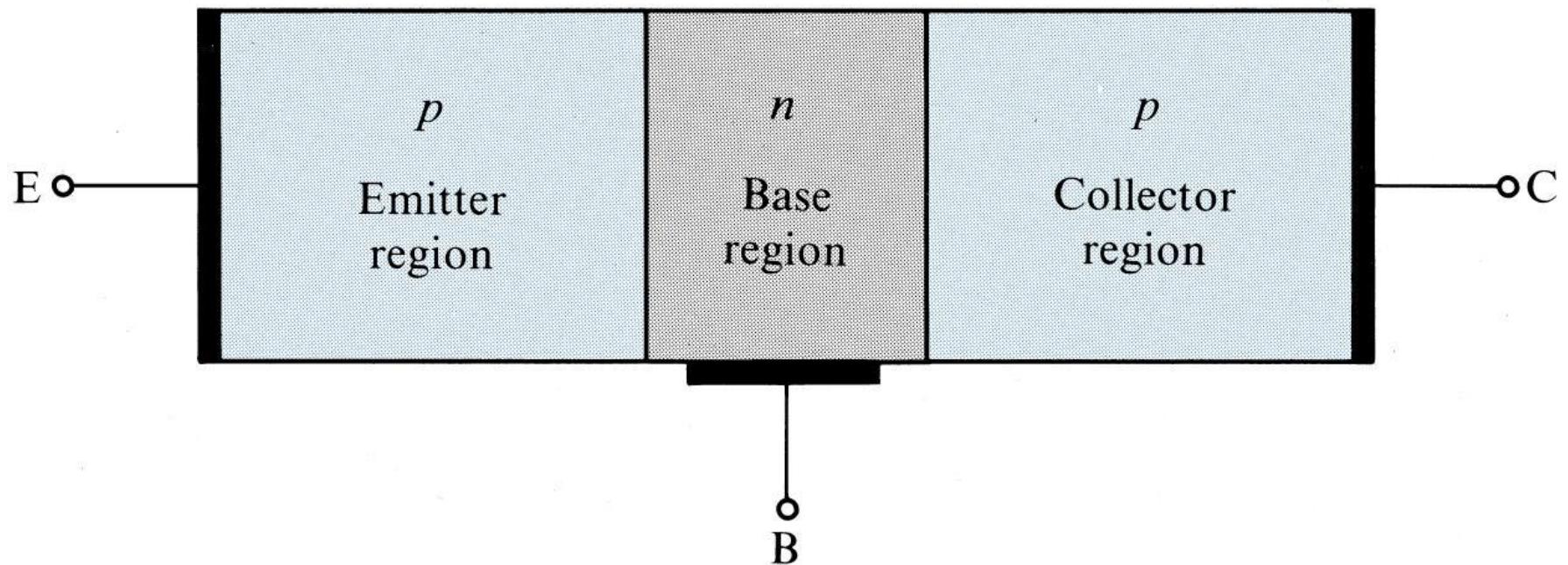


# BJT

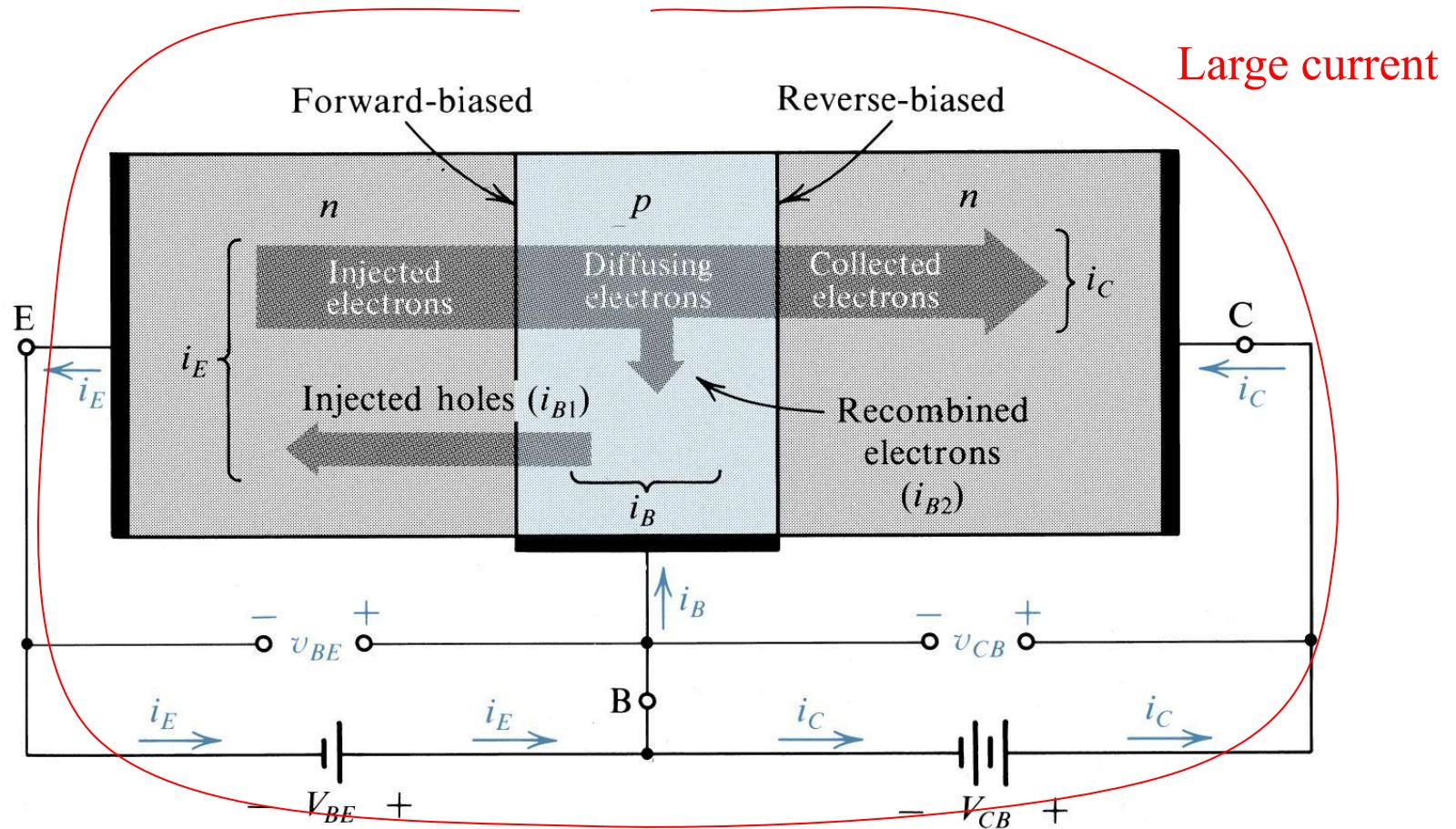
## **Bipolar Junction Transistor**

- Widely used in amplifier circuits
- Formed by junction of 3 materials
- npn or pnp structure

# pnp transistor



# Operation of npn transistor

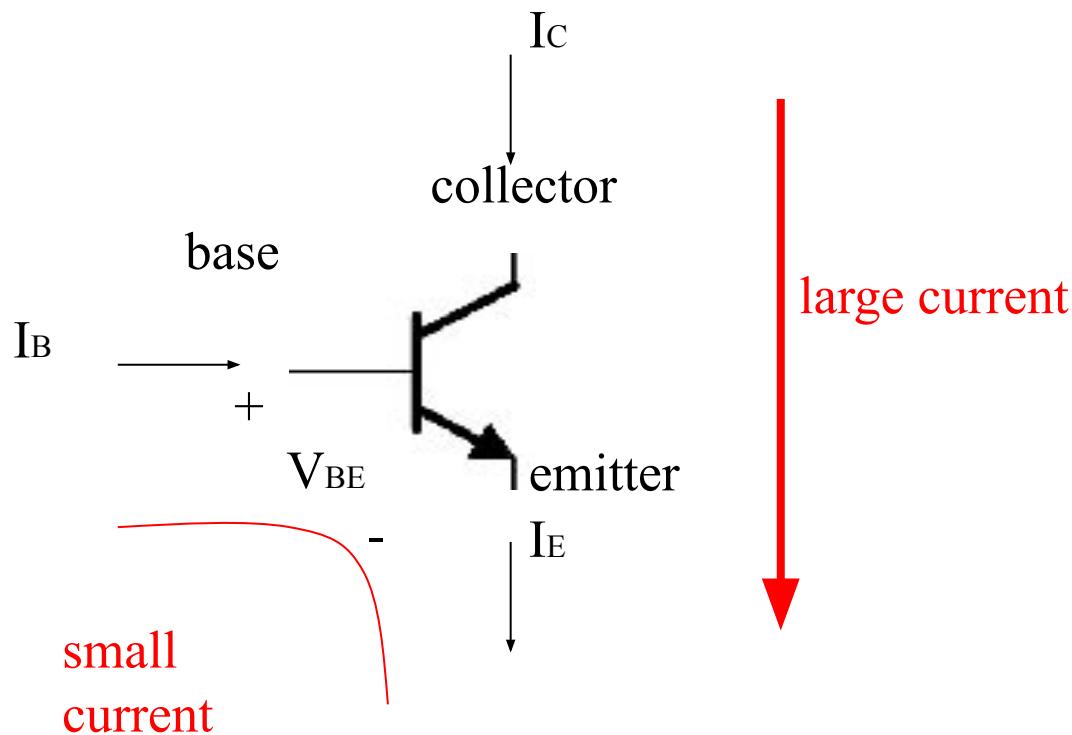


# Modes of operation of a BJT transistor

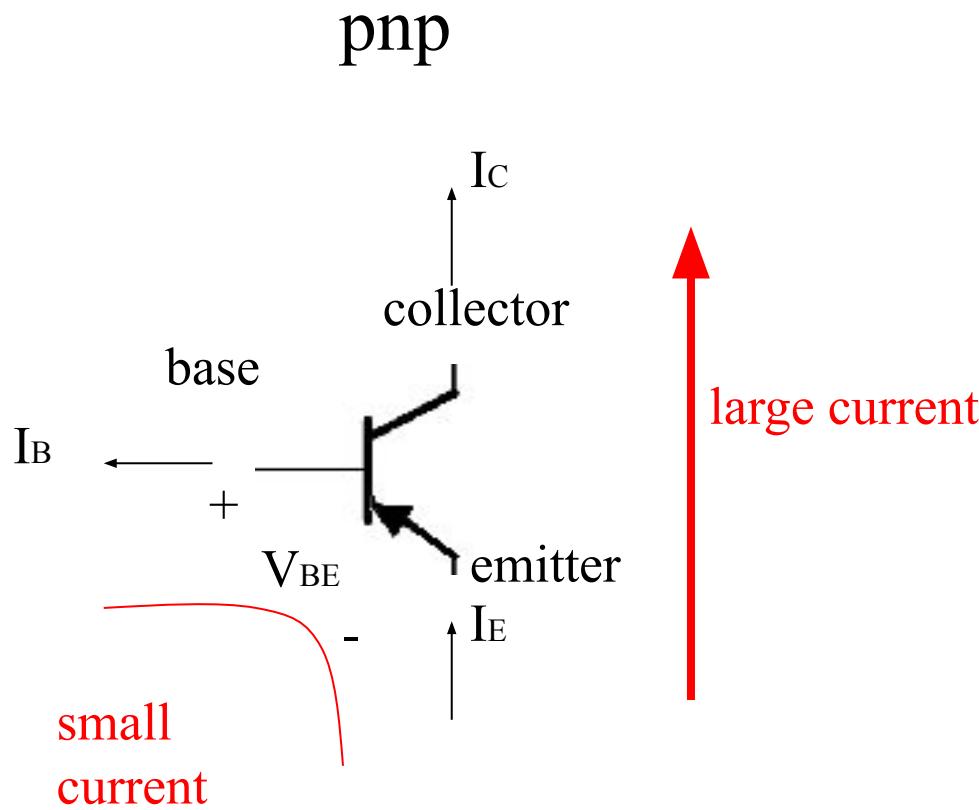
<u>Mode</u>	<u>BE junction</u>	<u>BC junction</u>
cutoff	reverse biased	reverse biased
linear(active)	forward biased	reverse biased
saturation	forward biased	forward biased

# Summary of *npn* transistor behavior

npn



## Summary of pnp transistor behavior



## Summary of equations for a BJT

$$I_E \approx I_C$$

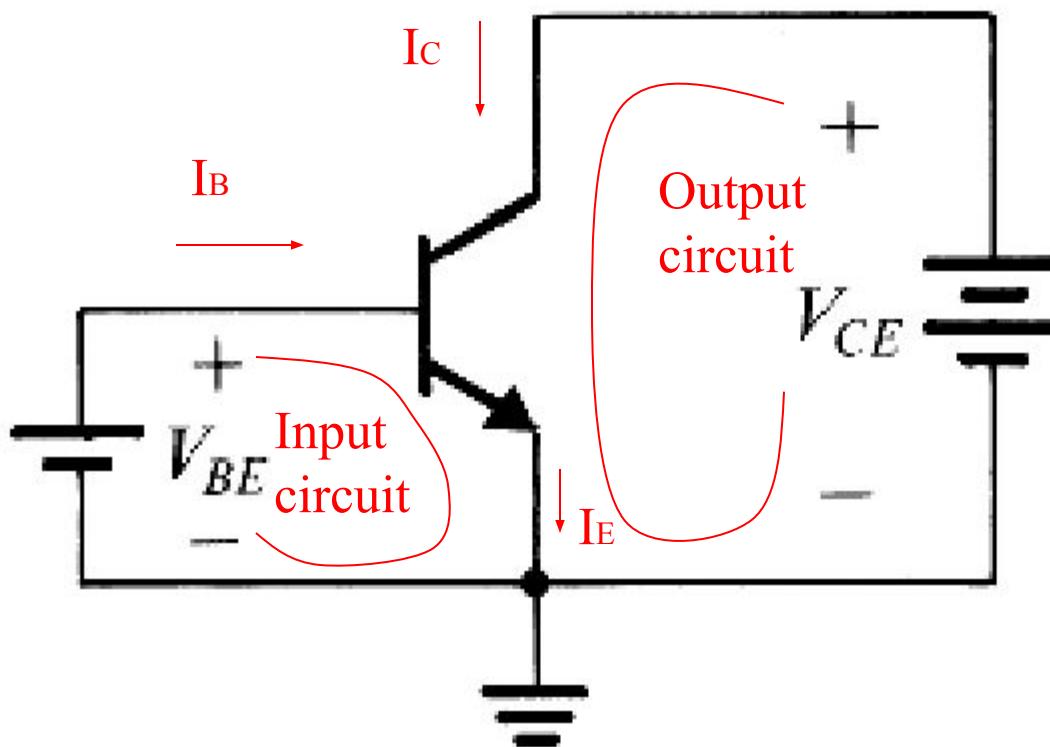
$$I_C = \beta I_B$$

$\beta$  is the current gain of the transistor  $\approx 100$

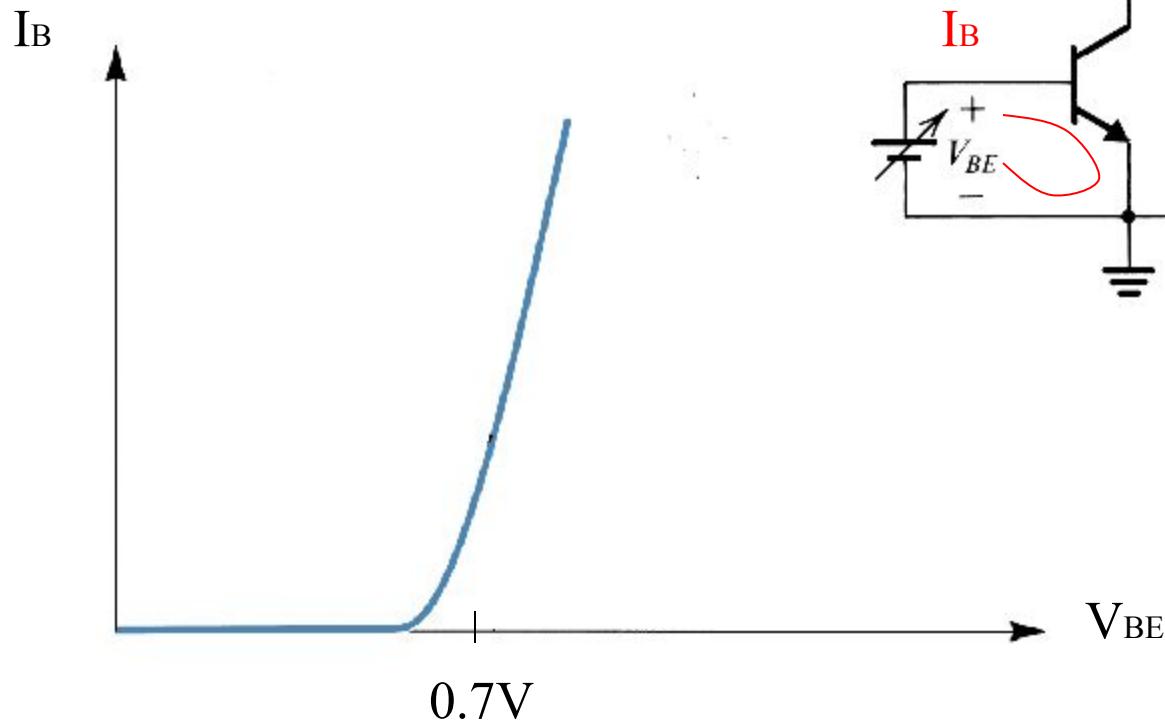
$$V_{BE} = 0.7V(\text{npn})$$

$$V_{BE} = -0.7V(\text{pnp})$$

# Graphical representation of transistor characteristics

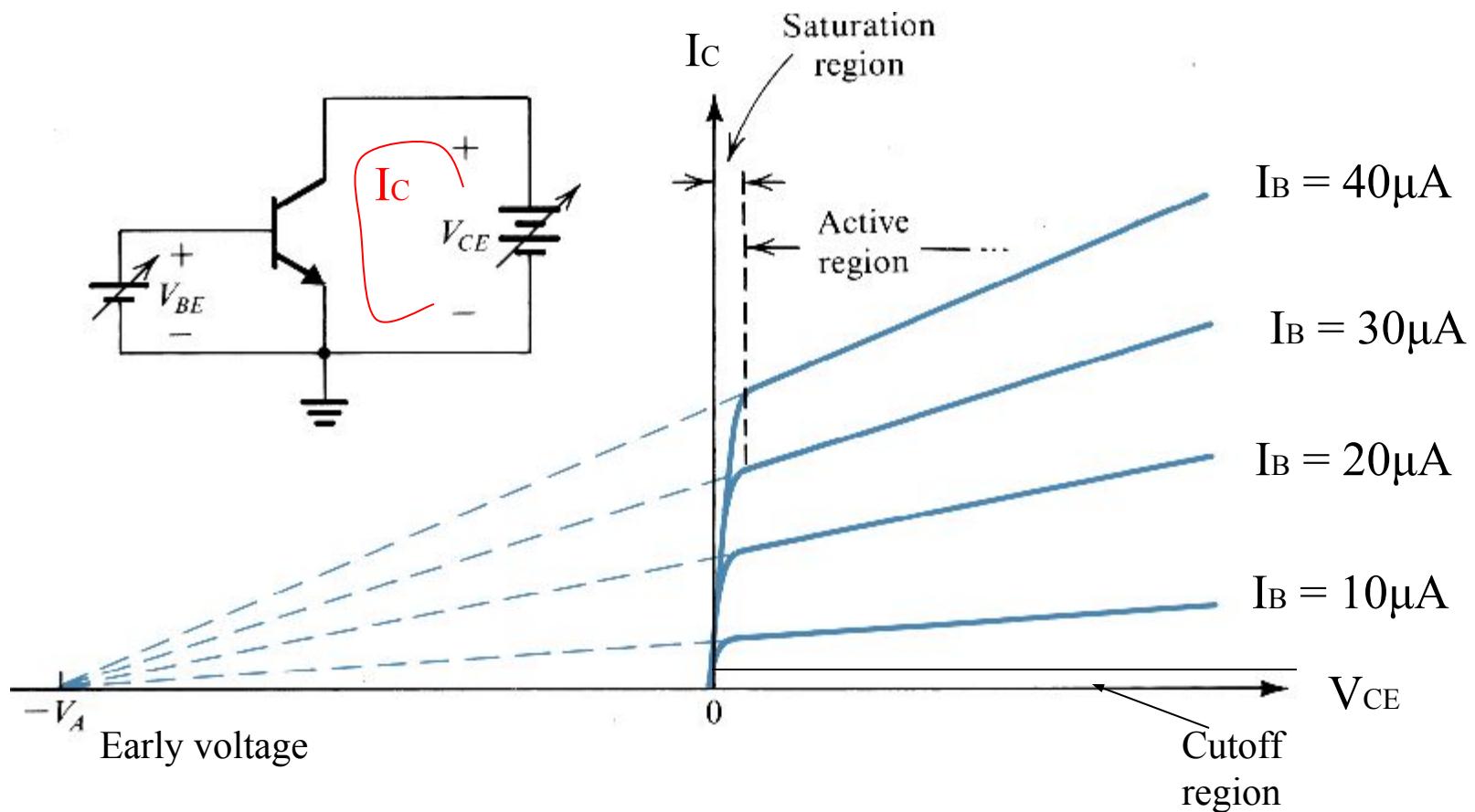


## Input characteristics



- Acts as a diode
- $V_{BE} \approx 0.7V$

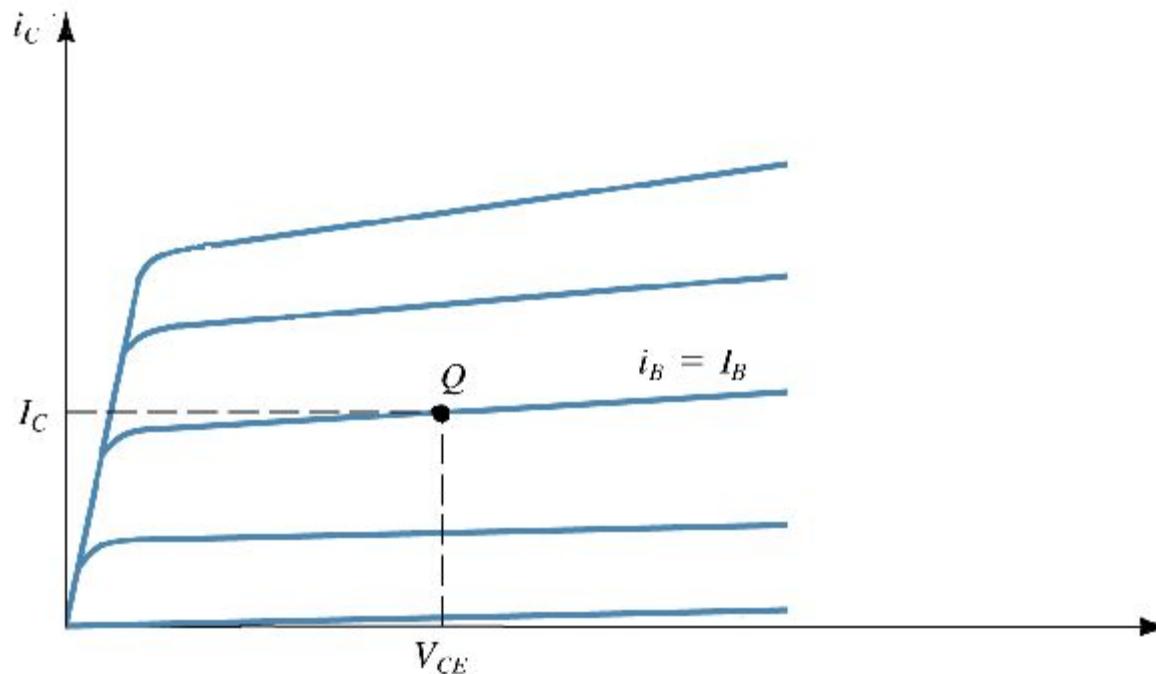
# Output characteristics



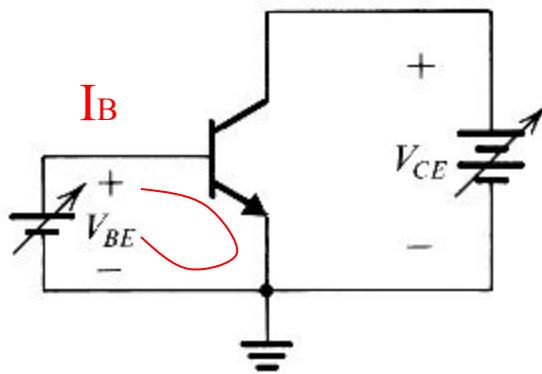
- At a fixed  $I_B$ ,  $I_C$  is not dependent on  $V_{CE}$
- Slope of output characteristics in linear region is near 0 (scale exaggerated)

# Biassing a transistor

- We must operate the transistor in the linear region.
- A transistor's operating point (Q-point) is defined by  $I_C$ ,  $V_{CE}$ , and  $I_B$ .

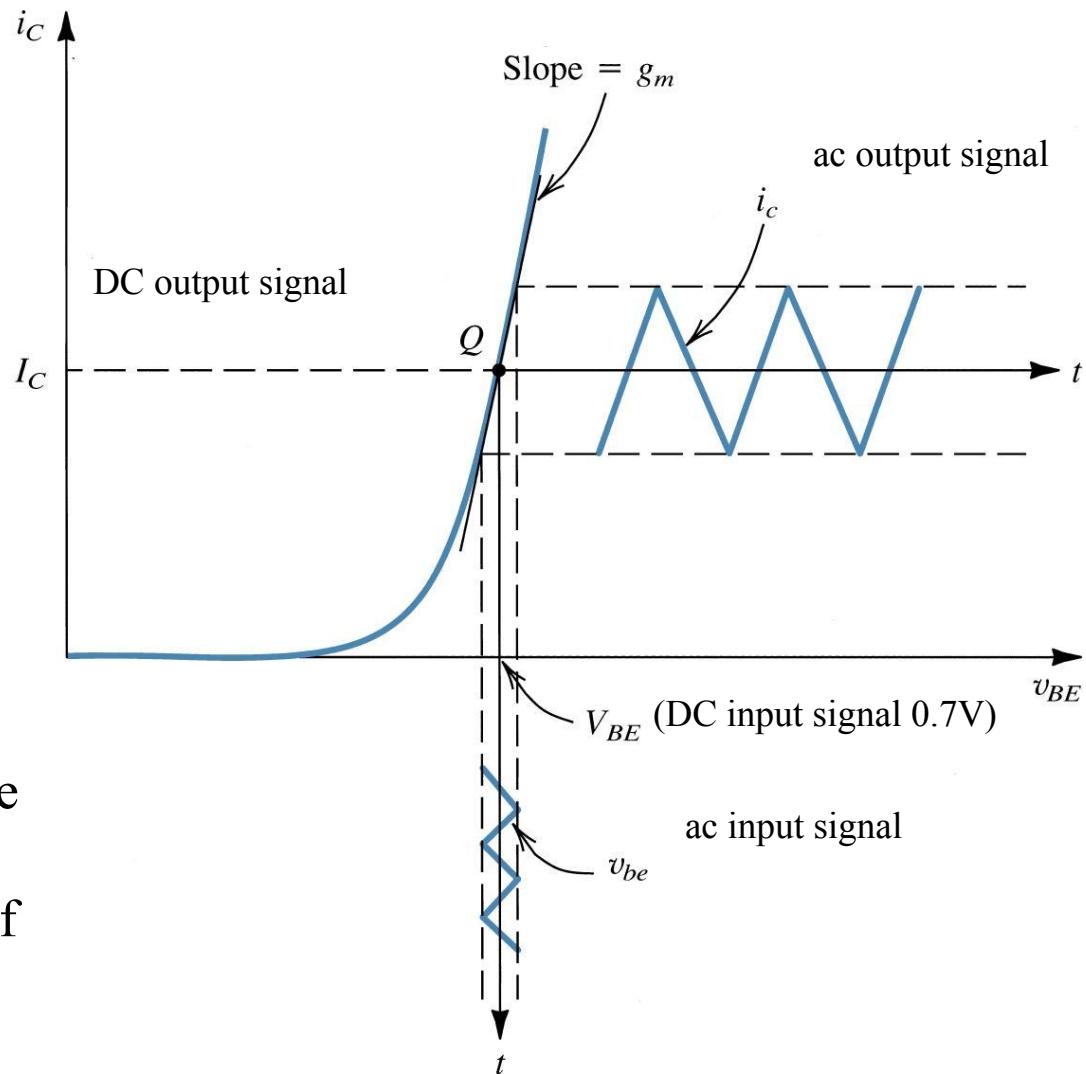


# Transconductance



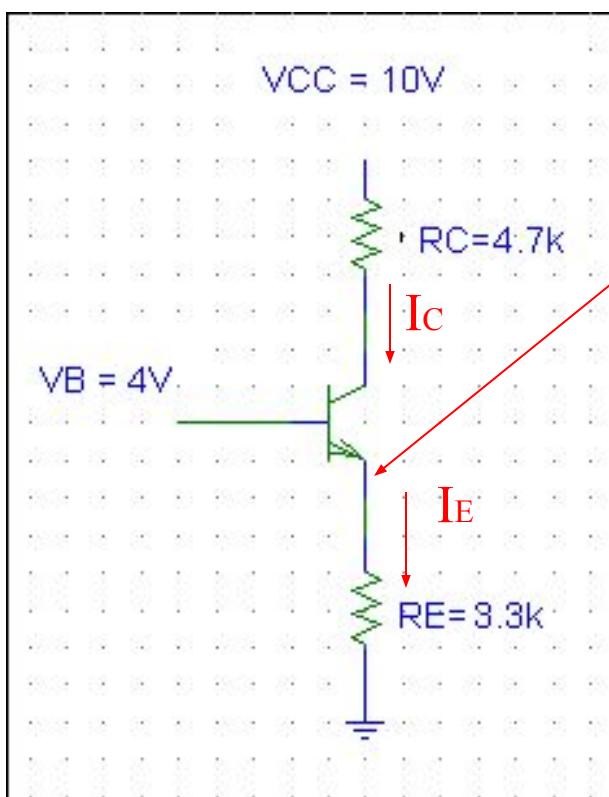
A small ac signal  $v_{be}$  is superimposed on the DC voltage  $V_{BE}$ . It gives rise to a collector signal current  $i_c$ , superimposed on the dc current  $I_C$ .

The slope of the  $i_c - v_{BE}$  curve at the bias point Q is the **transconductance  $g_m$** : the amount of ac current produced by an ac voltage.



# Analysis of transistor circuits at DC

For all circuits: assume transistor operates in linear region  
write B-E voltage loop  
write C-E voltage loop



Example -1

B-E junction acts like a diode

$$V_E = V_B - V_{BE} = 4V - 0.7V = 3.3V$$

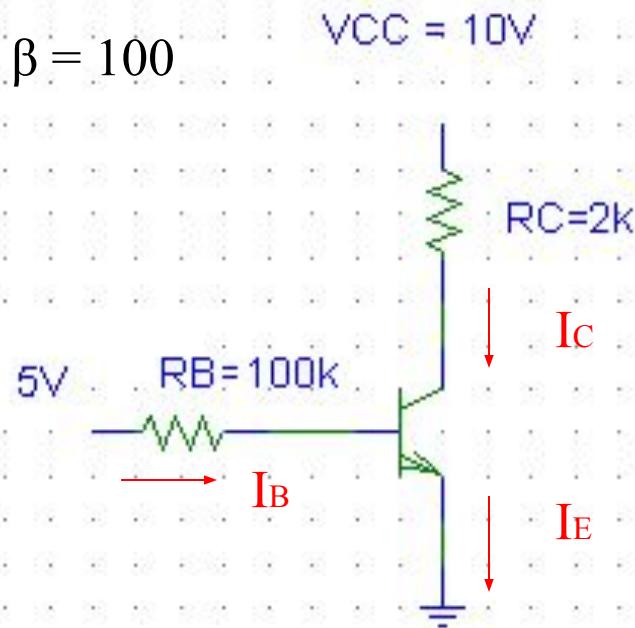
$$I_E = (V_E - 0)/R_E = 3.3/3.3K = 1mA$$

$$I_C \approx I_E = 1mA$$

$$V_C = 10 - I_C R_C = 10 - 1(4.7) = 5.3V$$

## Example-2

$\beta = 100$



B-E Voltage loop

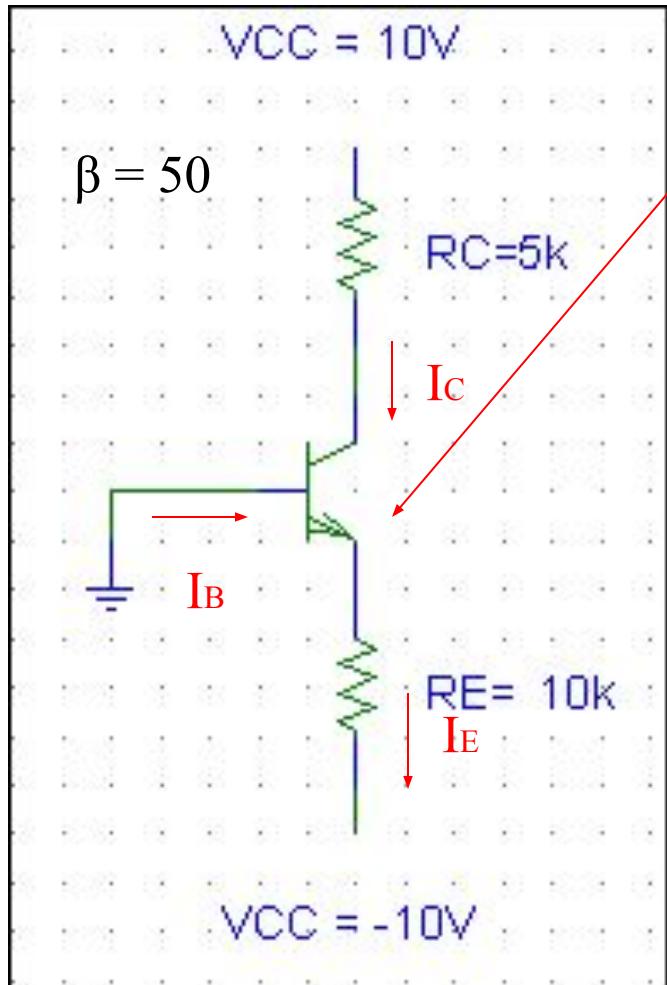
$$5 = I_B R_B + V_{BE}, \text{ solve for } I_B$$

$$I_B = (5 - V_{BE}) / R_B = (5 - .7) / 100k = 0.043mA$$

$$I_C = \beta I_B = (100)0.043mA = 4.3mA$$

$$V_C = 10 - I_C R_C = 10 - 4.3(2) = 1.4V$$

## Exercise-3



$$V_E = 0 - .7 = -0.7V$$

$$I_E = (V_E - -10)/R_E = (-.7 + 10)/10K = 0.93mA$$

$$I_C \approx I_E = 0.93mA$$

$$I_B = I_E/\beta = .93mA/50 = 18.6\mu A$$

$$V_C = 10 - I_C R_C = 10 - .93(5) = 5.35V$$

## Prob.

- Use a voltage divider,  $R_{B1}$  and  $R_{B2}$  to bias  $V_B$  to avoid two power supplies.
- Make the current in the voltage divider about 10 times  $I_B$  to simplify the analysis. Use  $V_B = 3V$  and  $I = 0.2mA$ .

(a)  $R_{B1}$  and  $R_{B2}$  form a voltage divider.

Assume  $I \gg I_B$   $I = V_{CC}/(R_{B1} + R_{B2})$

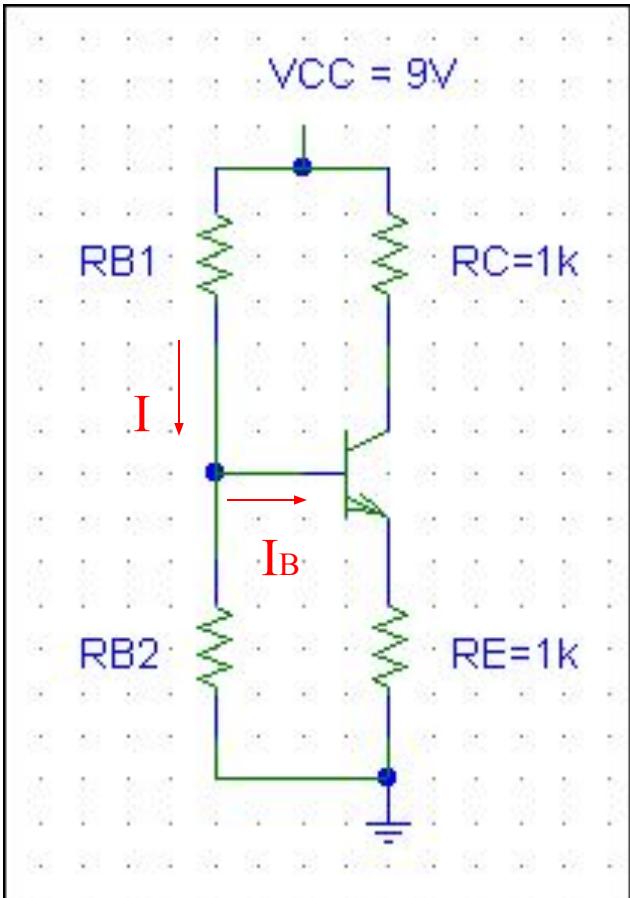
$$.2mA = 9 / (R_{B1} + R_{B2})$$

AND

$$V_B = V_{CC}[R_{B2}/(R_{B1} + R_{B2})]$$

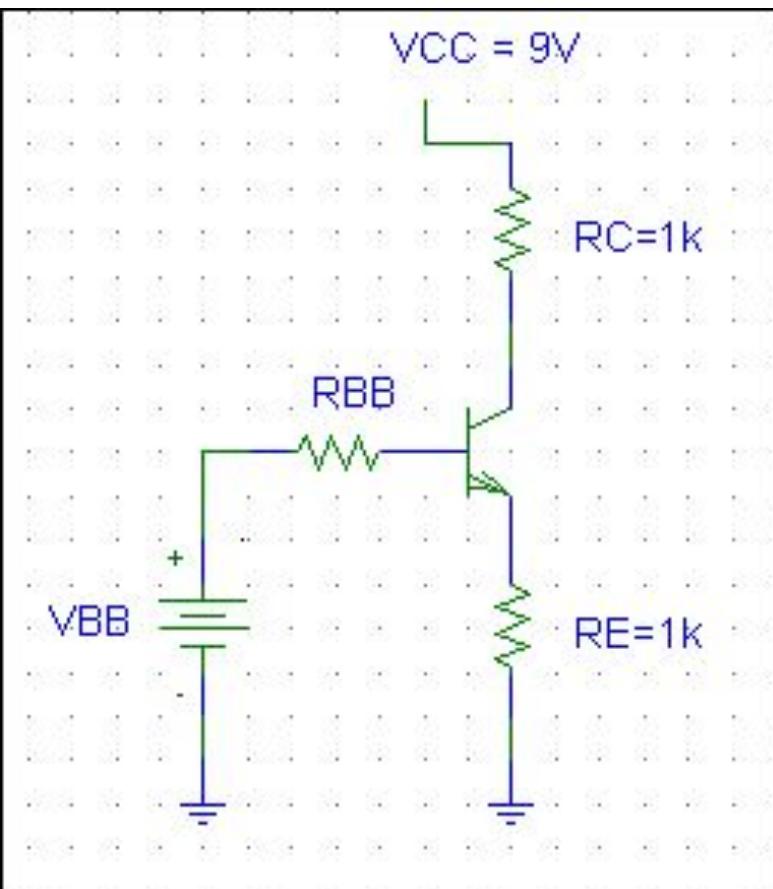
$$3 = 9 [R_{B2}/(R_{B1} + R_{B2})], \text{ Solve for } R_{B1} \text{ and } R_{B2}.$$

$$R_{B1} = 30K\Omega, \text{ and } R_{B2} = 15K\Omega.$$



# Prob.

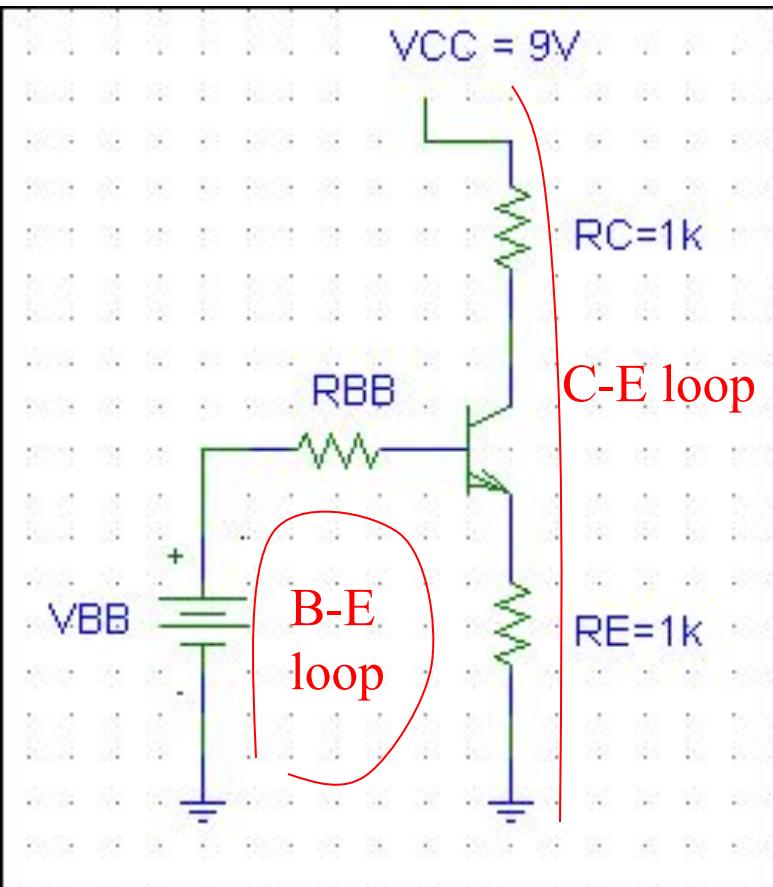
Find the operating point



- Use the Thevenin equivalent circuit for the base
- Makes the circuit simpler
- $V_{BB} = V_B = 3V$
- $R_{BB}$  is measured with voltage sources grounded
- $R_{BB} = R_{B1} \parallel R_{B2} = 30K\Omega \parallel 15K\Omega = 10K\Omega$

# Prob.

Write B-E loop and C-E loop



B-E loop

$$V_{BB} = I_B R_{BB} + V_{BE} + I_E R_E$$

$$I_E = 2.09 \text{ mA}$$

C-E loop

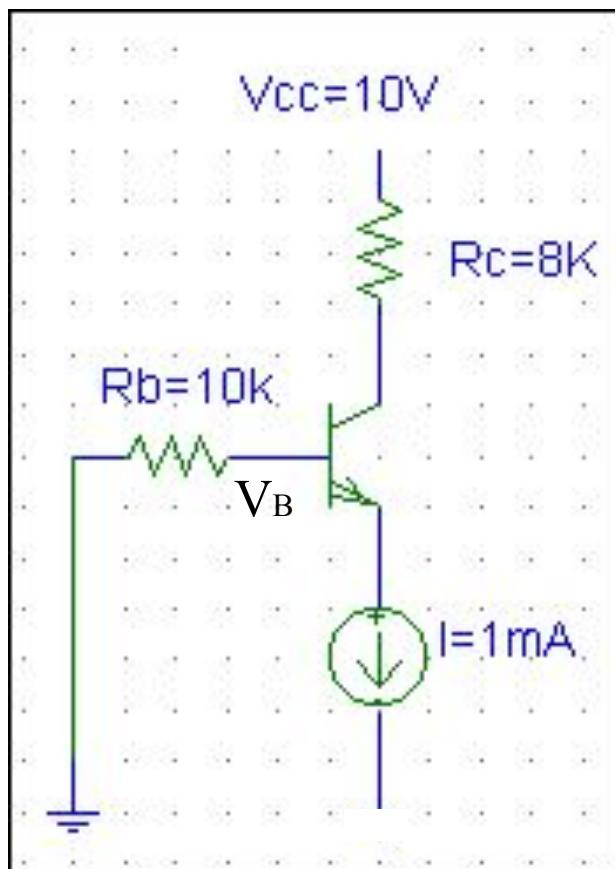
$$V_{CC} = I_C R_C + V_{CE} + I_E R_E$$

$$V_{CE} = 4.8 \text{ V}$$

This is how all DC circuits are analyzed  
and designed!

## Exercise-4

(a) Find  $V_C$ ,  $V_B$ , and  $V_E$ , given:  $\beta = 100$ ,  $V_A = 100V$



$$I_E = 1 \text{ mA}$$

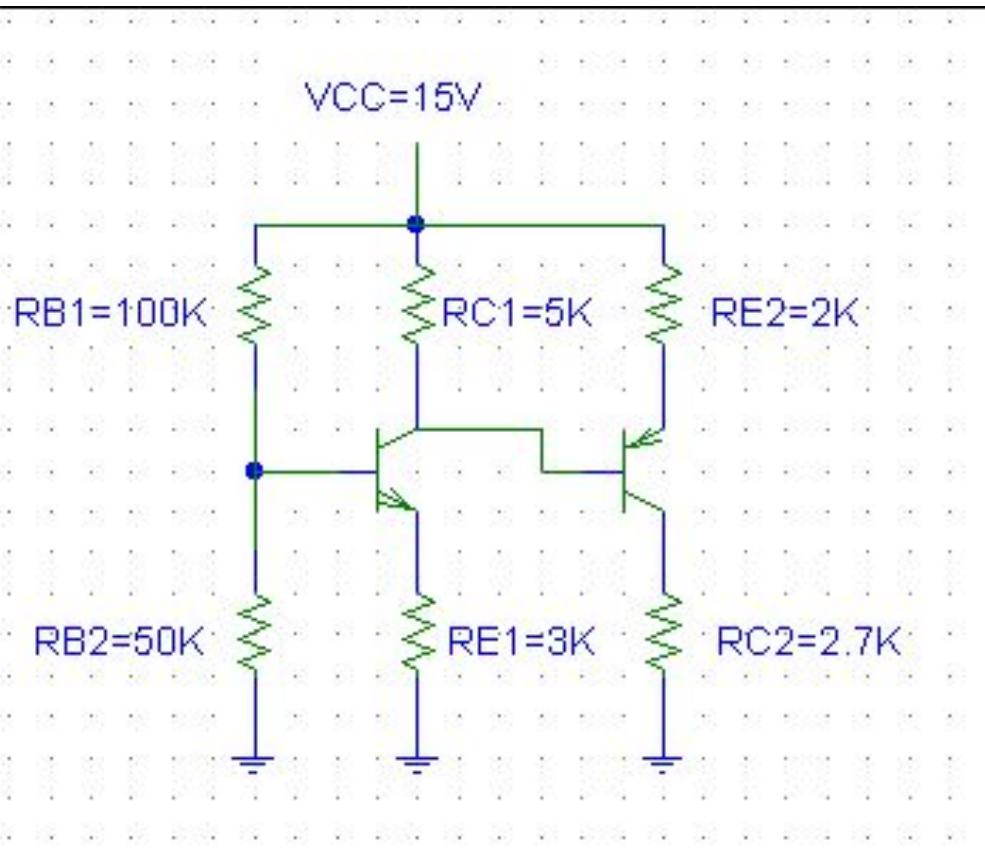
$$I_B \approx I_E/\beta = 0.01 \text{ mA}$$

$$V_B = 0 - I_B 10K = -0.1 \text{ V}$$

$$V_E = V_B - V_{BE} = -0.1 - 0.7 = -0.8 \text{ V}$$

$$V_C = 10V - I_C 8K = 10 - 1(8) = 2 \text{ V}$$

## Example-5



- 2-stage amplifier, 1st stage has an npn transistor; 2nd stage has an pnp transistor.

$$I_C = \beta I_B$$

$$I_C \approx I_E$$

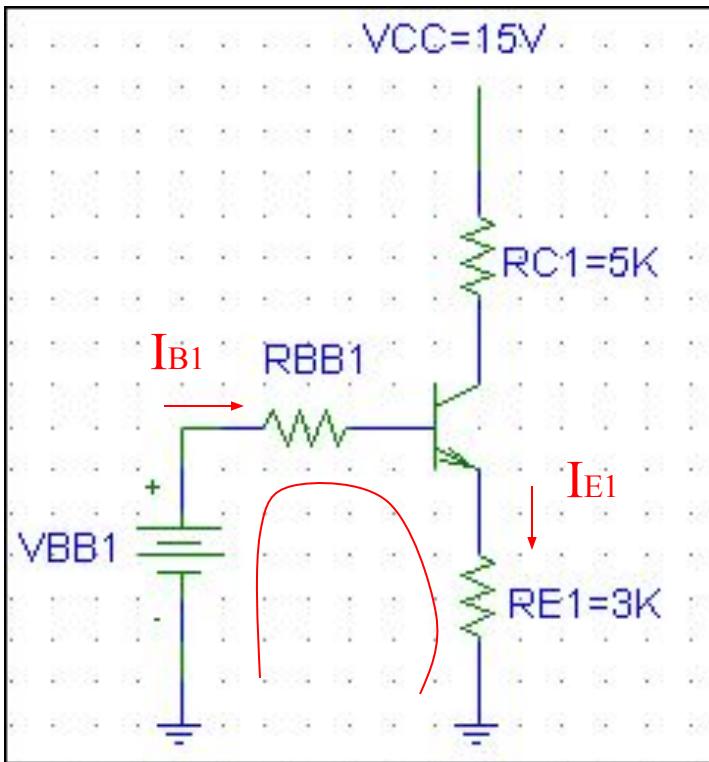
$$V_{BE} = 0.7_{(npn)} = -0.7_{(pnp)}$$

$$\beta = 100$$

Find  $I_{C1}$ ,  $I_{C2}$ ,  $V_{CE1}$ ,  $V_{CE2}$

- Use Thevenin circuits.

## Example -5



- $R_{BB1} = R_{B1} \parallel R_{B2} = 33K$

- $V_{BB1} = V_{CC} [R_{B2}/(R_{B1}+R_{B2})]$

$$V_{BB1} = 15[50K/150K] = 5V$$

Stage 1

- B-E loop

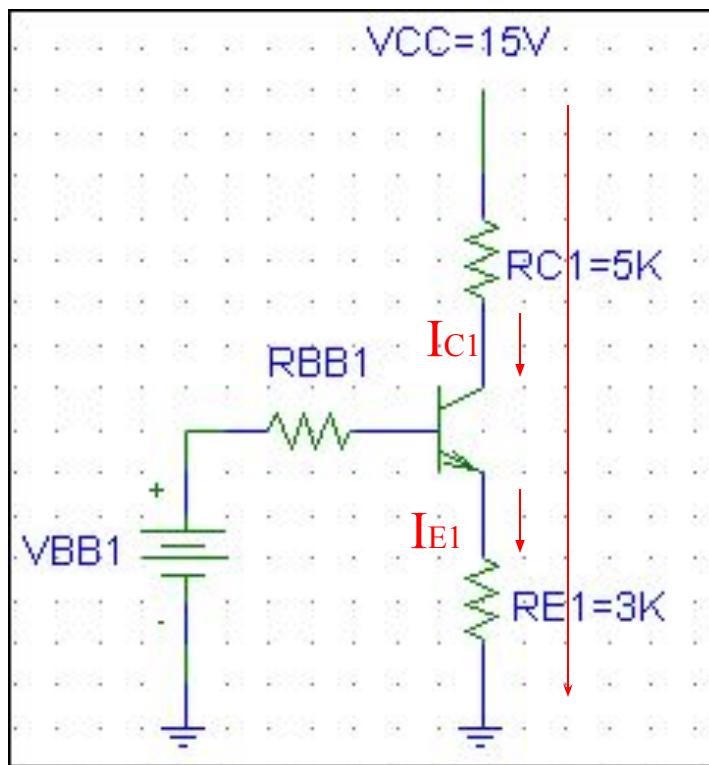
$$V_{BB1} = I_{B1}R_{BB1} + V_{BE} + I_{E1}R_{E1}$$

Use  $I_{B1} \approx I_{E1}/\beta$

$$5 = I_{E1}33K / 100 + .7 + I_{E1}3K$$

$$I_{E1} = 1.3mA$$

## Example -5



C-E loop

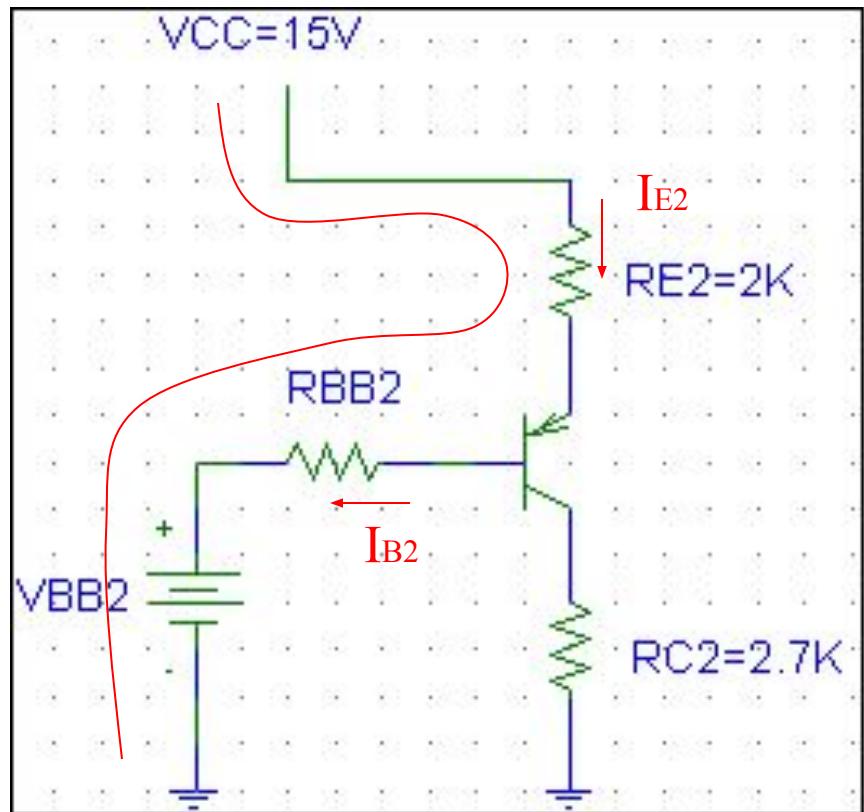
neglect  $IB_2$  because it is  $IB_2 \ll IC_1$

$$V_{CC} = I_{C1}R_{C1} + V_{CE1} + I_{E1}R_{E1}$$

$$15 = 1.3(5) + V_{CE1} + 1.3(3)$$

$$V_{CE1} = 4.87V$$

## Example-5



Stage 2

- B-E loop

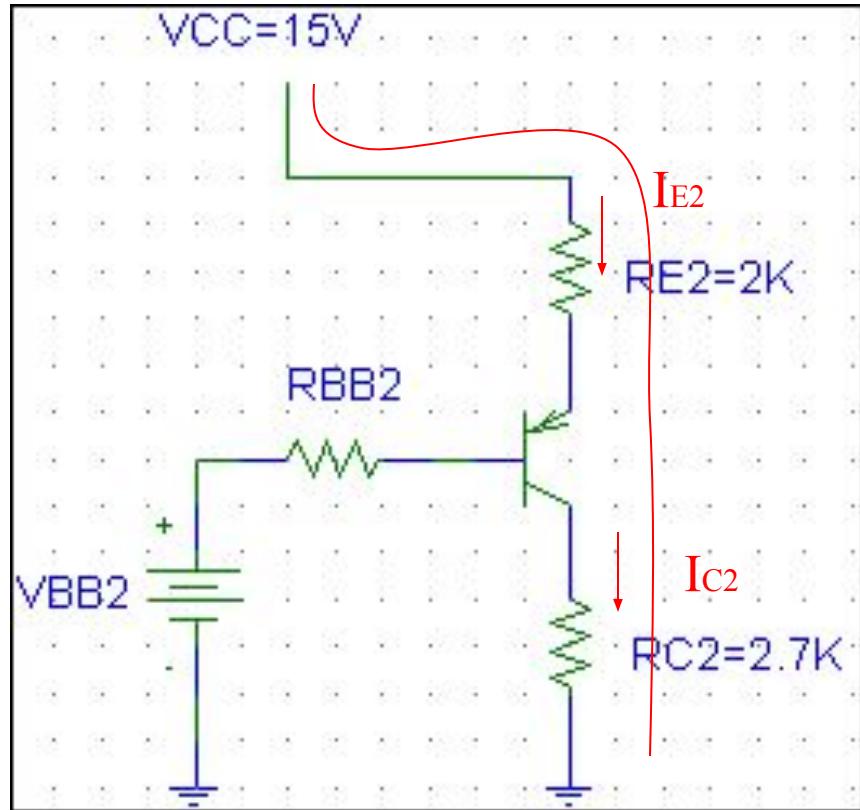
$$V_{CC} = I_{E2}R_{E2} + V_{EB} + I_{B2}R_{BB2} + V_{BB2}$$

$$15 = I_{E2}(2K) + .7 + I_{B2}(5K) + 4.87 + 1.3(3)$$

Use  $I_{B2} \approx I_{E2}/\beta$ , solve for  $I_{E2}$

$$I_{E2} = 2.8 \text{mA}$$

## Example-5



Stage 2

- C-E loop

$$V_{CC} = I_{E2}R_{E2} + V_{EC2} + I_{C2}R_{C2}$$

$$15 = 2.8(2) + V_{EC2} + 2.8(2.7)$$

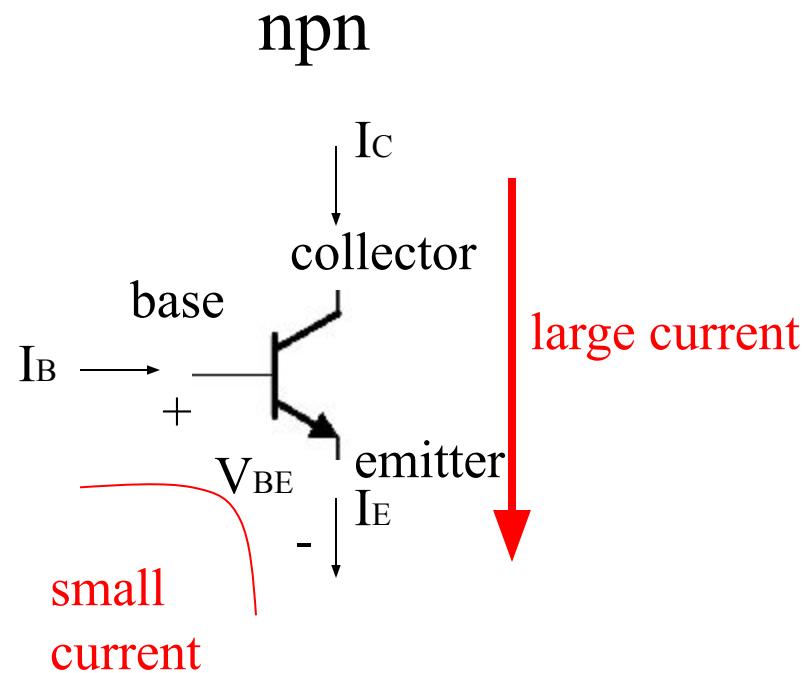
solve for  $V_{EC2}$

$$V_{CE2} = 1.84V$$

## Summary of DC problem

- Bias transistors so that they operate in the linear region B-E junction forward biased, C-E junction reversed biased
- Use  $V_{BE} = 0.7$  (npn),  $I_C \approx I_E$ ,  $I_C = \beta I_B$
- Represent base portion of circuit by the Thevenin circuit
- Write B-E, and C-E voltage loops.
- For analysis, solve for  $I_C$ , and  $V_{CE}$ .
- For design, solve for resistor values ( $I_C$  and  $V_{CE}$  specified).

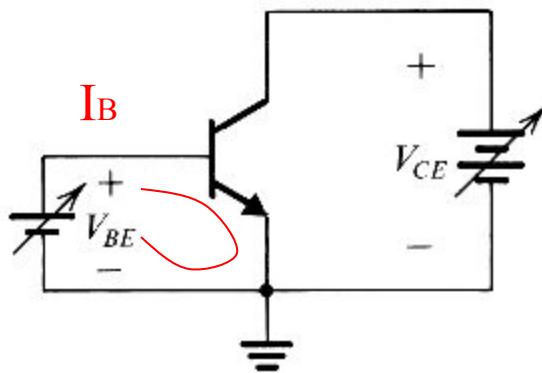
## Summary of npn transistor behavior



## Transistor as an amplifier

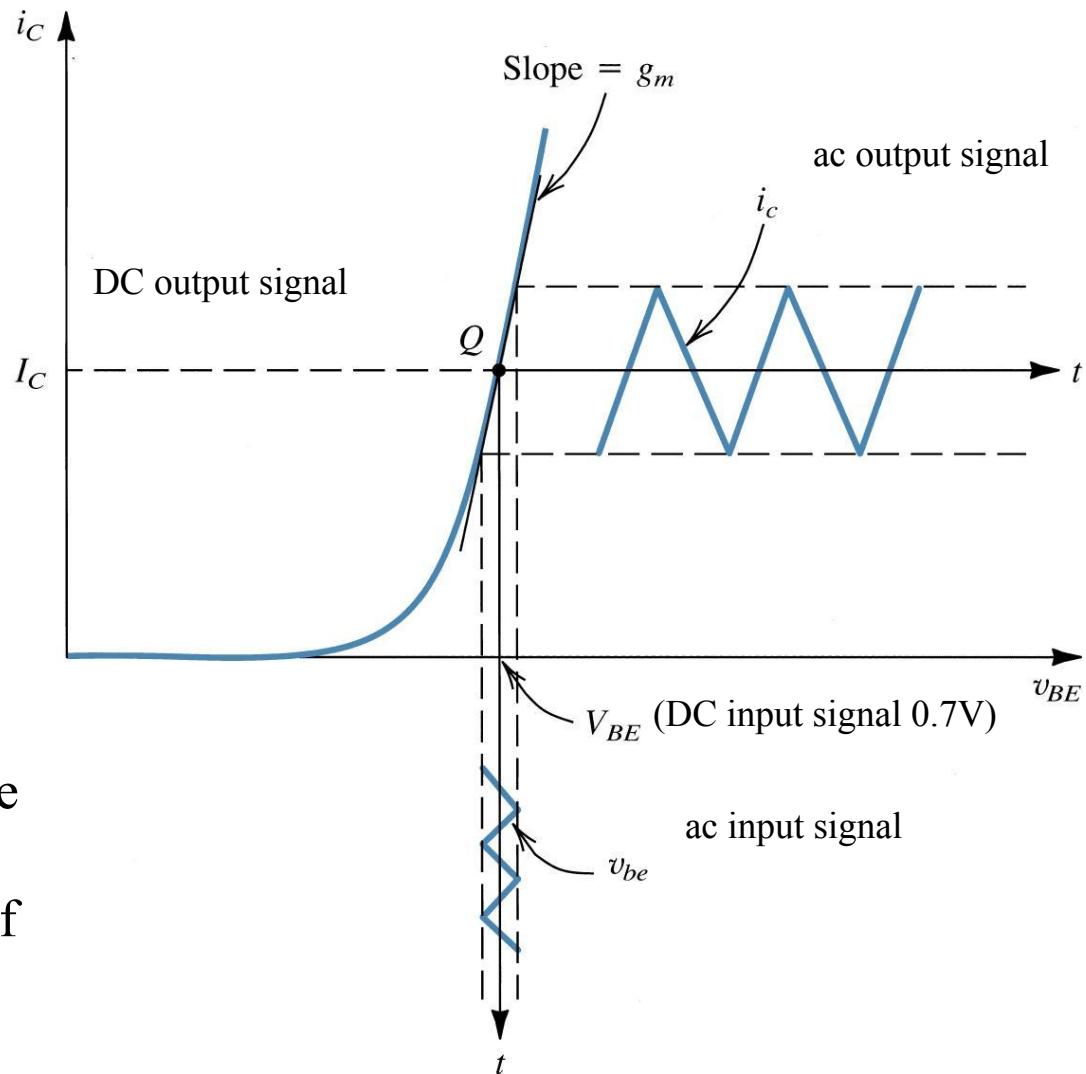
- Transistor circuits are analyzed and designed in terms of DC and ac versions of the same circuit.
- An ac signal is usually superimposed on the DC circuit.
- The location of the operating point (values of  $I_C$  and  $V_{CE}$ ) of the transistor affects the ac operation of the circuit.
- There are at least two ac parameters determined from DC quantities.

# Transconductance



A small ac signal  $v_{be}$  is superimposed on the DC voltage  $V_{BE}$ . It gives rise to a collector signal current  $i_c$ , superimposed on the dc current  $I_C$ .

The slope of the  $i_c - v_{BE}$  curve at the bias point Q is the **transconductance  $g_m$** : the amount of ac current produced by an ac voltage.



# Transconductance

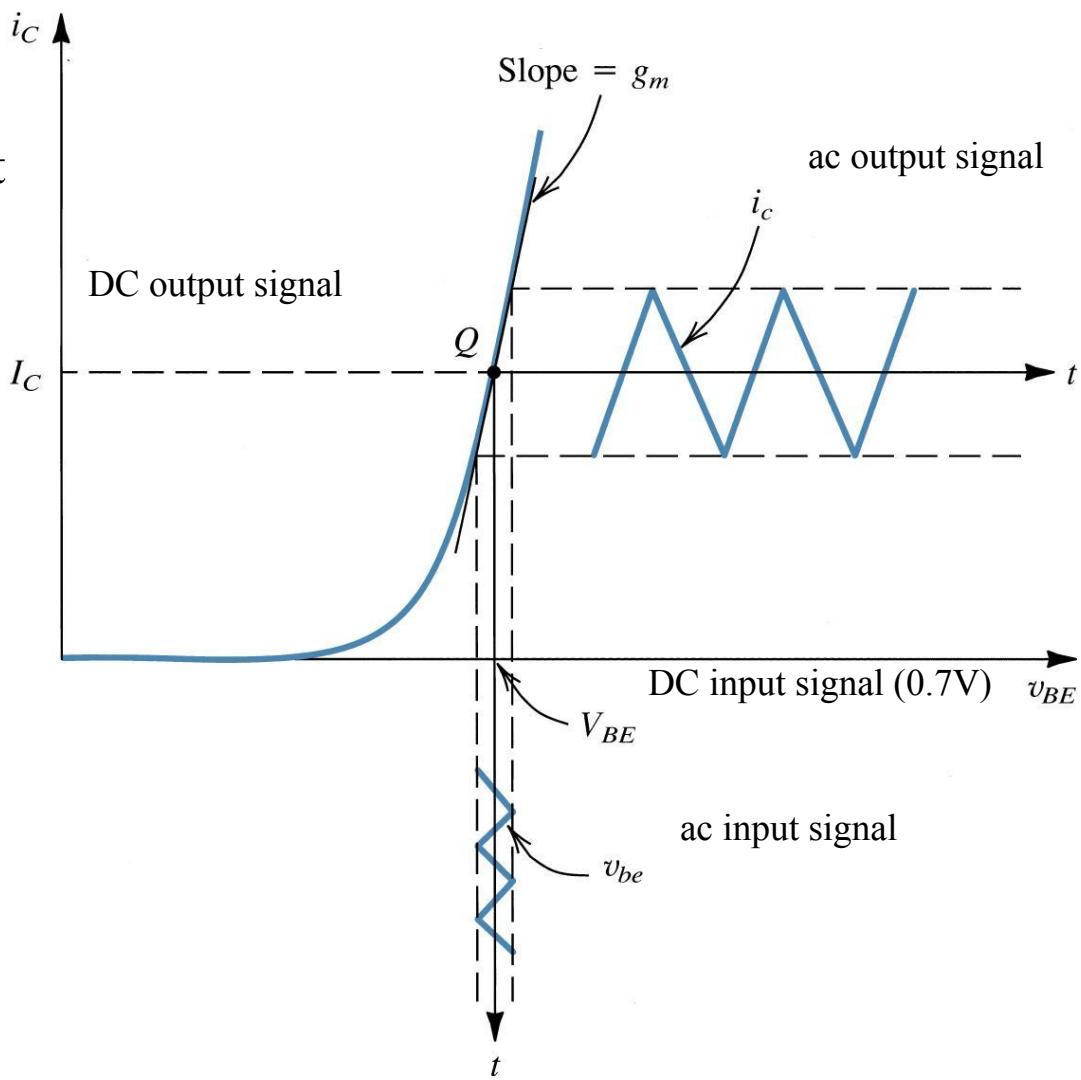
Transconductance = slope at Q point

$$g_m = di_c/dv_{BE} \Big|_{i_c = ICQ}$$

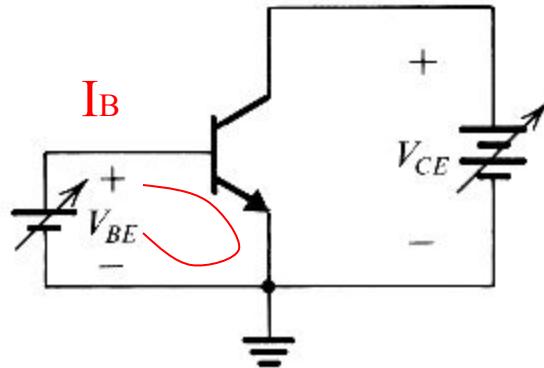
where  $I_c = I_s[\exp(-V_{BE}/V_T) - 1]$ ; the equation for a diode.

$$g_m = I_s \exp(-V_{BE}/V_T) (1/V_T)$$

$$g_m \approx I_c/V_T \text{ (A/V)}$$



# ac input resistance of transistor

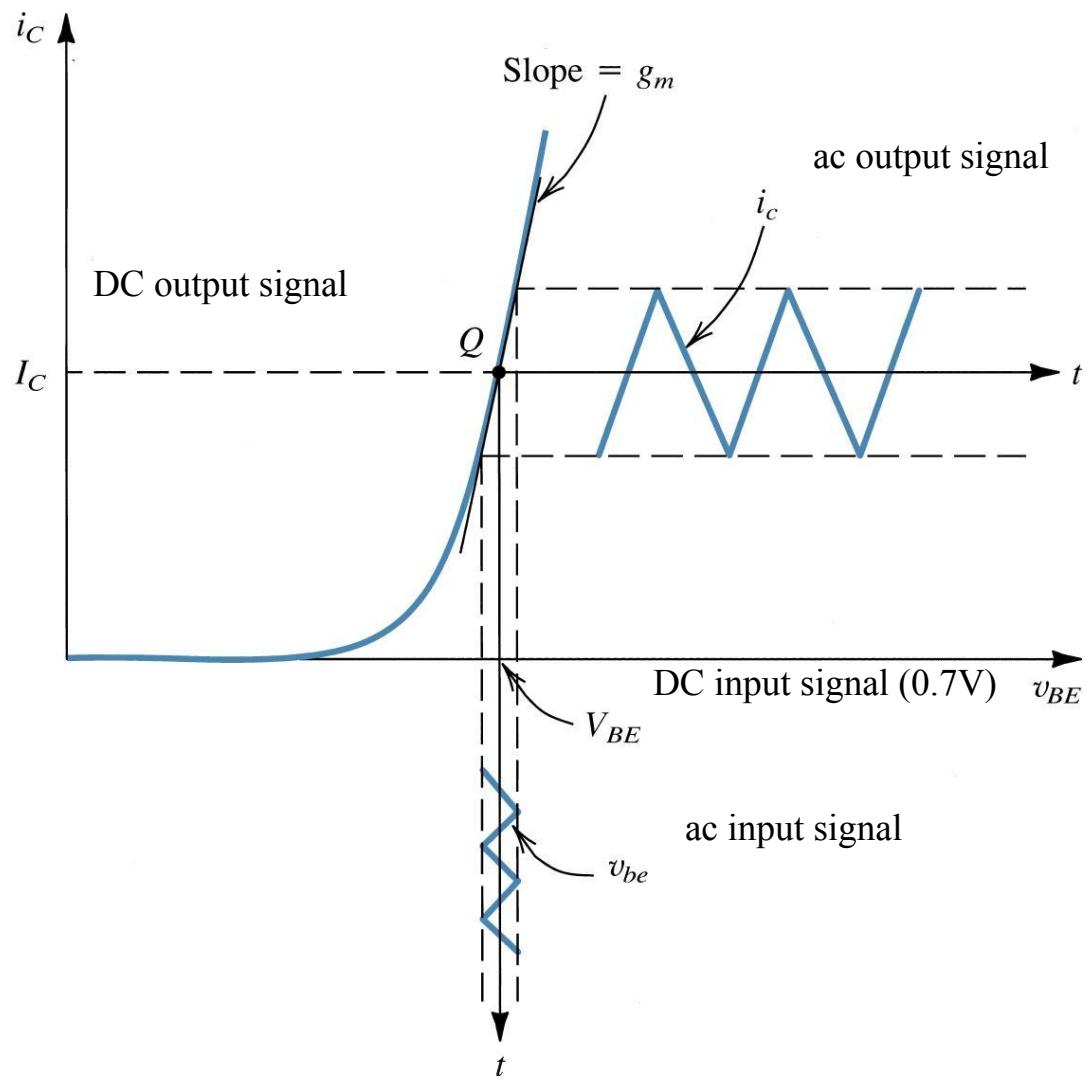


ac input resistance  $\propto 1/\text{slope at } Q$   
point

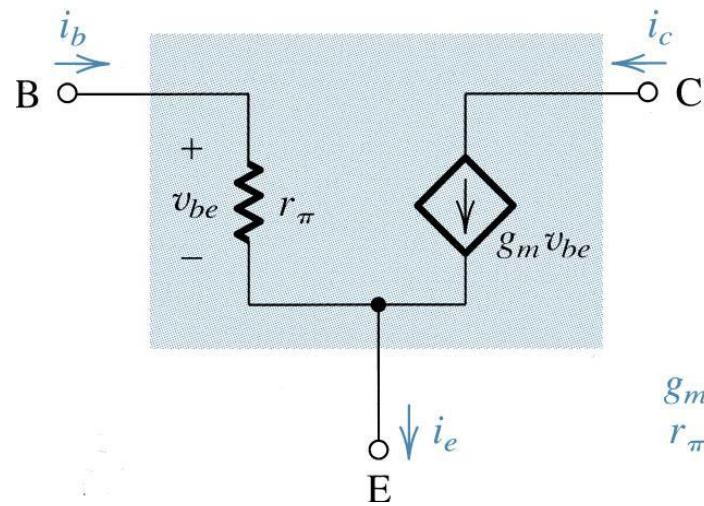
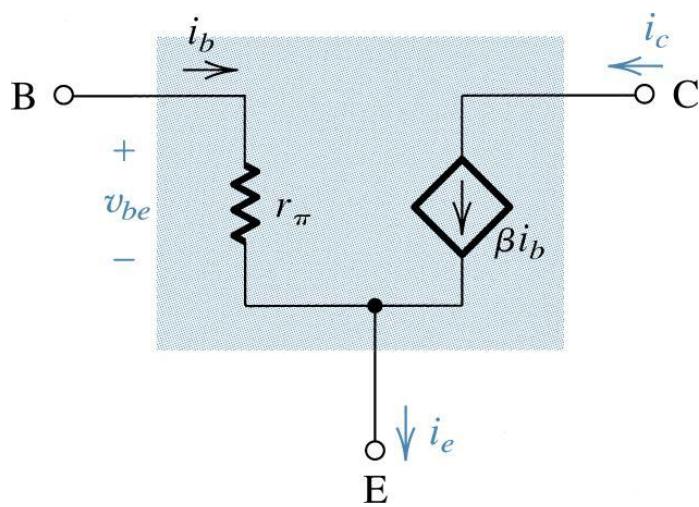
$$r_\pi = \frac{dV_{BE}}{di_b} \Big|_{ic = ICQ}$$

$$r_\pi \approx V_T / I_B$$

$$r_e \approx V_T / I_E$$



# Small-signal equivalent circuit models



$$g_m = I_C / V_T$$
$$r_\pi = \beta / g_m$$

- ac model
- Hybrid- $\pi$  model
- They are equivalent
- Works in linear region only

# Steps to analyze a transistor circuit

## 1 DC problem

Set ac sources to zero, solve for DC quantities,  $I_C$  and  $V_{CE}$ .

## 2 Determine ac quantities from DC parameters

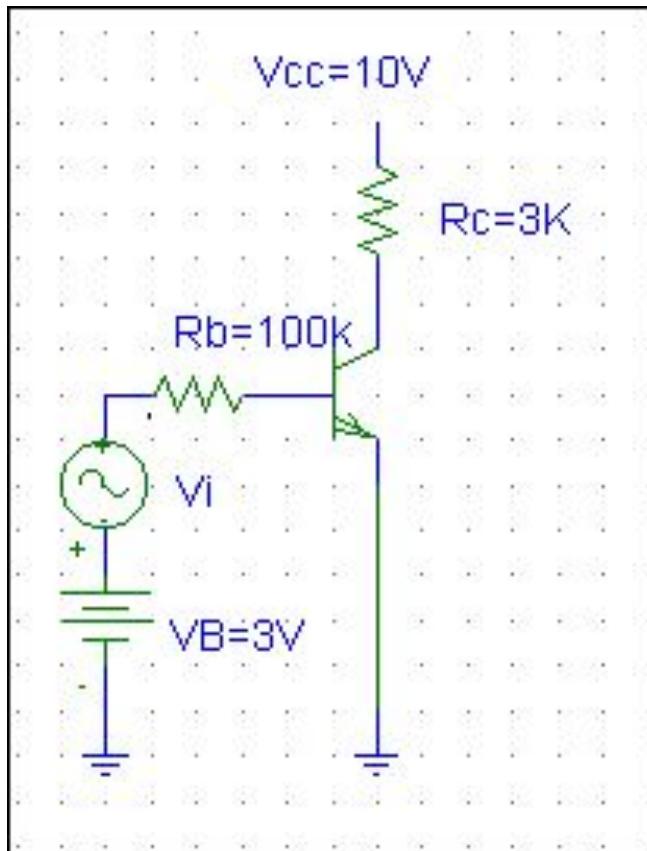
Find  $g_m$ ,  $r_\pi$ , and  $r_e$ .

## 3 ac problem

Set DC sources to zero, replace transistor by hybrid- $\pi$  model, find ac quantities,  $R_{in}$ ,  $R_{out}$ ,  $A_v$ , and  $A_i$ .

## Example-6

Find  $V_{out}/V_{in}$ , ( $\beta = 100$ )



DC problem

Short  $V_i$ , determine  $I_c$  and  $V_{CE}$

B-E voltage loop

$$3 = I_B R_B + V_{BE}$$

$$I_B = (3 - .7)/R_B = 0.023\text{mA}$$

C-E voltage loop

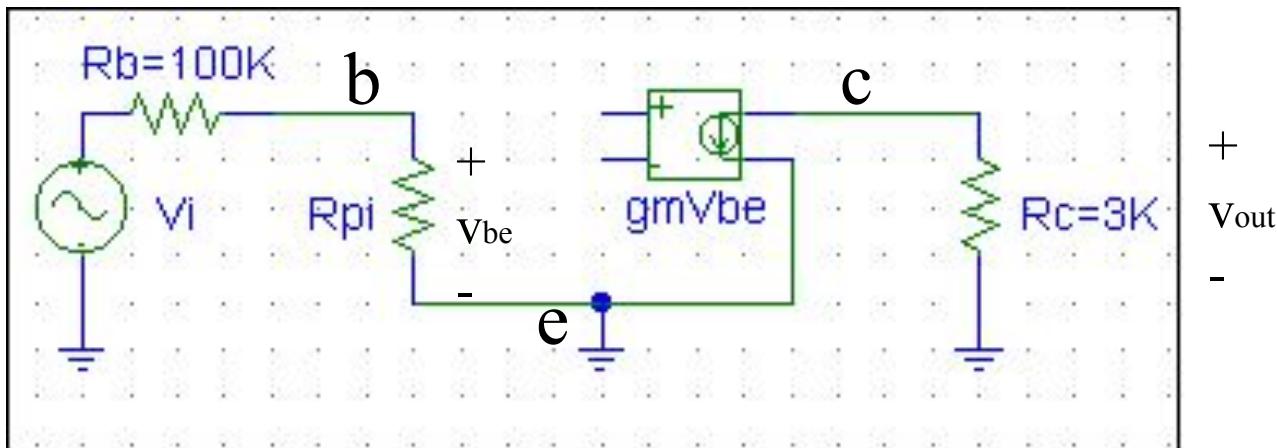
$$V_{CE} = 10 - I_c R_c$$

$$V_{CE} = 10 - (2.3)(3)$$

$$V_{CE} = 3.1\text{V}$$

Q point:  $V_{CE} = 3.1\text{V}$ ,  $I_c = 2.3\text{mA}$

## Example -6



ac problem

Short DC sources, input and output circuits are separate, only coupled mathematically

$$g_m = I_c/V_T = 2.3\text{mA}/25\text{mV} = 92\text{mA/V}$$

$$r_\pi = V_T/I_B = 25\text{mV}/.023\text{mA} = 1.1\text{K}$$

$$V_{be} = V_i [r_\pi / (100\text{K} + r_\pi)] = 0.011V_i$$

$$V_{out} = - g_m V_{be} R_C$$

$$V_{out} = - 92(0.011V_i)3\text{K}$$

$$V_{out}/V_i = -3.04$$

## Exercise-7

Find  $g_m$ ,  $r_\pi$ , and  $r_0$ , given:  $\beta = 100$ ,  $V_A = 100V$ ,  $I_C = 1 \text{ mA}$

$$g_m = I_C/V_T = 1 \text{ mA}/25\text{mV} = 40 \text{ mA/V}$$

$$r_\pi = V_T/ I_B = 25\text{mV}/.01\text{mA} = 2.5\text{K}$$

$r_0$  = output resistance of transistor

$r_0$  = 1/slope of transistor output characteristics

$$r_0 = |V_A|/I_C = 100\text{K}$$

## Summary of transistor analysis

- Transistor circuits are analyzed and designed in terms of DC and ac versions of the same circuit.
- An ac signal is usually superimposed on the DC circuit.
- The location of the operating point (values of  $I_C$  and  $V_{CE}$ ) of the transistor affects the ac operation of the circuit.
- There are at least two ac parameters determined from DC quantities.

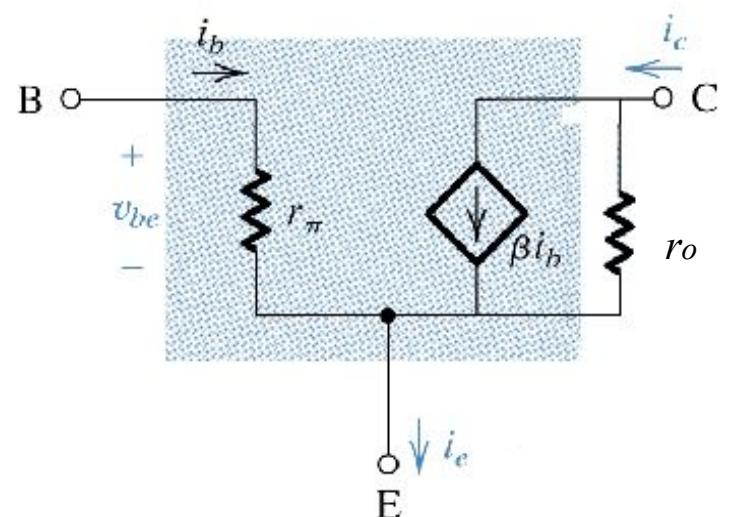
# Steps to analyze a transistor circuit

1 DC Analysis Set ac sources to zero, solve for DC quantities,  $I_C$  and  $V_{CE}$ .

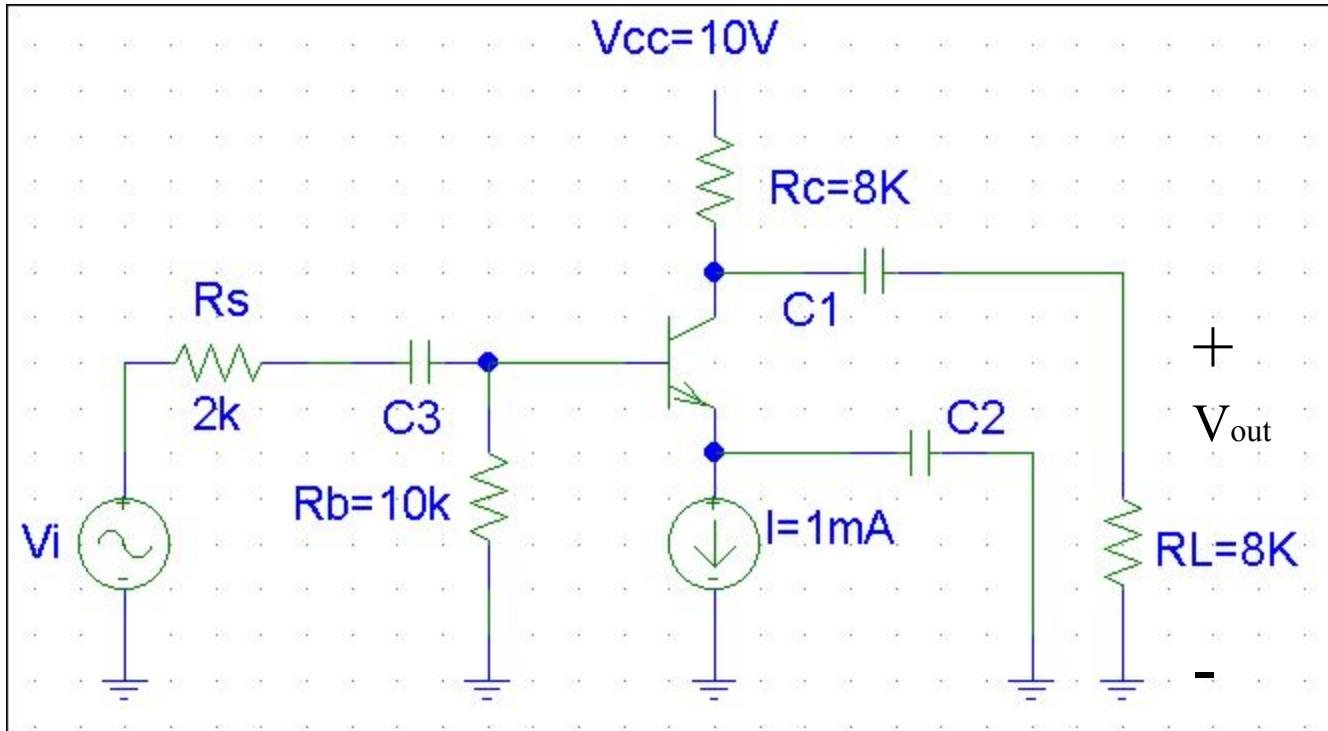
2 Determine ac quantities from DC parameters  
Find  $g_m$ ,  $r_\pi$ , and  $r_o$ .

3 AC Analysis

Set DC sources to zero, replace transistor by hybrid- $\pi$  model, find ac quantities,  $R_{in}$ ,  $R_{out}$ ,  $A_v$ , and  $A_i$ .



# Circuit



$$I_E = 1 \text{ mA}$$

$$V_C = 10\text{V} - I_c 8\text{K} = 10 - 1(8) = 2\text{V}$$

$$I_B \approx I_E/\beta = 0.01\text{mA}$$

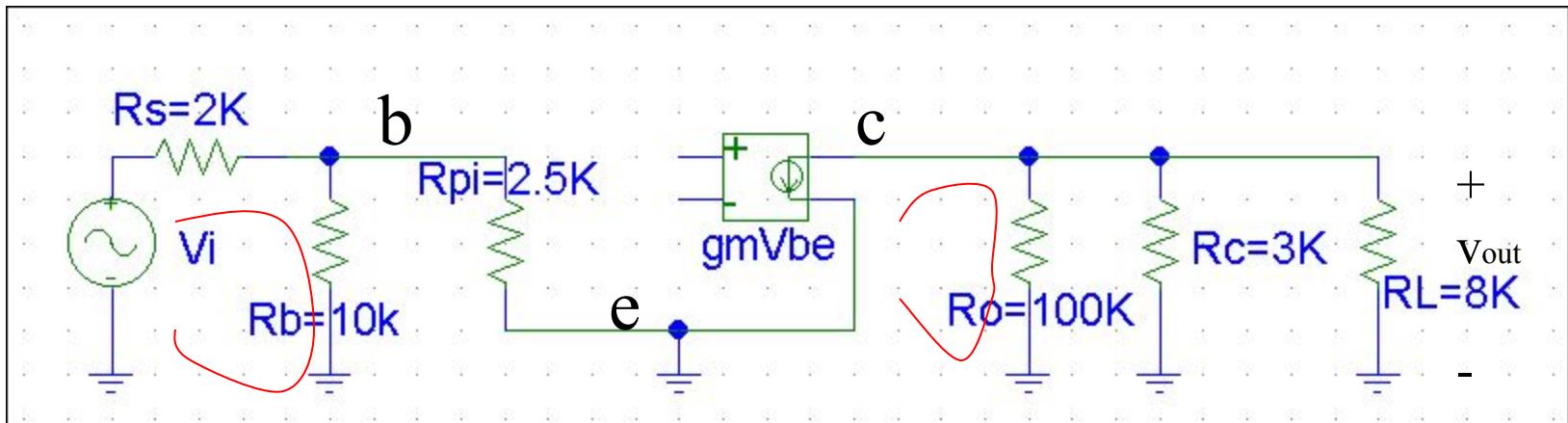
$$g_m = I_c/V_T = 1 \text{ mA}/25\text{mV} = 40 \text{ mA/V}$$

$$V_B = 0 - I_B 10\text{K} = -0.1\text{V}$$

$$r_\pi = V_T / I_B = 25\text{mV}/.01\text{mA} = 2.5\text{K}$$

$$V_E = V_B - V_{BE} = -0.1 - 0.7 = -0.8\text{V}$$

# ac equivalent circuit



$$V_{be} = (R_b \parallel R_{pi}) / [(R_b \parallel R_{pi}) + R_s] V_i$$

$$V_{be} = 0.5 V_i$$

Neglecting  $R_o$

$$V_{out} = -(g_m V_{be}) \parallel (R_c \parallel R_L)$$

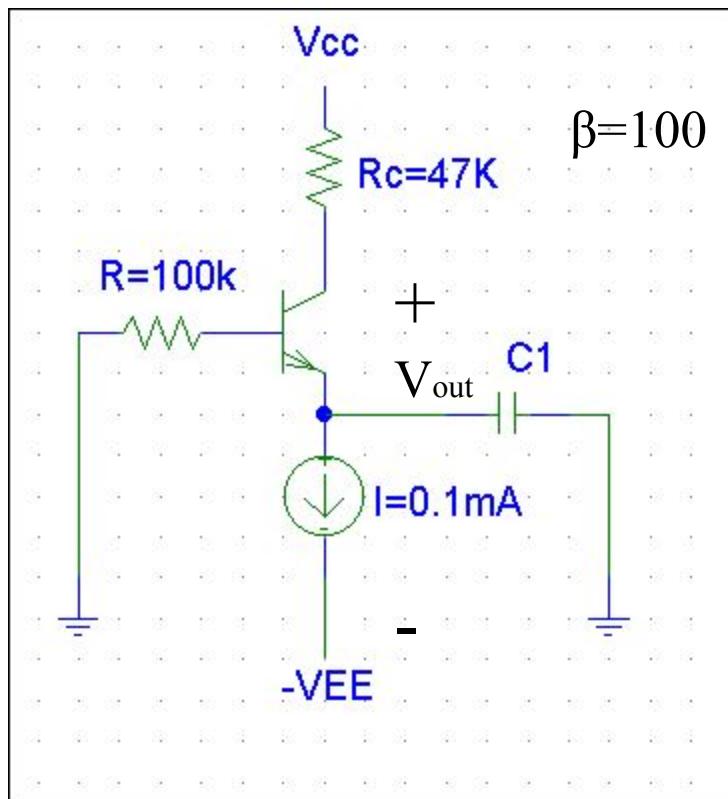
$$A_v = V_{out}/V_i = -80$$

$$V_{out} = -(g_m V_{be}) \parallel (R_o \parallel R_c \parallel R_L)$$

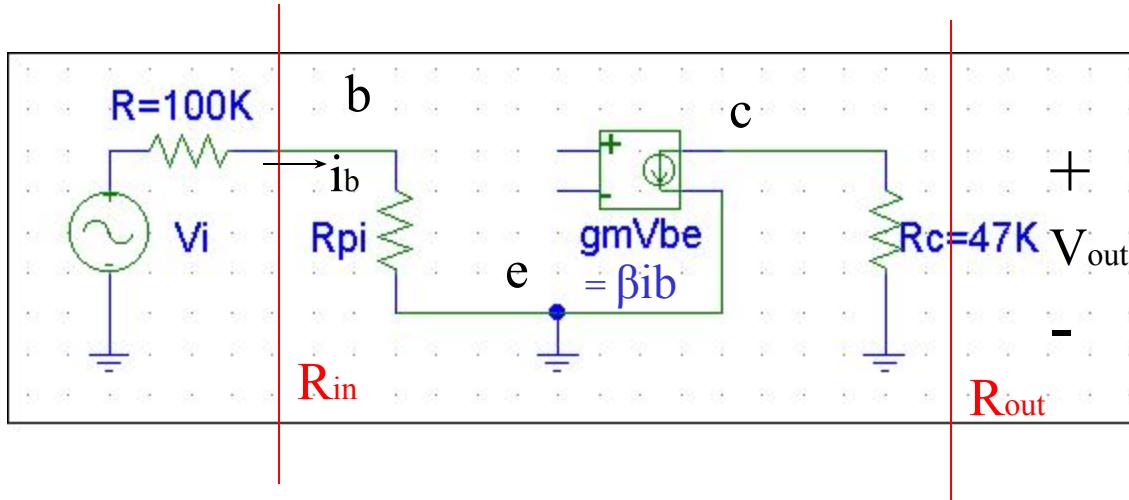
$$V_{out} = -154 V_{be}$$

$$A_v = V_{out}/V_i = -77$$

# Prob.



# Prob.



(a) Find  $R_{in}$

$$R_{in} = R_{pi} = V_T/I_B = (25\text{mV})100/.1 = 2.5\text{K}\Omega$$

(c) Find  $R_{out}$

$$R_{out} = R_c = 47\text{K}\Omega$$

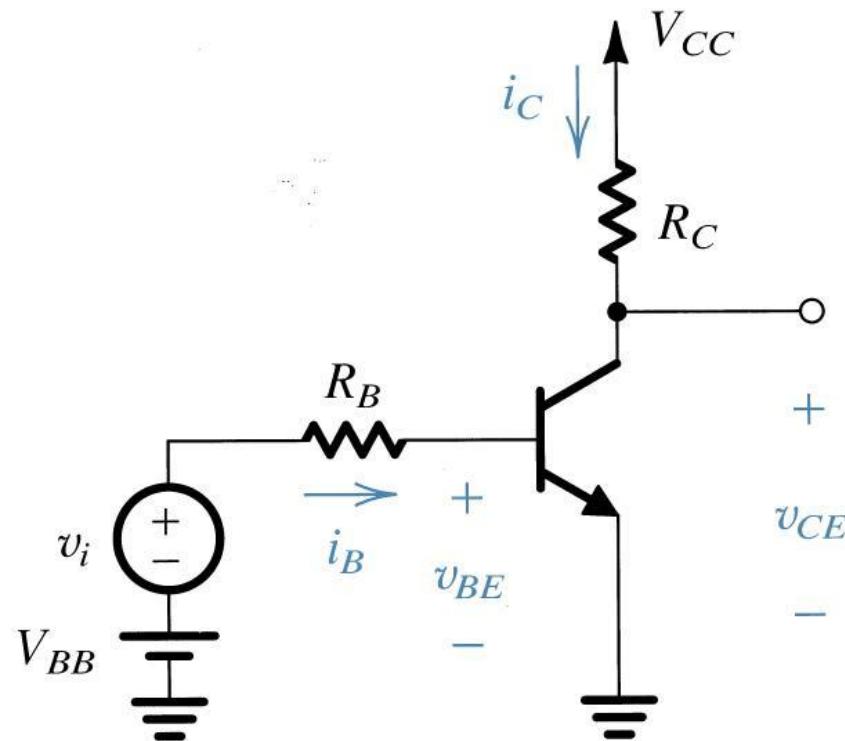
(b) Find  $A_v = V_{out}/V_{in}$

$$V_{out} = - \beta i_b R_c$$

$$V_{in} = i_b (R + R_{pi})$$

$$\begin{aligned} A_v &= V_{out}/V_{in} = - \beta i_b R_c / i_b (R + R_{pi}) \\ &= - \beta R_c / (R + R_{pi}) \\ &= - 100(47\text{K}) / (100\text{K} + 2.5\text{K}) \\ &= - 37.6 \end{aligned}$$

# Graphical analysis

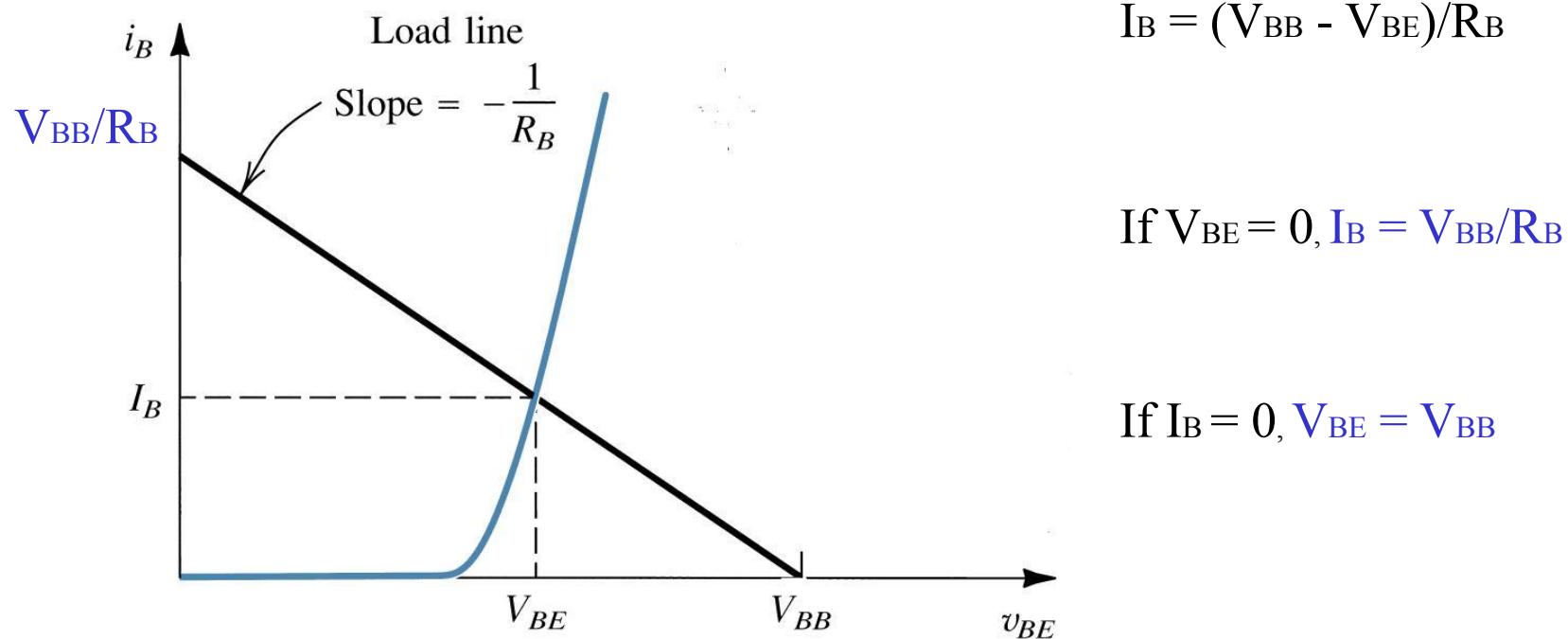


Input circuit  
B-E voltage loop

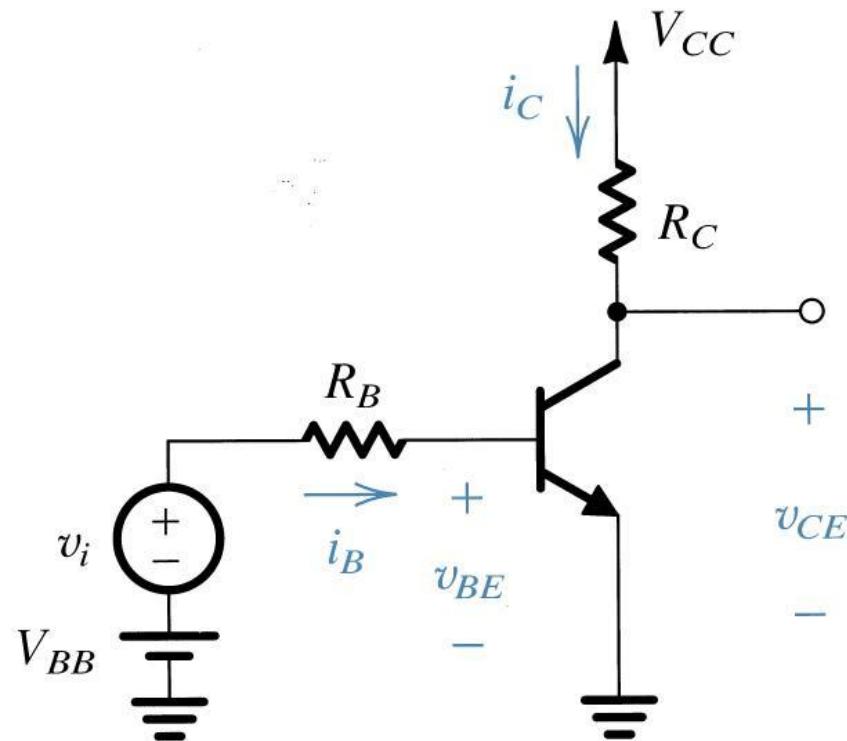
$$V_{BB} = I_B R_B + V_{BE}$$

$$I_B = (V_{BB} - V_{BE})/R_B$$

## Graphical construction of $I_B$ and $V_{BE}$



# Load line

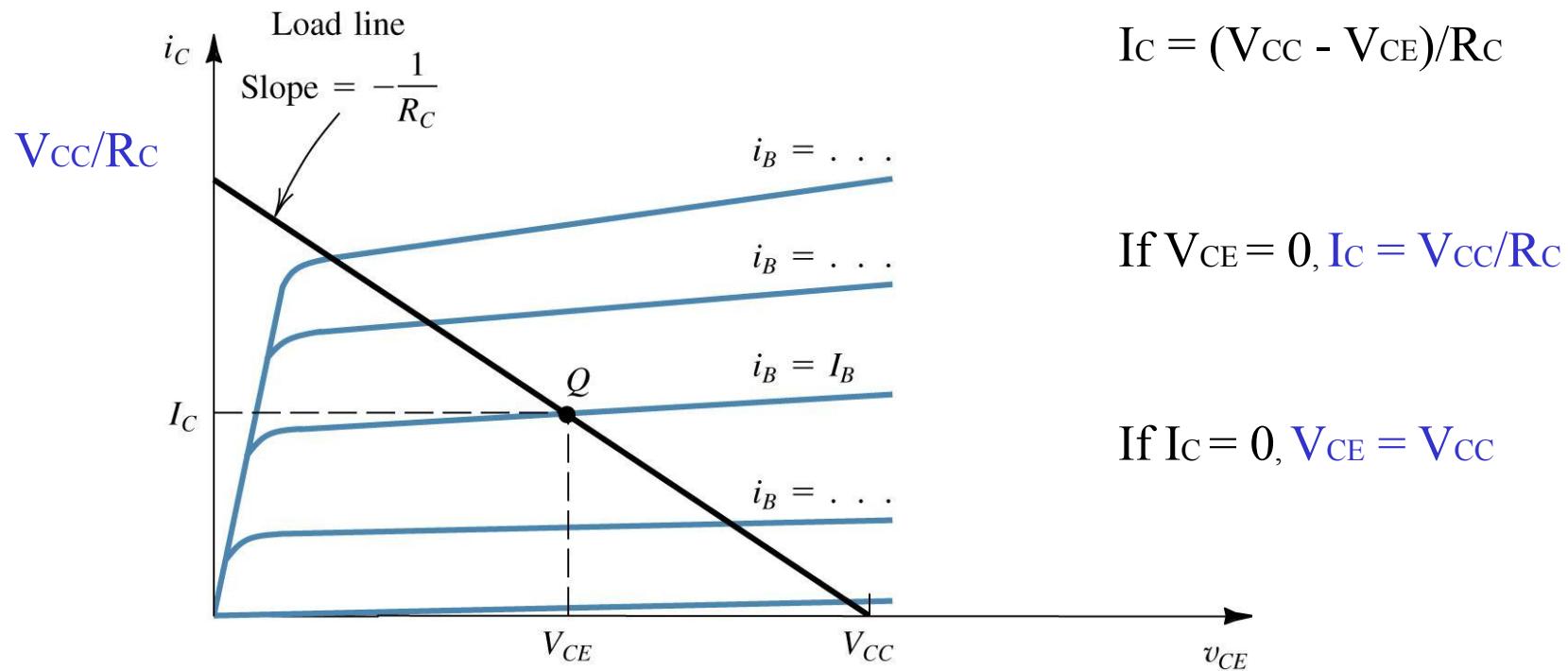


Output circuit  
C-E voltage loop

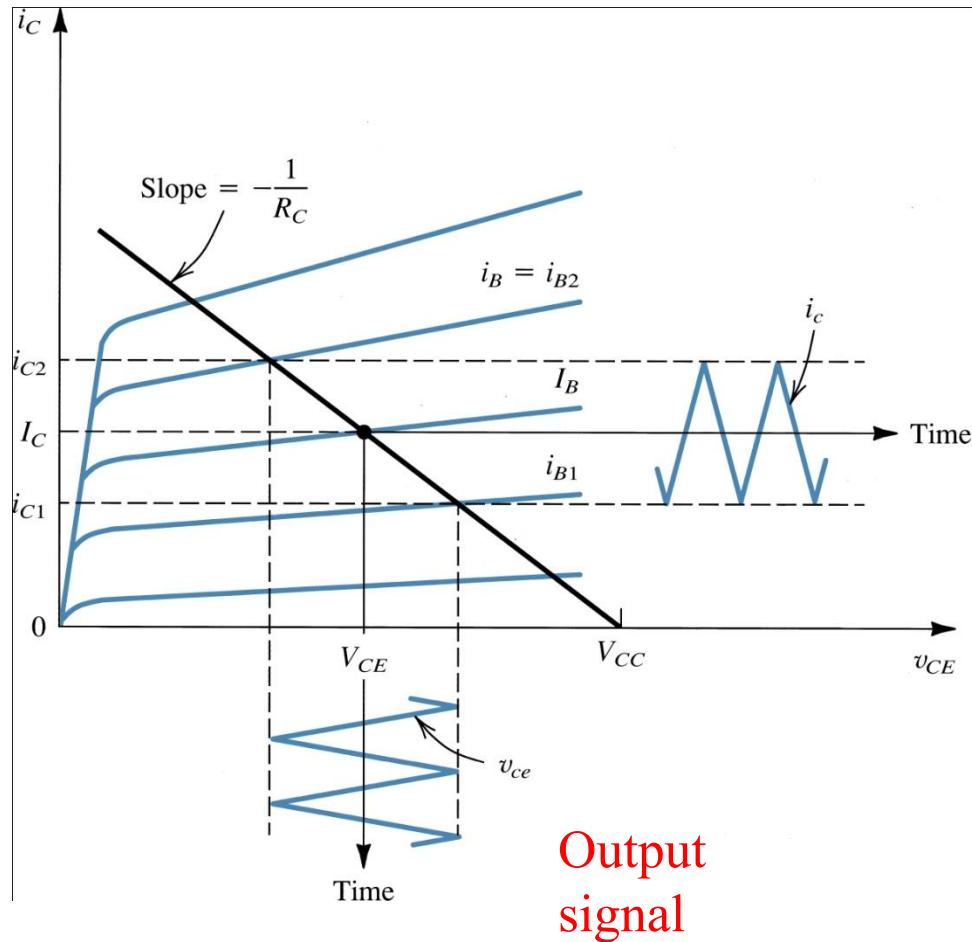
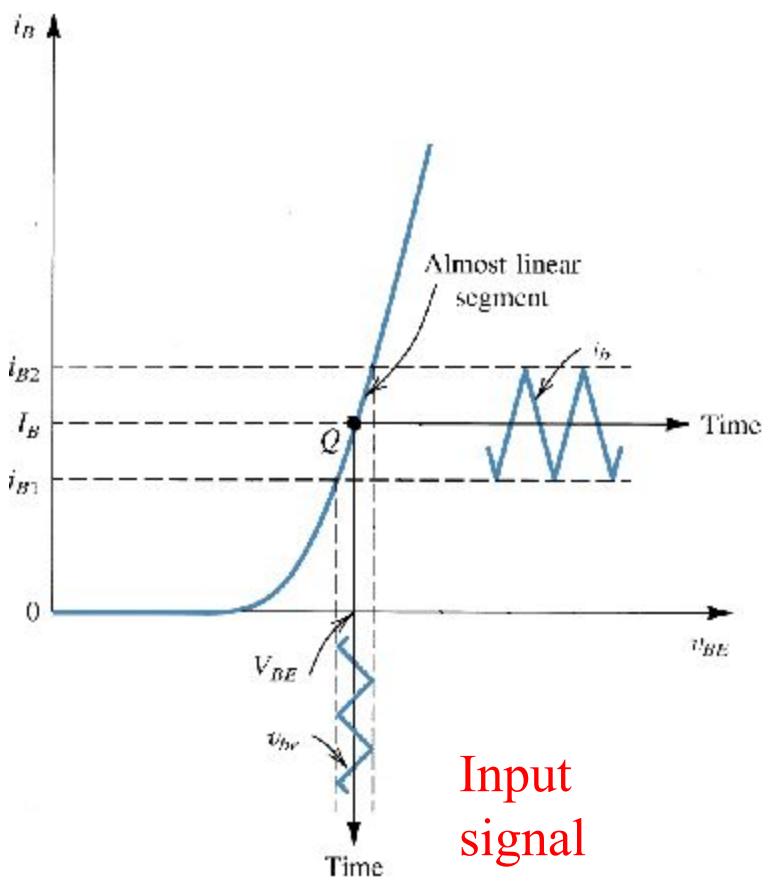
$$V_{CC} = I_C R_C + V_{CE}$$

$$I_C = (V_{CC} - V_{CE})/R_C$$

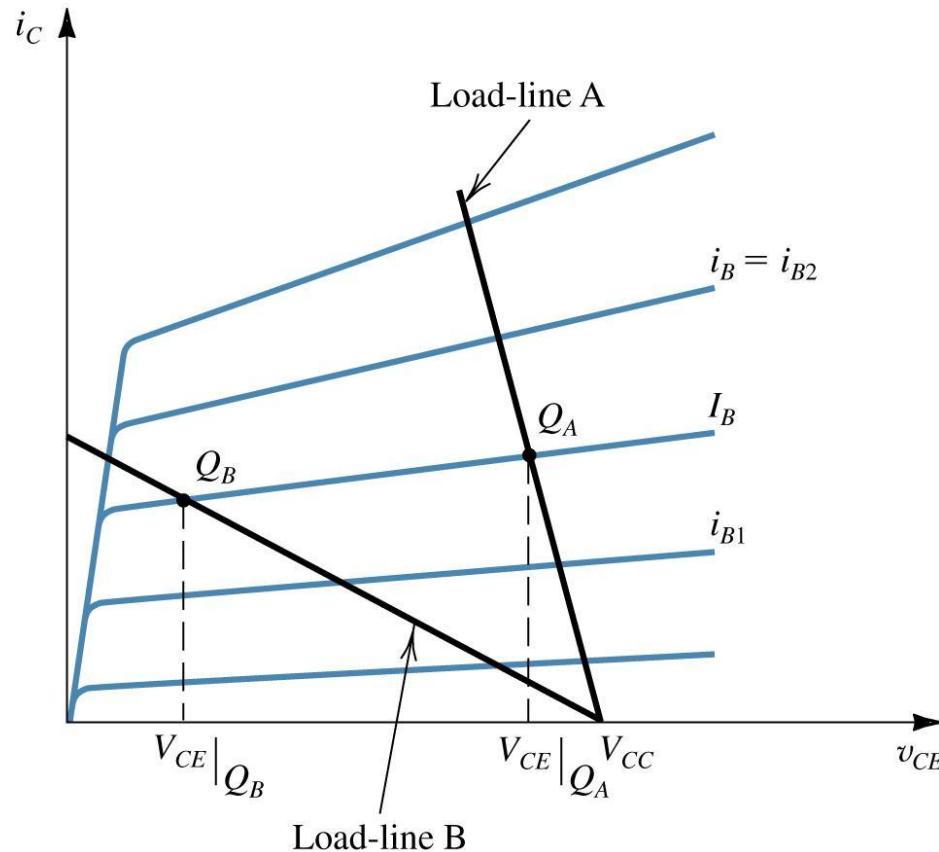
# Graphical construction of $I_C$ and $V_{CE}$



# Graphical analysis



# Bias point location effects



- Load-line A results in bias point  $Q_A$  which is too close to  $V_{CC}$  and thus limits the positive swing of  $v_{CE}$ .
- Load-line B results in an operating point too close to the saturation region, thus limiting the negative swing of  $v_{CE}$ .

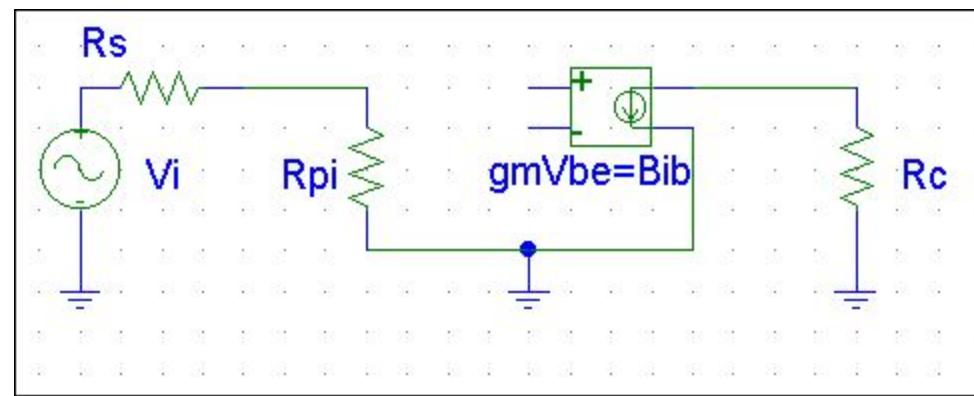
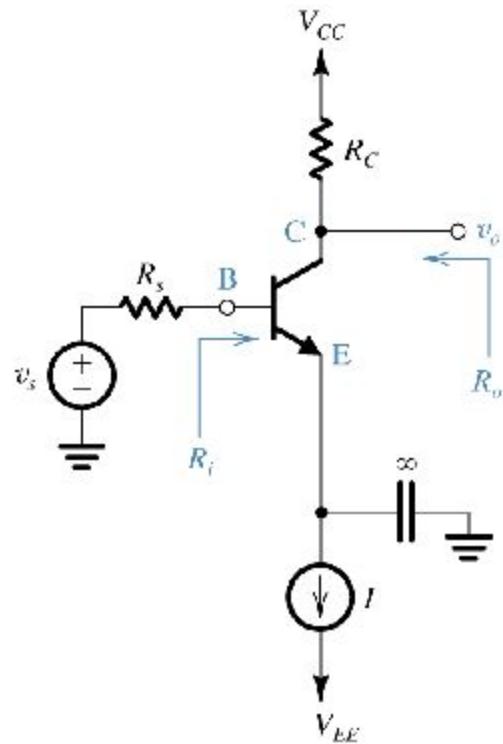
# Basic single-stage BJT amplifier configurations

We will study 3 types of BJT amplifiers

- CE - common emitter**, used for  $A_v$ ,  $A_i$ , and general purpose
- CE with  $R_E$  - common emitter with  $R_E$** ,  
same as CE but more stable
- CC common collector**, used for  $A_i$ , low output resistance,  
used as an output stage

CB common base (not covered)

# Common emitter amplifier



ac equivalent circuit

# Common emitter amplifier

$R_{in}$

(Does not include source)

$$R_{in} = R_{pi}$$

$R_{out}$

(Does not include load)

$$R_{out} = R_C$$

$A_v$

$$= V_{out}/V_{in}$$

$$V_{out} = -\beta i_b R_C$$

$$V_{in} = i_b(R_s + R_{pi})$$

$$A_v = -\beta R_C / (R_s + R_{pi})$$

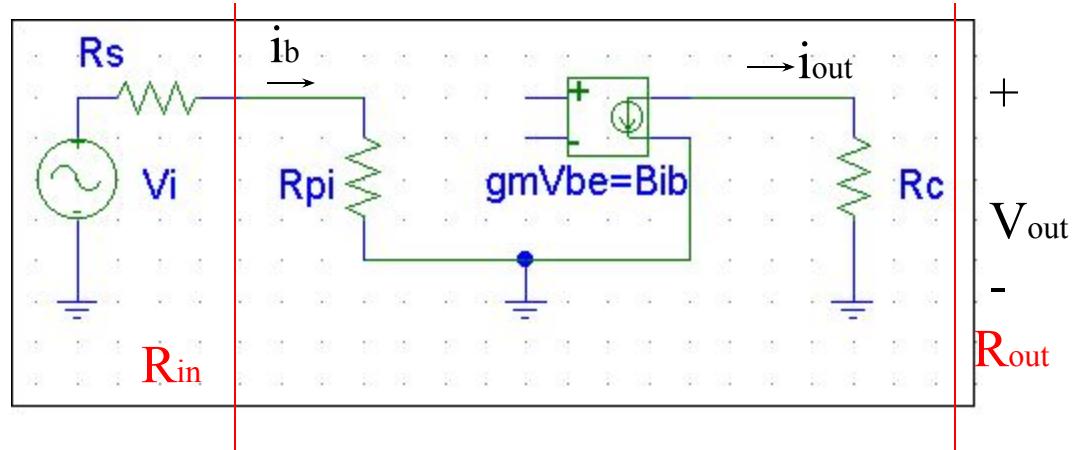
$$A_i = -\beta$$

$A_i$

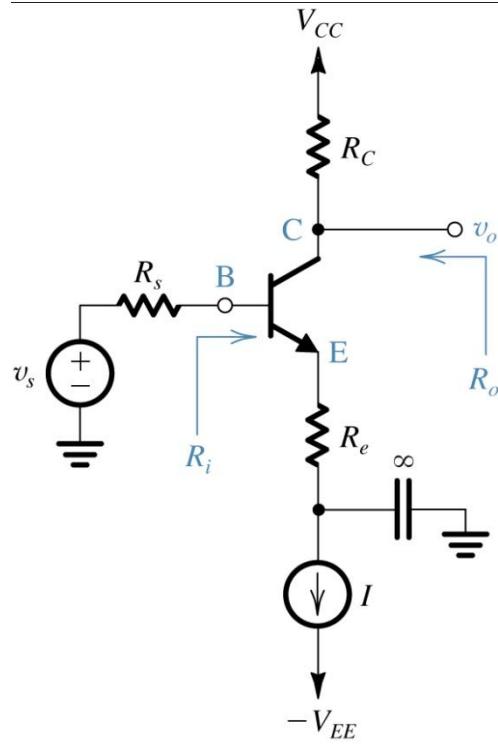
$$= i_{out}/i_{in}$$

$$i_{out} = -\beta i_b$$

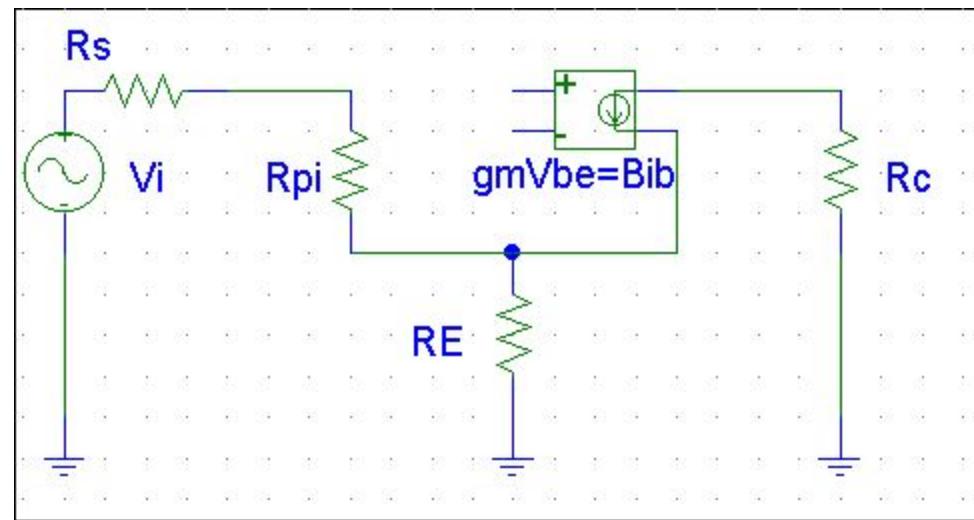
$$i_{in} = i_b$$



# Common emitter with $R_E$ amplifier



(a)



ac equivalent circuit

# Common emitter with $R_E$ amplifier

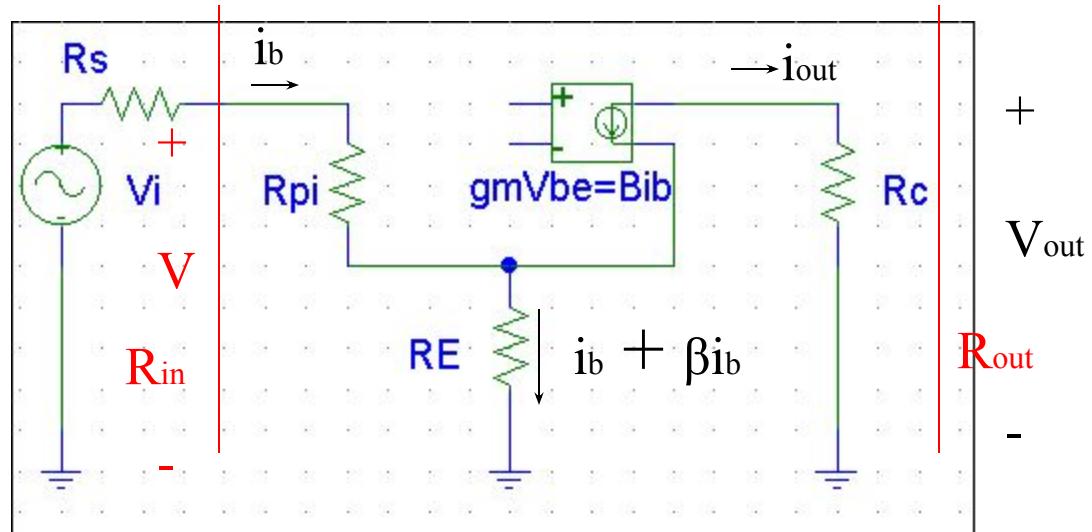
$R_{in}$

$$R_{in} = V/i_b$$

$$V = i_b R_{pi} + (i_b + \beta i_b) R_E$$

$$R_{in} = R_{pi} + (1 + \beta) R_E$$

(usually large)



$R_{out}$

$$R_{out} = R_C$$

$A_v$

$$= V_{out}/V_{in}$$

$$V_{out} = -\beta i_b R_C$$

$$V_{in} = i_b R_s + i_b R_{pi} + (i_b + \beta i_b) R_E$$

$$A_v = -\beta R_C / (R_s + R_{pi} + (1 + \beta) R_E)$$

(less than CE, but less sensitive to  $\beta$  variations)

$A_i$

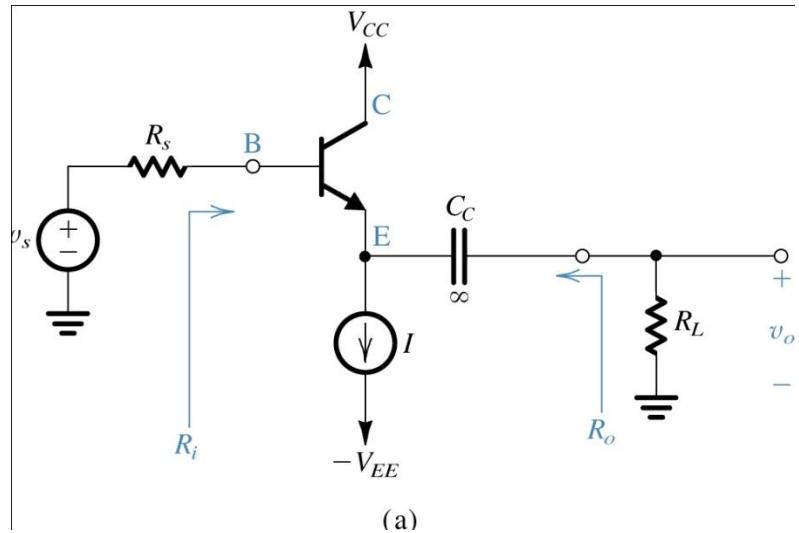
$$= i_{out}/i_{in}$$

$$i_{out} = -\beta i_b$$

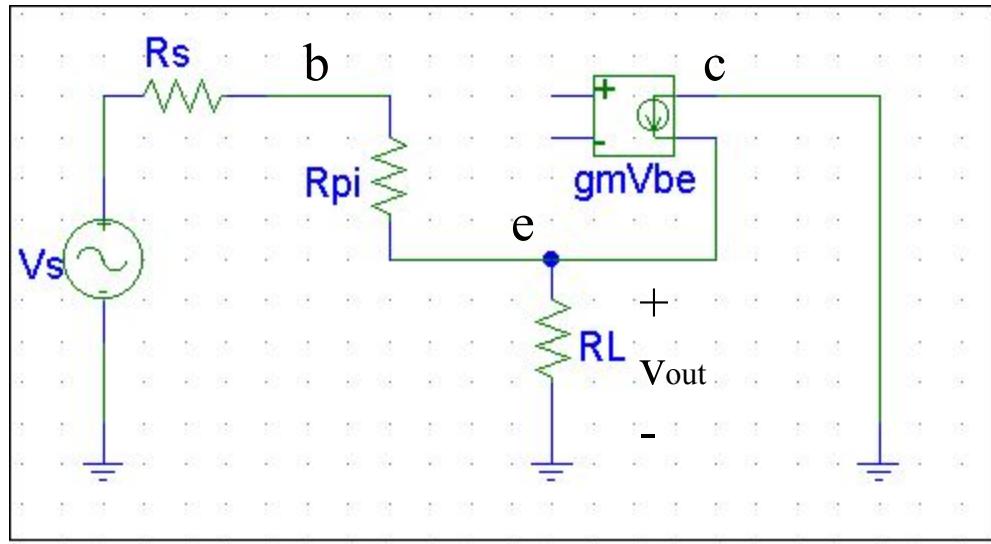
$$i_{in} = i_b$$

$$A_i = -\beta$$

# Common collector (emitter follower) amplifier



( $v_{out}$  at emitter)



ac equivalent circuit

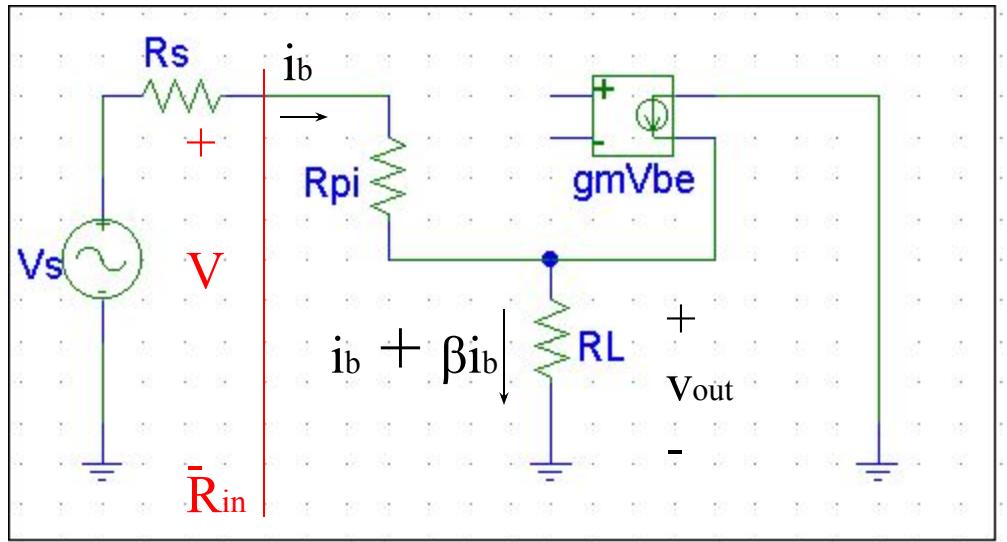
# Common collector amplifier

$R_{in}$

$$R_{in} = V/i_b$$

$$V = i_b R_{pi} + (i_b + \beta i_b) R_L$$

$$R_{in} = R_{pi} + (1 + \beta) R_L$$



$A_v$

$$= V_{out}/V_s$$

$$V_{out} = (i_b + \beta i_b) R_L$$

$$V_s = i_b R_s + i_b R_{pi} + (i_b + \beta i_b) R_L$$

$$A_v = (1 + \beta) R_L / (R_s + R_{pi} + (1 + \beta) R_L)$$

(always  $\leq 1$ )

# Common collector amplifier

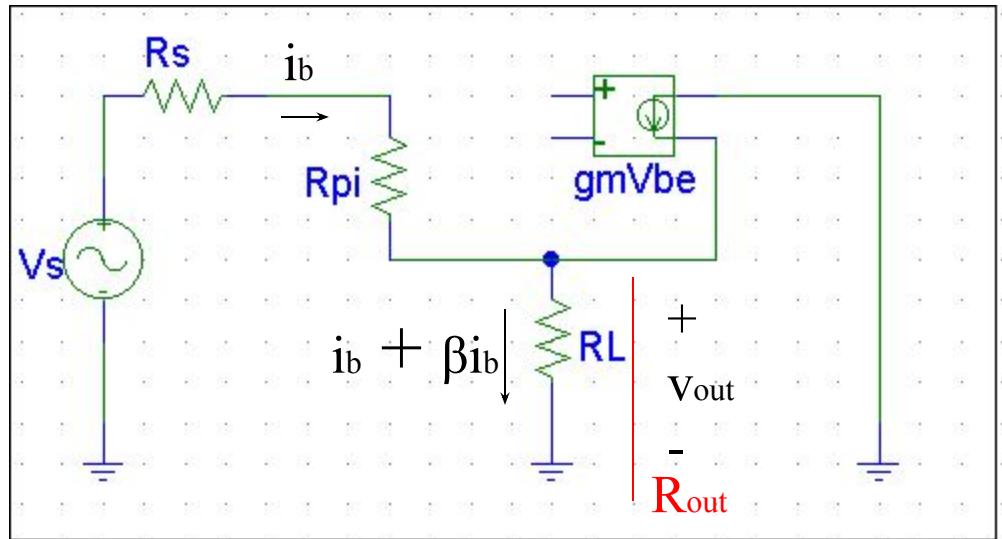
**A<sub>i</sub>**

$$= i_{\text{out}} / i_{\text{in}}$$

$$i_{\text{out}} = i_b + \beta i_b$$

$$i_{\text{in}} = i_b$$

$$A_i = \beta + 1$$



**R<sub>out</sub>**

(don't include RL, set Vs = 0)

$$R_{\text{out}} = V_{\text{out}} / (i_b + \beta i_b)$$

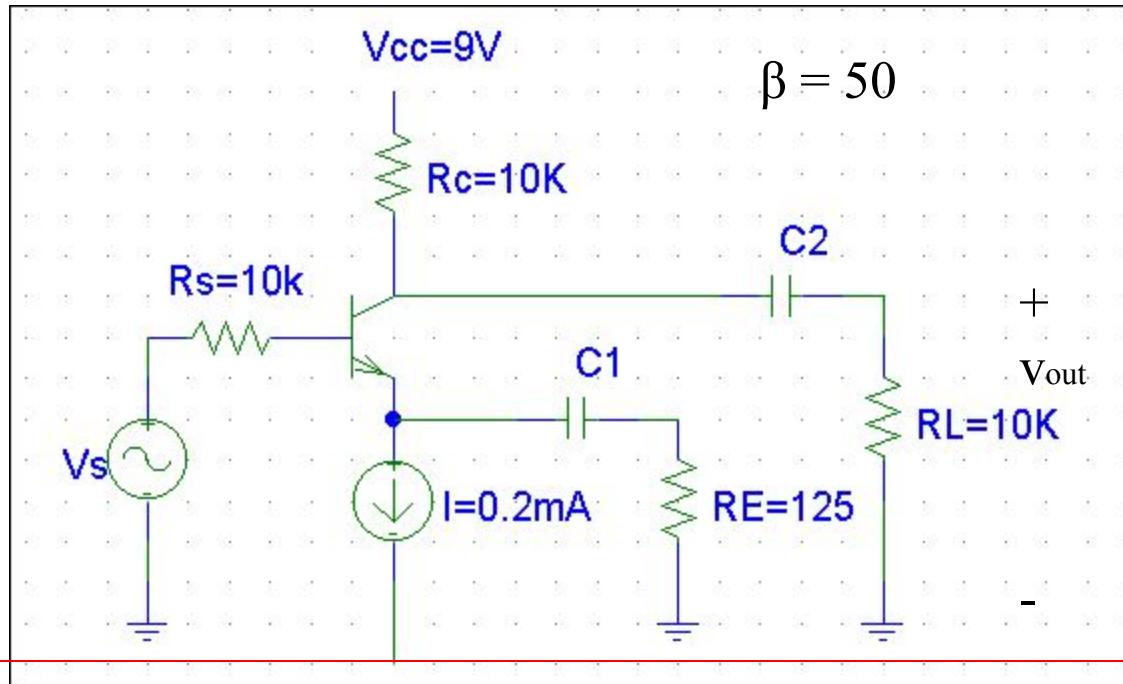
$$V_{\text{out}} = -i_b R_{\text{pi}} + -i_b R_s$$

$$R_{\text{out}} = (R_{\text{pi}} + R_s) / (1 + \beta)$$

(usually low)

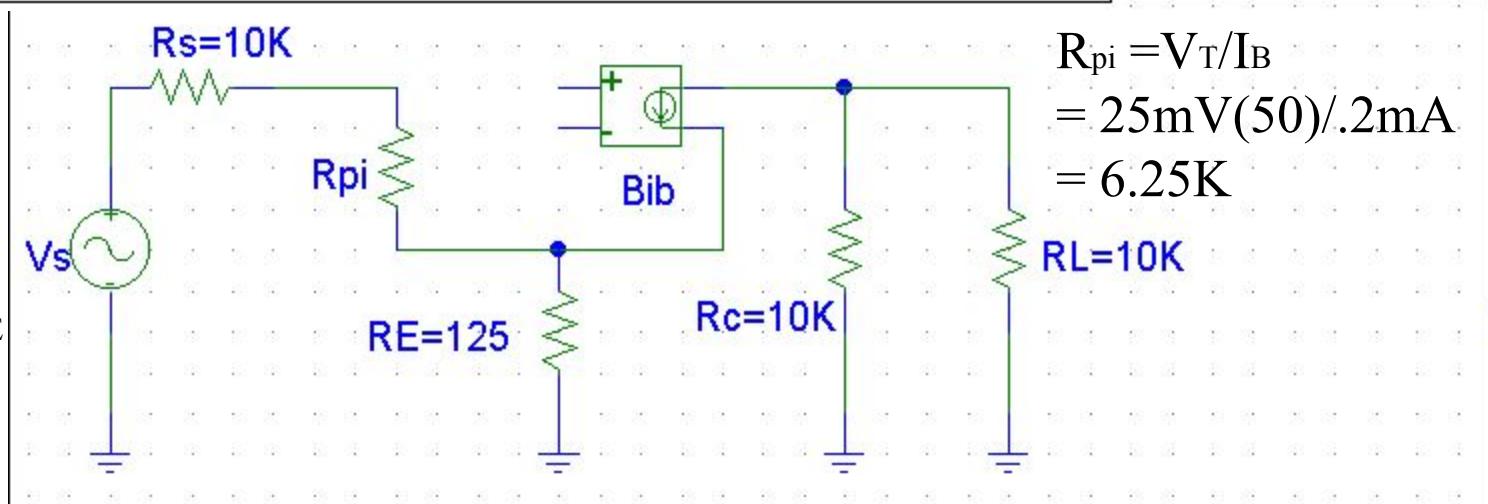
# Prob

Given

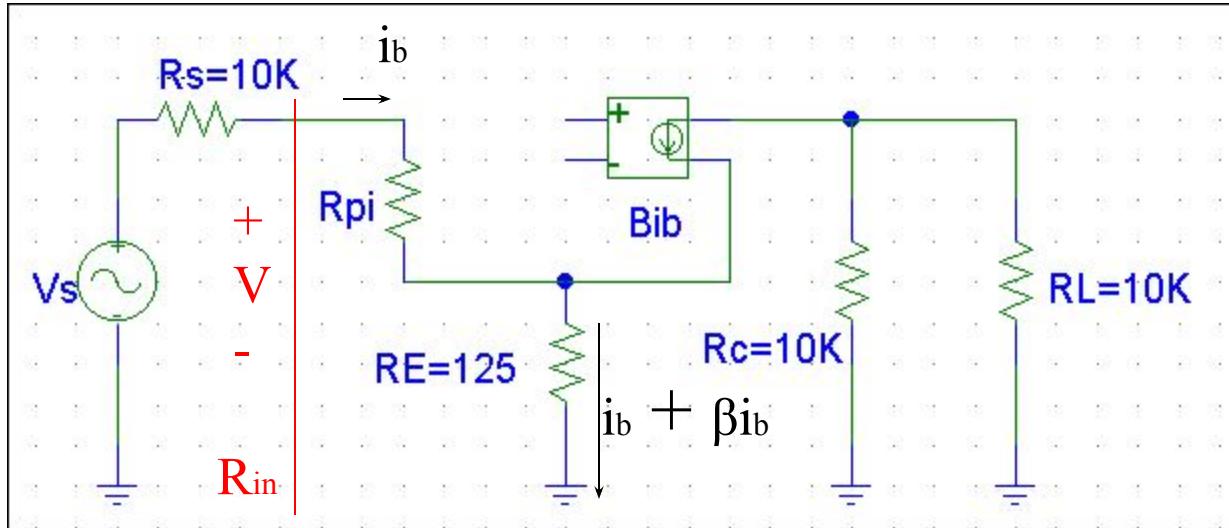


ac  
circuit

CE with  $R_E$   
amp, because  $R_E$   
is in ac circuit



# Prob.



(a) Find  $R_{in}$

$$R_{in} = V/i_b$$

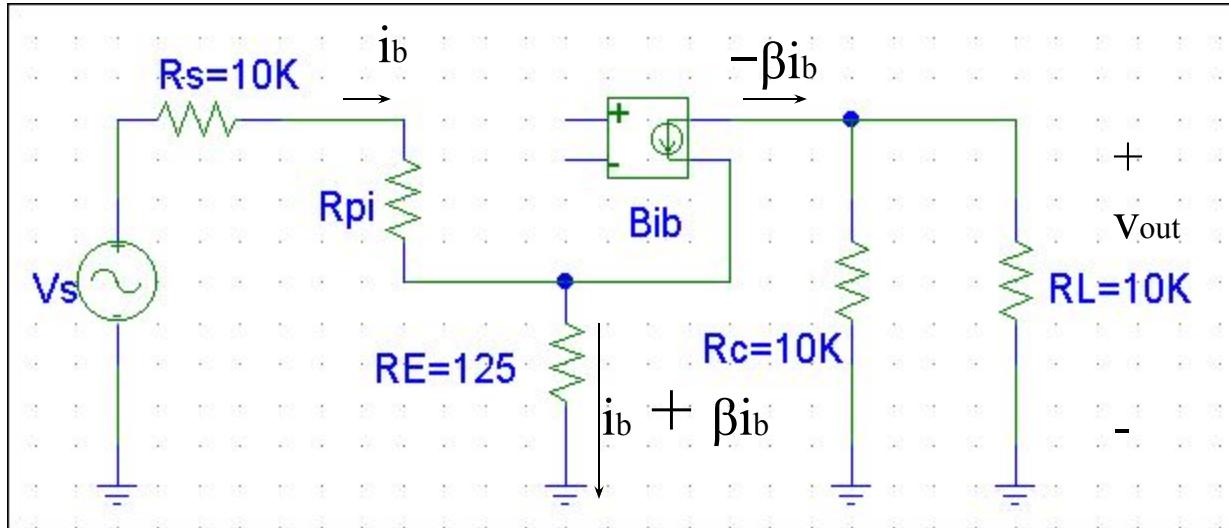
$$V = i_b R_{pi} + (i_b + \beta i_b) R_E$$

$$R_{in} = R_{pi} + (1 + \beta) R_E$$

$$R_{in} = 6.25K + (1 + 50)125$$

$$R_{in} \approx 12.62K$$

# Prob.



(b) Find  $A_v = V_{out}/V_s$

$$V_{out} = -\beta i_b (R_C \parallel R_L)$$

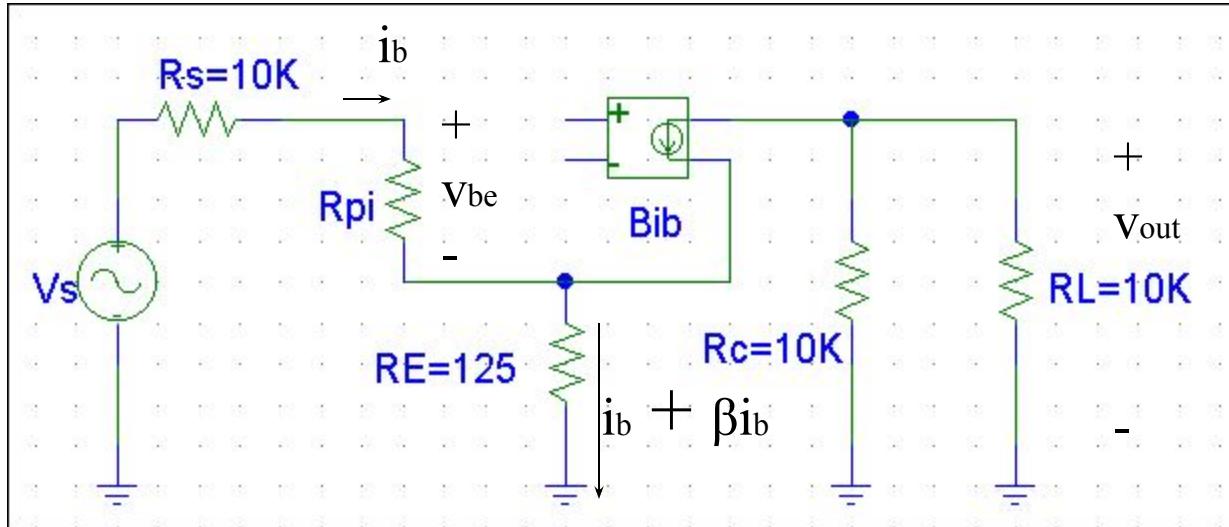
$$V_s = i_b R_s + i_b R_{pi} + (i_b + \beta i_b) R_E$$

$$A_v = -\beta (R_C \parallel R_L) / (R_s + R_{pi} + (1 + \beta) R_E)$$

$$A_v = -50 (10K \parallel 10K) / (10K + 6.25K_i + (1 + 50)125)$$

$$A_v \approx -11$$

# Prob.



(c) If  $v_{be}$  is limited to 5mV, what is the largest signal at input and output?

$$v_{be} = i_b R_{pi} = 5\text{mV}$$

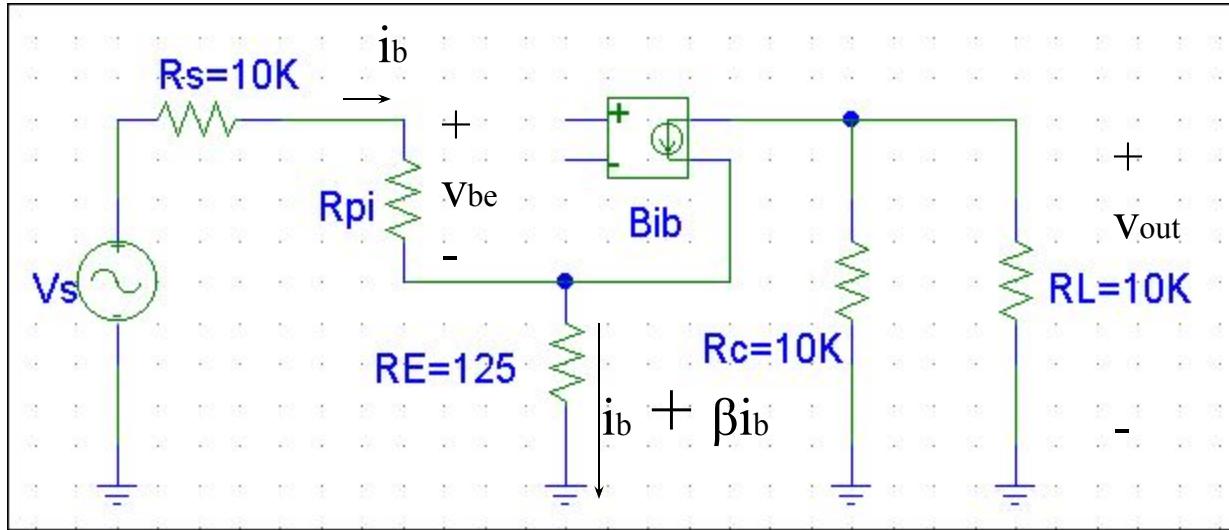
$$i_b = v_{be} / R_{pi} = 5\text{mV} / 6.25\text{K} = 0.8\mu\text{A} \text{ (ac value)}$$

$$v_s = i_b R_s + i_b R_{pi} + (i_b + \beta i_b) R_E$$

$$v_s = (0.8\mu\text{A})10\text{K} + (0.8\mu\text{A}) 6.25\text{K} + (0.8\mu\text{A} + (50)0.8\mu\text{A}) 125$$

$$v_s \approx 18\text{mV}$$

# Prob.



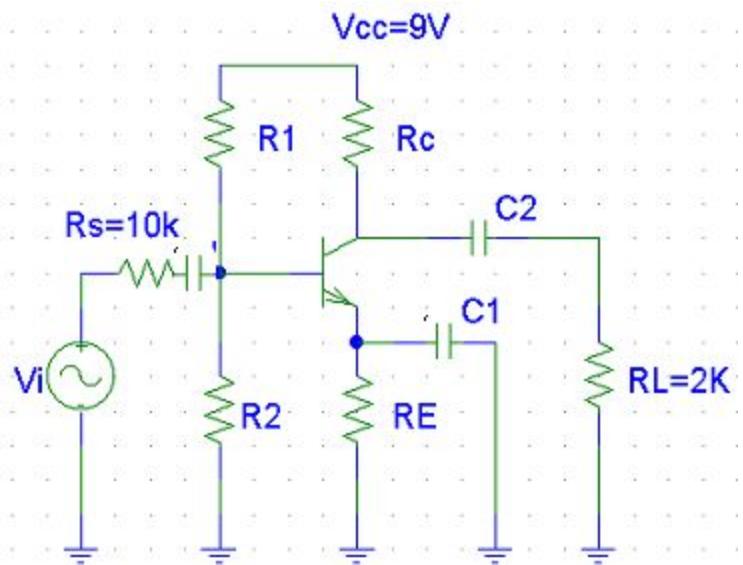
(c) If  $v_{be}$  is limited to 5mV, what is the largest signal at input and output?

$$V_{out} = V_s A_v$$

$$V_{out} = 17.4\text{mV}(-11)$$

$$V_{out} \approx -191\text{mV} \text{ (ac value)}$$

# Prob.



$$\beta = 100$$

Using this circuit, design an amp with:

$$I_E = 2\text{mA}$$

$$A_v = -8$$

current in voltage divider  $I = 0.2\text{mA}$

(CE amp because  $RE$  is not in ac circuit)

## Voltage divider

$$V_{cc}/I = 9/0.2\text{mA} = 45\text{K}$$

$$45\text{K} = R_1 + R_2$$

Choose  $V_B \approx 1/3 V_{cc}$  to put operating point near the center of the transistor characteristics  
 $R_2/(R_1 + R_2) = 3V$

Combining gives,  $R_1 = 30\text{K}$ ,  $R_2 = 15\text{K}$

# Prob.

Find RE (input circuit)  
Use Thevenin equivalent

B-E loop

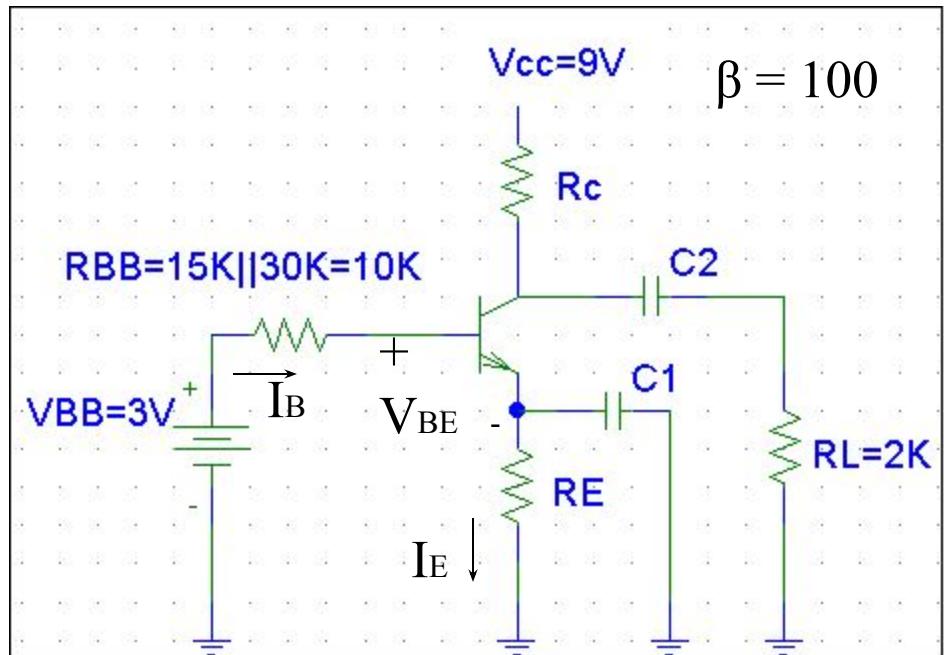
$$V_{BB} = I_B R_{BB} + V_{BE} + I_E R_E$$

using  $I_B \approx I_E/\beta$

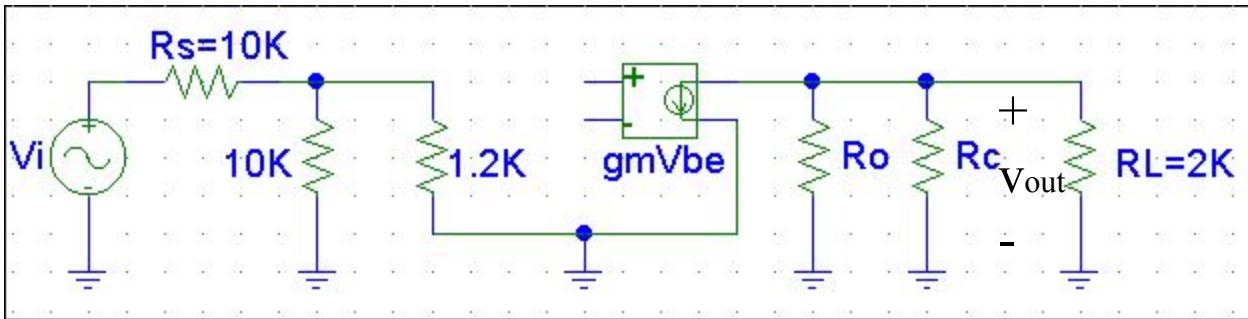
$$R_E = [V_{BB} - V_{BE} - (I_E/\beta)R_{BB}] / I_E$$

$$R_E = [3 - .7 - (2\text{mA}/100)10\text{K}] / 2\text{mA}$$

$$R_E = 1.05\text{K}\Omega$$



# Prob.



Find  $R_c$  (ac circuit)

$$R_{pi} = V_T/I_B = 25mV(100)/2mA = 1.25K$$

$$R_o = V_A/I_C = 100/2mA = 50K$$

$$A_v = V_{out}/V_{in}$$

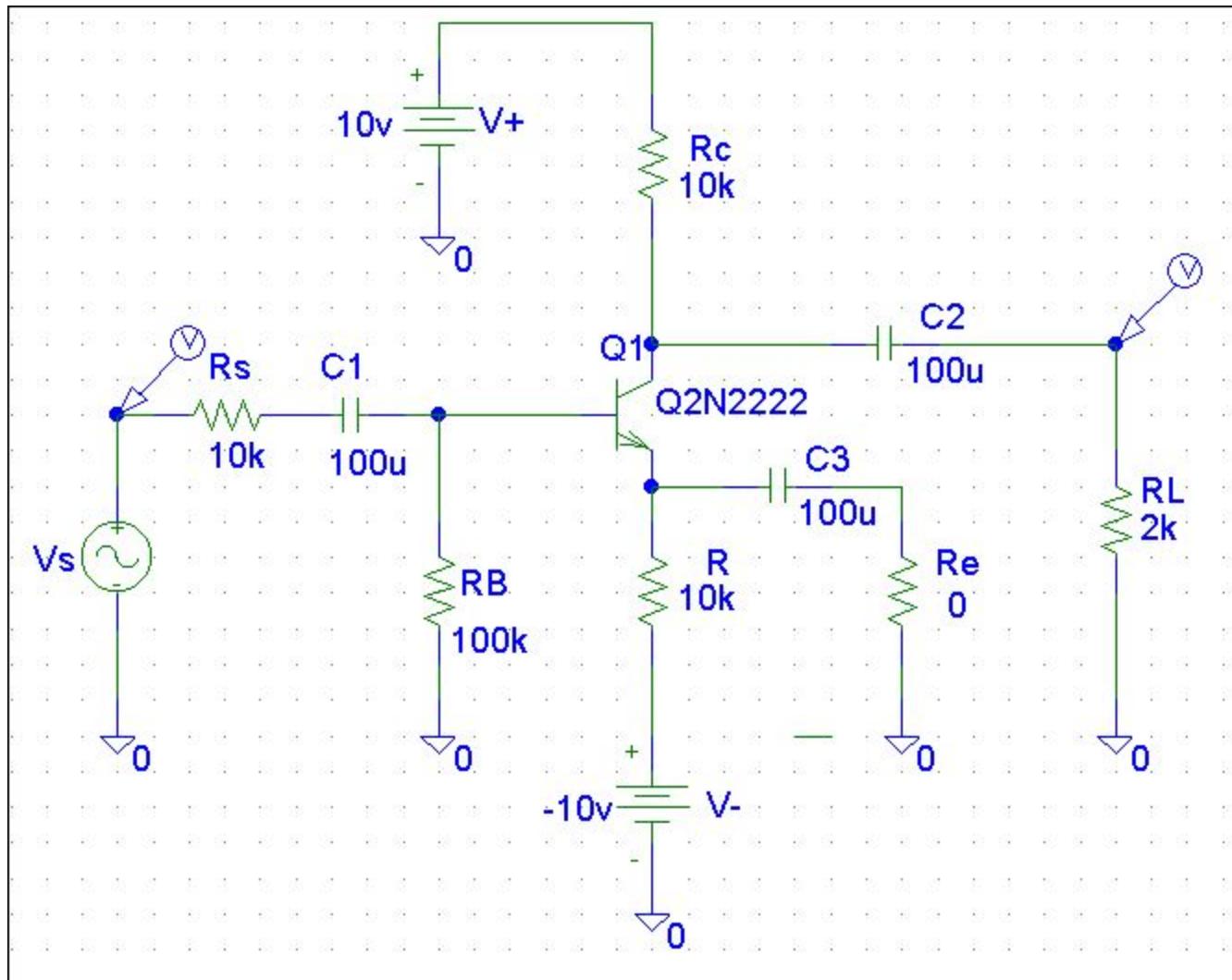
$$V_{out} = -g_m V_{be} (R_o || R_c || R_L)$$

$$V_{be} = 10K || 1.2K / [10K + 10K || 1.2K] V_i$$

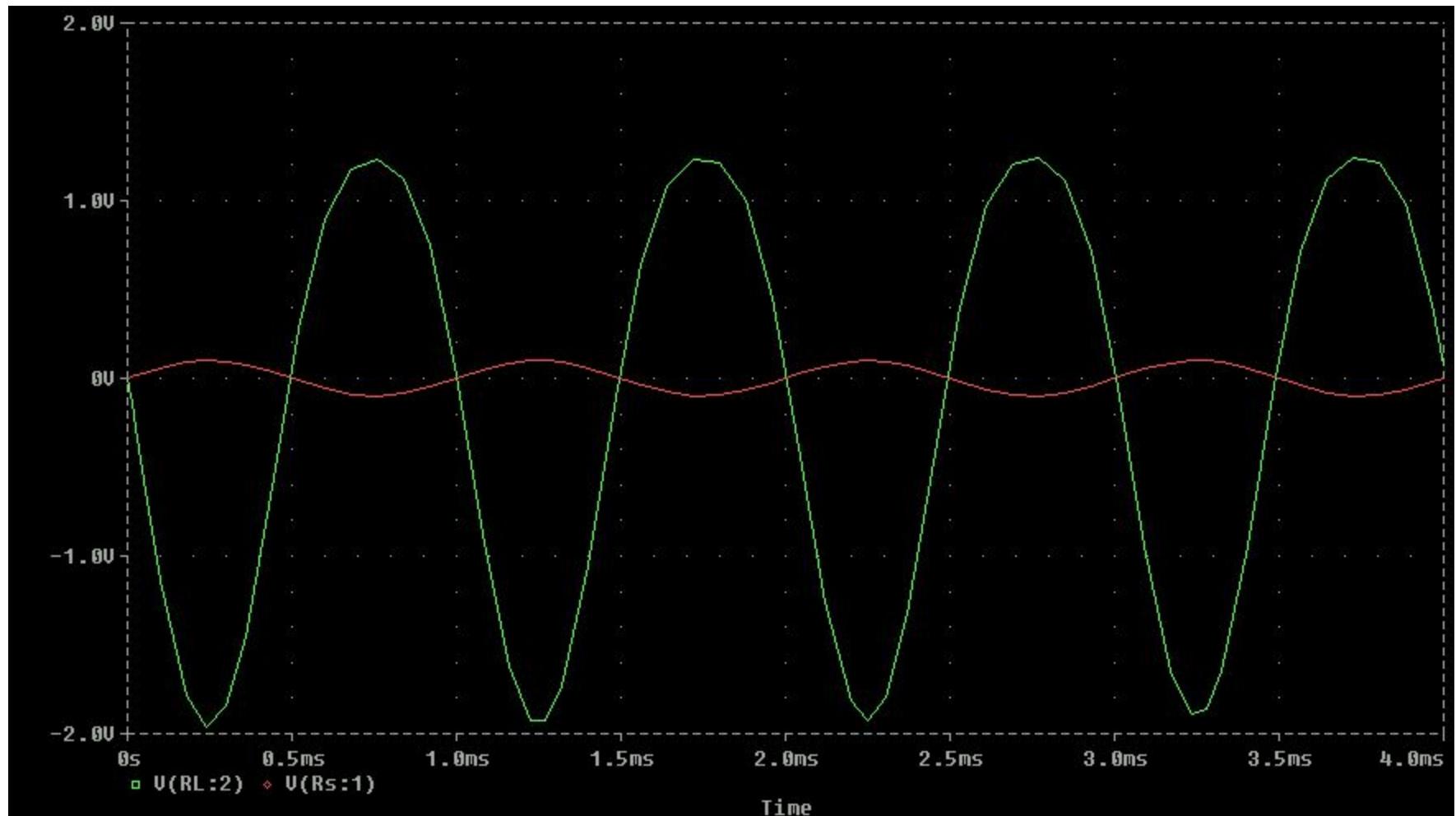
$$A_v = -g_m (R_o || R_c || R_L) (10K || 1.2K) / [10K || 1.2K + R_s]$$

Set  $A_v = -8$ , and solve for  $R_c$ ,  $R_c \approx 2K$

# CE amplifier



# CE amplifier



$$Av \approx -12.2$$

## CE amplifier

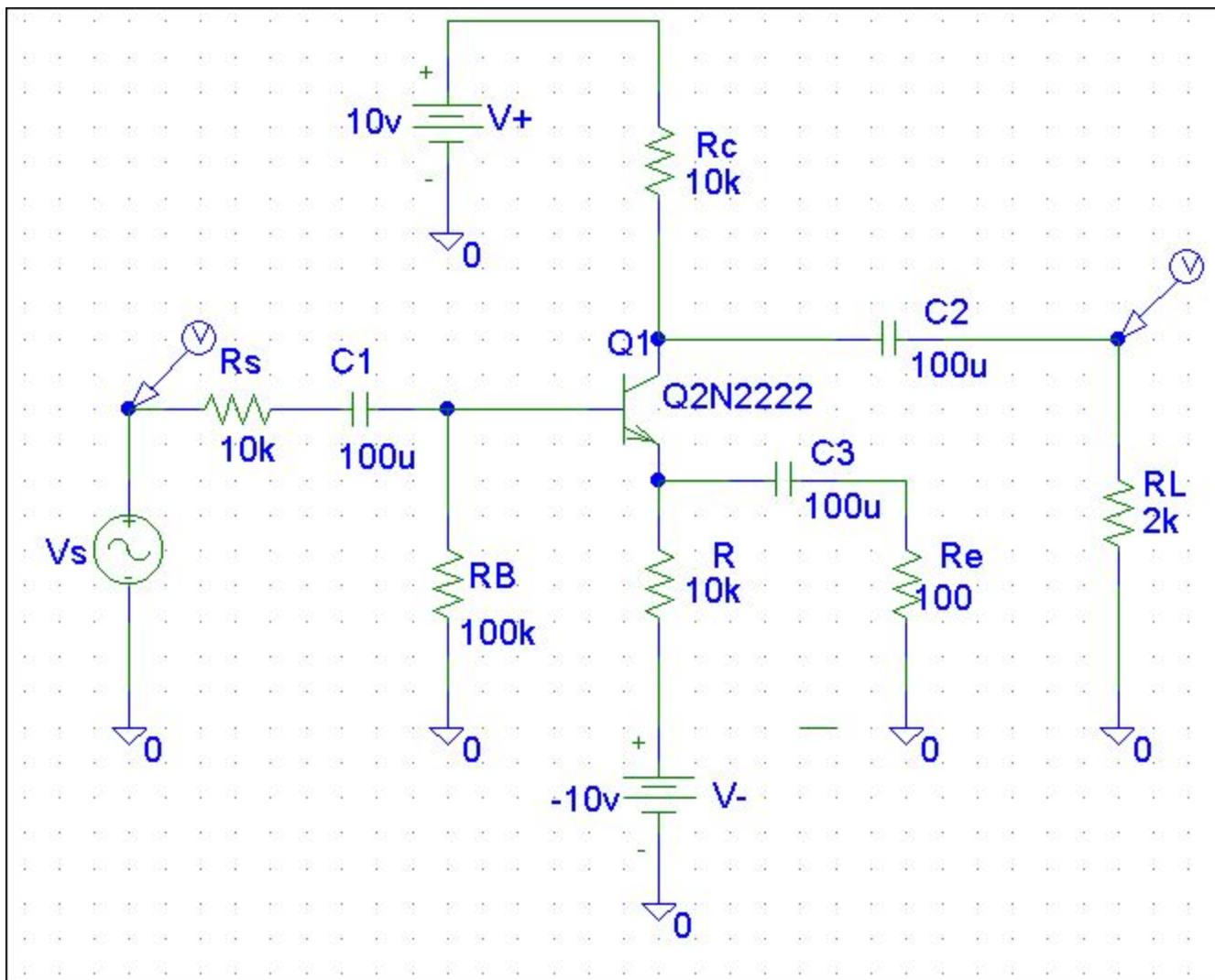
FOURIER COMPONENTS OF TRANSIENT RESPONSE V(\$N\_0009)

DC COMPONENT = -1.226074E-01

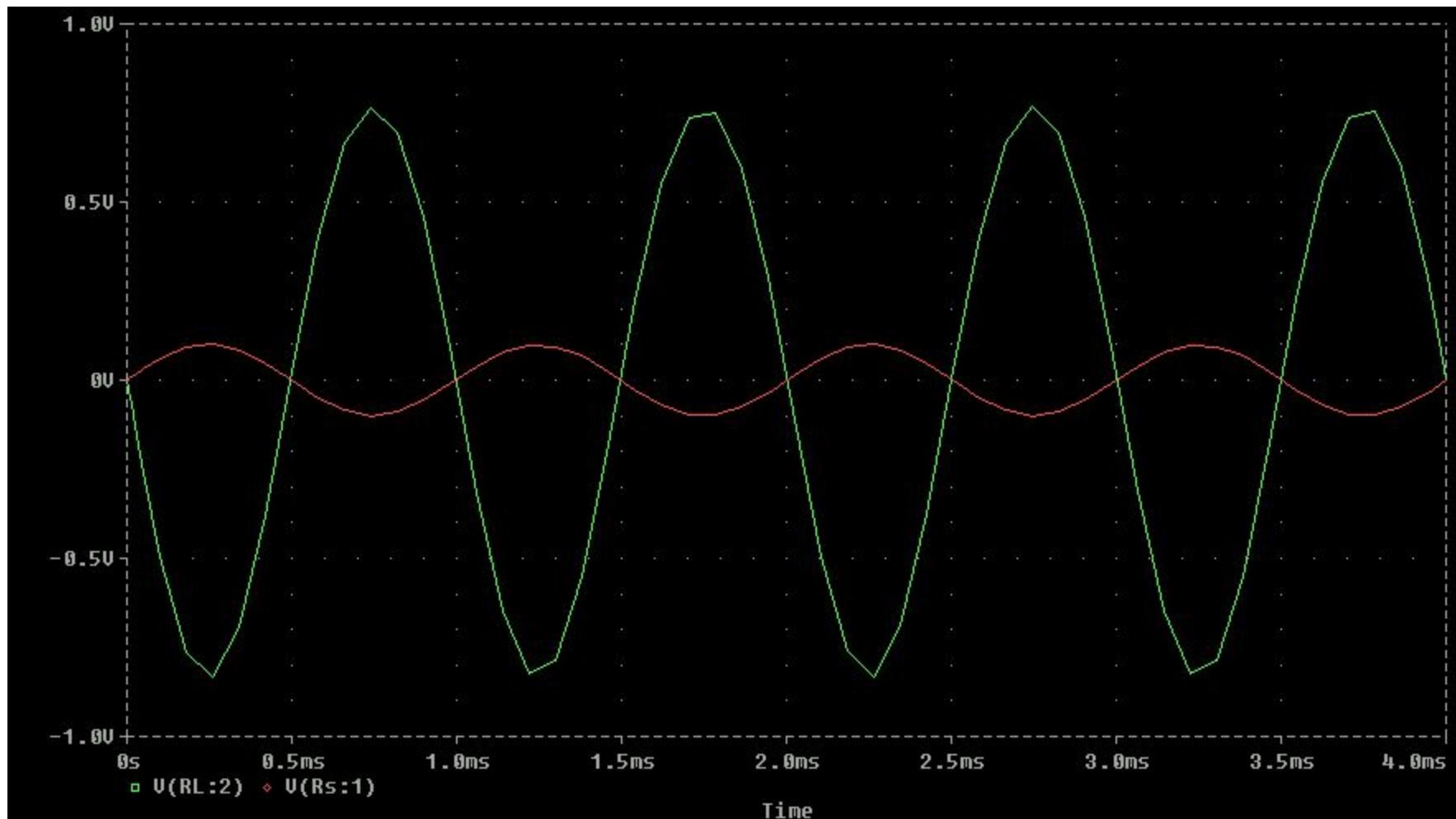
HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	1.000E+03	1.581E+00	1.000E+00	-1.795E+02	0.000E+00
2	2.000E+03	1.992E-01	1.260E-01	9.111E+01	2.706E+02
3	3.000E+03	2.171E-02	1.374E-02	-1.778E+02	1.668E+00
4	4.000E+03	3.376E-03	2.136E-03	-1.441E+02	3.533E+01

TOTAL HARMONIC DISTORTION = 1.267478E+01 PERCENT

# CE amplifier with $R_E$



## CE amplifier with $R_E$



$$Av \approx -7.5$$

## FOURIER COMPONENTS OF TRANSIENT RESPONSE V(\$N\_0009)

DC COMPONENT = -1.353568E-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	1.000E+03	7.879E-01	1.000E+00	-1.794E+02	0.000E+00
2	2.000E+03	1.604E-02	2.036E-02	9.400E+01	2.734E+02
3	3.000E+03	5.210E-03	6.612E-03	-1.389E+02	4.056E+01
4	4.000E+03	3.824E-03	4.854E-03	-1.171E+02	6.231E+01

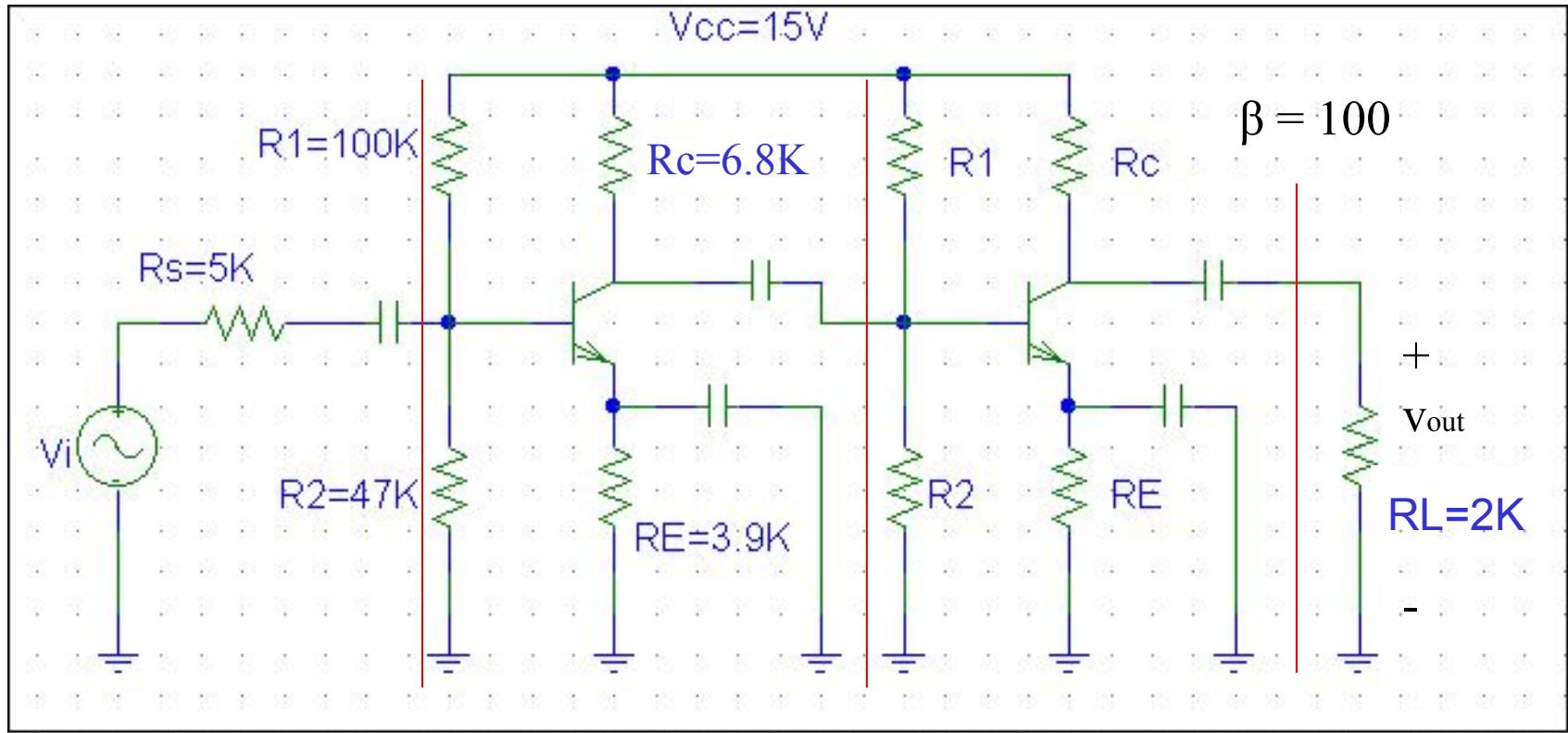
TOTAL HARMONIC DISTORTION = 2.194882E+00 PERCENT

## Summary

	<b>Av</b>	<b>THD</b>
CE	-12.2	12.7%

CE w/RE ( $R_E = 100$ )	-7.5	2.19%
-------------------------	------	-------

# Prob.



- 2 stage amplifier
- Both stages are the same
- Capacitively coupled

(a) Find  $I_c$  and  $V_c$  of each transistor  
(same for each stage)

## Prob.

(a) Find  $I_c$  and  $V_C$  of each transistor  
(same for each stage)

B-E voltage loop

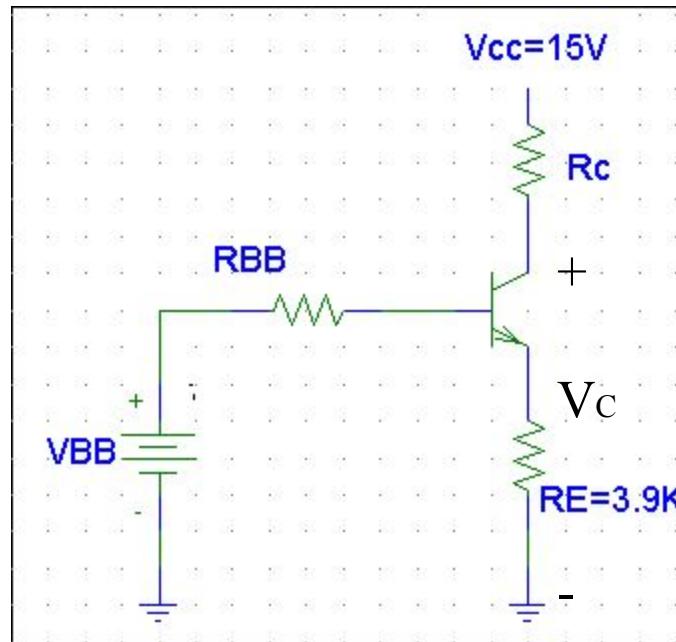
$$V_{BB} = I_B R_{BB} + V_{BE} + I_E R_E$$

where  $R_{BB} = R_1 \parallel R_2 = 32K$

$V_{BB} = V_{CC} R_2 / (R_1 + R_2) = 4.8V$ , and  
 $I_B \approx I_E / \beta$

$$I_E = [V_{BB} - V_{BE}] / [R_{BB}/\beta + R_E]$$

$$I_E = 0.97mA$$



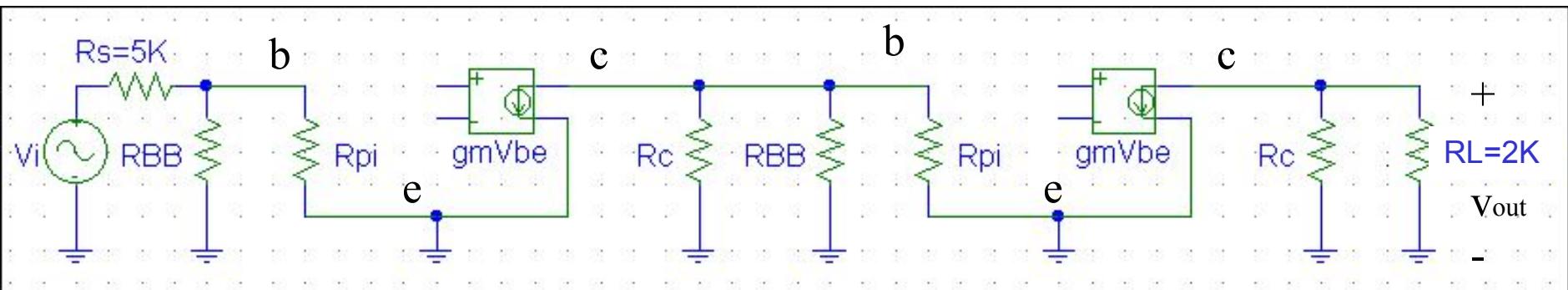
$$V_C = V_{CC} - I_c R_c$$

$$V_C = 15 - .97(6.8)$$

$$V_C = 8.39V$$

# Prob.

(b) find ac circuit

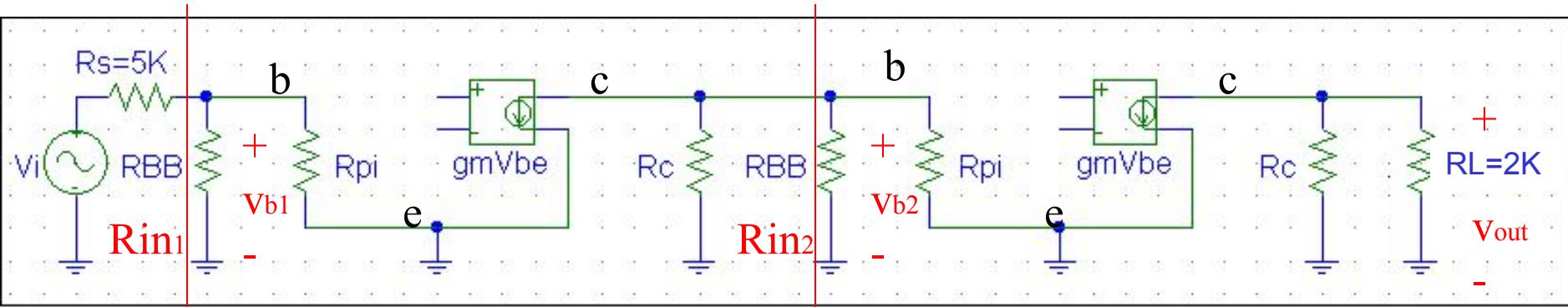


$$R_{BB} = R_1 \parallel R_2 = 100K \parallel 47K = 32K\Omega$$

$$R_{pi} = V_T/I_B = 25mV(100)/.97mA \approx 2.6K\Omega$$

$$g_m = I_C/V_T = .97mA/25mV \approx 39mA/V$$

# Prob.



(c) find  $R_{in_1}$

$$\begin{aligned} R_{in_1} &= R_{BB} \parallel R_{pi} \\ &= 32K \parallel 2.6K \\ &= 2.4K\Omega \end{aligned}$$

find  $V_{b1}/V_i$

$$\begin{aligned} &= R_{in_1} / [R_{in_1} + R_s] \\ &= 2.4K / [2.4K + 5K] \\ &= 0.32 \end{aligned}$$

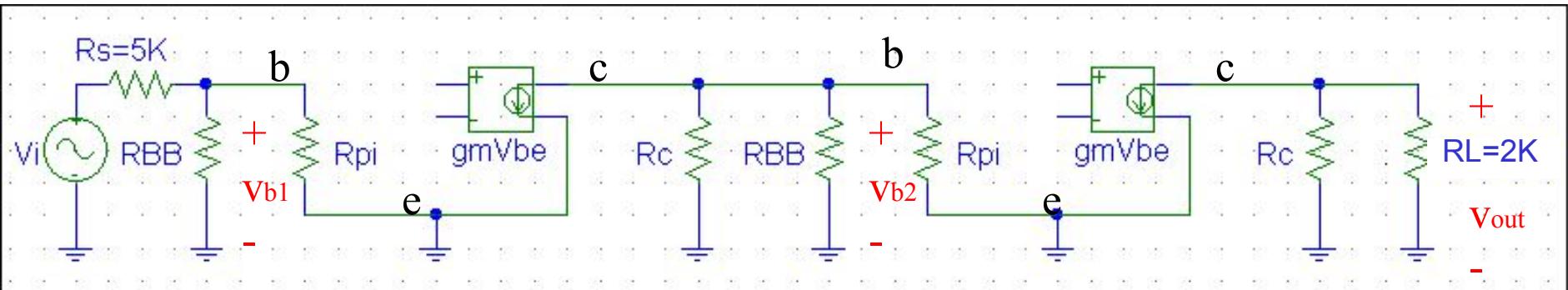
(d) find  $R_{in_2}$

$$\begin{aligned} R_{in_2} &= R_{BB} \parallel R_{pi} \\ &= 2.4K\Omega \end{aligned}$$

find  $V_{b2}/V_{b1}$

$$\begin{aligned} V_{b2} &= -g_m V_{be1} [R_c \parallel R_{BB} \parallel R_{pi}] \\ V_{b2}/V_{be1} &= -g_m [R_c \parallel R_{BB} \parallel R_{pi}] \\ V_{b2}/V_{b1} &= -(39mA/V)[6.8 \parallel 32K \parallel 2.6K] \\ &= -69.1 \end{aligned}$$

# Prob.



(e) find  $V_{out}/V_{b2}$

$$V_{out} = -g_m V_{be2} [R_C \parallel R_L]$$

$$V_{out}/V_{be2} = -g_m [R_C \parallel R_L]$$

$$V_{b2}/V_{b1} = -(39\text{mA/V})[6.8\text{K} \parallel 2\text{K}]$$

$$= -60.3$$

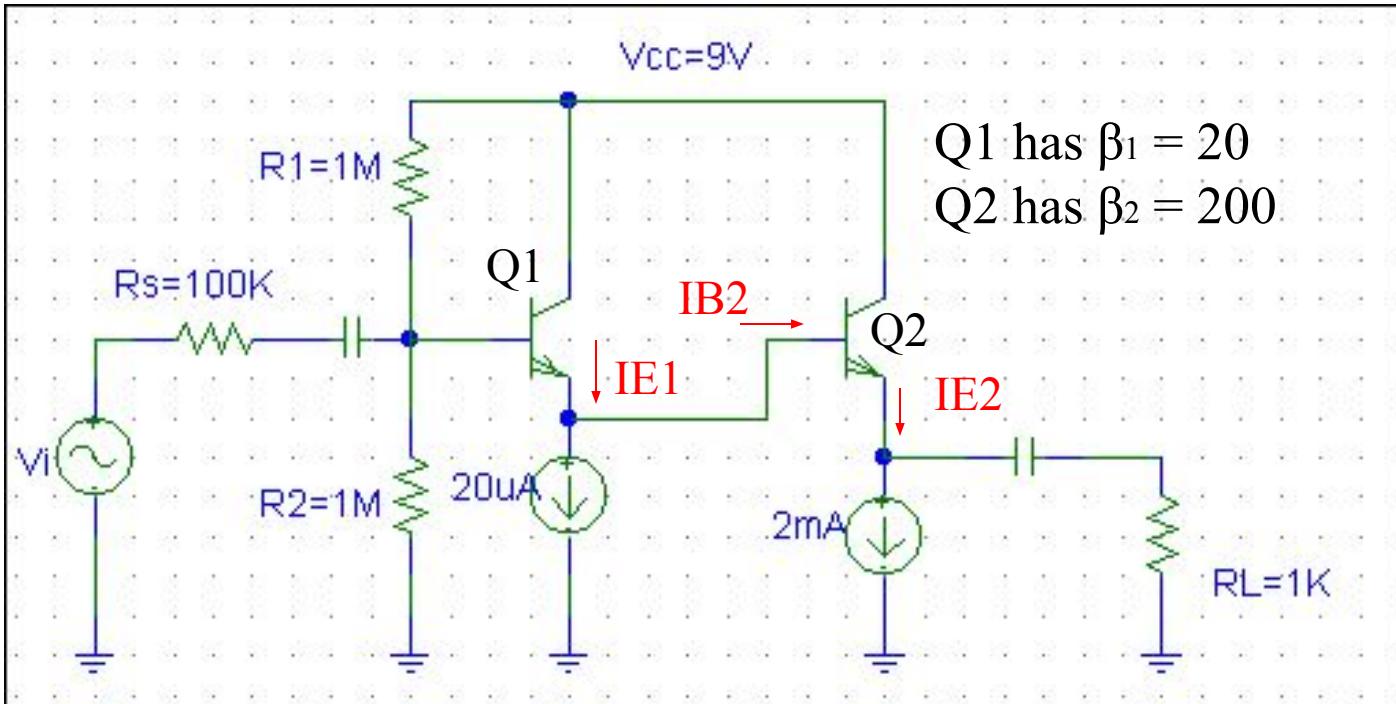
(f) find overall voltage gain

$$V_{out}/V_i = (V_{b1}/V_i) (V_{b2}/V_{b1}) (V_{out}/V_{b2})$$

$$V_{out}/V_i = (0.32) (-69.1) (-60.3)$$

$$V_{out}/V_i = 1332$$

# Prob.



Find  $I_{E1}$ ,  $I_{E2}$ ,  $V_{B1}$ , and  $V_{B2}$

$$I_{E2} = 2\text{mA}$$

$$I_{E1} = I_{20\mu\text{A}} + I_{B2}$$

$$I_{E1} = I_{20\mu\text{A}} + I_{E2}/\beta_2$$

$$I_{E1} = 20\mu\text{A} + 10\mu\text{A}$$

$$I_{E1} = 30\mu\text{A}$$

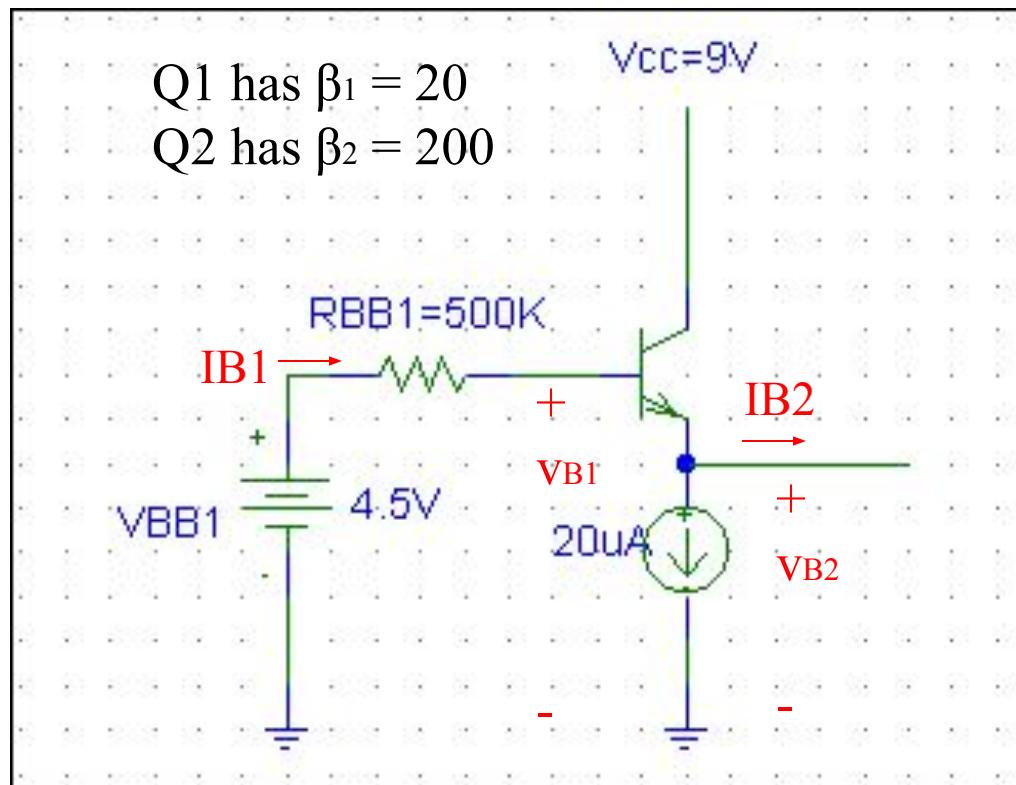
# Prob.

Find  $V_{B1}$ , and  $V_{B2}$

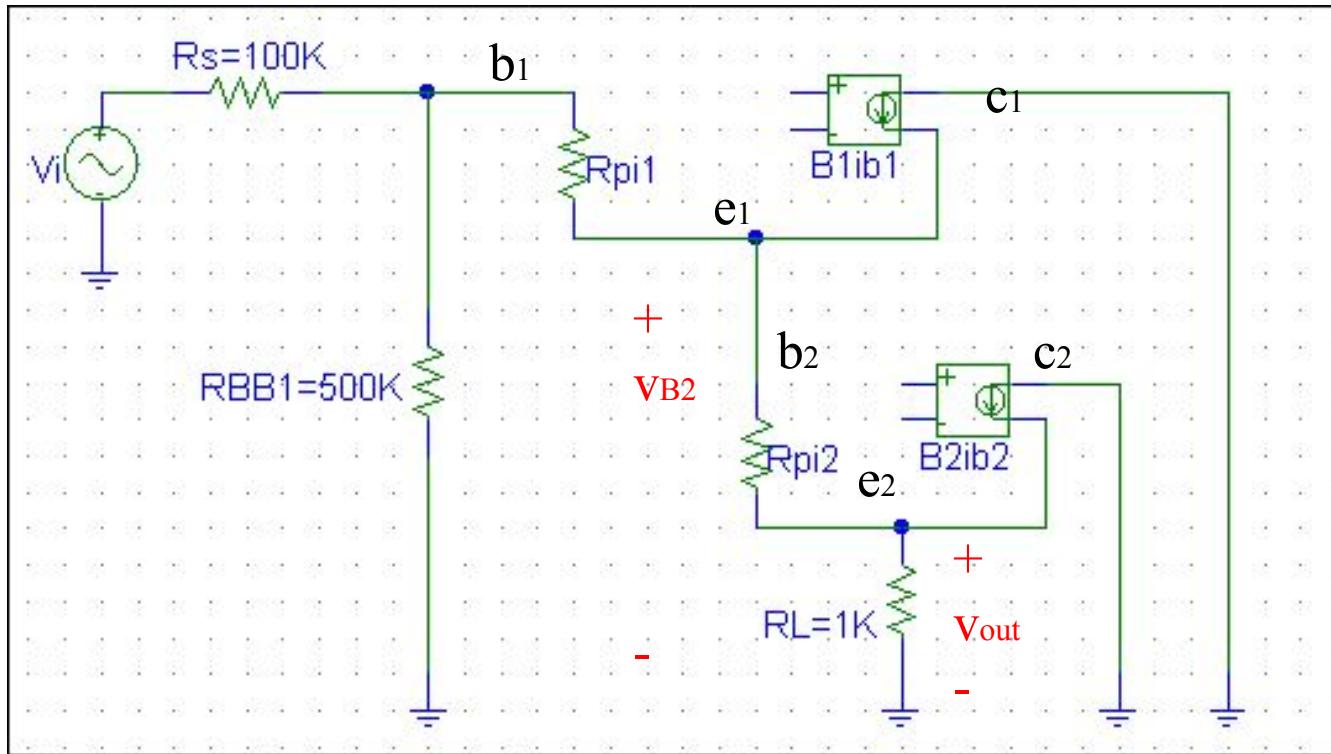
Use Thevenin equivalent

$$\begin{aligned} V_{B1} &= V_{BB1} - I_{B1}(R_{BB2}) \\ &= 4.5 - (30\mu A/20)500K \\ &= 3.8V \end{aligned}$$

$$\begin{aligned} V_{B2} &= V_{B1} - V_{BE} \\ &= 3.8V - 0.7 \\ &= 3.1V \end{aligned}$$



# Prob.



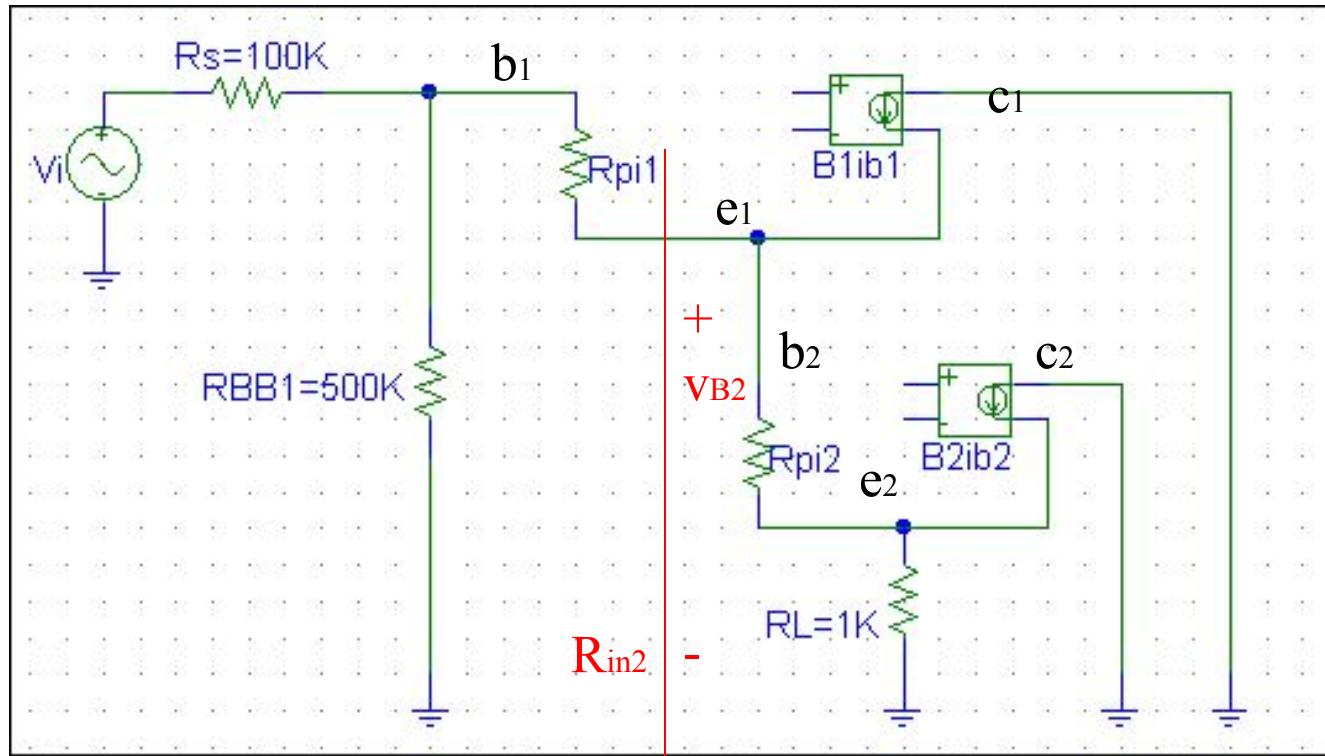
(b) find  $V_{out}/V_{b2}$

$$\begin{aligned} R_{pi2} &= V_T/I_{B2} \\ &= V_T \beta_2/I_{E2} \\ &= 25mV(200)/2mA \\ &= 2.5K\Omega \end{aligned}$$

$$\begin{aligned} V_{out} &= (i_{b2} + \beta_2 i_{b2}) R_L \\ V_{b2} &= (i_{b2} + \beta_2 i_{b2}) R_L + i_{b2} R_{pi2} \end{aligned}$$

$$\begin{aligned} V_{out}/V_{b2} &= (1 + \beta_2) R_L / [(1 + \beta_2) R_L + R_{pi2}] \\ &= (1 + 200) 1K / [(1 + 200) 1K + 2.5K] \\ &\approx 0.988 \end{aligned}$$

# Prob.

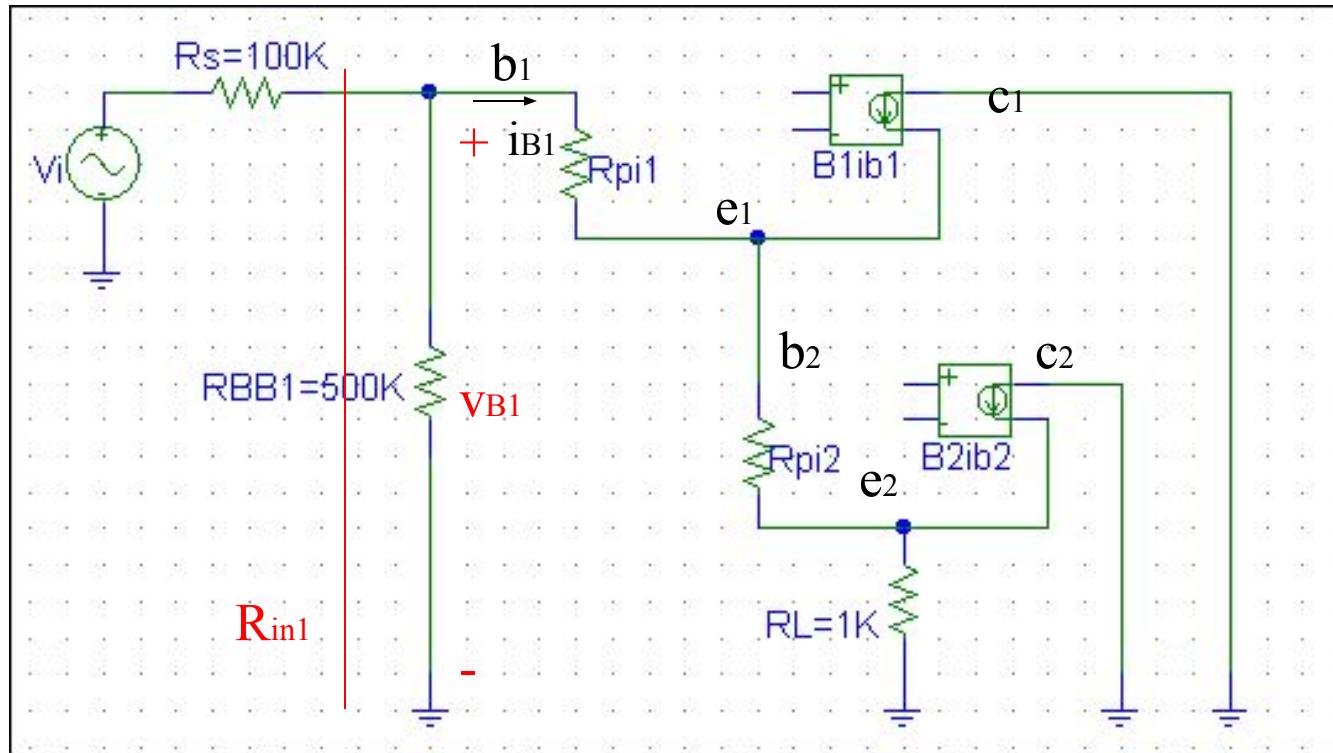


(b) find  $R_{in2} = v_{b2}/i_{b2}$

$$v_{b2} = (i_{b2} + \beta_2 i_{b2})R_L + i_{b2}R_{pi2}$$

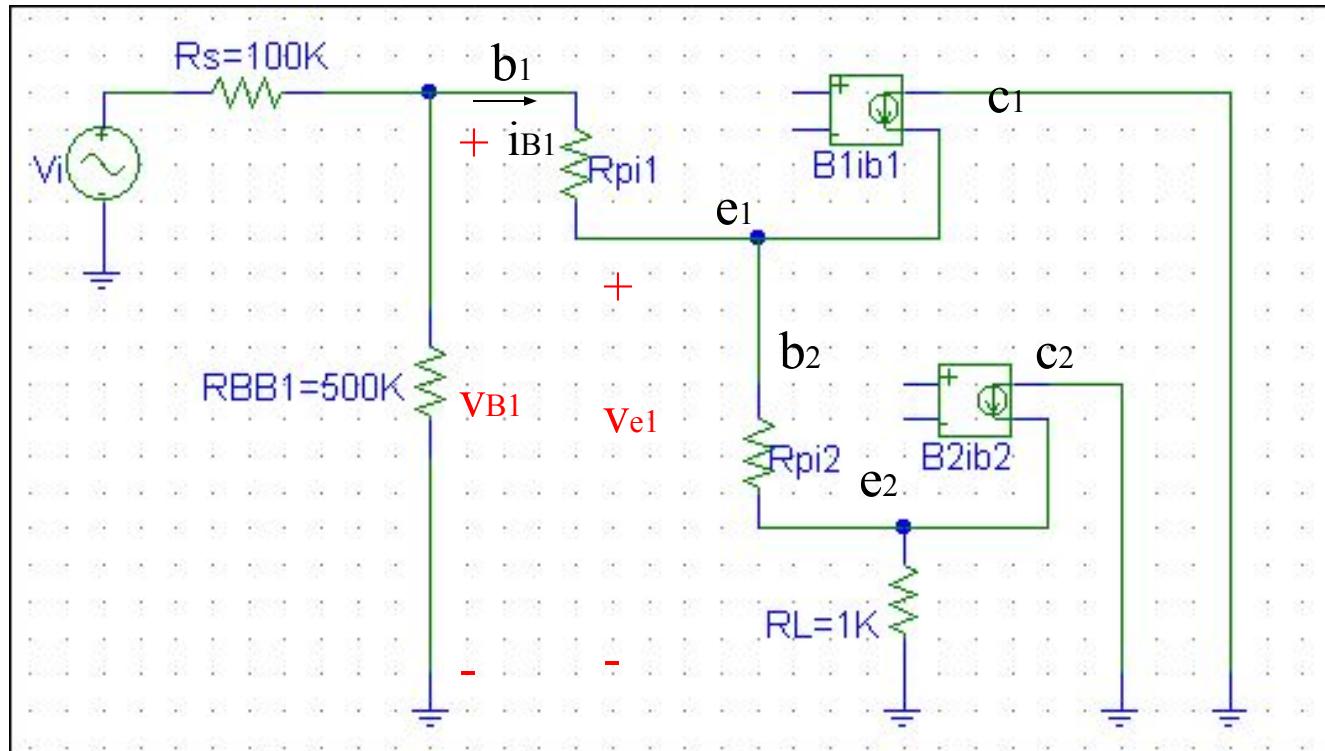
$$\begin{aligned} R_{in2} &= v_{b2}/i_{b2} = (1 + \beta_2)R_L + R_p \\ &= (1 + 200)1K + 2.5K \\ &\approx 204K \end{aligned}$$

# Prob.



$$\begin{aligned}
 (c) \text{ find } R_{in1} &= R_{BB1} \parallel (V_{b1}/i_{b1}) \\
 &= R_{BB1} \parallel [i_{b1}R_{pi1} + (i_{b1} + \beta_1 i_{b1})R_{in2}] / i_{b1} \\
 &= R_{BB1} \parallel [R_{pi1} + (1 + \beta_1)R_{in2}], \\
 \text{where } R_{pi1} &= V_T \beta_1 / I_{E1} = 25mV(20)/30\mu A = 16.7K \\
 &= 500K \parallel [16.7K + (1 + 20)204K] \\
 &\approx 500K\Omega
 \end{aligned}$$

# Prob.



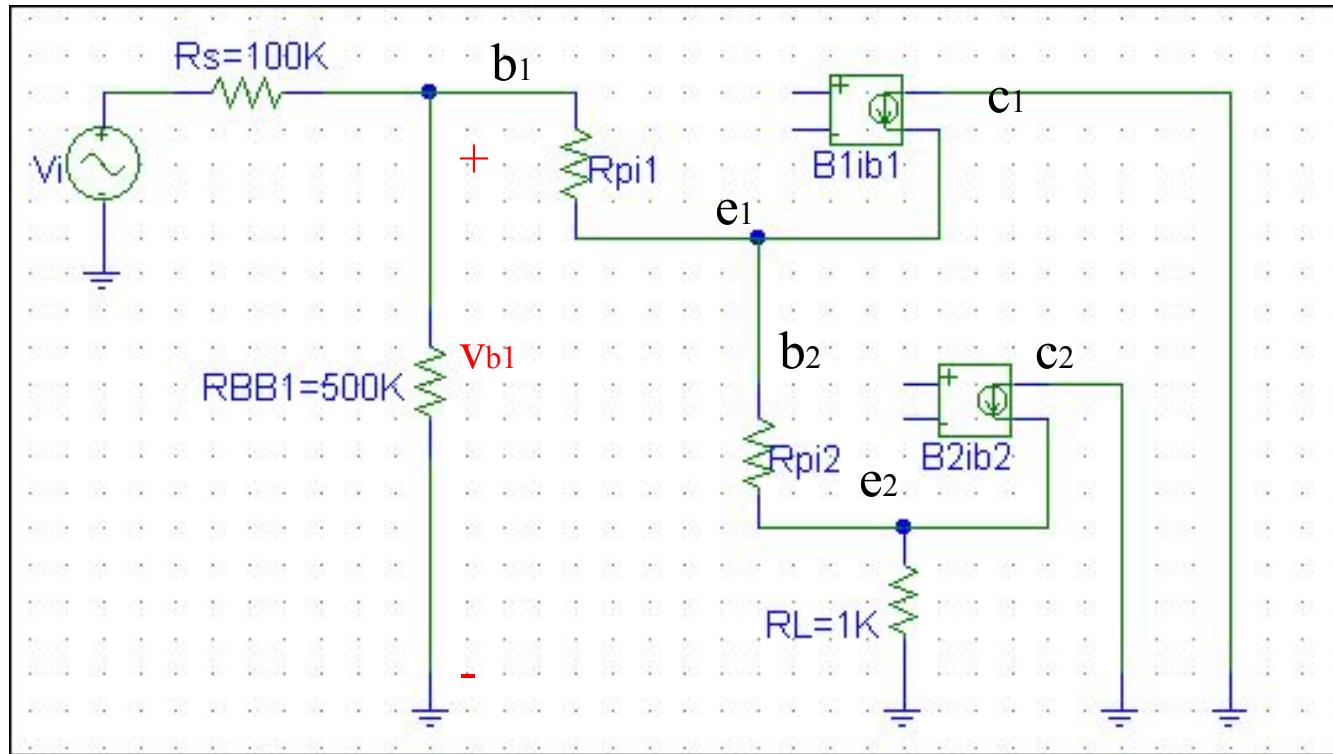
(c) find  $V_{e1}/V_{b1}$

$$V_{e1} = (i_{b1} + \beta_1 i_{b1}) R_{in2}$$

$$V_{b1} = (i_{b1} + \beta_1 i_{b1}) R_{in2} + i_{b1} R_{pi1}$$

$$\begin{aligned} V_{e1}/V_{b1} &= (1 + \beta_1) R_{in2} / [(1 + \beta_1) R_{in2} + R_{pi1}] \\ &= (1 + 20) 204K / [(1 + 20) 204K + 16.7K] \\ &\approx 0.996 \end{aligned}$$

# Prob.



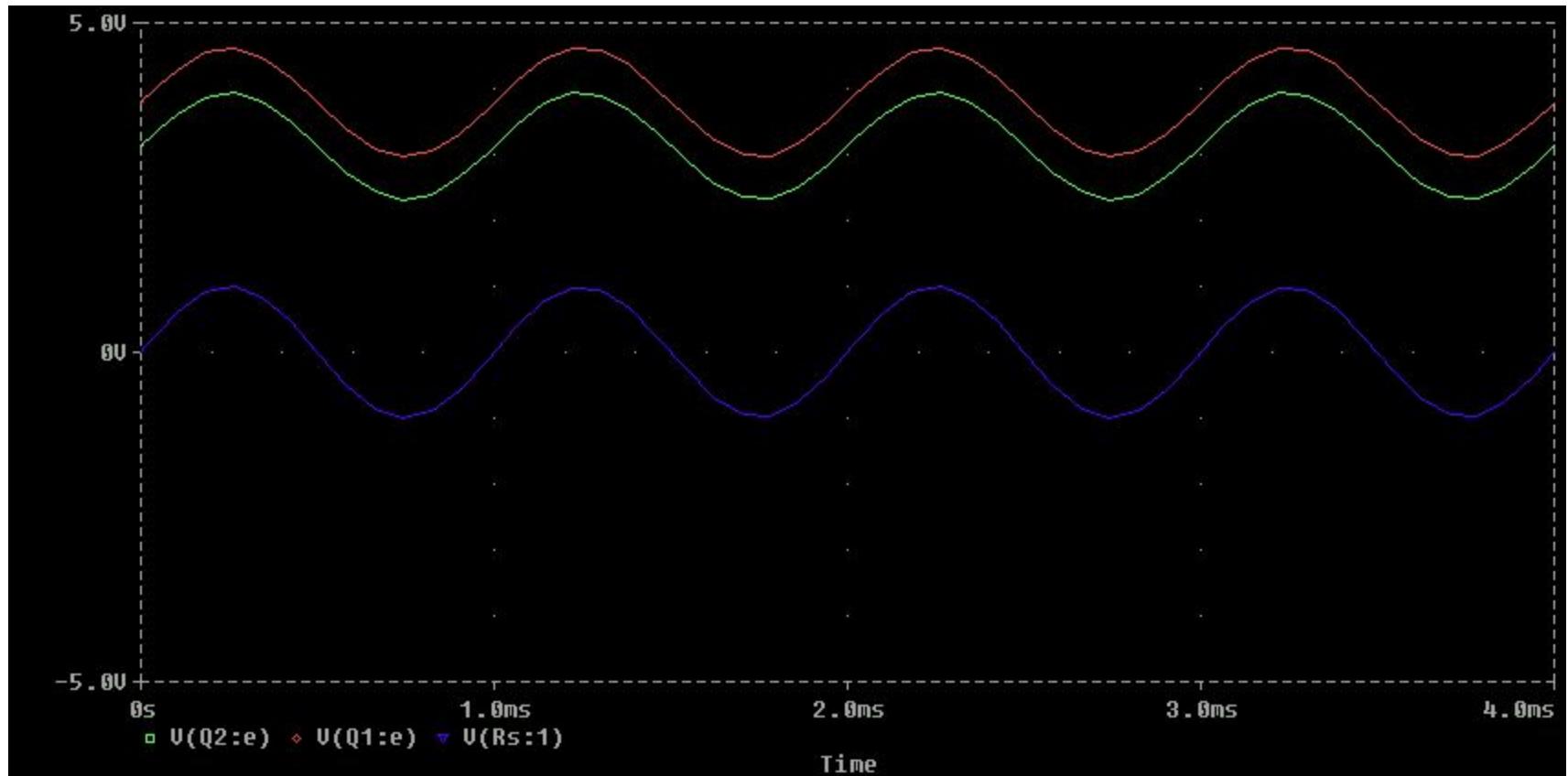
(d) find  $V_{b1}/V_i$

$$\begin{aligned} V_{b1}/V_i &= R_{in1}/[R_s + R_{in1}] \\ &= 0.82 \end{aligned}$$

(e) find overall voltage gain

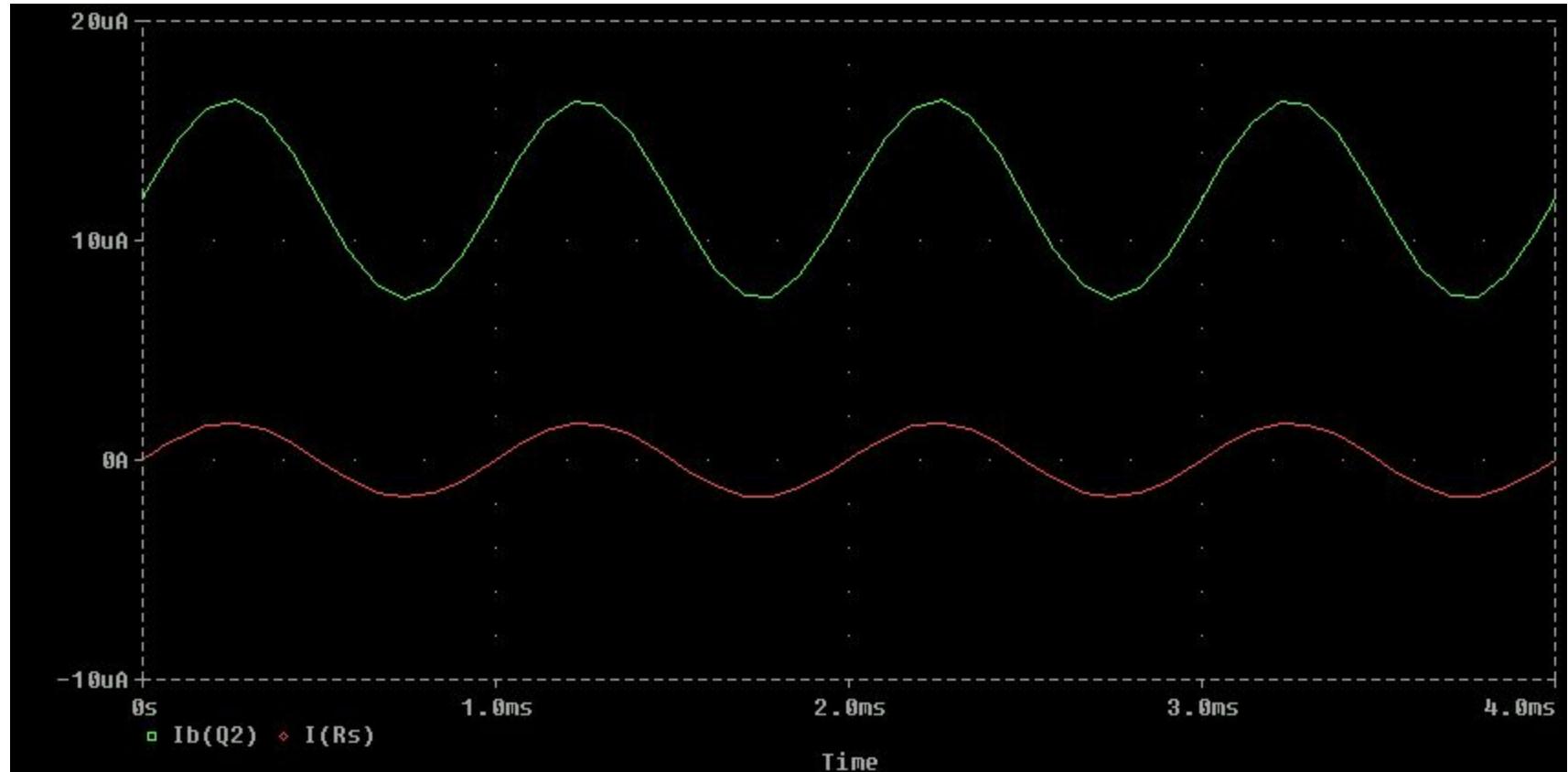
$$\begin{aligned} V_{out}/V_i &= (V_{b1}/V_i) (V_{e1}/V_{b1}) (V_{out}/V_{e1}) \\ V_{out}/V_i &= (0.82) (0.99) (0.99) \\ V_{out}/V_i &= 0.81 \end{aligned}$$

# Voltage outputs at each stage



Output of  
stage 2      Output of  
stage 1

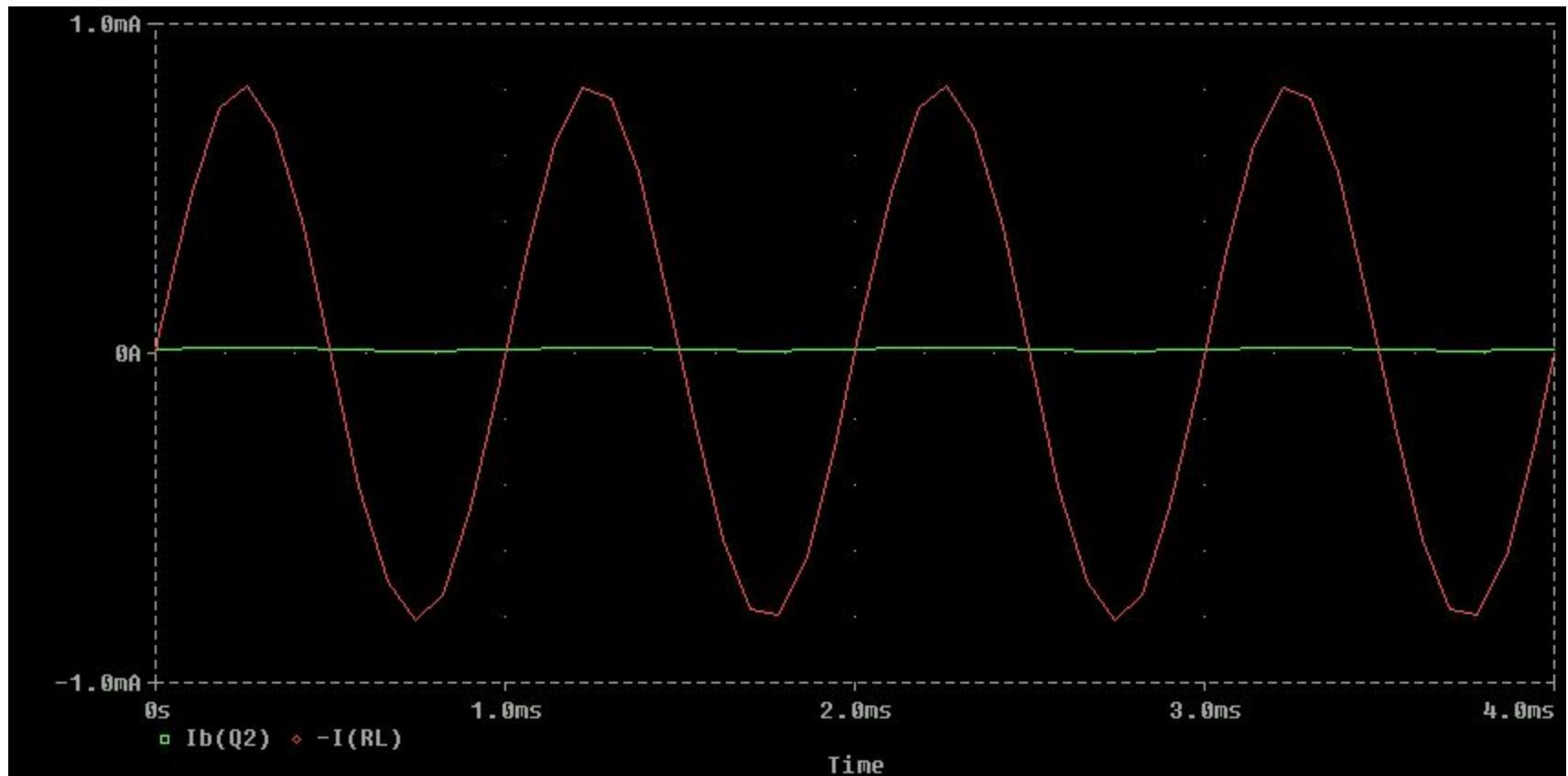
# Current



Input to  
stage 2 ( $i_{b2}$ )

Input  
current

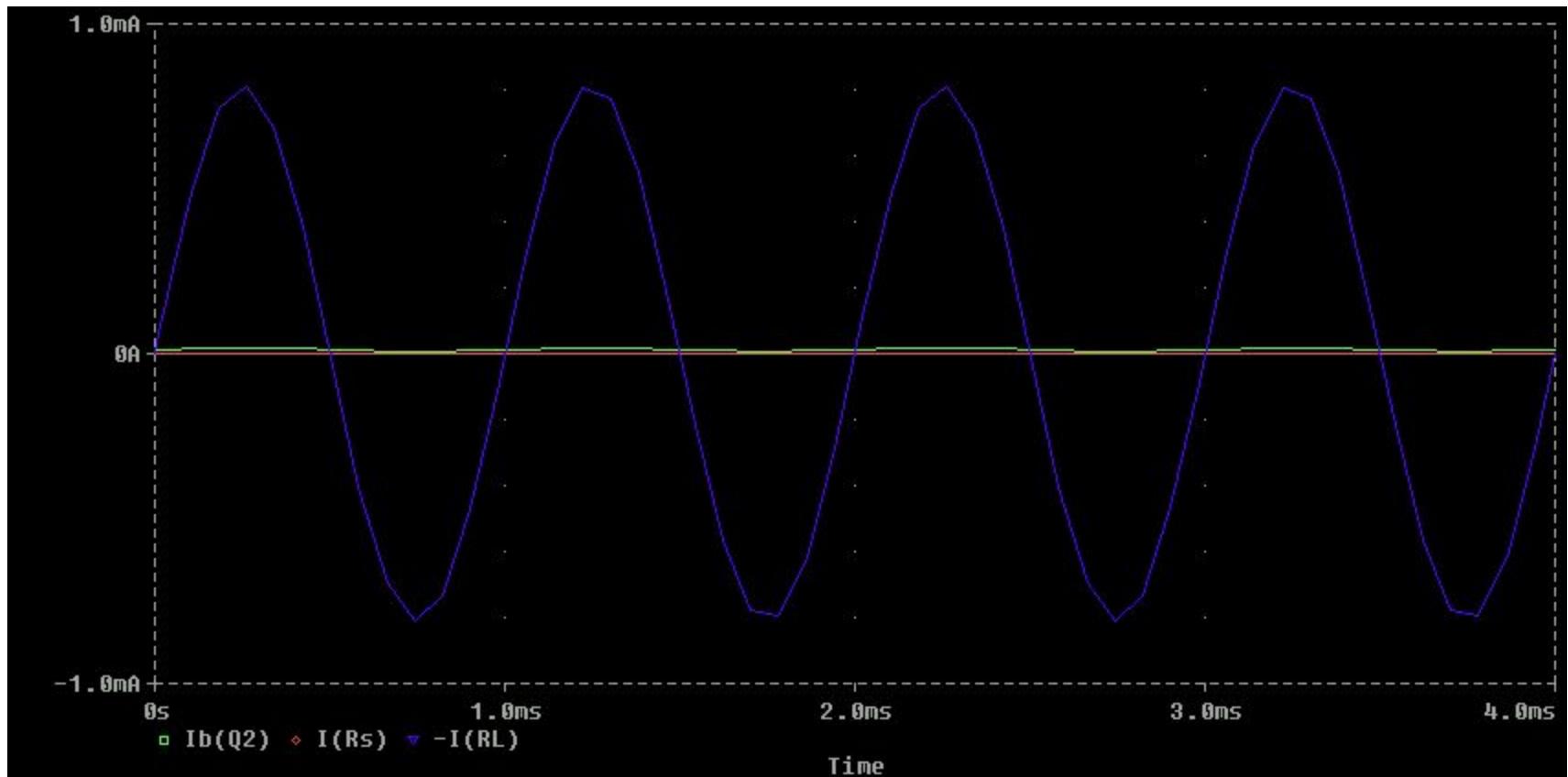
# Current



Input to  
stage 2 ( $I_b2$ )

output  
current

# Current



Input to  
stage 2 (ib2)

**Input  
current**

output  
current

## Power and current gain

$$\text{Input current} = (V_i)/R_{in} = 1/500K = 2.0\mu A$$

$$\text{output current} = (V_{out})/R_L = (0.81V)/1K = 0.81mA$$

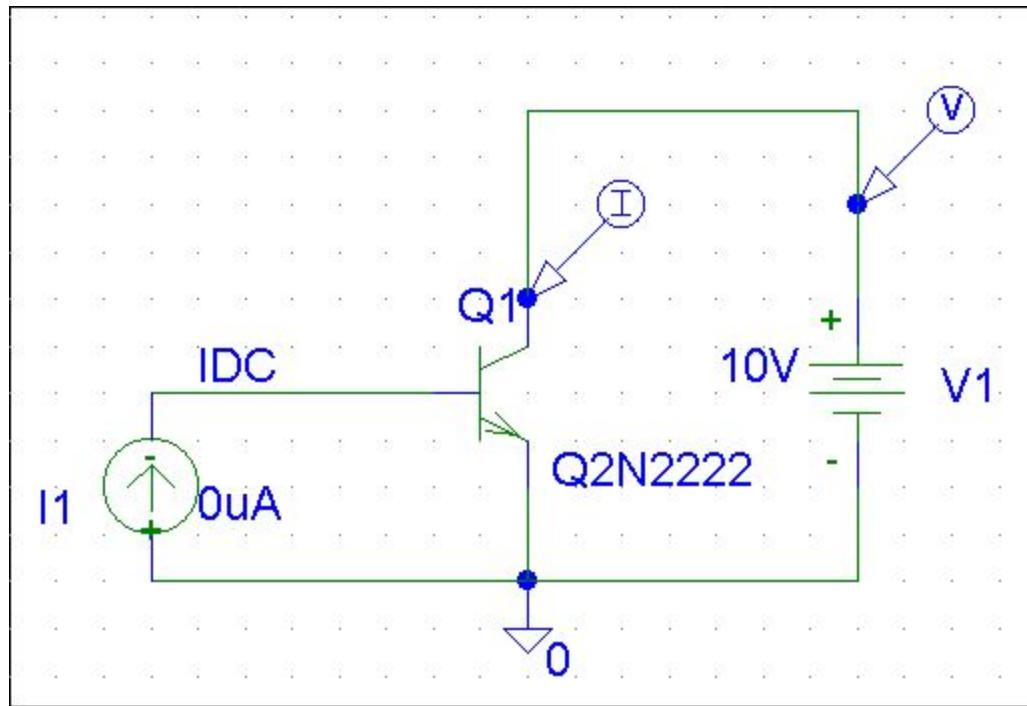
$$\text{current gain} = 0.81mA / 2.0\mu A = 405$$

$$\text{Input power} = (V_i) (V_i)/R_{in} = 1 \times 1/500K = 2.0\mu W$$

$$\text{output power} = (V_{out}) (V_{out})/R_L = (0.81V) (0.81V)/1K = 656\mu W$$

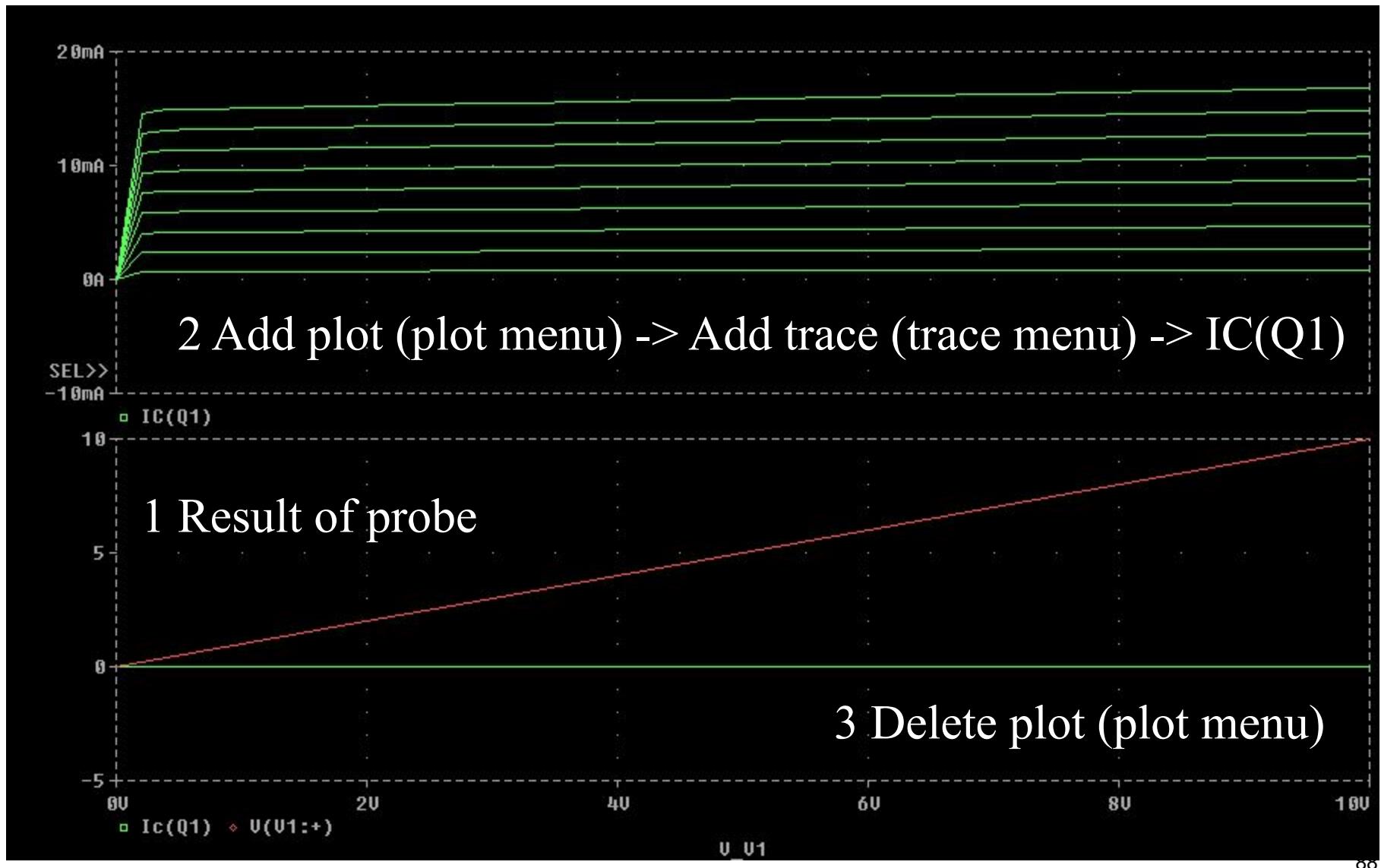
$$\text{power gain} = 656\mu W / 2\mu W = 329$$

# BJT Output Characteristics

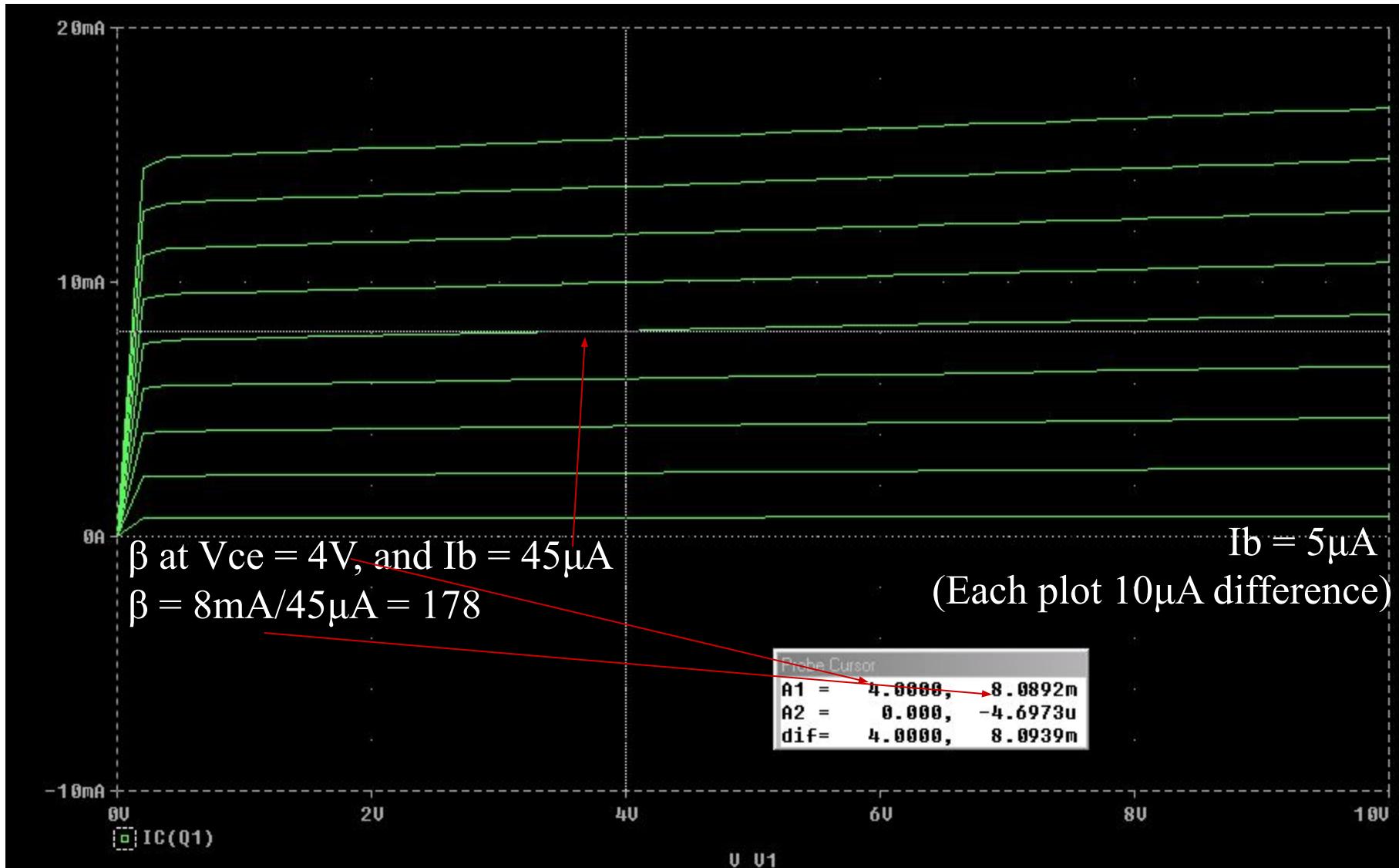


- Plot  $I_c$  vs.  $V_{ce}$  for multiple values of  $V_{ce}$  and  $I_b$
  - From **Analysis** menu use **DC Sweep**
  - Use **Nested sweep** in **DC Sweep** section

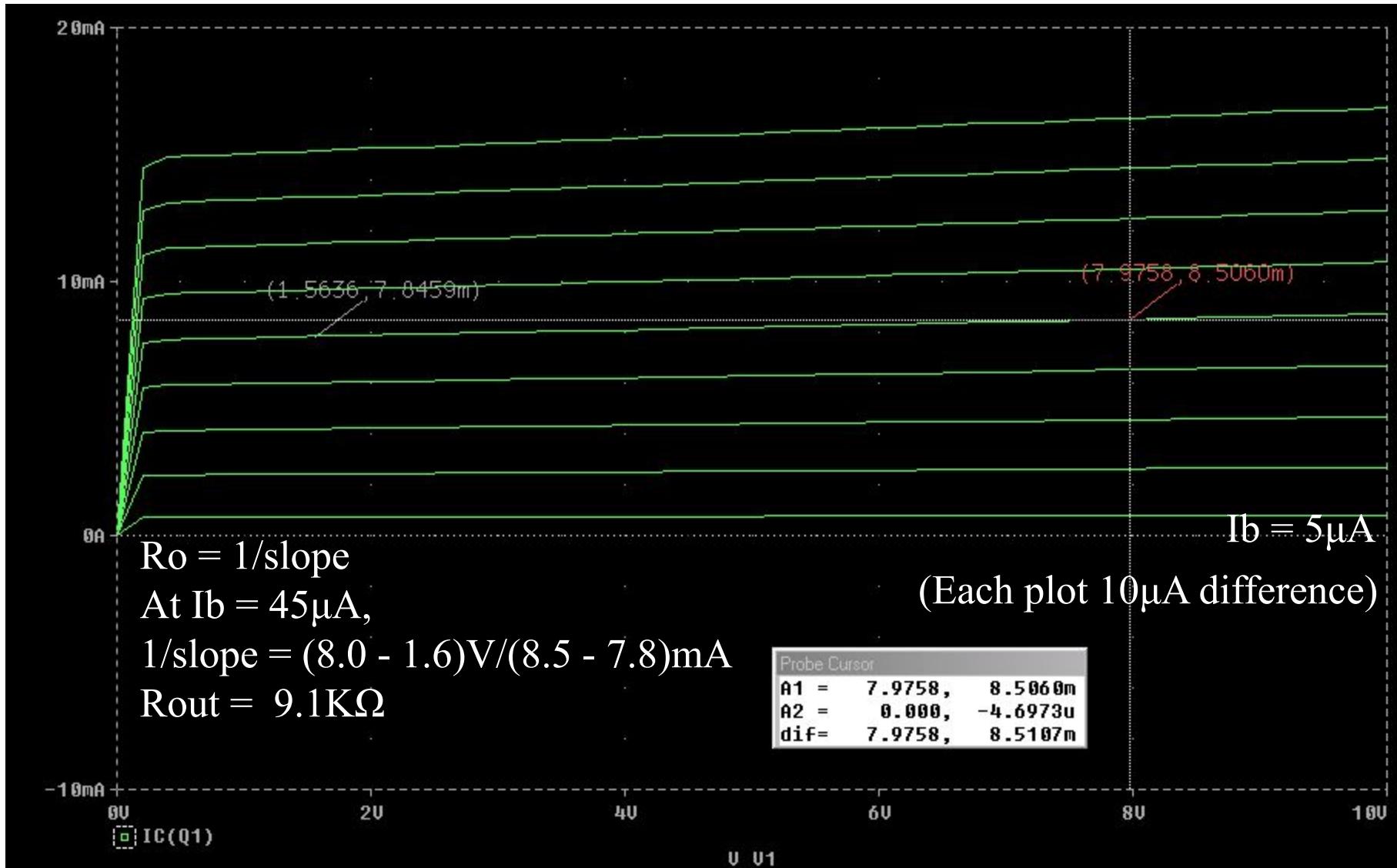
# Probe: BJT Output Characteristics



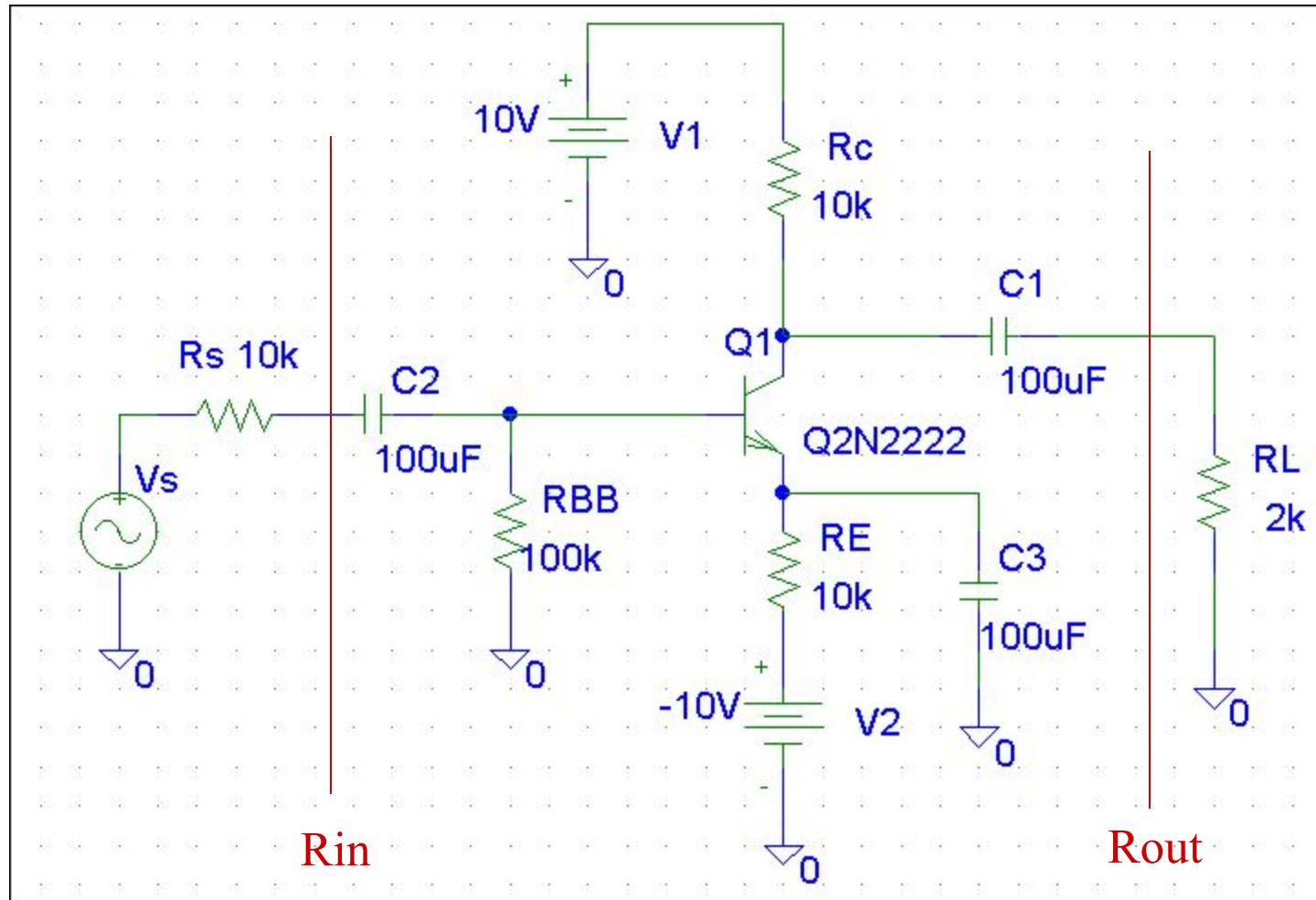
# BJT Output Characteristics: current gain



# BJT Output Characteristics: transistor output resistance



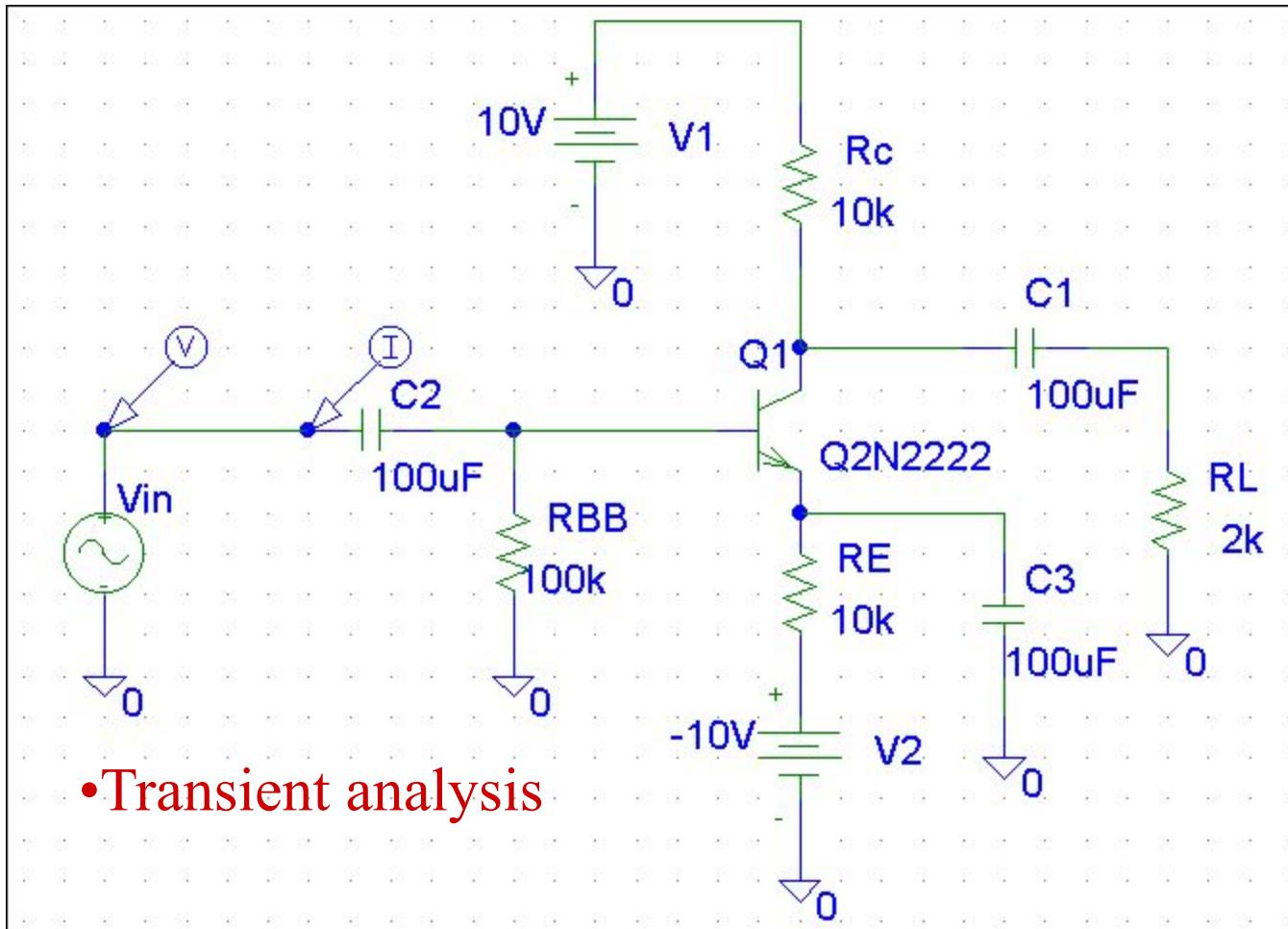
# CE Amplifier: Measurements with Spice



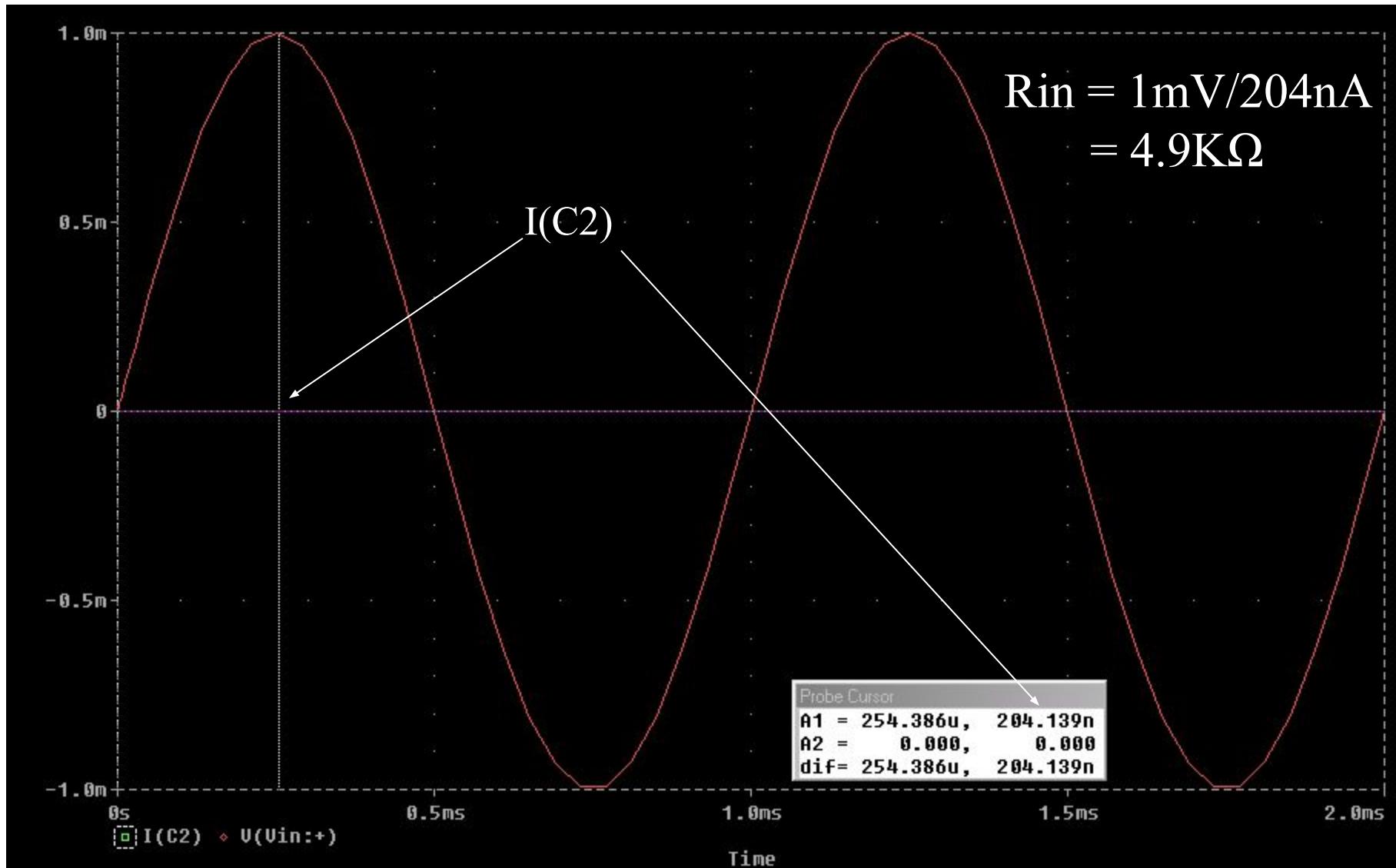
# Input Resistance Measurement Using SPICE

- Replace source, Vs and Rs with Vin, measure  
 $R_{in} = V_{in}/I_{in}$
- Do not change DC problem: keep capacitive coupling if present
- Source (Vin) should be a high enough frequency so that capacitors act as shorts:  $R_{cap} = |1/\omega C|$ . For  $C = 100\mu F$ ,  $\omega = 1\text{KHz}$ ,  $R_{cap} = 1/2\pi(1\text{K})(100\text{E-}6) \approx 1.6\Omega$
- $V_{in}$  should have a small value so operating point does not change  
 $V_{in} \approx 1\text{mV}$

# Rin Measurement



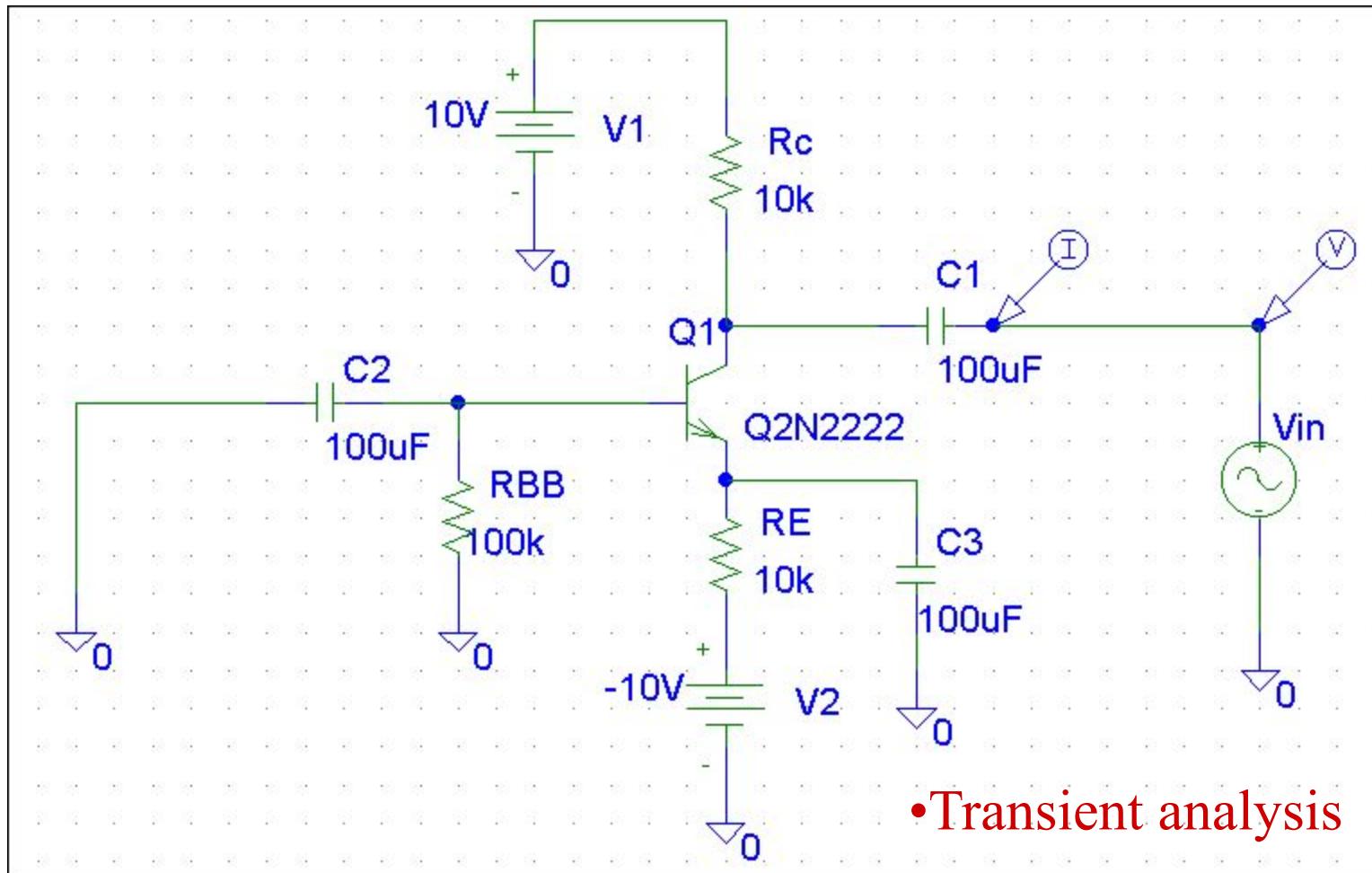
# Probe results



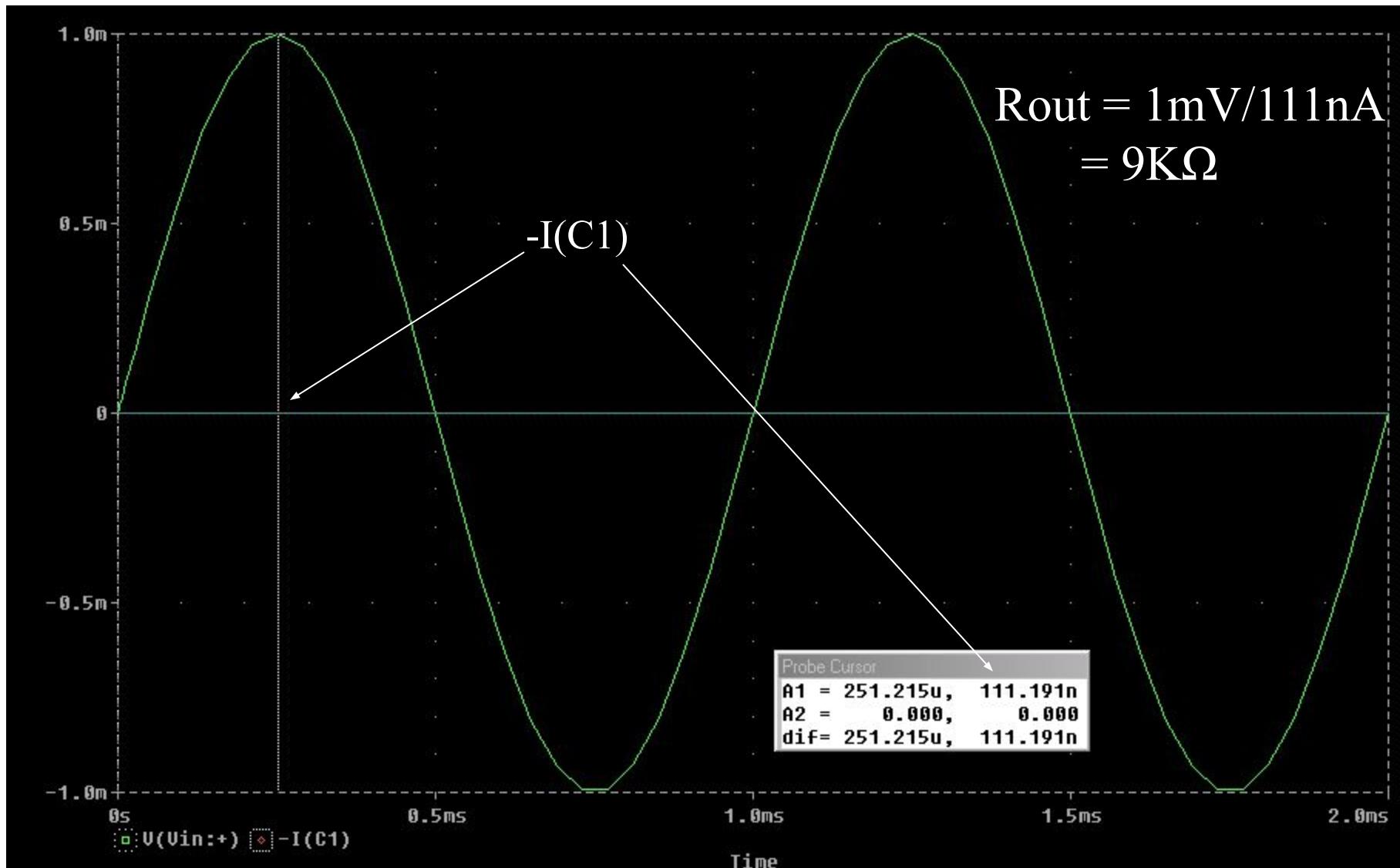
# Output Resistance Measurement Using SPICE

- Replace load,  $R_L$  with  $V_{in}$ , measure  $R_{in} = V_{in}/I_{in}$
- Set  $V_S = 0$
- Do not change DC problem: keep capacitive coupling if present
- Source ( $V_{in}$ ) should be a high enough frequency so that capacitors act as shorts:  $R_{cap} = |1/\omega C|$ . For  $C = 100\mu F$ ,  $\omega = 1KHz$ ,  $R_{cap} = 1/2\pi(1K)(100E-6) \approx 1.6\Omega$
- $V_{in}$  should have a small value so operating point does not change  
 $V_{in} \approx 1mV$

# R<sub>out</sub> Measurement

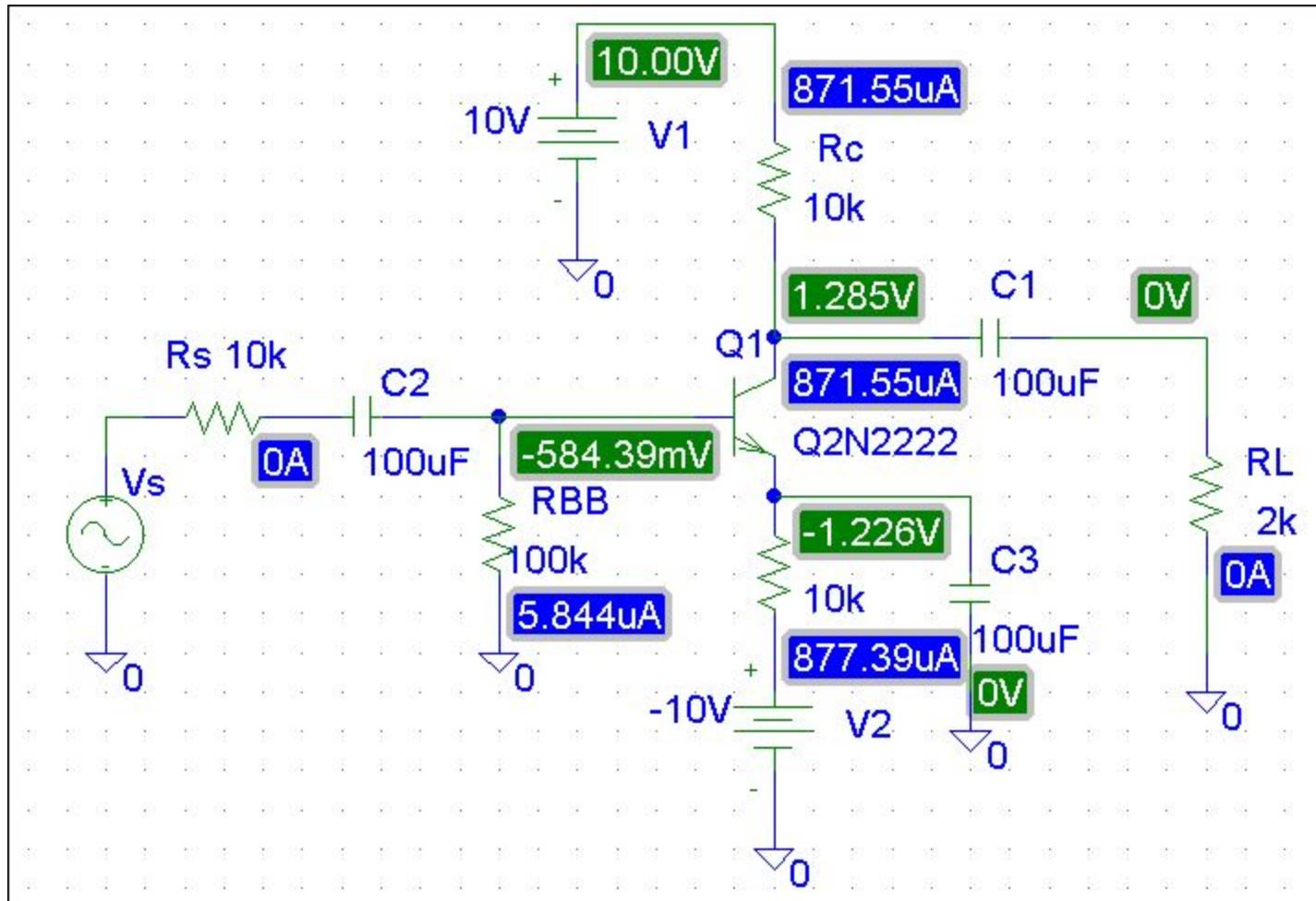


# Probe results



-I(C1) is current in Vin flowing out of + terminal

# DC Power measurements



Power delivered by  $\pm 10$  sources:

$$(10)(872\mu\text{A}) + (10)(877\mu\text{A}) = 8.72\text{mW} + 8.77\text{mW} = 17.4\text{mW}$$

# ac Power Measurements of Load

