CHAPTER 7

Transistor Amplifiers
BJT Cases

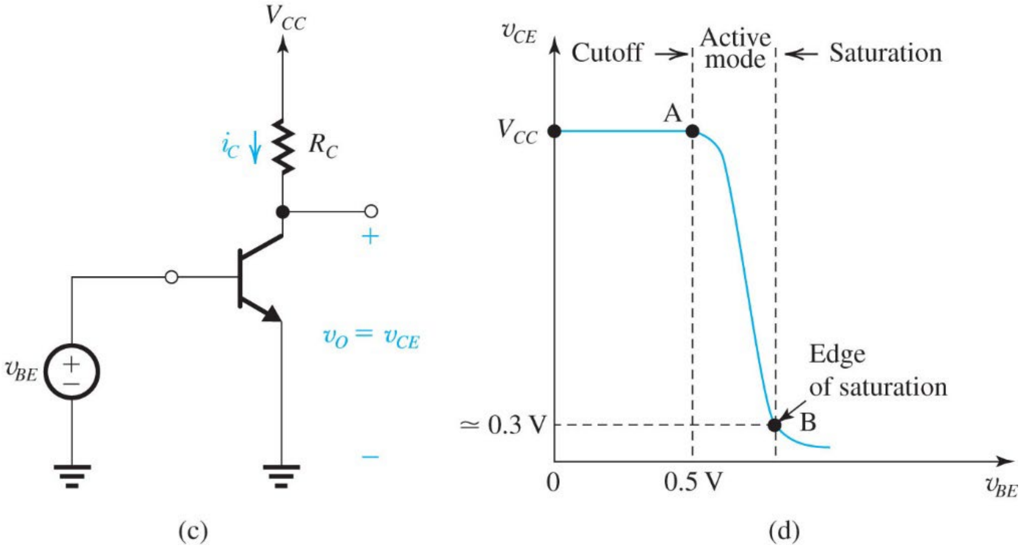
Outlines

- 7.1 Basic principles
- 7.2 Small-signal models
- 7.3 Basic configurations

7.1 Basic principles

- The basis of amplifier operation
  - Operating a NPN transistor in the active mode
    - $v_{BE} \approx 0.7V$, and $v_{CE} \geq 0.3V$ results in $v_{CB} \geq -0.4V$
  - Convert a transconductance amplifier to a voltage amplifier

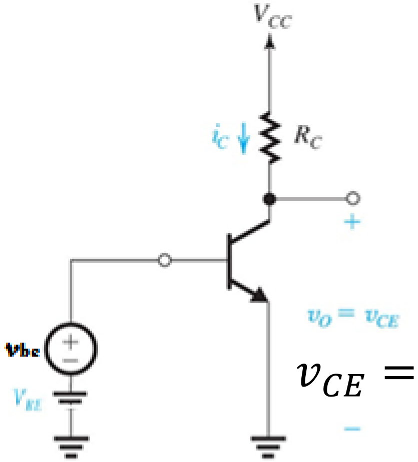
$$v_o = v_{CE} \quad v_i = v_{BE}$$



(c) (d)

Figure 7.2 (**c**) a *npn* amplifier and (**d**) its VTC.

- 7.1.4 Obtaining linear amplification by biasing the transistor
  - Quiescent (Q) point / bias point / dc operation point
  - $v_{BE}(t) = V_{BE} + v_{be}(t)$, $v_{be}(t)$ is superimposed on the bias V_{BE}
    - $v_{be}(t)$ is small enough to restrict the excursion of the instantaneous operating point to a short, almost-linear segment of the VTC around the bias point
    - The shorter the segment, the greater the linearity achieved, and the closer to an ideal triangular wave the signal component at the output will be.



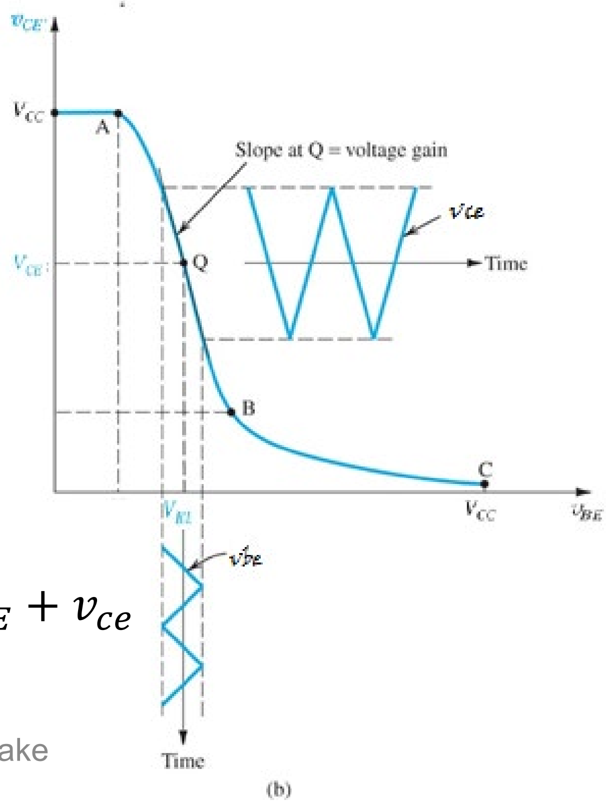


Figure 7.4 The npn BJT amplifier with a small time-varying signal $v_{be}(t)$ superimposed on the dc bias voltage V_{BE}. The npn BJT operates on a short almost-linear segment of the VTC around the bias point Q and provides an output voltage $v_{ce} = A_v v_{be}$

$$v_{BE} = V_{BE} + v_{be}$$

$$v_{CE} = V_{CE} + v_{ce}$$

- Obtaining linear amplification
  - If $v_{be}(t)$ is large, the output v_{CE} will exhibit nonlinear distortion and may leave the segment AB altogether
    - Negative part of $v_{be}(t)$: the positive peak of v_{CE} will be clipped off
    - Positive part of $v_{be}(t)$: the negative peak of v_{CE} will becomes flattened.
    - Thus, the selection of Q has a profound effect on the maximum allowable amplitude of v_{CE}

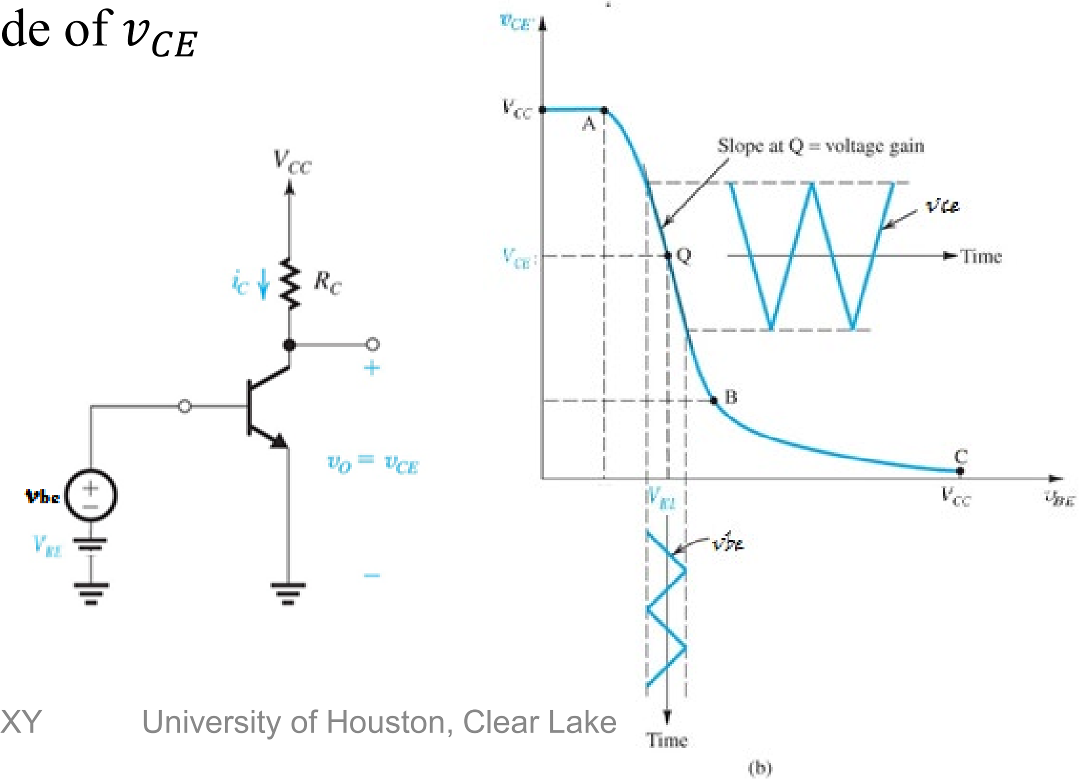


Figure 7.4 The MOSFET amplifier with a small time-varying signal $v_{be}(t)$ superimposed on the dc bias voltage V_{BE}. The MOSFET operates on a short almost-linear segment of the VTC around the bias point Q and provides an output voltage $v_{ce} = A_v v_{be}$

7.2 Small-signal models

- The DC bias point (setting v_{be} to 0)

$$I_C = \alpha I_E = \beta I_B$$

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

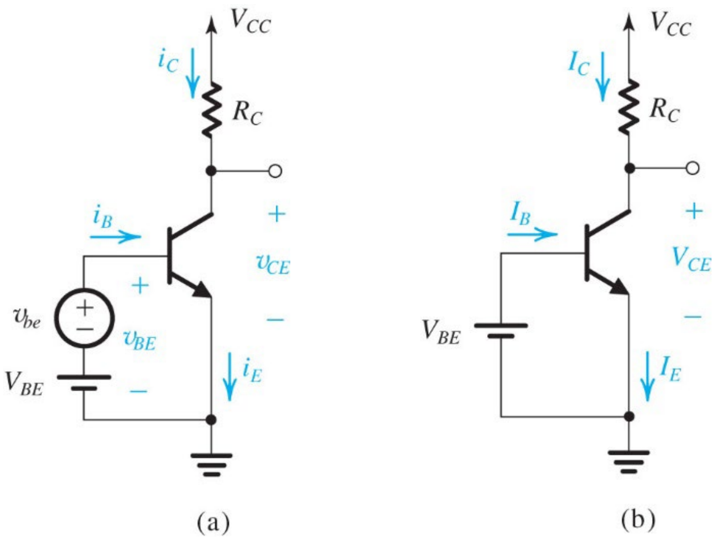


Figure 7.20 (a) Conceptual circuit to illustrate the operation of the transistor as an amplifier. (b) the circuit of (a) with the signal source v_{be} eliminated for dc (bias) analysis.

- The collector current and the transconductance

$$v_{BE} = V_{BE} + v_{be} \Rightarrow$$
$$i_C = I_S e^{v_{BE}/V_T} = I_S e^{(V_{BE}+v_{be})/V_T} = I_S e^{V_{BE}/V_T} e^{v_{be}/V_T} = I_C e^{v_{be}/V_T}$$

e^{v_{be}/V_T} represents non-linear distortion

However, if $v_{be} \ll V_T$,

$$i_C \approx I_C\left(1 + \frac{v_{be}}{V_T}\right) = I_C + i_c,\ i_c = \frac{I_C}{V_T} v_{be}$$

Rewritten as (Conclusion#1)

$$i_c = g_m v_{be},\ g_m = \frac{I_C}{V_T}\ (g_m\text{: transconductance})$$

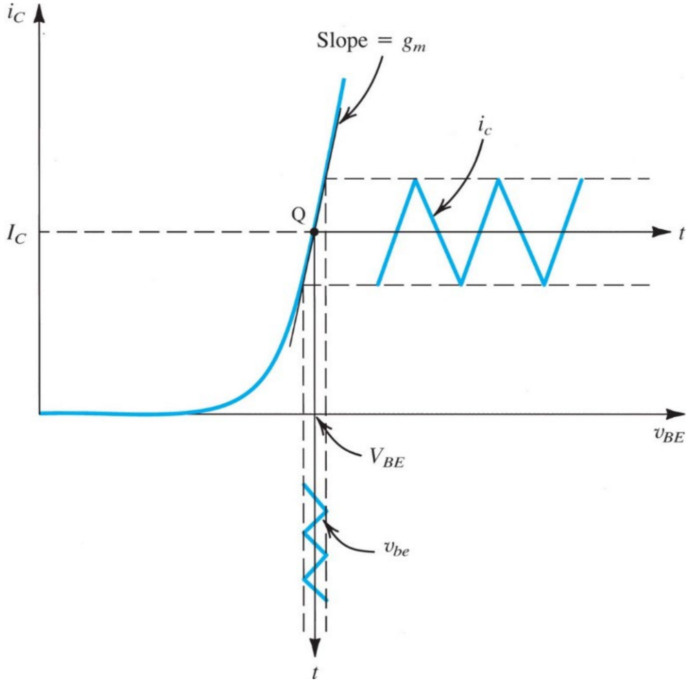


Figure 7.21 Linear operation of the transistor under the small-signal condition: A small-signal v_{be} with a triangular waveform is superimposed on the dc voltage V_{BE} . It gives rise to a collector-signal current i_c, also of triangular waveform, superimposed on the dc current I_C . Here, $i_C = g_m v_{be}$, where g_m is the slope of the $i_C - v_{BE}$ curve at the bias point Q.

- The base current and the input impedance at base

$$i_b = \frac{i_c}{\beta} = \frac{g_m}{\beta} v_{be} \Rightarrow \frac{v_{be}}{i_b} = \frac{\beta}{g_m}$$

The small signal input resistance between base and emitter, looking into the base, is denoted as

$r_\pi = \frac{v_{be}}{i_b} = \frac{\beta}{g_m}$ or $\beta = g_m r_\pi$

Since $g_m = \frac{I_C}{V_T}$

$$r_\pi = \frac{V_T}{I_B}$$

Conclusion#2: $r_\pi = \frac{\beta}{g_m} = \frac{V_T}{I_B}$

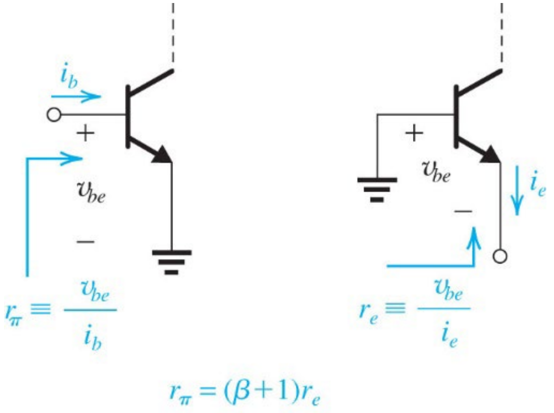
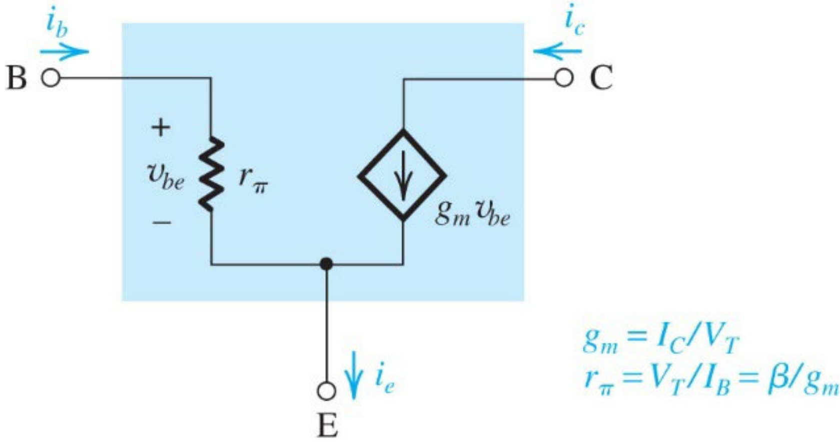
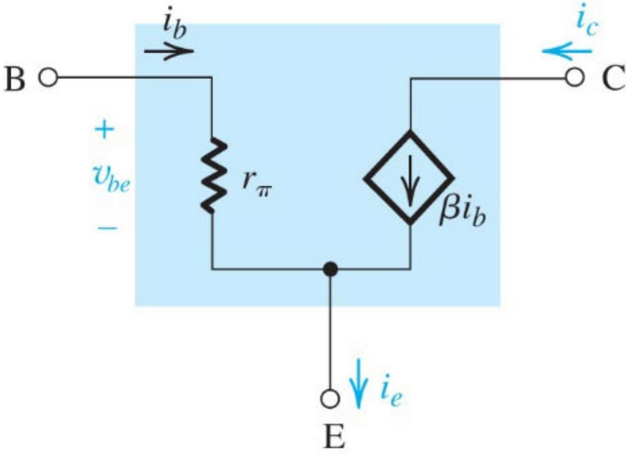


Figure 7.22 Illustrating the definition of r_π and r_e.

- The hybrid-π model (without emitter resistor)
  - Conclusion#1: $g_m = \frac{I_C}{V_T}$
  - Conclusion#2: $r_\pi = \frac{V_T}{I_B} = \frac{\beta}{g_m}$
  - $i_c = g_m v_{be} = \beta i_b$
  - $i_b = \frac{v_{be}}{r_\pi}$ (looking into B)



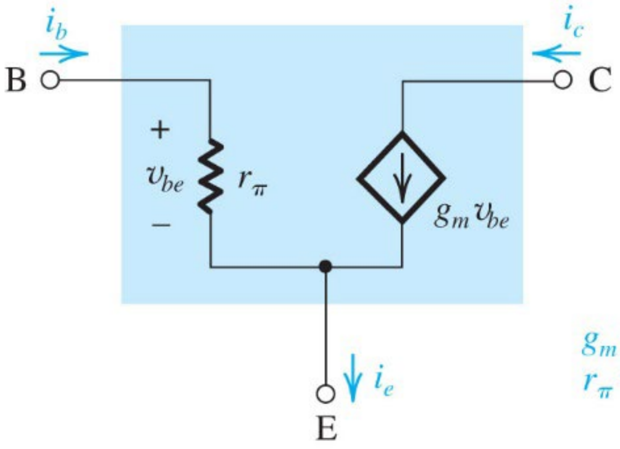
(a)



(b)

Figure 7.24 Two slightly different versions of the hybrid-π model for the small-signal operation of the BJT. The equivalent circuit in (**a**) represents the BJT as a voltage-controlled current source (a transconductance amplifier), and that in (**b**) represents the BJT as a current-controlled current source (a current amplifier).

• Summary table Small-signal models of BJT



(a)

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

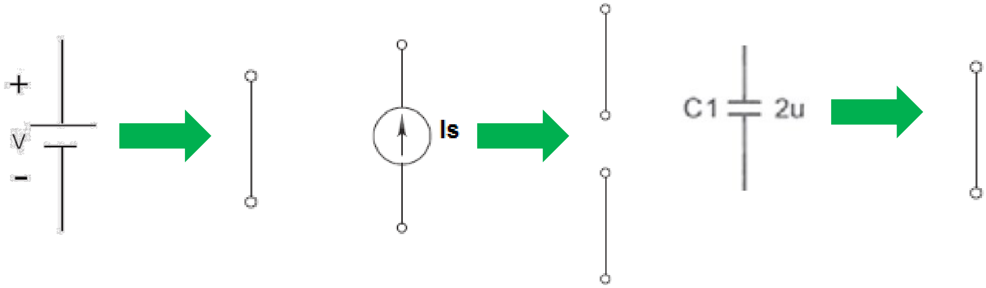
Conclusion#1:
$i_c = g_m v_{be},\ g_m = \frac{I_C}{V_T}$

Conclusion#2: $r_\pi = \frac{\beta}{g_m} = \frac{V_T}{I_B}$

- For DC circuit
  - Eliminate the input signal/small signal v_i
  - Open-circuit capacitors since they block dc currents
- Small-signal equivalent-circuit models
  - The rest of the circuits remains unchanged except for:
    - Ideal constant dc voltage source: replaced by short circuit.

      Reason: the voltage across an ideal constant dc voltage source doesn’t change, thus the voltage signal will always be 0 across a constant dc voltage source.
    - Ideal constant dc current source: replaced by an open circuit

      Reason: the signal current of an ideal constant dc current source will always be 0.
    - Capacitor: short circuit



- Procedure for analyzing BJT circuits (Table 7.1)
  - D.C. circuit (setting Q point in active region)

    1) Determine the dc operating points of the transistor.

    Small-signal source <-> eliminate

    Capacitor <-> open circuit

    2) Calculate the values of the parameters of the small-signal model, using conclusion 1~4.
  - A.C. circuit (amplifying small-signal input)

    1) Eliminate the dc sources and capacitors with

    D.C. voltage source <-> short circuit

    D.C. current source <-> open circuit

    Capacitor <-> short circuit

    2) Small-signal model

    With R_e <-> T model without R_e <-> π model

    3) Analyze the small-signal circuit to determine the required quantities (voltage gain, input/output resistance, etc.)

• Example 7.5

Analyze the amplifier to determine its voltage gain $\frac{v_o}{v_i}$. Assume $\beta = 100$ and neglect the early effect.

1. D.C. analysis: find the quiescent operating point.

1) Set $v_i = 0$ and thus obtain the dc circuit in (b).

$$I_B = \frac{V_{BB}-0.7}{R_{BB}} = 0.023mA$$

$$I_C = \beta I_B = 2.3mA$$

$$V_C = V_{CC} - I_C R_C = 10V - 2.3 \times 3 = 3.1V$$

Since CE>0.3V, the transistor is in active region in the quiescent condition.

2) Calculate parameters of the small-signal model

$$r_\pi = \frac{V_T}{I_B} = \frac{25}{0.023} = 1.09k\Omega \text{ (Conclusion \#2)}$$

$$g_m = \frac{I_C}{V_T} = \frac{2.3}{0.025} = 92\frac{mA}{V} \text{ (Conclusion \#1)}$$

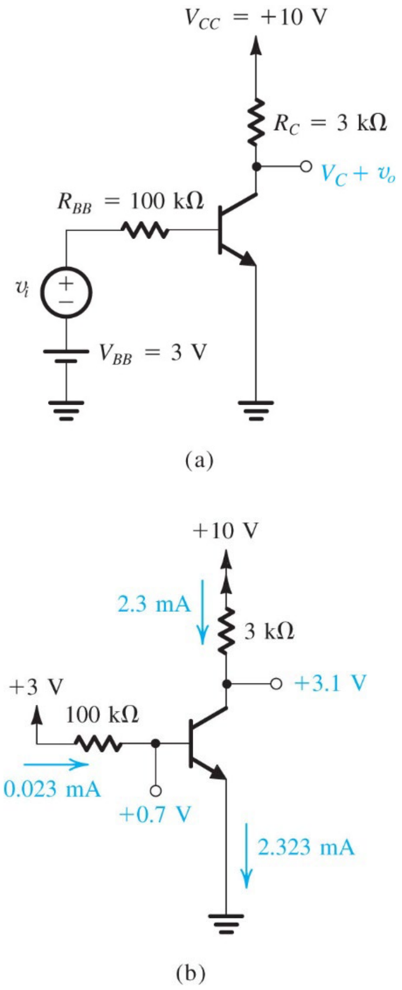


Figure 7.28 Example 7.5: (**a**) amplifier circuit; (**b**) circuit for dc analysis

- Example 7.5 Cont.

Analyze the amplifier to determine its voltage gain $\frac{v_o}{v_i}$. Assume $\beta = 100$ and neglect the early effect.

2 A.C circuit:

1) Small-signal model:

Set V_{CC} and V_{BB} as short circuits

2) Analyze the small-signal circuit

$$v_{be} = \frac{r_\pi}{r_\pi + R_{BB}} v_i = \frac{1.09}{1.09 + 100} v_i = 0.011 v_i$$

$$\frac{v_o}{v_i} = \frac{-g_m v_{be} R_C}{v_i} = \frac{-g_m R_C \times 0.011 v_i}{v_i} = -3.04\ V/V$$

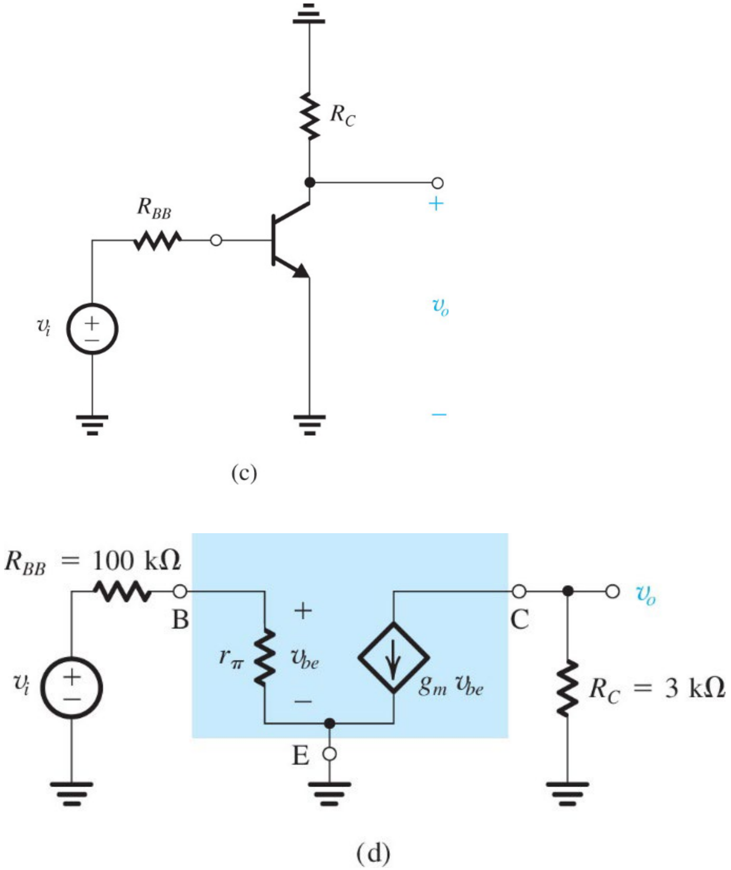
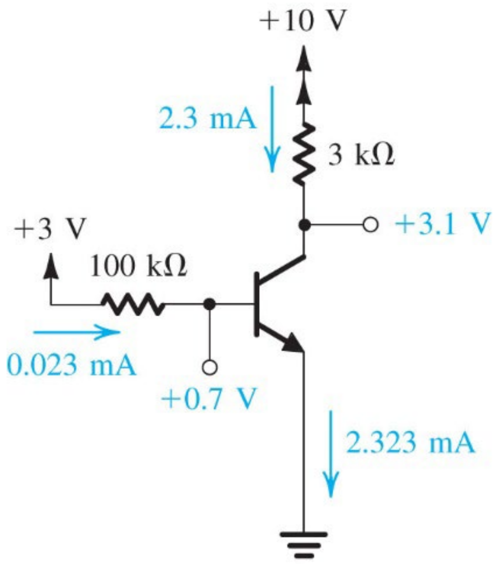


Figure 7.28 Example 7.5: (**c**) amplifier circuit with dc sources replaced by short circuits; (**d**) amplifier circuit with transistor replaced by its hybrid-π, small-signal model.

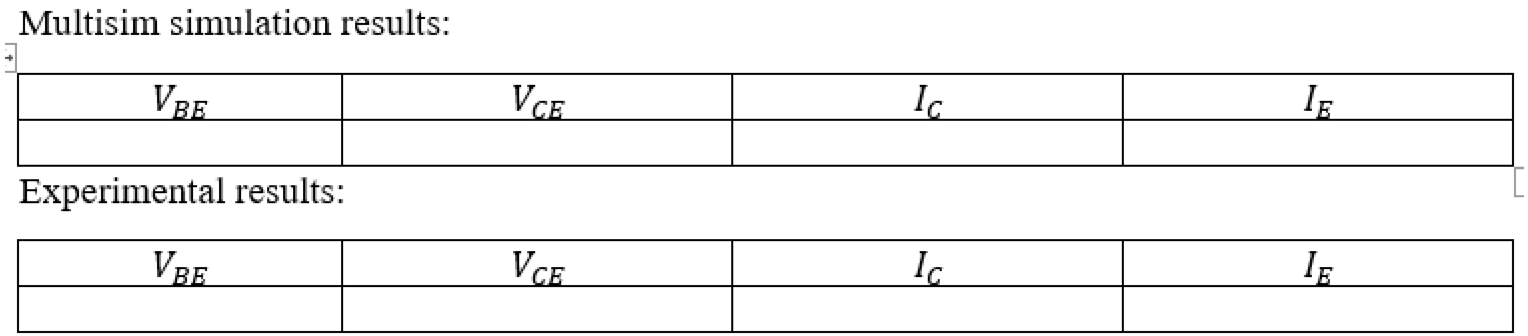
- # Experiment 10.1

Set up the following circuit with NPN BJT (**2N3904/2N4401**).

Do the proper measurements that compare your measurements with the design requirements. They might have a bit differences.



Multisim simulation results:


Multisim simulation results:

V_{BE}	V_{CE}	I_C	I_E

Experimental results:

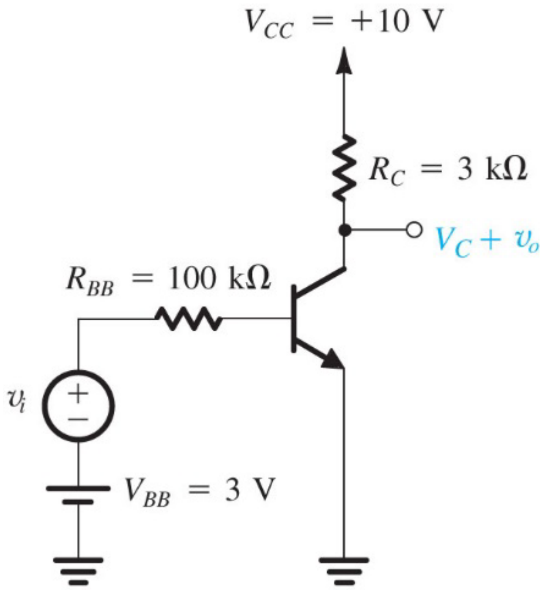
V_{BE}	V_{CE}	I_C	I_E

- # Experiment 10.2

Add the signal to the above bias circuit using functional generator.

$v_i(t) = \ Vp \cdot sine(\omega t) volts\ and\ Vp = 50\ mV.$

Measure $v_o(t)$ as a function of ω/f. Briefly explain and comment your results.



Multisim simulation results:

Freq. (Hz)	100	200	1k	5k	10k	20k	50k
$v_{o(p-p)}$							
$G_v = \frac{v_o}{v_{sig}}$							

Freq. (Hz)	100k	200k	500k	800k	1M	2M	5M	10M
$v_{o(p-p)}$								
$G_v = \frac{v_o}{v_{sig}}$								

Experimental results:

Freq. (Hz)	100	200	1k	5k	10k	20k	50k
$v_{o(p-p)}$							
$G_v = \frac{v_o}{v_{sig}}$							

Freq. (Hz)	100k	200k	500k	800k	1M	2M	5M	10M
$v_{o(p-p)}$								
$G_v = \frac{v_o}{v_{sig}}$								

7.3 Basic configurations

- Three base configuration for MOSFET
  - – Common emitter
  - – Common base
  - – Common collector (voltage buffer/emitter follower)

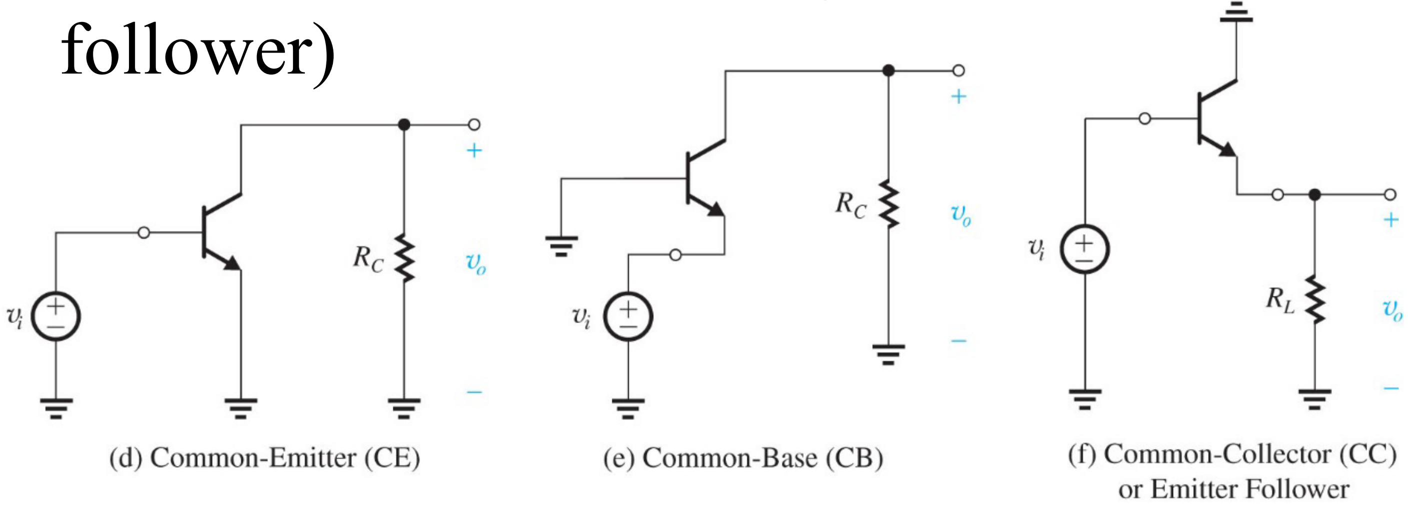


Figure 7.33 The basic configurations of transistor amplifiers. (**d**)–(**f**) for the BJT.

- Characterizing amplifiers
  - Input resistance: $R_{in} = \frac{v_i}{i_i}$
  - Output resistance: $R_o = \frac{v_x}{i_x}$

    (excluding R_L and set $v_i = 0$)
  - Open-circuit voltage gain

    $A_{vo} = \frac{v_o}{v_i}|_{R_L=\infty}$
  - Voltage gain of amplifier

    $A_v = \frac{v_o}{v_i} = A_{vo}\frac{R_L}{R_L+R_o}$
  - Overall voltage gain

    $G_v = \frac{v_o}{v_{sig}} = \frac{R_{in}}{R_{in}+R_{sig}} A_{vo} \frac{R_L}{R_L+R_o}$

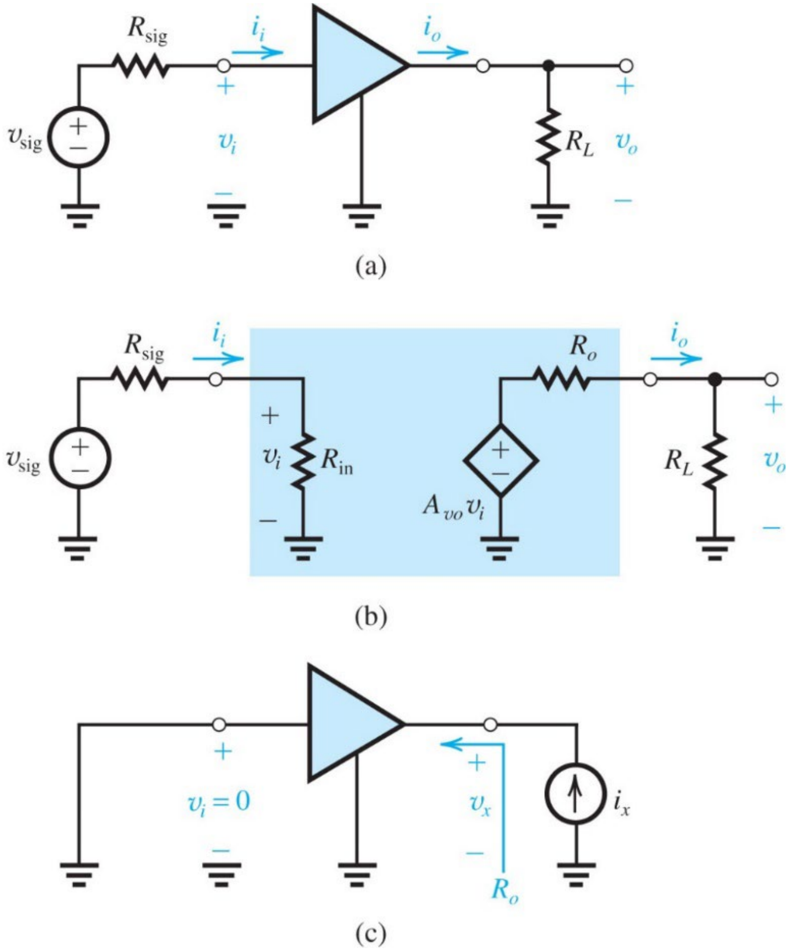


Figure 7.34 Characterization of the amplifier as a functional block: **(a)** An amplifier fed with a voltage signal v_{sig} having a source resistance R_{sig}, and feeding a load resistance R_L; **(b)** equivalent-circuit representation of the circuit in **(a)**; **(c)** determining the amplifier output resistance R_o.

7.3.3 Common-emitter amplifier

$R_{in} = r_\pi$

$R_o = R_C$

$$A_{vo} = \frac{v_o}{v_i}\Big|_{R_L=\infty} = \frac{-g_m R_c v_\pi}{v_\pi} = -g_m R_C$$

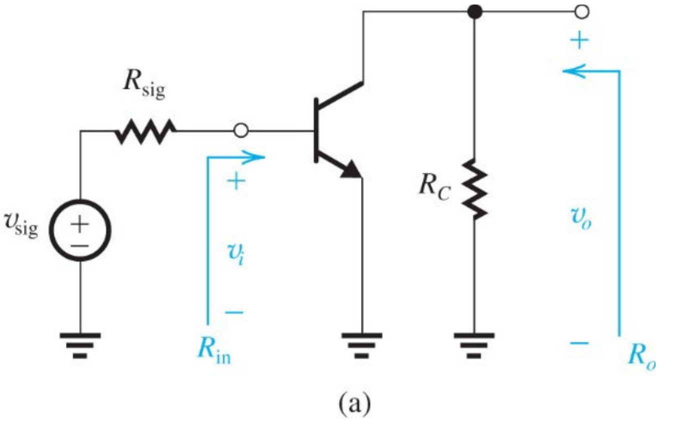
If a load R_L is connected across R_C

$$A_v = \frac{v_o}{v_i} = -g_m(R_C||R_L)$$

Since $v_i = \frac{r_\pi}{r_\pi + R_{sig}} v_{sig}$

$$G_v = \frac{v_o}{v_{sig}} = \frac{v_o}{v_i} \times \frac{v_i}{v_{sig}}$$

$$= -g_m(R_C||R_L)\frac{r_\pi}{r_\pi + R_{sig}}$$



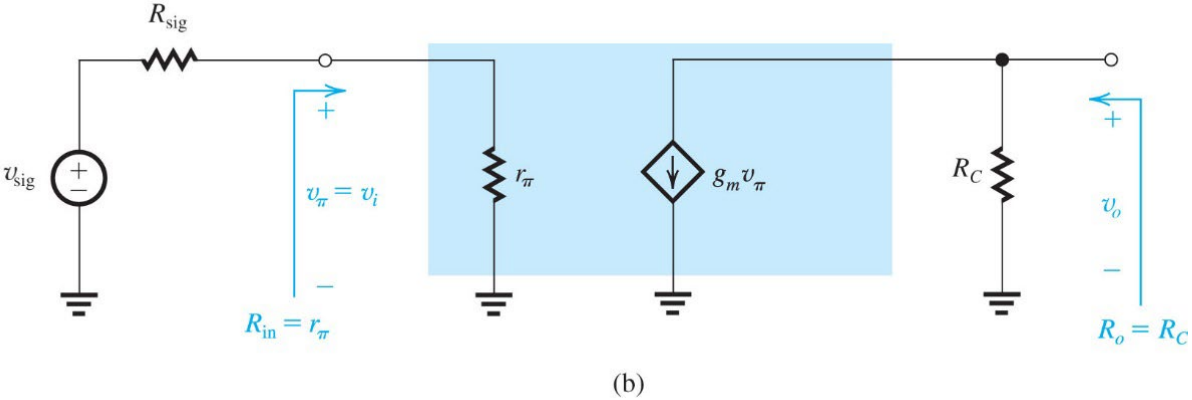


Figure 7.36 (**a**) Common-emitter amplifier fed with a signal v_{sig} from a generator with a resistance R_{sig}. The bias circuit is omitted. (**b**) The common-emitter amplifier circuit with the BJT replaced by its hybrid-π model.

- Final remark of the CE (without emitter resistor)
  - The most useful of all transistor amplifier configurations
  - High input impedance

$$R_{in}\uparrow = r_\pi = \frac{\beta}{g_m\downarrow} = \frac{V_T}{I_C\downarrow}$$

  - Output impedance

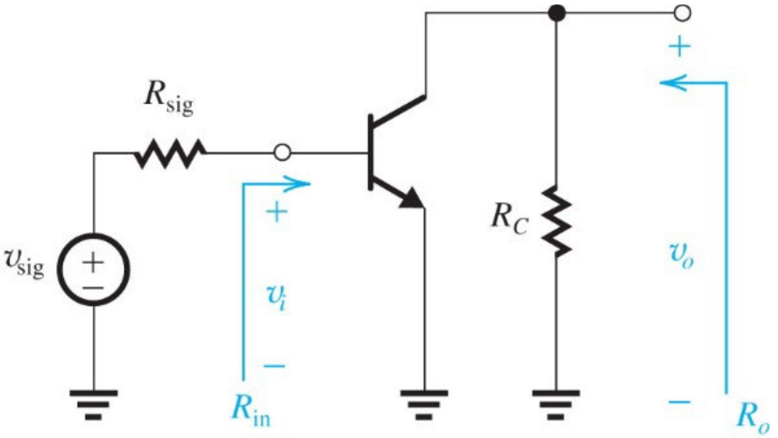
$$R_{in} = r_\pi \uparrow$$

$$R_o = R_C$$

$$A_{vo} = -g_m R_C \downarrow$$

$$A_v = \frac{v_o}{v_i} = -g_m(R_C||R_L)\downarrow$$

$$G_v = -g_m(R_C||R_L)\frac{r_\pi}{r_\pi + R_{sig}}\downarrow$$



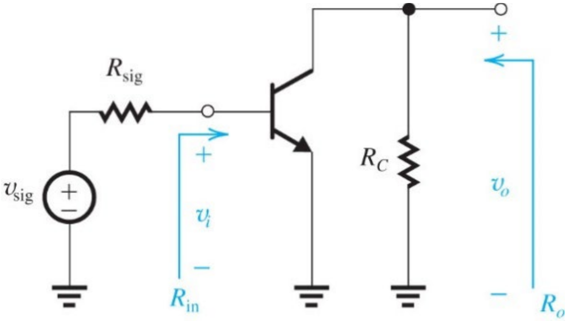
(a)

Example 7.8

A CE amplifier uses a BJT with $\beta = 100$ is biased at $I_C = 1mA$, and has a collector resistance $R_C = 5k\Omega$.

(a) Find R_{in}, A_{vo}, R_o.

(b) If the amplifier is fed with a signal source having $R_{sig} = 5k\Omega$ and a $R_L = 5k\Omega$ load is connected to the output. Find A_v, G_v.



(a)

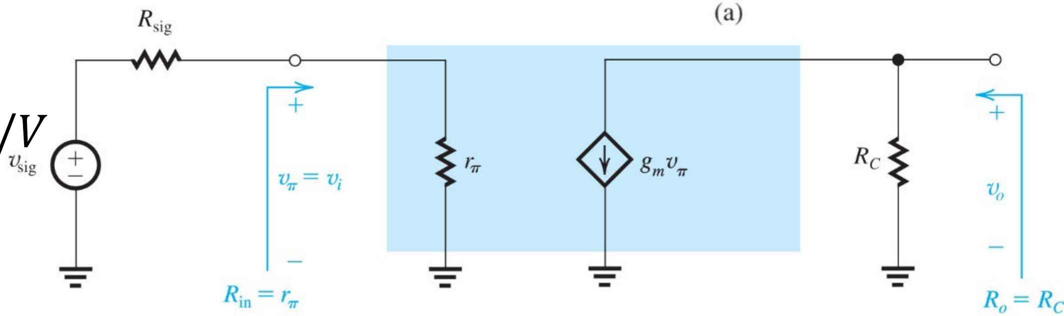
(a) $g_m = \frac{I_C}{V_T} = \frac{1mA}{25mV} = 40mA/V$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40mA/V} = 2.5k\Omega$$

$R_{in} = r_\pi = 2.5k\Omega$

$R_o = R_C = 5k\Omega$

$A_{vo} = -g_m R_C = -40 \times 5 = -200V/V$



(b)

(b) If a load R_L is connected across R_C

$$A_v = \frac{v_o}{v_i} = -g_m(R_C||R_L) = -40 \times 2.5 = -100V/V$$

$$G_v = -g_m(R_C||R_L)\frac{r_\pi}{r_\pi + R_{sig}} = -100 \times \frac{2.5}{2.5+5} = -33.3\ V/V$$

• Example 7.8 Cont.

A CE amplifier uses a BJT with $\beta = 100$ is biased at $\mathrm{I_C} = 1mA$, and has a collector resistance $\mathrm{R_C} = 5k\Omega$.

(c) If $\widehat{v_\pi}$ is to be limited to 5mV, what are the corresponding $\widehat{v_{sig}}$ and $\widehat{v_o}$ with the load connected?

Since $v_i = \frac{r_\pi}{r_\pi + R_{sig}} v_{sig}$, if $\widehat{v_\pi}$ is to be limited to 5mV

$$\widehat{v_{sig}} = \frac{r_\pi + R_{sig}}{r_\pi} \widehat{v_i} = 15mV$$

And the output signal will be

$$\widehat{v_o} = A_v \widehat{v_i} = 100 \times 5mV = 0.5V$$

HW7

- Problems
  - PP.487, 7.50 – Small signal model #1
  - PP.487, 7.52 – Small signal model #2
  - PP.487, 7.68 – Basic configuration
- Submission requirement:
  - Add the cover page!!!
  - Print the HW7.pdf out and answer all the questions
- HW7 Due: TBA (Late assignments: 40% deduction.)