ENEE 303 Recitation 09

Instructor: Dr. Agisilaos Iliadis

TA: Chang-Mu Han

04/10/2020

All pictures are from Microelectronic Circuits, Sedra and Smith, 6th and 7th edition.

Week Notes

- Three basic configurations of transistor amplifiers and characterizing these amplifiers
  - Common source/emitter
  - Common gate/base
  - Common drain/collector
- 4 example problems + 1 optional example problem

Basic configurations

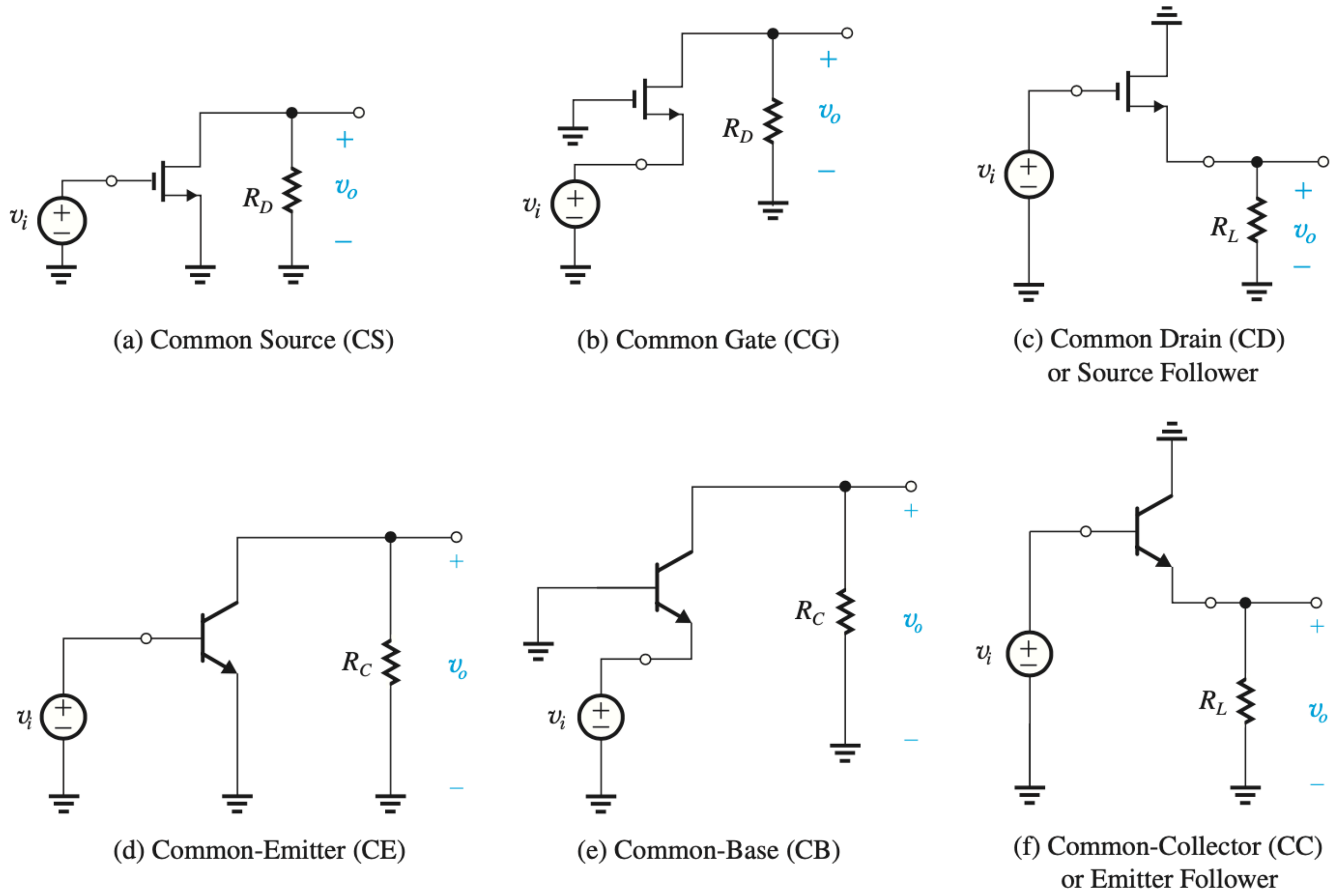
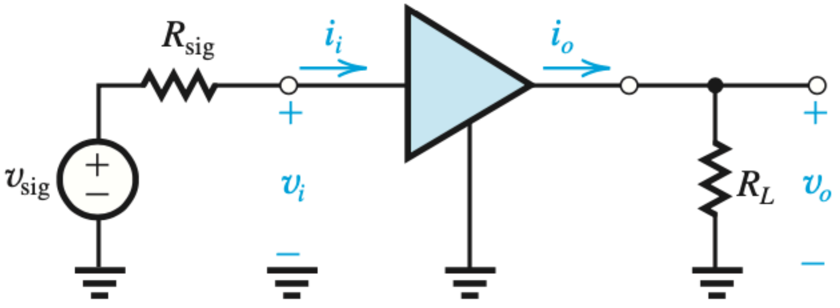
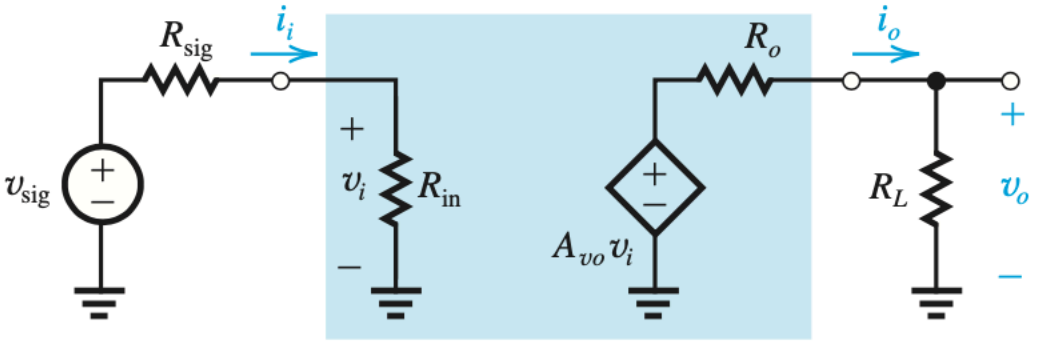


Figure 7.33 The basic configurations of transistor amplifiers. (**a**)–(**c**) For the MOSFET; (**d**)–(**f**) for the BJT.

Characterizing transistor amplifiers



(a)



(b)

Unilateral amplifier: input resistance is independent of load resistance

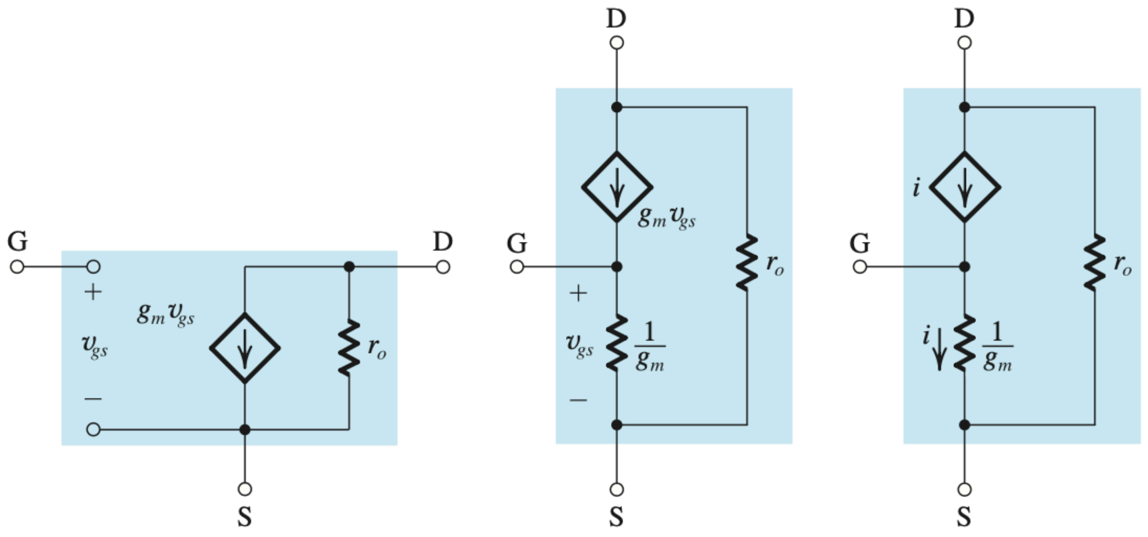
$$R_{in} \equiv \frac{v_i}{i_i} \qquad A_{vo} \equiv \left.\frac{v_o}{v_i}\right|_{R_L=\infty} \qquad R_o = \frac{v_x}{i_x}$$

$$A_v \equiv \frac{v_o}{v_i} = A_{vo}\frac{R_L}{R_L + R_o} \qquad G_v \equiv \frac{v_o}{v_{sig}}$$

Small signal models

MOSFET

Small-Signal, Equivalent-Circuit Models



Hybrid-π model

T models

Small signal condition: $v_{gs} \ll 2(V_{GS} - V_t)$

$$g_m \equiv \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}} = k_n(V_{GS} - V_t)$$

$$A_v \equiv \frac{v_{ds}}{v_{gs}} = -g_m R_D$$

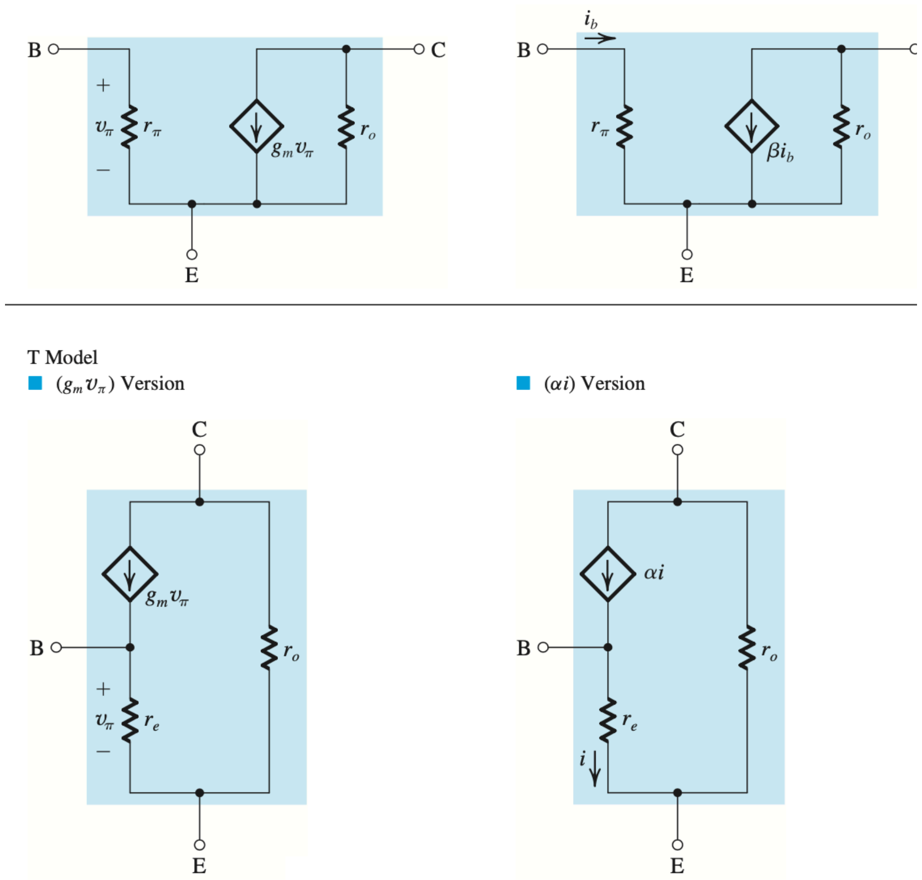
BJT

Hybrid-π Model

- $(g_m v_\pi)$ Version
- (βi_b) Version

T Model

- $(g_m v_\pi)$ Version
- (αi) Version



$$v_{be} \ll V_T$$

$$g_m = \left.\frac{\partial i_C}{\partial v_{BE}}\right|_{i_C=I_C} = \frac{I_C}{V_T} \qquad r_\pi = \frac{\beta}{g_m}$$

$$A_v \equiv \frac{v_{ce}}{v_{be}} = -g_m R_C$$

The common-source/emitter amplifiers

- Characteristics of the CS amplifier

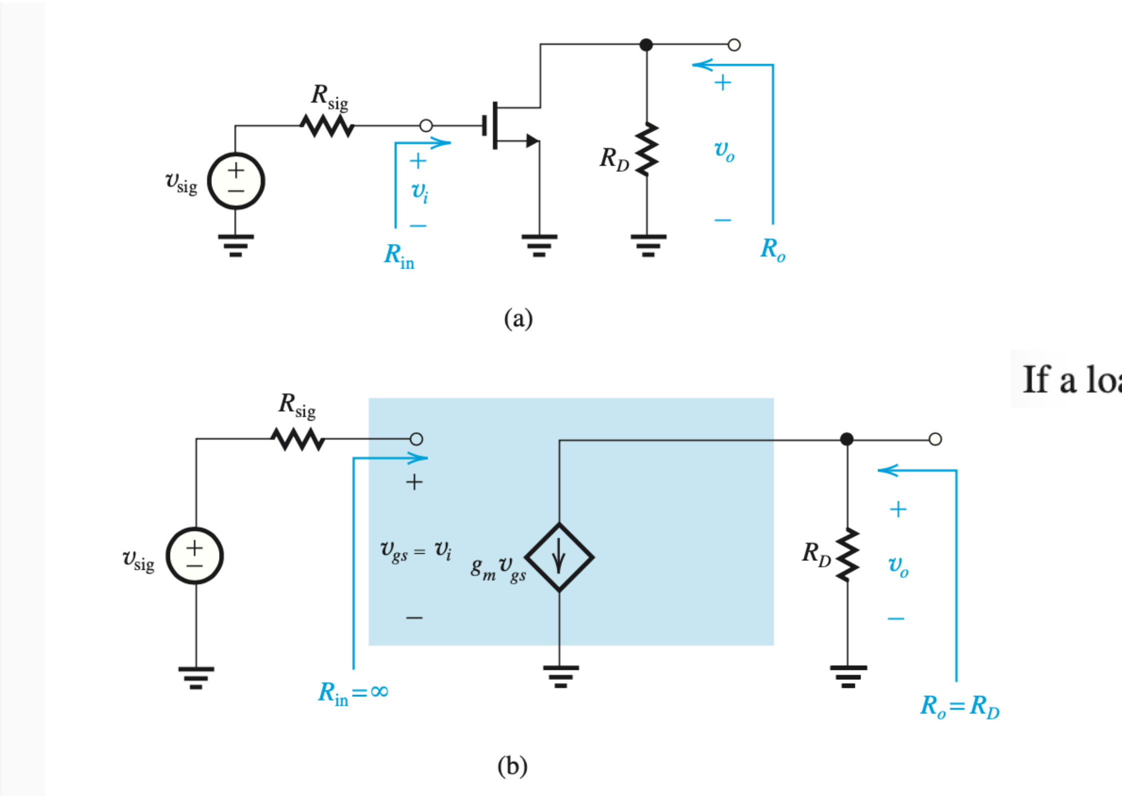


Figure 7.35 **(a)** Common-source amplifier fed with a signal v_{sig} from a generator with a resistance R_{sig}. The bias circuit is omitted. **(b)** The common-source amplifier with the MOSFET replaced with its hybrid-π model.

$$R_{in} = \infty$$
$$v_i = v_{sig}$$
$$v_{gs} = v_i$$
$$v_o = -g_m v_{gs} R_D$$

$$A_{vo} \equiv \frac{v_o}{v_i} = -g_m R_D$$
$$R_o = R_D$$

If a load resistance R_L is connected across R_D, the voltage gain A_v can be obtained

$$A_v = -g_m (R_D \| R_L)$$

$$G_v \equiv \frac{v_o}{v_{sig}} = -g_m (R_D \| R_L)$$

The common-source/emitter amplifiers

- Characteristics of the CE amplifier

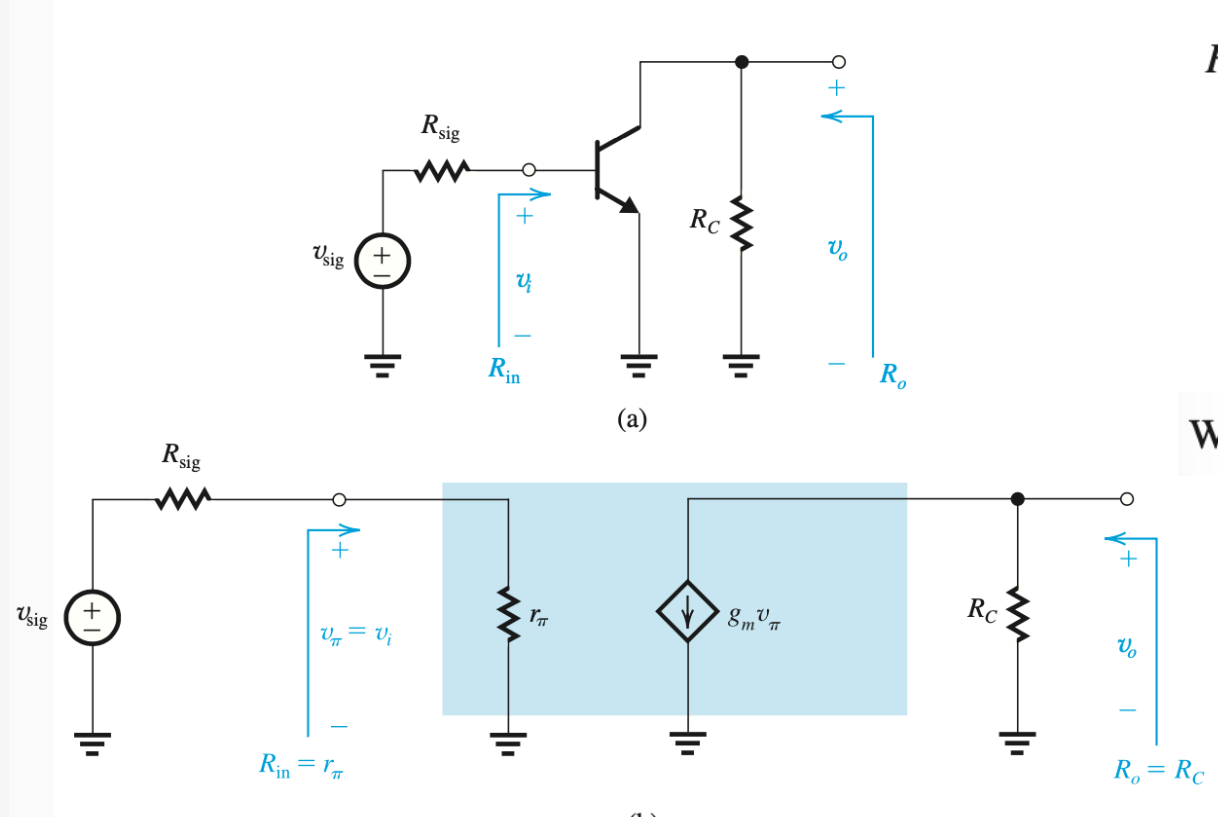


Figure 7.36 (**a**) Common-emitter amplifier fed with a signal v_{sig} from a generator with a resistance R_{sig}. The bias circuit is omitted. (**b**) The common-emitter amplifier circuit with the BJT replaced by its hybrid-π model.

$$R_{in} = r_\pi = \beta/g_m$$

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

$$v_\pi = v_i$$

$$v_o = -g_m v_\pi R_C$$

$$A_{vo} \equiv \frac{v_o}{v_i} = -g_m R_C$$

$$R_o = R_C$$

With a load resistance R_L connected across R_C,

$$A_v = -g_m (R_C \| R_L)$$

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

The common-source/emitter amplifiers with a source/emitter resistance

- Characteristics of the CS amplifier with a source resistance

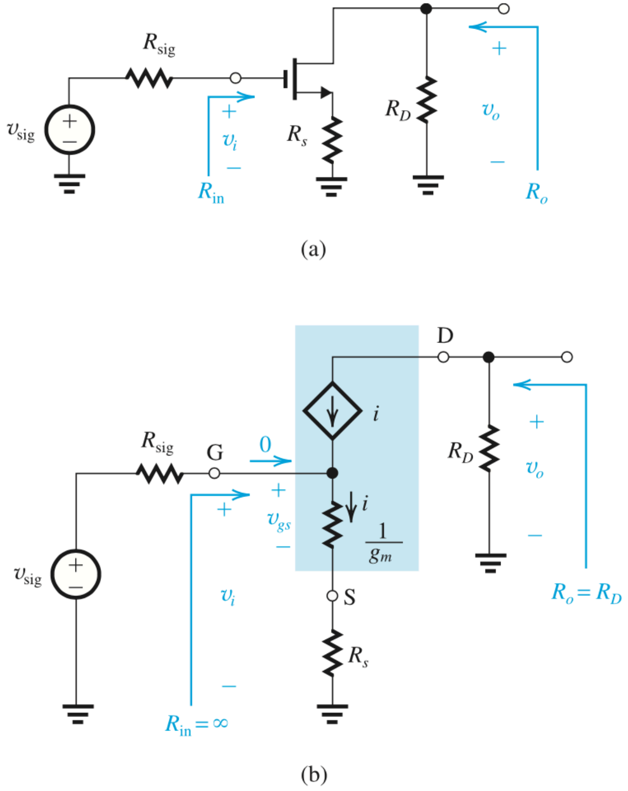


Figure 7.37 The CS amplifier with a source resistance R_s: **(a)** circuit without bias details; **(b)** equivalent circuit with the MOSFET represented by its T model.

$$v_{gs} = v_i \frac{1/g_m}{1/g_m + R_s} = \frac{v_i}{1 + g_m R_s}$$

$$v_o = -iR_D \qquad i = \frac{v_i}{1/g_m + R_s} = \left(\frac{g_m}{1 + g_m R_s}\right) v_i \qquad A_{vo} = -\frac{R_D}{1/g_m + R_s}$$

consider the situation of a load resistance R_L connected at the output.

$$R_o = R_D$$

$$A_v = -\frac{g_m (R_D \| R_L)}{1 + g_m R_s}$$

The common-source/emitter amplifiers with a source/emitter resistance

- Characteristics of the CE amplifier with a source resistance

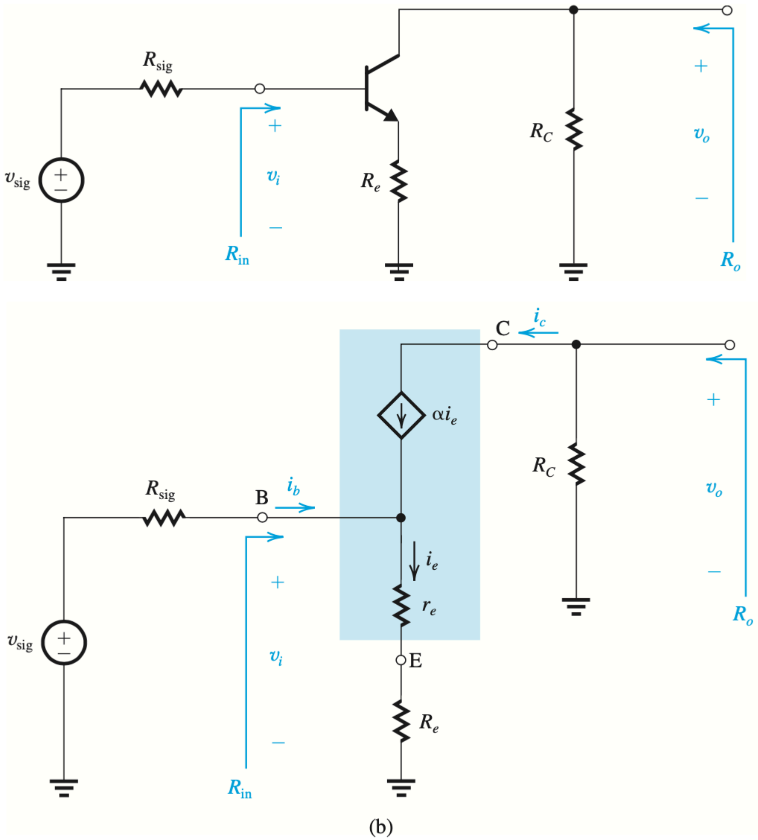


Figure 7.38 The CE amplifier with an emitter resistance R_e; (**a**) circuit without bias details; (**b**) equivalent circuit with the BJT replaced with its T model.

$$R_{in} = (\beta + 1)(r_e + R_e)$$

$$\frac{R_{in}(\text{with } R_e \text{ included})}{R_{in}(\text{without } R_e)} = \frac{(\beta+1)(r_e+R_e)}{(\beta+1)r_e}$$
$$= 1 + \frac{R_e}{r_e} \simeq 1 + g_m R_e$$

$$A_{vo} = -\alpha \frac{R_C}{r_e + R_e} \simeq -\frac{g_m R_C}{1 + g_m R_e}$$

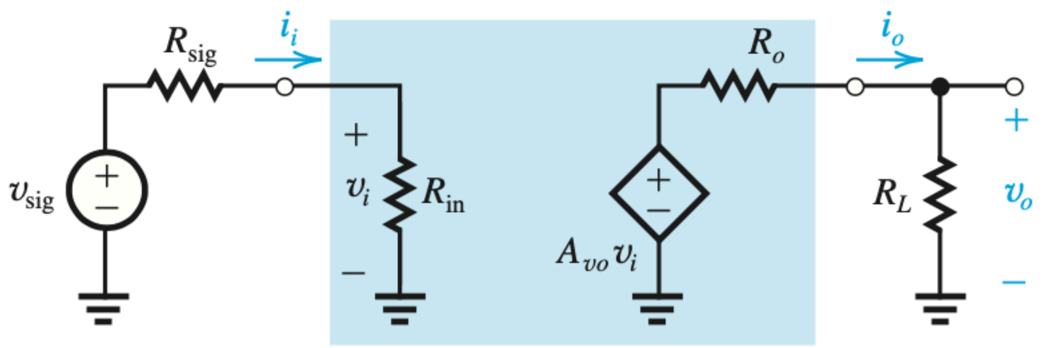
If a load resistance R_L is connected at the amplifier output, A_v can be found as

$$A_v = A_{vo} \frac{R_L}{R_L + R_o}$$
$$= -\alpha \frac{R_C}{r_e + R_e} \frac{R_L}{R_L + R_C}$$
$$= -\alpha \frac{R_C \| R_L}{r_e + R_e}$$

$$G_v = -\beta \frac{R_C \| R_L}{R_{sig} + (\beta+1)(r_e + R_e)}$$

Example problem 1

An amplifier with an input resistance of 100 kΩ, an open-circuit voltage gain of 100 V/V, and an output resistance of 100 Ω is connected between a 20 kΩ signal source and a 2 kΩ load. Find the overall voltage gain G_v. Also find the current gain, defined as the ratio of the load current to the current drawn from the signal source.



(b)

$R_{in} = 100\ \text{k}\Omega$ $\quad R_{sig} = 20\ \text{k}\Omega$

$R_o = 100\ \Omega$ $\quad R_L = 2\ \text{k}\Omega$

$A_{vo} = 100\ \text{V/V}$

$$G_v \equiv \frac{v_o}{v_{sig}}$$

$$v_i = \frac{R_{in}}{R_{in} + R_{sig}} v_{sig}$$

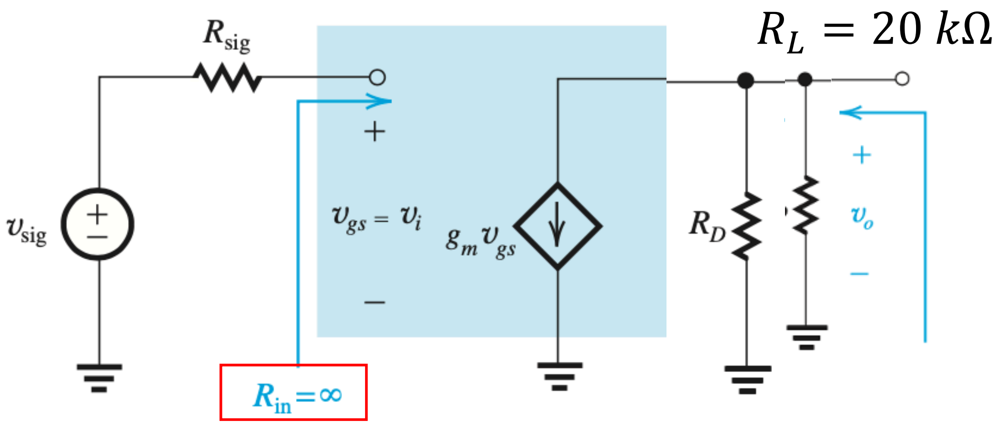
$$v_o = \frac{R_L}{R_o + R_L} A_{vo} v_i = \frac{R_L}{R_o + R_L} A_{vo} \frac{R_{in}}{R_{in} + R_{sig}} v_{sig}$$

$$\boxed{G_v = \frac{R_L}{R_o + R_L} A_{vo} \frac{R_{in}}{R_{in} + R_{sig}} = 952\ V/V}$$

$$\boxed{A_i = \frac{i_o}{i_i} = \frac{\frac{v_0}{R_L}}{\frac{v_i}{R_{in}}} = \frac{v_0 R_{in}}{v_i R_L} = \frac{\frac{R_L}{R_o + R_L} A_{vo} v_i R_{in}}{v_i R_L} = 416.6\ A/A}$$

Example Problem 2

7.21 A CS amplifier utilizes a MOSFET biased at $I_D = 0.25$ mA with $V_{OV} = 0.25$ V and $R_D = 20$ kΩ. The amplifier is fed with a signal source having $R_{sig} = 100$ kΩ, and a 20-kΩ load is connected to the output. Find R_{in}, A_{vo}, R_o, A_v, and G_v. If, to maintain reasonable linearity, the peak of the input sine-wave signal is limited to 10% of $2V_{OV}$, what is the peak of the sine-wave voltage at the output?



$$I_D = \frac{1}{2} k_n V_{OV}^2 \qquad g_m = \frac{i_d}{v_{gs}} = k_n V_{OV}$$

$$g_m = \frac{2I_D}{V_{OV}} = 2\ mS$$

$$\boxed{R_o = R_D}$$

$$\boxed{A_{vo} = -g_m R_0 = -4\ \mathrm{V/V}}$$

$$\boxed{A_v = \frac{v_o}{v_i} = -g_m(R_D||R_L) = -20\ \mathrm{V/V}}$$

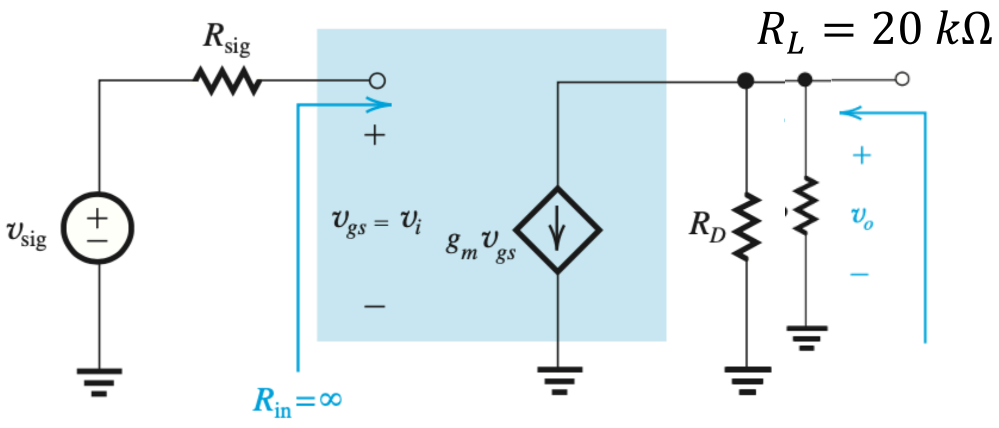
$$\boxed{G_v = \frac{v_o}{v_{sig}} = \frac{v_o}{v_i} = A_v}$$

$$|v_{sig}| = 10\%(2V_{OV}) = 0.05\ V$$

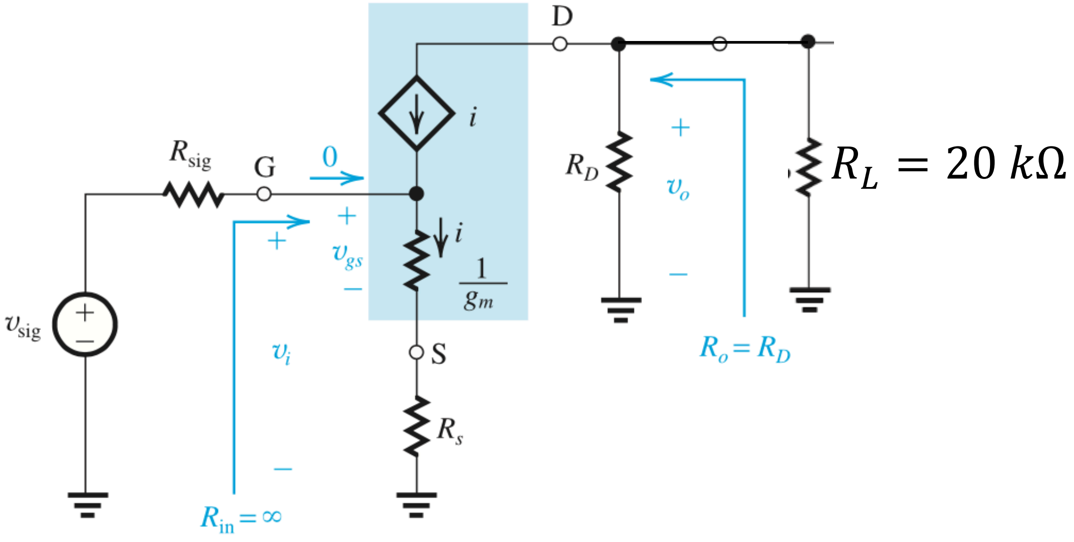
$$\boxed{|v_0| = G_V |v_{sig}| = 1\ V}$$

Example problem 3

7.23 In Exercise 7.21 we applied an input signal v_{sig} of 50 mV peak and obtained an output signal of approximately 1 V peak. Assume that for some reason we now have an input signal v_{sig} that is 0.2 V peak and that we wish to modify the circuit to keep v_{gs} unchanged, and thus keep the nonlinear distortion from increasing. What value should we use for R_s? What value of G_v will result? What will the peak signal at the output become? Assume $r_o = \infty$.



$$|A_v| = \frac{v_o}{v_i} = 20\ V/V$$



Example problem 3 continued

$$v_{gs} = \frac{\frac{1}{g_m}}{\frac{1}{g_m} + R_s} v_i = \frac{1}{1 + g_m R_s} v_{sig}$$

$$\boxed{R_s = \frac{1}{g_m}\left(\frac{v_{sig}}{v_{gs}} - 1\right) = 1.5\ k\Omega}$$

$$v_{sig} = 200\ mV$$

$$v_{gs} = 50\ mV$$

$$\boxed{G_v = A_v = -\frac{g_m (R_D \| R_L)}{1 + g_m R_s} = -5\ V}/V$$

$$\boxed{|v_0| = G_V |v_{sig}| = 1\ V}$$

Example problem 4

- Design a CE amplifier with a resistance R_e in the emitter to meet the following specifications:
  - (i) Input resistance R_{in} = 15 kΩ.
  - (ii) When fed from a signal source with a peak amplitude of 0.15 V and a source resistance of 30 kΩ, the peak amplitude of v_{BE} is 5 mV.
- Specify R_e and the bias current I_C . The BJT has β = 74. If the total resistance in the collector is 6 kΩ, find the overall voltage gain G_v and the peak amplitude of the output signal v_o .

Example problem 4 continued

$$R_{in} = \frac{v_i}{i_b}$$

$$i_e = i_b + i_c = (1+\beta) i_b \qquad i_b = \frac{i_e}{1+\beta}$$

$$v_i = i_e(r_e + R_e)$$

$$\boxed{R_{in} = (1+\beta)(r_e + R_e) = 15\ \text{k}\Omega}$$

$$\frac{v_{BE}}{v_i} = \frac{r_e}{r_e + R_e}$$

$$v_i = i_b R_{in} \qquad i_b = \frac{v_{sig} - v_i}{R_{sig}}$$

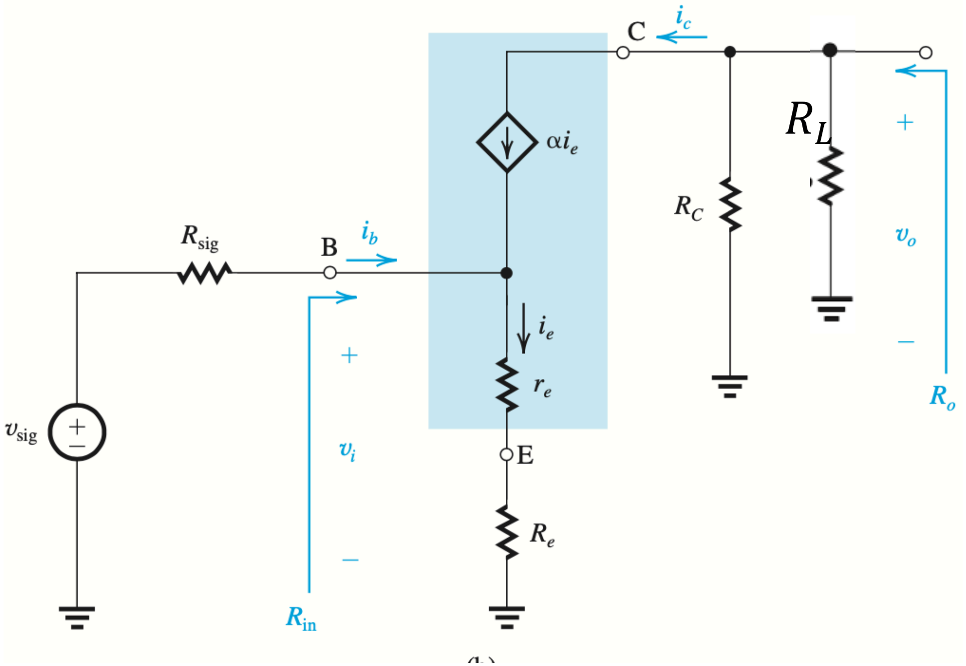
$$v_i = (v_{sig} - v_i)\frac{R_{in}}{R_{sig}}$$

$$v_i = \frac{v_{sig}}{(1 + \frac{R_{in}}{R_{sig}})}$$

$$\boxed{\frac{v_{BE}}{v_{sig}} = \frac{r_e}{r_e + R_e}\frac{R_{sig}}{R_{sig} + R_{in}}}$$

$$\boxed{r_e = 100\ \Omega}$$

$$\boxed{R_e = 200\ \Omega}$$



Input resistance R_{in} = 15 kΩ

$R_{sig} = 30\ \text{k}\Omega$

$v_{sig} = 0.15\ V$

$v_{BE} = 5\ mV$

β = 74

Example problem 4 continued

$$v_i = \frac{v_{sig}}{(1 + \frac{R_{in}}{R_{sig}})} = 0.1\ V \qquad i_e = \frac{v_i}{(r_e + R_e)} = 50\ \mu A$$

$$i_c = \alpha i_e \qquad \alpha = \frac{\beta}{1+\beta} \qquad \boxed{i_c = 49.3\ \mu A}$$

$$G_v = -\beta \frac{R_C \parallel R_L}{R_{\text{sig}} + (\beta+1)(r_e + R_e)} = -9.86\ \text{V/V}$$

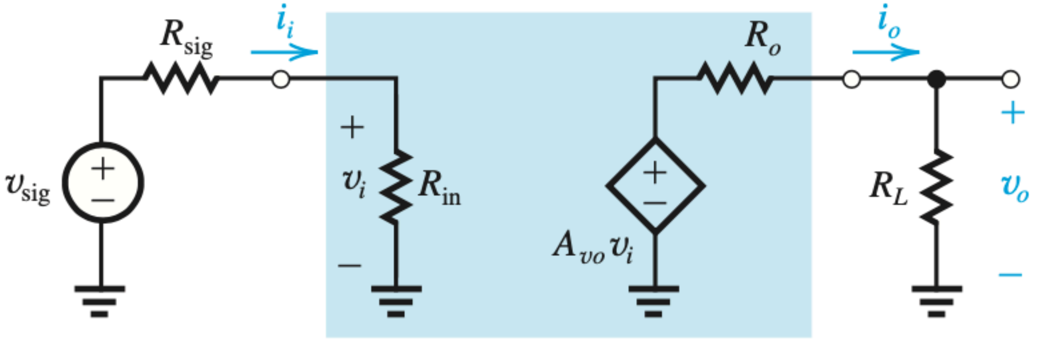
$$A_v = \frac{v_o}{v_i} = -\alpha \frac{R_c || R_L}{r_e + R_e}$$

$$\boxed{v_o = -\alpha \frac{R_c || R_L}{r_e + R_e} v_i = -2.96\ \text{V}}$$

Example problem 5 (optional)

- Specify the parameters R_{in} , A_{vo} , and R_o of an amplifier that is to be connected between a 100-kΩ source and a 2-kΩ load and is required to meet the following specifications:
- (a) No more than 5% of the signal strength is lost in the connection to the amplifier input;
- (b) If the load resistance changes from the nominal value of 2 kΩ to a low value of 1 kΩ, the change in output voltage is limited to 5% of nominal value; and
- (c) The nominal overall voltage gain is 10 V/V.

Example problem 5 continued



(b)

$R_{sig} = 100\ \text{k}\Omega$

$R_L = 2\ \text{k}\Omega$

$$|v_i| = 0.95|v_{sig}| = \frac{R_{in}}{R_{in} + R_{sig}}|v_{sig}|$$

$R_{in} = 1.9\ M\Omega$

$$v_{0@2k} = A_{Vo}\frac{R_{2k}}{R_{2k} + R_o}\frac{R_{in}}{R_{in} + R_{sig}}v_{sig}$$

$$v_{0@1k} = A_{Vo}\frac{R_{1k}}{R_{1k} + R_o}\frac{R_{in}}{R_{in} + R_{sig}}v_{sig}$$

$$\frac{v_o}{v_i} = A_{VO}\frac{R_L}{R_L + R_o}$$

Example problem 5 continued

$$\frac{v_{0@1k}}{v_{0@2k}} = \frac{\dfrac{R_{1k}}{R_{1k} + R_o}}{\dfrac{R_{2k}}{R_{2k} + R_o}}$$, where $v_{0@1k} = 0.95 v_{0@2k}$

$$\boxed{R_o = 111\ \Omega}$$

$$G_v = \frac{v_o}{v_{sig}} = A_{Vo} \frac{R_{1k}}{R_{1k} + R_o} \frac{R_{in}}{R_{in} + R_{sig}} = 10\ V/V$$

$$\boxed{A_{Vo} = 11.7\ V/V}$$