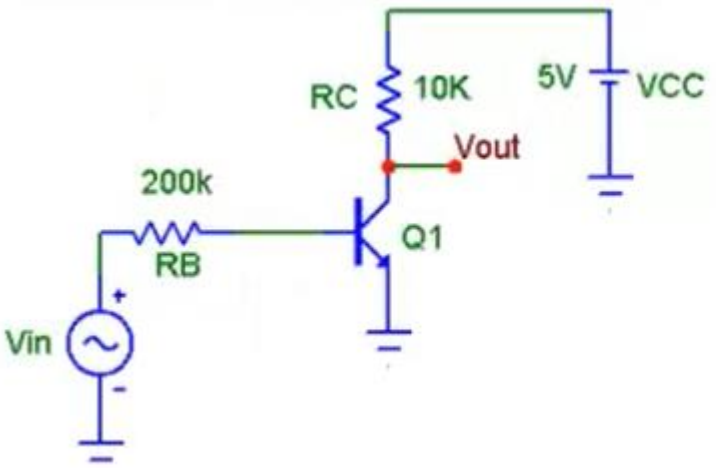
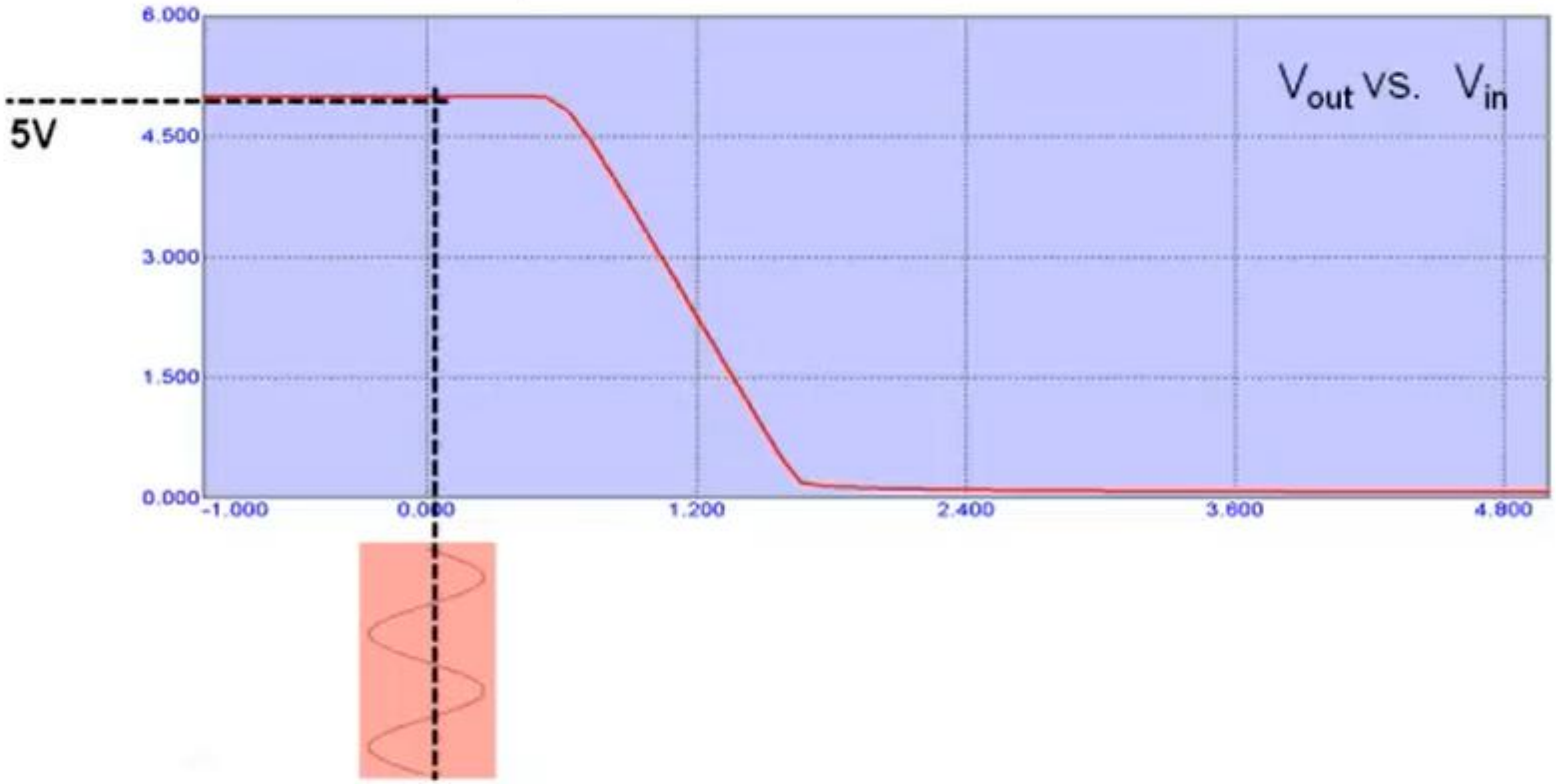
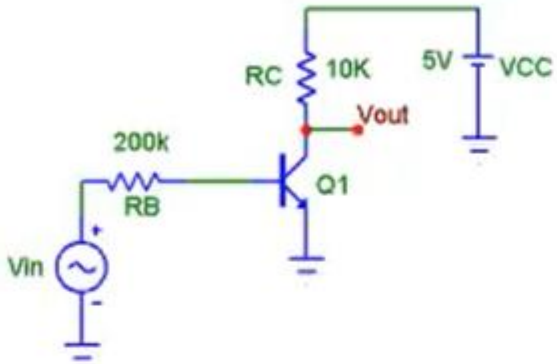
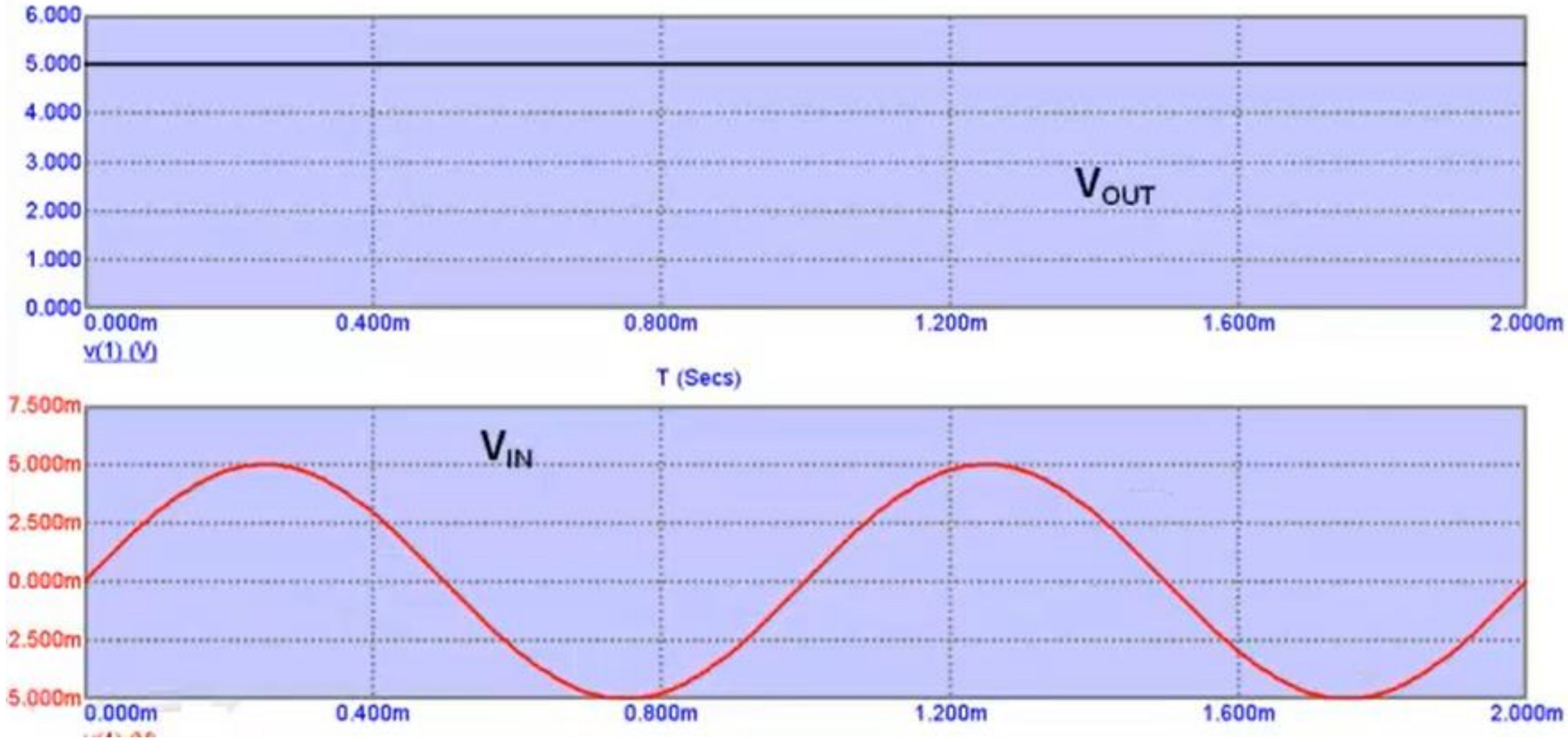

RC
10K
5V
VCC
Vout
200k
RB
Q1
Vin
+
-


6.000
4.500
3.000
1.500
0.000
-1.000
0.000
1.200
2.400
3.600
4.800
5V
V_{out} vs. V_{in}



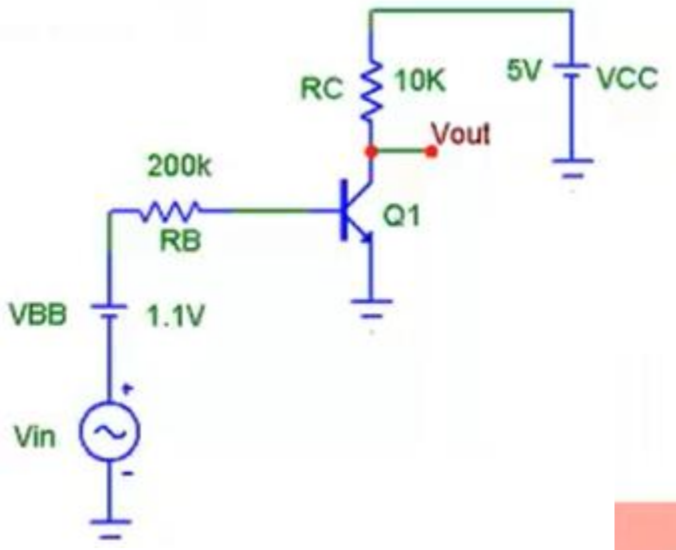
RC
10K
5V
VCC
Vout
200k
RB
Q1
Vin

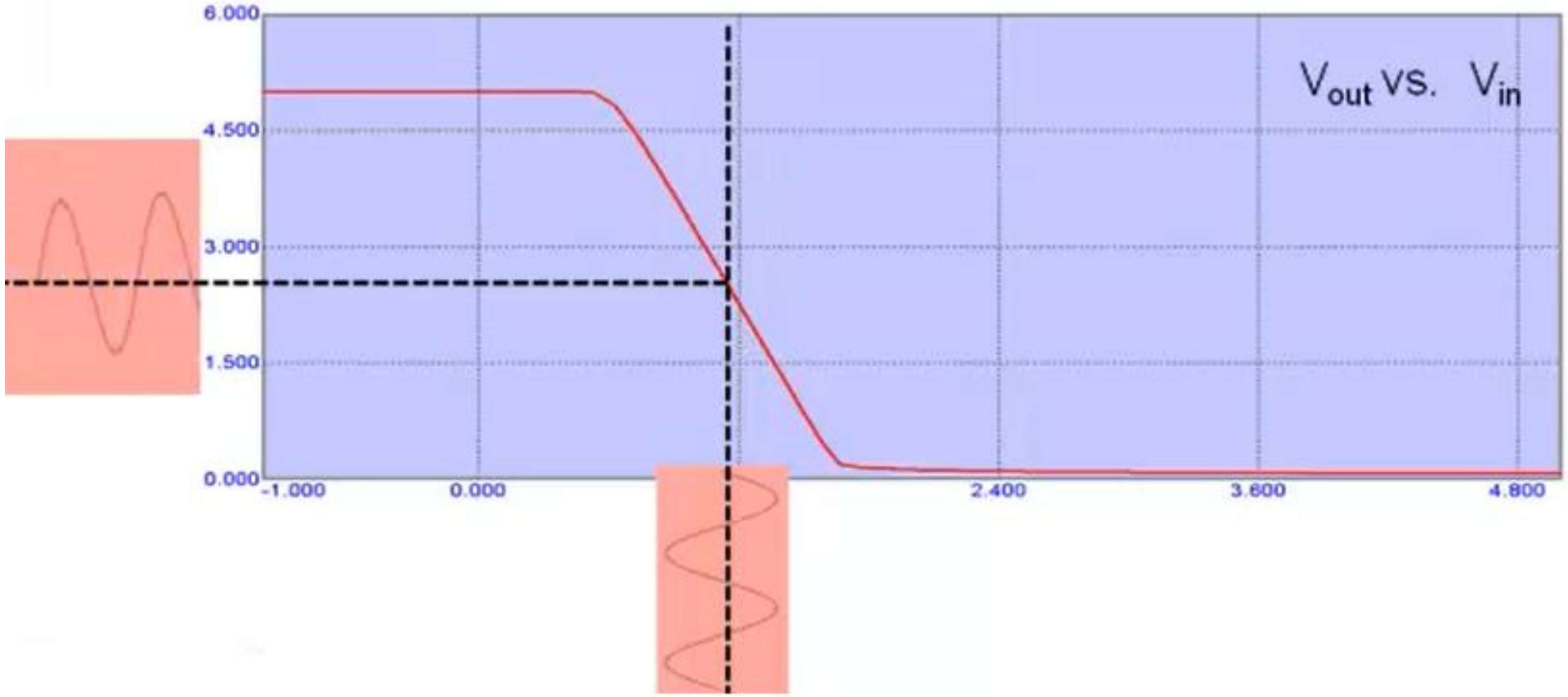
V_{out} vs. V_{in}

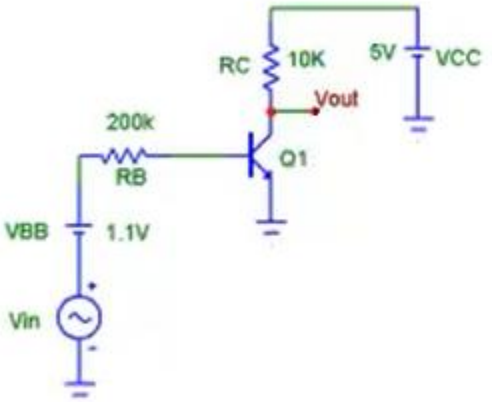


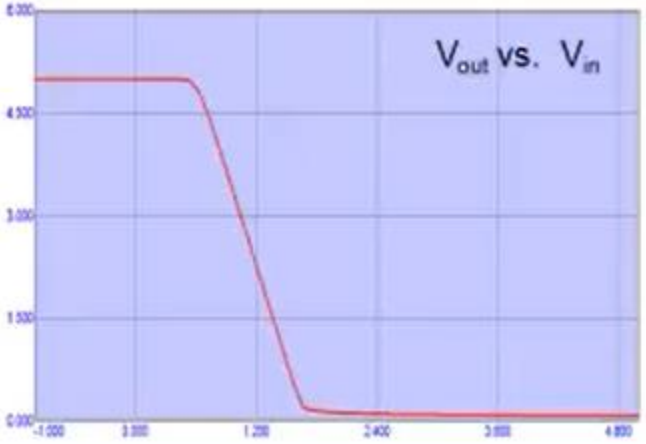
6.000
5.000
4.000
3.000
2.000
1.000
0.000
V_{OUT}
0.000m
0.400m
0.800m
1.200m
1.600m
2.000m
v(1) (V)
T (Secs)
7.500m
5.000m
2.500m
0.000m
2.500m
5.000m
V_{IN}
0.000m
0.400m
0.800m
1.200m
1.600m
2.000m

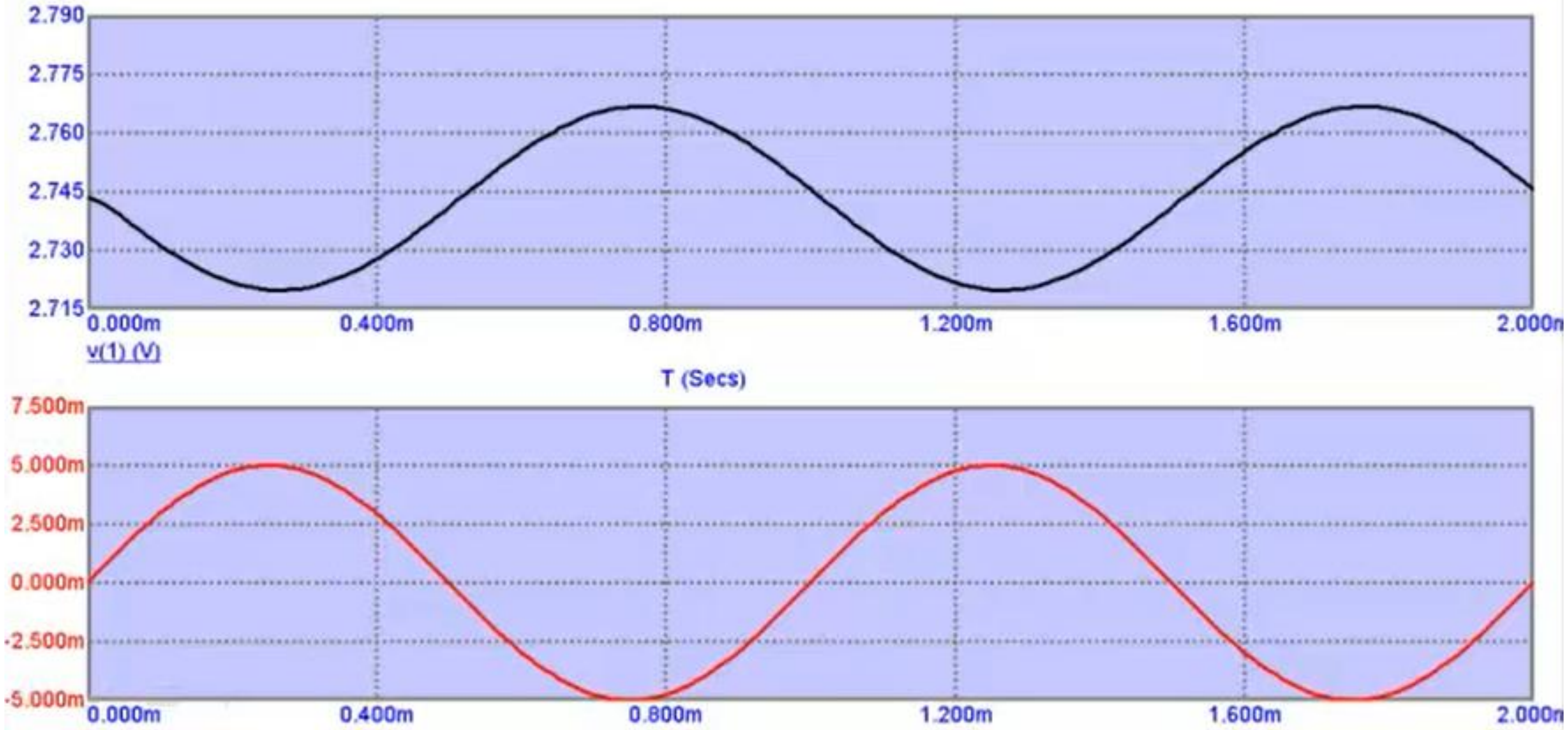
How do we amplify the weak signal?

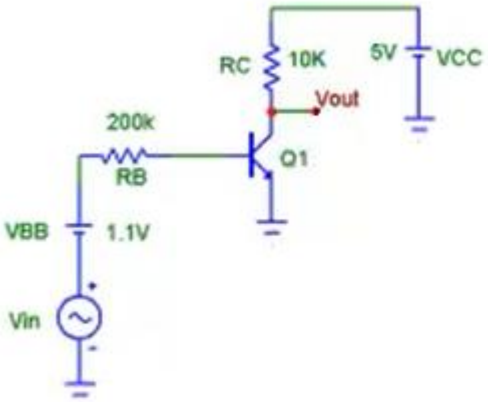


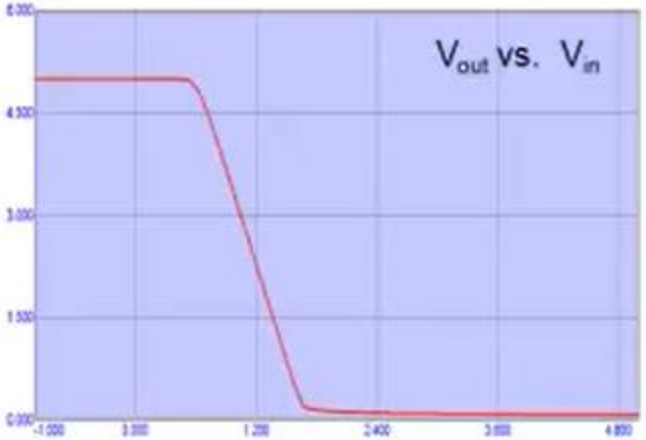


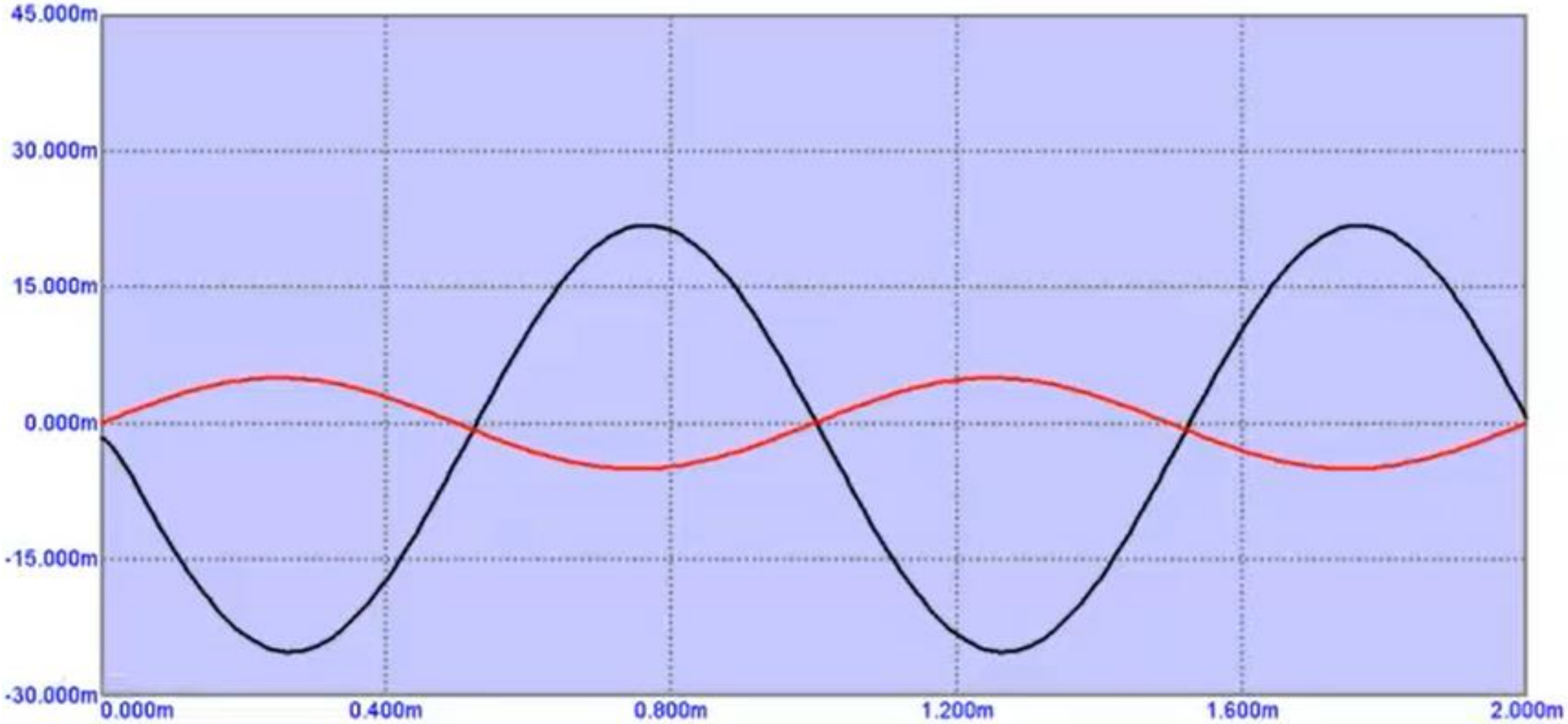

RC
10K
5V
VCC
Vout
200k
RB
Q1
VBB
1.1V
Vin


V_{out} vs. V_{in}

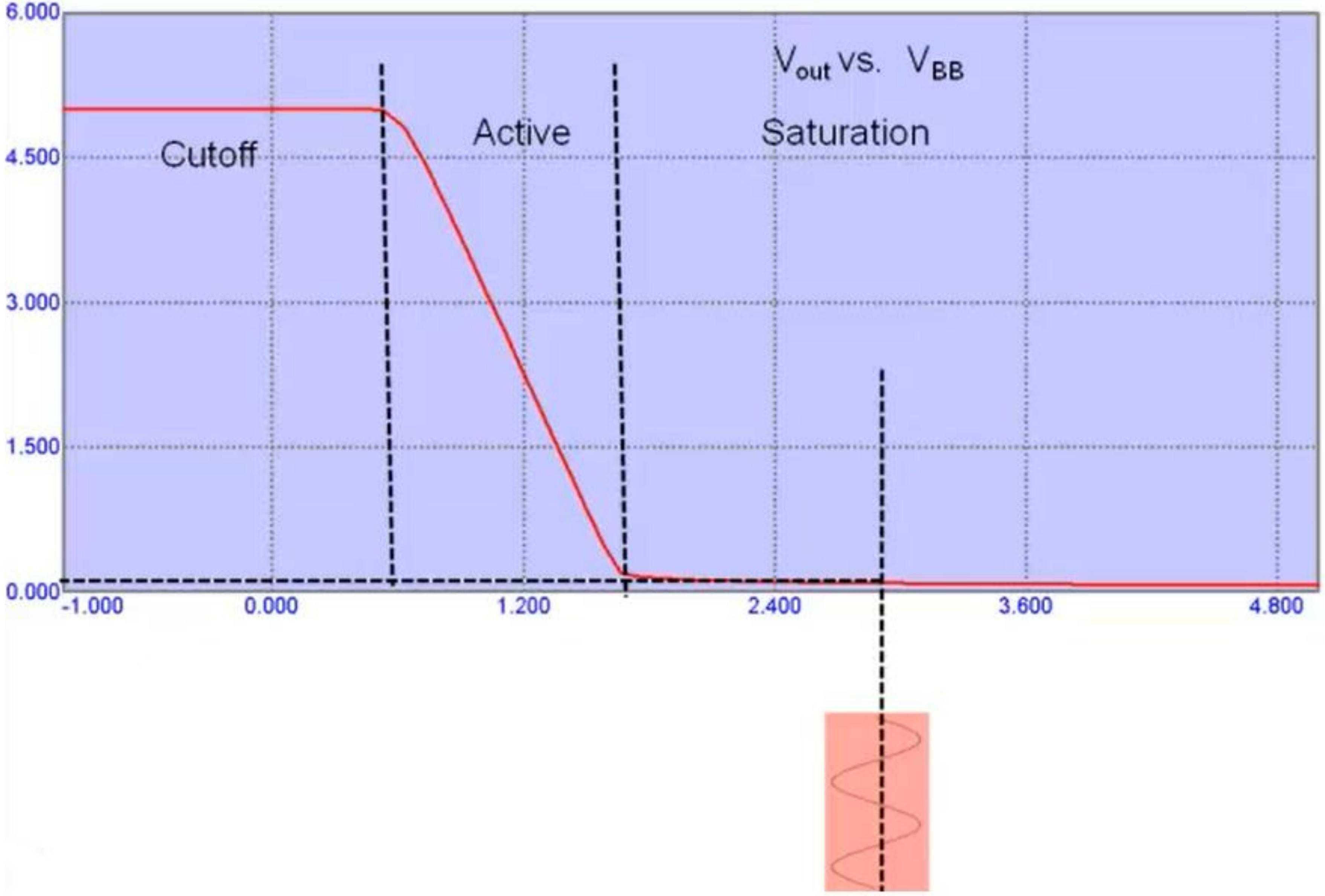

2.790
2.775
2.760
2.745
2.730
2.715
0.000m
0.400m
0.800m
1.200m
1.600m
2.000m
v(1) (V)
T (Secs)
7.500m
5.000m
2.500m
0.000m
-2.500m
-5.000m
0.000m
0.400m
0.800m
1.200m
1.600m
2.000m


RC
10K
5V
VCC
Vout
200k
Q1
RB
VBB
1.1V
Vin

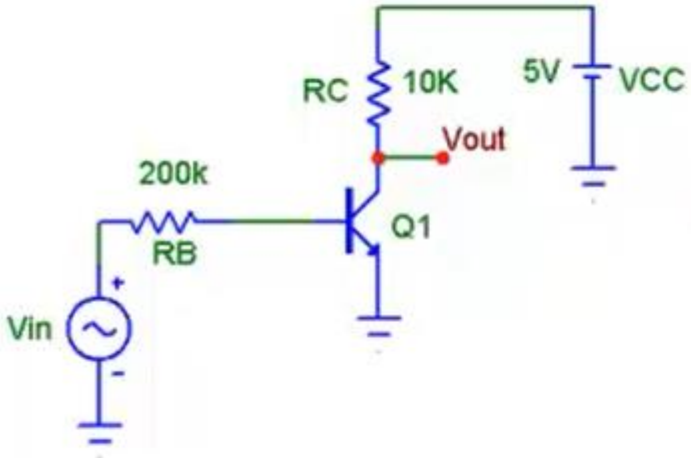

V_{out} vs. V_{in}

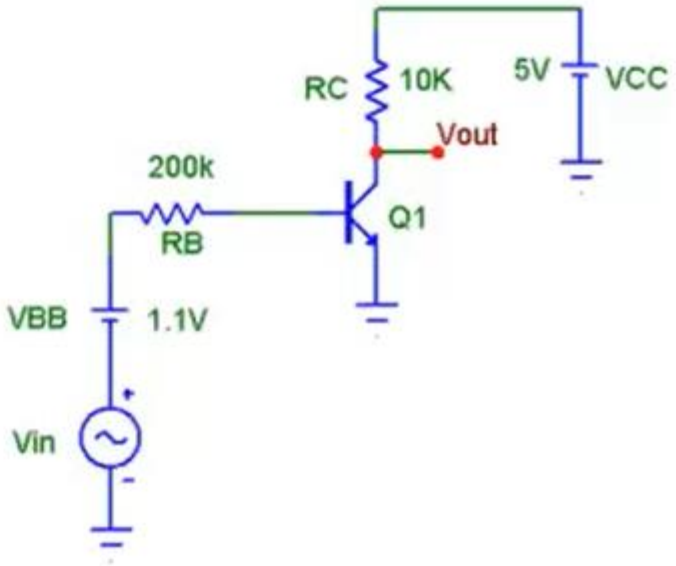

45.000m
30.000m
15.000m
0.000m
-15.000m
-30.000m
0.000m
0.400m
0.800m
1.200m
1.600m
2.000m

Transistor biased in saturation also does not result in Amplification



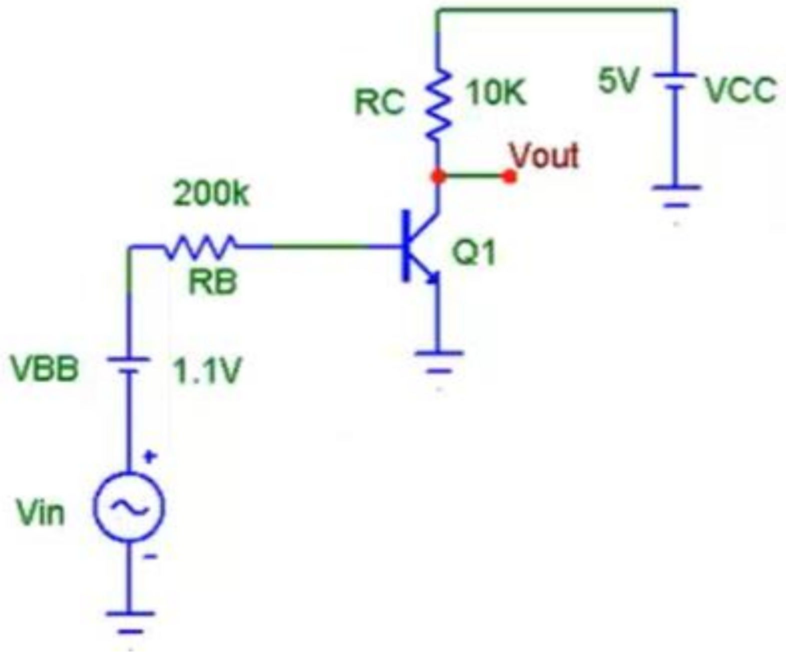
Transistor needs to be biased in Forward active mode in order to obtain voltage Amplification

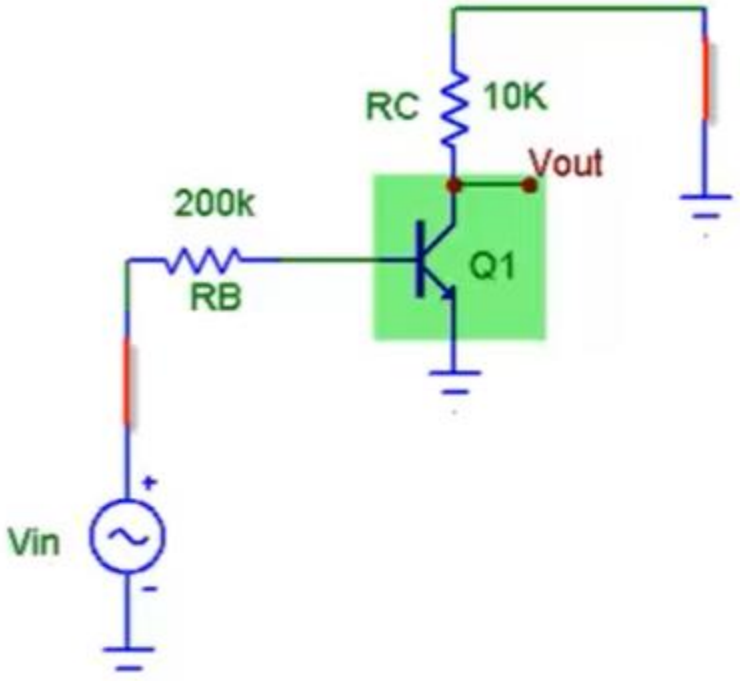




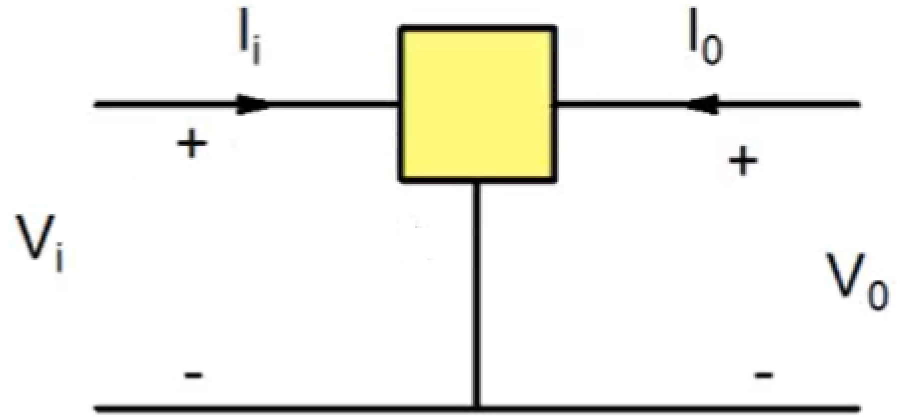
To determine amplification factor, we need to carry out small signal analysis

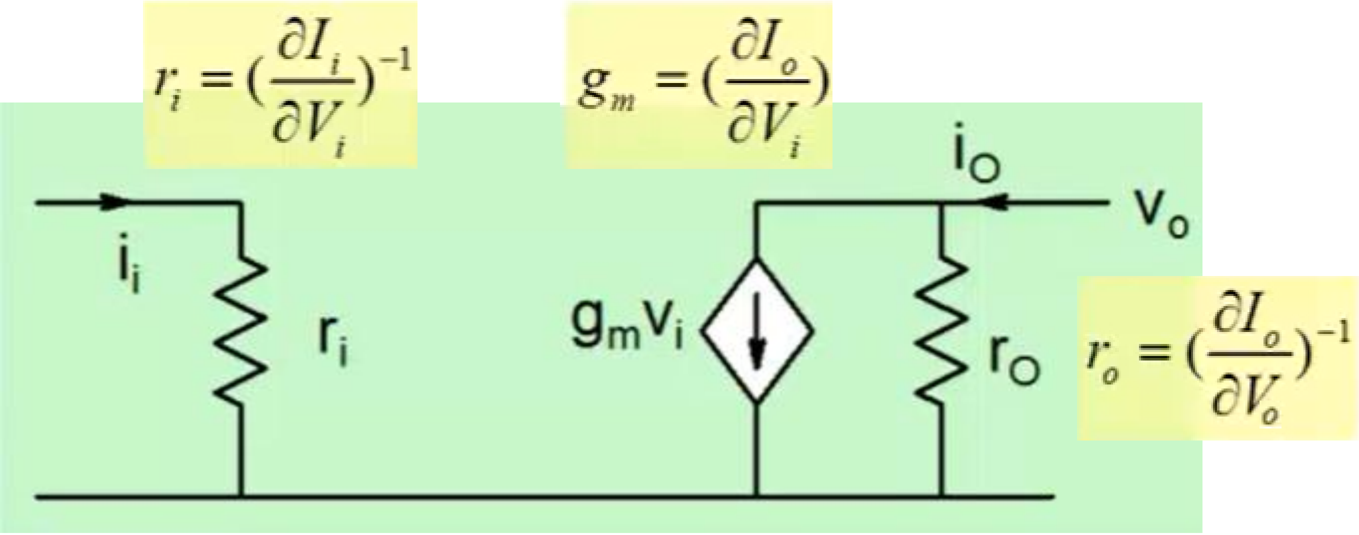
BJT : Small Signal Model



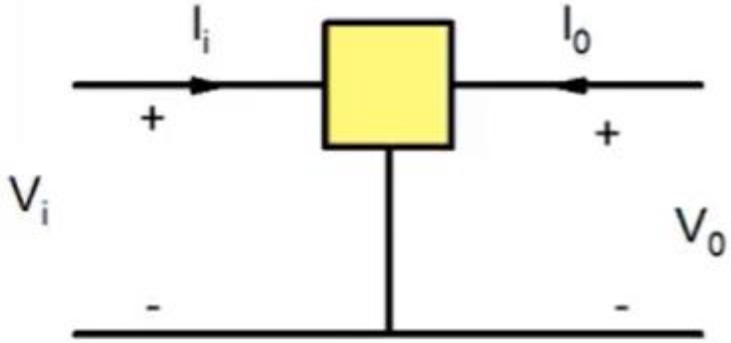


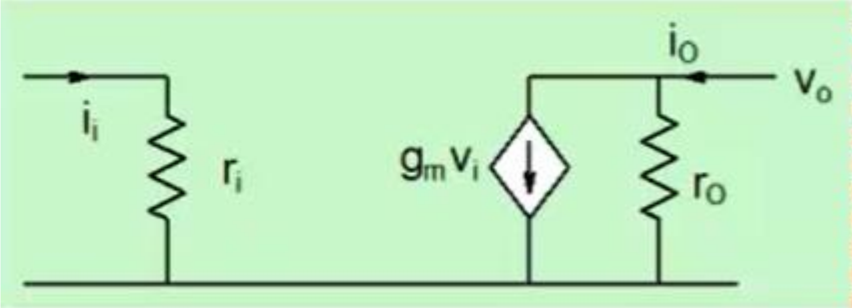
Complete small signal model (dc) for a 3-terminal unilateral device.





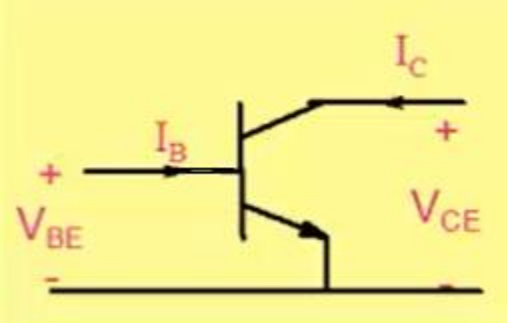
Complete small signal model (dc) for a 3-terminal unilateral device.

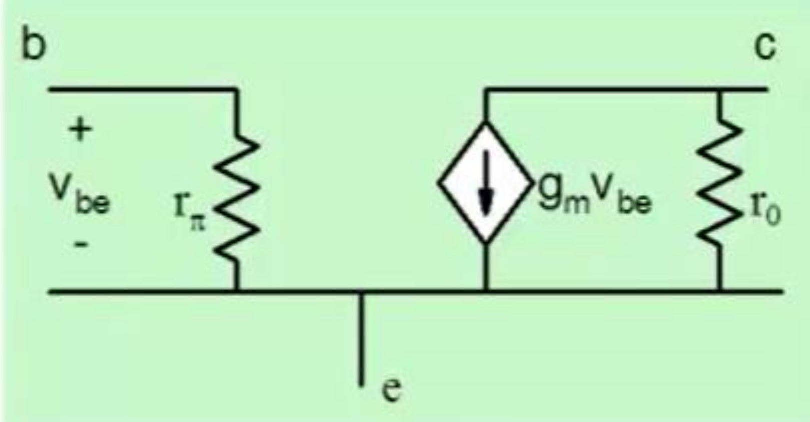




$$r_i = \left(\frac{\partial I_i}{\partial V_i}\right)^{-1} \qquad g_m = \left(\frac{\partial I_o}{\partial V_i}\right)$$

$$r_o = \left(\frac{\partial I_o}{\partial V_o}\right)^{-1}$$

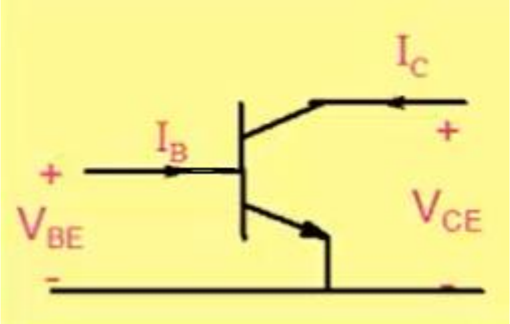


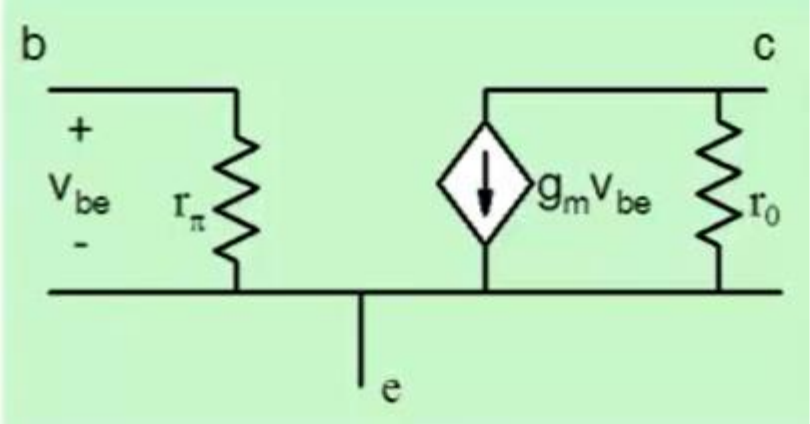


$$I_b = \frac{I_S}{\beta_F}\left(\exp\left(\frac{V_{be}}{V_T}\right) - 1\right)$$

$$r_\pi^{-1} = \left.\frac{\partial I_b}{\partial V_{be}}\right|_{I_B} \cong \frac{I_B}{V_T}$$

$$r_\pi = \frac{V_T}{I_B} = \frac{V_T}{I_C} \cdot \beta\,; \quad r_\pi = r_E \cdot \beta$$



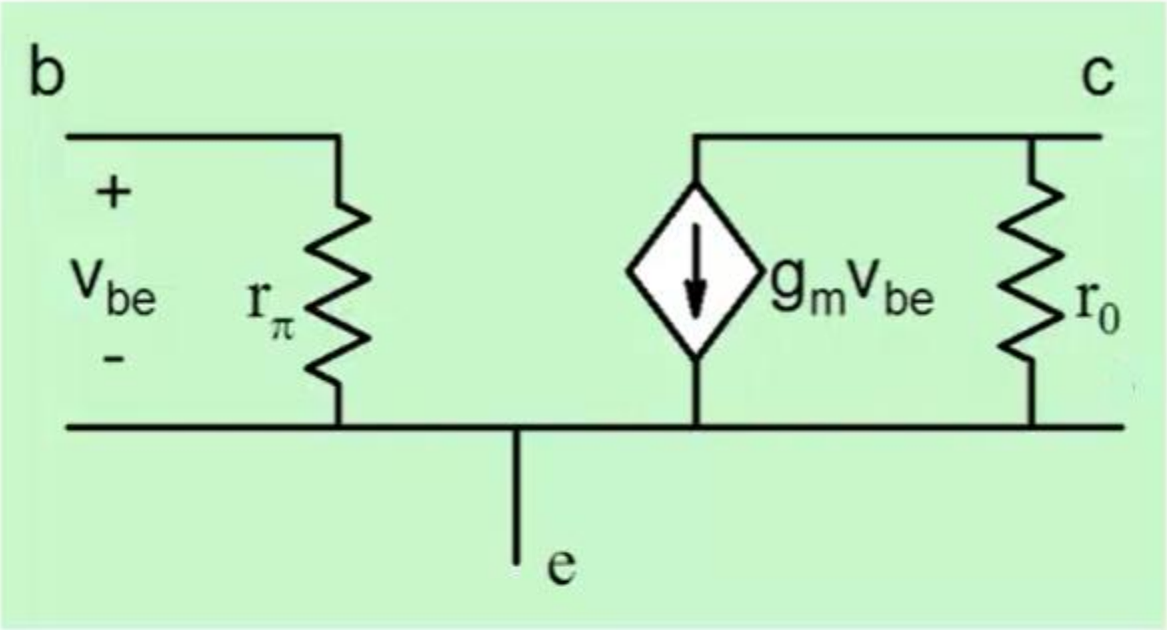


$$I_c = I_S\left(\exp\left(\frac{V_{be}}{V_T}\right) - 1\right)\left(1 + \frac{V_{ce}}{V_A}\right)$$

$$g_m = \left.\frac{\partial I_c}{\partial V_{be}}\right|_{V_{CE}} \cong \frac{I_C}{V_T}$$

$$r_0^{-1} = \left.\frac{\partial I_c}{\partial V_{ce}}\right|_{V_{BE}} = \frac{I_C}{V_{CE} + V_A} \approx \frac{I_C}{V_A}$$

Hybrid-pi Small Signal Model : low frequency



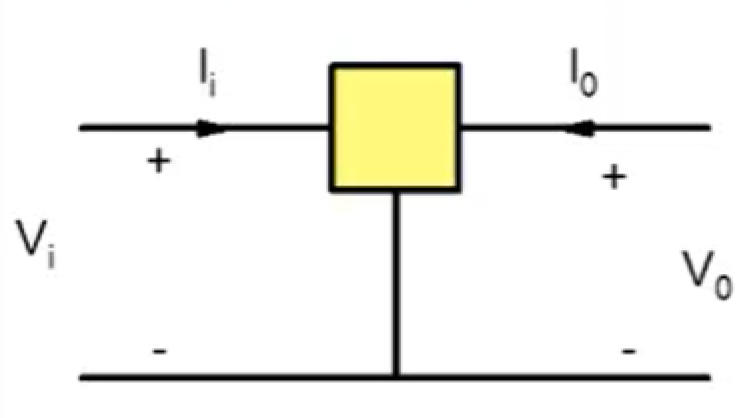
$$r_\pi = \frac{V_T}{I_B} = \frac{V_T}{I_C} \cdot \beta$$

$$g_m = \frac{I_C}{V_T} \; ; \; r_0 = \frac{V_A}{I_C}$$

$$I_b = \frac{I_S}{\beta_F}\left(\exp\left(\frac{V_{be}}{V_T}\right) - 1\right) \qquad I_c = I_S\left(\exp\left(\frac{V_{be}}{V_T}\right) - 1\right)\left(1 + \frac{V_{ce}}{V_A}\right)$$

Validity : $v_{be} \ll V_T$

Device is not strictly unilateral



$$I_i = f(V_i, V_o)$$

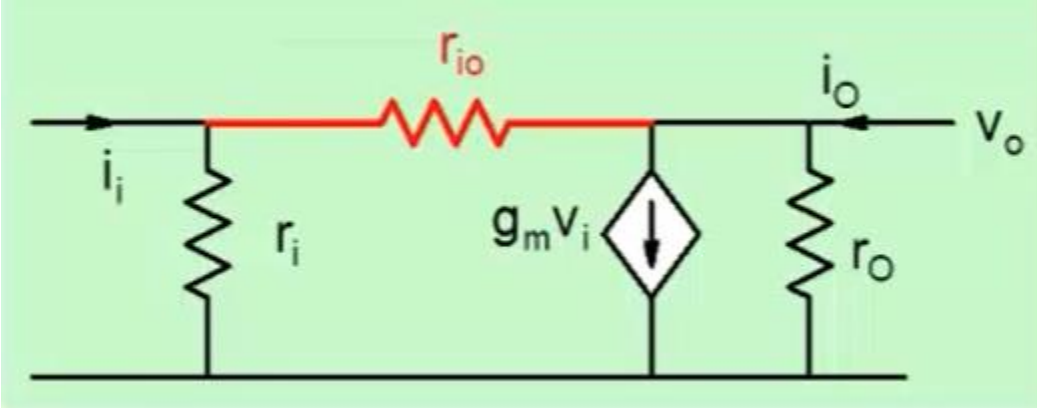
$$\Delta I_i = \left.\frac{\partial f}{\partial V_i}\right| \times \Delta V_i + \left.\frac{\partial f}{\partial V_o}\right| \times \Delta V_o$$

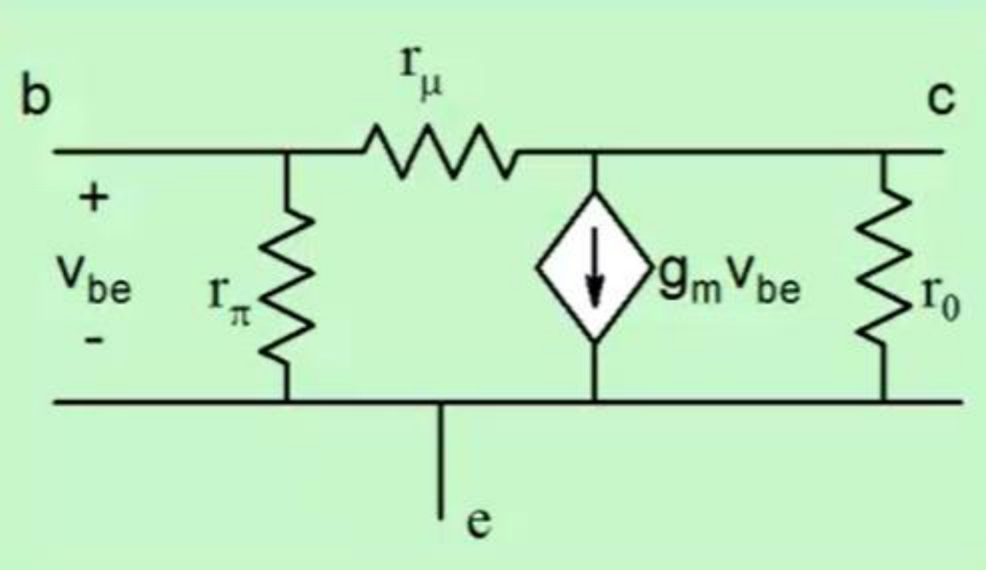
-ve

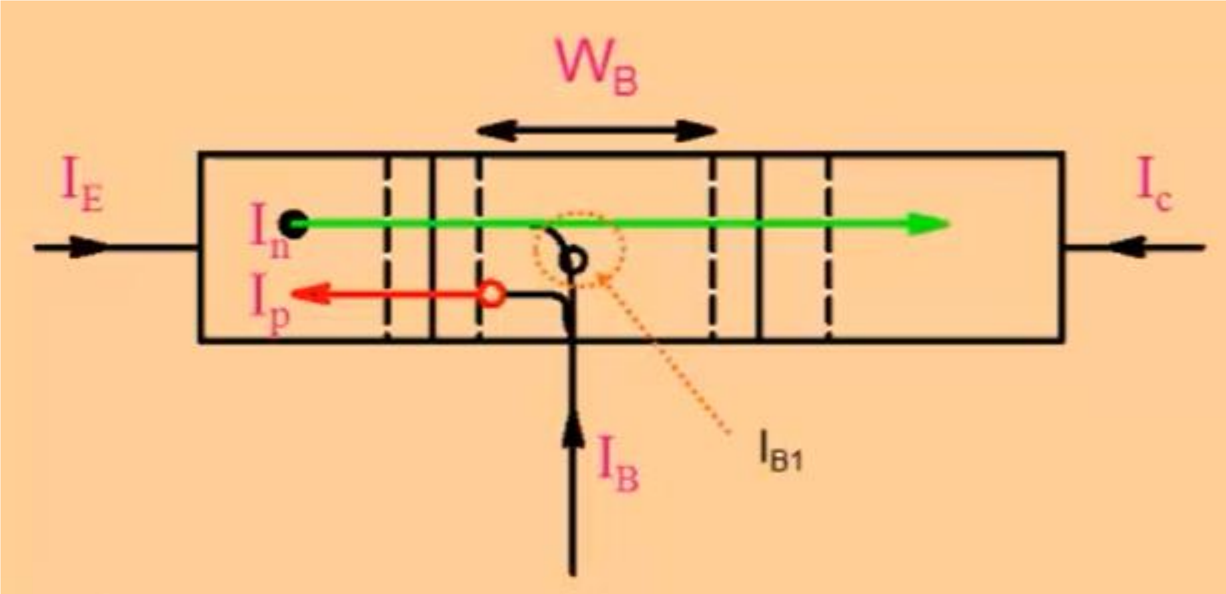
$$i_i = \frac{v_i}{r_i} - \frac{v_o}{r_{io}}$$

$$i_i = \left(\frac{v_i}{r_i} - \frac{v_i}{r_{io}}\right) + \frac{v_i - v_o}{r_{io}} \simeq \frac{v_i}{r_i} + \frac{v_i - v_o}{r_{io}}$$

$$r_{io} \gg r_i$$







$I_B = I_P + I_{B1}$

$I_{B1} \alpha W_B$

$I_{B1} = f_1(V_{CB})$

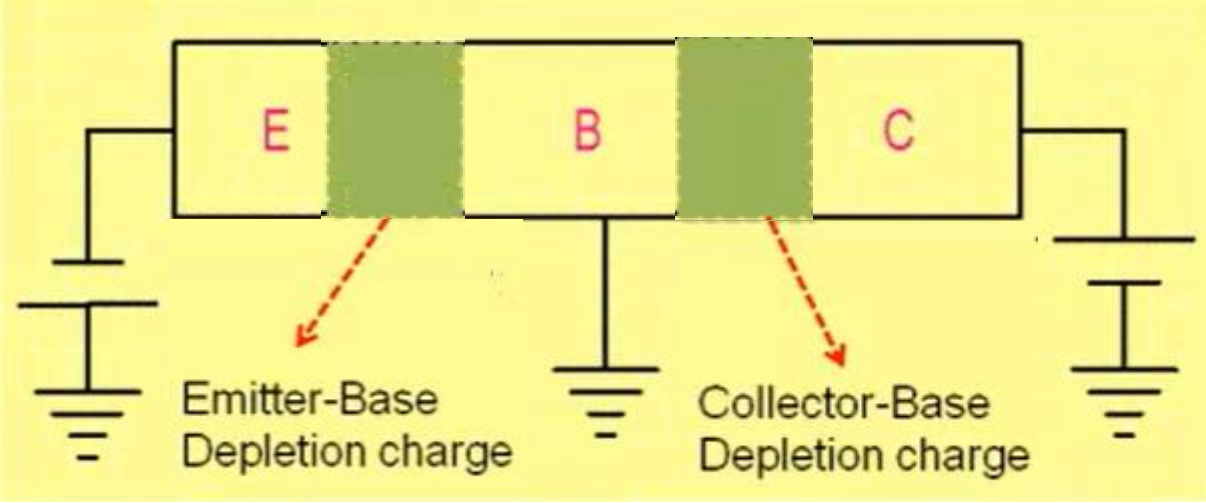
Capacitances and High Frequency Model

Capacitances in a BJT

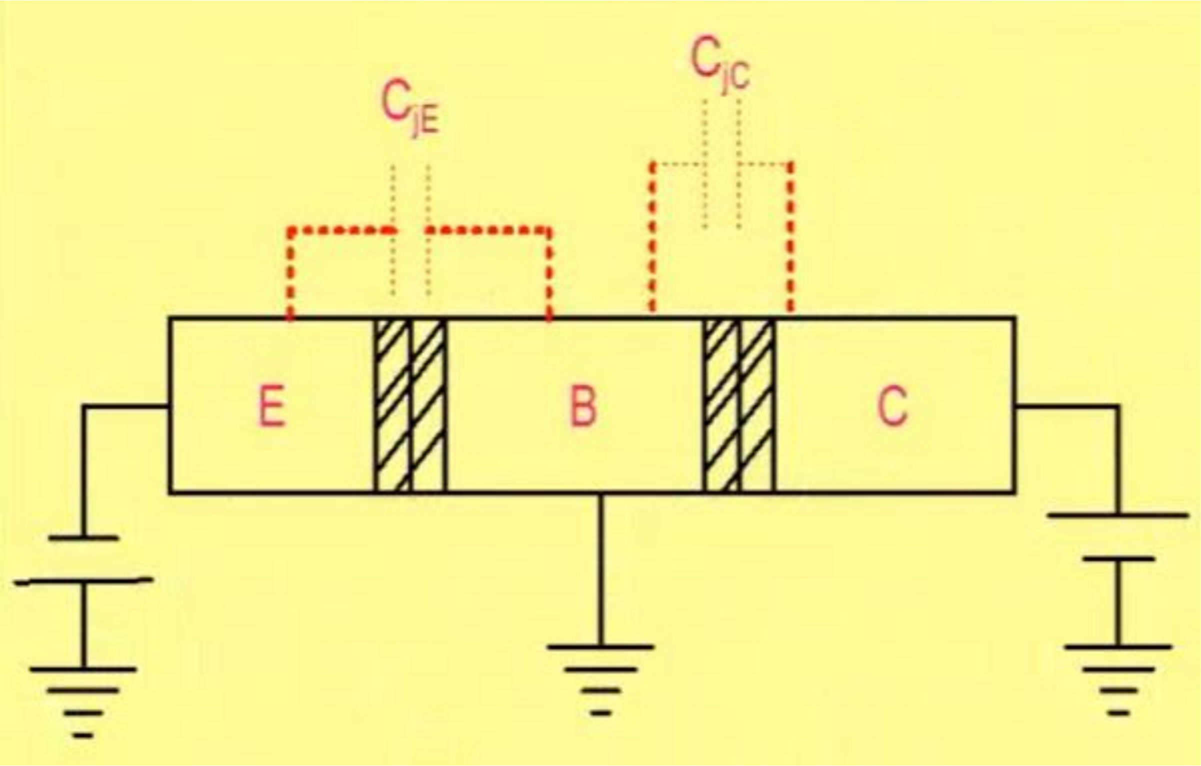
Anytime we have a charge which changes with voltage, we have a capacitance

$$C = \frac{\partial Q}{\partial V}$$

There are two kinds of charges:
1. Depletion charge
2. Diffusion charge



Change in emitter-base depletion charge with base-emitter voltage gives rise to base-emitter junction capacitance. Similarly, change in collector-base depletion charge with base-collector voltage gives rise to base-collector junction capacitance



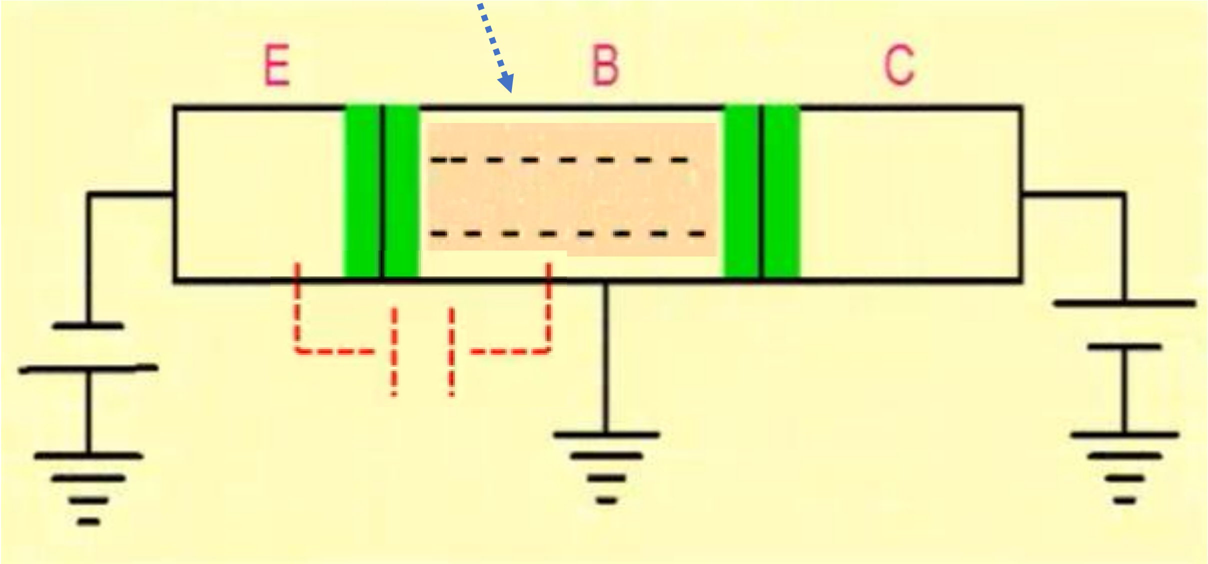
$$C_{je} = \frac{C_{jeo}}{(1 - \frac{V_{BE}}{V_{bi}})^m}$$

$$C_{jc} = \frac{C_{jco}}{(1 - \frac{V_{BC}}{V_{bi}})^m}$$

Diffusion Charge and Capacitance

When base-emitter junction is forward biased, electrons are injected into base. These excess electrons constitute diffusion charge Q_D

$$C_d = \frac{\partial Q_d}{\partial V_{be}}$$

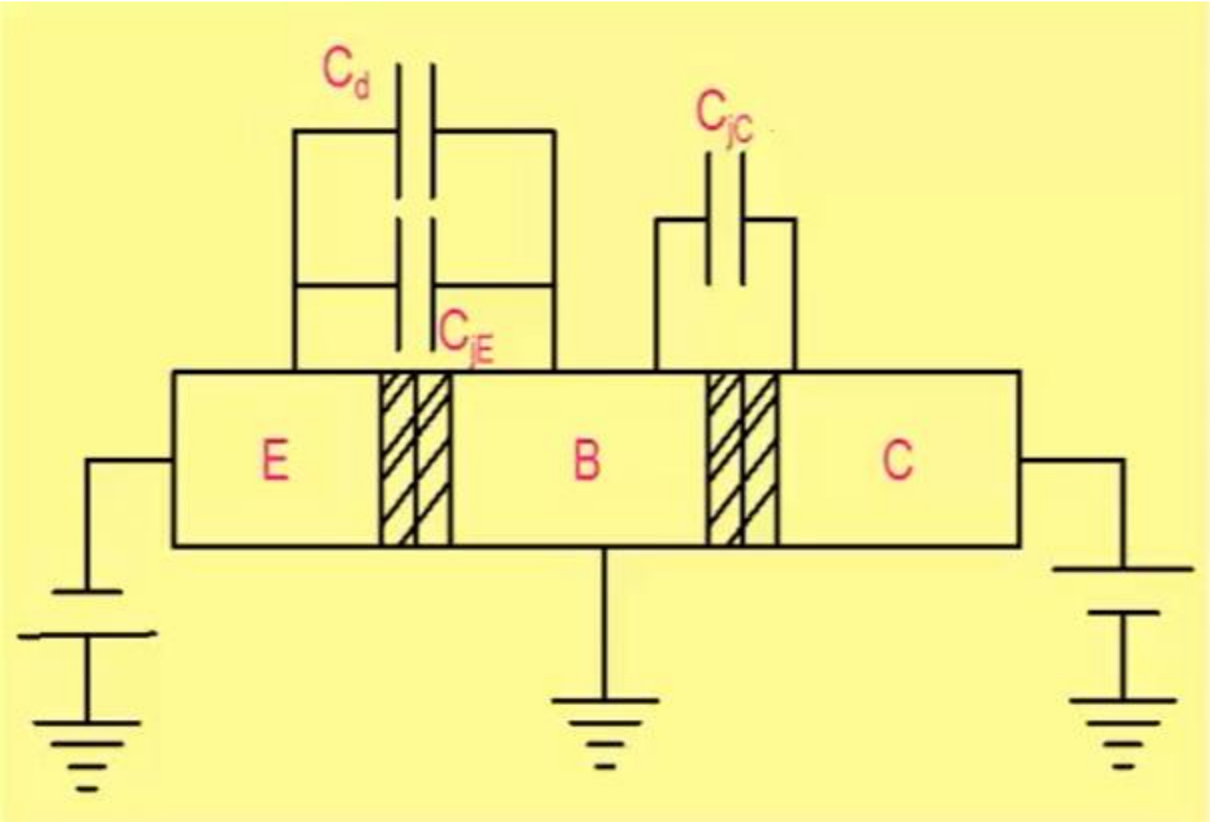


$$C_{diff} = \frac{I_C}{V_T} \times \tau_F$$
$$= g_m \times \tau_F$$

$$\tau_F = K \times \frac{W_B^2}{\mu} + \ldots$$

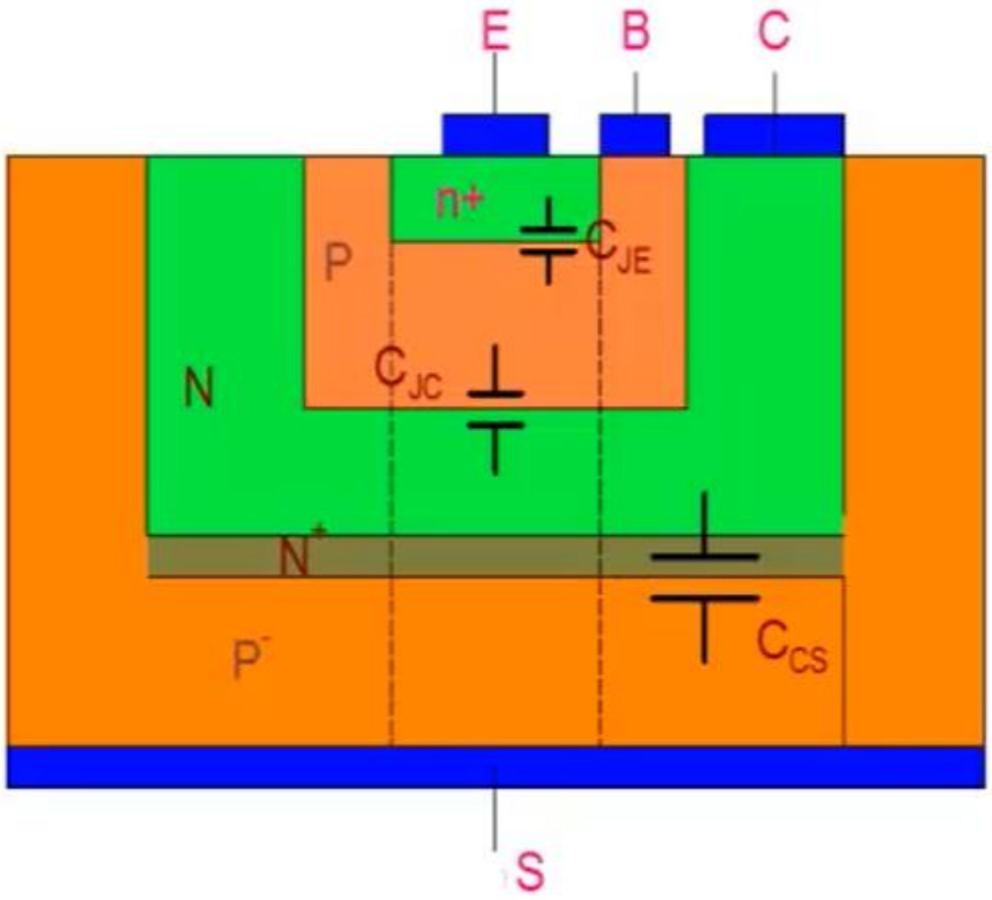
In Forward active mode, collector-base junction is reverse biased so no carriers are injected and hence there is no collector-base diffusion capacitance .

Capacitances in a BJT



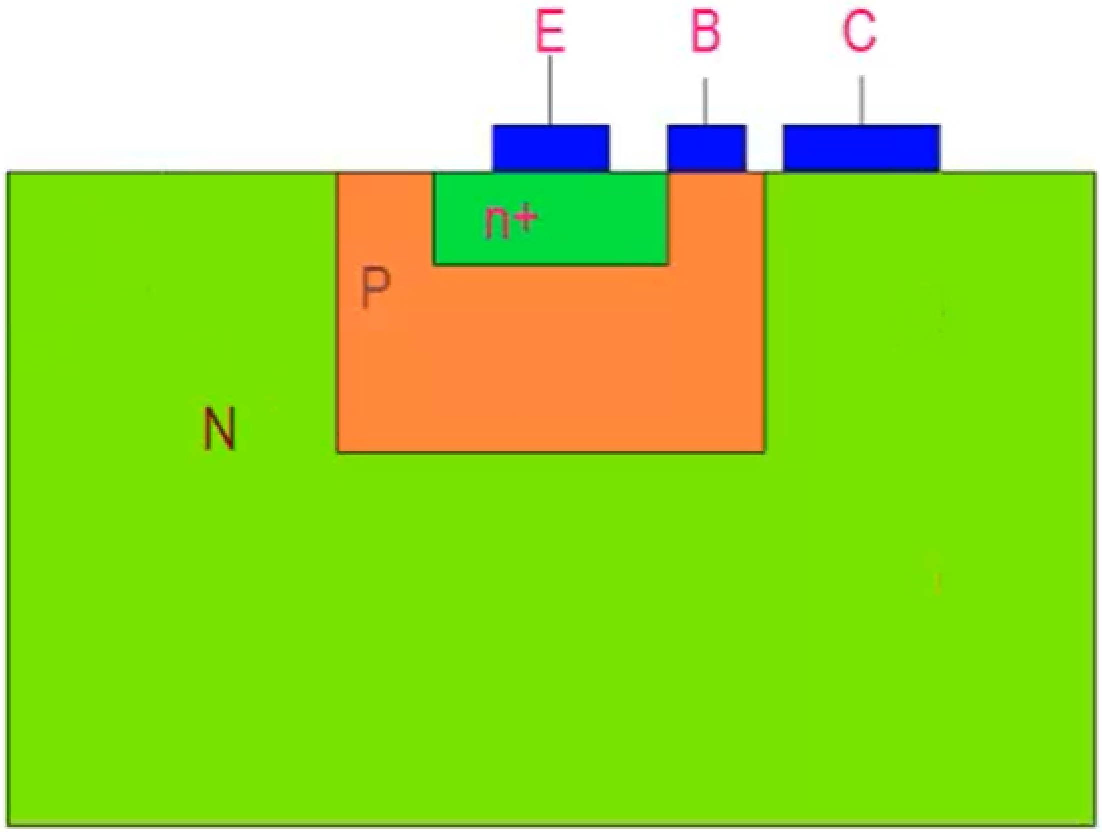
There is one more capacitance which is not observable in this one dimensional view of the transistor

Collector Substrate Capacitance

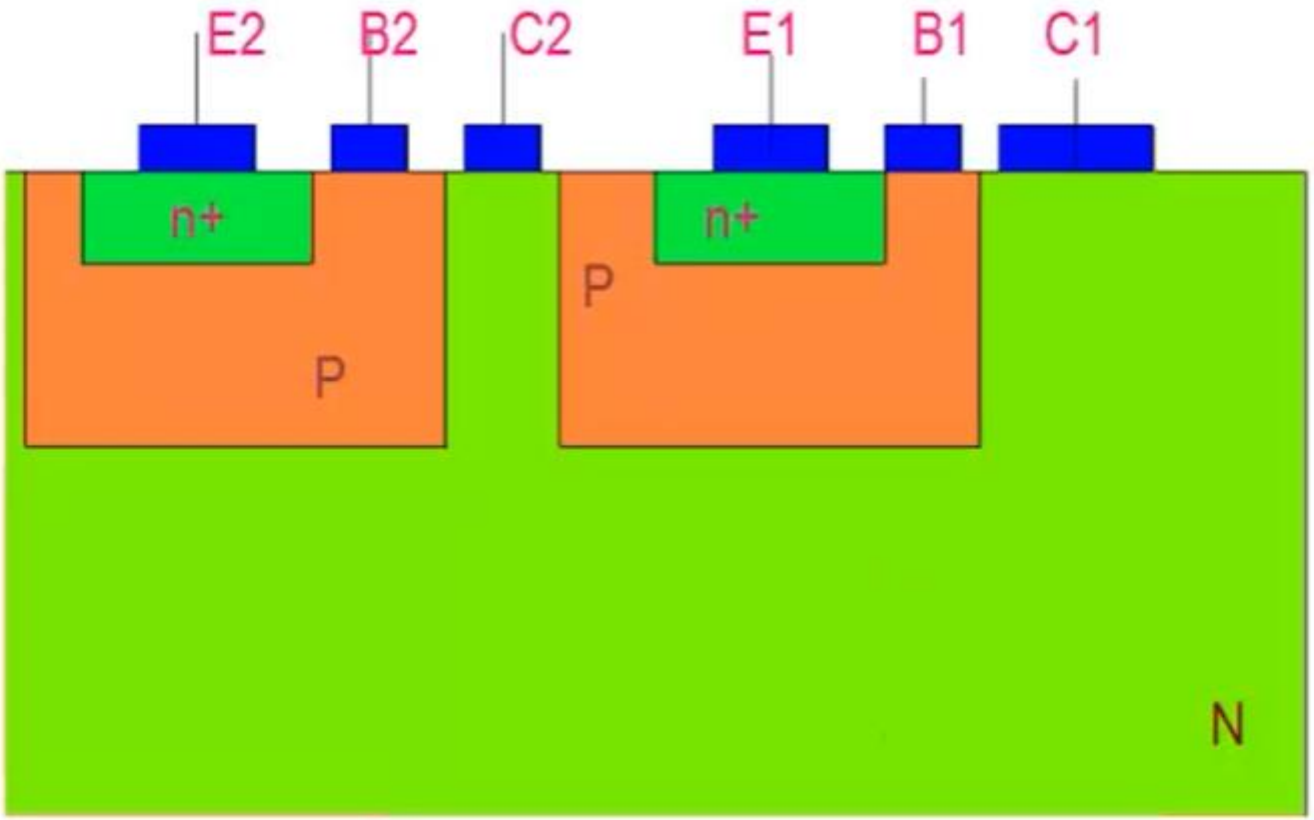


Why do we use a P substrate and not make a transistor on N-Silicon ?

Transistor on an N-substrate that serves as a Collector

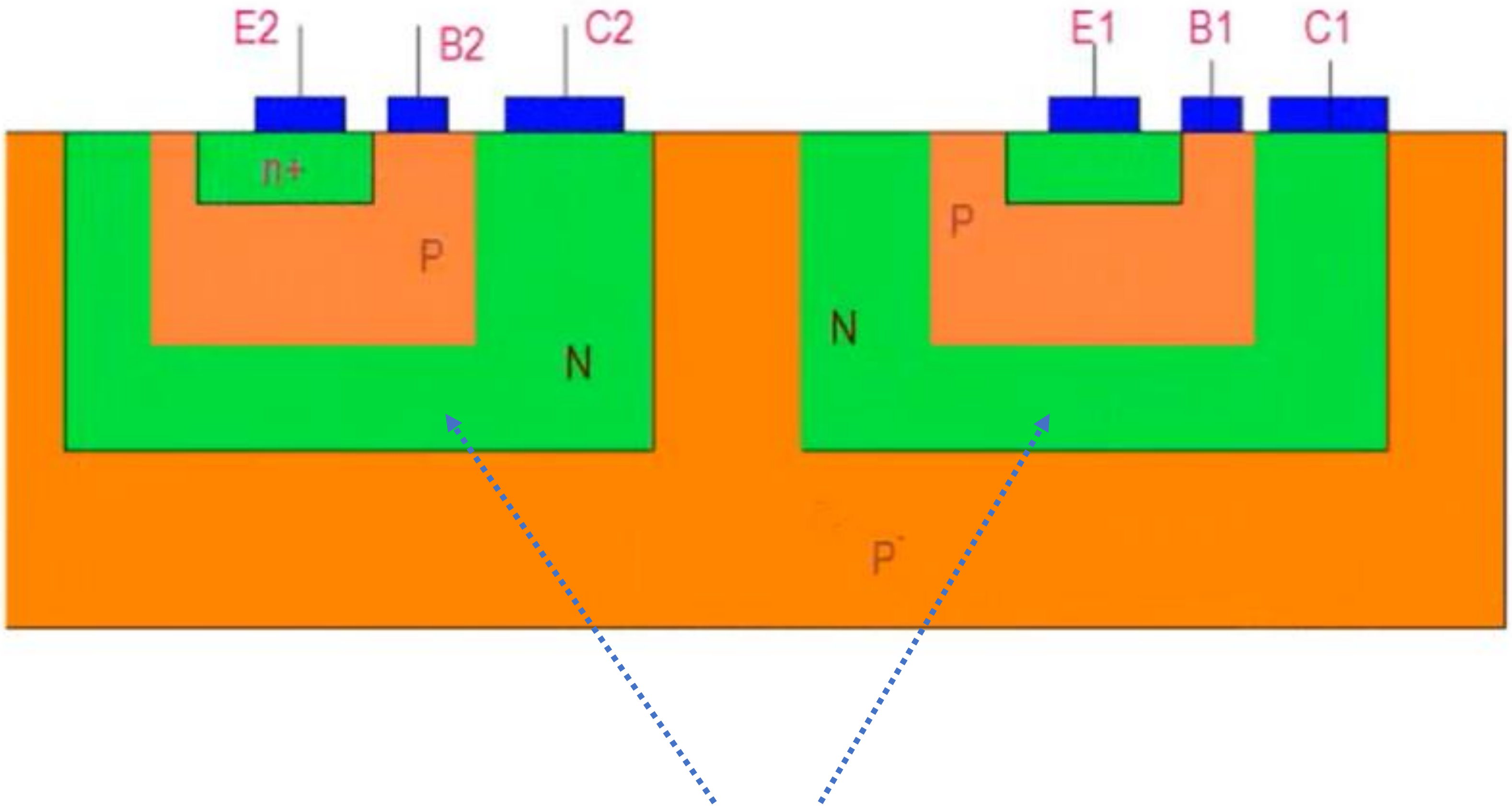


The problem is that we have to make not just one but several transistors on the same silicon substrate



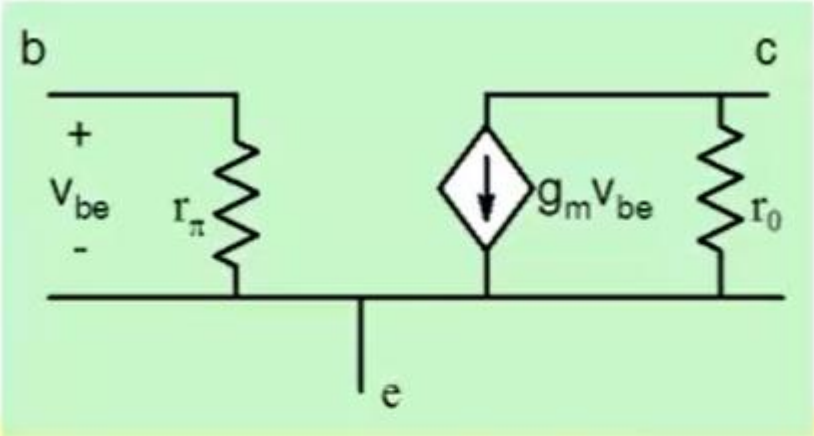
The two collectors are shorted together !

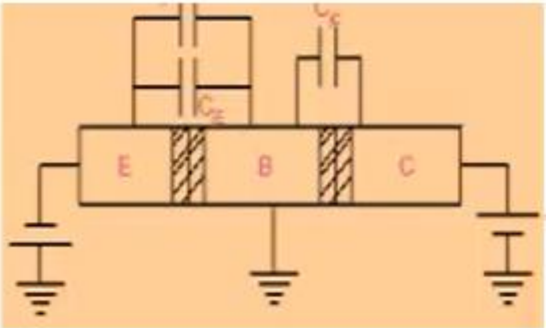
With a P-substrate, it is easy to isolate the transistors

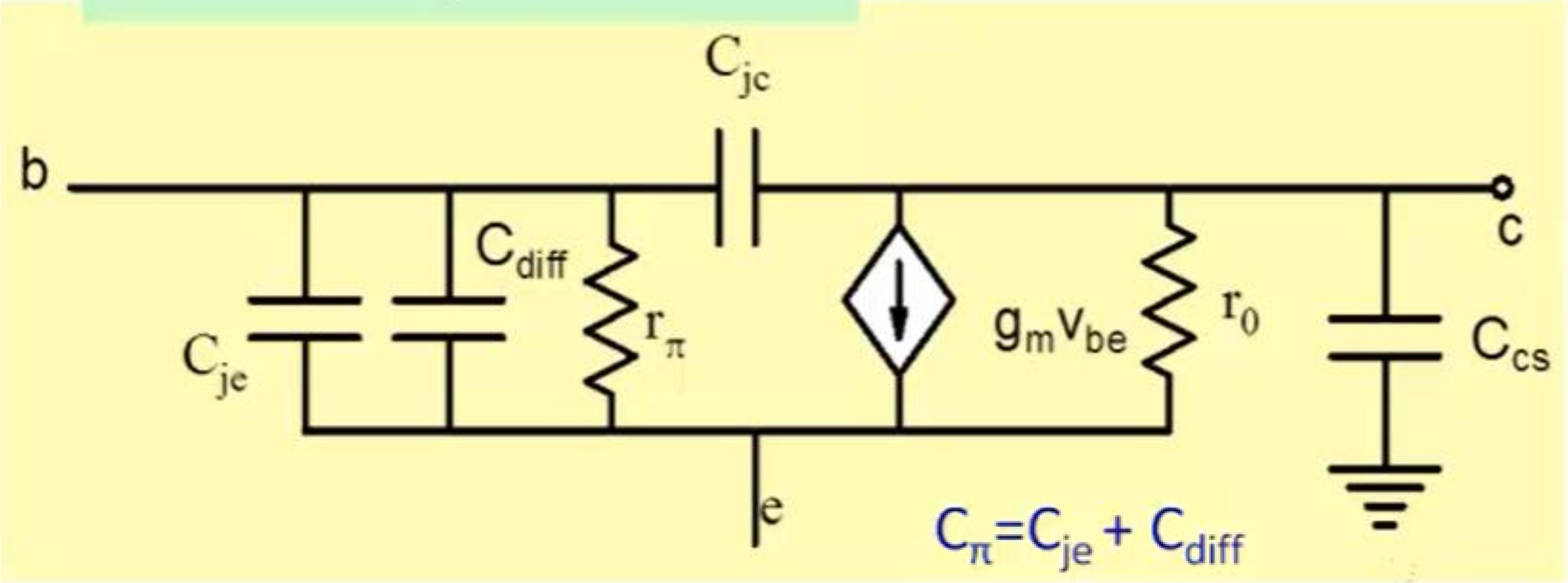


Reversed Biased PN junction maintains isolation

High Frequency Hybrid-pi Model

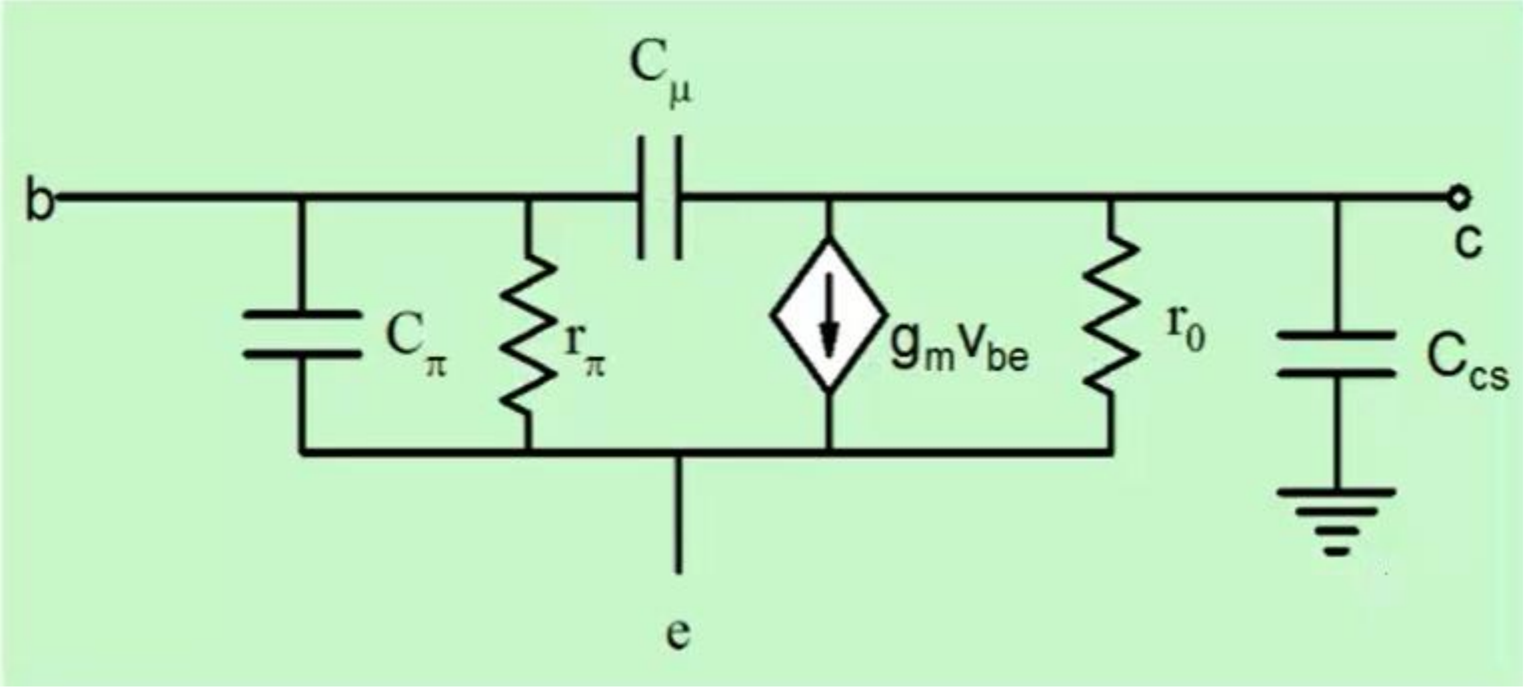






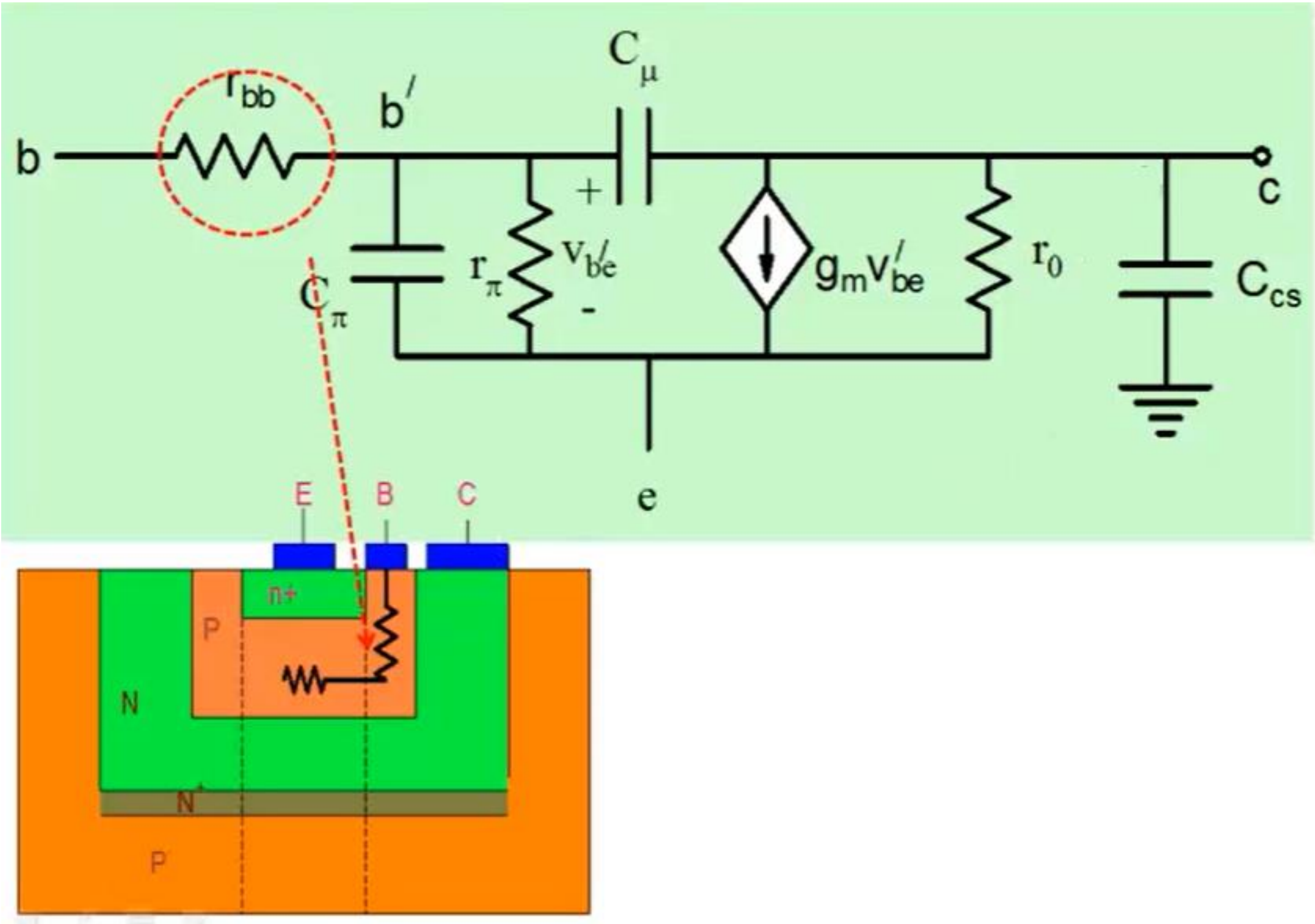
$C_\pi = C_{je} + C_{diff}$

$C_\mu = C_{jc}$

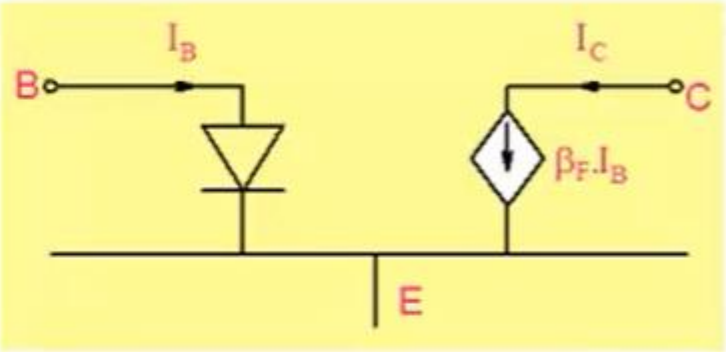


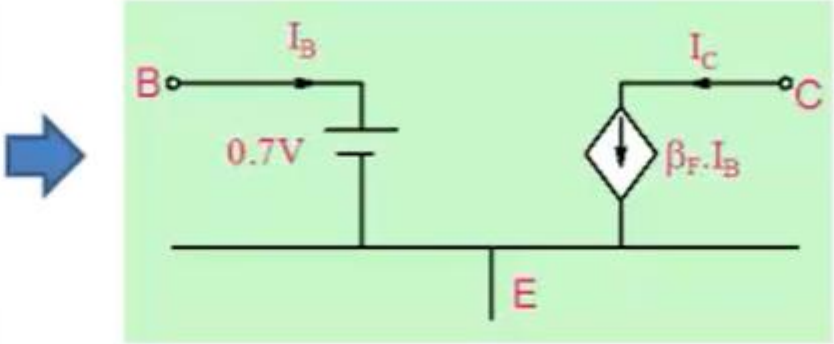
Cμ
b
c
Cπ
rπ
gmvbe
r0
Ccs
e

High Frequency Hybrid-pi Model



Model of an NPN BJT in forward active mode

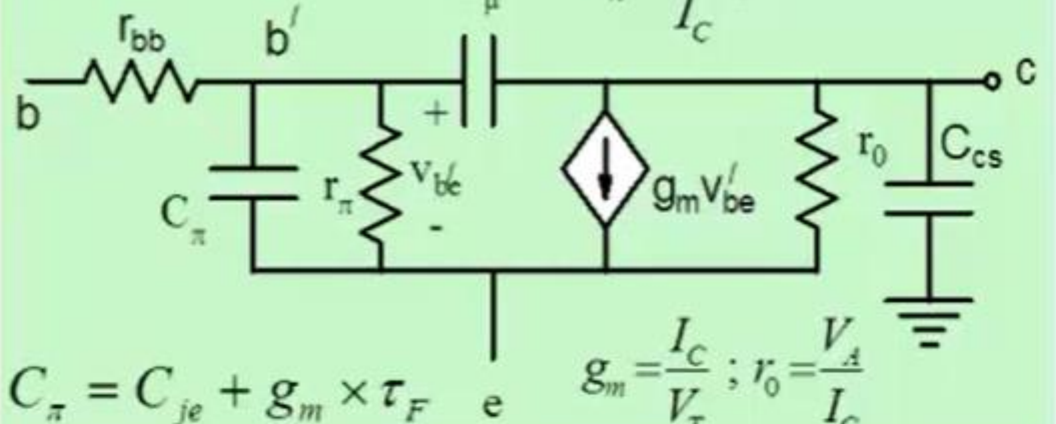




$$I_C = I_S\left(\exp(\frac{V_{BE}}{V_T})-1\right)\left(1+\frac{V_{CE}}{V_A}\right)$$

$$I_B = \frac{I_S\left(\exp(\frac{V_{BE}}{V_T})-1\right)}{\beta_F}$$

$$I_C = \beta_F\, I_B\left(1+\frac{V_{CE}}{V_A}\right)$$

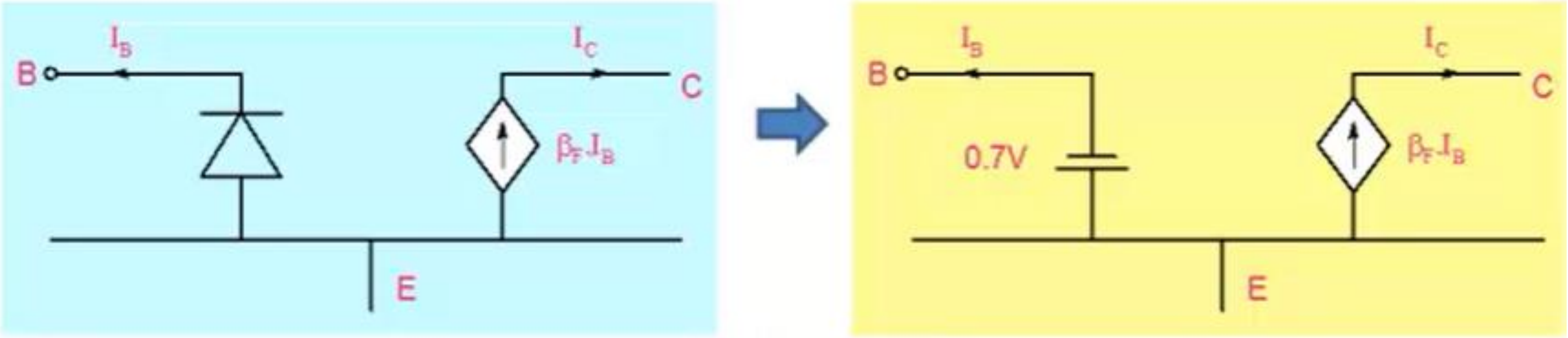


$$r_\pi = \frac{V_T}{I_C}\cdot\beta$$

$$C_\pi = C_{je} + g_m \times \tau_F$$

$$g_m = \frac{I_C}{V_T}\ ;\ r_0 = \frac{V_A}{I_C}$$

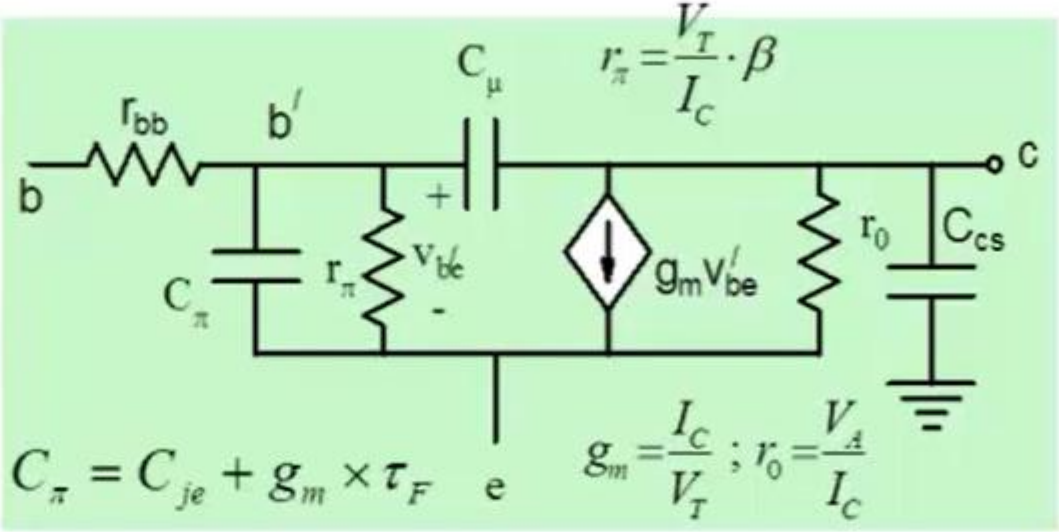
Model of an PNP BJT in forward active mode



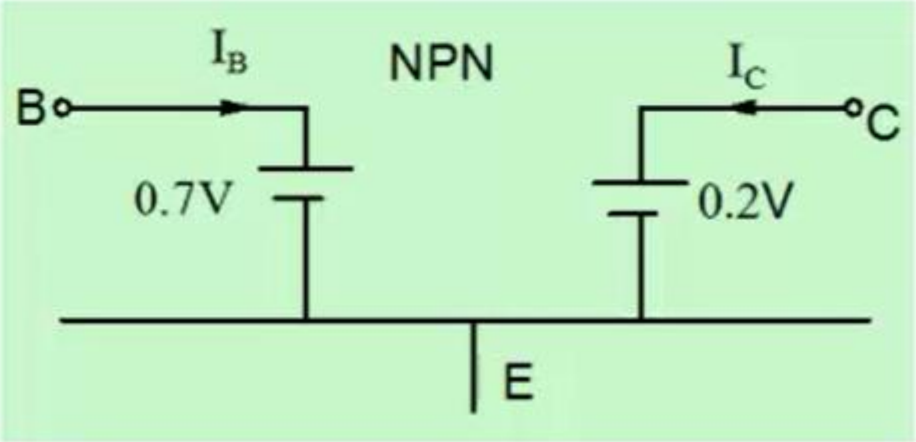
$$I_C = I_S \left(\exp(\frac{V_{EB}}{V_T}) - 1 \right) \left(1 + \frac{V_{EC}}{V_A} \right)$$

$$I_B = \frac{I_S \left(\exp(\frac{V_{EB}}{V_T}) - 1 \right)}{\beta_F}$$

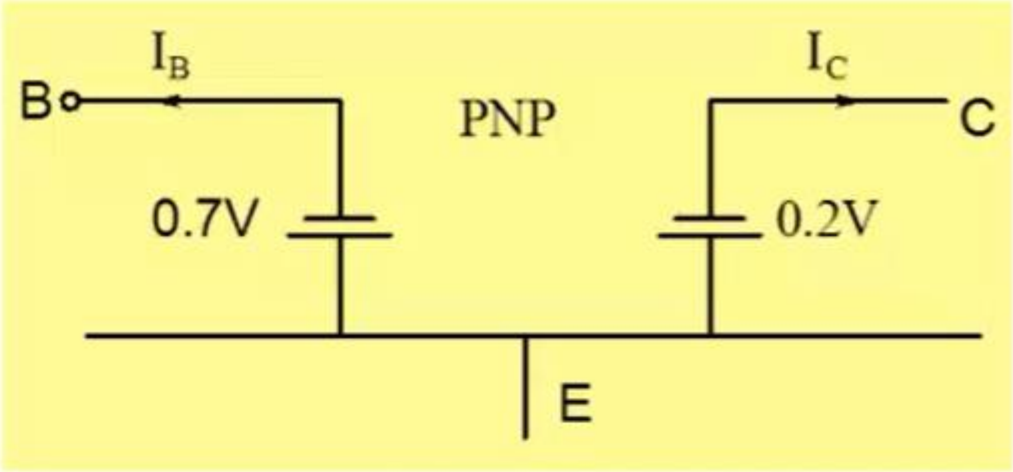
$$I_C = \beta_F \, I_B \left(1 + \frac{V_{EC}}{V_A} \right)$$



Model of a BJT in Saturation mode



$$I_C \neq \beta_F \, I_B$$

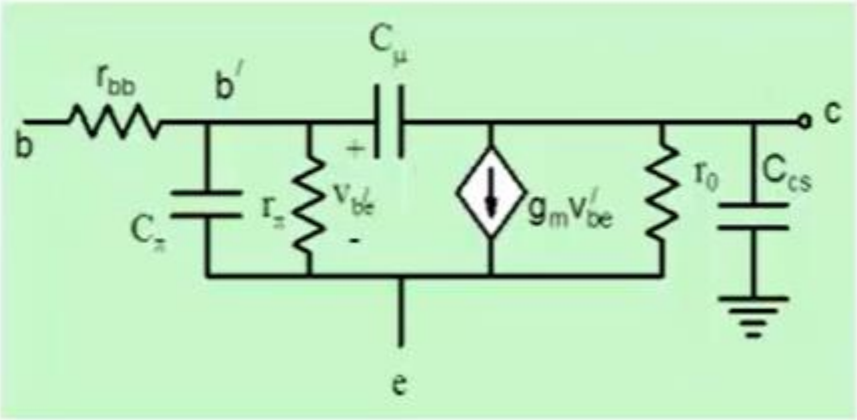


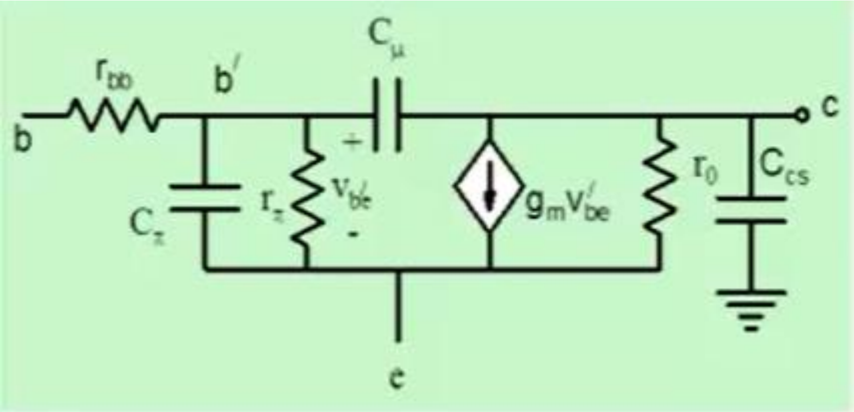
Example:

$$I_S = 2.03\times10^{-15}A; \beta_F = 100; \beta_R = 1; V_A = 100; r_{bb} = 200\Omega; V_T = 26mV$$
$$C_{jeo} = 1pF; C_{jco} = 0.5pF; C_{jso} = 3pF; m = 0.5; V_{bi} = 0.85; \tau_F = 1ns$$

Dc bias condition:
$$V_{BE} = 0.7V; V_{BC} = -3V; V_{CS} = 2V$$
$$I_C = 1mA; I_B = 10\mu A$$

Small Signal Model parameters evaluated at the bias point:





$$g_m = \frac{I_C}{V_T} = 38m\mho;$$

$$r_\pi = \frac{V_T}{I_C} \times \beta = 2.6k\Omega;$$

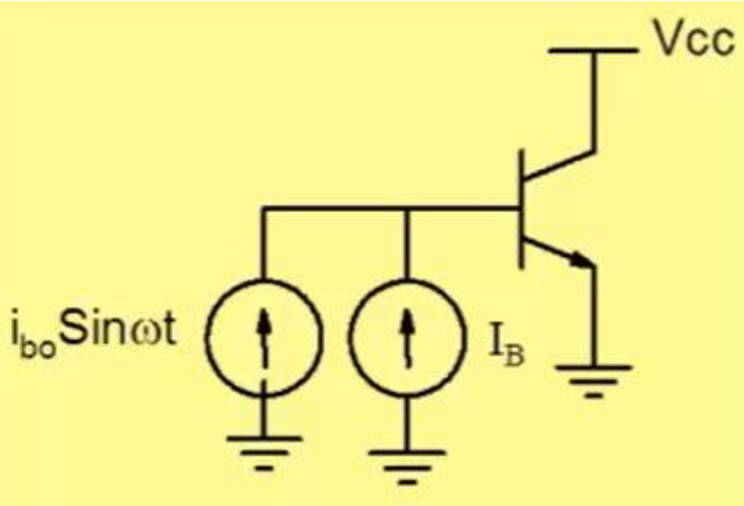
$$r_0 = \frac{V_A}{I_C} = 100k\Omega$$

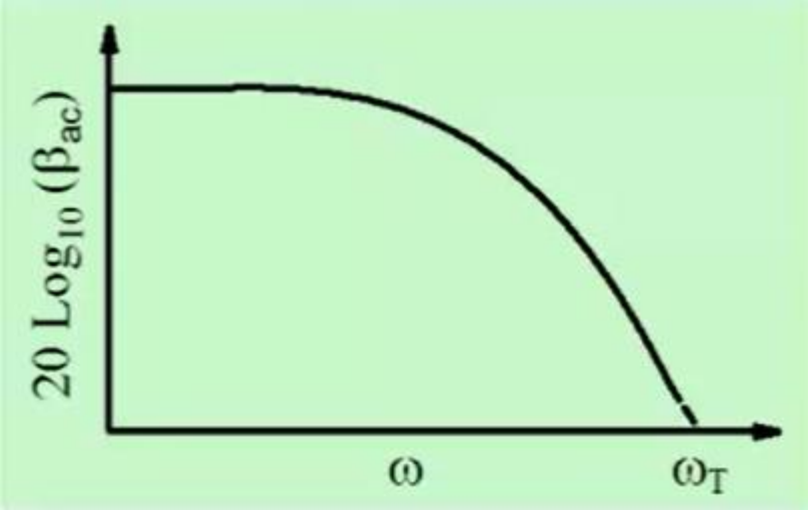
$$C_\pi = g_m \tau_F + C_{je} = g_m \tau_F + \frac{C_{jeo}}{(1 - \frac{V_{BE}}{V_{bi}})^m} = 38.5pF$$

$$C_\mu = C_{jc} = \frac{C_{jco}}{(1 - \frac{V_{BC}}{V_{bi}})^m} = 0.23pF$$

$$C_{js} = \frac{C_{jso}}{(1 + \frac{V_{CS}}{V_{bi}})^m} = 1.6pF$$

Unity Gain Frequency: a measure of speed of transistor





$$\beta_{ac}(\omega) = \frac{i_c}{i_b}$$

$$\beta_{ac}(\omega) = \frac{i_c}{i_b} = \frac{\beta_{ac}(0)}{1 + j\beta_{ac}(0)\frac{\omega}{\omega_T}}$$

Transistor is useful only for frequencies less than unity gain frequency

Importance of Amplifier Characteristics

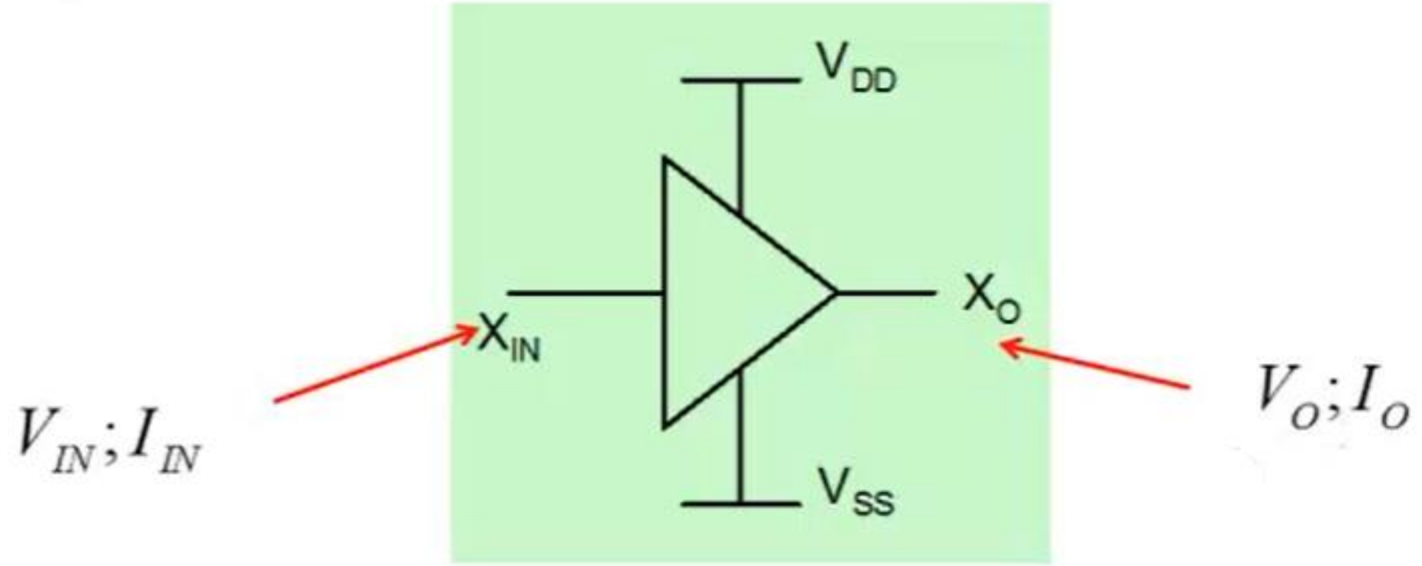
3Qs

- Can an amplifier with a voltage gain rating of 100 provide less gain than an amplifier with a rating of 10?

- Why does an amplifiers performance degrade at higher output power ?

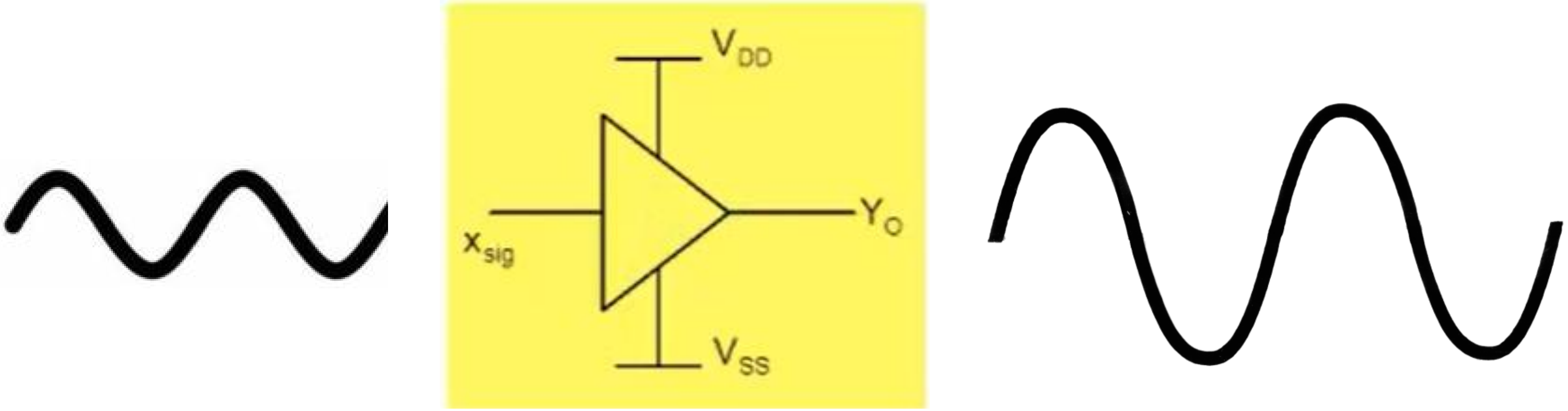
- How small a signal can an amplifier amplify?

Depending on the input and output, there can be four broad classes of amplifiers



INPUT	OUTPUT	Amplifier
V	V	Voltage
V	I	Transconductance
I	I	Current
I	V	Transresistance

Ideal Voltage Amplifier

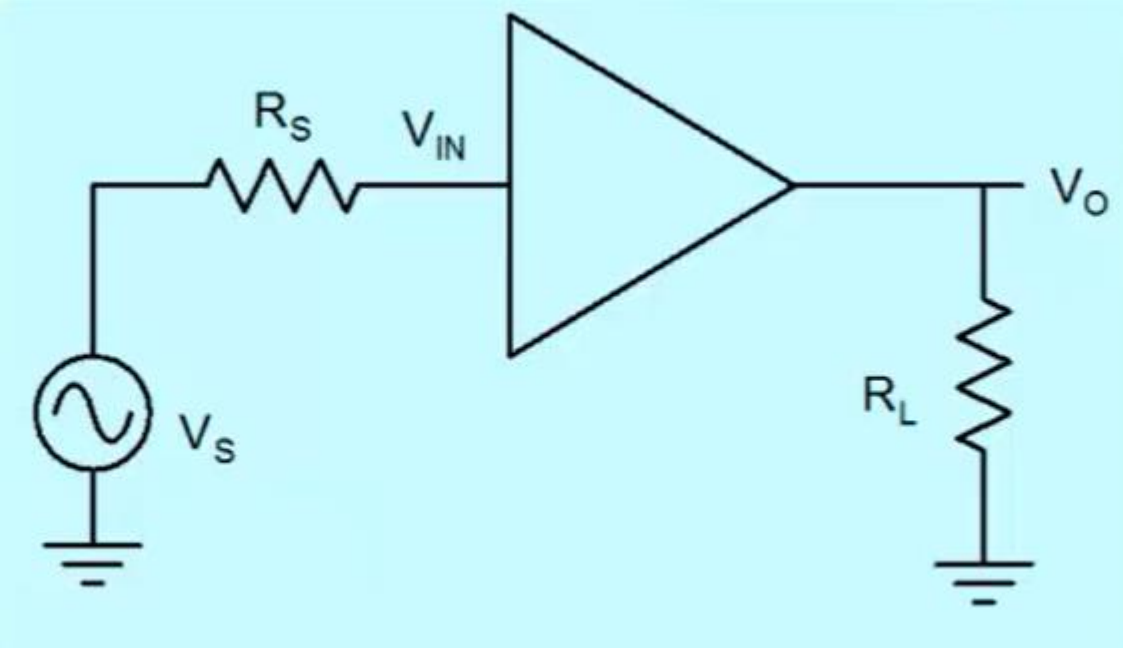


$$V_O = A_v \times V_{IN}$$

A_v is a constant

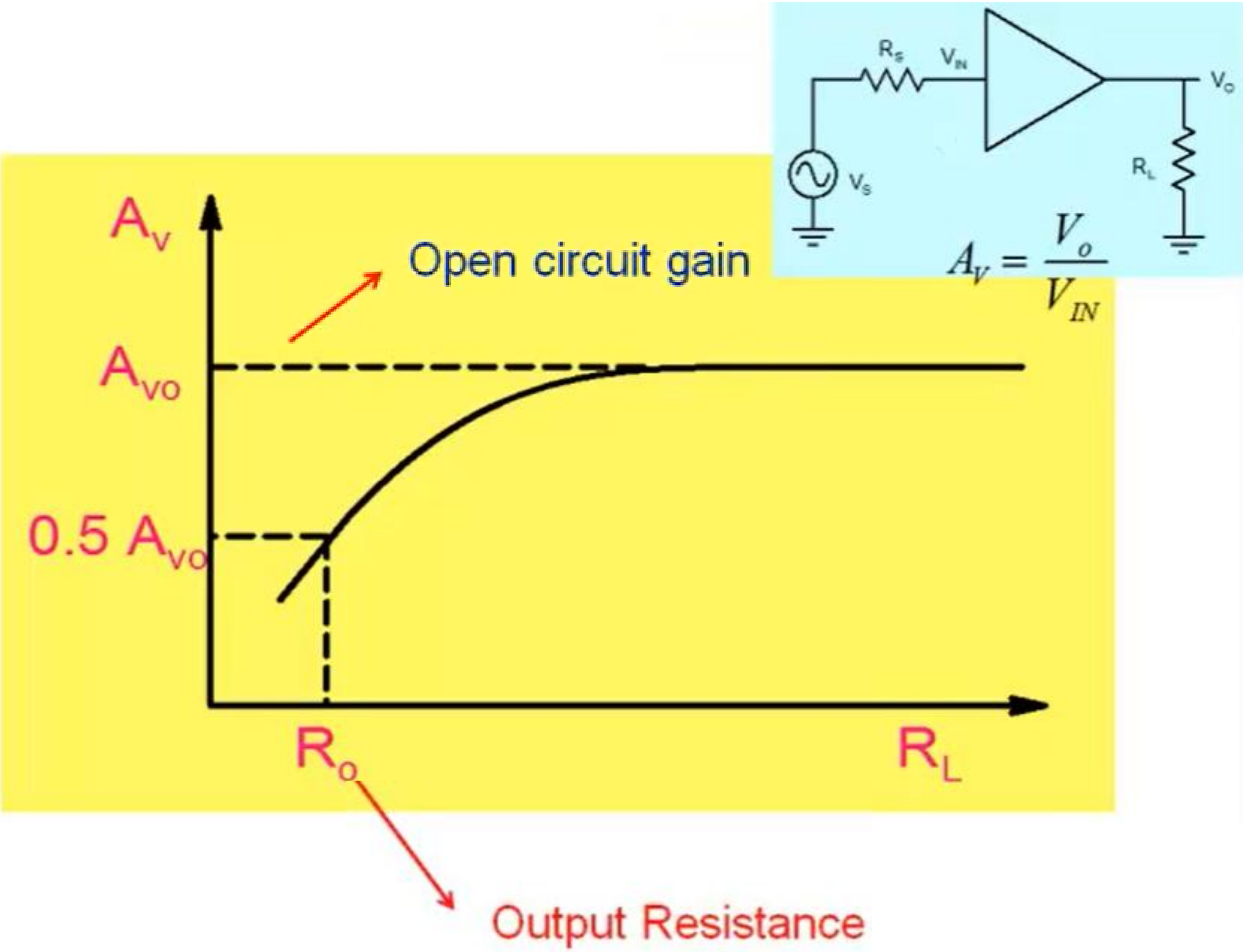
Practical Amplifier

$$V_O = A_v \times V_{IN}$$

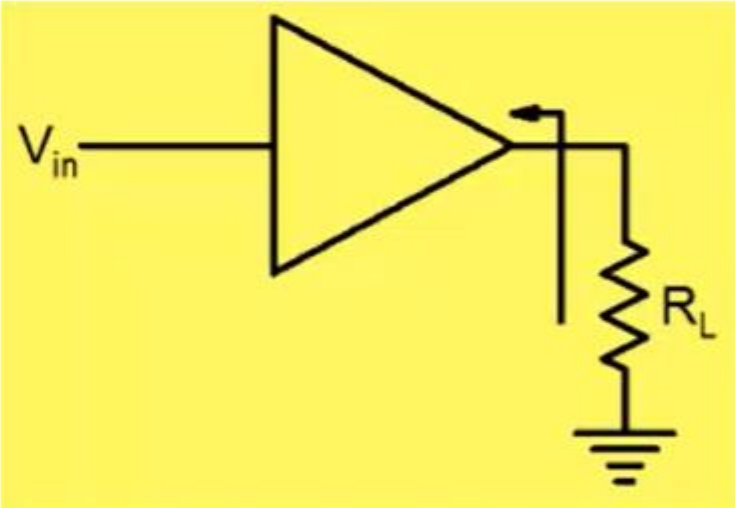


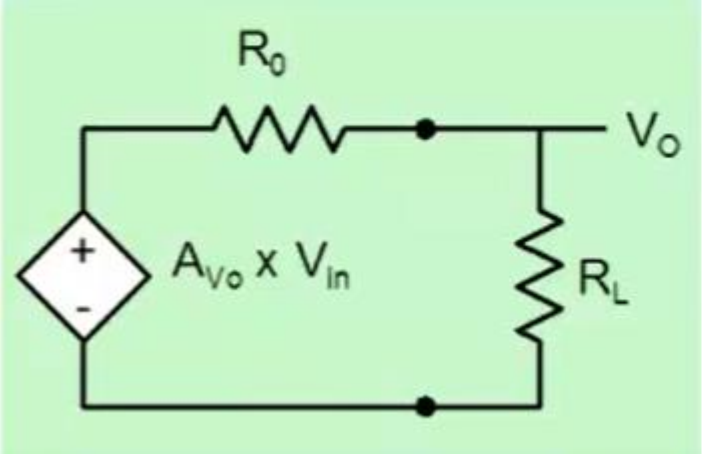
$$V_o = A_v(V_{in}, f, R_L, R_S, V_{DD}, T) \times v_{in} + \tilde{e}_N$$

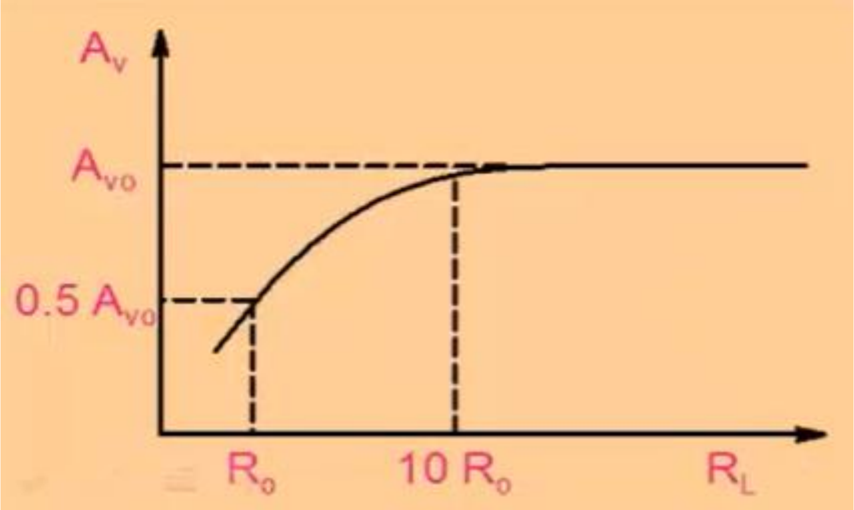
Effect of Load Resistance



Open circuit voltage gain and output resistance

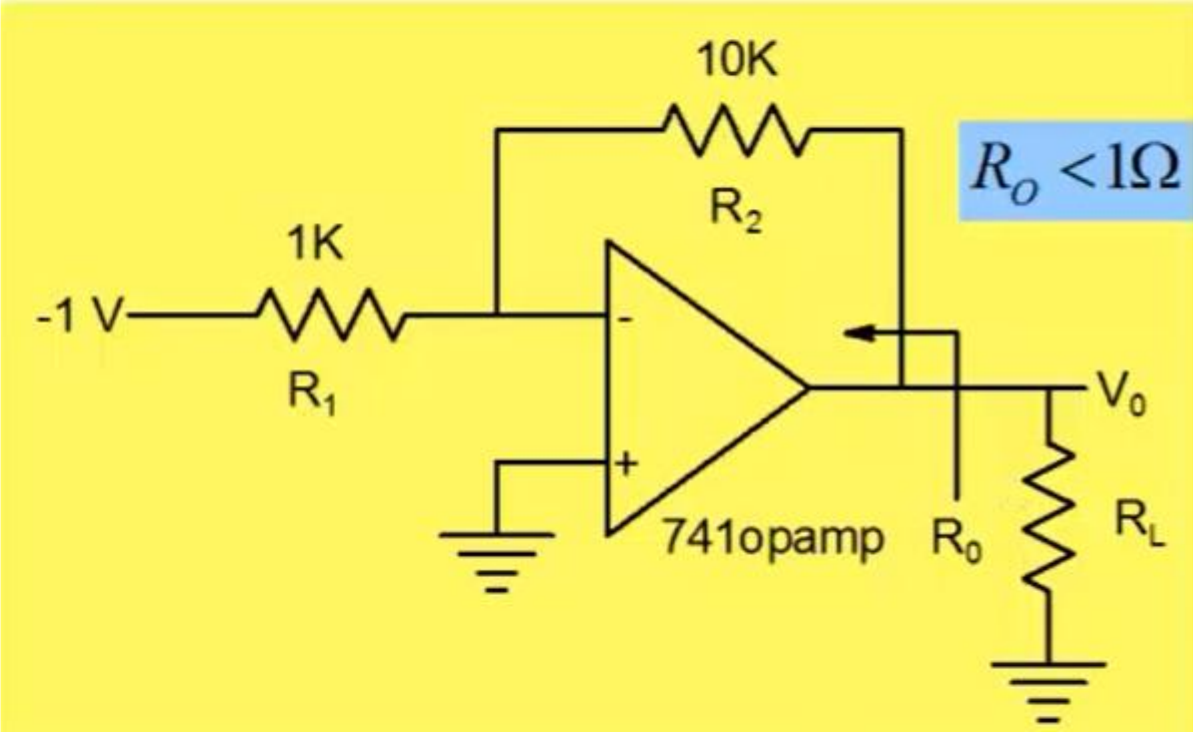




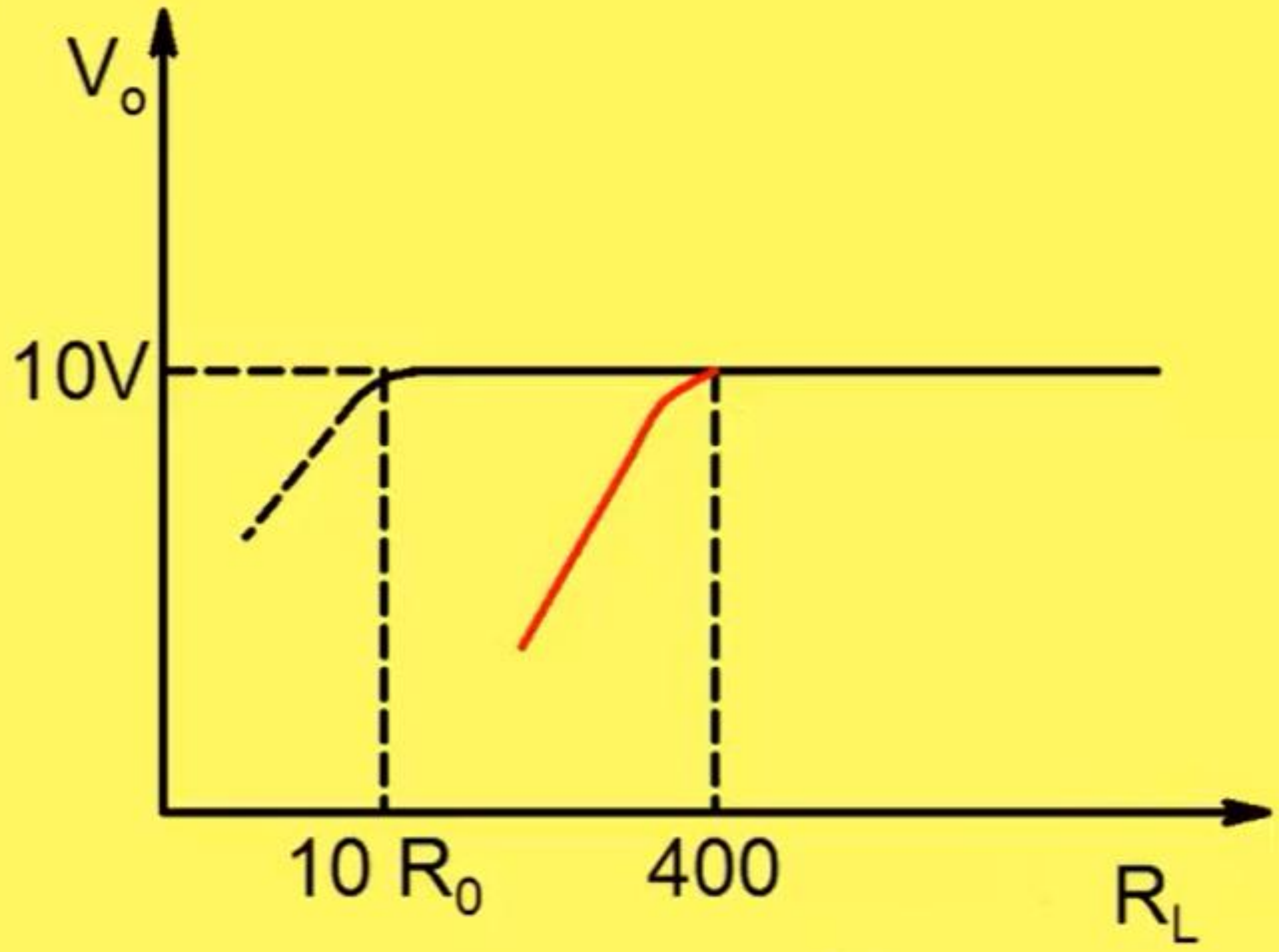


$$V_0 = A_{V0} \times V_{in}\left(\frac{R_L}{R_0 + R_L}\right)$$

Maximum Current Driving Capability

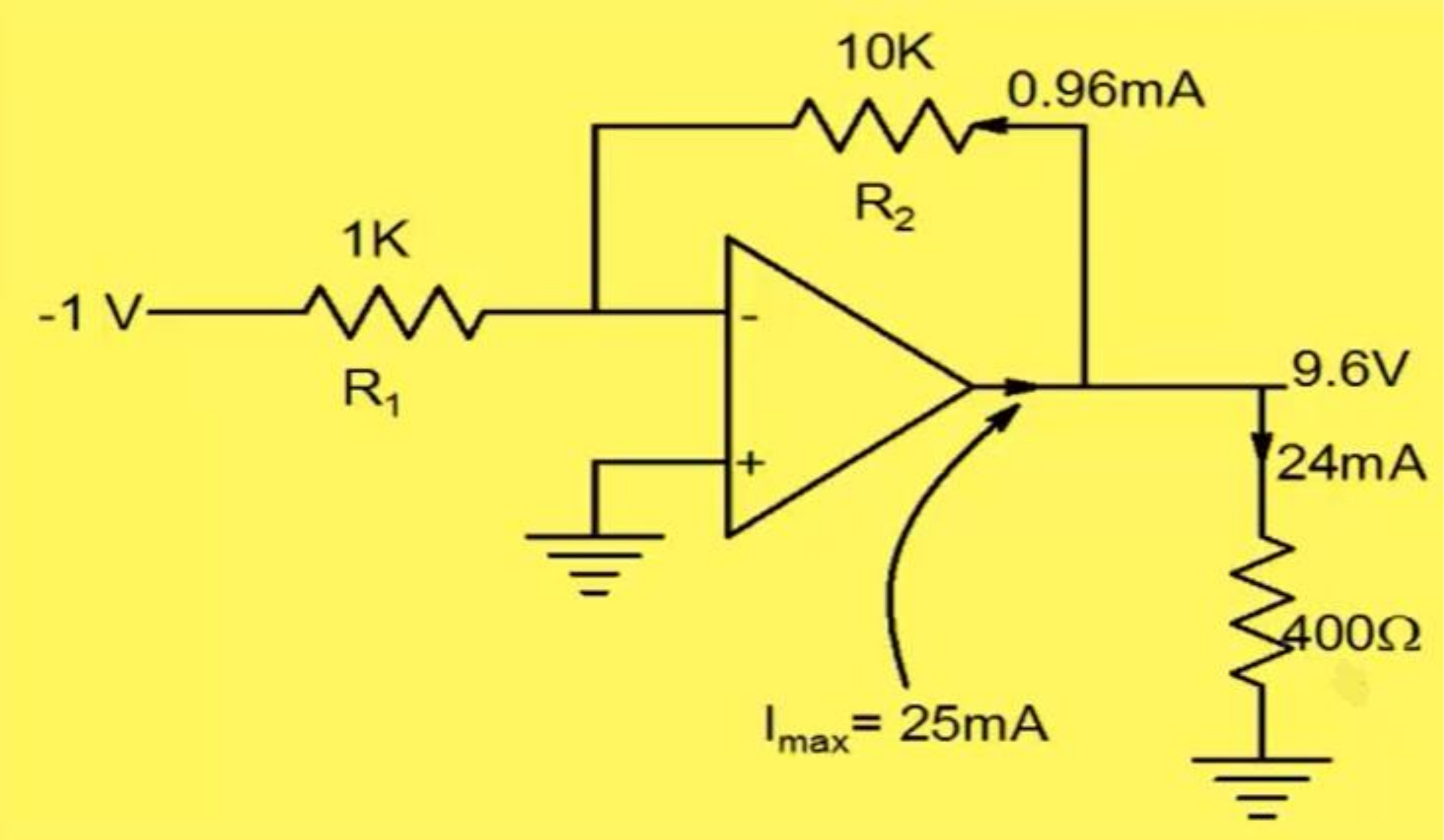


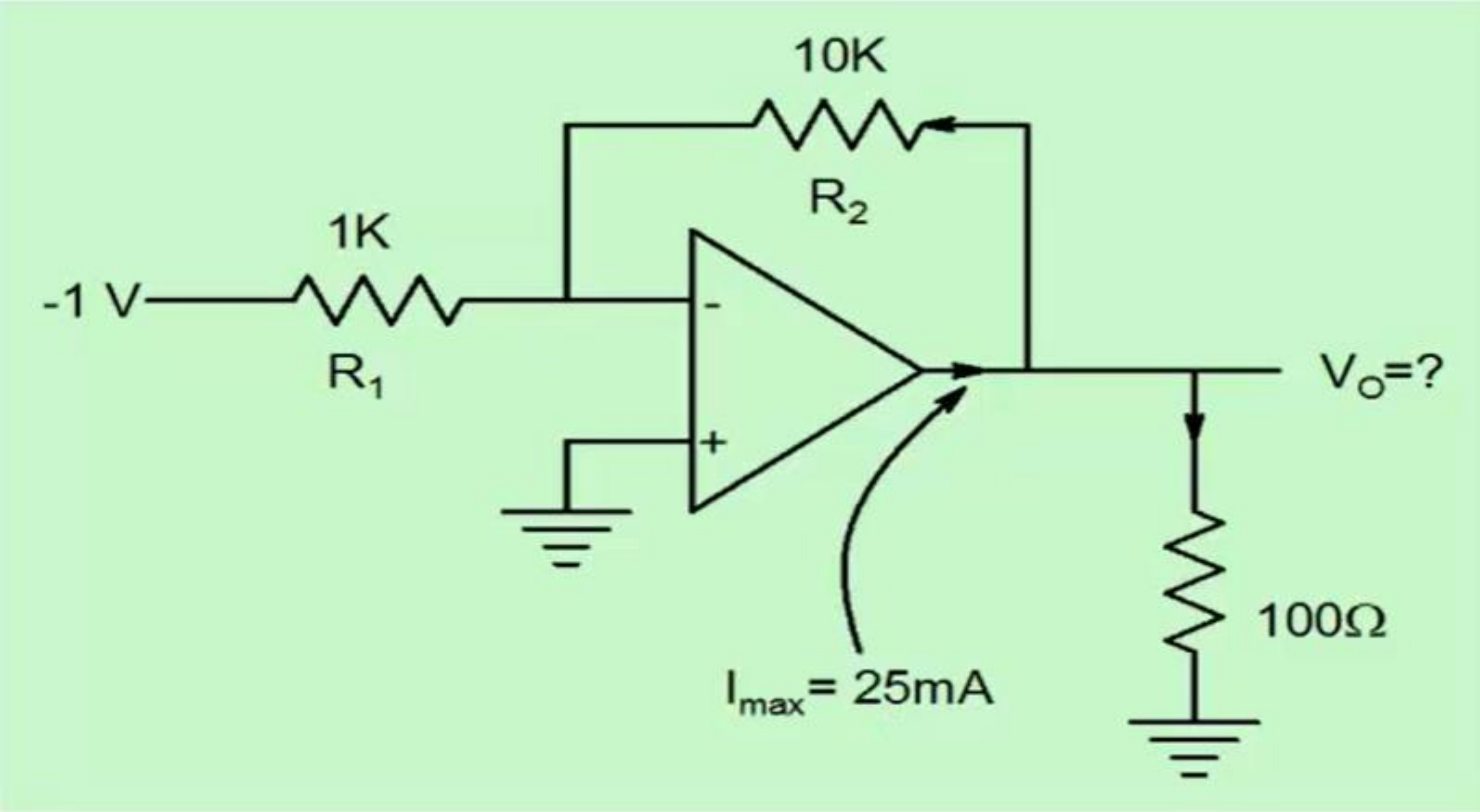
$$V_0 = -\frac{R_2}{R_1} V_{in} = 10V$$



V_o
10V
10 R_0
400
R_L

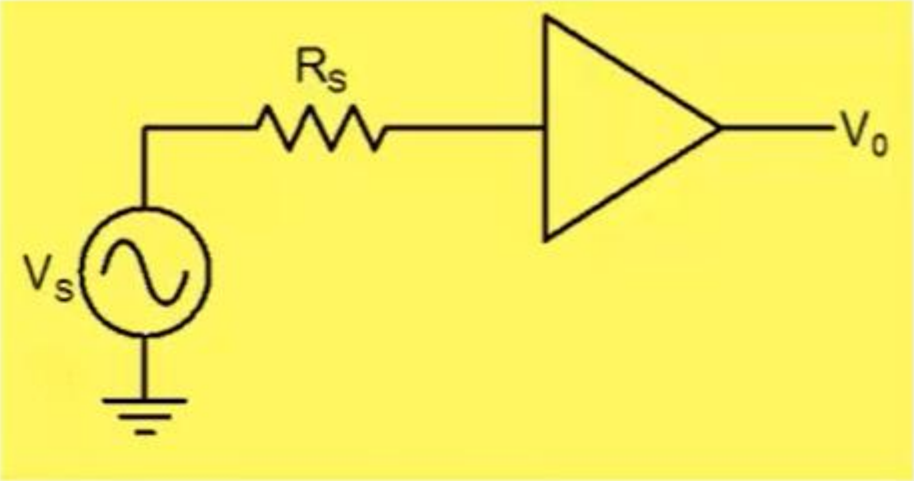
Opamp has maximum current drive capability of 25mA



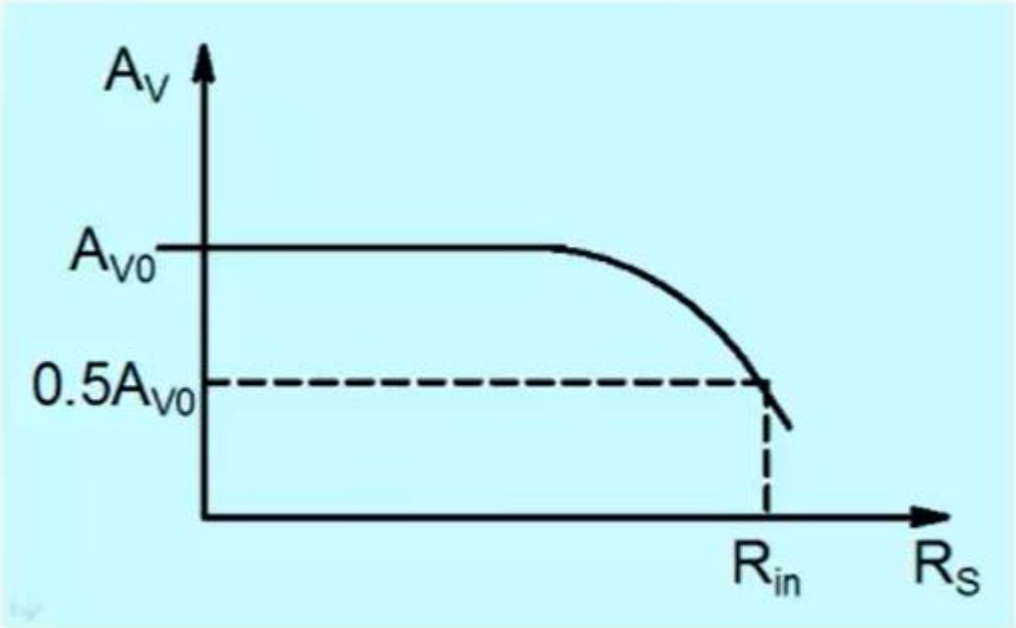


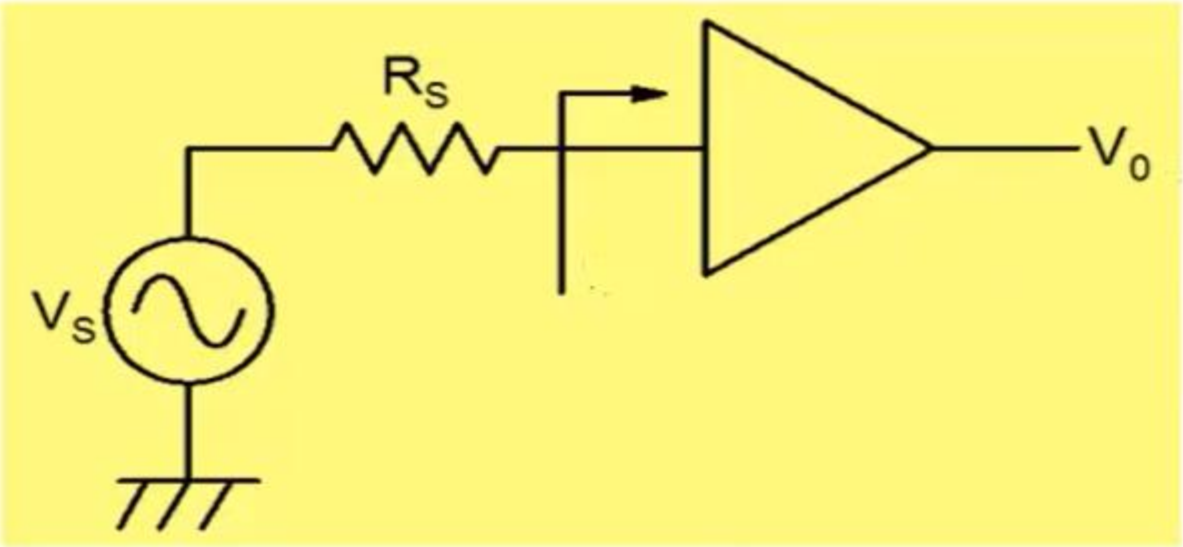
10K
R2
1K
-1 V
R1
-
+
Vo=?
100Ω
Imax= 25mA

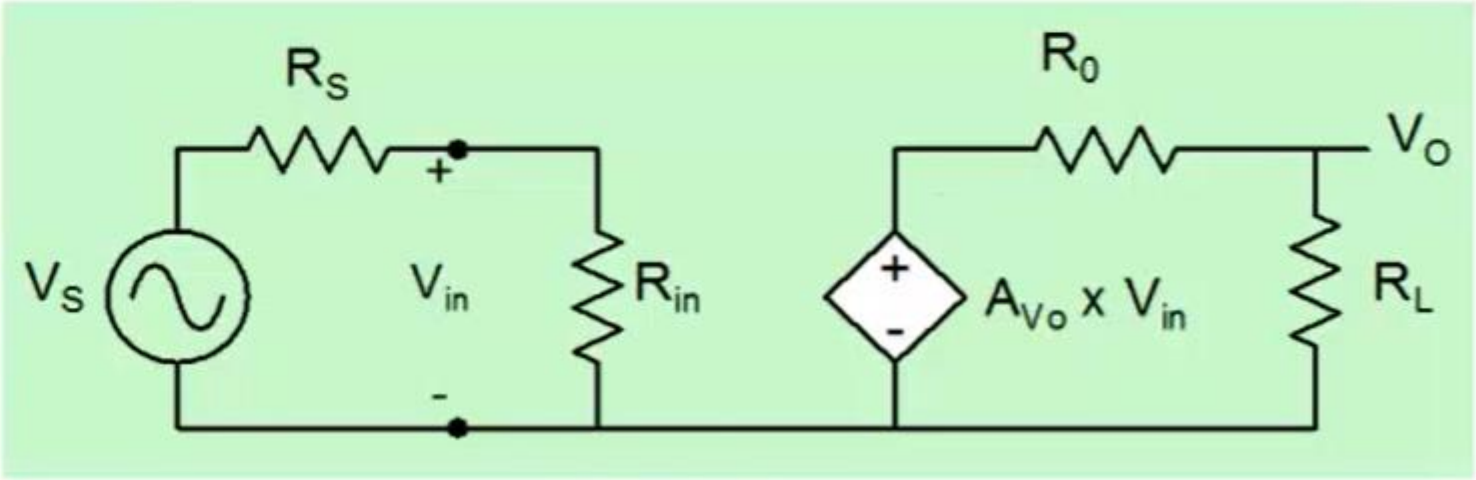
Input Resistance



$$A_{VS} = \frac{V_0}{V_S}$$



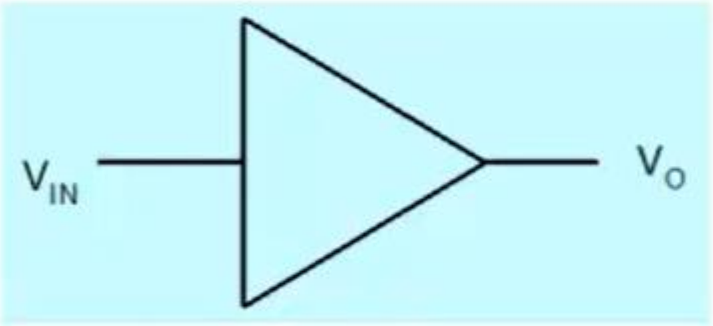




$$A_{VS} = A_{V0} \times \frac{R_{in}}{R_S + R_{in}} \times \frac{R_L}{R_0 + R_L}$$

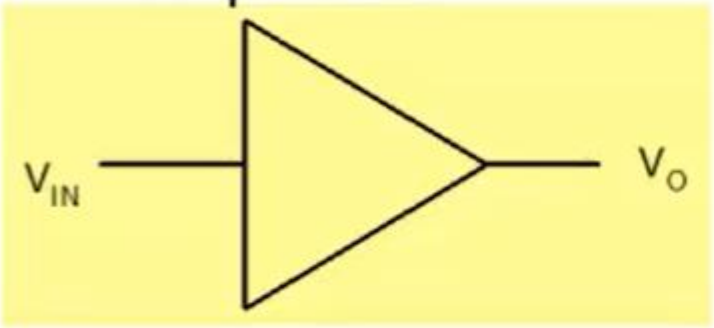
Create situations where one amplifier is better than the other

Amplifier-1



$$A_{V0} = 10^2$$
$$R_{in} = 1k\Omega$$
$$R_o = 1k\Omega$$

Amplifier-2

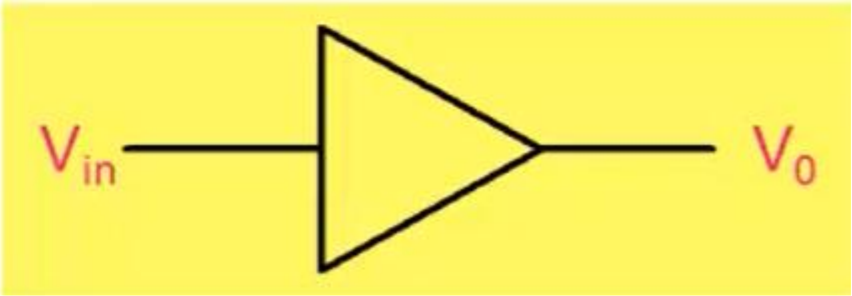


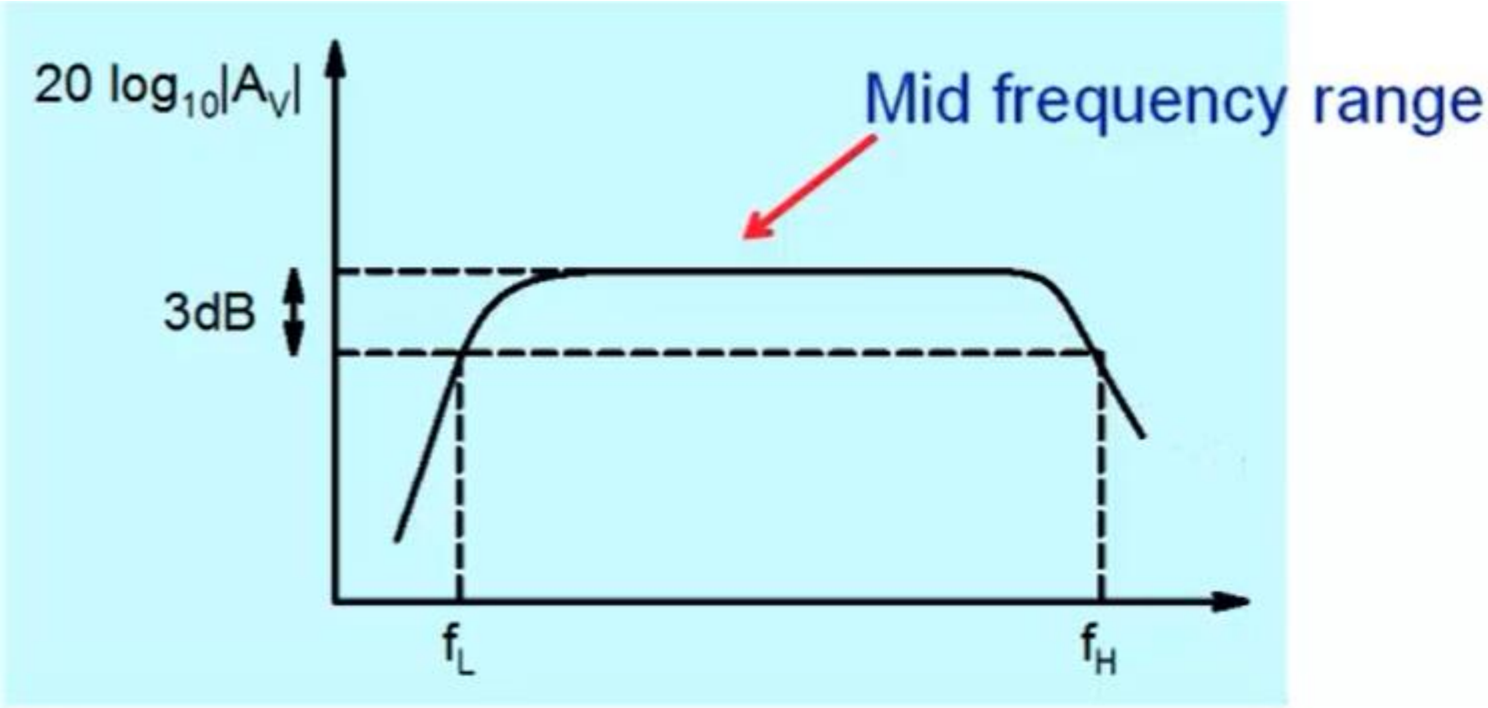
$$A_{V0} = 10^1$$
$$R_{in} = 100k\Omega$$
$$R_o = 1k\Omega$$

Can the following amplifier be useful?
Can it be called an amplifier?

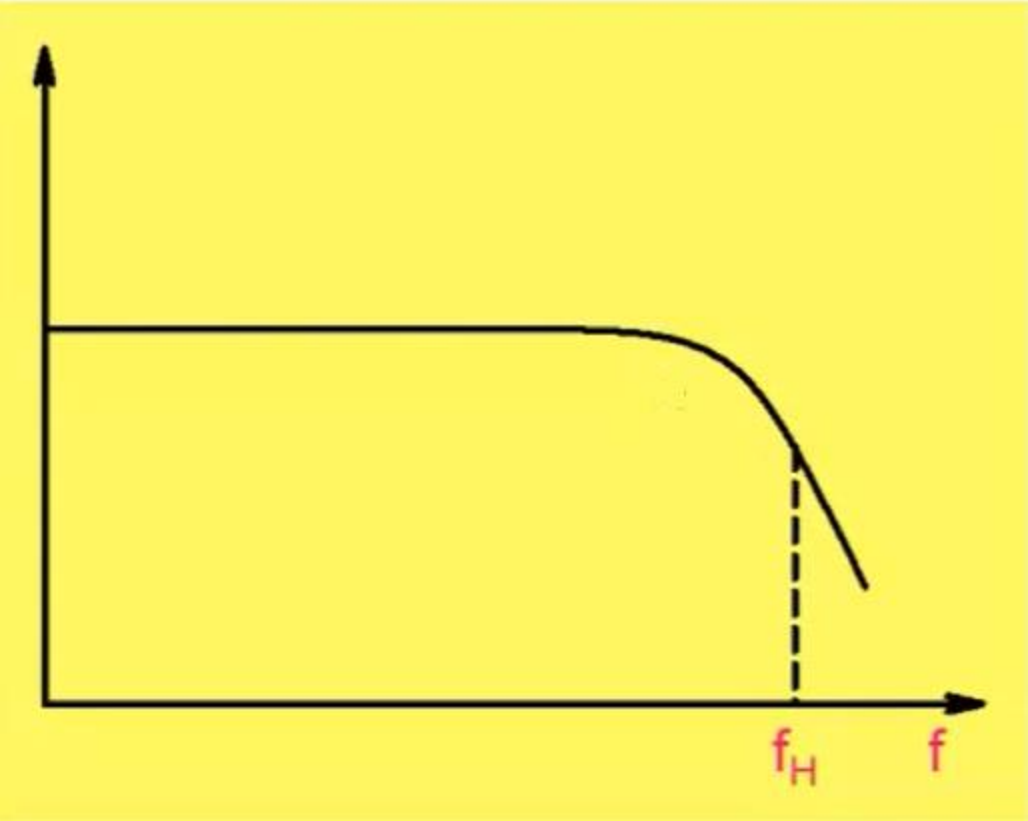
$$A_{V0} = 1; R_{in} = 10k\Omega; R_o = 10\Omega$$

Frequency Response

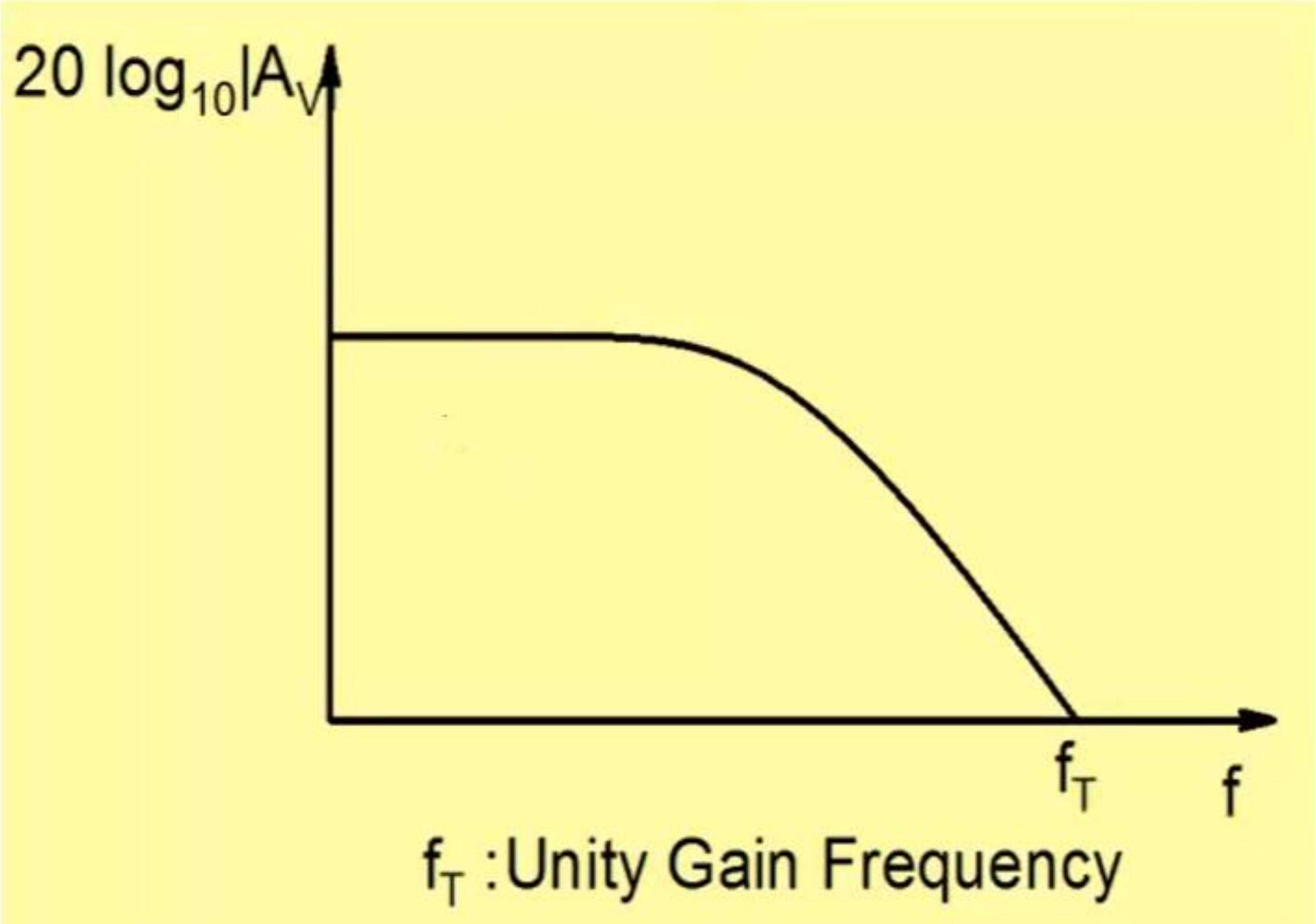




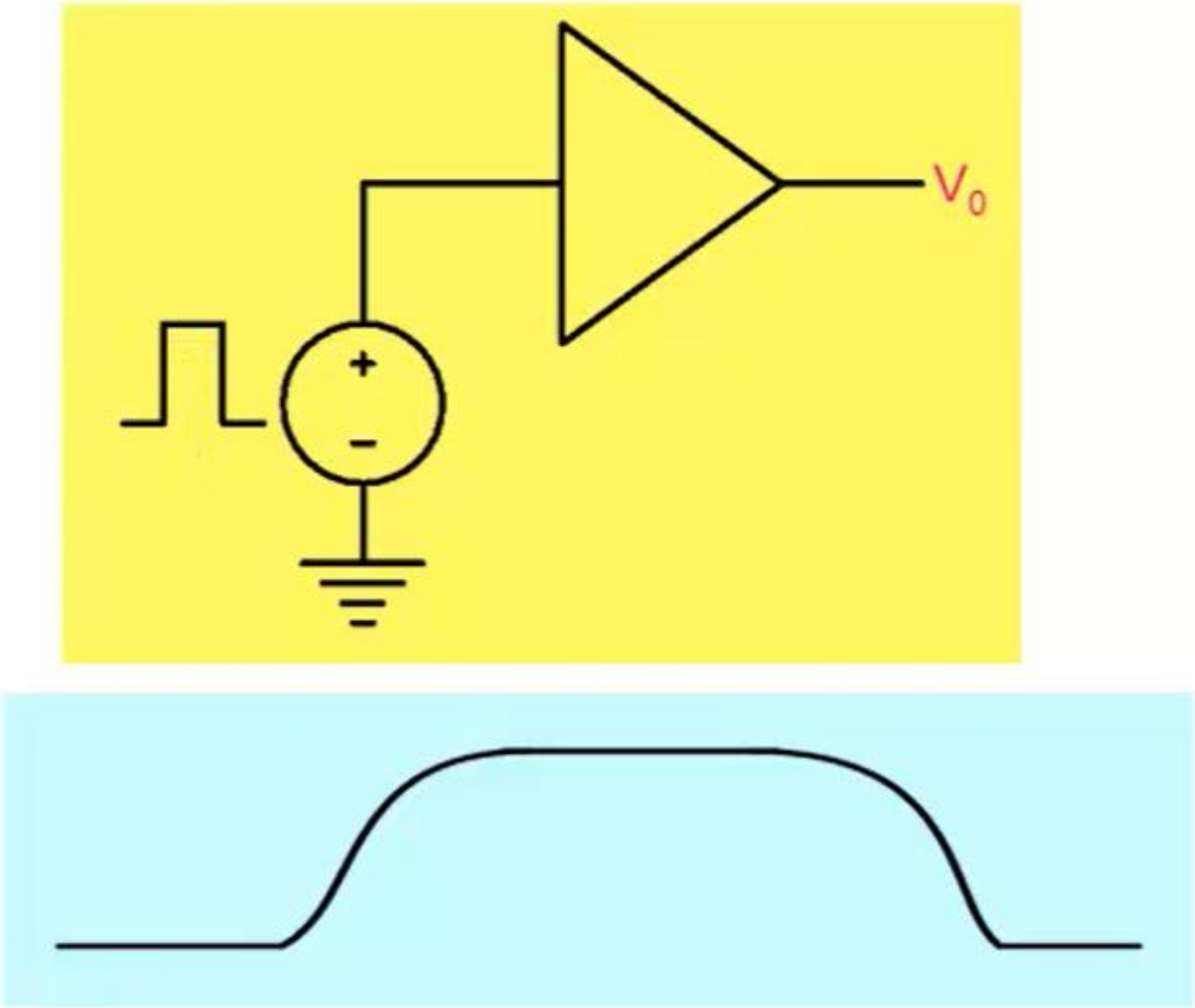
dc Amplifier



Unity Gain Frequency



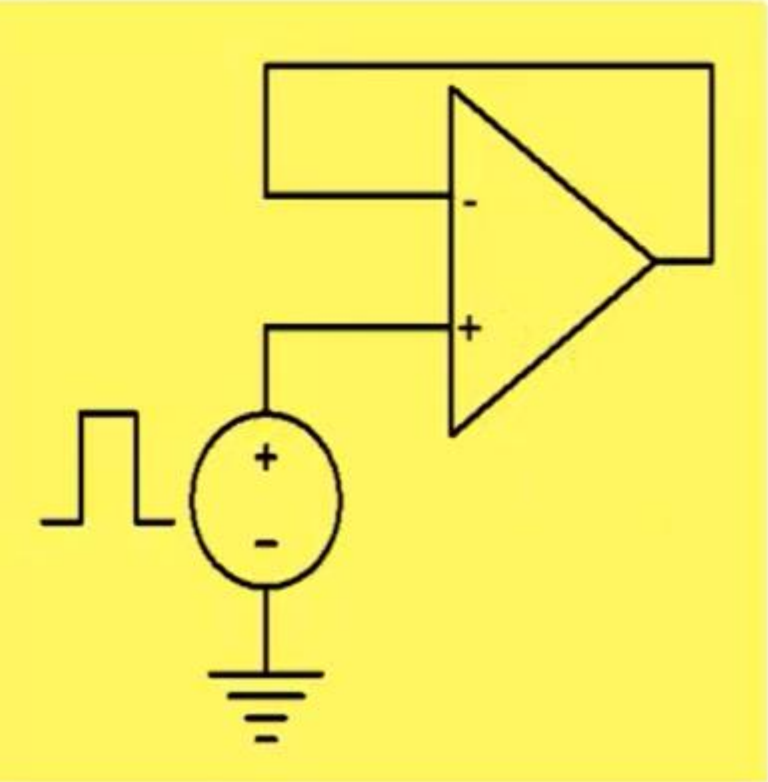
Transient Response

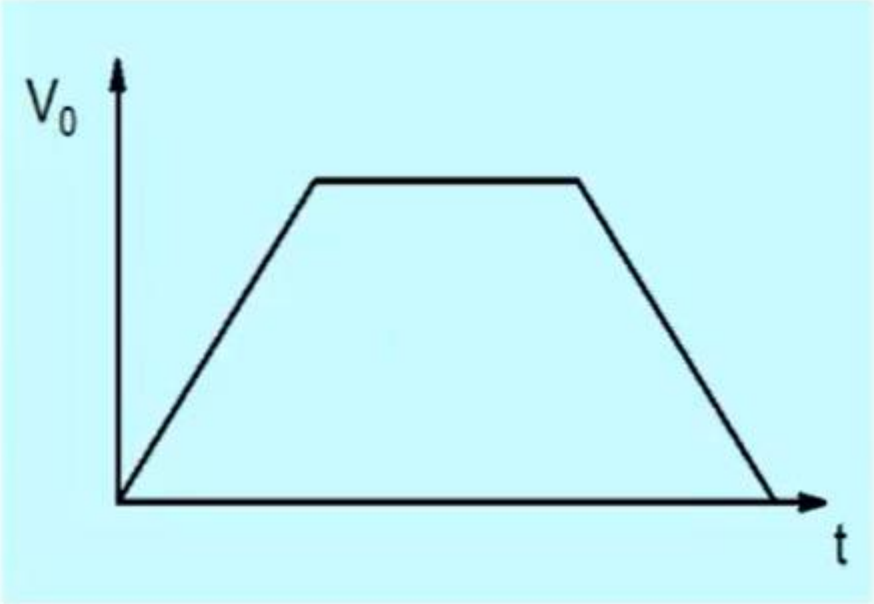


Rise time and fall time

Overshoot and time Settling time

Slew rate

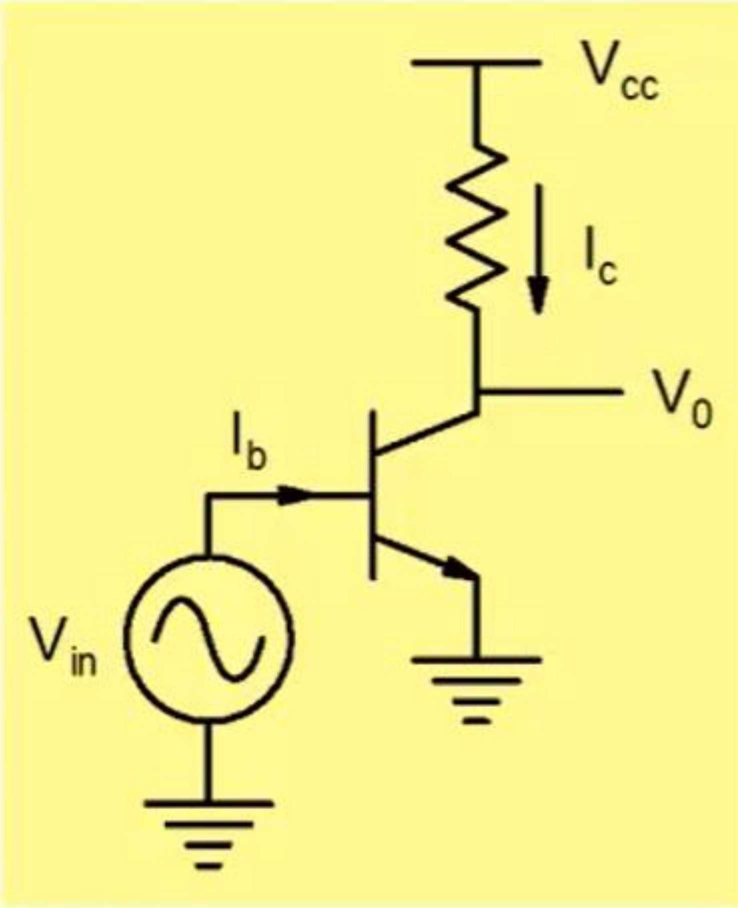


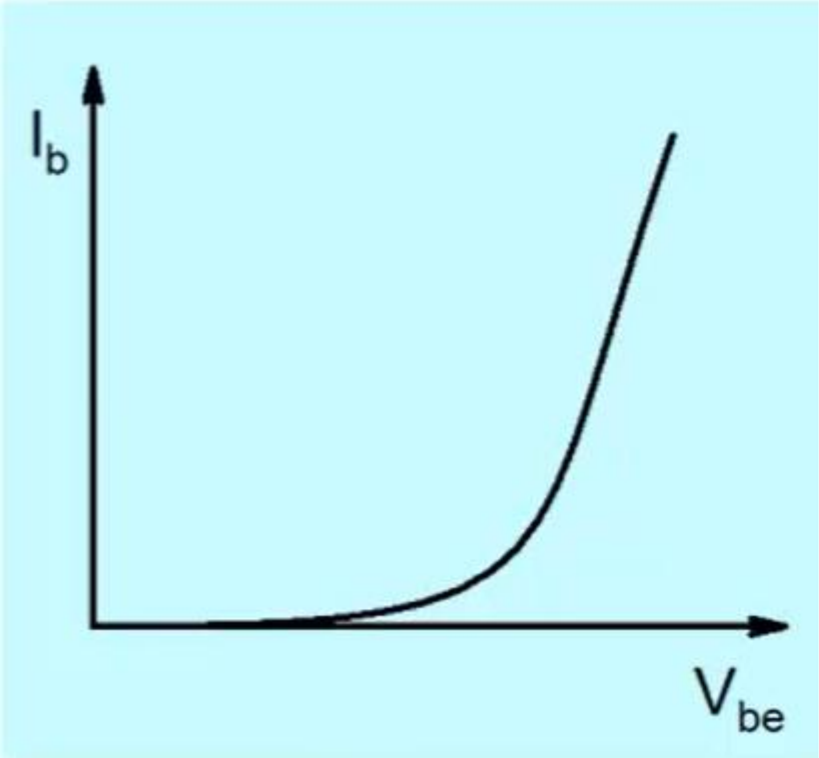


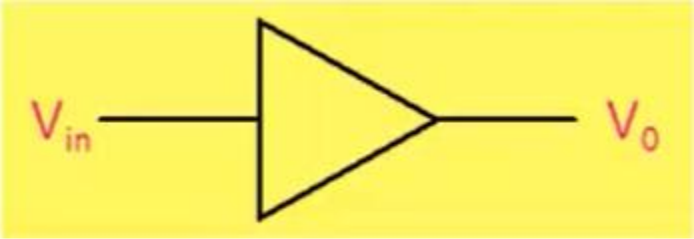
$$\text{Slew rate} = \left.\frac{dv_0}{dt}\right|_{max}$$

Distortion:

All amplifiers are nonlinear because transistors used for building amplifier are nonlinear elements.







$V_{in} = a_0 \sin wt$

$V_0 = b_0 + b_1 \sin \omega t + b_2 \sin 2\omega t + b_3 \sin 3\omega t + \dots\dots\dots$

$$HD_2 = \frac{b_2}{b_1} \times 100$$

$$HD_3 = \frac{b_3}{b_1} \times 100$$

$$THD = \frac{\sqrt{{b_2}^2 + {b_3}^2 + \dots\dots}}{b_1} \times 100$$

Example

$$V_0 = kV_{in} + \frac{k}{10} V_{in}^{\ 2}$$

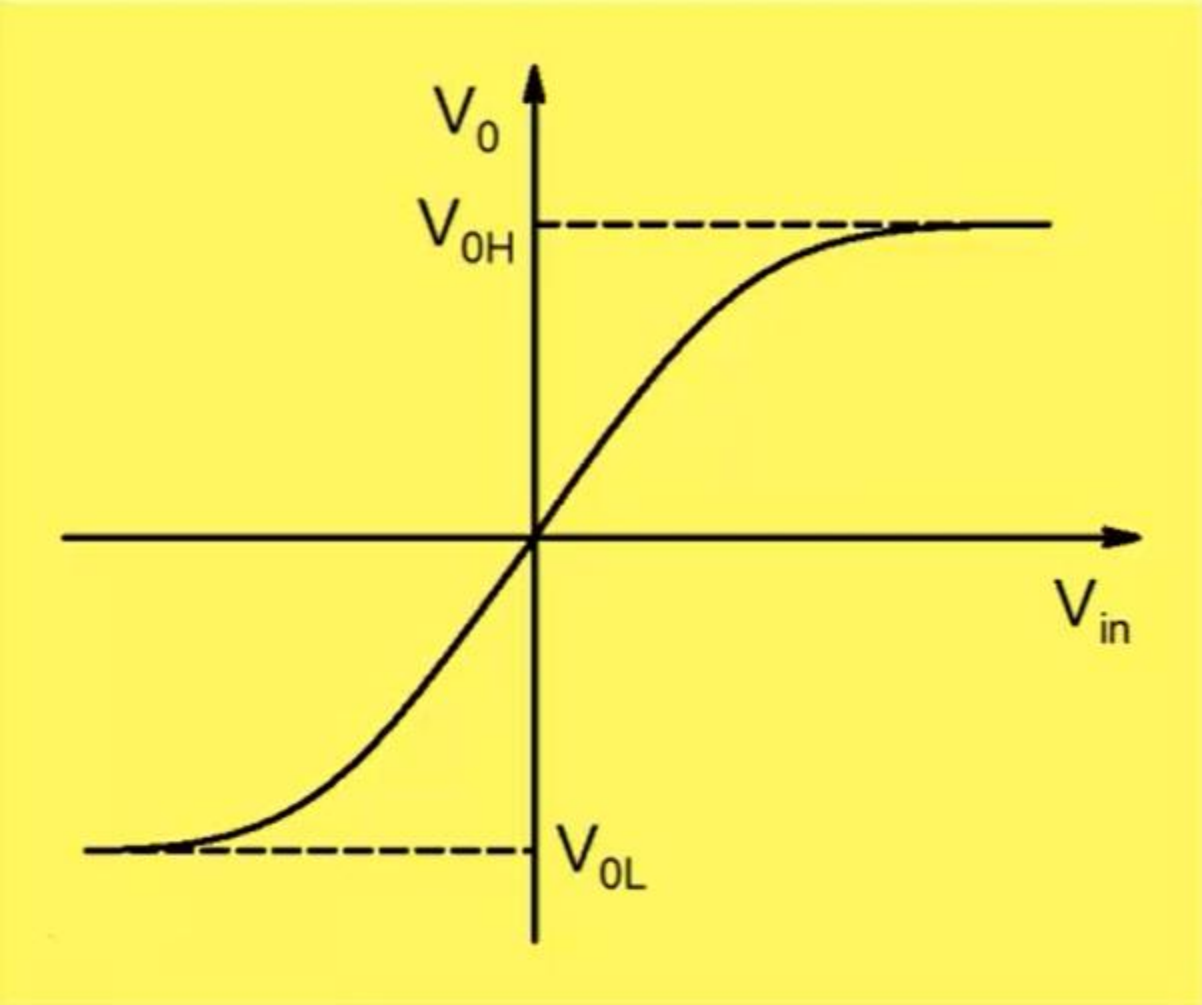
$$V_{in} = a_0 \sin \omega t$$

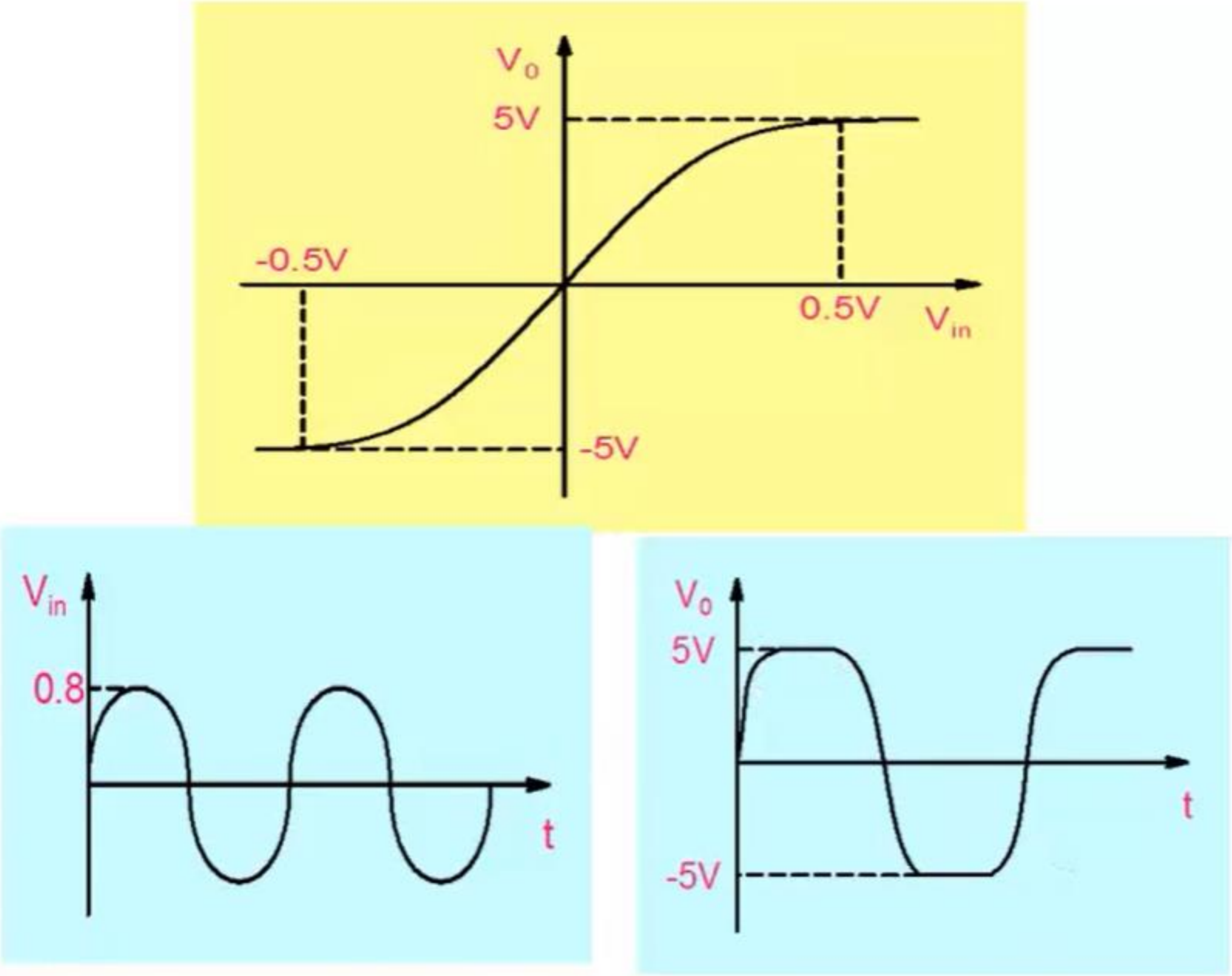
$$V_0 = \frac{ka_0^{\ 2}}{20} + ka_0 \sin \omega t - \frac{ka_0^{\ 2}}{20} \cos 2\omega t$$

$$THD = HD_2 = \frac{ka_0^{\ 2}/20}{ka_0} \times 100 = 5a_0$$

Distortion increases with magnitude of input signal !

Maximum Voltage Swing

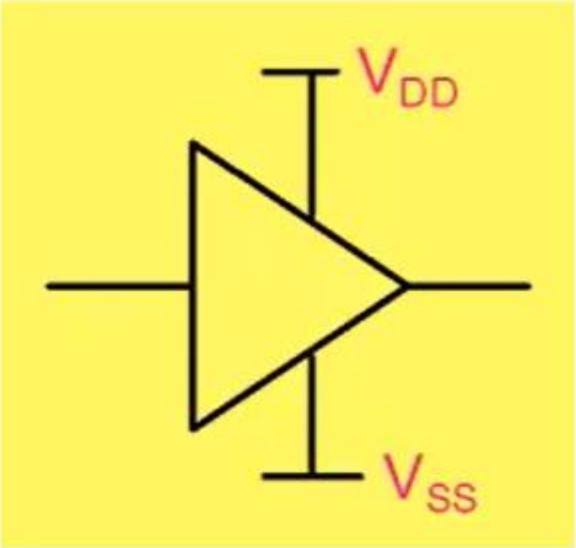


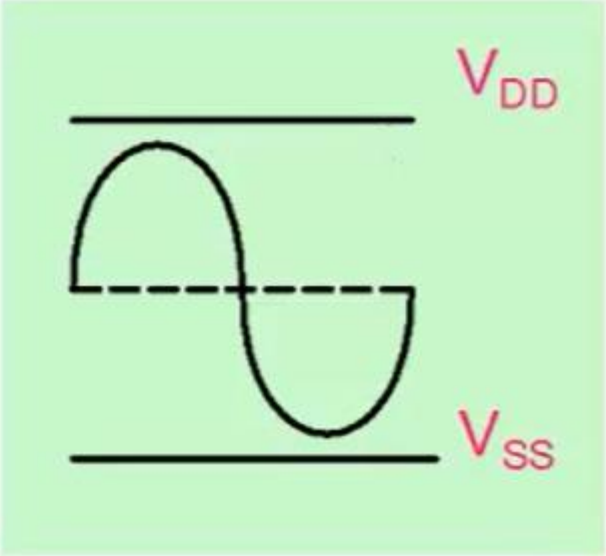


Vo
5V
-0.5V
0.5V
Vin
-5V
Vin
0.8
t
Vo
5V
t
-5V

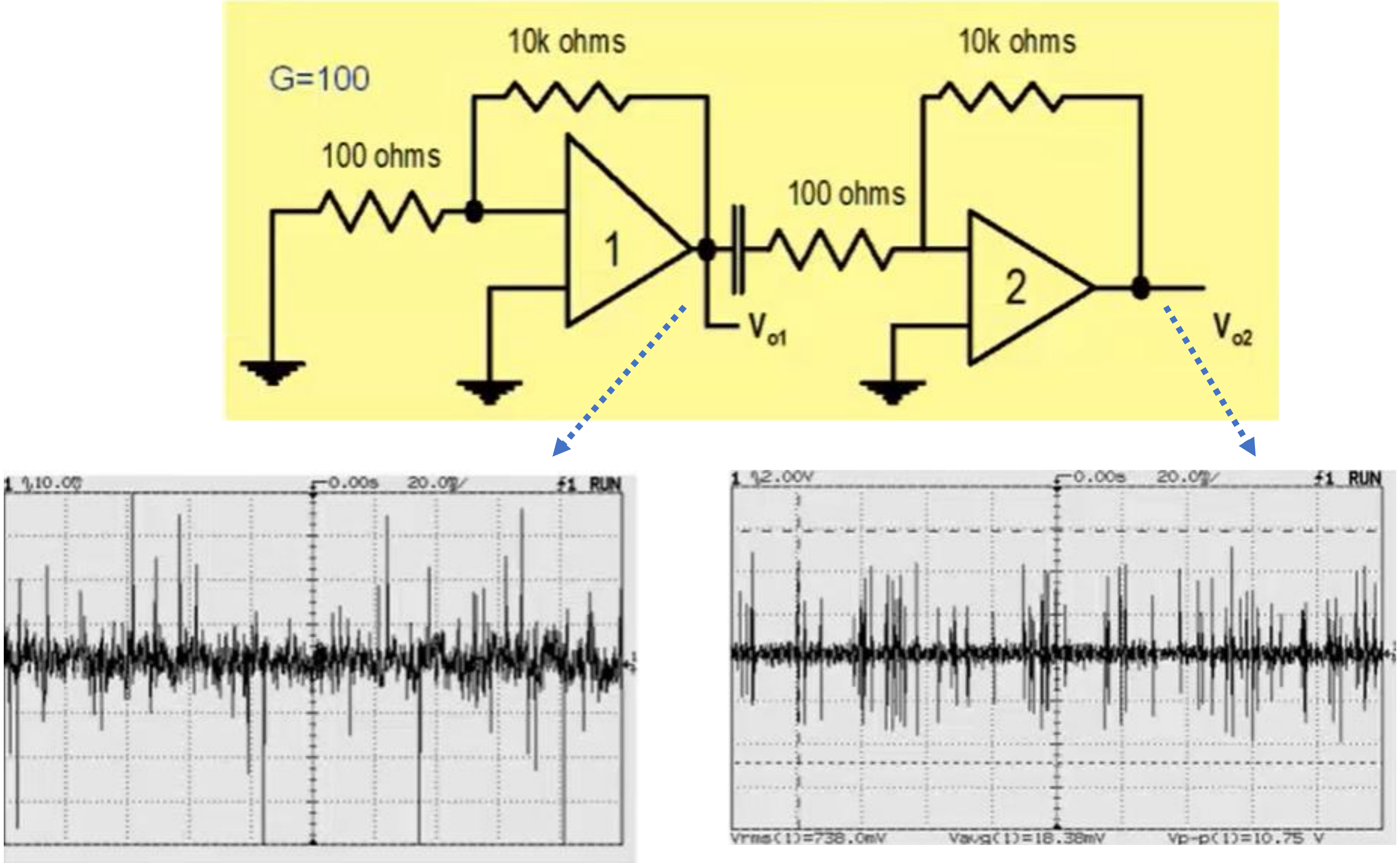
Rail-to-Rail output voltage swing

$V_{OH} \leq V_{DD}$ $V_{OL} \geq V_{SS}$





NOISE



G=100
10k ohms
100 ohms
1
V_{o1}
10k ohms
100 ohms
2
V_{o2}
-0.00s
RUN
Vrms(1)=738.0mV
Vavg(1)=18.38mV
Vp-p(1)=10.75 V