Whether one of the two poles is dominant will depend on the relative values of R_{sig} and R_L. If the two poles are close to each other, then the 3-dB frequency f_H can be determined either by exact analysis—that is, finding the frequency at which the gain is down by 3 dB—or by using the approximate formula in Eq. (9.77),

$$f_H \simeq 1 \bigg/ \sqrt{\frac{1}{f_{P1}^2} + \frac{1}{f_{P2}^2}} \tag{9.164}$$

EXERCISE

9.30 For the CC–CB amplifier of Fig. 9.41(a), let $I = 0.5$ mA, $\beta = 100$, $C_\pi = 6$ pF, $C_\mu = 2$ pF, $R_{sig} = 10$ kΩ, and $R_L = 10$ kΩ. Find the low-frequency overall voltage gain A_M, the frequencies of the poles, and the 3-dB frequency f_H. Find f_H both exactly and using the approximate formula in Eq. (9.164).
Ans. 50 V/V; 6.4 MHz and 8 MHz; f_H by exact evaluation = 4.6 MHz; f_H using Eq. (9.164) = 5 MHz.

Summary

- The coupling and bypass capacitors utilized in discrete-circuit amplifiers cause the amplifier gain to fall off at low frequencies. In the CS amplifier, the capacitors do not interact, and the frequencies of the low-frequency poles can be estimated by considering each of these capacitors separately and determining the resistance seen by the capacitor. The highest-frequency pole is the one that determines the lower 3-dB frequency f_L. In the CE amplifier, the capacitors interact, and thus the poles cannot be easily determined. Rather the method of short-circuit time constants can be used to obtain an estimate of the 3-dB frequency, f_L.
- Both the MOSFET and the BJT have internal capacitive effects that can be modeled by augmenting the device hybrid-π model with capacitances. Usually at least two capacitances are needed: C_{gs} and C_{gd} (C_π and C_μ for the BJT). A figure of merit for the high-frequency operation of the transistor is the frequency f_T at which the short-circuit current gain of the CS (CE) transistor reduces to unity. For the MOSFET, $f_T = g_m/2\pi(C_{gs}+C_{gd})$, and for the BJT, $f_T = g_m/2\pi(C_\pi + C_\mu)$.
- The internal capacitances of the MOSFET and the BJT cause the amplifier gain to fall off at high frequencies. An estimate of the amplifier bandwidth is provided by the frequency f_H at which the gain drops 3 dB below its value at midband, A_M. A figure of merit for the amplifier is the gain–bandwidth product $GB = A_M f_H$. Usually, it is possible to trade off gain for increased bandwidth, with GB remaining nearly constant. For amplifiers with a dominant pole with frequency f_H, the gain falls off at a uniform 6-dB/octave (20-dB/decade) rate, reaching 0 dB at $f_t = GB$.
- The high-frequency response of the CS and CE amplifiers is severely limited by the Miller effect: The small capacitance C_{gd} (C_μ) is multiplied by a factor approximately equal to the gain from gate to drain (base to collector) $g_m R_L'$ and thus gives rise to a large capacitance at the amplifier input. The increased C_{in} interacts with the effective signal-source resistance R_{sig}' and causes the amplifier gain to have a 3-dB frequency $f_H = 1/(2\pi R_{sig}' C_{in})$.
- The method of open-circuit time constants provides a simple and powerful way to obtain a reasonably good estimate of the upper 3-dB frequency f_H. The capacitors that limit the high-frequency response are considered one at time with $V_{sig} = 0$ and all the other capacitances set to zero (open circuited). The resistance seen by each capacitance is determined, and the overall time constant τ_H is obtained by summing the individual time constants. Then f_H is found as $1/2\pi\tau_H$.
- The CG and CB amplifiers do *not* suffer from the Miller effect. Thus the cascode amplifier, which consists of a cascade of CS and CG stages (CE and CB stages), can be designed to obtain wider bandwidth than that achieved in the CS (CE) amplifier alone. The key, however, is to design the cascode so that the gain obtained in the CS (CE) stage is minimized.
- The source and emitter followers can have complex poles. Thus, their frequency response is evaluated using the complete transfer function. Followers of both types exhibit wide bandwidths.
- The high-frequency response of the differential amplifier can be obtained by considering the differential and common-mode half-circuits. The CMRR falls off at a relatively low frequency determined by the output impedance of the bias current source.
- The high-frequency response of the current-mirror-loaded differential amplifier is complicated by the fact that there are two signal paths between input and output: a direct path and one through the current mirror.
- Combining two transistors in a way that eliminates or minimizes the Miller effect can result in a much wider bandwidth. Some such configurations are presented in Section 9.8.

PROBLEMS

Computer Simulation Problems

SIM Problems identified by the Multisim/PSpice icon are intended to demonstrate the value of using SPICE simulation to verify hand analysis and design, and to investigate important issues such as gain–bandwidth trade-off. Instructions to assist in setting up PSpice and Multisim simulations for all the indicated problems can be found in the corresponding files on the website. Note that if a particular parameter value is not specified in the problem statement, you are to make a reasonable assumption.

Section 9.1: Low-Frequency Response of Discrete-Circuit Common-Source and Common-Emitter Amplifiers

D 9.1 For the amplifier in Fig. 9.3(a), if $R_{G1} = 2$ MΩ, $R_{G2} = 1$ MΩ, and $R_{sig} = 200$ kΩ, find the value of the coupling capacitor C_{C1} (specified to one significant digit) that places the associated pole at 10 Hz or lower.

D 9.2 For the amplifier in Fig. 9.3(a), if $R_D = 10$ kΩ, $R_L = 10$ kΩ, and r_o is very large, find the value of C_{C2} (specified to one significant digit) that places the associated pole at 10 Hz or lower.

D 9.3 The amplifier in Fig. 9.3(a) is biased to operate at $g_m = 5$ mA/V, and $R_S = 1.8$ kΩ. Find the value of C_S (specified to one significant digit) that places its associated pole at 100 Hz or lower. What are the actual frequencies of the pole and zero realized?

9.4 The amplifier in Fig. 9.3(a) is biased to operate at $g_m = 5$ mA/V, and has the following component values: $R_{sig} = 100$ kΩ, $R_{G1} = 47$ MΩ, $R_{G2} = 10$ MΩ, $C_{C1} = 0.01$ µF, $R_S = 2$ kΩ, $C_S = 10$ µF, $R_D = 4.7$ kΩ, $R_L = 10$ kΩ, and $C_{C2} = 1$ µF. Find A_M, f_{P1}, f_{P2}, f_Z, f_{P3}, and f_L.

D 9.5 The amplifier in Fig. P9.5 is biased to operate at $g_m = 2$ mA/V. Neglect r_o.

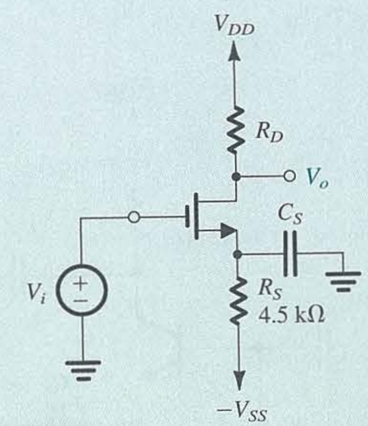

Figure P9.5

(a) Determine the value of R_D that results in a midband gain of −20 V/V.
(b) Determine the value of C_S that results in a pole frequency of 100 Hz.
(c) What is the frequency of the transmission zero introduced by C_S?
(d) Give an approximate value for the 3-dB frequency f_L.

(e) Sketch a Bode plot for the gain of this amplifier. What does the plot tell you about the gain at dc? Does this make sense? Why or why not?

D 9.6 Figure P9.6 shows a CS amplifier biased by a constant-current source I. Let $R_{sig} = 0.5\ \text{M}\Omega$, $R_G = 2\ \text{M}\Omega$, $g_m = 3\ \text{mA/V}$, $R_D = 20\ \text{k}\Omega$, and $R_L = 10\ \text{k}\Omega$. Find A_M. Also, design the coupling and bypass capacitors to locate the three low-frequency poles at 100 Hz, 10 Hz, and 1 Hz. Use a minimum total capacitance, with the capacitors specified only to a single significant digit. What value of f_L results?

D 9.7 Figure P9.7 shows a current-biased CE amplifier operating at 100 μA from ±3-V power supplies. It employs $R_C = 20\ \text{k}\Omega$, $R_B = 200\ \text{k}\Omega$, and operates between a 20-kΩ source and a 10-kΩ load. The transistor $\beta = 100$. Select C_E first, for a minimum value specified to one significant digit and providing up to 80% of f_L where f_L is to be 100 Hz. Then choose C_{C1} and C_{C2}, each specified to one significant digit, and each contributing about 10% of f_L. What f_L results? What total capacitance is needed?

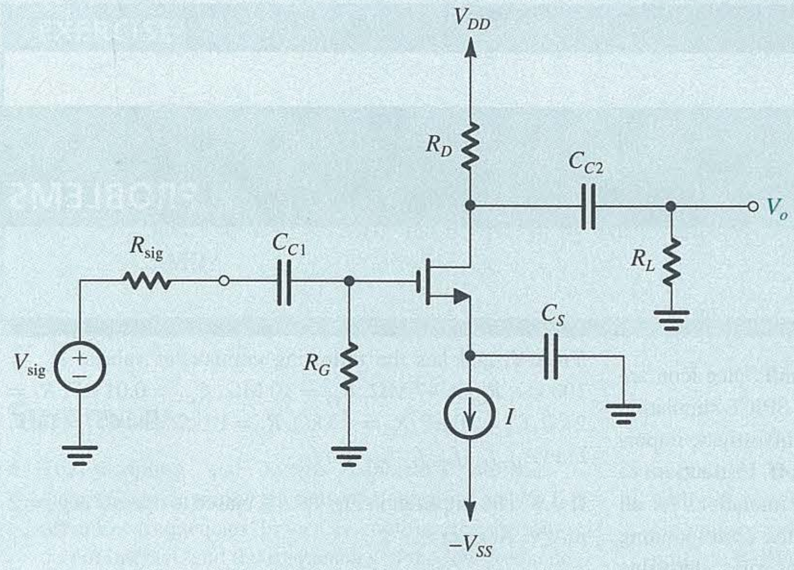

Figure P9.6

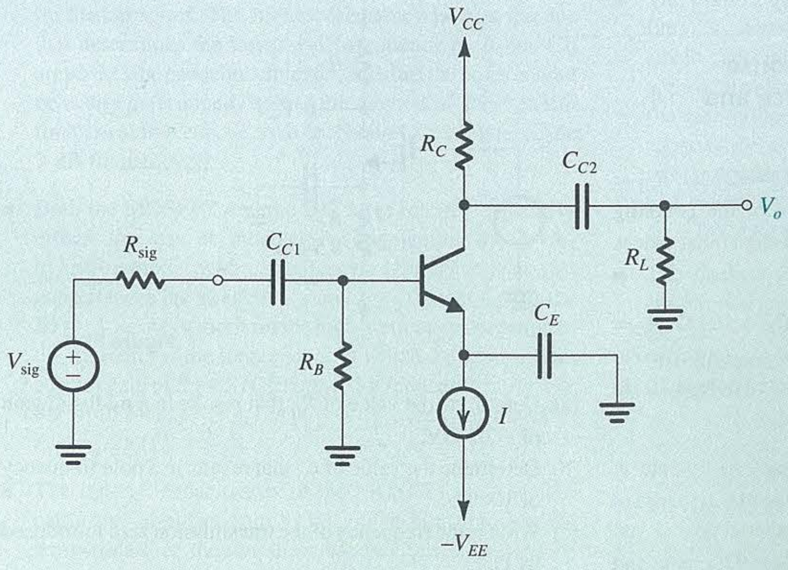

Figure P9.7

9.8 Consider the common-emitter amplifier of Fig. 9.9(a) under the following conditions: $R_{sig} = 5\ \text{k}\Omega$, $R_{B1} = 33\ \text{k}\Omega$, $R_{B2} = 22\ \text{k}\Omega$, $R_E = 3.9\ \text{k}\Omega$, $R_C = 4.7\ \text{k}\Omega$, $R_L = 5.6\ \text{k}\Omega$, $V_{CC} = 5\ \text{V}$. The dc emitter current can be shown to be $I_E \simeq 0.3\ \text{mA}$, at which $\beta = 120$. Find the input resistance R_{in} and the midband gain A_M. If $C_{C1} = C_{C2} = 1\ \mu\text{F}$ and $C_E = 20\ \mu\text{F}$, find the three short-circuit time constants and an estimate for f_L.

D 9.9 For the amplifier described in Problem 9.8, design the coupling and bypass capacitors for a lower 3-dB frequency of 50 Hz. Design so that the contribution of each of C_{C1} and C_{C2} to determining f_L is only 10%.

***9.10** The BJT common-emitter amplifier of Fig. P9.10 includes an emitter-degeneration resistance R_e.

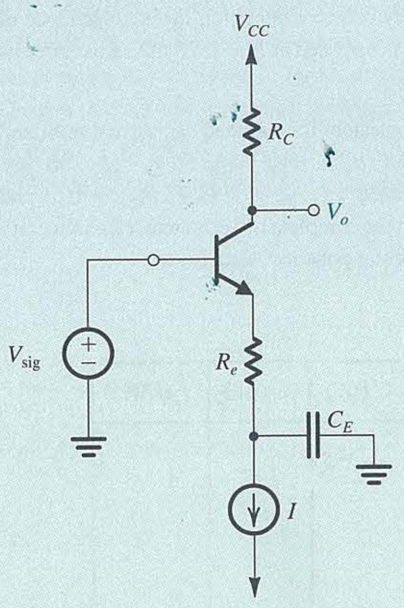

Figure P9.10

(a) Assuming $\alpha \simeq 1$, neglecting r_o, and assuming the current source to be ideal, derive an expression for the small-signal voltage gain $A(s) \equiv V_o/V_{sig}$ that applies in the midband and the low-frequency band. Hence find the midband gain A_M and the lower 3-dB frequency f_L.
(b) Show that including R_e reduces the magnitude of A_M by a certain factor. What is this factor?
(c) Show that including R_e reduces f_L by the same factor as in (b) and thus one can use R_e to trade off gain for bandwidth.
(d) For $I = 0.25\ \text{mA}$, $R_C = 10\ \text{k}\Omega$, and $C_E = 10\ \mu\text{F}$, find $|A_M|$ and f_L with $R_e = 0$. Now find the value of R_e that lowers f_L by a factor of 10. What will the gain become? Sketch on the same diagram a Bode plot for the gain magnitude for both cases.

D *9.11 For the common-emitter amplifier of Fig. P9.11, neglect r_o and assume the current source to be ideal.

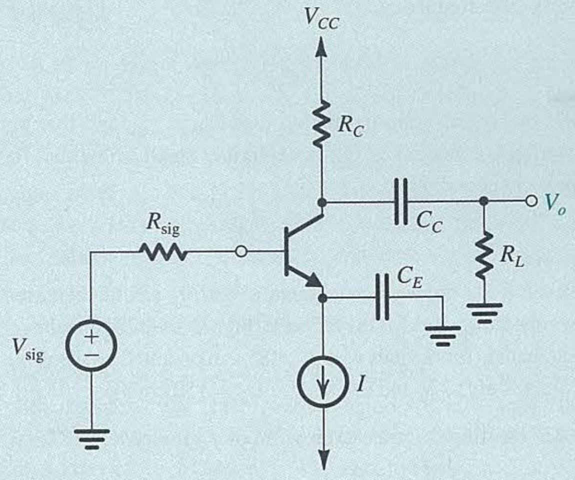

Figure P9.11

(a) Derive an expression for the midband gain.
(b) Convince yourself that the two poles caused by C_E and C_C do not interact. Find expressions for their frequencies, ω_{PE} and ω_{PC}.
(c) Give an expression for the amplifier voltage gain $V_o(s)/V_{sig}(s)$ in terms of A_M, ω_{PE}, and ω_{PC}.
(d) For $R_{sig} = R_C = R_L = 10\ \text{k}\Omega$, $\beta = 100$, and $I = 1\ \text{mA}$, find the value of the midband gain.
(e) Select values for C_E and C_C to place the two pole frequencies a decade apart and to obtain a lower 3-dB frequency of 100 Hz while minimizing the total capacitance.
(f) Sketch a Bode plot for the gain magnitude, and estimate the frequency at which the gain becomes unity.

Section 9.2: Internal Capacitive Effects and the High-Frequency Model of the MOSFET and the BJT

9.12 Refer to the MOSFET high-frequency model in Fig. 9.12(a). Evaluate the model parameters for an NMOS transistor operating at $I_D = 200\ \mu\text{A}$, $V_{SB} = 1$ V, and $V_{DS} = 1.5$ V. The MOSFET has $W = 20\ \mu\text{m}$, $L = 1\ \mu\text{m}$, $t_{ox} = 8$ nm, $\mu_n = 450\ \text{cm}^2/\text{V·s}$, $\gamma = 0.5\ \text{V}^{1/2}$, $2\phi_f = 0.65$ V, $\lambda = 0.05\ \text{V}^{-1}$, $V_0 = 0.7$ V, $C_{sb0} = C_{db0} = 20$ fF, and $L_{ov} = 0.05\ \mu\text{m}$. [Recall that $g_{mb} = \chi g_m$, where $\chi = \gamma/(2\sqrt{2\phi_f + V_{SB}})$, and that $\epsilon_{ox} = 3.45 \times 10^{-11}$ F/m.]

9.13 Find f_T for a MOSFET operating at $I_D = 200\ \mu\text{A}$ and $V_{OV} = 0.3$ V. The MOSFET has $C_{gs} = 25$ fF and $C_{gd} = 5$ fF.

9.14 Starting from the expression for the MOSFET unity-gain frequency,

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}$$

and making the approximation that $C_{gs} \gg C_{gd}$ and that the overlap component of C_{gs} is negligibly small, show that for an n-channel device

$$f_T \simeq \frac{3\mu_n V_{OV}}{4\pi L^2}$$

Observe that for a given channel length, f_T can be increased by operating the MOSFET at a higher overdrive voltage. Evaluate f_T for devices with $L = 0.5\ \mu\text{m}$ operated at overdrive voltages of 0.2 V and 0.4 V. Use $\mu_n = 450\ \text{cm}^2/\text{V·s}$.

9.15 Starting from the expression of f_T for a MOSFET,

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}$$

and making the approximation that $C_{gs} \gg C_{gd}$ and that the overlap component of C_{gs} is negligibly small, show that

$$f_T \simeq \frac{1.5}{\pi L}\sqrt{\frac{\mu_n I_D}{2C_{ox}WL}}$$

Thus note that to obtain a high f_T from a given device, it must be operated at a high current. Also note that faster operation is obtained from smaller devices.

9.16 It is required to calculate the intrinsic gain A_0 and the unity-gain frequency f_T of an n-channel transistor fabricated in a 0.13-μm CMOS process for which $L_{ov} = 0.1\ L$, $\mu_n = 400\ \text{cm}^2/\text{V·s}$, and $V_A' = 5$ V/μm. The device is operated at $V_{OV} = 0.2$ V. Find A_0 and f_T for devices with $L = L_{\min}$, $2L_{\min}$, $3L_{\min}$, $4L_{\min}$, and $5L_{\min}$. Present your results in a table. (*Hint:* For f_T, use the approximate expression $f_T \simeq \frac{3\mu_n V_{OV}}{4\pi L^2}$.)

9.17 A particular BJT operating at $I_C = 0.5$ mA has $C_\mu = 1$ pF, $C_\pi = 8$ pF, and $\beta = 100$. What are f_T and f_β for this situation?

9.18 For the transistor described in Problem 9.17, C_π includes a relatively constant depletion-layer capacitance of 2 pF. If the device is operated at $I_C = 0.25$ mA, what does its f_T become?

9.19 An *npn* transistor is operated at $I_C = 1$ mA and $V_{CB} = 2$ V. It has $\beta_0 = 100$, $V_A = 50$ V, $\tau_F = 30$ ps, $C_{je0} = 20$ fF, $C_{\mu 0} = 30$ fF, $V_{0c} = 0.75$ V, $m_{CBJ} = 0.5$, and $r_x = 100\ \Omega$. Sketch the complete hybrid-π model, and specify the values of all its components. Also, find f_T.

Transistor	I_E(mA)	r_e(Ω)	g_m(mA/V)	r_π (kΩ)	β_0	f_T(MHz)	C_μ(pF)	C_π(pF)	f_β(MHz)
(a)	2				100	500	2		
(b)		25					2	10.7	4
(c)				2.5	100	500		10.7	
(d)	10				100	500	2		
(e)	0.1				100	150	2		
(f)	1				10	500	2		
(g)						800	1	9	80

9.20 Measurement of h_{fe} of an *npn* transistor at 50 MHz shows that $|h_{fe}| = 10$ at $I_C = 0.2$ mA and 12 at $I_C = 1.0$ mA. Furthermore, C_μ was measured and found to be 0.1 pF. Find f_T at each of the two collector currents used. What must τ_F and C_{je} be?

9.21 For a BJT whose unity-gain bandwidth is 2 GHz and $\beta_0 = 200$, at what frequency does the magnitude of h_{fe} become 40? What is f_β?

***9.22** For a sufficiently high frequency, measurement of the complex input impedance of a BJT having (ac) grounded emitter and collector yields a real part approximating r_x. For what frequency, defined in terms of ω_β, is such an estimate of r_x good to within 10% under the condition that $r_x \le r_\pi/10$?

***9.23** Complete the table entries on the previous page for transistors (a) through (g), under the conditions indicated. Neglect r_x.

Section 9.3: High-Frequency Response of the CS and CE Amplifiers

9.24 In a particular common-source amplifier for which the midband voltage gain between gate and drain (i.e., $-g_m R_L'$) is −39 V/V, the NMOS transistor has $C_{gs} = 1.0$ pF and $C_{gd} = 0.1$ pF. What input capacitance would you expect? For what range of signal-source resistances can you expect the 3-dB frequency to exceed 1 MHz? Neglect the effect of R_G.

D 9.25 In the circuit of Fig. P9.25, the voltage amplifier is ideal (i.e., it has an infinite input resistance and a zero output resistance).

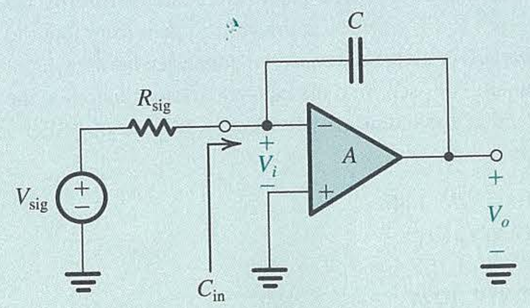

Figure P9.25

(a) Use the Miller approach to find an expression for the input capacitance C_{in} in terms of A and C.

(b) Use the expression for C_{in} to obtain the transfer function $V_o(s)/V_{sig}(s)$.

(c) If $R_{sig} = 1$ kΩ, and the gain V_o/V_{sig} is to have a dc value of 40 dB and a 3-dB frequency of 100 kHz, find the values required for A and C.

(d) Sketch a Bode plot for the gain and use it to determine the frequency at which its magnitude reduces to unity.

9.26 Reconsider Example 9.3 for the situation in which the transistor is replaced by one whose width W is half that of the original transistor while the bias current remains unchanged. Find modified values for all the device parameters along with A_M, f_H, and the gain–bandwidth product, GB. Contrast this with the original design by calculating the ratios of new value to old for W, V_{OV}, g_m, C_{gs}, C_{gd}, C_{in}, A_M, f_H, and GB.

D 9.27 A design is required for a CS amplifier for which the MOSFET is operated at $g_m = 5$ mA/V and has $C_{gs} = 5$ pF and $C_{gd} = 1$ pF. The amplifier is fed with a signal source having $R_{sig} = 1$ kΩ, and R_G is very large. What is the largest value of R_L' for which the upper 3-dB frequency is at least 6 MHz? What is the corresponding value of midband gain and gain–bandwidth product? If the specification on the upper 3-dB frequency can be relaxed by a factor of 3, that is, to 2 MHz, what can A_M and GB become?

D *9.28 In a CS amplifier, such as that in Fig. 9.3(a), the resistance of the source $R_{sig} = 100$ kΩ, amplifier input resistance (which is due to the biasing network) $R_{in} = 100$ kΩ, $C_{gs} = 1$ pF, $C_{gd} = 0.2$ pF, $g_m = 3$ mA/V, $r_o = 50$ kΩ, $R_D = 8$ kΩ, and $R_L = 10$ kΩ. Determine the expected 3-dB cutoff frequency f_H and the midband gain. In evaluating ways to double f_H, a designer considers the alternatives of changing either R_L or R_{in}. To raise f_H as described, what separate change in each would be required? What midband voltage gain results in each case?

9.29 A discrete MOSFET common-source amplifier has $R_G = 2$ MΩ, $g_m = 5$ mA/V, $r_o = 100$ kΩ, $R_D = 20$ kΩ, $C_{gs} = 3$ pF, and $C_{gd} = 0.5$ pF. The amplifier is fed from a voltage source with an internal resistance of 500 kΩ and is connected to a 20-kΩ load. Find:

(a) the overall midband gain A_M

(b) the upper 3-dB frequency f_H

(c) the frequency of the transmission zero, f_Z.

9.30 Consider the integrated-circuit CS amplifier in Fig. P9.30 for the case $I_{\text{BIAS}} = 100\ \mu\text{A}$, Q_2 and Q_3 are matched, and $R_{\text{sig}} = 200\ \text{k}\Omega$. For Q_1: $\mu_n C_{ox} = 90\ \mu\text{A/V}^2$, $V_A = 12.8$ V, $W/L = 100\ \mu\text{m}/1.6\ \mu\text{m}$, $C_{gs} = 0.2$ pF, and $C_{gd} = 0.015$ pF. For Q_2: $|V_A| = 19.2$ V. Neglecting the effect of the capacitance inevitably present at the output node, find the low-frequency gain, the 3-dB frequency f_H, and the frequency of the zero f_Z.

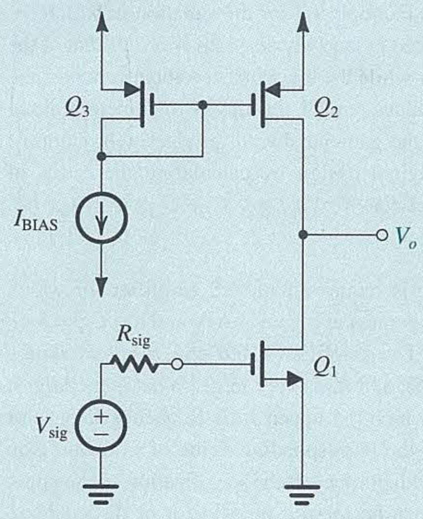

Figure P9.30

9.31 A common-emitter amplifier is measured at midband and found to have a gain of −50 V/V between base and collector. If $C_\pi = 10$ pF, $C_\mu = 1$ pF, and the effective source resistance $R'_{\text{sig}} = 5\ \text{k}\Omega$ [refer to Fig. 9.19(b)], find C_{in} and the 3-dB frequency f_H.

9.32 For a CE amplifier represented by the equivalent circuit in Fig. 9.19(a), let $R_{\text{sig}} = 10\ \text{k}\Omega$, $R_B = 100\ \text{k}\Omega$, $r_x = 100\ \Omega$, $C_\pi = 10$ pF, $C_\mu = 1$ pF, $g_m = 40$ mA/V, $r_o = 100\ \text{k}\Omega$, $R_C = 10\ \text{k}\Omega$, $R_L = 10\ \text{k}\Omega$, and $\beta = 100$. Find the midband gain and the 3-dB frequency f_H.

***9.33** The purpose of this problem is to investigate the high-frequency response of the CE amplifier when it is fed with a relatively large source resistance R_{sig}. Refer to the amplifier in Fig. 9.9(a) and to its high-frequency, equivalent-circuit model and the analysis shown in Fig. 9.19. Let $R_B \gg R_{\text{sig}}$, $r_x \ll R_{\text{sig}}$, $R_{\text{sig}} \gg r_\pi$, $g_m R'_L \gg 1$, and $g_m R'_L C_\mu \gg C_\pi$. Under these conditions, show that:

(a) the midband gain $A_M \simeq -\beta R'_L / R_{\text{sig}}$

(b) the upper 3-dB frequency $f_H \simeq 1/2\pi C_\mu \beta R'_L$

(c) the gain–bandwidth product $|A_M| f_H \simeq 1/2\pi C_\mu R_{\text{sig}}$

Evaluate this approximate value of the gain–bandwidth product for the case $R_{\text{sig}} = 25\ \text{k}\Omega$ and $C_\mu = 1$ pF. Now, if the transistor is biased at $I_C = 1$ mA and has $\beta = 100$, find the midband gain and f_H for the two cases $R'_L = 25\ \text{k}\Omega$ and $R'_L = 2.5\ \text{k}\Omega$. On the same coordinates, sketch Bode plots for the gain magnitude versus frequency for the two cases. What f_H is obtained when the gain is unity? What value of R'_L corresponds?

9.34 A designer wishes to investigate the effect of changing the bias current I_E on the midband gain and high-frequency response of the CE amplifier considered in Example 9.4. Let I_E be doubled to 2 mA, and assume that β_0 and f_T remain unchanged at 100 and 800 MHz, respectively. To keep the node voltages nearly unchanged, the designer reduces R_B and R_C by a factor of 2, to 50 kΩ and 4 kΩ, respectively. Assume $r_x = 50\ \Omega$, and recall that $V_A = 100$ V and that C_μ remains constant at 1 pF. As before, the amplifier is fed with a source having $R_{\text{sig}} = 5\ \text{k}\Omega$ and feeds a load $R_L = 5\ \text{k}\Omega$. Find the new values of A_M, f_H, and the gain–bandwidth product, $|A_M| f_H$. Comment on the results. Note that the price paid for whatever improvement in performance is achieved is an increase in power. By what factor does the power dissipation increase?

9.35 Consider an ideal voltage amplifier with a gain of 0.9 V/V, and a resistance $R = 100\ \text{k}\Omega$ connected in the feedback path—that is, between the output and input terminals. Use Miller's theorem to find the input resistance of this circuit.

9.36 The amplifiers listed below are characterized by the descriptor (A, C), where A is the voltage gain from input to output and C is an internal capacitor connected between input and output. For each, find the equivalent capacitances at the input and at the output as provided by the use of Miller's theorem:

(a) –1000 V/V, 1 pF
(b) –10 V/V, 10 pF
(c) –1 V/V, 10 pF
(d) +1 V/V, 10 pF
(e) +10 V/V, 10 pF

Note that the input capacitance found in case (e) can be used to cancel the effect of other capacitance connected from input to ground. In (e), what capacitance can be canceled?

9.37 Use Miller's theorem to investigate the performance of the inverting op-amp circuit shown in Fig. P9.37. Assume the op amp to be ideal except for having a finite differential gain, A. Without using any knowledge of op-amp circuit analysis, find R_{in}, V_i, V_o, and V_o/V_{sig}, for each of the following values of A: 10 V/V, 100 V/V, 1000 V/V, and 10,000 V/V. Assume $V_{\text{sig}} = 1$ V. Present your results in the table below.

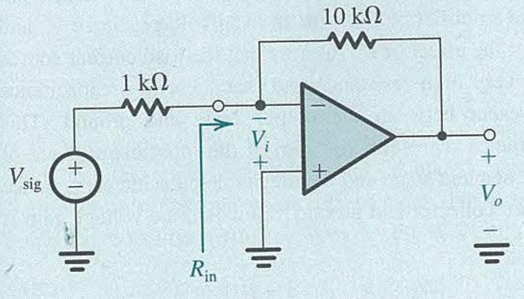

Figure P9.37

***9.38** Figure P9.38 shows an ideal voltage amplifier with a gain of +2 V/V (usually implemented with an op amp connected in the noninverting configuration) and a resistance R connected between output and input.

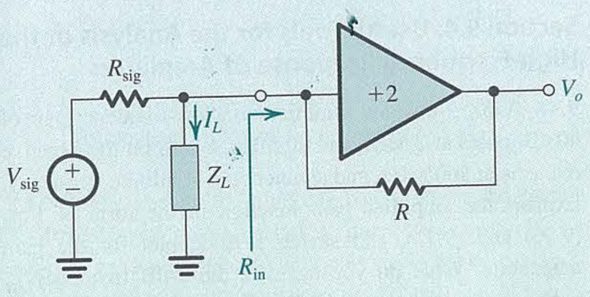

Figure P9.38

(a) Using Miller's theorem, show that the input resistance $R_{\text{in}} = -R$.

(b) Use Norton's theorem to replace V_{sig}, R_{sig}, and R_{in} with a signal current source and an equivalent parallel resistance. Show that by selecting $R_{\text{sig}} = R$, the equivalent parallel resistance becomes infinite and the current I_L into the load impedance Z_L becomes V_{sig}/R. The circuit then functions as an ideal voltage-controlled current source with an output current I_L.

(c) If Z_L is a capacitor C, find the transfer function V_o/V_{sig} and show it is that of an ideal noninverting integrator.

***9.39** The amplifier shown in Fig. P9.39 has $R_{\text{sig}} = R_L = 1\ \text{k}\Omega$, $R_C = 1\ \text{k}\Omega$, $R_B = 47\ \text{k}\Omega$, $\beta = 100$, $C_\mu = 0.8$ pF, and $f_T = 600$ MHz. Assume the coupling capacitors to be very large.

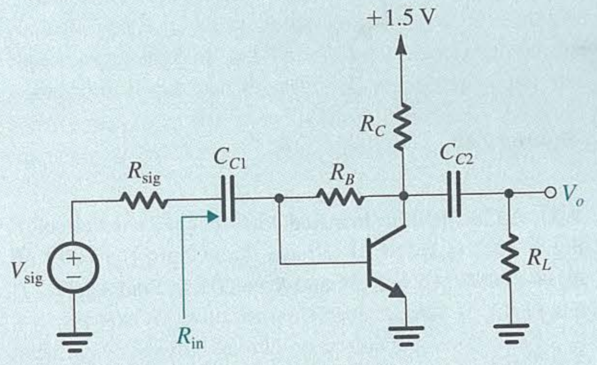

Figure P9.39

(a) Find the dc collector current of the transistor.
(b) Find g_m and r_π.
(c) Neglecting r_o, find the midband voltage gain from base to collector (neglect the effect of R_B).
(d) Use the gain obtained in (c) to find the component of R_{in} that arises as a result of R_B. Hence find R_{in}.

A	R_{in}	V_i	V_o	V_o/V_{sig}
10 V/V				
100 V/V				
1000 V/V				
10,000 V/V				

(e) Find the overall gain at midband.
(f) Find C_{in}.
(g) Find f_H.

***9.40** Figure P9.40 shows a diode-connected transistor with the bias circuit omitted. Utilizing the BJT high-frequency, hybrid-π model with $r_x = 0$ and $r_o = \infty$, derive an expression for $Z_i(s)$ as a function of r_e and C_π. Find the frequency at which the impedance has a phase angle of 45° for the case in which the BJT has $f_T = 400$ MHz and the bias current is relatively high. What is the frequency when the bias current is reduced so that $C_\pi \simeq C_\mu$? Assume $\alpha = 1$.

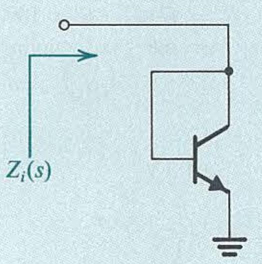

Figure P9.40

9.41 A CS amplifier modeled with the equivalent circuit of Fig. 9.22(a) is specified to have $C_{gs} = 2$ pF, $C_{gd} = 0.1$ pF, $g_m = 4$ mA/V, $C_L = 2$ pF, and $R_L' = 20$ kΩ. Find A_M, f_{3dB}, f_Z, and f_t.

D 9.42 A common-source amplifier fed with a low-resistance signal source and operating with $g_m = 2$ mA/V has a unity-gain frequency of 2 GHz. What additional capacitance must be connected to the drain node to reduce f_t to 1 GHz?

***9.43** It is required to analyze the high-frequency response of the CMOS amplifier shown in Fig. P9.30 for the case $R_{sig} = 0$. The dc bias current is 100 µA. For Q_1, $\mu_n C_{ox} = 90\ \mu\text{A/V}^2$, $V_A = 12.8$ V, $W/L = 100\ \mu\text{m}/1.6\ \mu\text{m}$, $C_{gs} = 0.2$ pF, $C_{gd} = 0.015$ pF, and $C_{db} = 20$ fF. For Q_2, $C_{gd} = 0.015$ pF, $C_{db} = 36$ fF, and $|V_A| = 19.2$ V. For simplicity, assume that the signal voltage at the gate of Q_2 is zero. Find the low-frequency gain, the frequency of the pole, and the frequency of the zero. (*Hint:* The total capacitance at the output mode $= C_{db1} + C_{db2} + C_{gd2}$).

9.44 A particular BJT operating at 2 mA is specified to have $f_T = 2$ GHz, $C_\mu = 1$ pF, $r_x = 100\ \Omega$, and $\beta = 120$. The device is used in a CE amplifier operating from a very-low-resistance voltage source.

(a) If the midband gain obtained is −10 V/V, what is the value of f_H?
(b) If the midband gain is reduced to −1 V/V (by changing R_L'), what f_H is obtained?

9.45 Consider an active-loaded common-emitter amplifier. Let the amplifier be fed with an ideal voltage source V_i, and neglect the effect of r_x. Assume that the load current source has a very high resistance and that there is a capacitance C_L present between the output node and ground. This capacitance represents the sum of the input capacitance of the subsequent stage and the inevitable parasitic capacitance between collector and ground. Show that the voltage gain is given by

$$\frac{V_o}{V_i} = -g_m r_o \frac{1 - s(C_\mu/g_m)}{1 + s(C_L + C_\mu)r_o}$$

If the transistor is biased at $I_C = 200\ \mu$A and $V_A = 100$ V, $C_\mu = 0.2$ pF, and $C_L = 1$ pF, find the dc gain, the 3-dB frequency, the frequency of the zero, and the frequency at which the gain reduces to unity. Sketch a Bode plot for the gain magnitude.

Section 9.4: Useful Tools for the Analysis of the High-Frequency Response of Amplifiers

9.46 A direct-coupled amplifier has a low-frequency gain of 40 dB, poles at 2 MHz and 20 MHz, a zero on the negative real axis at 200 MHz, and another zero at infinite frequency. Express the amplifier gain function in the form of Eqs. (9.70) and (9.71), and sketch a Bode plot for the gain magnitude. What do you estimate the 3-dB frequency f_H to be?

9.47 An amplifier with a dc gain of 60 dB has a single-pole, high-frequency response with a 3-dB frequency of 100 kHz.

(a) Give an expression for the gain function $A(s)$.
(b) Sketch Bode diagrams for the gain magnitude and phase.
(c) What is the gain–bandwidth product?

(d) What is the unity-gain frequency?
(e) If a change in the amplifier circuit causes its transfer function to acquire another pole at 1 MHz, sketch the resulting gain magnitude and specify the unity-gain frequency. Note that this is an example of an amplifier with a unity-gain bandwidth that is different from its gain–bandwidth product.

9.48 Consider an amplifier whose $F_H(s)$ is given by

$$F_H(s) = \frac{1}{\left(1 + \dfrac{s}{\omega_{P1}}\right)\left(1 + \dfrac{s}{\omega_{P2}}\right)}$$

with $\omega_{P1} < \omega_{P2}$. Find the ratio ω_{P2}/ω_{P1} for which the value of the 3-dB frequency ω_H calculated using the dominant-pole approximation differs from that calculated using the root-sum-of-squares formula (Eq. 9.77) by:

(a) 10%
(b) 1%

9.49 The high-frequency response of a direct-coupled amplifier having a dc gain of −1000 V/V incorporates zeros at ∞ and 10^4 rad/s (one at each frequency) and poles at 10^3 rad/s and 10^5 rad/s (one at each frequency). Write an expression for the amplifier transfer function. Find ω_H using

(a) the dominant-pole approximation
(b) the root-sum-of-squares approximation (Eq. 9.77).

If a way is found to lower the frequency of the finite zero to 10^3 rad/s, what does the transfer function become? What is the 3-dB frequency of the resulting amplifier?

9.50 A direct-coupled amplifier has a dominant pole at 1000 rad/s and three coincident poles at a much higher frequency. These nondominant poles cause the phase lag of the amplifier at high frequencies to exceed the 90° angle due to the dominant pole. It is required to limit the excess phase at $\omega = 10^7$ rad/s to 30° (i.e., to limit the total phase angle to −120°). Find the corresponding frequency of the nondominant poles.

9.51 An IC CS amplifier has $g_m = 2$ mA/V, $C_{gs} = 30$ fF, $C_{gd} = 5$ fF, $C_L = 30$ fF, $R_{sig}' = 10$ kΩ, and $R_L' = 20$ kΩ. Use the method of open-circuit time constants to obtain an estimate for f_H. Also, find the frequency of the transmission zero, f_Z.

9.52 A CS amplifier that can be represented by the equivalent circuit of Fig. 9.24 has $C_{gs} = 2$ pF, $C_{gd} = 0.1$ pF, $C_L = 2$ pF, $g_m = 4$ mA/V, and $R_{sig}' = R_L' = 20$ kΩ. Find the midband gain A_M, the input capacitance C_{in} using the Miller approximation, and hence an estimate of the 3-dB frequency f_H. Also, obtain another estimate of f_H using open-circuit time constants. Which of the two estimates is more appropriate and why?

9.53 Consider the high-frequency response of an amplifier consisting of two identical stages in cascade, each with an input resistance of 10 kΩ and an output resistance of 2 kΩ. The two-stage amplifier is driven from a 10-kΩ source and drives a 1-kΩ load. Associated with each stage is a parasitic input capacitance (to ground) of 10 pF and a parasitic output capacitance (to ground) of 2 pF. Parasitic capacitances of 10 pF and 7 pF also are associated with the signal-source and load connections, respectively. For this arrangement, find the three poles and estimate the 3-dB frequency f_H.

D 9.54 For a CS amplifier with $g_m = 5$ mA/V, $C_{gs} = 5$ pF, $C_{gd} = 1$ pF, $C_L = 5$ pF, $R_{sig}' = 10$ kΩ, and $R_L' = 10$ kΩ, find τ_H and f_H. What is the percentage of τ_H that is caused by the interaction of R_{sig}' with the input capacitance? To what value must R_{sig}' be lowered in order to double f_H?

D 9.55 For the CS amplifier in Example 9.8, find the value of the additional capacitance to be connected at the output node in order to lower f_H to 100 MHz.

9.56 Consider the CE amplifier whose equivalent circuit is shown in Fig. 9.19(a) but with a capacitance C_L connected across the output terminals. Let $R_{sig} = 5$ kΩ, $R_B = \infty$, $r_x = 0$, $g_m = 20$ mA/V, $\beta = 100$, $C_\pi = 10$ pF, $C_\mu = 1$ pF, $R_L' = 5$ kΩ, and $C_L = 10$ pF. Find A_M and f_H.

9.57 A common-emitter amplifier has $C_\pi = 10$ pF, $C_\mu = 0.3$ pF, $C_L = 3$ pF, $g_m = 40$ mA/V, $\beta = 100$, $r_x = 100\ \Omega$, $R_L' = 5$ kΩ, and $R_{sig} = 1$ kΩ. Find the midband gain A_M and an estimate of the 3-dB frequency f_H using the Miller approximation. Also, obtain another estimate of f_H using the method of open-circuit time constants. Which of the two estimates would you consider to be more realistic, and why?

9.58 Use the method of open-circuit time constants to find f_H for a CS amplifier for which $g_m = 1.5$ mA/V, $C_{gs} = C_{gd} = 0.2$ pF, $r_o = 20$ kΩ, $R_L = 12$ kΩ, and $R_{sig} = 100$ kΩ for the following cases: (a) $C_L = 0$, (b) $C_L = 10$ pF, and (c) $C_L = 50$ pF. Compare with the value of f_H obtained using the Miller approximation.

Section 9.5: High-Frequency Response of the Common-Gate and Cascode Amplifiers

9.59 A CG amplifier is specified to have $C_{gs} = 4$ pF, $C_{gd} = 0.2$ pF, $C_L = 2$ pF, $g_m = 5$ mA/V, $R_{sig} = 1$ kΩ, and $R_L = 10$ kΩ. Neglecting the effects of r_o, find the low-frequency gain V_o/V_{sig}, the frequencies of the poles f_{P1} and f_{P2}, and hence an estimate of the 3-dB frequency f_H.

***9.60** Sketch the high-frequency equivalent circuit of a CB amplifier fed from a signal generator characterized by V_{sig} and R_{sig} and feeding a load resistance R_L in parallel with a capacitance C_L.

(a) Show that for $r_x = 0$ and $r_o = \infty$, the circuit can be separated into two parts: an input part that produces a pole at

$$f_{P1} = \frac{1}{2\pi C_\pi (R_{sig} \| r_e)}$$

and an output part that forms a pole at

$$f_{P2} = \frac{1}{2\pi (C_\mu + C_L) R_L}$$

Note that these are the bipolar counterparts of the MOS expressions in Eqs. (9.94) and (9.95).

(b) Evaluate f_{P1} and f_{P2} and hence obtain an estimate for f_H for the case $C_\pi = 10$ pF, $C_\mu = 1$ pF, $C_L = 1$ pF, $I_C = 1$ mA, $R_{sig} = 1$ kΩ, and $R_L = 10$ kΩ. Also, find f_T of the transistor.

9.61 An IC CG amplifier is fed from a signal source with $R_{sig} = r_o/2$, where r_o is the MOSFET output resistance. It has a current-source load with an output resistance equal to r_o. The MOSFET is operated at $I_D = 100$ µA and has $g_m = 1.5$ mA/V, $V_A = 10$ V, $C_{gs} = 0.2$ pF, $C_{gd} = 0.015$ pF, and $C_{db} = 20$ fF. As well, the current-source load provides an additional 30 fF capacitance at the output node. Find f_H.

9.62 For the CG amplifier in Example 9.9, how much additional capacitance should be connected between the output node and ground to reduce f_H to 200 MHz?

9.63 Find the dc gain and the 3-dB frequency of a MOS cascode amplifier operated at $g_m = 2$ mA/V and $r_o = 20$ kΩ. The MOSFETs have $C_{gs} = 20$ fF, $C_{gd} = 5$ fF, and $C_{db} = 5$ fF. The amplifier is fed from a signal source with $R_{sig} = 100$ kΩ and is connected to a load resistance of 1 MΩ. There is also a load capacitance C_L of 20 fF.

***9.64** (a) Consider a CS amplifier having $C_{gd} = 0.2$ pF, $R_{sig} = R_L = 20$ kΩ, $g_m = 4$mA/V, $C_{gs} = 2$ pF, C_L (including C_{db}) = 1 pF, $C_{db} = 0.2$ pF, and $r_o = 20$ kΩ. Find the low-frequency gain A_M, and estimate f_H using open-circuit time constants. Hence determine the gain–bandwidth product.
(b) If a CG stage utilizing an identical MOSFET is cascaded with the CS transistor in (a) to create a cascode amplifier, determine the new values of A_M, f_H, and gain–bandwidth product. Assume R_L remains unchanged.

D 9.65 It is required to design a cascode amplifier to provide a dc gain of 74 dB when driven with a low-resistance generator and utilizing NMOS transistors for which $V_A = 10$ V, $\mu_n C_{ox} = 200$ µA/V², $W/L = 50$, $C_{gd} = 0.1$ pF, and $C_L = 1$ pF. Assuming that $R_L = R_o$, determine the overdrive voltage and the drain current at which the MOSFETs should be operated. Find the unity-gain frequency and the 3-dB frequency. If the cascode transistor is removed and R_L remains unchanged, what will the dc gain become?

9.66 (a) For an integrated-circuit MOS cascode amplifier fed with a source having a very small resistance and loaded in a resistance equal to its R_o, use the expression for the unity-gain bandwidth in Fig. 9.29 to show that

$$f_t = \frac{\sqrt{2\mu_n C_{ox}(W/L)}}{2\pi (C_L + C_{gd})} \sqrt{I_D}$$

(b) For $\mu_n C_{ox} = 400$ µA/V², $W/L = 20$, $C_L = 20$ fF, $C_{gd} = 5$ fF, and $V_A = 10$ V, provide in table form f_t (GHz), V_{OV} (V), g_m (mA/V), r_o (kΩ), R_o (MΩ), A_M (V/V), and f_H (MHz) for $I_D = 100$ µA, 200 µA, and 500 µA.

9.67 (a) Show that introducing a cascode transistor to an IC CS amplifier whose bandwidth is limited by the interaction of R_{sig} and the input capacitance, and whose load resistance is equal to r_o, increases the dc gain by approximately a factor of 2 and f_H by the factor N,

$$N = \frac{C_{gs} + \frac{1}{2}(g_m r_o) C_{gd}}{C_{gs} + 3C_{gd}}$$

Assume that the bandwidth of the cascode amplifier is primarily determined by the input circuit.

(b) If $C_{gd} = 0.1\,C_{gs}$ and the dc gain of the CS amplifier is 50, what is the value of N?

(c) If $V_A = 10$ V, $\mu_n C_{ox} = 400$ µA/V², and $W/L = 10$, find V_{OV} and I_D at which the transistors must be operating.

9.68 Consider a bipolar cascode amplifier biased at a current of 1 mA. The transistors used have $\beta = 100$, $r_o = 100$ kΩ, $C_\pi = 10$ pF, $C_\mu = 2$ pF, $C_{cs} = 0$, and $r_x = 50$ Ω. The amplifier is fed with a signal source having $R_{sig} = 5$ kΩ. The load resistance $R_L = 2$ kΩ. Find the low-frequency gain A_M, and estimate the value of the 3-dB frequency f_H.

***9.69** In this problem we consider the frequency response of the bipolar cascode amplifier in the case that r_o can be neglected.

(a) Refer to the circuit in Fig. 9.30, and note that the total resistance between the collector of Q_1 and ground will be equal to r_{e2}, which is usually very small. It follows that the pole introduced at this node will typically be at a very high frequency and thus will have negligible effect on f_H. It also follows that at the frequencies of interest the gain from the base to the collector of Q_1 will be $-g_{m1} r_{e2} \simeq -1$. Use this to find the capacitance at the input of Q_1 and hence show that the pole introduced at the input node will have a frequency

$$f_{P1} \simeq \frac{1}{2\pi R'_{sig}(C_{\pi 1} + 2C_{\mu 1})}$$

Then show that the pole introduced at the output node will have a frequency

$$f_{P2} \simeq \frac{1}{2\pi R_L (C_L + C_{cs2} + C_{\mu 2})}$$

(b) Evaluate f_{P1} and f_{P2}, and use the sum-of-the-squares formula to estimate f_H for the amplifier with $I = 1$ mA, $C_\pi = 10$ pF, $C_\mu = 2$ pF, $C_{cs} = C_L = 0$, $\beta = 100$, $R_L = 2$ kΩ, and $r_x = 0$ in the following two cases:
(i) $R_{sig} = 1$ kΩ
(ii) $R_{sig} = 10$ kΩ

9.70 A BJT cascode amplifier uses transistors for which $\beta = 100$, $V_A = 100$ V, $f_T = 1$ GHz, and $C_\mu = 0.1$ pF. It operates at a bias current of 0.1 mA between a source with $R_{sig} = r_\pi$ and a load $R_L = \beta r_o$. Let $C_L = C_{cs} = 0$, and $r_x = 0$. Find the overall voltage gain at dc. By evaluating the various components of τ_H show that the pole introduced at the output node is dominant. Find its frequency and hence an estimate of f_H and f_t.

Section 9.6: High-Frequency Response of the Source and Emitter Followers

9.71 A source follower has $g_m = 5$ mA/V, $g_{mb} = 0$, $r_o = 20$ kΩ, $R_{sig} = 20$ kΩ, $R_L = 2$ kΩ, $C_{gs} = 2$ pF, $C_{gd} = 0.1$ pF, and $C_L = 1$ pF. Find A_M, R_o, f_Z, the frequencies of the two poles, and an estimate of f_H.

9.72 Using the expression for the source follower f_H in Eq. (9.124) show that for situations in which $C_L = 0$, R_{sig} is large and R_L is small,

$$f_H \simeq \frac{1}{2\pi R_{sig}\left(C_{gd} + \dfrac{C_{gs}}{1 + g_m R_L'}\right)}$$

Find f_H for the case $R_{sig} = 100$ kΩ, $R_L = 2$ kΩ, $r_o = 20$ kΩ, $g_m = 5$ mA/V, $C_{gs} = 10$ pF, and $C_{gd} = 2$ pF.

9.73 Refer to Fig. 9.31(c). In situations in which R_{sig} is large, the high-frequency response of the source follower is determined by the low-pass circuit formed by R_{sig} and the input capacitance. An estimate of C_{in} can be obtained by using the Miller approximation to replace C_{gs} with an input capacitance $C_{eq} = C_{gs}(1 - K)$ where K is the gain from gate to source. Using the low-frequency value of $K = g_m R_L'/(1 + g_m R_L')$ find C_{eq} and hence C_{in} and an estimate of f_H.

9.74 A discrete-circuit source follower driven with $R_{sig} =$ 100 kΩ has $C_{gs} = 10$ pF, $C_{gd} = 1$ pF, $C_L = 10$ pF, $g_{mb} = 0$, and r_o very large. The transfer function of the source follower is measured as R_L is varied. At what value of R_L will the transfer function be maximally flat? At this value of R_L the dc gain is found to be 0.9 V/V. What is the 3-dB frequency? What is the value of g_m at which the source follower is operating?

9.75 A source follower has a maximally flat gain response with a dc gain of 0.8 and a 3-dB frequency of 1 MHz. Give its transfer function.

9.76 For an emitter follower biased at $I_C = 1$ mA, having $R_{sig} = R_L = 1$ kΩ, and using a transistor specified to have $f_T = 2$ GHz, $C_\mu = 0.1$ pF, $C_L = 0$, $r_x = 100$ Ω, $\beta = 100$, and $V_A = 20$ V, evaluate the low-frequency gain A_M, the frequency of the transmission zero, the pole frequencies, and an estimate of the 3-dB frequency f_H.

Section 9.7: High-Frequency Response of Differential Amplifiers

9.77 A MOSFET differential amplifier such as that shown in Fig. 9.34(a) is biased with a current source $I = 400$ μA. The transistors have $W/L = 16$, $k_n' = 400$ μA/V², $V_A = 20$ V, $C_{gs} = 40$ fF, $C_{gd} = 5$ fF, and $C_{db} = 5$ fF. The drain resistors are 10 kΩ each. Also, there is a 100-fF capacitive load between each drain and ground.

(a) Find V_{OV} and g_m for each transistor.
(b) Find the differential gain A_d.
(c) If the input signal source has a small resistance R_{sig} and thus the frequency response is determined primarily by the output pole, estimate the 3-dB frequency f_H.
(d) If, in a different situation, the amplifier is fed symmetrically with a signal source of 40 kΩ resistance (i.e., 20 kΩ in series with each gate terminal), use the open-circuit time-constants method to estimate f_H.

9.78 A MOS differential amplifier is biased with a current source having an output resistance $R_{SS} = 100$ kΩ and an output capacitance $C_{SS} = 1$ pF. If the differential gain is found to have a dominant pole at 20 MHz, what is the 3-dB frequency of the CMRR?

9.79 The differential gain of a MOS amplifier is 100 V/V with a dominant pole at 10 MHz. The common-mode gain is 0.1 V/V at low frequencies and has a transmission zero at 1 MHz. Sketch a Bode plot for the CMRR.

9.80 In a particular MOS differential amplifier design, the bias current $I = 100$ μA is provided by a single transistor operating at $V_{OV} = 0.4$ V with $V_A = 40$ V and output capacitance C_{SS} of 100 fF. What is the frequency of the common-mode gain zero (f_Z) at which A_{cm} begins to rise above its low-frequency value? To meet a requirement for reduced power supply, consideration is given to reducing V_{OV} to 0.2 V while keeping I unchanged. Assuming the current-source capacitance to be directly proportional to the device width, what is the impact on f_Z of this proposed change?

9.81 A BJT differential amplifier operating with a 0.5-mA current source uses transistors for which $\beta = 100$, $f_T = 500$ MHz, $C_\mu = 0.5$ pF, and $r_x = 100$ Ω. Each of the collector resistances is 10 kΩ, and r_o is very large. The amplifier is fed in a symmetrical fashion with a source resistance of 10 kΩ in series with each of the two input terminals.

(a) Sketch the differential half-circuit and its high-frequency equivalent circuit.
(b) Determine the low-frequency value of the overall differential gain.
(c) Use the Miller approximation to determine the input capacitance and hence estimate the 3-dB frequency f_H and the gain–bandwidth product.

9.82 A current-mirror-loaded MOS differential amplifier is biased with a current source $I = 0.2$ mA. The two NMOS transistors of the differential pair are operating at $V_{OV} = 0.2$ V, and the PMOS devices of the mirror are operating at $|V_{OV}| =$ 0.2 V. The Early voltage $V_{An} = |V_{Ap}| = 10$ V. The total capacitance at the input node of the mirror is 0.1 pF and that at the output node of the amplifier is 0.2 pF. Find the dc value and the frequencies of the poles and zero of the differential voltage gain.

9.83 Consider the current-mirror-loaded CMOS differential amplifier of Fig. 9.37(a) for the case of all transistors operated at the same $|V_{OV}|$ and having the same $|V_A|$. Also let the total capacitance at the output node (C_L) be four times the total capacitance at the input node of the current mirror C_m. Give expressions for A_d, f_{P1}, f_{P2}, and f_Z. Hence show that $f_{P2}/f_{P1} = 4A_d$ and $f_t = g_m/2\pi C_L$. For $V_A = 20$ V, $V_{OV} = 0.2$ V, $I = 0.2$ mA, $C_L = 100$ fF, and $C_m = 25$ fF, find the dc value of A_d, and the value of f_{P1}, f_t, f_{P2}, and f_Z and sketch a Bode plot for $|A_d|$.

***9.84** For the current mirror in Fig. P9.84, derive an expression for the current transfer function $I_o(s)/I_i(s)$ taking into account the BJT internal capacitances and neglecting r_x and r_o. Assume the BJTs to be identical. Observe that a signal ground appears at the collector of Q_2. If the mirror is biased at 1 mA and the BJTs at this operating point are characterized by $f_T = 500$ MHz, $C_\mu = 2$ pF, and $\beta_0 = 100$, find the frequencies of the pole and zero of the transfer function.

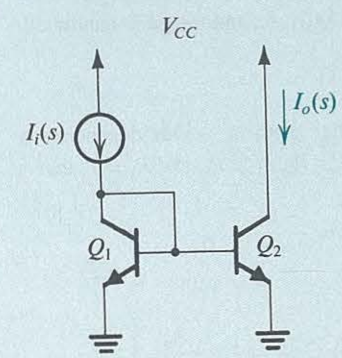

Figure P9.84

Section 9.8: Other Wideband Amplifier Configurations

9.85 Consider the case of a discrete-circuit CS amplifier in which a source-degeneration resistance is utilized to control the bandwidth. Assume that r_o is very large and C_L is negligibly small. Adapt the formulas given in the text for this case and thus give the expressions for A_M and f_H. Let $R_{sig} = 100$ kΩ, $g_m = 5$ mA/V, $R_L = 5$ kΩ, $C_{gs} = 10$ pF, and $C_{gd} = 2$ pF. Find $|A_M|$, f_H, and the gain–bandwidth product for these three cases: $R_s = 0$, 100 Ω, and 200 Ω.

D 9.86 (a) Use the approximate expression in Eq. (9.156) to determine the gain–bandwidth product of a CS amplifier with a source-degeneration resistance. Assume $C_{gd} = 0.2$ pF and $R_{sig} = 100$ kΩ.
(b) If a low-frequency gain of 20 V/V is required, what f_H corresponds?
(c) For $g_m = 5$ mA/V, $A_0 = 100$ V/V, and $R_L = 20$ kΩ, find the required value of R_s.

9.87 A CS amplifier is specified to have $g_m = 5$ mA/V, $r_o = 40$ kΩ, $C_{gs} = 2$ pF, $C_{gd} = 0.1$ pF, $C_L = 1$ pF, $R_{sig} = 20$ kΩ, and $R_L = 40$ kΩ.

(a) Find the low-frequency gain A_M, and use open-circuit time constants to estimate the 3-dB frequency f_H. Hence determine the gain–bandwidth product.
(b) If a 400-Ω resistance is connected in the source lead, find the new values of $|A_M|$, f_H, and the gain–bandwidth product.

9.88 For the CS amplifier with a source-degeneration resistance R_s, show for $R_{sig} \gg R_s$, $r_o \gg R_s$, and $R_L = r_o$ that

$$A_M = \frac{-A_0}{2+k}$$

and

$$\tau_H \simeq \frac{C_{gs}R_{sig}}{1+(k/2)} + C_{gd}R_{sig}\left(1+\frac{A_0}{2+k}\right) + (C_L + C_{gd})r_o\left(\frac{1+k}{2+k}\right)$$

where $k \equiv g_m R_s$

D *9.89 It is required to generate a table of $|A_M|$, f_H, and f_t versus $k \equiv g_m R_s$ for a CS amplifier with a source-degeneration resistance R_s. The table should have entries for $k = 0, 1, 2, \ldots, 15$. The amplifier is specified to have $g_m = 5$ mA/V, $r_o = 40$ kΩ, $R_L = 40$ kΩ, $R_{sig} = 20$ kΩ, $C_{gs} = 2$ pF, $C_{gd} = 0.1$ pF, and $C_L = 1$ pF. Use the formulas for A_M and τ_H given in the statement for Problem 9.98. If $f_H = 2$ MHz is required, find the value needed for R_s and the corresponding value of $|A_M|$.

***9.90** In this problem we investigate the bandwidth extension obtained by placing a source follower between the signal source and the input of the CS amplifier.

(a) First consider the CS amplifier of Fig. P9.90(a). Show that

$$A_M = -g_m r_o$$
$$\tau_H = C_{gs}R_{sig} + C_{gd}\left[R_{sig}(1+g_m r_o) + r_o\right] + C_L r_o$$

where C_L is the total capacitance between the output node and ground. Calculate the value of A_M, f_H, and the gain–bandwidth product for the case $g_m = 1$ mA/V, $r_o = 20$ kΩ, $R_{sig} = 20$ kΩ, $C_{gs} = 20$ fF, $C_{gd} = 5$ fF, and $C_L = 10$ fF.

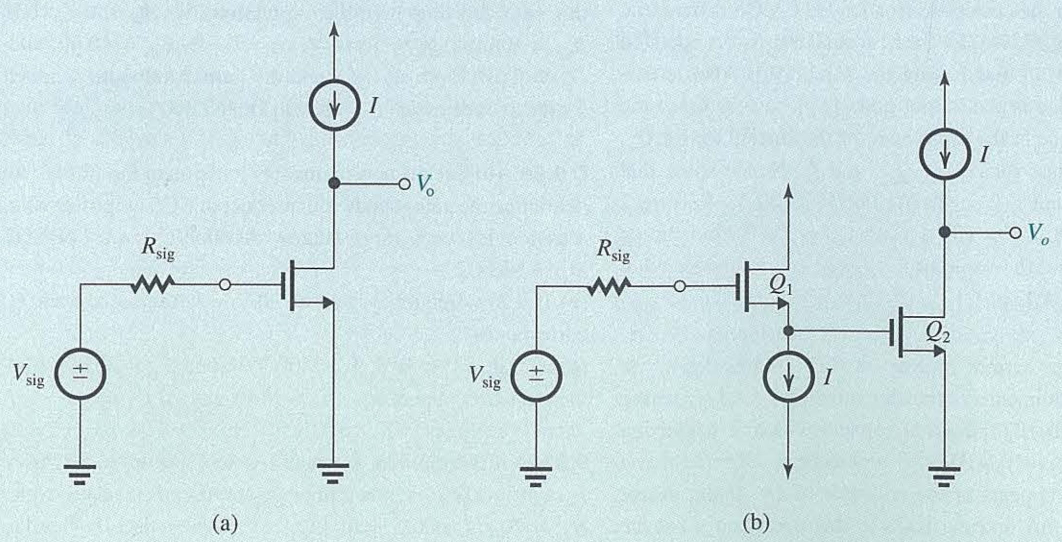

Figure P9.90

(b) For the CD–CS amplifier in Fig. P9.90(b), show that

$$A_M = -\frac{r_{o1}}{1/g_{m1} + r_{o1}}(g_{m2}r_{o2})$$
$$\tau_H = C_{gd1}R_{sig} + C_{gs1}\frac{R_{sig}+r_{o1}}{1+g_{m1}r_{o1}} + C_{gs2}\left(\frac{1}{g_{m1}} \| r_{o1}\right)$$
$$+ C_{gd2}\left[\left(\frac{1}{g_{m1}} \| r_{o1}\right)(1+g_{m2}r_{o2}) + r_{o2}\right]$$
$$+ C_L r_{o2}$$

Calculate the values of A_M, f_H, and the gain–bandwidth product for the same parameter values used in (a). Compare with the results of (a).

***9.91** The transistors in the circuit of Fig. P9.91 have $\beta_0 = 100$, $V_A = 100$ V, and $C_\mu = 0.2$ pF. At a bias current of 100 µA, $f_T = 200$ MHz. (Note that the bias details are not shown.)

(a) Find R_{in} and the midband gain.
(b) Find an estimate of the upper 3-dB frequency f_H. Which capacitor dominates? Which one is the second most significant?

(*Hint*: Use the formulas in Example 9.13.)

9.92 Consider the circuit of Fig. P9.92 for the case: $I = 200$ µA and $V_{OV} = 0.2$ V, $R_{sig} = 100$ kΩ, $R_D = 50$ kΩ, $C_{gs} = 4$ pF, and $C_{gd} = 0.5$ pF. Find the dc gain, the high-frequency poles, and an estimate of f_H.

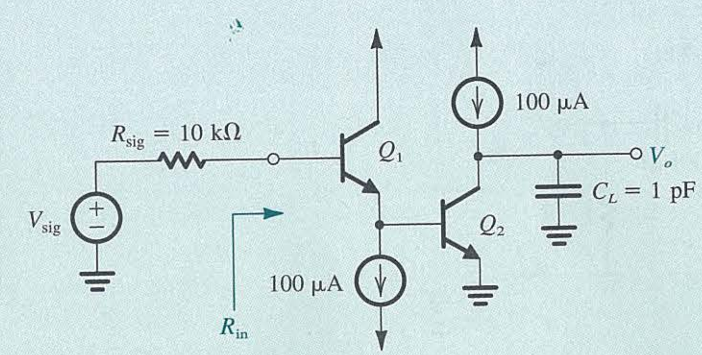

Figure P9.91

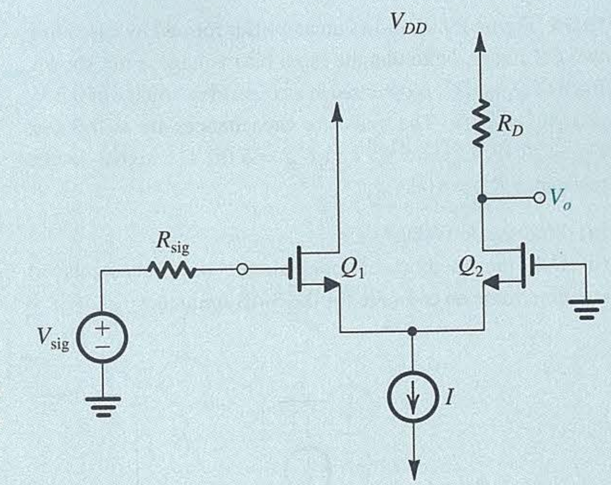

Figure P9.92

9.93 Consider the CD–CG amplifier of Fig. 9.41(c) for the case $g_m = 5$ mA/V, $C_{gs} = 2$ pF, $C_{gd} = 0.1$ pF, C_L (at the output node) = 1 pF, and $R_{sig} = R_L = 20$ kΩ. Neglecting r_o, find A_M and f_H. (*Hint:* Evaluate f_H directly from the transfer function.)

9.94 For the amplifier in Fig. 9.41(a), let $I = 1$ mA, $\beta = 120$, $f_T = 500$ MHz, and $C_\mu = 0.5$ pF, and neglect r_x and r_o. Assume that a load resistance of 10 kΩ is connected to the output terminal. If the amplifier is fed with a signal V_{sig} having a source resistance $R_{sig} = 12$ kΩ, find A_M and f_H.

***9.95** Figure P9.95 shows an amplifier formed by cascading two CS stages. Note that the input bias voltage is not shown. Each of Q_1 and Q_2 is operated at an overdrive voltage of 0.2 V, and $|V_A| = 10$ V. The transistor capacitances are as follows: $C_{gs} = 20$ fF, $C_{gd} = 5$ fF, and $C_{db} = 5$ fF. The signal-source resistance $R_{sig} = 10$ kΩ.

(a) Find the dc voltage gain.

(b) Use the method of open-circuit time constants to determine an estimate for the 3-dB frequency f_H.

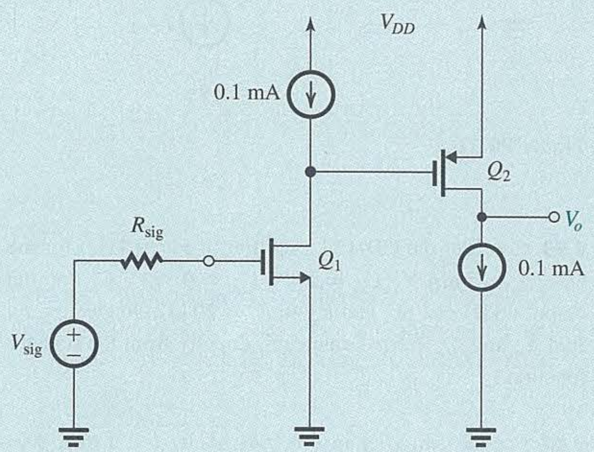

Figure P9.95

****9.96** Consider the BiCMOS amplifier shown in Fig. P9.96. The BJT has $|V_{BE}| = 0.7$ V, $\beta = 200$, $C_\mu = 0.8$ pF, and $f_T = 600$ MHz. The NMOS transistor has $V_t = 1$ V, $k_n'W/L = 2$ mA/V^2, and $C_{gs} = C_{gd} = 1$ pF.

(a) Consider the dc bias circuit. Neglect the base current of Q_2 in determining the current in Q_1. Find the dc bias currents in Q_1 and Q_2, and show that they are approximately 100 μA and 1 mA, respectively.

(b) Evaluate the small-signal parameters of Q_1 and Q_2 at their bias points.

(c) Consider the circuit at midband frequencies. First, determine the small-signal voltage gain V_o/V_i. (Note that R_G can be neglected in this process.) Then use Miller's theorem on R_G to determine the amplifier input resistance R_{in}. Finally, determine the overall voltage gain V_o/V_{sig}. Assume r_o of both transistors to be very large.

(d) Consider the circuit at low frequencies. Determine the frequency of the poles due to C_1 and C_2, and hence estimate the lower 3-dB frequency, f_L.

(e) Consider the circuit at higher frequencies. Use Miller's theorem to replace R_G with a resistance at the input. (The one at the output will be too large to matter.) Use open-circuit time constants to estimate f_H.

*****9.97** In each of the six circuits in Fig. P9.97, let $\beta = 100$, $C_\mu = 2$ pF, and $f_T = 400$ MHz, and neglect r_x and r_o. Calculate the midband gain A_M and the 3-dB frequency f_H.

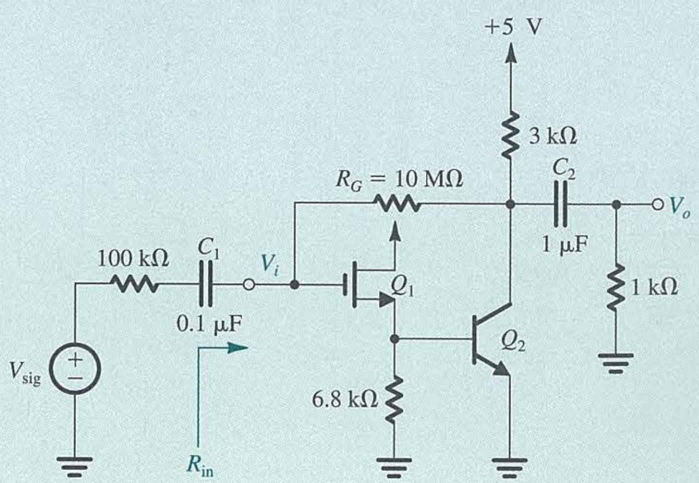

Figure P9.96

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem

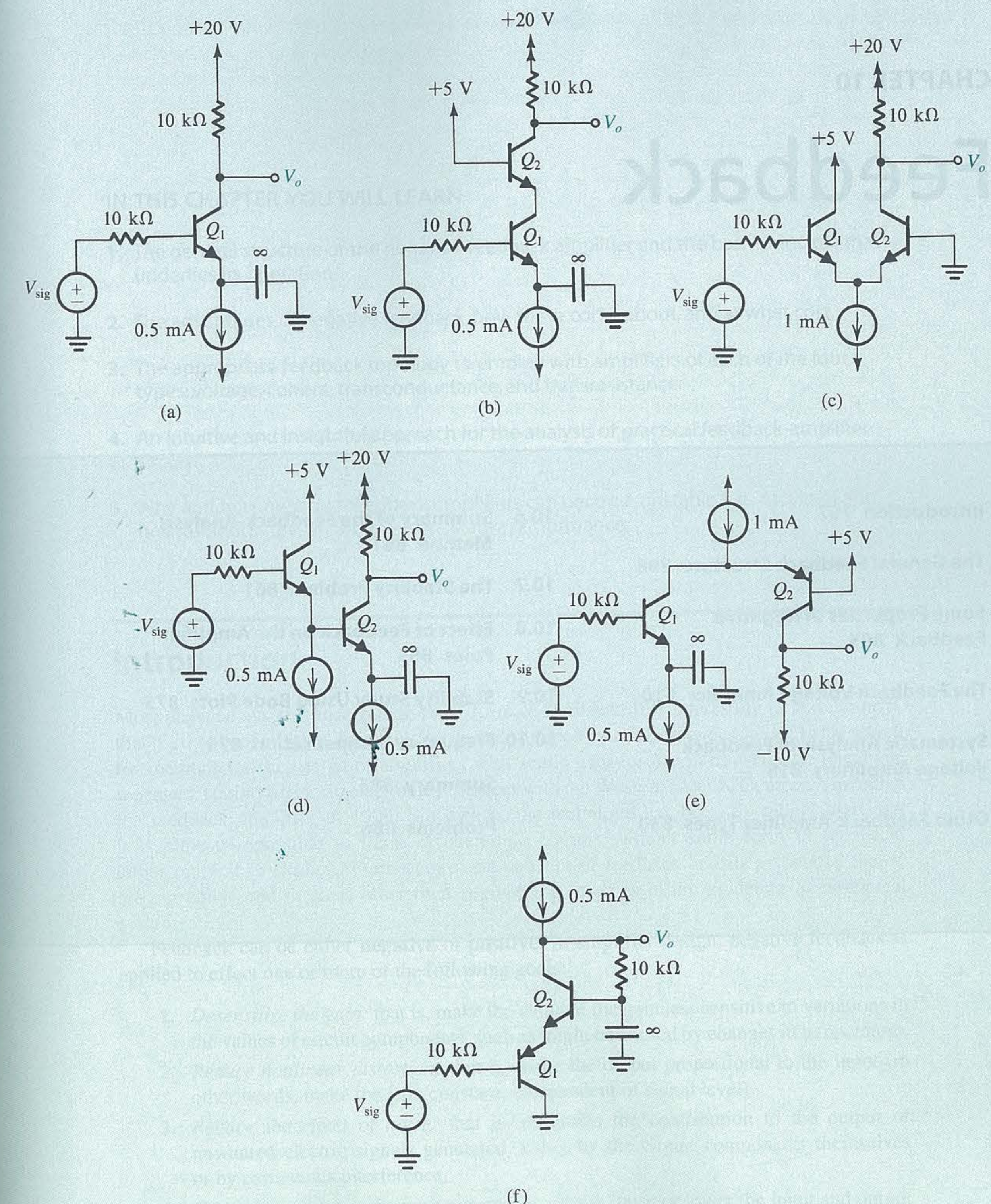

Figure P9.97