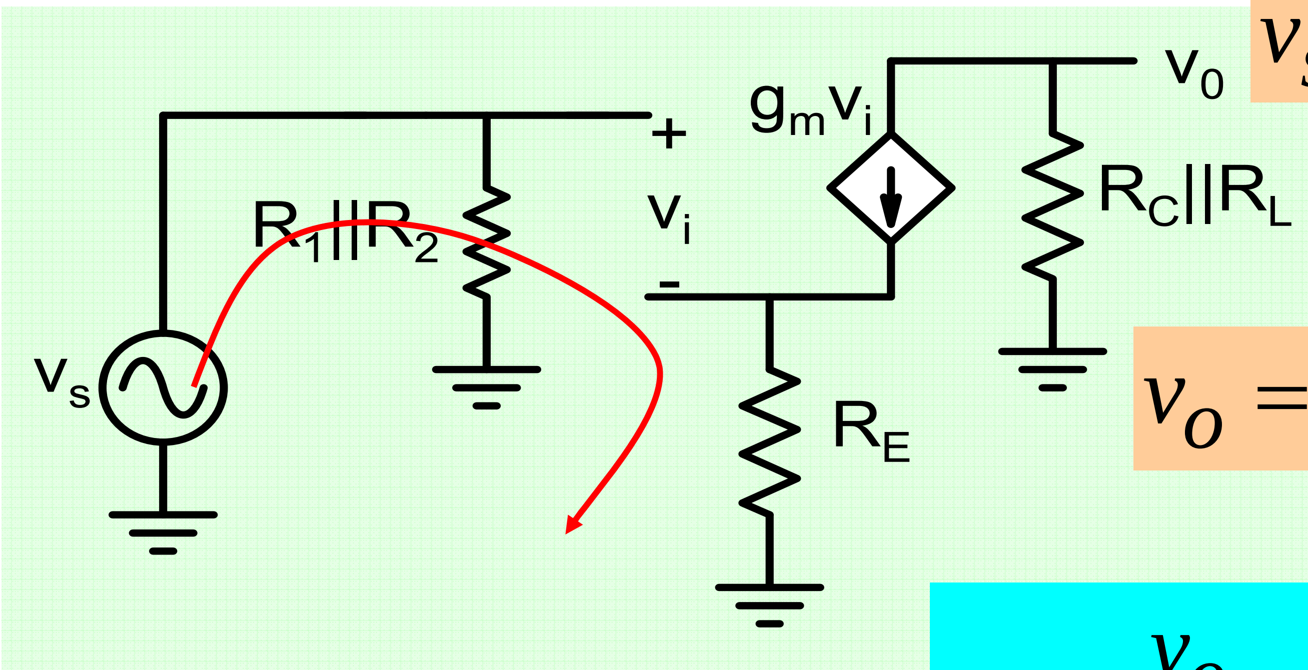


ac model
+
v_i
-
$g_m v_i$



v_0
z
+
$R_C||R_L$
$R_1||R_2$
v_i
-
R_E
v_s

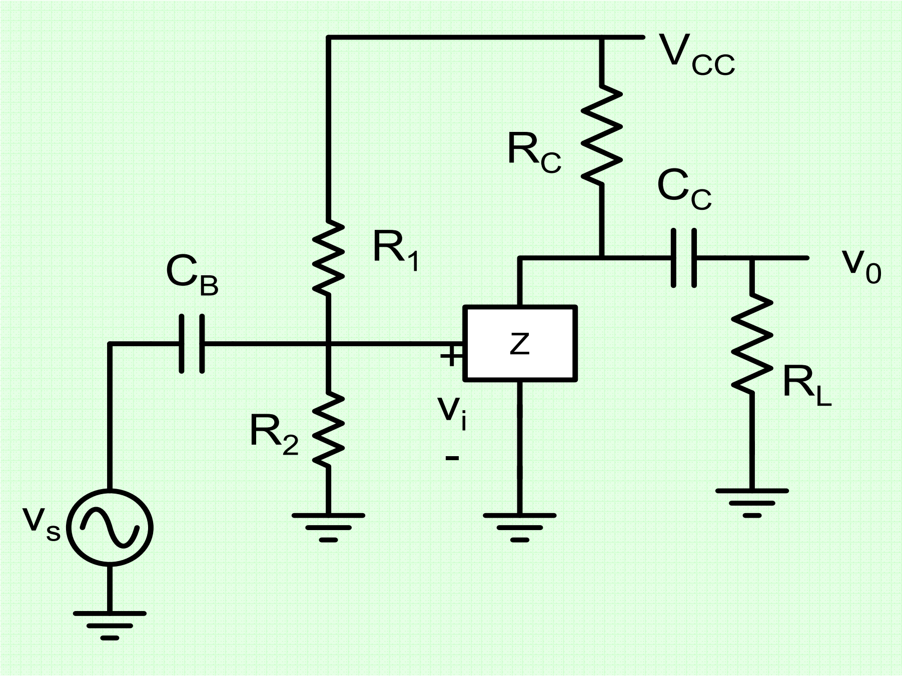




$$v_s = v_i + g_m v_i R_E$$

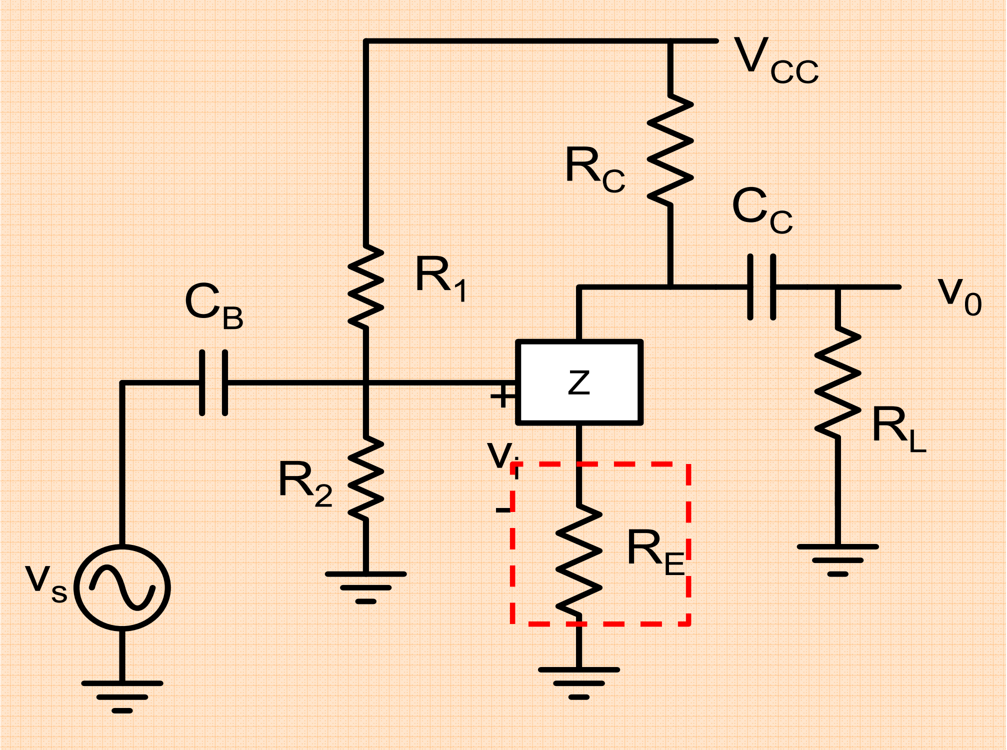
$$v_o = -g_m v_i \times R_C \| R_L$$

$$A_V = \frac{v_o}{v_s} = -\frac{g_m R_C \| R_L}{1 + g_m R_E}$$



Circuit is very sensitive to variations in resistor values, power supply, device parameters such as Vα

$$A_V = \frac{v_o}{v_s} = -g_m R_C \| R_L$$

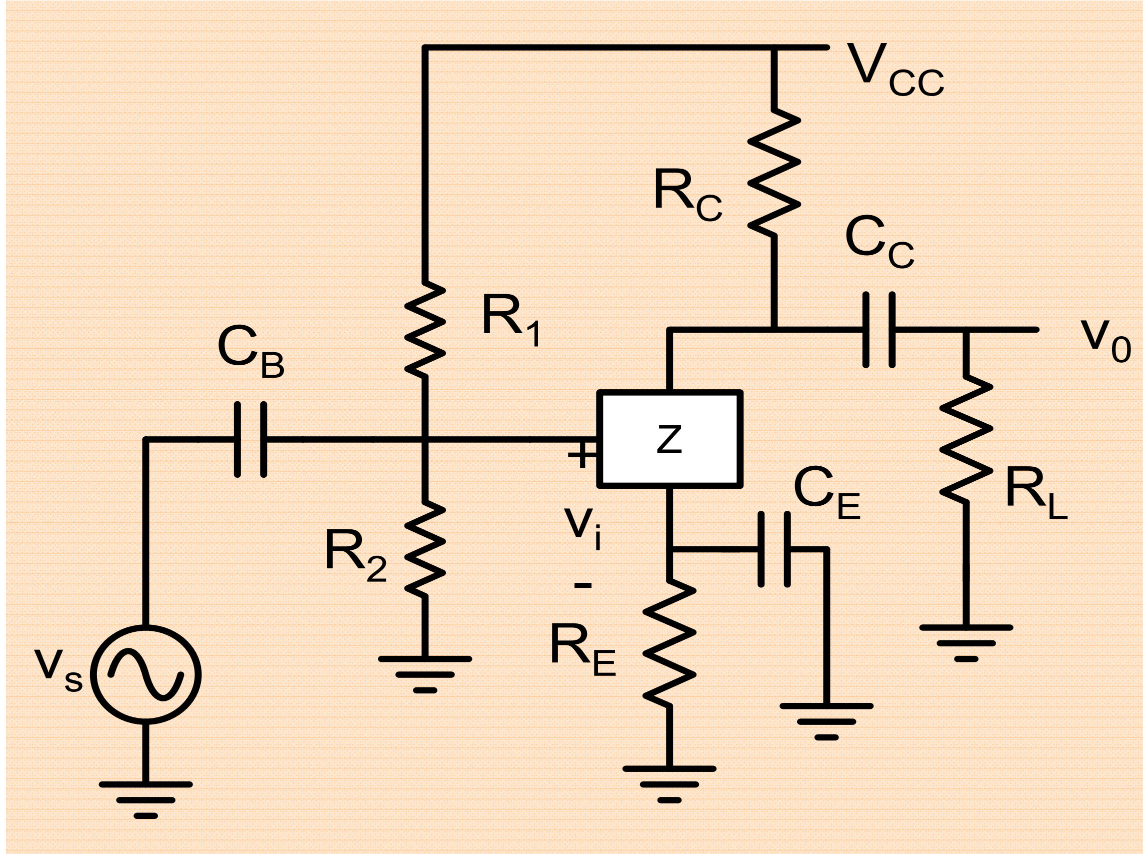


Circuit is much less sensitive to variations in circuit parameters

$$A_V = \frac{v_o}{v_s} = -\frac{g_m R_C \| R_L}{1 + g_m R_E}$$

But gain is smaller

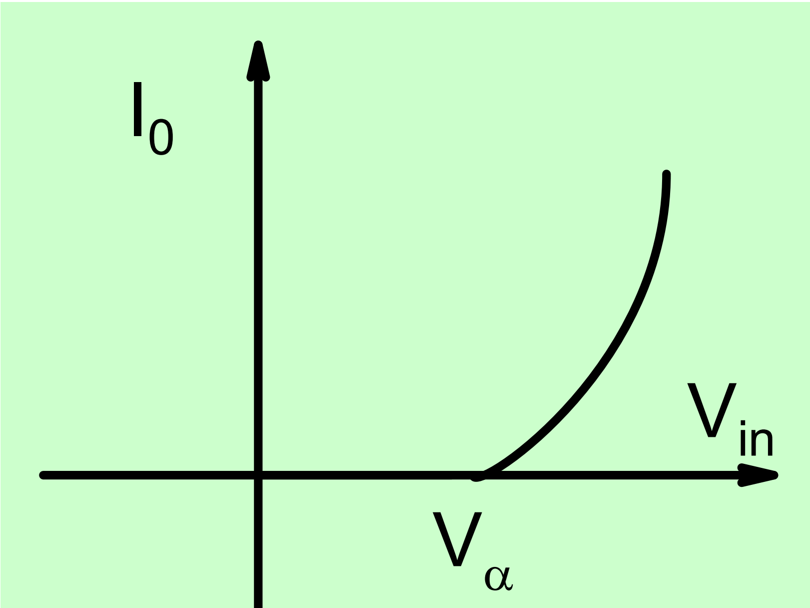
Simple Solution

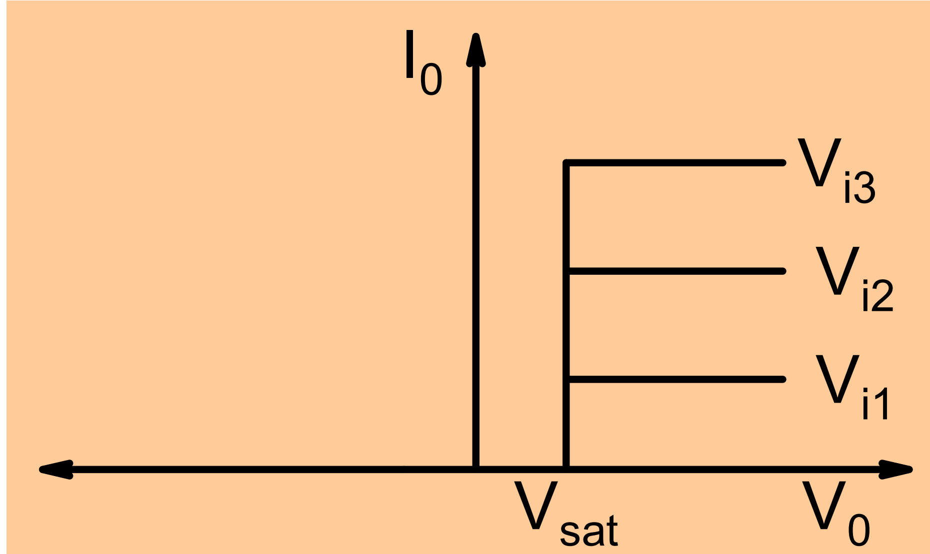


For dc, Capacitor C_E acts as open allowing R_E to reduce variations in current

For ac Capacitor C_E acts as a short circuit ($1/j\omega C \sim 0$) allowing high voltage gain to be obtained

Device Non-Linear:



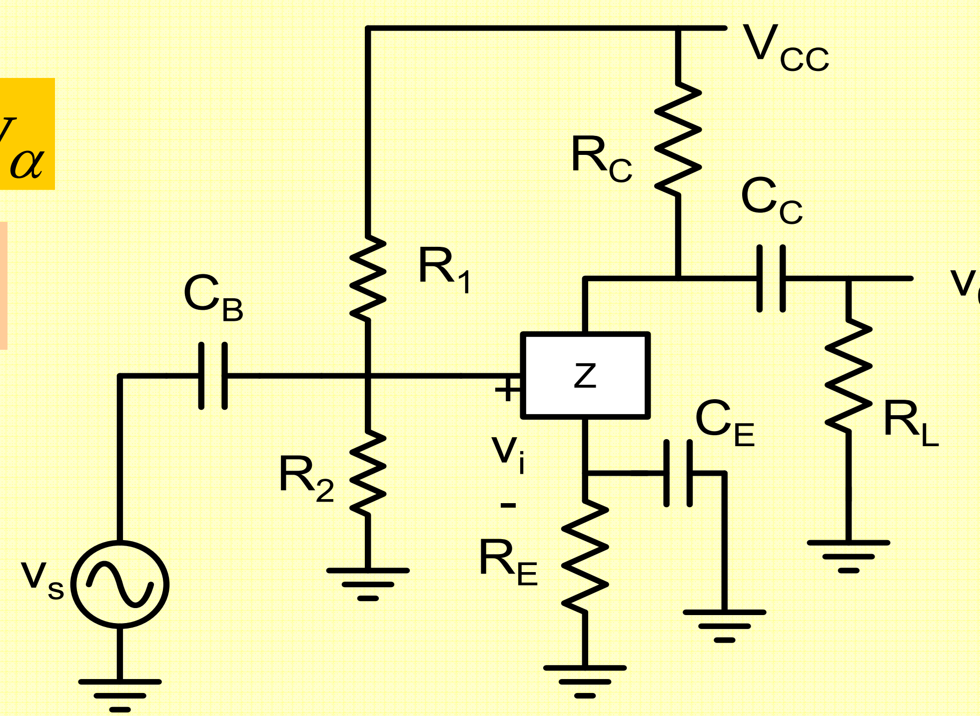


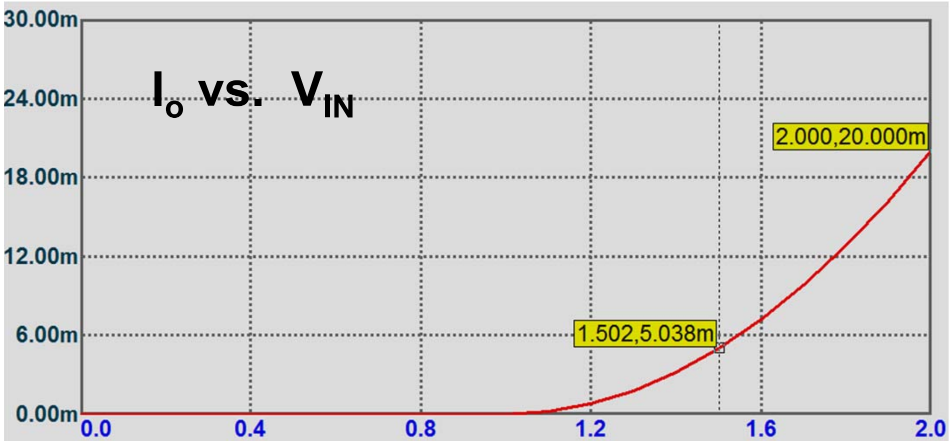
$$I_o = K \times (V_{in} - V_\alpha)^2 \text{ for } V_{in} \geq V_\alpha$$

$$V_\alpha = 1.0V \;;\; K = 0.01$$

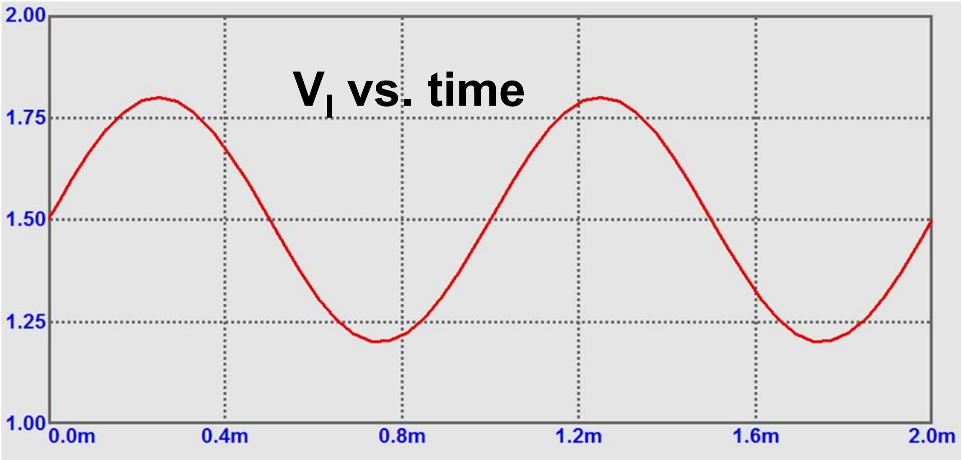
$$V_B = 1.5V$$

$$v_s = 0.3V \quad Sin \quad \omega t$$

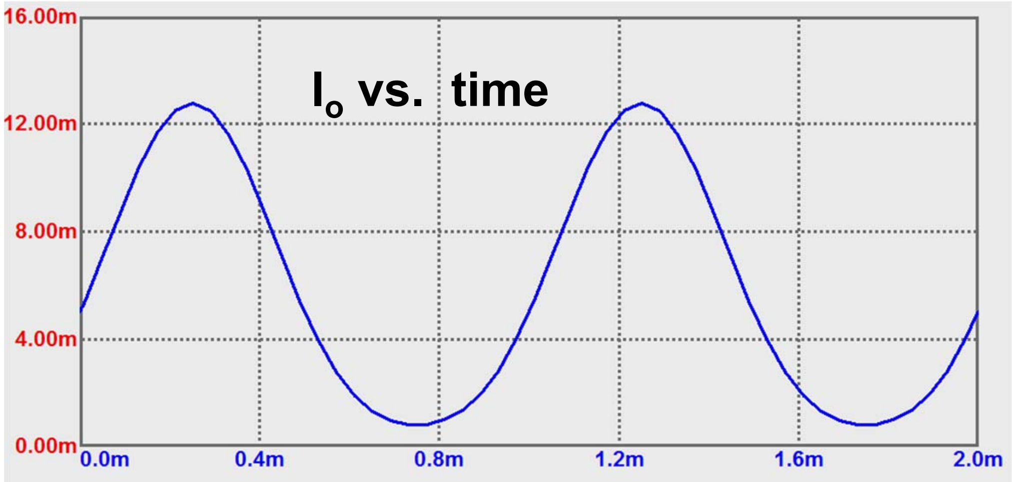




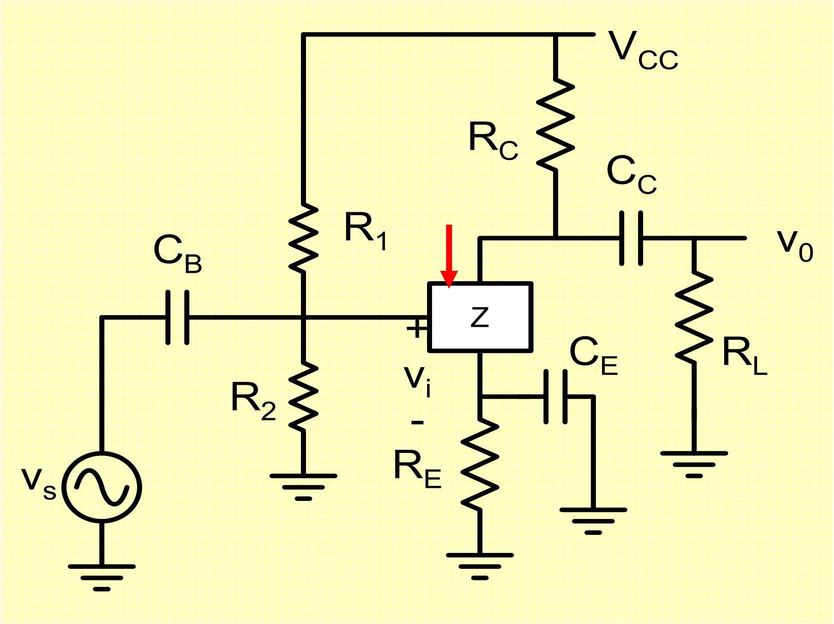
30.00m
24.00m
18.00m
12.00m
6.00m
0.00m
0.0
0.4
0.8
1.2
1.6
2.0
Io vs. VIN
2.000,20.000m
1.502,5.038m



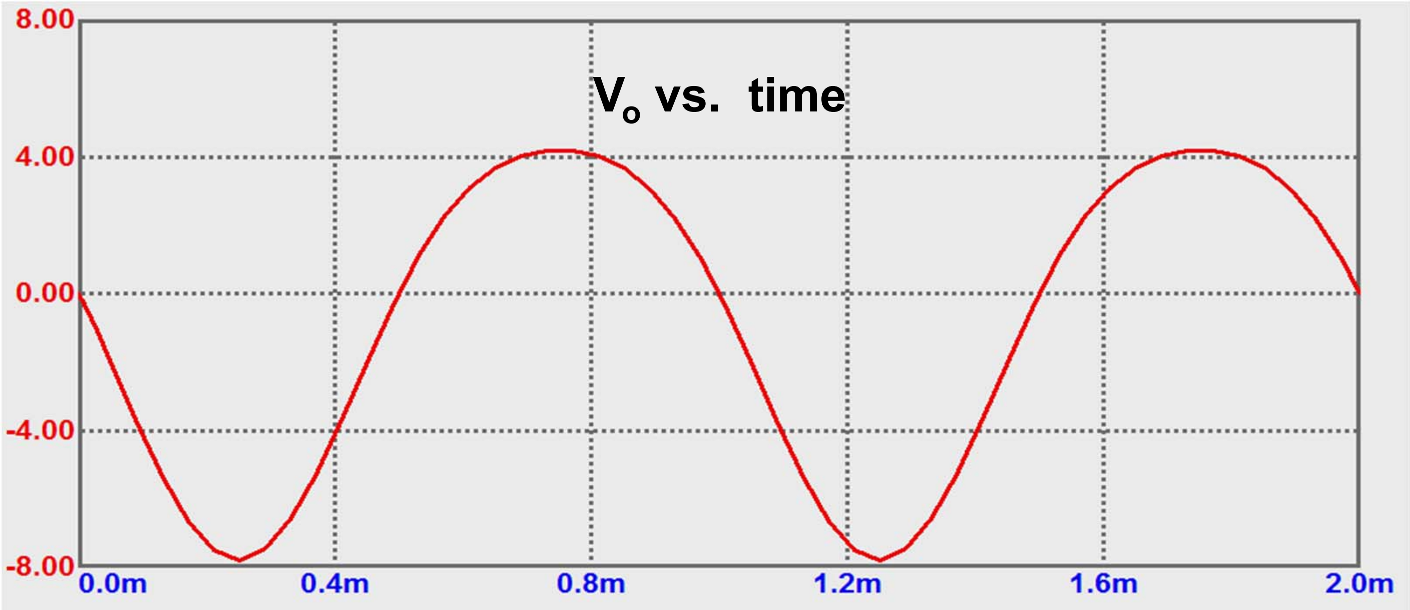
2.00
1.75
1.50
1.25
1.00
0.0m
0.4m
0.8m
1.2m
1.6m
2.0m
VI vs. time

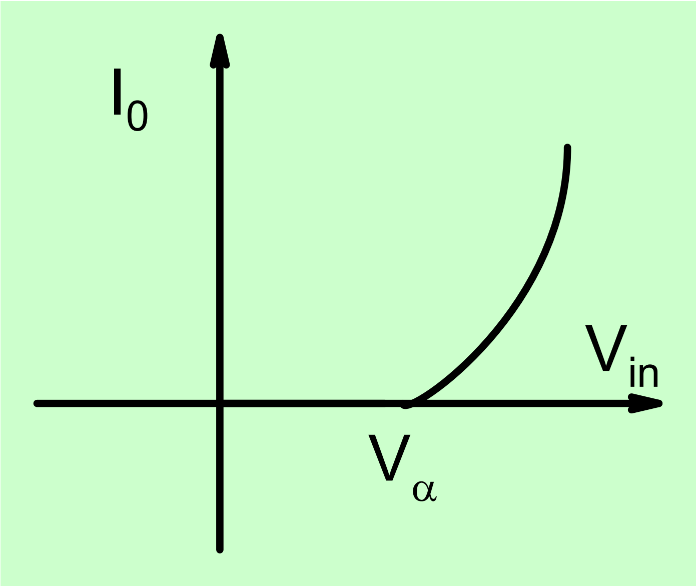


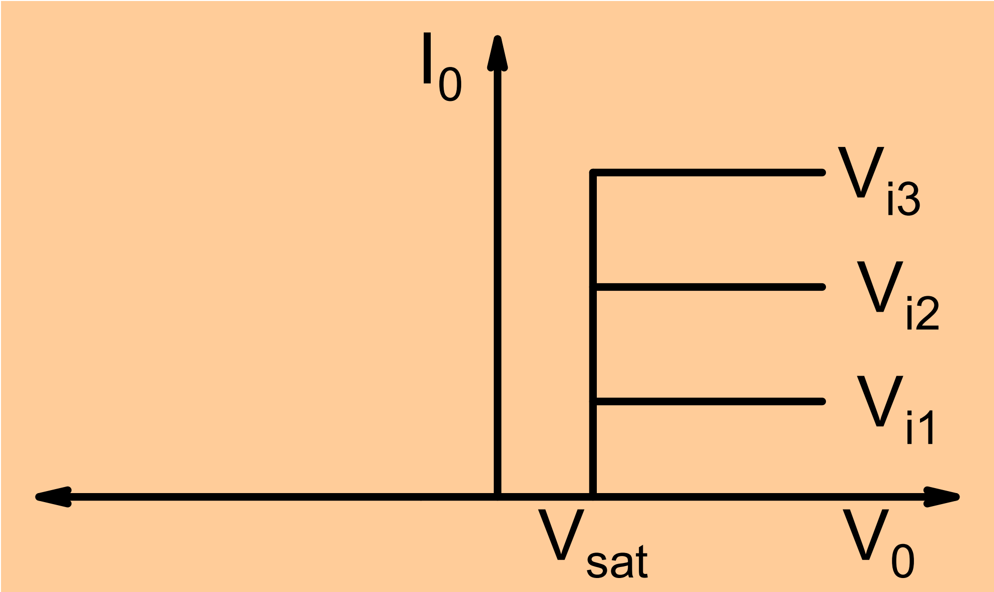
16.00m
12.00m
8.00m
4.00m
0.00m
0.0m
0.4m
0.8m
1.2m
1.6m
2.0m
Io vs. time



VCC
RC
CC
R1
CB
v0
Z
+
vi
-
CE
RL
R2
RE
Vs

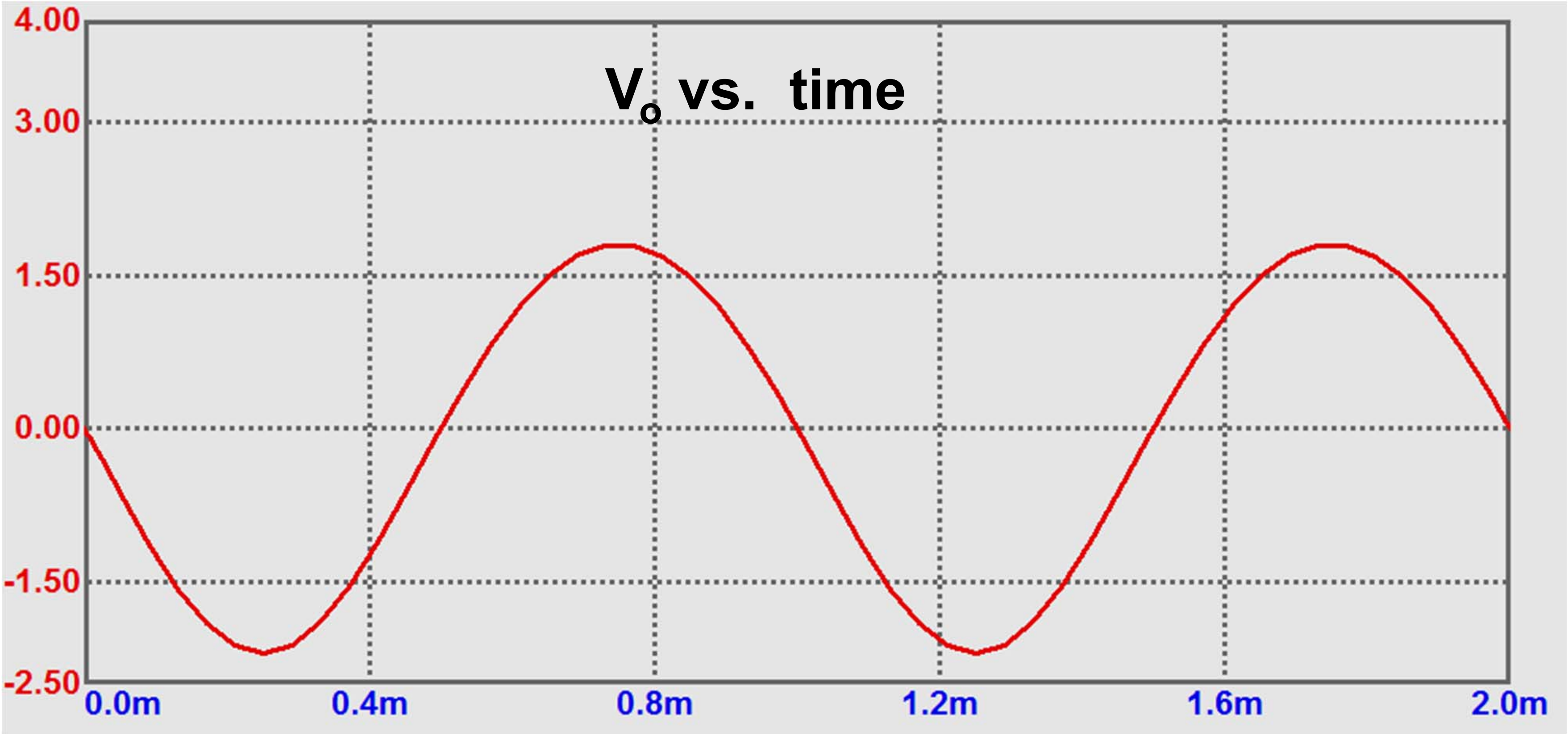






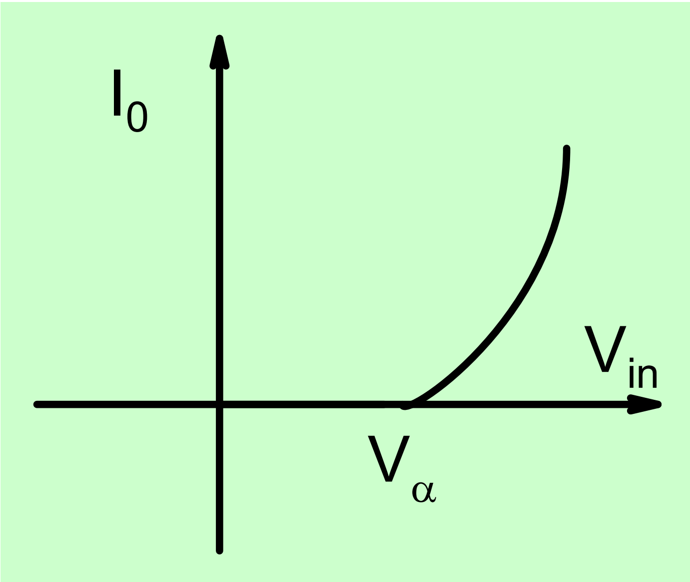
Because of Non-linearity the output waveform is distorted !

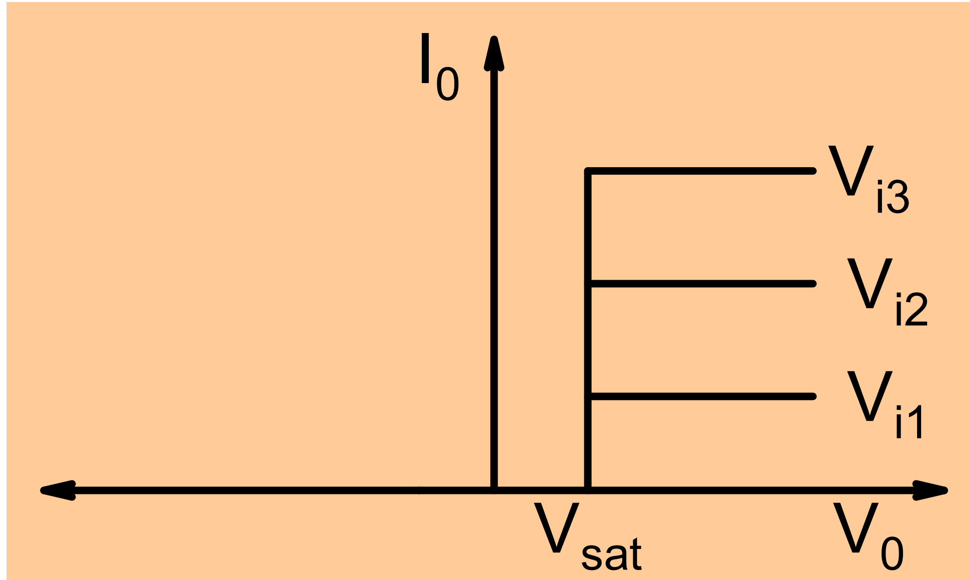
Suppose input is reduced to $v_s = 0.1V\ Sin(\omega t)$

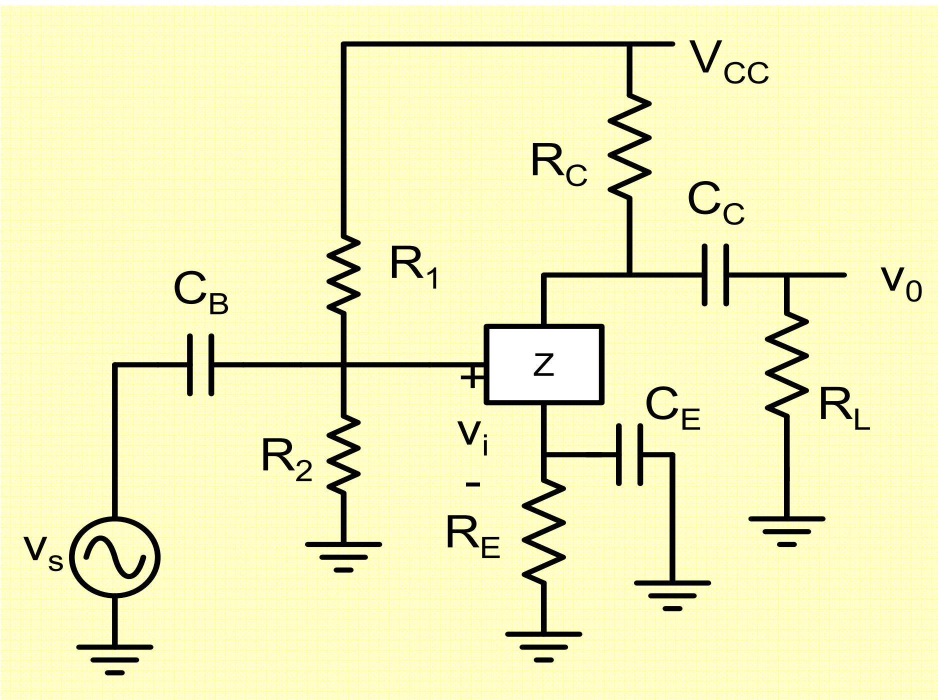


Distortion is much smaller if we restrict input voltage to a small value !

Building Amplifiers with non-linear devices





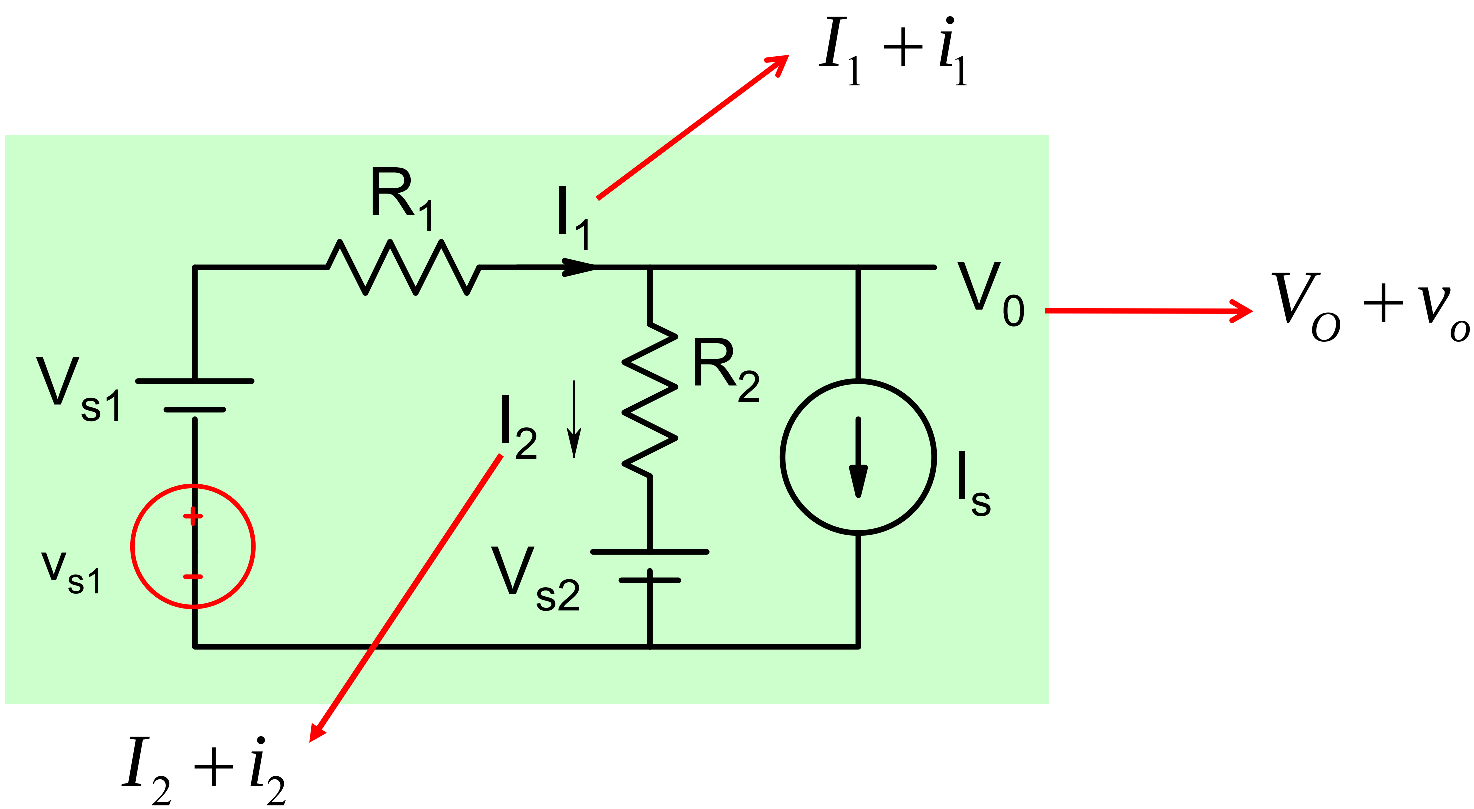


Amplifier will work properly (with small distortion only if we restrict the amplitude of input signal to small values.

How small depends on the nature of non-linearity. The stronger the non-linearity the lesser the signal amplitude.

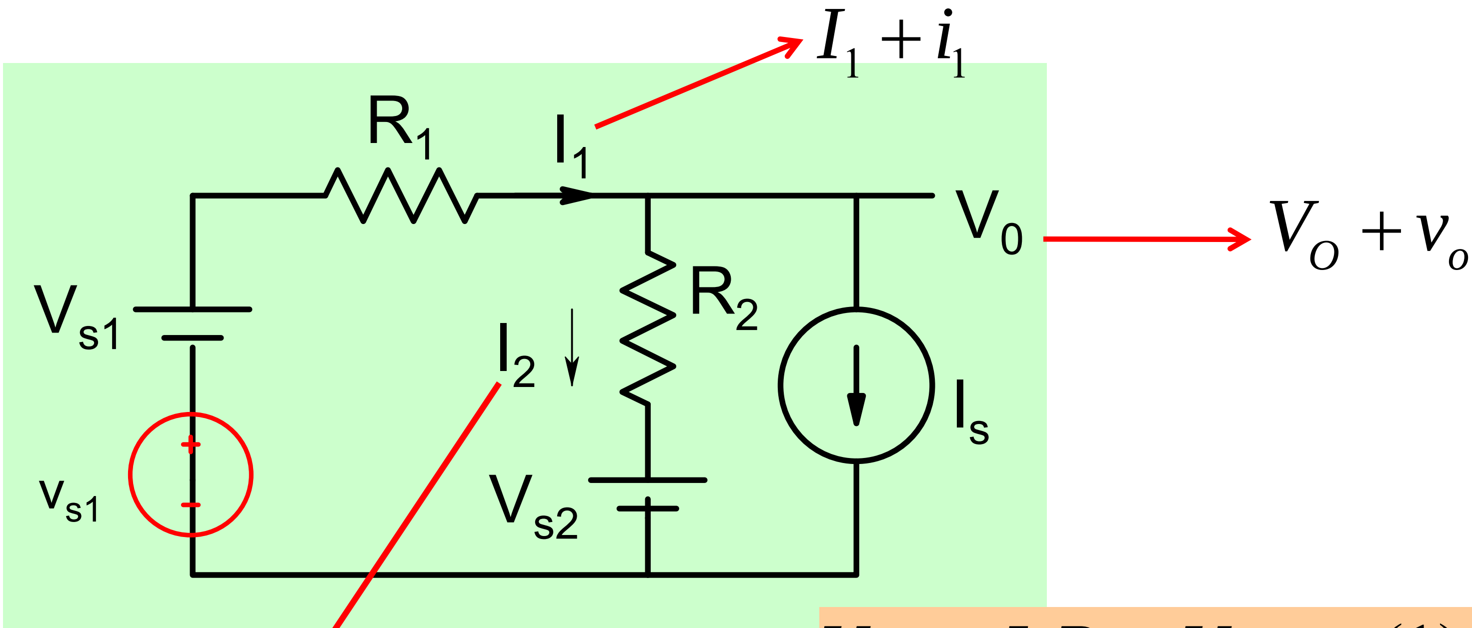
Appendix

Incremental (ac) Circuit Analysis



Incremental circuit analysis attempts to find the relationships between incremental voltages and currents v_{s1}, i_1, v_o…….

Incremental (ac) Circuit Analysis



$$V_{S1} = I_1 R_1 + V_0 \qquad (1)$$

$$I_1 = I_S + (V_0 - V_{S2})/R_2 \qquad (2)$$

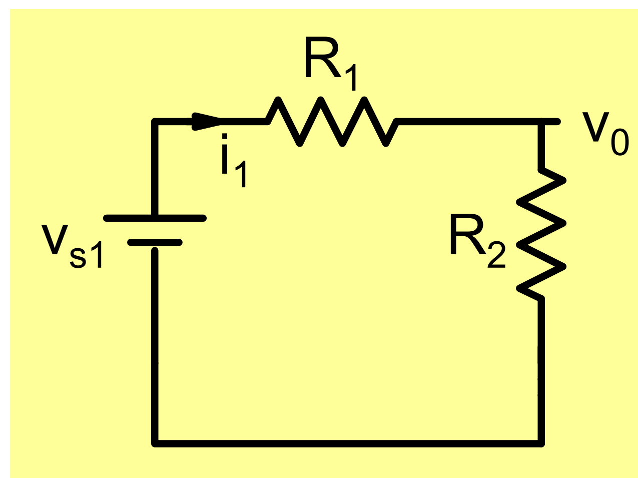
$$V_{S1} + v_{s1} = (I_1 + i_1) \times R_1 + V_0 + v_o \qquad (3)$$

$$I_1 + i_1 = I_S + (V_0 + v_o - V_{S2})/R_2 \qquad (4)$$

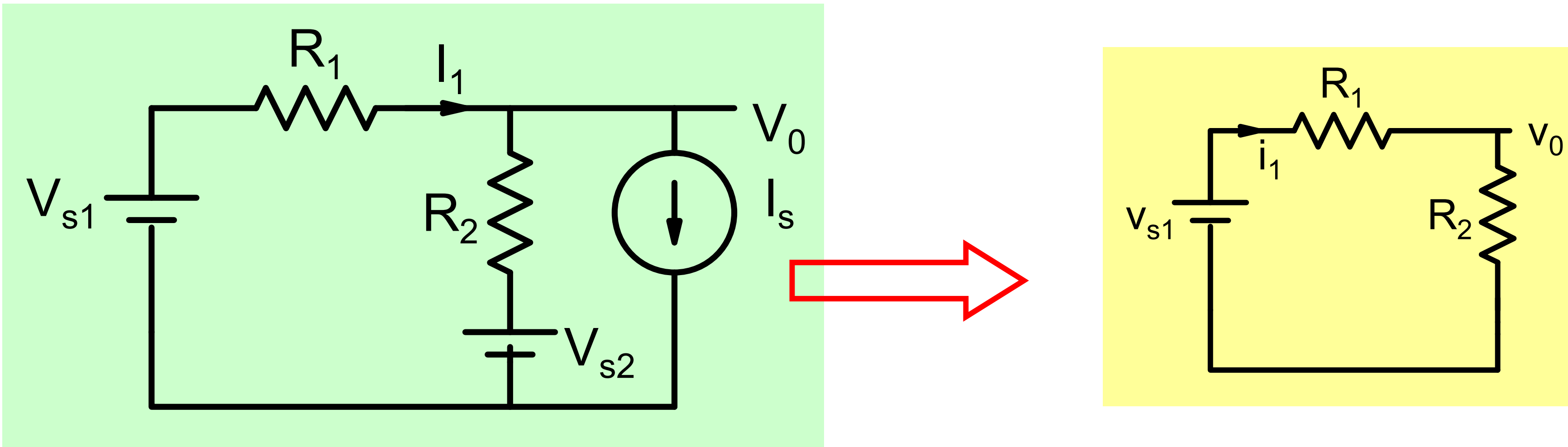
$$(3)\text{-}(1): v_{s1} = i_1 R_1 + v_o$$

$$(4)\text{-}(2): i_1 = v_o / R_2$$

$$v_{s1} = i_1 R_1 + i_1 R_2$$



Method: Incremental equivalent circuit



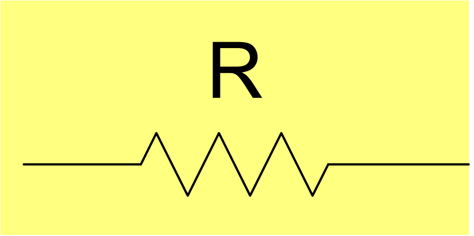
Analyze incremental equivalent circuit obtained by replacing each circuit element by its increment circuit model (sometimes called ac model).

Incremental model

$$I = f(V) \qquad I + i = f(V + v)$$

Relation between *i and v*

Incremental (ac) Models: Resistor



$$V = I \times R$$

$$V + v = (I + i) \times R$$

$$\Rightarrow \quad v = i \times R$$

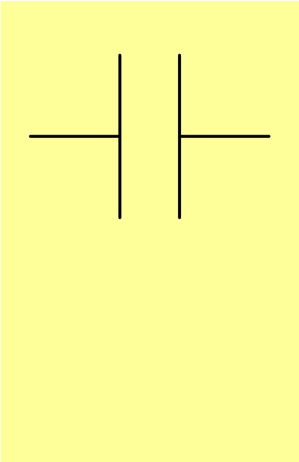
Incremental model of a resistor is a resistor of the same magnitude

Incremental (ac) Models: Capacitor

$$I = C\,\frac{dV}{dt}$$

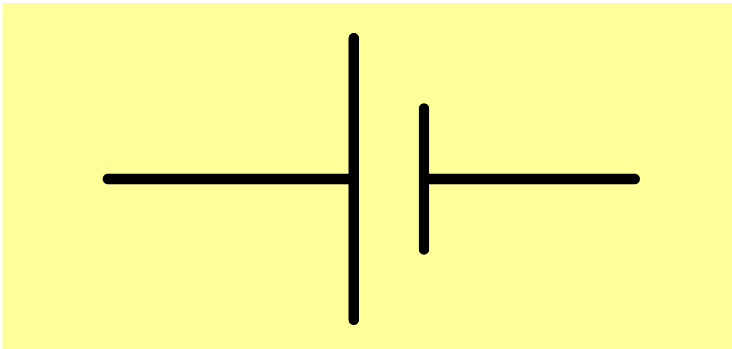
$$I + i = C\,\frac{d(V + v)}{dt}$$

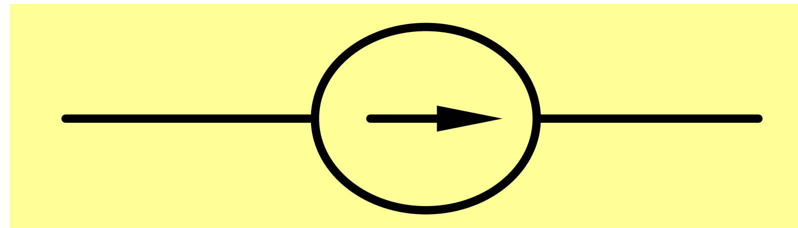
$$i = C \times \frac{dv}{dt}$$



Incremental model of a capacitor is a capacitor of the same magnitude. The same holds for an inductor as well.

Incremental (ac) Models





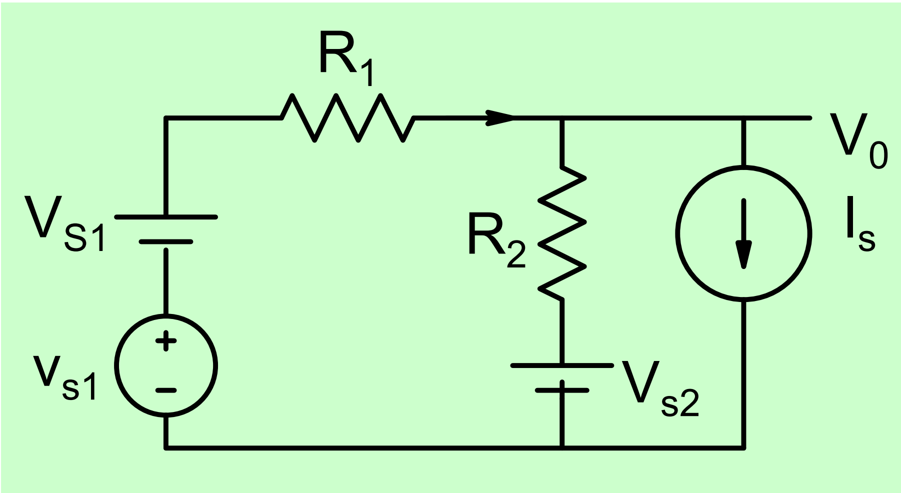
$$V = constant$$
$$\Rightarrow v = 0$$

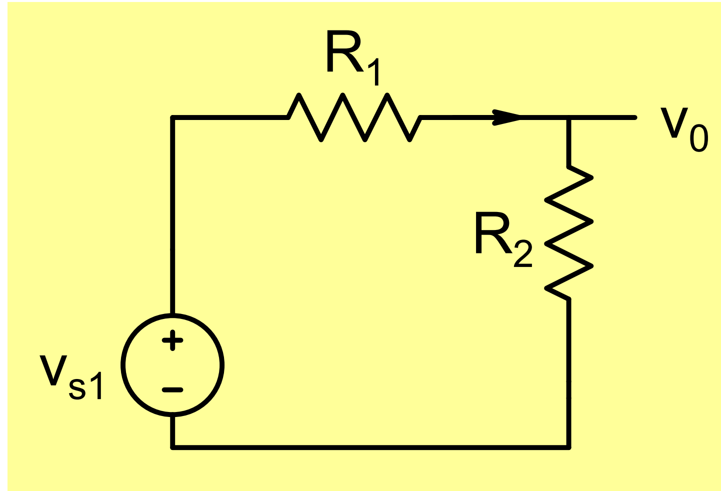
$$I = constant$$
$$\Rightarrow i = 0$$

Incremental model of a constant Voltage Source is a short circuit

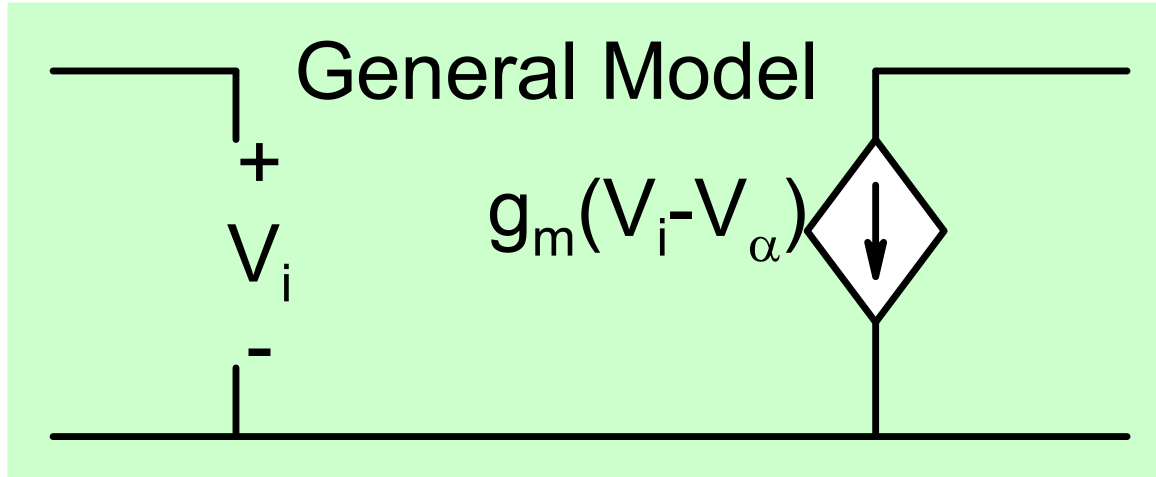
Incremental model of a constant current Source is an open circuit

Incremental (ac) circuit Analysis





$$v_o = v_{s1} \times \frac{R_2}{R_1 + R_2}$$



$$I_o = g_m(V_i - V_\alpha)$$

$$I_O + i_o = g_m(V_I + v_i - V_\alpha)$$

$$i_o = g_m v_i$$