SEDRA/SMITH

INSTRUCTOR'S SOLUTIONS MANUAL FOR
Microelectronic Circuits

EIGHTH EDITION

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Contents

Preface

This Instructor's Manual (ISM) contains complete solutions for about 450 in-chapter exercises and 1400 end-of-chapter problems included in the book ***Microelectronic Circuits, Eighth Edition***.

This manual has benefited from the work of the accuracy checkers, listed below. We are grateful to all of them. Dr. Amir Yazdani of Ryerson University deserves special mention as he has done a truly outstanding job in ensuring that this manual is as free of errors as possible. However, despite all of our combined efforts, there is little doubt that some errors remain. We will be most grateful to instructors who discover errors and point them out to us. Please send corrections and comments by email to: sedra@uwaterloo.ca.

As she has done for a number of editions of the book and the ISM, Jennifer Rodrigues most ably typed the majority of the solutions in this manual. We are very grateful for her excellent work.

At OUP, we wish to thank Senior Production Editor Keith Faivre, Senior Development Editor Eric Sinkins, and Assistant Editor Megan Carlson.

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Chapter 1

Solutions to Exercises within the Chapter

Ex: 1.1 When output terminals are open-circuited, as in Fig. 1.1a:

For circuit a. $v_{oc} = v_s(t)$

For circuit b. $v_{oc} = i_s(t) \times R_s$

When output terminals are short-circuited, as in Fig. 1.1b:

For circuit a. $i_{sc} = \dfrac{v_s(t)}{R_s}$

For circuit b. $i_{sc} = i_s(t)$

For equivalency

$R_s i_s(t) = v_s(t)$

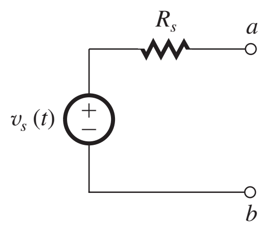


Figure 1.1a

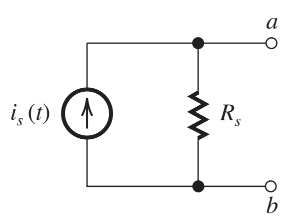
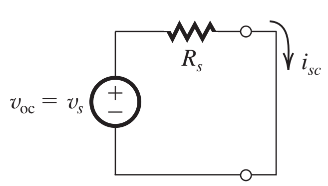


Figure 1.1b

Ex: 1.2



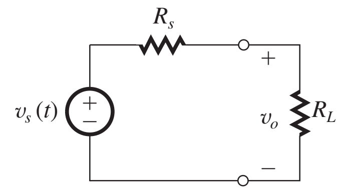
$v_{oc} = 10$ mV

$i_{sc} = 10$ μA

$R_s = \dfrac{v_{oc}}{i_{sc}} = \dfrac{10 \text{ mV}}{10\ \mu\text{A}} = 1 \text{ k}\Omega$

Ex: 1.3 Using voltage divider:

$v_o(t) = v_s(t) \times \dfrac{R_L}{R_s + R_L}$



Given $v_s(t) = 10$ mV and $R_s = 1$ kΩ.

If $R_L = 100$ kΩ

$v_o = 10 \text{ mV} \times \dfrac{100}{100 + 1} = 9.9 \text{ mV}$

If $R_L = 10$ kΩ

$v_o = 10 \text{ mV} \times \dfrac{10}{10 + 1} \simeq 9.1 \text{ mV}$

If $R_L = 1$ kΩ

$v_o = 10 \text{ mV} \times \dfrac{1}{1 + 1} = 5 \text{ mV}$

If $R_L = 100\ \Omega$

$v_o = 10 \text{ mV} \times \dfrac{100}{100 + 1 \text{ K}} \simeq 0.91 \text{ mV}$

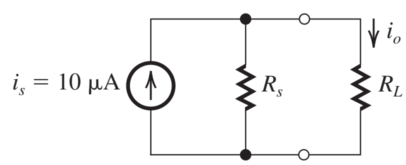
For $v_o = 0.8 v_s$,

$\dfrac{R_L}{R_L + R_s} = 0.8$

Since $R_s = 1$ kΩ,

$R_L = 4$ kΩ

Ex: 1.4 Using current divider:



$i_o = i_s \times \dfrac{R_s}{R_s + R_L}$

Given $i_s = 10$ μA, $R_s = 100$ kΩ.

For $R_L = 1 \text{ k}\Omega,\ i_o = 10\ \mu\text{A} \times \dfrac{100}{100 + 1} = 9.9\ \mu\text{A}$

For $R_L = 10 \text{ k}\Omega,\ i_o = 10\ \mu\text{A} \times \dfrac{100}{100 + 10} \simeq 9.1\ \mu\text{A}$

For $R_L = 100 \text{ k}\Omega,\ i_o = 10\ \mu\text{A} \times \dfrac{100}{100 + 100} = 5\ \mu\text{A}$

For $R_L = 1 \text{ M}\Omega,\ i_o = 10\ \mu\text{A} \times \dfrac{100 \text{ K}}{100 \text{ K} + 1 \text{ M}}$

$\simeq 0.9\ \mu$A

For $i_o = 0.8 i_s$, $\dfrac{100}{100 + R_L} = 0.8$

$\Rightarrow R_L = 25$ kΩ

Ex: 1.5 $f = \frac{1}{T} = \frac{1}{10^{-3}} = 1000$ Hz

$\omega = 2\pi f = 2\pi \times 10^3$ rad/s

Ex: 1.6 (a) $T = \frac{1}{f} = \frac{1}{60}$ s $= 16.7$ ms

(b) $T = \frac{1}{f} = \frac{1}{10^{-3}} = 1000$ s

(c) $T = \frac{1}{f} = \frac{1}{10^6}$ s $= 1$ µs

Ex: 1.7 If 6 MHz is allocated for each channel, then 470 MHz to 806 MHz will accommodate

$\frac{806 - 470}{6} = 56$ channels

Since the broadcast band starts with channel 14, it will go from channel 14 to channel 69.

Ex: 1.8 $P = \frac{1}{T}\int_0^T \frac{v^2}{R}\,dt$

$= \frac{1}{T} \times \frac{V^2}{R} \times T = \frac{V^2}{R}$

Alternatively,

$P = P_1 + P_3 + P_5 + \cdots$

$= \left(\frac{4V}{\sqrt{2}\pi}\right)^2 \frac{1}{R} + \left(\frac{4V}{3\sqrt{2}\pi}\right)^2 \frac{1}{R}$

$+ \left(\frac{4V}{5\sqrt{2}\pi}\right)^2 \frac{1}{R} + \cdots$

$= \frac{V^2}{R} \times \frac{8}{\pi^2} \times \left(1 + \frac{1}{9} + \frac{1}{25} + \frac{1}{49} + \cdots\right)$

It can be shown by direct calculation that the infinite series in the parentheses has a sum that approaches $\pi^2/8$; thus P becomes V^2/R as found from direct calculation.

Fraction of energy in fundamental

$= 8/\pi^2 = 0.81$

Fraction of energy in first five harmonics

$= \frac{8}{\pi^2}\left(1 + \frac{1}{9} + \frac{1}{25}\right) = 0.93$

Fraction of energy in first seven harmonics

$= \frac{8}{\pi^2}\left(1 + \frac{1}{9} + \frac{1}{25} + \frac{1}{49}\right) = 0.95$

Fraction of energy in first nine harmonics

$= \frac{8}{\pi^2}\left(1 + \frac{1}{9} + \frac{1}{25} + \frac{1}{49} + \frac{1}{81}\right) = 0.96$

Note that 90% of the energy of the square wave is in the first three harmonics, that is, in the fundamental and the third harmonic.

Ex: 1.9 (a) D can represent 15 equally-spaced values between 0 and 3.75 V. Thus, the values are spaced 0.25 V apart.

$v_A = 0$ V $\Rightarrow D = 0000$

$v_A = 0.25$ V $\Rightarrow D = 0000$

$v_A = 1$ V $\Rightarrow D = 0000$

$v_A = 3.75$ V $\Rightarrow D = 0000$

(b) (i) 1 level spacing: $2^0 \times +0.25 = +0.25$ V

(ii) 2 level spacings: $2^1 \times +0.25 = +0.5$ V

(iii) 4 level spacings: $2^2 \times +0.25 = +1.0$ V

(iv) 8 level spacings: $2^3 \times +0.25 = +2.0$ V

(c) The closest discrete value represented by D is +1.25 V; thus $D = 0101$. The error is -0.05 V, or $-0.05/1.3 \times 100 = -4\%$.

Ex: 1.10 Voltage gain $= 20 \log 100 = 40$ dB

Current gain $= 20 \log 1000 = 60$ dB

Power gain $= 10 \log A_p = 10 \log (A_v A_i)$

$= 10 \log 10^5 = 50$ dB

Ex: 1.11 $P_{dc} = 15 \times 8 = 120$ mW

$P_L = \frac{(6/\sqrt{2})^2}{1} = 18$ mW

$P_{dissipated} = 120 - 18 = 102$ mW

$\eta = \frac{P_L}{P_{dc}} \times 100 = \frac{18}{120} \times 100 = 15\%$

Ex: 1.12 $v_o = 1 \times \frac{10}{10^6 + 10} \simeq 10^{-5}$ V $= 10$ µV

$P_L = v_o^2/R_L = \frac{(10 \times 10^{-6})^2}{10} = 10^{-11}$ W

With the buffer amplifier:

$v_o = 1 \times \frac{R_i}{R_i + R_s} \times A_{vo} \times \frac{R_L}{R_L + R_o}$

$= 1 \times \frac{1}{1+1} \times 1 \times \frac{10}{10 + 10} = 0.25$ V

$P_L = \frac{v_o^2}{R_L} = \frac{0.25^2}{10} = 6.25$ mW

Voltage gain $= \frac{v_o}{v_s} = \frac{0.25\text{ V}}{1\text{ V}} = 0.25$ V/V

$= -12$ dB

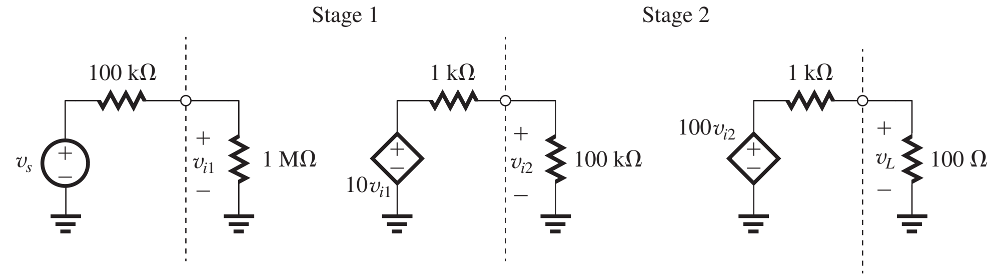
Power gain $(A_p) \equiv \frac{P_L}{P_i}$

where $P_L = 6.25$ mW and $P_i = v_i i_1$,

$v_i = 0.5$ V and

$i_i = \frac{1\text{ V}}{1\text{ M}\Omega + 1\text{ M}\Omega} = 0.5$ µA

This figure belongs to Exercise 1.15.



Thus,

$P_i = 0.5 \times 0.5 = 0.25\ \mu\text{W}$

and

$$A_p = \frac{6.25 \times 10^{-3}}{0.25 \times 10^{-6}} = 25 \times 10^3$$

$10 \log A_p = 44$ dB

Ex: 1.13 Open-circuit (no load) output voltage = $A_{vo} v_i$

Output voltage with load connected

$$= A_{vo} v_i \frac{R_L}{R_L + R_o}$$

$$0.8 = \frac{1}{R_o + 1} \Rightarrow R_o = 0.25\ \text{k}\Omega = 250\ \Omega$$

Ex: 1.14 $A_{vo} = 40\ \text{dB} = 100\ \text{V/V}$

$$P_L = \frac{v_o^2}{R_L} = \left(A_{vo} v_i \frac{R_L}{R_L + R_o}\right)^2 \Big/ R_L$$

$$= v_i^2 \times \left(100 \times \frac{1}{1+1}\right)^2 \Big/ 1000 = 2.5\ v_i^2$$

$$P_i = \frac{v_i^2}{R_i} = \frac{v_i^2}{10{,}000}$$

$$A_p \equiv \frac{P_L}{P_i} = \frac{2.5 v_i^2}{10^{-4} v_i^2} = 2.5 \times 10^4\ \text{W/W}$$

$10 \log A_p = 44$ dB

Ex: 1.15 Without stage 3 (see figure above)

$$\frac{v_L}{v_s} = \left(\frac{1\ \text{M}\Omega}{100\ \text{k}\Omega + 1\ \text{M}\Omega}\right)(10)\left(\frac{100\ \text{k}\Omega}{100\ \text{k}\Omega + 1\ \text{k}\Omega}\right)$$

$$\times (100)\left(\frac{100}{100 + 1\ \text{k}\Omega}\right)$$

$$\frac{v_L}{v_s} = (0.909)(10)(0.9901)(100)(0.0909)$$

$= 81.8$ V/V

Ex: 1.16 Refer the solution to Example 1.3 in the text.

$$\frac{v_{i1}}{v_s} = 0.909\ \text{V/V}$$

$v_{i1} = 0.909\ v_s = 0.909 \times 1 = 0.909$ mV

$$\frac{v_{i2}}{v_s} = \frac{v_{i2}}{v_{i1}} \times \frac{v_{i1}}{v_s} = 9.9 \times 0.909 = 9\ \text{V/V}$$

$v_{i2} = 9 \times v_S = 9 \times 1 = 9$ mV

$$\frac{v_{i3}}{v_s} = \frac{v_{i3}}{v_{i2}} \times \frac{v_{i2}}{v_{i1}} \times \frac{v_{i1}}{v_s} = 90.9 \times 9.9 \times 0.909$$

$= 818$ V/V

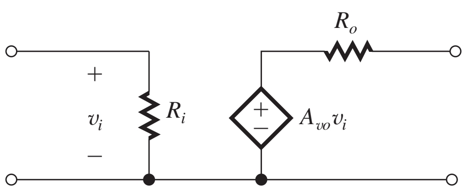
$v_{i3} = 818\ v_s = 818 \times 1 = 818$ mV

$$\frac{v_L}{v_s} = \frac{v_L}{v_{i3}} \times \frac{v_{i3}}{v_{i2}} \times \frac{v_{i2}}{v_{i1}} \times \frac{v_{i1}}{v_s}$$

$= 0.909 \times 90.9 \times 9.9 \times 0.909 \simeq 744$ V/V

$v_L = 744 \times 1\ \text{mV} = 744$ mV

Ex: 1.17 Using voltage amplifier model, the three-stage amplifier can be represented as



$R_i = 1\ \text{M}\Omega$

$R_o = 10\ \Omega$

$A_{vo} = A_{v1} \times A_{v2} \times A_{v3} = 9.9 \times 90.9 \times 1 = 900$ V/V

The overall voltage gain

$$\frac{v_o}{v_s} = \frac{R_i}{R_i + R_s} \times A_{vo} \times \frac{R_L}{R_L + R_o}$$

For $R_L = 10\ \Omega$

Overall voltage gain

$$= \frac{1\ \text{M}}{1\ \text{M} + 100\ \text{K}} \times 900 \times \frac{10}{10+10} = 409\ \text{V/V}$$

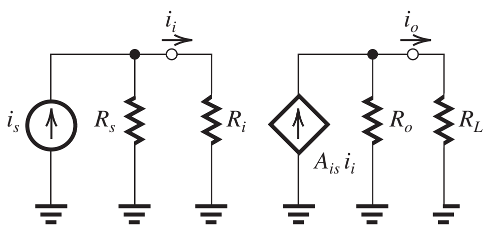
For $R_L = 1000\ \Omega$

Overall voltage gain

$$= \frac{1\ \text{M}}{1\ \text{M} + 100\ \text{K}} \times 900 \times \frac{1000}{1000+10} = 810\ \text{V/V}$$

$\therefore$ Range of voltage gain is from 409 V/V to 810 V/V.

Ex: 1.18



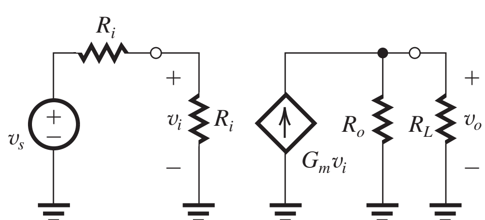
$$i_i = i_s \frac{R_s}{R_s + R_i}$$

$$i_o = A_{is} i_i \frac{R_o}{R_o + R_L} = A_{is} i_s \frac{R_s}{R_s + R_i} \frac{R_o}{R_o + R_L}$$

Thus,

$$\frac{i_o}{i_s} = A_{is} \frac{R_s}{R_s + R_i} \frac{R_o}{R_o + R_L}$$

Ex: 1.19



$$v_i = v_s \frac{R_i}{R_i + R_s}$$

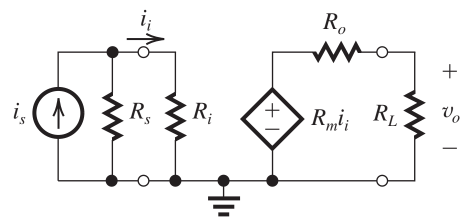
$$v_o = G_m v_i (R_o \parallel R_L)$$

$$= G_m v_s \frac{R_i}{R_i + R_s} (R_o \parallel R_L)$$

Thus,

$$\frac{v_o}{v_s} = G_m \frac{R_i}{R_i + R_s} (R_o \parallel R_L)$$

Ex: 1.20 Using the transresistance circuit model, the circuit will be



$$\frac{i_i}{i_s} = \frac{R_s}{R_i + R_s}$$

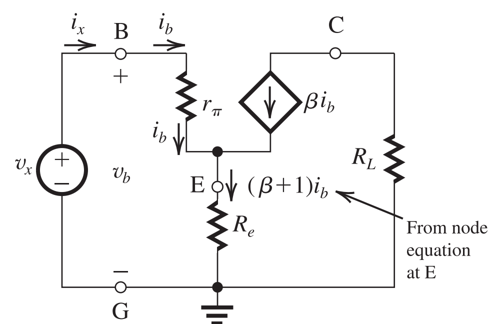
$$v_o = R_m i_i \times \frac{R_L}{R_L + R_o}$$

$$\frac{v_o}{i_i} = R_m \frac{R_L}{R_L + R_o}$$

$$\text{Now } \frac{v_o}{i_s} = \frac{v_o}{i_i} \times \frac{i_i}{i_s} = R_m \frac{R_L}{R_L + R_o} \times \frac{R_s}{R_i + R_s}$$

$$= R_m \frac{R_s}{R_s + R_i} \times \frac{R_L}{R_L + R_o}$$

Ex: 1.21



$$v_b = i_b r_\pi + (\beta + 1) i_b R_e$$

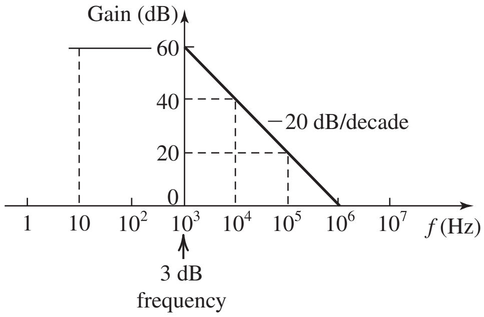
$$= i_b r_\pi + (\beta + 1) R_e$$

But $v_b = v_x$ and $i_b = i_x$, thus

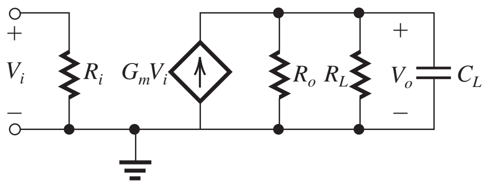
$$R_{\text{in}} \equiv \frac{v_x}{i_x} = \frac{v_b}{i_b} = r_\pi + (\beta + 1) R_e$$

Ex: 1.22

f	Gain
10 Hz	60 dB
10 kHz	40 dB
100 kHz	20 dB
1 MHz	0 dB



Ex: 1.23



$V_o = G_m V_i R_o \parallel R_L \parallel C_L$

$$= \frac{G_m V_i}{\frac{1}{R_o} + \frac{1}{R_L} + sC_L}$$

Thus, $\frac{V_o}{V_i} = \frac{G_m}{\frac{1}{R_o} + \frac{1}{R_L}} \times \frac{1}{1 + \frac{sC_L}{\frac{1}{R_o} + \frac{1}{R_L}}}$

$$\frac{V_o}{V_i} = \frac{G_m(R_L \parallel R_o)}{1 + sC_L(R_L \parallel R_o)}$$

which is of the STC LP type.

$$\omega_0 = \frac{1}{C_L(R_L \parallel R_o)}$$

$$= \frac{1}{4.5 \times 10^{-9}(10^3 \parallel R_o)}$$

For ω_0 to be at least $w\pi \times 40 \times 10^3$, the highest value allowed for R_o is

$$R_o = \frac{10^3}{2\pi \times 40 \times 10^3 \times 10^3 \times 4.5 \times 10^{-9} - 1}$$

$$= \frac{10^3}{1.131 - 1} = 7.64\text{ k}\Omega$$

The dc gain is

$G_m(R_L \parallel R_o)$

To ensure a dc gain of at least 40 dB (i.e., 100), the minimum value of G_m is

$\Rightarrow R_L \geq 100/(10^3 \parallel 7.64 \times 10^3) = 113.1$ mA/V

Ex: 1.24 Refer to Fig. E1.24

$$\frac{V_2}{V_s} = \frac{R_i}{R_s + \frac{1}{sC} + R_i} = \frac{R_i}{R_s + R_i} \frac{s}{s + \frac{1}{C(R_s + R_i)}}$$

which is an HP STC function.

$$f_{3\text{dB}} = \frac{1}{2\pi C(R_s + R_i)} \leq 100\text{ Hz}$$

$$C \geq \frac{1}{2\pi(1 + 9)10^3 \times 100} = 0.16\ \mu\text{F}$$

Chapter 2

Solutions to Exercises within the Chapter

Ex: 2.1 The minimum number of terminals required by a single op amp is 5: two input terminals, one output terminal, one terminal for positive power supply, and one terminal for negative power supply.

The minimum number of terminals required by a quad op amp is 14: each op amp requires two input terminals and one output terminal (accounting for 12 terminals for the four op amps). In addition, the four op amps can all share one terminal for positive power supply and one terminal for negative power supply.

Ex: 2.2 Relevant equations are:
$v_3 = A(v_2 - v_1)$; $v_{Id} = v_2 - v_1$,
$v_{Icm} = \frac{1}{2}(v_1 + v_2)$

(a)

$v_1 = v_2 - \frac{v_3}{A} = 0 - \frac{4}{10^3} = -0.004 \text{ V} = -4 \text{ mV}$

$v_{Id} = v_2 - v_1 = 0 - (-0.004) = +0.004 \text{ V}$

$= 4 \text{ mV}$

$v_{Icm} = \frac{1}{2}(-4 \text{ mV} + 0) = -2 \text{ mV}$

(b) $-10 = 10^3(2 - v_1) \Rightarrow v_1 = 2.01 \text{ V}$

$v_{Id} = v_2 - v_1 = 2 - 2.01 = -0.01 \text{ V} = -10 \text{ mV}$

$v_{Icm} = \frac{1}{2}(v_1 + v_2) = \frac{1}{2}(2.01 + 2) = 2.005 \text{ V}$

$\simeq 2 \text{ V}$

(c)

$v_3 = A(v_2 - v_1) = 10^3(1.998 - 2.002) = -4 \text{ V}$

$v_{Id} = v_2 - v_1 = 1.998 - 2.002 = -4 \text{ mV}$

$v_{Icm} = \frac{1}{2}(v_1 + v_2) = \frac{1}{2}(2.002 + 1.998) = 2 \text{ V}$

(d)

$-1.2 = 10^3 v_2 - (-1.2) = 10^3(v_2 + 1.2)$

$\Rightarrow v_2 = -1.2012 \text{ V}$

$v_{Id} = v_2 - v_1 = -1.2012 - (-1.2)$

$= -0.0012 \text{ V} = -1.2 \text{ mV}$

$v_{Icm} = \frac{1}{2}(v_1 + v_2) = \frac{1}{2}[-1.2 + (-1.2012)]$

$\simeq -1.2 \text{ V}$

Ex: 2.3 From Fig. E2.3 we have: $v_3 = \mu v_d$ and

$v_d = (G_m v_2 - G_m v_1)R = G_m R(v_2 - v_1)$

Therefore:

$v_3 = \mu G_m R(v_2 - v_1)$

That is, the open-loop gain of the op amp is $A = \mu G_m R$. For $G_m = 20$ mA/V and

$\mu = 50$, we have:

$A = 50 \times 20 \times 5 = 5000$ V/V, or equivalently, 74 dB.

Ex: 2.4 The gain and input resistance of the inverting amplifier circuit shown in Fig. 2.5 are $-\frac{R_2}{R_1}$ and R_1, respectively. Therefore, we have:

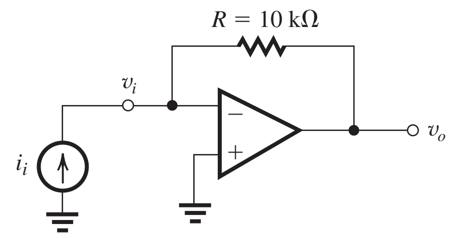
$R_1 = 100 \text{ k}\Omega$ and

$-\frac{R_2}{R_1} = -10 \Rightarrow R_2 = 10\ R_1$

Thus:

$R_2 = 10 \times 100 \text{ k}\Omega = 1 \text{ M}\Omega$

Ex: 2.5



From Table 1.1 we have:

$R_m = \left.\frac{v_o}{i_i}\right|_{i_o=0}$; that is, output is open circuit

The negative input terminal of the op amp (i.e., v_i) is a virtual ground, thus $v_i = 0$:

$v_o = v_i - Ri_i = 0 - Ri_i = -Ri_i$

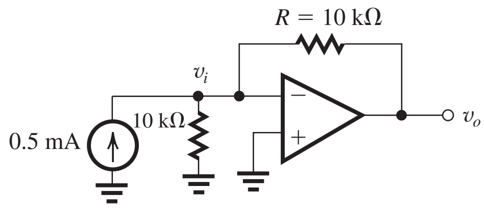
$R_m = \left.\frac{v_o}{i_i}\right|_{i_o=0} = -\frac{Ri_i}{i_i} = -R \Rightarrow R_m = -R$

$= -10 \text{ k}\Omega$

$R_i = \frac{v_i}{i_i}$ and v_i is a virtual ground ($v_i = 0$),

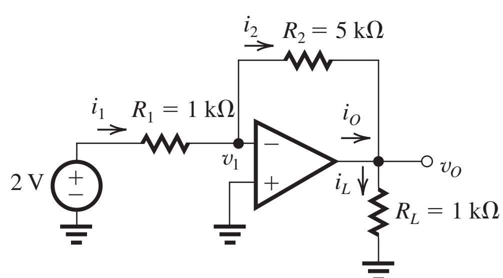
thus $R_i = \frac{0}{i_i} = 0 \Rightarrow R_i = 0\ \Omega$

Since we are assuming that the op amp in this transresistance amplifier is ideal, the op amp has zero output resistance and therefore the output resistance of this transresistance amplifier is also zero. That is $R_o = 0\ \Omega$.



Connecting the signal source shown in Fig. E2.5 to the input of this amplifier, we have:
v_i is a virtual ground that is $v_i = 0$, thus the current flowing through the 10-kΩ resistor connected between v_i and ground is zero. Therefore,
$v_o = v_i - R \times 0.5\ \text{mA} = 0 - 10\ \text{k}\Omega \times 0.5\ \text{mA}$
$= -5$ V.

Ex: 2.6



v_1 is a virtual ground, thus $v_1 = 0$ V

$$i_1 = \frac{2\ \text{V} - v_1}{R_1} = \frac{2 - 0}{1\ \text{k}\Omega} = 2\ \text{mA}$$

Assuming an ideal op amp, the current flowing into the negative input terminal of the op amp is zero. Therefore, $i_2 = i_1 \Rightarrow i_2 = 2$ mA

$$v_O = v_1 - i_2R_2 = 0 - 2\ \text{mA} \times 5\ \text{k}\Omega = -10\ \text{V}$$

$$i_L = \frac{v_o}{R_L} = \frac{-10\ \text{V}}{1\ \text{k}\Omega} = -10\ \text{mA}$$

$$i_O = i_L - i_2 = -10\ \text{mA} - 2\ \text{mA} = -12\ \text{mA}$$

Voltage gain $= \dfrac{v_O}{2\ \text{V}} = \dfrac{-10\ \text{V}}{1\ \text{V}} = -5$ V/V or 14 dB

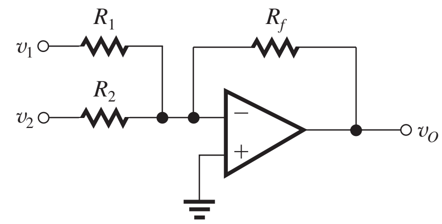
Current gain $= \dfrac{i_L}{i_1} = \dfrac{-10\ \text{mA}}{2\ \text{mA}} = -5$ A/A or 14 dB

Power gain

$$= \frac{P_L}{P_i} = \frac{-10(-10\ \text{mA})}{2\ \text{V} \times 2\ \text{mA}} = 25\ \text{W/W or 14 dB}$$

Note that power gain in dB is $10 \log_{10} \left| \dfrac{P_L}{P_i} \right|$.

Ex: 2.7



For the circuit shown above we have:

$$v_O = -\left(\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2\right)$$

Since it is required that $v_O = -(v_1 + 4v_2)$,

we want to have:

$$\frac{R_f}{R_1} = 1 \quad \text{and} \quad \frac{R_f}{R_2} = 4$$

It is also desired that for a maximum output voltage of 4 V, the current in the feedback resistor not exceed 1 mA.

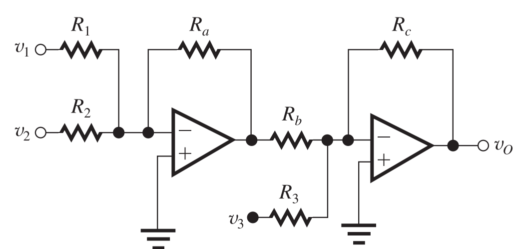
Therefore

$$\frac{4\ \text{V}}{R_f} \leq 1\ \text{mA} \Rightarrow R_f \geq \frac{4\ \text{V}}{1\ \text{mA}} \Rightarrow R_f \geq 4\ \text{k}\Omega$$

Let us choose R_f to be 4 kΩ, then

$R_1 = R_f = 4\ \text{k}\Omega$ and $R_2 = \dfrac{R_f}{4} = 1\ \text{k}\Omega$

Ex: 2.8



$$v_O = \left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right)v_1 + \left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right)v_2 - \left(\frac{R_c}{R_3}\right)v_3$$

We want to design the circuit such that

$$v_O = 2v_1 + v_2 - 4v_3$$

Thus we need to have

$$\left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right) = 2, \left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right) = 1, \text{ and } \frac{R_c}{R_3} = 4$$

From the above three equations, we have to find six unknown resistors; therefore, we can arbitrarily choose three of these resistors. Let us choose $R_a = R_b = R_c = 10\ \text{k}\Omega$.

Then we have

$$R_3 = \frac{R_c}{4} = \frac{10}{4} = 2.5\ \text{k}\Omega$$

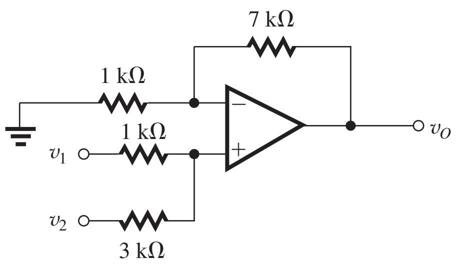
$$\left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right) = 2, \Rightarrow \frac{10}{R_1} \times \frac{10}{10} = 2$$

$$\Rightarrow R_1 = 5\ \text{k}\Omega$$

$$\left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right) = 1 \Rightarrow \frac{10}{R_2} \times \frac{10}{10} = 1$$

$$\Rightarrow R_2 = 10\ \text{k}\Omega$$

Ex: 2.9 Using the superposition principle to find the contribution of v_1 to the output voltage v_O, we set $v_2 = 0$



v_+ (the voltage at the positive input of the op amp is: $v_+ = \frac{3}{1+3}v_1 = 0.75v_1$

Thus $v_O = \left(1 + \frac{7\ \text{k}\Omega}{1\ \text{k}\Omega}\right)v_+ = 8 \times 0.75v_1 = 6v_1$

To find the contribution of v_2 to the output voltage v_O we set $v_1 = 0$.

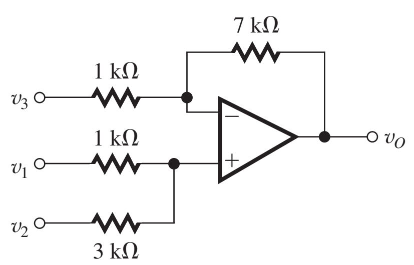
Then $v_+ = \frac{1}{1+3}v_2 = 0.25v_2$

Hence

$$v_O = \left(1 + \frac{7\ \text{k}\Omega}{1\ \text{k}\Omega}\right)v_+ = 8 \times 0.25v_2 = 2v_2$$

Combining the contributions of v_1 and v_2 to v_O, we have $v_O = 6v_1 + 2v_2$

Ex: 2.10



Using the superposition principle to find the contribution of v_1 to v_O, we set $v_2 = v_3 = 0$. Then we have (refer to the solution of Exercise 2.9): $v_O = 6v_1$

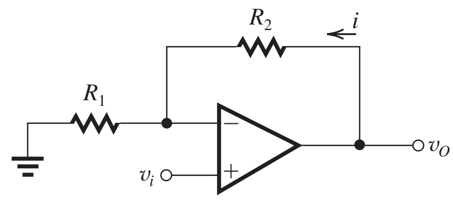
To find the contribution of v_2 to v_O, we set $v_1 = v_3 = 0$, then: $v_O = 2v_2$

To find the contribution of v_3 to v_O we set $v_1 = v_2 = 0$, then

$$v_o = -\frac{7\ \text{k}\Omega}{1\ \text{k}\Omega}\ v_3 = -7v_3$$

Combining the contributions of v_1, v_2, and v_3 to v_O we have: $v_O = 6v_1 + 4v_2 - 7v_3$.

Ex: 2.11



$$\frac{v_O}{v_i} = 1 + \frac{R_2}{R_1} = 2 \Rightarrow \frac{R_2}{R_1} = 1 \Rightarrow R_1 = R_2$$

If $v_O = 10$ V, then it is desired that $i = 10\ \mu$A.

Thus,

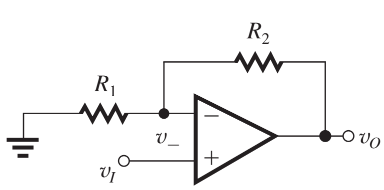
$$i = \frac{10\ \text{V}}{R_1 + R_2} = 10\ \mu\text{A} \Rightarrow R_1 + R_2 = \frac{10\ \text{V}}{10\ \mu\text{A}}$$

$R_1 + R_2 = 1\ \text{M}\Omega$ and

$R_1 = R_2 \Rightarrow R_1 = R_2 = 0.5\ \text{M}\Omega$

Ex: 2.12

(a)



$$v_I - v_- = v_O/A \Rightarrow v_- = v_I - v_O/A \qquad (1)$$

But from the voltage divider across v_O,

$$v_- = v_O \frac{R_1}{R_1 + R_2} \qquad (2)$$

Equating Eq. (1) and Eq. (2) gives

$$v_O \frac{R_1}{R_1 + R_2} = v_I - \frac{v_O}{A}$$

which can be manipulated to the form

$$\frac{v_O}{v_I} = \frac{1 + (R_2/R_1)}{1 + \dfrac{1 + (R_2/R_1)}{A}}$$

(b) For $R_1 = 1\ \text{k}\Omega$ and $R_2 = 9\ \text{k}\Omega$ the ideal value for the closed-loop gain is $1 + \frac{9}{1}$, that is, 10. The actual closed-loop gain is $G = \dfrac{10}{1 + 10/A}$.

If $A = 10^3$, then $G = 9.901$ and

$$\epsilon = \frac{G - 10}{10} \times 100 = -0.99\% \simeq -1\%$$

For $v_I = 1$ V, $v_O = G \times v_I = 9.901$ V and

$$v_O = A(v_+ - v_-) \Rightarrow v_+ - v_- = \frac{v_O}{A} = \frac{9.901}{1000}$$

$\simeq 9.9$ mV

If $A = 10^4$, then $G = 9.99$ and $\epsilon = -0.1\%$.

For $v_I = 1$ V, $v_O = G \times v_I = 9.99$ V,

therefore,

$$v_+ - v_- = \frac{v_O}{A} = \frac{9.99}{10^4} = 0.999\ \text{mV} \simeq 1\ \text{mV}$$

If $A = 10^5$, then $G = 9.999$ and $\epsilon = -0.01\%$

For $v_I = 1$ V, $v_O = G \times v_I = 9.999$ thus,

$$v_+ - v_- = \frac{v_O}{A} = \frac{9.999}{10^5} = 0.09999\ \text{mV}$$

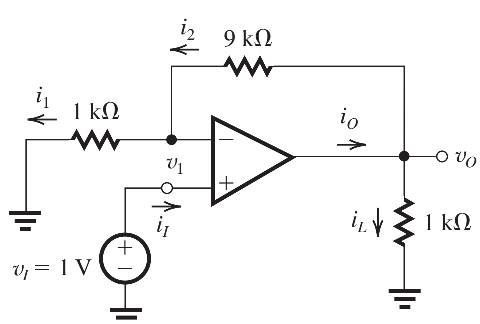
$\simeq 0.1$ mV

Ex: 2.13

$i_I = 0$ A, $v_1 = v_I = 1$ V

$$i_1 = \frac{v_1}{1\ \text{k}\Omega} = \frac{1\ \text{V}}{1\ \text{k}\Omega} = 1\ \text{mA}$$

$i_2 = i_1 = 1$ mA



$$v_O = v_1 + i_2 \times 9\ \text{k}\Omega = 1 + 1 \times 9 = 10\ \text{V}$$

$$i_L = \frac{v_O}{1\ \text{k}\Omega} = \frac{10\ \text{V}}{1\ \text{k}\Omega} = 10\ \text{mA}$$

$$i_O = i_L + i_2 = 11\ \text{mA}$$

$$\frac{v_O}{v_i} = \frac{10\ \text{V}}{1\ \text{V}} = 10\ \text{V/V or } 20\ \text{dB}$$

$$\frac{i_L}{i_I} = \frac{10\ \text{mA}}{0} = \infty$$

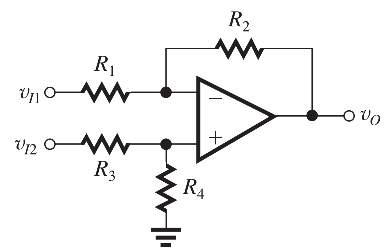
$$\frac{P_L}{P_I} = \frac{v_O \times i_L}{v_I \times i_I} = \frac{10 \times 10}{1 \times 0} = \infty$$

Ex: 2.14

(a) Load voltage $= \dfrac{1\ \text{k}\Omega}{1\ \text{k}\Omega + 1\ \text{M}\Omega} \times 1\ \text{V} \simeq 1\ \text{mV}$

(b) Load voltage = 1 V

Ex: 2.15



(a) $R_1 = R_3 = 2\ \text{k}\Omega$, $R_2 = R_4 = 200\ \text{k}\Omega$

Since $R_4/R_3 = R_2/R_1$ we have:

$$A_d = \frac{v_O}{v_{I2} - v_{I1}} = \frac{R_2}{R_1} = \frac{200}{2} = 100\ \text{V/V}$$

(b) $R_{id} = 2R_1 = 2 \times 2\ \text{k}\Omega = 4\ \text{k}\Omega$

Since we are assuming the op amp is ideal,

$R_o = 0\ \Omega$

(c)

$$A_{cm} \equiv \frac{v_O}{v_{Icm}} = \frac{R_4}{R_3 + R_4}\left(1 - \frac{R_2}{R_1}\frac{R_3}{R_4}\right)$$

The worst-case common-mode gain (i.e., the largest A_{cm}) occurs when the resistor tolerances are such that the quantity in parentheses is maximum. This in turn occurs when R_2 and R_3 are at their highest possible values (each one percent above nominal) and R_1 and R_4 are at their lowest possible values (each one percent below nominal), resulting in

$$A_{cm} = \frac{R_4}{R_3 + R_4}\left(1 - \frac{1.01 \times 1.01}{0.99 \times 0.99}\right)$$

$$|A_{cm}| \simeq \frac{R_4}{R_3 + R_4} \times 0.04 \simeq \frac{200}{202} \times 0.04 \simeq 0.04\ \text{V/V}$$

The corresponding CMRR is

$$\text{CMRR} = \frac{|A_d|}{|A_{cm}|} = \frac{100}{0.04} = 2500$$

or 68 dB.

Ex: 2.16 We choose $R_3 = R_1$ and $R_4 = R_2$. Then for the circuit to behave as a difference amplifier with a gain of 10 and an input resistance of 20 kΩ, we require

$A_d = \dfrac{R_2}{R_1} = 10$ and

$R_{Id} = 2R_1 = 20\ \text{k}\Omega \Rightarrow R_1 = 10\ \text{k}\Omega$ and

$R_2 = A_d R_1 = 10 \times 10\ \text{k}\Omega = 100\ \text{k}\Omega$

Therefore, $R_1 = R_3 = 10\ \text{k}\Omega$ and

$R_2 = R_4 = 100\ \text{k}\Omega$.

Ex: 2.17 Given $v_{Icm} = +5$ V

$v_{Id} = 10 \sin \omega t$ mV

$2R_1 = 1\ \text{k}\Omega,\ R_2 = 0.5\ \text{M}\Omega$

$R_3 = R_4 = 10\ \text{k}\Omega$

$v_{I1} = v_{Icm} - \dfrac{1}{2}v_{Id} = 5 - \dfrac{1}{2} \times 0.01 \sin \omega t$

$= 5 - 0.005 \sin \omega t$ V

$v_{I2} = v_{Icm} + \dfrac{1}{2}v_{Id}$

$= 5 + 0.005 \sin \omega t$ V

$v_{-}(\text{op amp } A_1) = v_{I1} = 5 - 0.005 \sin \omega t$ V

$v_{-}(\text{op amp } A_2) = v_{I2} = 5 + 0.005 \sin \omega t$ V

$v_{Id} = v_{I2} - v_{I1} = 0.01 \sin \omega t$

$v_{O1} = v_{I1} - R_2 \times \dfrac{v_{Id}}{2R_1}$

$= 5 - 0.005 \sin \omega t - 500\ \text{k}\Omega \times \dfrac{0.01 \sin \omega t}{1\ \text{k}\Omega}$

$= (5 - 5.005 \sin \omega t)$ V

$v_{O2} = v_{I2} + R_2 \times \dfrac{v_{Id}}{2R_1}$

$= (5 + 5.005 \sin \omega t)$ V

$v_{+}(\text{op amp } A_3) = v_{O2} \times \dfrac{R_4}{R_3 + R_4} = v_{O2}\dfrac{10}{10 + 10}$

$= \dfrac{1}{2}v_{O2} = \dfrac{1}{2}(5 + 5.005 \sin \omega t)$

$= (2.5 + 2.5025 \sin \omega t)$V

$v_{-}(\text{op amp } A_3) = v_{+}(\text{op amp } A_3)$

$= (2.5 + 2.5025 \sin \omega t)$ V

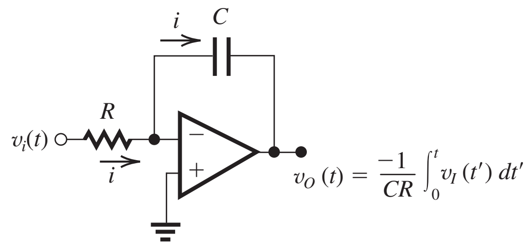
$v_O = \dfrac{R_4}{R_3}\left(1 + \dfrac{R_2}{R_1}\right) v_{Id}$

$\dfrac{10\ \text{k}\Omega}{10\ \text{k}\Omega}\left(1 + \dfrac{0.5\ \text{M}\Omega}{0.5\ \text{k}\Omega}\right) \times 0.01 \sin \omega t$

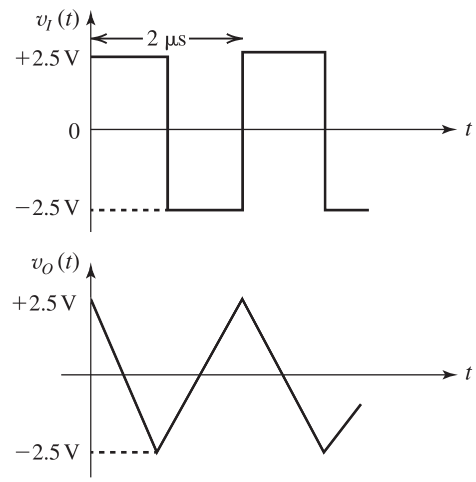
$= 1(1 + 1000) \times 0.01 \sin \omega t$

$= 10.01 \sin \omega t$ V

Ex: 2.18



The signal waveforms will be as shown.



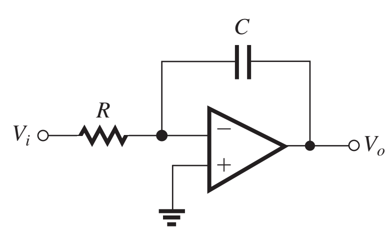
When $v_I = +2.5$ V, the current through the capacitor will be in the direction indicated, $i = 2.5\ \text{V}/R$, and the output voltage will decrease linearly from +2.5 V to −2.5 V. Thus in $(T/2)$ seconds, the capacitor voltage changes by 5 V. The charge equilibrium equation can be expressed as

$i(T/2) = C \times 5$ V

$\dfrac{2.5}{R}\dfrac{T}{2} = 5C \Rightarrow CR = \dfrac{2.5T}{10} = \dfrac{1}{4} \times 2 \times 10^{-6}$

$= 0.5\ \mu\text{s}$

Ex: 2.19



The input resistance of this inverting integrator is R; therefore, $R = 10\ \text{k}\Omega$.

Since the desired integration time constant is 10^{-3} s, we have: $CR = 10^{-3}$ s $\Rightarrow$

$$C = \frac{10^{-3}\ \text{s}}{10\ \text{k}\Omega} = 0.1\ \mu\text{F}$$

From Eq. (2.27) the transfer function of this integrator is:

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{1}{j\omega CR}$$

For $\omega = 10$ rad/s, the integrator transfer function has magnitude

$$\left|\frac{V_o}{V_i}\right| = \frac{1}{1 \times 10^{-3}} = 100\ \text{V/V}$$

and phase $\phi = 90^\circ$.

For $\omega = 1$ rad/s, the integrator transfer function has magnitude

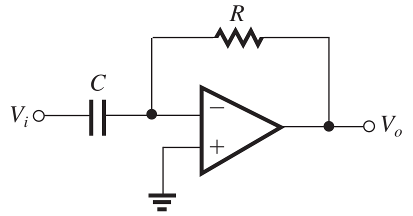
$$\left|\frac{V_o}{V_i}\right| = \frac{1}{1 \times 10^{-3}} = 1000\ \text{V/V}$$

and phase $\phi = 90^\circ$.

The frequency at which the integrator gain magnitude is unity is

$$\omega_{\text{int}} = \frac{1}{CR} = \frac{1}{10^{-3}} = 1000\ \text{rad/s}$$

Ex: 2.20



$C = 0.01\ \mu$F is the input capacitance of this differentiator. We want $CR = 10^{-2}$ s (the time constant of the differentiator); thus,

$$R = \frac{10^{-2}}{0.01\ \mu\text{F}} = 1\ \text{M}\Omega$$

From Eq. (2.33), the transfer function of the differentiator is

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -j\omega CR$$

Thus, for $\omega = 10$ rad/s the differentiator transfer function has magnitude

$$\left|\frac{V_o}{V_i}\right| = 10 \times 10^{-2} = 0.1\ \text{V/V}$$

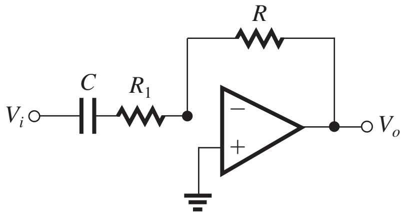
and phase $\phi = -90^\circ$.

For $\omega = 10^3$ rad/s, the differentiator transfer function has magnitude

$$\left|\frac{V_o}{V_i}\right| = 10^3 \times 10^{-2} = 10\ \text{V/V}$$

and phase $\phi = -90^\circ$.

If we add a resistor in series with the capacitor to limit the high-frequency gain of the differentiator to 100, the circuit would be:



At high frequencies the capacitor C acts like a short circuit. Therefore, the high-frequency gain of this circuit is: $\frac{R}{R_1}$. To limit the magnitude of this high-frequency gain to 100, we should have:

$$\frac{R}{R_1} = 100 \Rightarrow R_1 = \frac{R}{100} = \frac{1\ \text{M}\Omega}{100} = 10\ \text{k}\Omega$$

Ex: 2.21

Refer to the model in Fig. 2.27 and observe that

$$v_+ - v_- = V_{OS} + v_2 - v_1 = V_{OS} + v_{Id}$$

and since $v_O = v_3 = A(v_+ - v_-)$, then

$$v_O = A(v_{Id} + V_{OS}) \tag{1}$$

where $A = 10^4$ V/V and $V_{OS} = 5$ mV. From Eq. (1) we see that $v_{id} = 0$ results in $v_O = 50$ V, which is impossible; thus the op amp saturates and $v_O = +10$ V. This situation pertains for $v_{Id} \geq -4$ mV. If v_{Id} decreases below -4 mV, the op-amp output decreases correspondingly. For instance, $v_{Id} = -4.5$ mV results in $v_O = +5$ V; $v_{Id} = -5$ mV results in $v_O = 0$ V; $v_{Id} = -5.5$ mV results in $v_O = -5$ V; and $v_{Id} = -6$ mV results in $v_O = -10$ V, at which point the op amp saturates at the negative level of -10 V. Further decreases in v_{Id} have no effect on the output voltage. The result is the transfer characteristic sketched in Fig. E2.21. Observe that the linear range of the characteristic is now centered around $v_{Id} = -5$ mV rather than the ideal situation of $v_{Id} = 0$; this shift is obviously a result of the input offset voltage V_{OS}.

Ex: 2.22 (a) The inverting amplifier of -1000 V/V gain will exhibit an output dc offset voltage of $\pm V_{OS}(1 + R_2/R_1) =$ $\pm 3 \text{ mV} \times (1 + 1000) = \pm 3.03$ V. Now, since the op-amp saturation levels are ± 10 V, the room left for output signal swing is approximately ± 7 V. Thus to avoid op-amp saturation and the attendant clipping of the peak of the output sinusoid, we must limit the peak amplitude of the input sine wave to approximately $7 \text{ V}/1000 = 7$ mV.

(b) If at room temperature (25°C), V_{OS} is trimmed to zero and (i) the circuit is operated at a constant temperature, the peak of the input sine wave can be increased to 10 mV. (ii) However, if the circuit is to operate in the temperature range of 0°C to 75°C (i.e., at a temperature that deviates from room temperature by a maximum of 50°C), the input offset voltage will drift from by a maximum of $10\ \mu\text{V}/°\text{C} \times 50°\text{C} = 500\ \mu\text{V}$ or 0.5 mV. This will reduce the allowed peak amplitude of the input sinusoid to 9.5 mV.

Ex: 2.23

(a) If the amplifier is capacitively coupled in the manner of Fig. 2.32(a), then the input offset voltage V_{OS} will see a unity-gain amplifier [Fig. 2.32(b)] and the dc offset voltage at the output will be equal to V_{OS}, that is, 3 mV. Thus, almost the entire output range of ± 10 V will be available for signal swing, allowing a sine-wave input of approximately 10-mV peak without the risk of output clipping. Obviously, in this case there is no need for output trimming.

(b) We need to select a value of the coupling capacitor C that will place the 3-dB frequency of the resulting high-pass STC circuit at 1000 Hz, thus

$$1000 = \frac{1}{2\pi C R_1}$$

$$\Rightarrow C = \frac{1}{2\pi \times 1000 \times 1 \times 10^3} = 0.16\ \mu\text{F}$$

Ex: 2.24 From Eq. (2.35) we have:

$$V_O = I_{B1} R_2 \simeq I_B R_2$$

$$= 100 \text{ nA} \times 1 \text{ M}\Omega = 0.1 \text{ V}$$

From Eq. (2.37) the value of resistor R_3 (placed in series with positive input to minimize the output offset voltage) is

$$R_3 = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2} = \frac{10 \text{ k}\Omega \times 1 \text{ M}\Omega}{10 \text{ k}\Omega + 1 \text{ M}\Omega}$$

$$= 9.9 \text{ k}\Omega$$

$$R_3 = 9.9 \text{ k}\Omega \simeq 10 \text{ k}\Omega$$

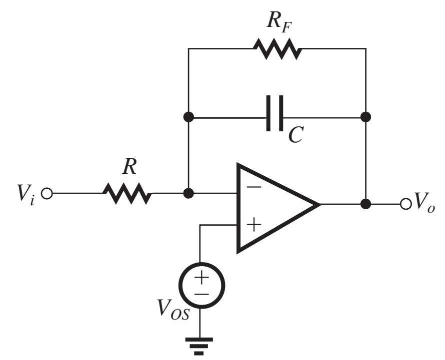
With this value of R_3, the new value of the output dc voltage [using Eq. (2.38)] is:

$$V_O = I_{OS} R_2 = 10 \text{ nA} \times 10 \text{ k}\Omega = 0.01 \text{ V}$$

Ex: 2.25 Using Eq. (2.39) we have:

$$v_O = V_{OS} + \frac{V_{OS}}{CR} t \Rightarrow 12 = 2 \text{ mV} + \frac{2 \text{ mV}}{1 \text{ ms}} t$$

$$\Rightarrow t = \frac{12 \text{ V} - 2 \text{ mV}}{2 \text{ mV}} \times 1 \text{ ms} \simeq 6 \text{ s}$$



With the feedback resistor R_F, to have at least ± 10 V of output signal swing available, we have to make sure that the output voltage due to V_{OS} has a magnitude of at most 2 V. From Eq. (2.34), we know that the output dc voltage due to V_{OS} is

$$V_O = V_{OS}\left(1 + \frac{R_F}{R}\right) \Rightarrow 2 \text{ V} = 2 \text{ mV}\left(1 + \frac{R_F}{10 \text{ k}\Omega}\right)$$

$$1 + \frac{R_F}{10 \text{ k}\Omega} = 1000 \Rightarrow R_F \simeq 10 \text{ M}\Omega$$

The corner frequency of the resulting STC network is $\omega_0 = \dfrac{1}{C R_F}$

We know $RC = 1$ ms and

$R = 10 \text{ k}\Omega \Rightarrow C = 0.1\ \mu\text{F}$

Thus $\omega_0 = \dfrac{1}{0.1\ \mu\text{F} \times 10 \text{ M}\Omega} = 1$ rad/s

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi} = 0.16 \text{ Hz}$$

Ex: 2.26

$$20 \log A_0 = 106 \text{ dB} \Rightarrow A_0 = 200{,}000 \text{ V/V}$$

$$f_t = 3 \text{ MHz}$$

$$f_b = f_t/A_0 = \frac{3 \text{ MHz}}{200{,}000} = 15 \text{ Hz}$$

At f_b, the open-loop gain drops by 3 dB below its value at dc; thus it becomes 103 dB.

For $f \gg f_b$, $|A| \simeq f_t/f$; thus

At $f = 300$ Hz, $|A| = \dfrac{3\text{ MHz}}{300\text{ Hz}} = 10^4$ V/V

or 80 dB

At $f = 3$ kHz, $|A| = \dfrac{3\text{ MHz}}{3\text{ kHz}} = 10^3$ V/V

or 60 dB

At $f = 12$ kHz, which is two octaves higher than 3 kHz, the gain will be $2 \times 6 = 12$ dB below its value at 3 kHz; that is, $60 - 12 = 48$ dB.

At $f = 60$ kHz, $|A| = \dfrac{3\text{ MHz}}{60\text{ kHz}} = 50$ V/V

or 34 dB

Ex: 2.27

$A_0 = 10^6$ V/V or 120 dB

The gain falls off at the rate of 20 dB/decade. Thus, it reaches 40 dB at a frequency four decades higher than f_b,

$10^4 f_b = 100\text{ kHz} \Rightarrow f_b = 10\text{ Hz}$

The unity-gain frequency f_t will be two decades higher than 100 kHz, that is,

$f_t = 100 \times 100\text{ kHz} = 10\text{ MHz}$

Alternatively, we could have found f_t from the gain-bandwidth product

$f_t = A_0 f_b = 10^6 \times 10\text{ Hz} = 10\text{ MHz}$

At a frequency $f \gg f_b$,

$|A| = f_t/f$

For $f = 10$ kHz, $|A| = \dfrac{10\text{ MHz}}{10\text{ kHz}} = 10^3$ V/V or 60 dB

Ex: 2.28

$20 \log A_0 = 106\text{ dB} \Rightarrow A_0 = 200{,}000$ V/V

$f_t = 20$ MHz

For a noninverting amplifier with a nominal dc gain of 100,

$1 + \dfrac{R_2}{R_1} = 100$

Since the nominal dc gain is much lower than A_0,

$$f_{3\text{dB}} \simeq f_t \Big/ \left(1 + \frac{R_2}{R_1}\right)$$

$$= \frac{20\text{ MHz}}{100} = 200\text{ kHz}$$

Ex: 2.29 For the input voltage step of magnitude V the output waveform will still be given by the exponential waveform of Eq. (2.56) if

$$\omega_t V \le SR$$

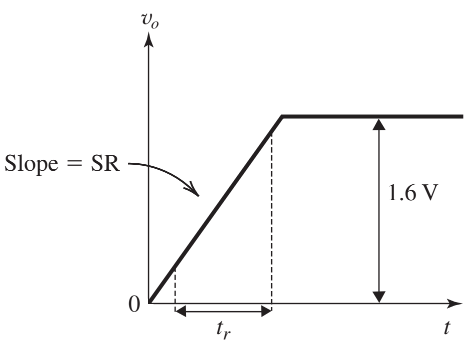
that is, $V \le \dfrac{SR}{\omega_t} \Rightarrow V \le \dfrac{SR}{2\pi f_t}$ resulting in

$$V \le 0.16\text{ V}$$

From Appendix F we know that the 10% to 90% rise time of the output waveform of the form of Eq. (2.56) is $t_r \simeq 2.2 \times$ time constant $= \dfrac{2.2}{\omega_t}$.

Thus, $t_r \simeq 0.35$ µs

If an input step of amplitude 1.6 V (10 times as large compared to the previous case) is applied, the output will be slew-rate limited and thus linearly rising with a slope equal to the slew rate, as shown in the following figure.



$$t_r = \frac{0.9 \times 1.6 - 0.1 \times 1.6}{1\text{ V}/\mu\text{s}}$$

$$\Rightarrow t_r = 1.28\ \mu\text{s}$$

Ex: 2.30 From Eq. (2.57) we have:

$$f_M = \frac{SR}{2\pi V_{O\ \max}} = 318\text{ kHz}$$

Using Eq. (2.58), for an input sinusoid with frequency $f = 5\ f_M$, the maximum possible amplitude that can be accommodated at the output without incurring SR distortion is:

$$V_O = V_{O\ \max}\left(\frac{f_M}{5 f_M}\right) = 5 \times \frac{1}{5} = 1\text{ V (peak)}$$

Chapter 3

Solutions to Exercises within the Chapter

Ex: 3.1 $T = 50$ K

$n_i = BT^{3/2}e^{-Eg/(2kT)}$

$= 7.3 \times 10^{15}(50)^{3/2}\ e^{-1.12/(2\times8.62\times10^{-5}\times50)}$

$\simeq 9.6 \times 10^{-39}/\text{cm}^3$

$T = 350$ K

$n_i = BT^{3/2}e^{-Eg/(2kT)}$

$= 7.3 \times 10^{15}(350)^{3/2}\ e^{-1.12/(2\times8.62\times10^{-5}\times350)}$

$= 4.15 \times 10^{11}/\text{cm}^3$

Ex: 3.2 $N_D = 10^{17}/\text{cm}^3$

From Exercise 3.1, n_i at

$T = 350\ \text{K} = 4.15 \times 10^{11}/\text{cm}^3$

$n_n = N_D = 10^{17}/\text{cm}^3$

$p_n \cong \dfrac{ni^2}{N_D}$

$= \dfrac{(4.15 \times 10^{11})^2}{10^{17}}$

$= 1.72 \times 10^6/\text{cm}^3$

Ex: 3.3 At 300 K, $n_i = 1.5 \times 10^{10}/\text{cm}^3$

$p_p = N_A$

Want electron concentration

$= n_p = \dfrac{1.5 \times 10^{10}}{10^6} = 1.5 \times 10^4/\text{cm}^3$

$\therefore N_A = p_p = \dfrac{ni^2}{n_p}$

$= \dfrac{(1.5 \times 10^{10})^2}{1.5 \times 10^4}$

$= 1.5 \times 10^{16}/\text{cm}^3$

Ex: 3.4 (a) $v_{n-\text{drift}} = -\mu_n E$

Here negative sign indicates that electrons move in a direction opposite to E.

We use

$v_{n\text{-drift}} = 1350 \times \dfrac{1}{2 \times 10^{-4}}\ \because 1\ \mu\text{m} = 10^{-4}$ cm

$= 6.75 \times 10^6\ \text{cm/s} = 6.75 \times 10^4\ \text{m/s}$

(b) Time taken to cross 2-μm

length $= \dfrac{2 \times 10^{-6}}{6.75 \times 10^4} \simeq 30$ ps

(c) In n-type silicon, drift current density J_n is

$J_n = qn\mu_n E$

$= 1.6 \times 10^{-19} \times 10^{16} \times 1350 \times \dfrac{1\ \text{V}}{2 \times 10^{-4}}$

$= 1.08 \times 10^4\ \text{A/cm}^2$

(d) Drift current $I_n = AJ_n$

$= 0.25 \times 10^{-8} \times 1.08 \times 10^4$

$= 27\ \mu\text{A}$

The resistance of the bar is

$$R = \rho \times \frac{L}{A}$$
$$= qn\mu_n \times \frac{L}{A}$$
$$= 1.6 \times 10^{-19} \times 10^{16} \times 1350 \times \frac{2 \times 10^{-4}}{0.25 \times 10^{-8}}$$
$$= 37.0\ \text{k}\Omega$$

Alternatively, we may simply use the preceding result for current and write

$R = V/I_n = 1\ \text{V}/27\ \mu\text{A} = 37.0\ \text{k}\Omega$

Note that $0.25\ \mu\text{m}^2 = 0.25 \times 10^{-8}\ \text{cm}^2$.

Ex: 3.5 $J_n = qD_n\dfrac{dn(x)}{dx}$

From Fig. E3.5,

$n_0 = 10^{17}/\text{cm}^3 = 10^5/(\mu\text{m})^3$

$D_n = 35\ \text{cm}^2/\text{s} = 35 \times (10^4)^2\ (\mu\text{m})^2/\text{s}$

$= 35 \times 10^8\ (\mu\text{m})^2/\text{s}$

$\dfrac{dn}{dx} = \dfrac{10^5 - 0}{0.5} = 2 \times 10^5 \mu\text{m}^{-4}$

$J_n = qD_n\dfrac{dn(x)}{dx}$

$= 1.6 \times 10^{-19} \times 35 \times 10^8 \times 2 \times 10^5$

$= 112 \times 10^{-6}\ \text{A}/\mu\text{m}^2$

$= 112\ \mu\text{A}/\mu\text{m}^2$

For $I_n = 1\ \text{mA} = J_n \times A$

$\Rightarrow A = \dfrac{1\ \text{mA}}{J_n} = \dfrac{10^3\ \mu\text{A}}{112\ \mu\text{A}/(\mu\text{m})^2} \simeq 9\ \mu\text{m}^2$

Ex: 3.6 Using Eq. (3.20),

$\dfrac{D_n}{\mu_n} = \dfrac{D_p}{\mu_p} = V_T$

$D_n = \mu_n V_T = 1350 \times 25.9 \times 10^{-3}$

$\cong 35\ \text{cm}^2/\text{s}$

$D_p = \mu_p V_T = 480 \times 25.9 \times 10^{-3}$

$\cong 12.4\ \text{cm}^2/\text{s}$

Ex: 3.7 Equation (3.25)

$$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0}$$

$$= \sqrt{\frac{2\epsilon_s}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)V_0}$$

$$W^2 = \frac{2\epsilon_s}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)V_0$$

$$V_0 = \frac{1}{2}\left(\frac{q}{\epsilon_s}\right)\left(\frac{N_A N_D}{N_A + N_D}\right)W^2$$

Ex: 3.8 In a p^+n diode $N_A \gg N_D$

Equation (3.26) $W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0}$

We can neglect the term $\frac{1}{N_A}$ as compared to $\frac{1}{N_D}$, thus

$$W \simeq \sqrt{\frac{2\epsilon_s}{qN_D} \cdot V_0}$$

Equation (3.26) $x_n = W\frac{N_A}{N_A + N_D}$

$$\simeq W\,\frac{N_A}{N_A}$$

$$= W$$

Equation (3.28), $x_p = W\frac{N_D}{N_A + N_D}$

since $N_A \gg N_D$

$$\simeq\ W\,\frac{N_D}{N_A} = W\bigg/\left(\frac{N_A}{N_D}\right)$$

Equation (3.28), $Q_J = Aq\left(\frac{N_A N_D}{N_A + N_D}\right)W$

$$\simeq Aq\frac{N_A N_D}{N_A}W$$

$$= AqN_D W$$

Equation (3.29), $Q_J = A\sqrt{2\epsilon_s q\left(\frac{N_A N_D}{N_A + N_D}\right)V_0}$

$\simeq A\sqrt{2\epsilon_s q\left(\frac{N_A N_D}{N_A}\right)V_0}$ since $N_A \gg N_D$

$$= A\sqrt{2\epsilon_s q N_D V_0}$$

Ex: 3.9 In Example 3.5, $N_A = 10^{18}/\text{cm}^3$ and $N_D = 10^{16}/\text{cm}^3$

In the n-region of this pn junction

$$n_n = N_D = 10^{16}/\text{cm}^3$$

$$p_n = \frac{n_i^2}{n_n} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4/\text{cm}^3$$

As one can see from above equation, to increase minority-carrier concentration (p_n) by a factor of 2, one must lower N_D ($= n_n$) by a factor of 2.

Ex: 3.10

Equation (3.40) $I_S = Aqn_i^2\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right)$

since $\frac{D_p}{L_p}$ and $\frac{D_n}{L_n}$ have approximately similar values, if $N_A \gg N_D$, then the term $\frac{D_n}{L_n N_A}$ can be neglected as compared to $\frac{D_p}{L_p N_D}$

$$\therefore I_S \cong Aqn_i^2\frac{D_p}{L_p N_D}$$

Ex: 3.11 $I_S = Aqn_i^2\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right)$

$$= 10^{-4} \times 1.6 \times 10^{-19} \times (1.5 \times 10^{10})^2 \times \left(\frac{10}{5 \times 10^{-4} \times \frac{10^{16}}{2}} + \frac{18}{10 \times 10^{-4} \times 10^{18}}\right)$$

$$= 1.46 \times 10^{-14}\ \text{A}$$

$$I = I_S(e^{V/V_T} - 1)$$

$$\simeq I_S e^{V/V_T} = 1.45 \times 10^{-14} e^{0.605/(25.9\times10^{-3})}$$

$$= 0.2\ \text{mA}$$

Ex: 3.12 $W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 - V_F)}$

$$= \sqrt{\frac{2 \times 1.04 \times 10^{-12}}{1.6 \times 10^{-19}}\left(\frac{1}{10^{18}} + \frac{1}{10^{16}}\right)(0.814 - 0.605)}$$

$$= 1.66 \times 10^{-5}\ \text{cm} = 0.166\ \mu\text{m}$$

Ex: 3.13 $W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + V_R)}$

$$= \sqrt{\frac{2 \times 1.04 \times 10^{-12}}{1.6 \times 10^{-19}}\left(\frac{1}{10^{18}} + \frac{1}{10^{16}}\right)(0.814 + 2)}$$

$$= 6.08 \times 10^{-5}\ \text{cm} = 0.608\ \mu\text{m}$$

Using Eq. (3.28),

$$Q_J = Aq\left(\frac{N_A N_D}{N_A + N_D}\right)W$$

$$= 10^{-4} \times 1.6 \times 10^{-19}\left(\frac{10^{18} \times 10^{16}}{10^{18} + 10^{16}}\right) \times 6.08 \times 10^{-5}\ \text{cm}$$

$$= 9.63\ \text{pC}$$

Reverse current

$$I = I_S = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$$

$$= 10^{-14} \times 1.6 \times 10^{-19} \times (1.5 \times 10^{10})^2$$

$$\times\left(\frac{10}{5 \times 10^{-4} \times 10^{16}} + \frac{18}{10 \times 10^{-4} \times 10^{18}}\right)$$

$$= 7.3 \times 10^{-15}\text{ A}$$

Ex: 3.14 Equation (3.47),

$$C_{j0} = A\sqrt{\left(\frac{\epsilon_s q}{2}\right)\left(\frac{N_AN_D}{N_A + N_D}\right)\left(\frac{1}{V_0}\right)}$$

$$= 10^{-4}\sqrt{\left(\frac{1.04 \times 10^{-12} \times 1.6 \times 10^{-19}}{2}\right)}$$

$$\sqrt{\left(\frac{10^{18} \times 10^{16}}{10^{18} + 10^{16}}\right)\left(\frac{1}{0.814}\right)}$$

$$= 3.2\text{ pF}$$

Equation (3.46),

$$C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{V_0}}}$$

$$= \frac{3.2 \times 10^{-12}}{\sqrt{1 + \frac{2}{0.814}}}$$

$$= 1.72\text{ pF}$$

Ex: 3.15 $C_d = \dfrac{dQ}{dV} = \dfrac{d}{dV}(\tau_T I)$

$$= \frac{d}{dV}\tau_T \times I_S(e^{V/V_T} - 1)$$

$$= \tau_T I_S\,\frac{d}{dV}\,(e^{V/V_T} - 1)$$

$$= \tau_T I_S\,\frac{1}{V_T}\,e^{V/V_T}$$

$$= \frac{\tau_T}{V_T} \times I_S e^{V/V_T}$$

$$\cong \left(\frac{\tau_T}{V_T}\right)I$$

Ex: 3.16 Equation (3.49),

$$\tau_p = \frac{L_p^2}{D_p}$$

$$= \frac{(5 \times 10^{-4})^2}{10}$$

$$= 25\text{ ns}$$

Equation (3.57),

$$C_d = \left(\frac{\tau_T}{V_T}\right)I$$

In Example 3.6, $N_A = 10^{18}/\text{cm}^3$,

$N_D = 10^{16}/\text{cm}^3$

Assuming $N_A \gg N_D$,

$\tau_T \simeq \tau_p = 25$ ns

$$\therefore C_d = \left(\frac{25 \times 10^{-9}}{25.9 \times 10^{-3}}\right)0.1 \times 10^{-3}$$

$$= 96.5\text{ pF}$$

Chapter 4

Solutions to Exercises within the Chapter

Ex: 4.1 Refer to Fig. 4.3(a). For $v_I \geq 0$, the diode conducts and presents a zero voltage drop. Thus $v_O = v_I$. For $v_I < 0$, the diode is cut off, zero current flows through R, and $v_O = 0$. The result is the transfer characteristic in Fig. E4.1.

Ex: 4.2 See Fig. 4.3a and 4.3b. During the positive half of the sinusoid, the diode is forward biased, so it conducts resulting in $v_D = 0$. During the negative half cycle of the input signal v_I, the diode is reverse biased. The diode does not conduct, resulting in no current flowing in the circuit. So $v_O = 0$ and $v_D = v_I - v_O = v_I$. This results in the waveform shown in Fig. E4.2.

Ex: 4.3 $\hat{i}_D = \dfrac{\hat{v}_I}{R} = \dfrac{10\text{ V}}{1\text{ k}\Omega} = 10\text{ mA}$

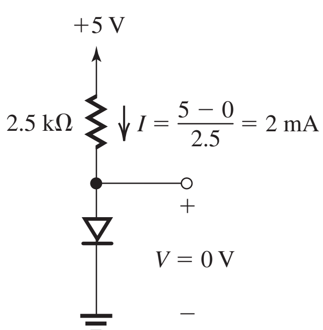
dc component of $v_O = \dfrac{1}{\pi}\hat{v}_O$

$= \dfrac{1}{\pi}\hat{v}_I = \dfrac{10}{\pi}$

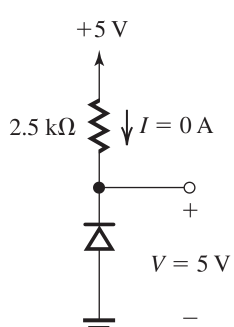
$= 3.18$ V

Ex: 4.4

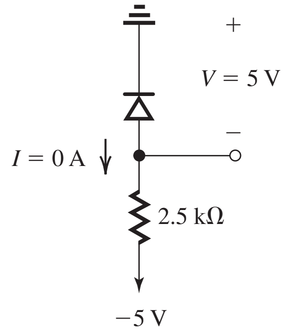
(a)



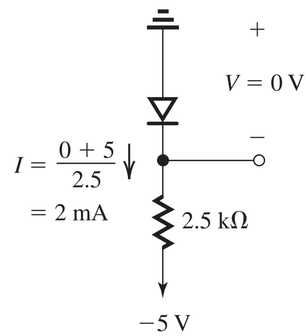
(b)



(c)



(d)



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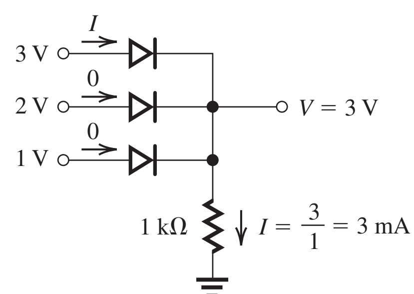
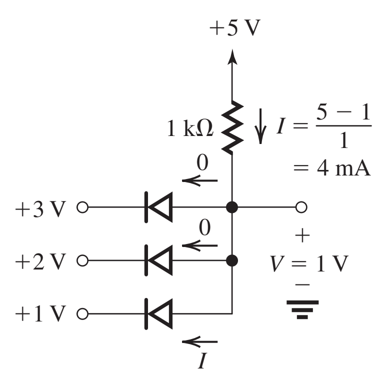


(f)



Ex: 4.5 $V_{\text{avg}} = \dfrac{10}{\pi}$

$$50 + R = \frac{\frac{10}{\pi}}{1\text{ mA}} = \frac{10}{\pi}\text{ k}\Omega$$

$\therefore\ R = 3.133\text{ k}\Omega$

Ex: 4.6 The maximum current arises when $|v_I| = 20$ V. In this case,

$$i_D = \frac{20 - 5}{R}$$

To ensure this is 50 mA,

$$R = \frac{20 - 5}{50} = 0.3\ \text{k}\Omega = 300\Omega$$

Ex: 4.7 Equation (4.5)

$$V_2 - V_1 = 2.3\ V_T \log\left(\frac{I_2}{I_1}\right)$$

At room temperature $V_T = 25$ mV

$$V_2 - V_1 = 2.3 \times 25 \times 10^{-3} \times \log\left(\frac{10}{0.1}\right)$$

$$= 115\ \text{mV}$$

Ex: 4.8 $i = I_S e^{v/V_T}$ (1)

$1\ (\text{mA}) = I_S e^{0.7/V_T}$ (2)

Dividing (1) by (2), we obtain

$$i\ (\text{mA}) = e^{(v-0.7)/V_T}$$

$$\Rightarrow v = 0.7 + 0.025\ \ln(i)$$

where i is in mA. Thus,

for $i = 0.1$ mA,

$$v = 0.7 + 0.025\ \ln(0.1) = 0.64\ \text{V}$$

and for $i = 10$ mA,

$$v = 0.7 + 0.025\ \ln(10) = 0.76\ \text{V}$$

Ex: 4.9 $i_D = I_S e^{v/V_T}$

$$\Rightarrow I_S = i_D e^{-v/V_T} = 0.25 \times e^{-300/25}$$

$$= 1.23 \times 10^{6} mA = 1.23 \times 10^{-9}\text{A}$$

Ex: 4.10 $\Delta T = 125 - 25 = 100°\text{C}$

$$I_S = 10^{-14} \times 1.15^{\Delta T}$$

$$= 1.17 \times 10^{-8}\text{A}$$

Ex: 4.11 At 20°C $I = \dfrac{1\ \text{V}}{1\ \text{M}\Omega} = 1\ \mu\text{A}$

Since the reverse leakage current doubles for every 10°C increase, at 40°C

$$I = 4 \times 1\ \mu\text{A} = 4\ \mu\text{A}$$

$$\Rightarrow V = 4\ \mu\text{A} \times 1\ \text{M}\Omega = 4.0\ \text{V}$$

@ 0°C $\quad I = \dfrac{1}{4}\ \mu\text{A}$

$$\Rightarrow V = \frac{1}{4} \times 1 = 0.25\ \text{V}$$

Ex: 4.12 a. Use iteration:

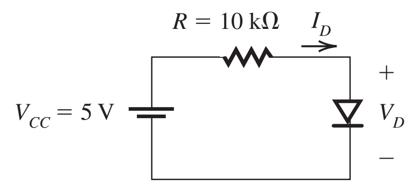
Diode has 0.7 V drop at 1 mA current.

Assume $V_D = 0.7$ V

$$I_D = \frac{5 - 0.7}{10\ \text{k}\Omega} = 0.43\ \text{mA}$$

Use Eq. (4.5) and note that

$$V_1 = 0.7\ \text{V}, \quad I_1 = 1\ \text{mA}$$



$$V_2 - V_1 = 2.3 \times V_T \log\left(\frac{I_2}{I_1}\right)$$

$$V_2 = V_1 + 2.3 \times V_T \log\left(\frac{I_2}{I_1}\right)$$

First iteration

$$V_2 = 0.7 + 2.3 \times 25 \times 10^{-3} \log\left(\frac{0.43}{1}\right)$$

$$= 0.679\ \text{V}$$

Second iteration

$$I_2 = \frac{5 - 0.679}{10\ \text{k}\Omega} = 0.432\ \text{mA}$$

$$V_2 = 0.7 + 2.3 \times 25.3 \times 10^{-3} \log\left(\frac{0.432}{1}\right)$$

$$= 0.679\ \text{V} \simeq 0.68\ \text{V}$$

we get almost the same voltage.

$\therefore$ The iteration yields

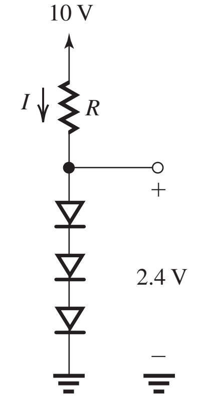
$$I_D = 0.43\ \text{mA}, \ \ V_D = 0.68\ \text{V}$$

b. Use constant voltage drop model:

$V_D = 0.7$ V $\quad$ constant voltage drop

$$I_D = \frac{5 - 0.7}{10\ \text{k}\Omega} = 0.43\ \text{mA}$$

Ex: 4.13



Diodes have 0.7 V drop at 1 mA

$\therefore 1 \text{ mA} = I_S e^{0.7/V_T}$ (1)

At a current I (mA),

$I = I_S e^{V_D/V_T}$ (2)

Using (1) and (2), we obtain

$I = e^{(V_D - 0.7)/V_T}$

For an output voltage of 2.4 V, the voltage drop across each diode $= \dfrac{2.4}{3} = 0.8$ V

Now I, the current through each diode, is

$I = e^{(0.8-0.7)/0.025}$

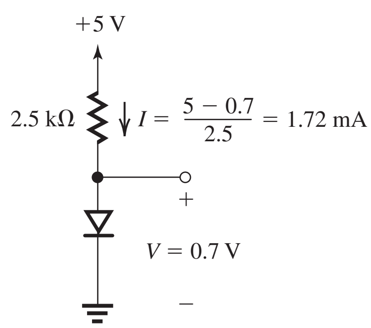
$= 54.6$ mA

$R = \dfrac{10 - 2.4}{54.6 \times 10^{-3}}$

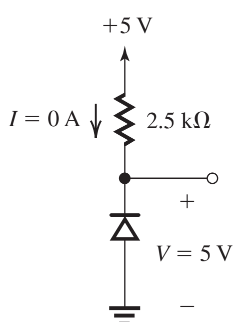
$= 139\ \Omega$

Ex: 4.14

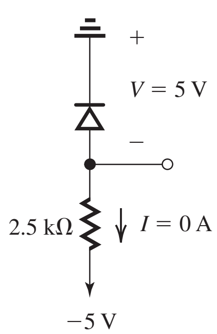
(a)



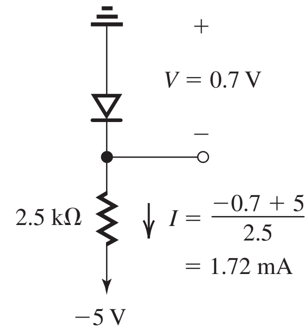
(b)



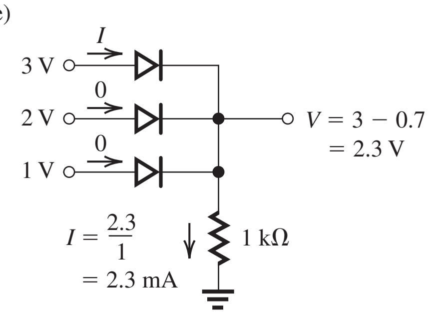
(c)



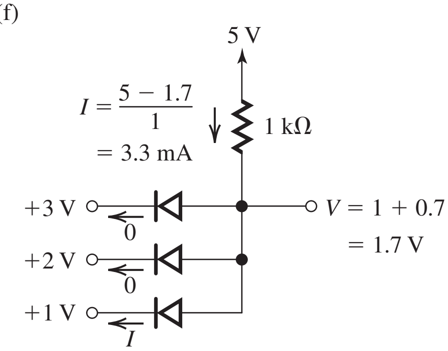
(d)



(e)



(f)



Ex: 4.15 With a reverse voltage, the diode in Fig. 4.10 will not conduct. Thus, the voltage drop on R will be zero, and the reverse voltage on the diode is $-V_D = -V_{DD}$. To ensure we respect the peak inverse voltage, we require $V_{DD} = V_D > -30$ V. Hence, the minimum voltage on V_{DD} is -30 V.

Ex: 4.16 When conducting a reverse current of 20 mA, the reverse voltage is

$V_Z = V_{ZT} + \Delta I_Z r_z =$
$3.5 \text{ V} + (20 \text{ mA} - 10 \text{ mA})10\Omega$

$= 3.6$ V

The maximum current, $I_{\max}$, is the current at 200 mW power dissipation.

$200 \text{ mW} = I_{\max}(3.5 \text{ V} + 10\Omega(I_{\max} - 10 \text{ mA}))$

$0.2 = 3.5I_{max} + 10I_{max}^2 - 0.1I_{max}$

$\Rightarrow I_{max}^2 + 0.34I_{max} - 0.02 = 0$

$\Rightarrow I_{max} = \frac{1}{2}\left(-0.34 + \sqrt{0.34^2 + 4 \times 0.02}\right)$

$= 51$ mA

Ex: 4.17 $r_d = \frac{V_T}{I_D}$

$I_D = 0.1$ mA $\quad r_d = \frac{25 \times 10^{-3}}{0.1 \times 10^{-3}} = 250\ \Omega$

$I_D = 1$ mA $\quad r_d = \frac{25 \times 10^{-3}}{1 \times 10^{-3}} = 25\ \Omega$

$I_D = 10$ mA $\quad r_d = \frac{25 \times 10^{-3}}{10 \times 10^{-3}} = 2.5\ \Omega$

Ex: 4.18 For small signal model,

$\Delta i_D = \Delta v_D / r_d \qquad (1)$

where $r_d = \frac{V_T}{I_D}$

For exponential model,

$i_D = I_S e^{V/V_T}$

$\frac{i_{D2}}{i_{D1}} = e^{(V_2 - V_1)/V_T} = e^{\Delta v_D / V_T}$

$\Delta i_D = i_{D2} - i_{D1} = i_{D1} e^{\Delta v_D / V_T} - i_{D1}$

$= i_{D1}\left(e^{\Delta v_D / V_T} - 1\right) \qquad (2)$

In this problem, $i_{D1} = I_D = 1$ mA.

Using Eqs. (1) and (2) with $V_T = 25$ mV, we obtain

	Δv_D (mV)	Δi_D (mA) small signal	Δi_D (mA) exponential model
a	−10	−0.4	−0.33
b	−5	−0.2	−0.18
c	+5	+0.2	+0.22
d	+10	+0.4	+0.49

Ex: 4.19

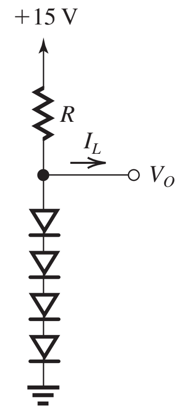
a. In this problem, $\frac{\Delta V_O}{\Delta i_L} = \frac{20 \text{ mV}}{1 \text{ mA}} = 20\ \Omega$.

$\therefore$ Total small-signal resistance of the four diodes $= 20\ \Omega$

$\therefore$ For each diode, $r_d = \frac{20}{4} = 5\ \Omega$.

But $r_d = \frac{V_T}{I_D} \Rightarrow 5 = \frac{25 \text{ mV}}{I_D}$.

$\therefore I_D = 5$ mA



and $R = \frac{15 - 3}{5 \text{ mA}} = 2.4$ kΩ.

b. For $V_O = 3$ V, voltage drop across each diode $= \frac{3}{4} = 0.75$ V

$i_D = I_S e^{V/V_T}$

$I_S = \frac{i_D}{e^{V/V_T}} = \frac{5 \times 10^{-3}}{e^{0.75/0.025}} = 4.7 \times 10^{-16}$ A

c. If $i_D = 5 - i_L = 5 - 1 = 4$ mA.

Across each diode the voltage drop is

$V_D = V_T \ln\left(\frac{I_D}{I_S}\right)$

$= 25 \times 10^{-3} \times \ln\left(\frac{4 \times 10^{-3}}{4.7 \times 10^{-16}}\right)$

$= 0.7443$ V

Voltage drop across 4 diodes

$= 4 \times 0.7443 = 2.977$ V

so change in $V_O = 3 - 2.977 = 23$ mV.

Ex: 4.20 When the diode current is halved, the voltage changes by

$\Delta V_Z = r_z \Delta I_Z = 80\Omega \times \frac{-5 \text{ mA}}{2} = -200$ mV

$\Rightarrow V_Z = 6 - 0.2 = 5.8$ V

When the diode current is doubled,

$\Delta V_Z = r_z \Delta I_Z = 80\Omega \times 5 \text{ mA} = 400$ mV

$\Rightarrow V_Z = 6 + 0.4 = 6.4$ V

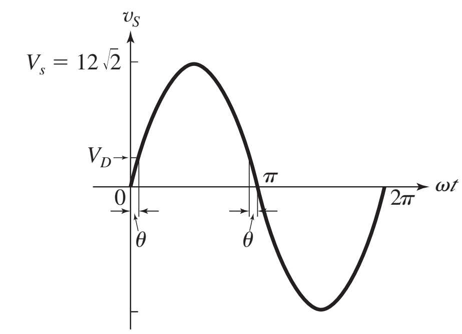
Finally, the value of V_{Z0} is that obtained by using the model at zero current.

$V_Z = V_{Z0} + r_z I_Z$

$\Rightarrow V_{Z0} = V_Z - r_z I_Z = 6 \text{ V} - 80\Omega \times 5 \text{ mA}$

$= 5.6$ V

Ex: 4.21



a. The diode starts conduction at

$v_S = V_D = 0.7$ V

$v_S = V_s \sin \omega t$, here $V_s = 12\sqrt{2}$

At $\omega t = \theta$,

$v_S = V_s \sin\theta = V_D = 0.7$ V

$12\sqrt{2}\sin\theta = 0.7$

$$\theta = \sin^{-1}\left(\frac{0.7}{12\sqrt{2}}\right) \simeq 2.4^\circ$$

Conduction starts at θ and stops at $180 - \theta$.

$\therefore$ Total conduction angle $= 180 - 2\theta = 175.2^\circ$

b. $$v_{O,\text{avg}} = \frac{1}{2\pi}\int_{\theta}^{(\pi-\theta)} (V_s \sin\phi - V_D)\, d\phi$$

$$= \frac{1}{2\pi}[-V_s \cos\phi - V_D\phi]_{\phi-\theta}^{\phi=\pi-\theta}$$

$$= \frac{1}{2\pi}\,[V_s \cos\theta - V_s \cos(\pi-\theta) - V_D(\pi - 2\theta)]$$

But $\cos\theta \simeq 1$, $\cos(\pi-\theta) \simeq -1$, and

$\pi - 2\theta \simeq \pi$

$$v_{O,\text{avg}} = \frac{2V_s}{2\pi} - \frac{V_D}{2}$$

$$= \frac{V_s}{\pi} - \frac{V_D}{2}$$

For $V_s = 12\sqrt{2}$ and $V_D = 0.7$ V

$$v_{O,\text{avg}} = \frac{12\sqrt{2}}{\pi} - \frac{0.7}{2} = 5.05 \text{ V}$$

c. The peak diode current occurs at the peak diode voltage.

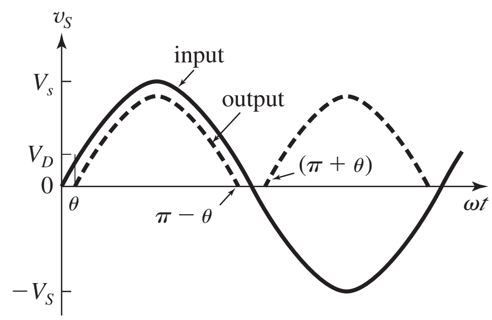
$$\therefore \hat{i}_D = \frac{V_s - V_D}{R} = \frac{12\sqrt{2} - 0.7}{100}$$

$= 163$ mA

PIV $= +V_S = 12\sqrt{2}$

$\simeq 17$ V

Ex: 4.22



a. As shown in the diagram, the output is zero between $(\pi - \theta)$ to $(\pi + \theta)$

$= 2\theta$

Here θ is the angle at which the input signal reaches V_D.

$\therefore\ V_s \sin\theta = V_D$

$$\theta = \sin^{-1}\left(\frac{V_D}{V_s}\right)$$

$$2\theta = 2\sin^{-1}\left(\frac{V_D}{V_s}\right)$$

b. Average value of the output signal is given by

$$V_O = \frac{1}{2\pi}\left[2 \times \int_{\theta}^{(\pi-\theta)} (V_s \sin\phi - V_D)\, d\phi\right]$$

$$= \frac{1}{\pi}[-V_s \cos\phi - V_D\phi]_{\phi=\theta}^{\pi-\theta}$$

$$\simeq 2\frac{V_s}{\pi} - V_D, \qquad \text{for } \theta \text{ small.}$$

c. Peak current occurs when $\phi = \frac{\pi}{2}$.

Peak current

$$= \frac{V_s \sin(\pi/2) - V_D}{R} = \frac{V_s - V_D}{R}$$

If v_S is 12 V(rms),

then $V_s = \sqrt{2} \times 12 = 12\sqrt{2}$

$$\text{Peak current} = \frac{12\sqrt{2} - 0.7}{100} \simeq 163 \text{ mA}$$

Nonzero output occurs for angle $= 2(\pi - 2\theta)$

The fraction of the cycle for which $v_O > 0$ is

$$= \frac{2(\pi - 2\theta)}{2\pi} \times 100$$

$$= \frac{2\left[\pi - 2\sin^{-1}\left(\frac{0.7}{12\sqrt{2}}\right)\right]}{2\pi} \times 100$$

$\simeq 97.4$ %

Average output voltage V_O is

$$V_O = 2\frac{V_s}{\pi} - V_D = \frac{2 \times 12\sqrt{2}}{\pi} - 0.7 = 10.1 \text{ V}$$

Peak diode current $\hat{i}_D$ is

$$\hat{i}_D = \frac{V_s - V_D}{R} = \frac{12\sqrt{2} - 0.7}{100}$$

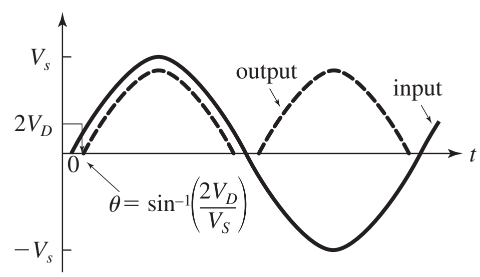
$= 163$ mA

$\text{PIV} = V_s - V_D + V_S$

$= 12\sqrt{2} - 0.7 + 12\sqrt{2}$

$= 33.2$ V

Ex: 4.23



(a) $V_{O,\text{avg}} = \frac{1}{2\pi}\int (V_s \sin\phi - 2V_D)\, d\phi$

$$= \frac{2}{2\pi}[-V_s\cos\phi - 2V_D\phi]_{\phi=\theta}^{\pi-\theta}$$

$$= \frac{1}{\pi}[V_s\cos\phi - V_s\cos(\pi - \theta) - 2V_D(\pi - 2\theta)]$$

But $\cos\theta \approx 1$,

$\cos(\pi - \theta) \approx -1$

$\pi - 2\theta \approx \pi$. Thus

$$\Rightarrow V_{O,\text{avg}} \simeq \frac{2V_s}{\pi} - 2V_D$$

$$= \frac{2 \times 12\sqrt{2}}{\pi} - 1.4 = 9.4 \text{ V}$$

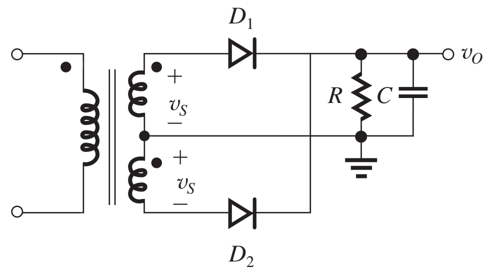
(b) Peak diode current $= \frac{\text{Peak voltage}}{R}$

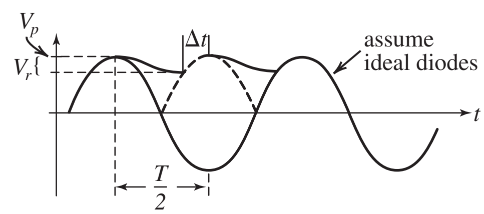
$$= \frac{V_s - 2V_D}{R} = \frac{12\sqrt{2} - 1.4}{100}$$

$= 156$ mA

$\text{PIV} = V_s - V_D = 12\sqrt{2} - 0.7 = 16.3$ V

Ex: 4.24 Full-wave peak rectifier:





The ripple voltage is the amount of voltage reduction during capacitor discharge that occurs when the diodes are not conducting. The output voltage is given by

$$v_O = V_p e^{-t/RC}$$

$V_p - V_r = V_p e^{-\frac{T/2}{RC}}$ $\leftarrow$ discharge is only half the period. We also assumed $\Delta t \ll \frac{T}{2}$.

$$V_r = V_p\left(1 - e^{-\frac{T/2}{RC}}\right)$$

$$e^{-\frac{T/2}{RC}} \simeq 1 - \frac{T/2}{RC}, \qquad \text{for } CR \gg \text{T}/2$$

Thus $V_r \simeq V_p\left(1 - 1 + \frac{T/2}{RC}\right)$

$$V_r = \frac{V_p}{2fRC} \qquad \text{(a)} \qquad \text{Q.E.D.}$$

To find the average diode current, note that the charge supplied to C during conduction is equal to the charge lost during discharge.

$$Q_{\text{SUPPLIED}} = Q_{\text{LOST}}$$

$i_{C\text{av}}\Delta t = CV_r$ SUB (a)

$$\left(i_{D,\text{av}} - I_L\right)\Delta t = C\frac{V_p}{2fRC} = \frac{V_p}{2fR}$$

$$= \frac{V_p\pi}{\omega R}$$

$$i_{D,\text{av}} = \frac{V_p\pi}{\omega\Delta t R} + I_L$$

where $\omega\Delta t$ is the conduction angle.

Note that the conduction angle has the same expression as for the half-wave rectifier and is given by Eq. (4.30),

$$\omega\Delta t \cong \sqrt{\frac{2V_r}{V_p}} \quad \text{(b)}$$

Substituting for $\omega\Delta t$, we get

$$\Rightarrow i_{D,\text{av}} = \frac{\pi V_p}{\sqrt{\frac{2V_r}{V_p}} \cdot R} + I_L$$

Since the output is approximately held at V_p, $\frac{V_p}{R} \approx I_L$. Thus

$$\Rightarrow i_{D,\text{av}} \cong \pi I_L \sqrt{\frac{V_p}{2V_r}} + I_L$$

$$= I_L\left[1 + \pi\sqrt{\frac{V_p}{2V_r}}\right] \qquad \text{Q.E.D.}$$

If $t = 0$ is at the peak, the maximum diode current occurs at the onset of conduction or at $t = -\omega\Delta t$.

During conduction, the diode current is given by

$$i_D = i_C + i_L$$

$$i_{D,\max} = C\left.\frac{dv_S}{dt}\right|_{t=-\omega\Delta t} + i_L$$

assuming i_L is const. $i_L \simeq \frac{V_p}{R} = I_L$

$$= C\frac{d}{dt}\left(V_p \cos\omega t\right) + I_L$$

$$= -C \sin\omega t \times \omega V_p + I_L$$

$$= -C \sin(-\omega\Delta t) \times \omega V_p + I_L$$

For a small conduction angle

$\sin(-\omega\Delta t) \approx -\omega\Delta t$. Thus

$$\Rightarrow i_{D,\max} = C\omega\Delta t \times \omega V_p + I_L$$

Sub (b) to get

$$i_{D,\max} = C\sqrt{\frac{2V_r}{V_p}}\omega V_p + I_L$$

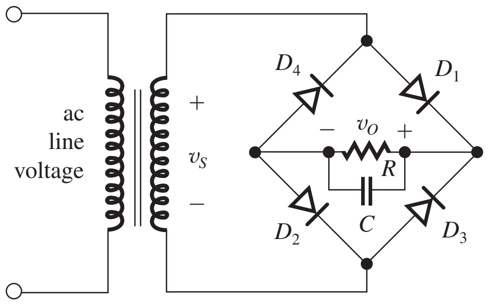
Substituting $\omega = 2\pi f$ and using (a) together with $V_p/R \simeq I_L$ results in

$$i_{D\max} = I_L\left[1 + 2\pi\sqrt{\frac{V_p}{2V_r}}\right] \qquad \text{Q.E.D.}$$

Ex: 4.25

The output voltage, v_O, can be expressed as

$$v_O = \left(V_p - 2V_D\right)e^{-t/RC}$$



At the end of the discharge interval

$$v_O = V_p - 2V_D - V_r$$

The discharge occurs almost over half of the time period $\simeq T/2$.

For time constant $RC \gg \frac{T}{2}$

$$e^{-t/RC} \simeq 1 - \frac{T}{2} \times \frac{1}{RC}$$

$$\therefore V_P - 2V_D - V_r = \left(V_p - 2V_D\right)\left(1 - \frac{T}{2} \times \frac{1}{RC}\right)$$

$$\Rightarrow V_r = \left(V_p - 2V_D\right) \times \frac{T}{2RC}$$

Here $V_p = 12\sqrt{2}$ and $V_r = 1$ V

$$V_D = 0.8 \text{ V}$$

$$T = \frac{1}{f} = \frac{1}{60} \text{ s}$$

$$1 = (12\sqrt{2} - 2 \times 0.8) \times \frac{1}{2 \times 60 \times 100 \times C}$$

$$C = \frac{(12\sqrt{2} - 1.6)}{2 \times 60 \times 100} = 1281\ \mu\text{F}$$

Without considering the ripple voltage, the dc output voltage

$$= 12\sqrt{2} - 2 \times 0.8 = 15.4 \text{ V}$$

If ripple voltage is included, the output voltage is

$$= 12\sqrt{2} - 2 \times 0.8 - \frac{V_r}{2} = 14.9 \text{ V}$$

$$I_L = \frac{14.9}{100\ \Omega} \simeq 0.15 \text{ A}$$

The conduction angle $\omega\Delta t$ can be obtained using Eq. (4.30) but substituting $V_p = 12\sqrt{2} - 2 \times 0.8$:

$$\omega\Delta t = \sqrt{\frac{2V_r}{V_p}} = \sqrt{\frac{2 \times 1}{12\sqrt{2} - 2 \times 0.8}}$$

$$= 0.36 \text{ rad} = 20.7^\circ$$

The average and peak diode currents can be calculated using Eqs. (4.34) and (4.35):

$i_{D\text{av}} = I_L\left(1 + \pi\sqrt{\frac{V_p}{2V_r}}\right)$, where $I_L = \frac{14.9\text{ V}}{100\ \Omega}$,

$V_p = 12\sqrt{2} - 2 \times 0.8$, and $V_r = 1$ V; thus

$i_{D\text{av}} = 1.45$ A

$i_{D\max} = I\left(1 + 2\pi\sqrt{\frac{V_p}{2V_r}}\right)$

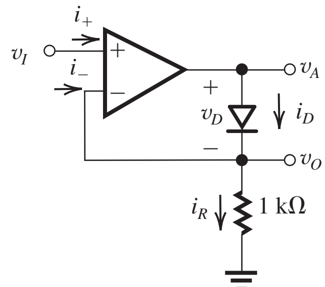
$= 2.76$ A

PIV of the diodes

$= V_S - V_{DO} = 12\sqrt{2} - 0.8 = 16.2$ V

To provide a safety margin, select a diode capable of a peak current of 3.5 to 4A and having a PIV rating of 20 V.

Ex: 4.26



The diode has 0.7 V drop at 1 mA current.

$i_D = I_S e^{v_D/V_T}$

$\frac{i_D}{1\text{ mA}} = e^{(v_D - 0.7)/V_T}$

$\Rightarrow v_D = V_T \ln\left(\frac{i_D}{1\text{ mA}}\right) + 0.7$ V

For $v_I = 10$ mV, $\quad v_O = v_I = 10$ mV

It is an ideal op amp, so $i_+ = i_- = 0$.

$\therefore i_D = i_R = \frac{10\text{ mV}}{1\text{ k}\Omega} = 10\ \mu\text{A}$

$v_D = 25 \times 10^{-3} \ln\left(\frac{10\ \mu\text{A}}{1\text{ mA}}\right) + 0.7 = 0.58$ V

$v_A = v_D + 10$ mV

$= 0.58 + 0.01$

$= 0.59$ V

For $v_I = 1$ V

$v_O = v_I = 1$ V

$i_D = \frac{v_O}{1\text{ k}\Omega} = \frac{1}{1\text{ k}\Omega} = 1$ mA

$v_D = 0.7$ V

$V_A = 0.7\text{ V} + 1\text{ k}\Omega \times 1\text{ mA}$

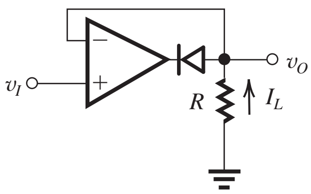
$= 1.7$ V

For $v_I = -1$ V, the diode is cut off.

$\therefore v_O = 0$ V

$v_A = -12$ V

Ex: 4.27



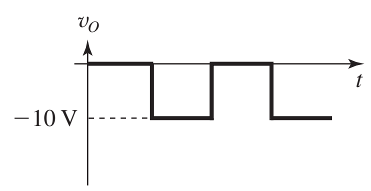
$v_I > 0 \sim$ diode is cut off, loop is open, and the opamp is saturated:

$v_O = 0$ V

$v_I < 0 \sim$ diode conducts and closes the negative feedback loop:

$v_O = v_I$

Ex: 4.28 Reversing the diode results in the peak output voltage being clamped at 0 V:



Here the dc component of $v_O = V_O = -5$ V

Ex: 4.29 The capacitor voltage accounts for the shift of the voltage waveforms from v_I to v_O. Thus, from Fig. 4.30, we see the capacitor voltage is $V_p + V_{CC} = 8$ V. The diode's peak inverse voltage arises at the peaks of v_O,

$\text{PIV} = v_{O\max} - V_{CC}$

$= V_{CC} + 2V_p - V_{CC}$

$= 2V_p = 6$ V

Ex: 4.30 $C_{j0} = 100$ fF, $V_0 = 3$ V, $m = 3$. Using Equation (3.47),

at $V_R = 1$ V: $C_j = \frac{100\text{ fF}}{\left(1 + \frac{1}{3}\right)^3} = 42.2$ fF, and

at $V_R = 3$ V: $C_j = \frac{100\text{ fF}}{\left(1 + \frac{3}{3}\right)^3} = 12.5$ fF.

Ex: 4.31 The reverse current is

$-i_D = I_D + i_P = I_D + R \times P$

At an incident light power of $P = 1$ mW,

$-i_D = 10^{-4} + 0.5 \times 1 = 0.5$ mA

At an incident light power of $P = 1$ μW,

$-i_D = 10^{-4} + 0.5 \times 10^{-3} = 6 \times 10^{-4}$ mA = 0.6 μA

Ex: 4.32 Neglecting dark current,

$i_P = R \times P$

t

$10^{-6} = 0.3 \times 0.01 \times A$

$\Rightarrow A = \dfrac{10^{-6}}{0.3 \times 10^{-2}} = 3.33 \times 10^{-4}\ \text{m}^2 =$ 3.33 cm^2

The capacitance is 10 pF per mm^2 or, equivalently, 1 nF per cm^2. Thus,

$C_j = 1 \times 3.33 = 3.33$ nF

Ex: 4.33

$$R = \frac{9 - 3 \times 1.8}{20} = 0.18\ \text{k}\Omega = 180\Omega$$

Ex: 4.34

$$R = \frac{9 - 3 \times 2.2}{20} = 0.12\ \text{k}\Omega = 120\Omega$$

Chapter 5

Solutions to Exercises within the Chapter

Ex: 5.1

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{34.5 \text{ pF/m}}{4 \text{ nm}} = 8.625 \text{ fF/}\mu\text{m}^2$$

$$\mu_n = 450 \text{ cm}^2/\text{V} \cdot \text{S}$$

$$k'_n = \mu_n C_{ox} = 388\ \mu\text{A/V}^2$$

$$v_{OV} = v_{GS} - V_t = 0.5 \text{ V}$$

$$g_{DS} = \frac{1}{1 \text{ k}\Omega} = k'_n \frac{W}{L} v_{OV} \Rightarrow \frac{W}{L} = 5.15$$

$L = 0.18\ \mu\text{m}$, so $W = 0.93\ \mu\text{m}$

Ex: 5.2

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{34.5 \text{ pF/m}}{1.4 \text{ nm}} = 24.6 \text{ fF/}\mu\text{m}^2$$

$$\mu_n = 216 \text{ cm}^2/\text{V} \cdot \text{s}$$

$$k'_n = \mu_n C_{ox} = 531\ \mu\text{A/V}^2$$

$$i_D = \frac{1}{2} k'_n \frac{W}{L} v_{OV}^2$$

$$50 = \frac{1}{2} \times 531 \times 10 \times v_{OV}^2$$

$$\therefore\ v_{OV} = 0.14 \text{ V}$$

$$v_{GS} = V_t + v_{OV} = 0.49 \text{ V}$$

$$v_{DS,\ \text{min}} = v_{OV} = 0.14 \text{ V},$$

Ex: 5.3 $i_D = \frac{1}{2} k'_n \frac{W}{L} v_{OV}^2$ in saturation

Change in i_D is:

(a) double L, 0.5

(b) double W, 2

(c) double v_{OV}, $2^2 = 4$

(d) double v_{DS}, no change (ignoring length modulation)

(e) changes (a)–(d), 4

Case (c) would cause leaving saturation if

$v_{DS} < 2v_{OV}$

Ex: 5.4 For saturation $v_{DS} \geq v_{OV}$, so v_{DS} must be changed to $2v_{OV}$

$i_D = \frac{1}{2} k'_n \frac{W}{L} v_{OV}^2$, so i_D increases by a factor of 4.

Ex: 5.5 $v_{OV} = 0.5$ V

$$g_{DS} = k'_n \frac{W}{L} v_{OV} = \frac{1}{1 \text{ k}\Omega}$$

$$\therefore k_n = k'_n \frac{W}{L} = \frac{1}{1 \times 0.5} = 2 \text{ mA/V}^2$$

At $v_{DS} = 0.2$ V, $v_{DS} < v_{OV}$, thus the transistor is operating in the triode region,

$$i_D = k_n(v_{OV}\, v_{DS} - \frac{1}{2} v_{DS}^2)$$

$$= 2(0.5 \times 0.2 - \frac{1}{2} \times 0.2^2) = 0.16 \text{ mA}$$

At $v_{DS} = 0.5$ V, $v_{DS} = v_{OV}$, thus the transistor is operating in saturation,

$$i_D = \frac{1}{2} k_n v_{OV}^2 = \frac{1}{2} \times 2 \times 0.5^2 = 0.25 \text{ mA}$$

At $v_{DS} = 1$ V, $v_{DS} > v_{OV}$ and the transistor is operating in saturation with $i_D = 0.25$ mA.

Ex: 5.6 $V_A = V'_A L = 5 \times 0.8 = 4$ V

$$\lambda = \frac{1}{V_A} = 0.25 \text{ V}^{-1}$$

$$v_{DS} = 0.8 \text{ V} > v_{OV} = 0.2 \text{ V}$$

$$\Rightarrow \text{Saturation: } i_D = \frac{1}{2} k'_n \frac{W}{L} v_{OV}^2\ (1 + \lambda v_{DS})$$

$$i_D = \frac{1}{2} \times 400 \times \frac{16}{0.8} \times 0.2^2\ (1 + 0.25 \times 0.8)$$

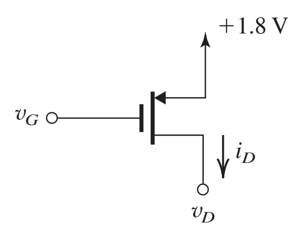
$$= 0.192 \text{ mA}$$

$$r_o = \frac{V_A}{i_D} = \frac{4}{0.16} = 25 \text{ k}\Omega$$

where i_D is the value of i_D without channel-length modulation taken into account.

$$r_o = \frac{\Delta v_{DS}}{\Delta i_D} \Rightarrow \Delta i_D = \frac{1 \text{ V}}{25 \text{ k}\Omega} = 0.04 \text{ mA} = 40\ \mu\text{A}$$

Ex: 5.7



$$V_{tp} = -0.5 \text{ V}$$

$$k'_p = 100\ \mu\text{A/V}^2$$

$$\frac{W}{L} = 10 \Rightarrow k_p = 1 \text{ mA/V}^2$$

(a) Conduction occurs for $V_{SG} \geq |V_{tp}| = 0.5$ V

$$\Rightarrow v_G \leq 1.8 - 0.5 = +1.3 \text{ V}$$

(b) Triode region occurs for $v_{DG} \geq |V_{tp}| = 0.5$ V

$$\Rightarrow v_D \geq v_G + 0.5$$

(c) Conversely, for saturation

$v_{DG} \le |V_{tp}| = 0.5$ V

$\Rightarrow v_D \le v_G + 0.5$

(d) Given $\lambda \cong 0$,

$$i_D = \frac{1}{2} k'_p \frac{W}{L} |v_{OV}|^2 = 50\ \mu\text{A}$$

$\therefore |v_{OV}| = 0.32\ \text{V} = v_{SG} - |V_{tp}|$

$\Rightarrow v_{SG} = |v_{OV}| + |V_{tp}| = 0.82$ V

$v_G = 1.8 - v_{SG} = 0.98$ V

$v_D \le v_G + 0.5 = 1.48$ V

(e) For $\lambda = -0.2\ \text{V}^{-1}$ and $|v_{OV}| = 0.32$ V,

$$i_D = 50\ \mu\text{A and } r_o = \frac{1}{|\lambda| i_D} = 100\ \text{k}\Omega$$

(f) At $v_D = +1$ V, $v_{SD} = 0.8$ V,

$$i_D = \frac{1}{2} k'_n \frac{W}{L} |v_{OV}|^2 (1 + |\lambda||v_{SD}|)$$

$= 50\ \mu\text{A}\,(1.16) = 58\ \mu\text{A}$

At $v_D = 0$ V, $v_{SD} = 1.8$ V,

$i_D = 50\ \mu\text{A}\,(1.36) = 68\ \mu\text{A}$

$$r_o = \frac{\Delta v_{DS}}{\Delta i_D} = \frac{1\ \text{V}}{10\ \mu\text{A}} = 100\ \text{k}\Omega$$

which is the same value found in (c).

Ex: 5.8

$$R_D = \frac{V_{DD} - v_D}{I_D} = \frac{1 - 0.2}{0.1} = 8\ \text{k}\Omega$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{OV}^2 \Rightarrow$$

$$100 = \frac{1}{2} \times 400 \times \frac{5}{0.4} V_{OV}^2 \Rightarrow$$

$V_{OV} = 0.2\ \text{V} \Rightarrow V_{GS} = V_{OV} + V_t = 0.2 + 0.4$

$= 0.6$ V

$$V_S = -0.6\ \text{V} \Rightarrow R_S = \frac{V_S - V_{SS}}{I_D}$$

$$= \frac{-0.6 - (-1)}{0.1}$$

$R_S = 4\ \text{k}\Omega$

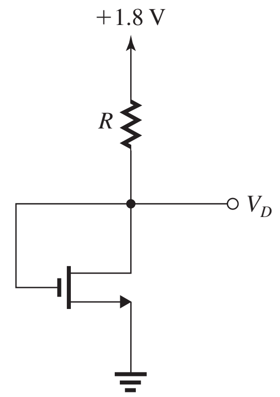
Ex: 5.9

$V_{tn} = 0.5$ V

$\mu_n C_{ox} = 0.4\ \text{mA/V}^2$

$$\frac{W}{L} = \frac{0.72\ \mu\text{m}}{0.18\ \mu\text{m}} = 4.0$$

$\lambda = 0$



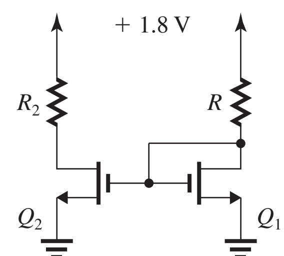
Saturation mode ($v_{GD} = 0 < V_{tn}$):

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_D - V_{tn})^2 = 0.032\ \text{mA}$$

$V_D = 0.7\ \text{V} = 1.8 - I_D R$

$$\therefore R = \frac{1.8 - 0.7}{0.032\ \text{mA}} = 34.4\ \text{k}\Omega$$

Ex: 5.10



Since Q_2 is identical to Q_1 and their V_{GS} values are the same,

$I_{D2} = I_{D1} = 0.032$ mA

For Q_2 to operate at the triode–saturation boundary, we must have

$V_{D2} = V_{OV} = 0.7 - 0.5 = 0.2$ V

$$\therefore R_2 = \frac{1.8\ \text{V} - 0.2\ \text{V}}{0.032\ \text{mA}} = 50\ \text{k}\Omega$$

Ex: 5.11 $R_D = 6.55 \times 2 = 13.1\ \text{k}\Omega$

$V_{GS} = 2$ V, assume triode region:

$$\left.\begin{aligned} I_D &= k'_n \frac{W}{L}\left[(V_{GS} - V_{\text{tn}})V_{DS} - \frac{1}{2}V_{DS}^2\right] \\ I_D &= \frac{V_{DD} - V_{DS}}{R} \end{aligned}\right\} \Rightarrow$$

$$\frac{2 - V_{DS}}{13.1} = 2 \times \left[(2 - 0.5)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

$\Rightarrow V_{DS}^2 - 3.076 V_{DS} + 0.15 = 0$

$\Rightarrow V_{DS} = 0.05\text{ V} < V_{OV} \Rightarrow$ triode region

$$I_D = \frac{2 - 0.05}{13.1} = 0.15\text{ mA}$$

Ex: 5.12 As indicated in Example 5.6,

$V_D \geq V_G - V_t$ for the transistor to be in the saturation region.

$$V_{D\min} = V_G - V_t = 5 - 1 = 4\text{ V}$$

$$I_D = 0.5\text{ mA} \Rightarrow R_{D\max} = \frac{V_{DD} - V_{D\min}}{I_D}$$

$$= \frac{10 - 4}{0.5} = 12\text{ k}\Omega$$

Ex: 5.13

$$I_D = 0.32\text{ mA} = \frac{1}{2}k_n'\frac{W}{L}V_{OV}^2 = \frac{1}{2} \times 1 \times V_{OV}^2$$

$$\Rightarrow V_{OV} = 0.8\text{ V}$$

$$V_{GS} = 0.8 + 1 = 1.8\text{ V}$$

$$V_G = V_S + V_{GS} = 1.6 + 1.8 = 3.4\text{ V}$$

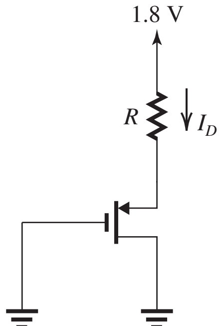
$$R_{G2} = \frac{V_G}{I} = \frac{3.4}{1\ \mu\text{A}} = 3.4\text{ M}\Omega$$

$$R_{G1} = \frac{5 - 3.4}{1\ \mu\text{A}} = 1.6\text{ M}\Omega$$

$$R_S = \frac{V_S}{0.32} = 5\text{ k}\Omega$$

$$V_D = 3.4\text{ V, then } R_D = \frac{5 - 3.4}{0.32} = 5\text{ k}\Omega$$

Ex: 5.14



$$V_{tp} = -0.4\text{ V}$$

$$k_p' = 0.1\text{ mA/V}^2$$

$$\frac{W}{L} = \frac{10\ \mu\text{m}}{0.18\ \mu\text{m}} \Rightarrow k_p = 5.56\text{ mA/V}^2$$

$$V_{SG} = |V_{tp}| + |V_{OV}|$$

$$= 0.4 + 0.6 = 1\text{ V}$$

$$V_S = +1\text{ V}$$

Since $V_{DG} = 0$, the transistor is operating in saturation, and

$$I_D = \frac{1}{2}k_p V_{OV}^2 = 1\text{ mA}$$

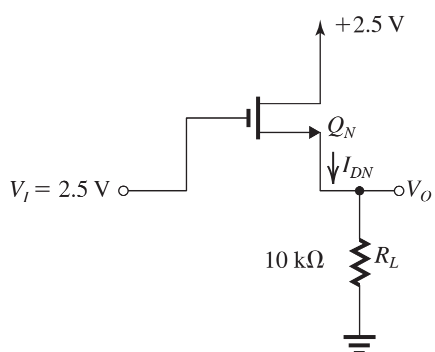
$$\therefore\ R = \frac{1.8 - V_S}{I_D} = \frac{1.8 - 1}{1} = 0.8\text{ k}\Omega$$

$$= 800\ \Omega$$

Ex: 5.15 $V_I = 0$: since the circuit is perfectly symmetrical, $V_O = 0$ and therefore $V_{GS} = 0$, which implies that the transistors are turned off and $I_{DN} = I_{DP} = 0$.

$V_I = 2.5$ V: if we assume that the NMOS is turned on, then V_O would be less than 2.5 V, and this implies that PMOS is off ($V_{SGP} < 0$).

$$I_{DN} = \frac{1}{2}k_n'\frac{W}{L}(V_{GS} - V_t)^2$$



$$I_{DN} = \frac{1}{2} \times 1(2.5 - V_O - 1)^2$$

$$I_{DN} = 0.5(1.5 - V_O)^2$$

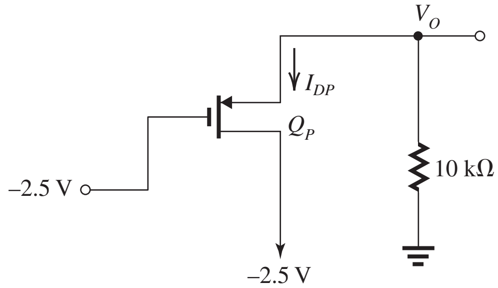
Also: $V_O = R_L I_{DN} = 10 I_{DN}$

$$I_{DN} = 0.5(1.5 - 10I_{DN})^2$$

$$\Rightarrow 100I_{DN}^2 - 32I_{DN} + 2.25 = 0 \Rightarrow I_{DN}$$

$$= 0.104\text{ mA} \qquad I_{DP} = 0$$

$$V_O = 10 \times 0.104 = 1.04\text{V}$$



$V_I = -2.5$ V: Again if we assume that Q_P is turned on, then $V_O > -2.5$ V and $V_{GSN} < 0$, which implies that the NMOS Q_N is turned off.

$I_{DN} = 0$

Because of the symmetry,

$I_{DP} = 0.104$ mA,

$V_O = -I_{DP} \times 10\ \text{k}\Omega$

$= -1.04$ V

Ex: 5.16 $V_t = 0.8 + 0.4\left[\sqrt{0.7 + 3} - \sqrt{0.7}\right]$

$= 1.23$ V

Ex: 5.17 $v_{DS\min} = v_{GS} + |V_t|$

$= 1 + 2 = 3$ V

$I_D = \frac{1}{2} \times 2\ [1 - (-2)]^2$

$= 9$ mA

Chapter 6

Solutions to Exercises within the Chapter

Ex: 6.1 $i_C = I_S\, e^{v_{BE}/V_T}$

$v_{BE2} - v_{BE1} = V_T \ln\left[\frac{i_{C2}}{i_{C1}}\right]$

$v_{BE2} = 700 + 25 \ln\left[\frac{0.1}{1}\right]$

$= 642$ mV

$v_{BE3} = 700 + 25 \ln\left[\frac{10}{1}\right]$

$= 758$ mV

Ex: 6.2 $\therefore \alpha = \frac{\beta}{\beta + 1}$

$\frac{50}{50+1} < \alpha < \frac{150}{150+1}$

$0.980 < \alpha < 0.993$

Ex: 6.3 $I_C = I_E - I_B$

$= 1.460$ mA $-$ 0.01446 mA

$= 1.446$ mA

$\alpha = \frac{I_C}{I_E} = \frac{1.446}{1.460} = 0.99$

$\beta = \frac{I_C}{I_B} = \frac{1.446}{0.01446} = 100$

$I_C = I_S e^{v_{BE}/V_T}$

$I_S = \frac{I_C}{e^{v_{BE}/V_T}} = \frac{1.446}{e^{700/25}}$

$= \frac{1.446}{e^{28}}$ mA $= 10^{-15}$ A

Ex: 6.4 $\beta = \frac{\alpha}{1 - \alpha}$ and $I_C = 10$ mA

For $\alpha = 0.99$, $\beta = \frac{0.99}{1 - 0.99} = 99$

$I_B = \frac{I_C}{\beta} = \frac{10}{99} = 0.1$ mA

For $\alpha = 0.98$, $\beta = \frac{0.98}{1 - 0.98} = 49$

$I_B = \frac{I_C}{\beta} = \frac{10}{49} = 0.2$ mA

Ex: 6.5 Given:

$I_S = 10^{-16}$ A, $\beta = 100$, $I_C = 1$ mA

We write

$I_{SE} = I_S/\alpha = I_S \times \left(1 + \frac{1}{\beta}\right)$

$= 10^{-16} \times 1.01 = 1.01 \times 10^{-16}$ A

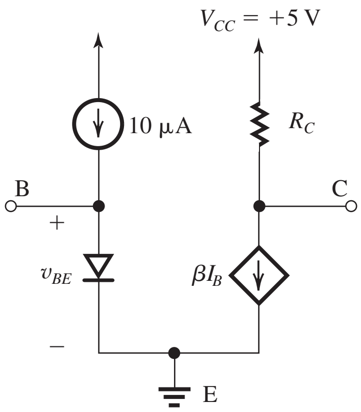
$I_{SB} = \frac{I_S}{\beta} = \frac{10^{-16}}{100} = 10^{-18}$ A

$V_{BE} = V_T \ln\left[\frac{I_C}{I_S}\right] = 25 \ln\left[\frac{1\text{ mA}}{10^{-16}\text{ A}}\right]$

$= 25 \times 29.9336$

$= 748$ mV

Ex: 6.6



$v_{BE} = 690$ mV

$I_C = 1$ mA

For active range $V_C \geq V_B$,

$R_{C\max} = \frac{V_{CC} - 0.690}{I_C}$

$= \frac{5 - 0.69}{1}$

$= 4.31$ kΩ

Ex: 6.7 $I_S = 10^{-15}$ A

$\text{Area}_C = 100 \times \text{Area}_E$

$I_{SC} = 100 \times I_S = 10^{-13}$ A

Ex: 6.8 $i_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}$

for $i_C = 0$

$I_S e^{v_{BE}/V_T} = I_{SC} e^{v_{BC}/V_T}$

$\frac{I_{SC}}{I_S} = \frac{e^{v_{BE}/V_T}}{e^{v_{BC}/V_T}}$

$= e^{(v_{BE} - v_{BC})/V_T}$

$\therefore V_{CE} = V_{BE} - V_{BC} = V_T \ln\left[\frac{I_{SC}}{I_S}\right]$

For collector Area = 100 × Emitter area

$V_{CE} = 25 \ln\left[\frac{100}{1}\right] = 115$ mV

Ex: 6.9 $I_C = I_S e^{V_{BE}/V_T} - I_{SC} e^{V_{BC}/V_T}$

$$I_B = \frac{I_S}{\beta} e^{V_{BE}/V_T} + I_{SC} e^{V_{BC}/V_T}$$

$$\beta_{\text{forced}} = \left.\frac{I_C}{I_B}\right|_{\text{sat}} < \beta$$

$$= \beta \frac{I_S e^{V_{BE}/V_T} - I_{SC} e^{V_{BC}/V_T}}{I_S e^{V_{BE}/V_T} + \beta I_{SC} e^{V_{BC}/V_T}}$$

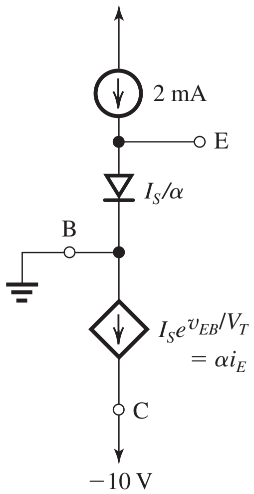
$$= \beta \frac{I_S e^{(V_{BE}-V_{BC})/V_T} - I_{SC}}{I_S e^{(V_{BE}-V_{BC})/V_T} + \beta I_{SC}}$$

$$= \beta \frac{e^{V_{CE\text{sat}}/V_T} - I_{SC}/I_S}{e^{V_{CE\text{sat}}/V_T} + \beta I_{SC}/I_S} \qquad \text{Q.E.D.}$$

$$\beta_{\text{forced}} = 100 \frac{e^{200/25} - 100}{e^{200/25} + 100 \times 100}$$

$$= 100 \times 0.2219 \approx 22.2$$

Ex: 6.10



$$I_E = \frac{I_S}{\alpha} e^{V_{BE}/V_T}$$

$$2\text{ mA} = \frac{51}{50} 10^{-14} e^{V_{BE}/V_T}$$

$$V_{BE} = 25 \ln\left[\frac{2}{10^3} \times \frac{50}{51} \times 10^{14}\right]$$

$$= 650\text{ mV}$$

$$I_C = \frac{\beta}{\beta+1} I_E = \frac{50}{51} \times 2$$

$$= 1.96\text{ mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{1.96}{50} \Rightarrow 39.2\ \mu\text{A}$$

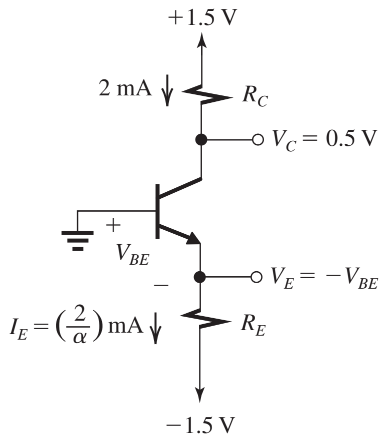
Ex: 6.11 $I_C = I_S e^{V_{BE}/V_T} = 1.5$ A

$$\therefore V_{BE} = V_T \ln\left[1.5/10^{-11}\right]$$

$$= 25 \times 25.734$$

$$= 643\text{ mV}$$

Ex: 6.12



$$R_C = \frac{1.5 - V_C}{I_C} = \frac{1.5 - 0.5}{2}$$

$$= 0.5\text{ k}\Omega = 500\ \Omega$$

Since at $I_C = 1$ mA, $V_{BE} = 0.8$ V, then at $I_C = 2$ mA,

$$V_{BE} = 0.8 + 0.025 \ln\left(\frac{2}{1}\right)$$

$$= 0.8 + 0.017$$

$$= 0.817\text{ V}$$

$$V_E = -V_{BE} = -0.817\text{ V}$$

$$I_E = \frac{2\text{ mA}}{\alpha} = \frac{2}{0.99} = 2.02\text{ mA}$$

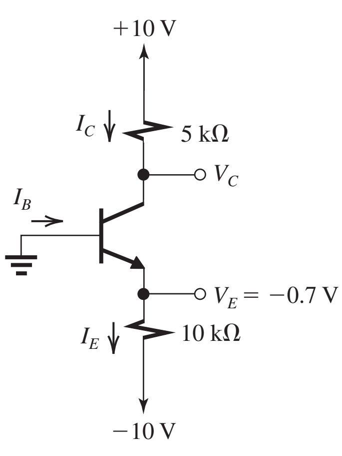
$$I_E = \frac{V_E - (-1.5)}{R_E}$$

Thus,

$$R_E = \frac{-0.817 + 1.5}{2.02} = 0.338\text{ k}\Omega$$

$$= 338\ \Omega$$

Ex: 6.13



$$I_E = \frac{V_E - (-10)}{10} = \frac{-0.7 + 10}{10}$$

$= 0.93$ mA

Assuming active-mode operation,

$$I_B = \frac{I_E}{\beta + 1} = \frac{0.93}{50 + 1} = 0.0182 \text{ mA}$$

$= 18.2\ \mu$A

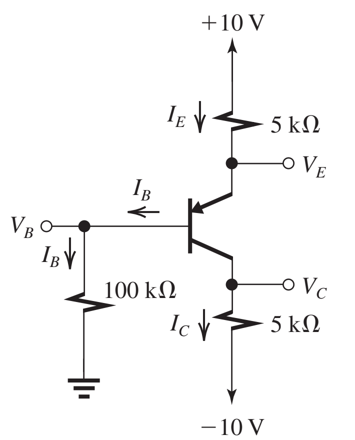
$I_C = I_E - I_B = 0.93 - 0.0182 = 0.91$ mA

$V_C = 10 - I_C \times 5$

$= 10 - 0.91 \times 5 = 5.45$ V

Since $V_C > V_B$, the transistor is operating in the active mode, as assumed.

Ex: 6.14



$V_B = 1.0$ V

Thus,

$$I_B = \frac{V_B}{100\text{ k}\Omega} = 0.01 \text{ mA}$$

$V_E = +1.7$ V

Thus,

$$I_E = \frac{10 - V_E}{5\text{ k}\Omega} = \frac{10 - 1.7}{5} = 1.66 \text{ mA}$$

and

$$\beta + 1 = \frac{I_E}{I_B} = \frac{1.66}{0.01} = 166$$

$\Rightarrow \beta = 165$

$$\alpha = \frac{\beta}{\beta + 1} = \frac{165}{165 + 1} = 0.994$$

Assuming active-mode operation,

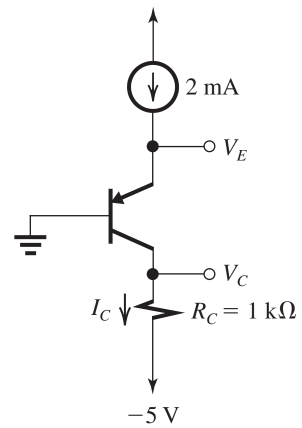
$I_C = \alpha I_E = 0.994 \times 1.66 = 1.65$ mA

and

$V_C = -10 + 1.65 \times 5 = -1.75$ V

Since $V_C < V_B$, the transistor is indeed operating in the active mode.

Ex: 6.15



The transistor is operating at a constant emitter current. Thus, a change in temperature of +30°C results in a change in V_{EB} by

$\triangle V_{EB} = -2 \text{ mV} \times 30 = -60$ mV

Thus,

$\triangle V_E = -60$ mV

Since the collector current remains unchanged at αI_E, the collector voltage does not change:

$\triangle V_C = 0$ V

Ex: 6.16 Refer to Fig. 6.19(a):

$$i_C = I_S e^{v_{BE}/V_T} + \frac{v_{CE}}{r_o} \tag{1}$$

Now using Eqs. (6.21) and (6.22), we can express r_o as

$$r_o = \frac{V_A}{I_S e^{v_{BE}/V_T}}$$

Substituting in Eq. (1), we have

$$i_C = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$$

which is Eq. (6.18). Q.E.D.

Ex: 6.17 $r_o = \dfrac{V_A}{I_C} = \dfrac{100}{I_C}$

At $I_C = 0.1$ mA, $r_o = 1$ MΩ

At $I_C = 1$ mA, $r_o = 100$ kΩ

At $I_C = 10$ mA, $r_o = 10$ kΩ

Ex: 6.18 $\triangle I_C = \dfrac{\triangle V_{CE}}{r_o}$

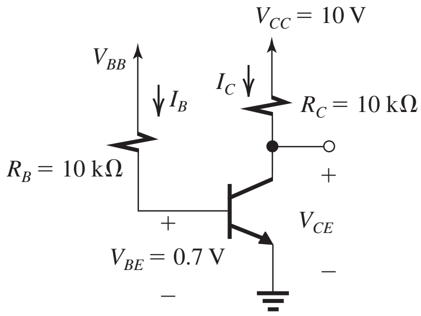
where

$r_o = \dfrac{V_A}{I_C} = \dfrac{100}{1} = 100\ \text{k}\Omega$

$\triangle I_C = \dfrac{11-1}{100} = 0.1\ \text{mA}$

Thus, I_C becomes 1.1 mA.

Ex: 6.19



(a) For operation in the active mode with $V_{CE} = 5$ V,

$I_C = \dfrac{V_{CC} - V_C}{R_C} = \dfrac{10-5}{10} = 0.5\ \text{mA}$

$I_B = \dfrac{I_C}{\beta} = \dfrac{0.5}{50} = 0.01\ \text{mA}$

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

$= 0.7 + 0.01 \times 10 = 0.8$ V

(b) For operation at the edge of saturation,

$V_{CE} = 0.3$ V

$I_C = \dfrac{V_{CC} - V_{CE}}{R_C} = \dfrac{10-0.3}{10} = 0.97\ \text{mA}$

$I_B = \dfrac{I_C}{\beta} = \dfrac{0.97}{50} = 0.0194\ \text{mA}$

$V_{BB} = V_B + I_B R_B$

$= 0.7 + 0.0194 \times 10 = 0.894$ V

(c) For operation deep in saturation with $\beta_{\text{forced}} = 10$, we have

$V_{CE} \simeq 0.2$ V

$I_C = \dfrac{10-0.2}{10} = 0.98\ \text{mA}$

$I_B = \dfrac{I_C}{\beta_{\text{forced}}} = \dfrac{0.98}{10} = 0.098\ \text{mA}$

$V_{BB} = V_B + I_B R_B$

$= 0.7 + 0.098 \times 10 = 1.68$ V

Ex: 6.20 For $V_{BB} = 0$ V, $I_B = 0$ and the transistor is cut off. Thus,

$I_C = 0$

and

$V_C = V_{CC} = +10$ V

Ex: 6.21 Refer to the circuit in Fig. 6.22 and let $V_{BB} = 1.7$ V. The current I_B can be found from

$I_B = \dfrac{V_{BB} - V_B}{R_B} = \dfrac{1.7-0.7}{10} = 0.1\ \text{mA}$

Assuming operation in the active mode,

$I_C = \beta\ I_B = 50 \times 0.1 = 5\ \text{mA}$

Thus,

$V_C = V_{CC} - R_C I_C$

$= 10 - 1 \times 5 = 5$ V

which is greater than V_B, verifying that the transistor is operating in the active mode, as assumed.

(a) To obtain operation at the edge of saturation, R_C must be increased to the value that results in $V_{CE} = 0.3$ V:

$R_C = \dfrac{V_{CC} - 0.3}{I_C}$

$= \dfrac{10-0.3}{5} = 1.94\ \text{k}\Omega$

(b) Further increasing R_C results in the transistor operating in saturation. To obtain saturation-mode operation with $V_{CE} = 0.2$ V and $\beta_{\text{forced}} = 10$, we use

$I_C = \beta_{\text{forced}} \times I_B$

$= 10 \times 0.1 = 1$ mA

The value of R_C required can be found from

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

$= \dfrac{10-0.2}{1} = 9.8\ \text{k}\Omega$

Ex: 6.22 Refer to the circuit in Fig. 6.23(a) with the base voltage raised from 4 V to V_B. If at this value of V_B, the transistor is at the edge of saturation then,

$V_C = V_B - 0.4$ V

Since $I_C \simeq I_E$, we can write

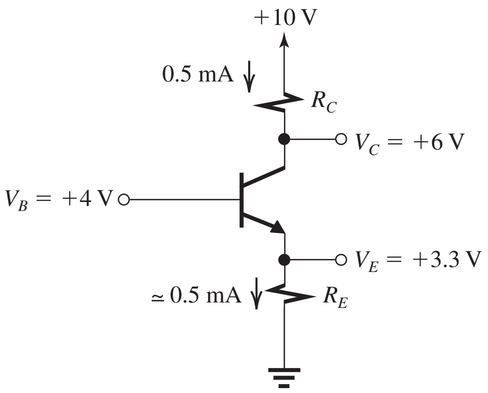
$\dfrac{10 - V_C}{R_C} = \dfrac{V_E}{R_E} = \dfrac{V_B - 0.7}{R_E}$

Thus,

$$\frac{10-(V_B-0.4)}{4.7}=\frac{V_B-0.7}{3.3}$$

$$\Rightarrow V_B=+4.7\text{ V}$$

Ex: 6.23



To establish a reverse-bias voltage of 2 V across the CBJ,

$V_C=+6\text{ V}$

From the figure we see that

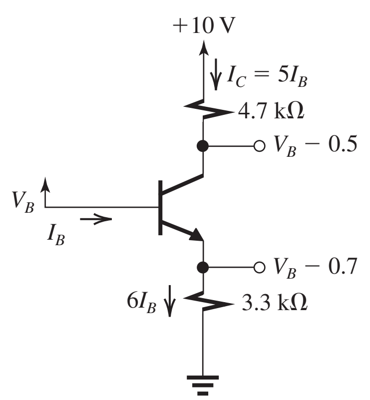
$$R_C=\frac{10-6}{0.5}=8\text{ k}\Omega$$

and

$$R_E=\frac{3.3}{0.5}=6.6\text{ k}\Omega$$

where we have assumed $\alpha\simeq 1$.

Ex: 6.24



The figure shows the circuit with the base voltage at V_B and the BJT operating in saturation with $V_{CE}=0.2$ V and $\beta_{\text{forced}}=5$.

$$I_C=5I_B=\frac{10-(V_B-0.5)}{4.7} \quad (1)$$

$$I_E=6I_B=\frac{V_B-0.7}{3.3} \quad (2)$$

Dividing Eq. (1) by Eq. (2), we have

$$\frac{5}{6}=\frac{10.5-V_B}{V_B-0.7}\times\frac{3.3}{4.7}$$

$$\Rightarrow V_B=+5.18\text{ V}$$

Ex: 6.25 Refer to the circuit in Fig. 6.26(a). The largest value for R_C while the BJT remains in the active mode corresponds to

$V_C=+0.4\text{ V}$

Since the emitter and collector currents remain unchanged, then from Fig. 6.26(b) we obtain

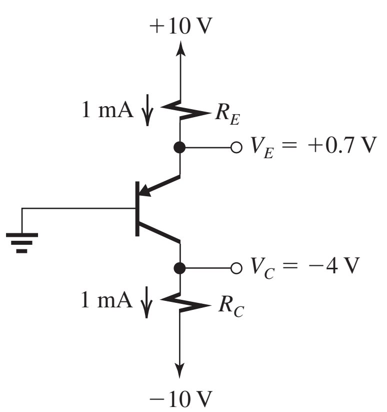
$I_C=4.65\text{ mA}$

Thus,

$$R_C=\frac{V_C-(-10)}{I_C}$$

$$=\frac{+0.4+10}{4.65}=2.26\text{ k}\Omega$$

Ex: 6.26



For a 4-V reverse-biased voltage across the CBJ,

$V_C=-4\text{ V}$

Refer to the figure.

$$I_C=1\text{ mA}=\frac{V_C-(-10)}{R_C}$$

$$\Rightarrow R_C=\frac{-4+10}{1}=6\text{ k}\Omega$$

$$R_E=\frac{10-V_E}{I_E}$$

Assuming $\alpha=1$,

$$R_E=\frac{10-0.7}{1}=9.3\text{ k}\Omega$$

Ex: 6.27 Refer to the circuit in Fig. 6.27:

$$I_B = \frac{5 - 0.7}{100} = 0.043 \text{ mA}$$

To ensure that the transistor remains in the active mode for β in the range 50 to 150, we need to select R_C so that for the highest collector current possible, the BJT reaches the edge of saturation, that is, $V_{CE} = 0.3$ V. Thus,

$$V_{CE} = 0.3 = 10 - R_C I_{C\max}$$

where

$$I_{C\max} = \beta_{\max} I_B$$

$$= 150 \times 0.043 = 6.45 \text{ mA}$$

Thus,

$$R_C = \frac{10 - 0.3}{6.45} = 1.5 \text{ k}\Omega$$

For the lowest β,

$$I_C = \beta_{\min} I_B$$

$$= 50 \times 0.043 = 2.15 \text{ mA}$$

and the corresponding V_{CE} is

$$V_{CE} = 10 - R_C I_C = 10 - 1.5 \times 2.15$$

$$= 6.775 \text{ V}$$

Thus, V_{CE} will range from 0.3 V to 6.8 V.

Ex: 6.28 Refer to the solution of Example 6.10.

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + R_{BB}/(\beta + 1)}$$

$$= \frac{5 - 0.7}{3 + (33.3/51)} = 1.177 \text{ mA}$$

$$I_C = \alpha I_E = 0.98 \times 1.177 = 1.15 \text{ mA}$$

Thus the current is reduced by

$$\triangle I_C = 1.28 - 1.15 = 0.13 \text{ mA}$$

which is a -10% change.

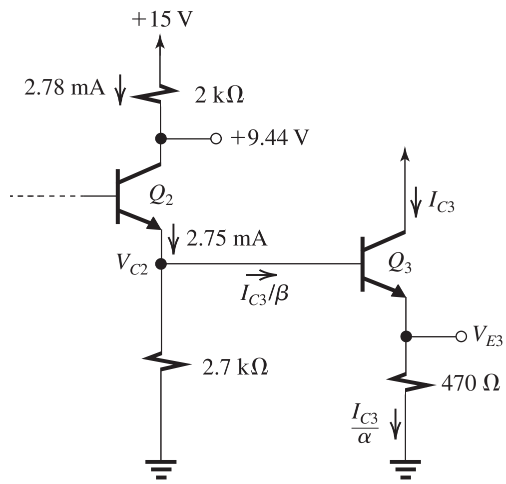
Ex: 6.29 Refer to the circuit in Fig. 6.30(b). The total current drawn from the power supply is

$$I = 0.103 + 1.252 + 2.78 = 4.135 \text{ mA}$$

Thus, the power dissipated in the circuit is

$$P = 15 \text{ V} \times 4.135 \text{ mA} = 62 \text{ mW}$$

Ex: 6.30



From the figure we see that

$$V_{E3} = \frac{I_{C3}}{\alpha} \times 0.47$$

$$V_{C2} = V_{E3} + 0.7 = \frac{I_{C3}}{\alpha} \times 0.47 + 0.7 \qquad (1)$$

A node equation at the collector of Q_2 yields

$$2.75 = \frac{V_{C2}}{2.7} + \frac{I_{C3}}{\beta}$$

Substituting for V_{C2} from Eq. (1), we obtain

$$2.75 = \frac{(0.47\ I_{C3}/\alpha) + 0.7}{2.7} + \frac{I_{C3}}{\beta}$$

Substituting $\alpha = 0.99$ and $\beta = 100$ and solving for I_{C3} results in

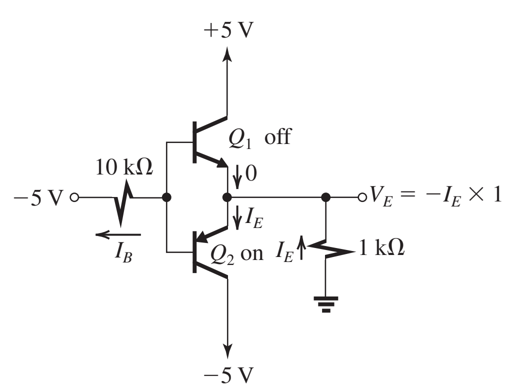
$$I_{C3} = 13.4 \text{ mA}$$

Now, V_{E3} and V_{C2} can be determined:

$$V_{E3} = \frac{I_{C3}}{\alpha} \times 0.47 = \frac{13.4}{0.99} \times 0.47 = +6.36 \text{ V}$$

$$V_{C2} = V_{E3} + 0.7 = +7.06 \text{ V}$$

Ex: 6.31



From the figure we see that Q_1 will be off and Q_2 will be on. Since the base of Q_2 will be at a voltage higher than −5 V, transistor Q_2 will be operating in the active mode. We can write a loop equation for the loop containing the 10-kΩ resistor, the EBJ of Q_2 and the 1-kΩ resistor:

$$-I_E \times 1 - 0.7 - I_B \times 10 = -5$$

Substituting $I_B = I_E/(\beta + 1) = I_E/101$ and rearranging gives

$$I_E = \frac{5 - 0.7}{\frac{10}{101} + 1} = 3.9 \text{ mA}$$

Thus,

$V_E = -3.9$ V

$V_{B2} = -4.6$ V

$I_B = 0.039$ mA

Ex: 6.32 With the input at + 10 V, there is a strong possibility that the conducting transistor Q_1 will be saturated. Assuming this to be the case, the analysis steps will be as follows:

$V_{CE\text{sat}}|_{Q_1} = 0.2$ V

$V_E = 5\text{ V} - V_{CE\text{sat}} = +4.8$ V

$$I_{E1} = \frac{4.8 \text{ V}}{1 \text{ k}\Omega} = 4.8 \text{ mA}$$

$V_{B1} = V_E + V_{BE1} = 4.8 + 0.7 = +5.5$ V

$$I_{B1} = \frac{10 - 5.5}{10} = 0.45 \text{ mA}$$

$I_{C1} = I_{E1} - I_{B1} = 4.8 - 0.45 = 4.35$ mA

$$\beta_{\text{forced}} = \frac{I_C}{I_B} = \frac{4.35}{0.45} = 9.7$$

which is lower than β_{min}, verifying that Q_1 is indeed saturated.

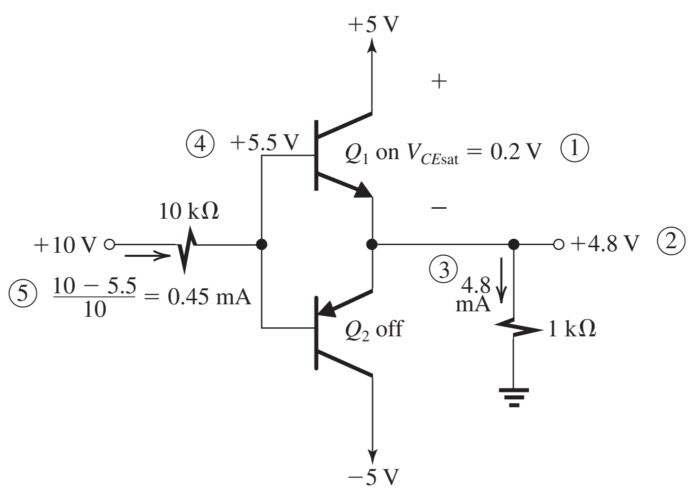
Finally, since Q_2 is off,

$I_{C2} = 0$

Ex: 6.33 $V_O = +10 - BV_{BCO} = 10 - 70$

$= -60$ V

This figure belongs to Exercise 6.32.



Chapter 7

Solutions to Exercises within the Chapter

Ex: 7.1 Refer to Fig. 7.2(a) and 7.2(b).

Coordinates of point A: V_t and V_{DD}; thus 0.4 V and 1.8 V. To determine the coordinates of point B, we use Eqs. (7.7) and (7.8) as follows:

$$V_{OV}\big|_B = \frac{\sqrt{2k_n R_D V_{DD} + 1} - 1}{k_n R_D}$$

$$= \frac{\sqrt{2 \times 4 \times 17.5 \times 1.8 + 1} - 1}{4 \times 17.5}$$

$$= 0.213 \text{ V}$$

Thus,

$$V_{GS}\big|_B = V_t + V_{OV}\big|_B = 0.4 + 0.213 = 0.613 \text{ V}$$

and

$$V_{DS}\big|_B = V_{OV}\big|_B = 0.213 \text{ V}$$

Thus, coordinates of B are 0.613 V and 0.213 V. At point C, the MOSFET is operating in the triode region, thus

$$i_D = k_n\left[(v_{GS}\big|_C - V_t)v_{DS}\big|_C - \frac{1}{2}v_{DS}^2\big|_C\right]$$

If $v_{DS}\big|_C$ is very small,

$$i_D \simeq k_n(v_{GS}\big|_C - V_t)v_{DS}\big|_C$$

$$= 4(1.8 - 0.4)v_{DS}\big|_C$$

$$= 5.6v_{DS}\big|_C, \text{ mA}$$

But

$$i_D = \frac{V_{DD} - v_{DS}\big|_C}{R_D} \simeq \frac{V_{DD}}{R_D} = \frac{1.8}{17.5} = 0.1 \text{ mA}$$

Thus, $v_{DS}\big|_C = \dfrac{0.1}{5.6} = 0.018 \text{ V} = 18 \text{ mV}$, which is indeed very small, as assumed.

Ex: 7.2 Refer to Example 7.1 and Fig. 7.4(a).

Design 1:

$$V_{OV} = 0.2 \text{ V}, \; V_{GS} = 0.6 \text{ V}$$

$$I_D = 0.08 \text{ mA}$$

Now,

$$A_v = -k_n V_{OV} R_D$$

Thus,

$$-10 = -0.4 \times 10 \times 0.2 \times R_D$$

$$\Rightarrow R_D = 12.5 \text{ k}\Omega$$

$$V_{DS} = V_{DD} - R_D I_D$$

$$= 1.8 - 12.5 \times 0.08 = 0.8 \text{ V}$$

Design 2:

$$R_D = 17.5 \text{ k}\Omega$$

$$A_v = -k_n V_{OV} R_D$$

$$-10 = -0.4 \times 10 \times V_{OV} \times 17.5$$

Thus,

$$V_{OV} = 0.14 \text{ V}$$

$$V_{GS} = V_t + V_{OV} = 0.4 + 0.14 = 0.54 \text{ V}$$

$$I_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)V_{OV}^2$$

$$= \frac{1}{2} \times 0.4 \times 10 \times 0.14^2 = 0.04 \text{ mA}$$

$$R_D = 17.5 \text{ k}\Omega$$

$$V_{DS} = V_{DD} - R_D I_D$$

$$= 1.8 - 17.5 \times 0.04 = 1.1 \text{ V}$$

Ex: 7.3

$$A_v = -\frac{I_C R_C}{V_T}$$

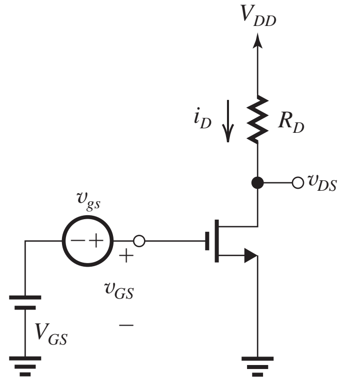
$$-320 = -\frac{1 \times R_C}{0.025} \Rightarrow R_C = 8 \text{ k}\Omega$$

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

$$= 10 - 1 \times 8 = 2 \text{ V}$$

Since the collector voltage is allowed to decrease to +0.3 V, the largest negative swing allowed at the output is $2 - 0.3 = 1.7$ V. The corresponding input signal amplitude can be found by dividing 1.7 V by the gain magnitude (320 V/V), resulting in 5.3 mV.

Ex: 7.4



$$V_{DD} = 5 \text{ V}$$

$$V_{GS} = 2 \text{ V}$$

$$V_t = 1 \text{ V}$$

$$\lambda = 0$$

$$k_n' = 20 \; \mu\text{A/V}^2$$

$$R_D = 10 \text{ k}\Omega$$

$\frac{W}{L} = 20$

(a) $V_{GS} = 2\text{ V} \Rightarrow V_{OV} = 1\text{ V}$

$I_D = \frac{1}{2} k_n' \frac{W}{L} V_{OV}^2 = 200\ \mu\text{A} = 0.2\text{ mA}$

$V_{DS} = V_{DD} - I_D R_D = +3\text{ V}$

(b) $g_m = k_n' \frac{W}{L} V_{OV} = 400\ \mu\text{A/V} = 0.4\text{ mA/V}$

(c) $A_v = \frac{v_{ds}}{v_{gs}} = -g_m R_D = -4\text{ V/V}$

(d) $v_{gs} = 0.2 \sin\omega t\text{ V}$

$v_{ds} = -0.8 \sin\omega t\text{ V}$

$v_{DS} = V_{DS} + v_{ds} \Rightarrow 2.2\text{ V} \leq v_{DS} \leq 3.8\text{ V}$

(e) Using Eq. (7.28), we obtain

$i_D = \frac{1}{2} k_n (V_{GS} - V_t)^2$

$+ k_n (V_{GS} - V_t) v_{gs} + \frac{1}{2} k_n v_{gs}^2$

$i_D = 200 + 80 \sin\omega t$

$+ 8 \sin^2 \omega t, \mu\text{A}$

$= [200 + 80 \sin\omega t + (4 - 4\ \cos 2\omega t)]$

$= 204 + 80 \sin\omega t - 4 \cos 2\omega t, \mu\text{A}$

Thus, I_D shifts by 4 μA and

$2\text{HD} = \frac{\hat{i}_{2\omega}}{\hat{i}_\omega} = \frac{4\ \mu\text{A}}{80\ \mu\text{A}} = 0.05\ (5\%)$

Ex: 7.5

(a) $V_{GS} = 1.5\text{V} \Rightarrow V_{OV} = 1.5 - 1 = 0.5\text{ V}$

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

$I_D = \frac{1}{2} k_n' \frac{W}{L} V_{OV}^2 = \frac{1}{2} \times 60 \times 40 \times 0.5^2$

$I_D = 300\ \mu\text{A} = 0.3\text{ mA}$

$g_m = \frac{2 \times 0.3}{0.5} = 1.2\text{ mA/V}$

$r_o = \frac{V_A}{I_D} = \frac{15}{0.3} = 50\text{ k}\Omega$

(b) $I_D = 0.5\text{ mA} \Rightarrow g_m = \sqrt{2\ \mu_n C_{ox} \frac{W}{L} I_D}$

$= \sqrt{2 \times 60 \times 40 \times 0.5 \times 10^3}$

$g_m = 1.55\text{ mA/V}$

$r_o = \frac{V_A}{I_D} = \frac{15}{0.5} = 30\text{ k}\Omega$

Ex: 7.6

$I_D = 0.1\text{ mA},\ g_m = 1\text{ mA/V},\ k_n' = 500\ \mu\text{A/V}^2$

$g_m = \frac{2 I_D}{V_{OV}} \Rightarrow V_{OV} = \frac{2 \times 0.1}{1} = 0.2\text{ V}$

$I_D = \frac{1}{2} k_n' \frac{W}{L} V_{OV}^2 \Rightarrow \frac{W}{L} = \frac{2 I_D}{k_n' V_{OV}^2}$

$= \frac{2 \times 0.1}{\frac{500}{1000} \times 0.2^2} = 10$

Ex: 7.7

$g_m = \mu_n C_{ox} \frac{W}{L} V_{OV}$

Same bias conditions, so same V_{OV} and also same L and g_m for both PMOS and NMOS.

$\mu_n C_{ox} W_n = \mu_p C_{ox} W_p \Rightarrow \frac{\mu_p}{\mu_n} = 0.4 = \frac{W_n}{W_p}$

$\Rightarrow \frac{W_p}{W_n} = 2.5$

Ex: 7.8

$I_D = \frac{1}{2} k_p' \frac{W}{L} (V_{SG} - |V_t|)^2$

$= \frac{1}{2} \times 60 \times \frac{16}{0.8} \times\ (1.6 - 1)^2$

$I_D = 216\ \mu\text{A}$

$g_m = \frac{2 I_D}{|V_{OV}|} = \frac{2 \times 216}{1.6 - 1} = 720\ \mu\text{A/V}$

$= 0.72\text{ mA/V}$

$|\lambda| = 0.04 \Rightarrow |V_A'| = \frac{1}{|\lambda|} = \frac{1}{0.04} = 25\text{ V}/\mu\text{m}$

$r_o = \frac{|V_A'| \times L}{I_D} = \frac{25 \times 0.8}{0.216} = 92.6\text{ k}\Omega$

Ex: 7.9

$g_m r_o = \frac{2 I_D}{V_{OV}} \times \frac{V_A}{I_D} = \frac{2 V_A}{V_{OV}}$

$V_A = V_A' \times L = 6 \times 3 \times 0.18 = 3.24\text{ V}$

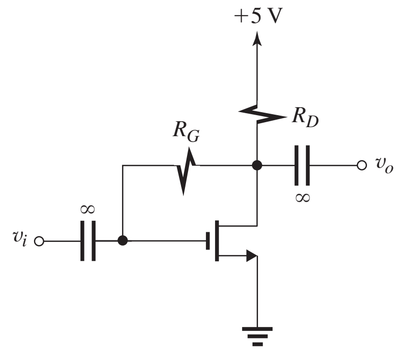
$g_m r_o = \frac{2 \times 3.24}{0.2} = 32.4\text{ V/V}$

Ex: 7.10

Refer to the solution of Example 7.3. From Eq. (7.47), $A_v \equiv \frac{v_o}{v_i} = -g_m R_D$ (note that R_L is absent).

Thus,

$g_m R_D = 25$



Substituting for $g_m = k_n V_{OV}$, we have

$k_n V_{OV} R_D = 25$

where $k_n = 1\ \text{mA/V}^2$, thus

$$V_{OV} R_D = 25 \qquad (1)$$

Next, consider the bias equation

$V_{GS} = V_{DS} = V_{DD} - R_D I_D$

Thus,

$V_t + V_{OV} = V_{DD} - R_D I_D$

Substituting $V_t = 0.7$ V, $V_{DD} = 5$ V, and

$$I_D = \frac{1}{2} k_n V_{OV}^2 = \frac{1}{2} \times 1 \times V_{OV}^2 = \frac{1}{2} V_{OV}^2$$

we obtain

$$0.7 + V_{OV} = 5 - \frac{1}{2} V_{OV}^2 R_D \qquad (2)$$

Equations (1) and (2) can be solved to obtain

$V_{OV} = 0.319$ V

and

$R_D = 78.5\ \text{k}\Omega$

The dc current I_D can be now found as

$$I_D = \frac{1}{2} k_n V_{OV}^2 = 50.9\ \mu\text{A}$$

To determine the required value of R_G we use Eq. (7.48), again noting that R_L is absent:

$$R_{\text{in}} = \frac{R_G}{1 + g_m R_D}$$

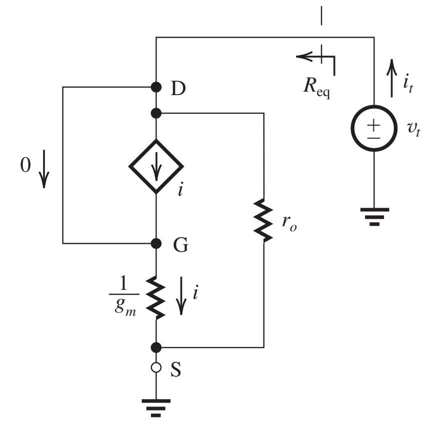
$$0.5\ \text{M}\Omega = \frac{R_G}{1 + 25}$$

$\Rightarrow R_G = 13\ \text{M}\Omega$

Finally, the maximum allowable input signal $\hat{v}_i$ can be found as follows:

$$\hat{v}_i = \frac{V_t}{|A_v| + 1} = \frac{0.7\ \text{V}}{25 + 1} = 27\ \text{mV}$$

Ex: 7.11



$$i_t = \frac{v_t}{r_o} + i = \frac{v_t}{r_o} + g_m v_t$$

$$\therefore R_{\text{eq}} = \frac{v_t}{i_t} = r_o \| \frac{1}{g_m}$$

Ex: 7.12

Given: $g_m = \left.\dfrac{\partial i_C}{\partial v_{BE}}\right|_{i_C = I_C}$

where $I_C = I_S e^{v_{BE}/V_T}$

$$\left.\frac{\partial i_C}{\partial v_{BE}}\right|_{i_C = I_C} = \frac{I_S e^{v_{BE}/V_T}}{V_T} = \frac{I_C}{V_T}$$

Thus,

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

Ex: 7.13

$$g_m = \frac{I_C}{V_T} = \frac{0.5\ \text{mA}}{25\ \text{mV}} = 20\ \text{mA/V}$$

Ex: 7.14

$I_C = 0.5$ mA (constant)

For $\beta = 50$:

$$g_m = \frac{I_C}{V_T} = \frac{0.5\ \text{mA}}{25\ \text{mV}} = 20\ \text{mA/V}$$

$$I_B = \frac{I_C}{\beta} = \frac{0.5}{50} = 10\ \mu\text{A}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{50}{20} = 2.5\ \text{k}\Omega$$

For $\beta = 200$,

$$g_m = \frac{I_C}{V_T} = 20\ \text{mA/V}$$

$$I_B = \frac{I_C}{\beta} = \frac{0.5\ \text{mA}}{200} = 2.5\ \mu\text{A}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{200}{20} = 10\ \text{k}\Omega$$

Ex: 7.15

$\beta = 100 \quad I_C = 1$ mA

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

$$r_e = \frac{V_T}{I_E} = \frac{\alpha V_T}{I_C} \simeq \frac{25 \text{ mV}}{1 \text{ mA}} = 25\ \Omega$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40} = 2.5 \text{ k}\Omega$$

Ex: 7.16

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

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

$= -40 \times 10$

$= -400$ V/V

$V_C = V_{CC} - I_C R_C$

$= 15 - 1 \times 10 = 5$ V

$v_C(t) = V_C + v_c(t)$

$= V_C + A_v v_{be}(t)$

$= 5 - 400 \times 0.005 \sin\omega t$

$= 5 - 2 \sin\omega t$

$i_B(t) = I_B + i_b(t)$

where

$$I_B = \frac{I_C}{\beta} = \frac{1 \text{ mA}}{100} = 10\ \mu\text{A}$$

and $i_b(t) = \dfrac{g_m v_{be}(t)}{\beta}$

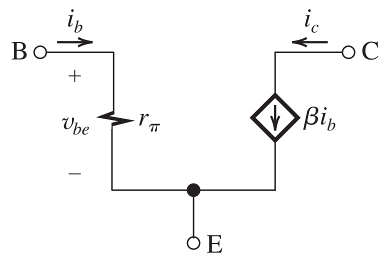
$$= \frac{40 \times 0.005 \sin\omega t}{100}$$

$= 2 \sin\omega t,\ \mu$A

Thus,

$i_B(t) = 10 + 2 \sin\omega t,\ \mu$A

Ex: 7.17



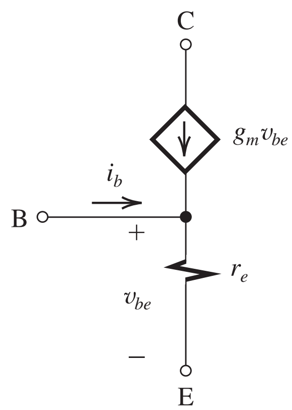
$$i_c = \beta i_b = \beta \frac{v_{be}}{r_\pi}$$

$$= \left(\frac{\beta}{r_\pi}\right) v_{be} = g_m v_{be}$$

$$i_e = i_b + \beta i_b = (\beta + 1) i_b = (\beta + 1) \frac{v_{be}}{r_\pi}$$

$$= \frac{v_{be}}{r_\pi/(\beta + 1)} = \frac{v_{be}}{r_e}$$

Ex: 7.18



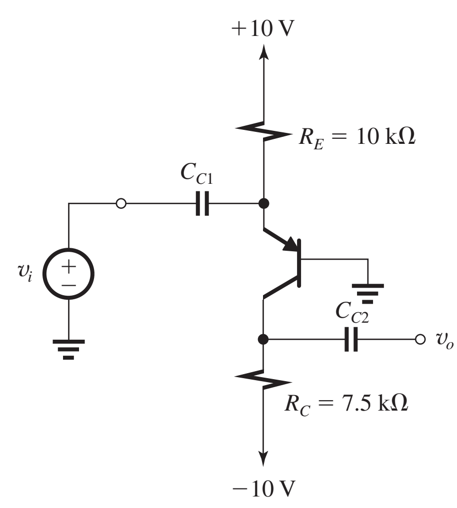
$$i_b = \frac{v_{be}}{r_e} - g_m v_{be}$$

$$= v_{be}\left(\frac{1}{r_e} - g_m\right)$$

$$= v_{be}\left(\frac{1}{r_{\pi/\beta+1}} - \frac{\beta}{r_\pi}\right)$$

$$= v_{be}\left(\frac{\beta + 1}{r_\pi} - \frac{\beta}{r_\pi}\right) = \frac{v_{be}}{r_\pi}$$

Ex: 7.19



$$I_E = \frac{10 - 0.7}{10} = 0.93 \text{ mA}$$

$$I_C = \alpha I_E = 0.99 \times 0.93$$

$$= 0.92 \text{ mA}$$

$$V_C = -10 + I_C R_C$$

$$= -10 + 0.92 \times 7.5 = -3.1 \text{ V}$$

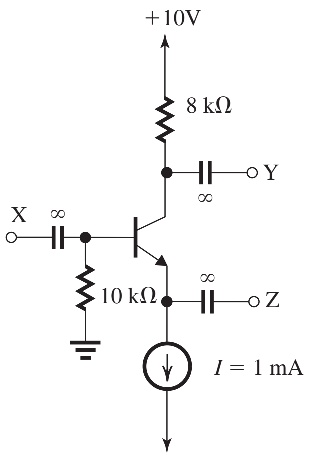
$$A_v = \frac{v_o}{v_i} = \frac{\alpha R_C}{r_e}$$

where $r_e = \dfrac{25 \text{ mV}}{0.93 \text{ mA}} = 26.9\ \Omega$

$$A_v = \frac{0.99 \times 7.5 \times 10^3}{26.9} = 276.2 \text{ V/V}$$

For $\hat{v}_i = 10$ mV, $\hat{v}_o = 276.2 \times 10 = 2.76$ V

Ex: 7.20



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

$$I_C = \frac{100}{101} \times 1 = 0.99 \text{ mA}$$

$$I_B = \frac{1}{101} \times 1 = 0.0099 \text{ mA}$$

(a) $V_C = 10 - 8 \times 0.99 = 2.08 \simeq 2.1$ V

$$V_B = -10 \times 0.0099 = -0.099 \simeq -0.1 \text{ V}$$

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

(b) $g_m = \dfrac{I_C}{V_T} = \dfrac{0.99}{0.025} \simeq 40$ mA/V

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40} \simeq 2.5 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{100}{0.99} = 101 \simeq 100 \text{ k}\Omega$$

(c) See figure below.
$R_{\text{sig}} = 2$ kΩ $R_B = 10$ kΩ $r_\pi = 2.5$ kΩ

$$g_m = 40 \text{ mA/V}$$

$R_C = 8$ kΩ $R_L = 8$ kΩ $r_o = 100$ kΩ

$$\frac{V_y}{V_{\text{sig}}} = \frac{V_\pi}{V_{\text{sig}}} \times \frac{V_y}{V_\pi}$$

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

$$= \frac{10 \,\|\, 2.5}{(10 \,\|\, 2.5) + 2} \times -40(8 \,\|\, 8 \,\|\, 100)$$

$$= -0.5 \times 40 \times 3.846 = -77 \text{ V/V}$$

If r_o is negelected, $\dfrac{V_y}{V_{\text{sig}}} = -80$, for an error of 3.9%.

Ex: 7.21

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.25}{0.25} = 2 \text{ mA/V}$$

$$R_{\text{in}} = \infty$$

$$A_{vo} = -g_m R_D = -2 \times 20 = -40 \text{ V/V}$$

$$R_o = R_D = 20 \text{ k}\Omega$$

$$A_v = A_{vo} \frac{R_L}{R_L + R_o} = -40 \times \frac{20}{20 + 20}$$

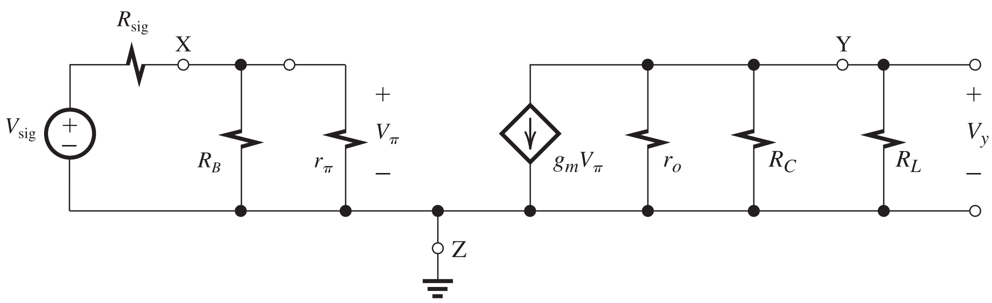
$$= -20 \text{ V/V}$$

$$G_v = A_v = -20 \text{ V/V}$$

$$\hat{v}_i = 0.1 \times 2V_{OV} = 0.1 \times 2 \times 0.25 = 0.05 \text{ V}$$

$$\hat{v}_o = 0.05 \times 20 = 1 \text{ V}$$

This figure belongs to Exercise 7.20c.



Ex: 7.22

$I_C = 0.5$ mA

$g_m = \frac{I_C}{V_T} = \frac{0.5 \text{ mA}}{0.025 \text{ V}} = 20$ mA/V

$r_\pi = \frac{\beta}{g_m} = \frac{100}{20} = 5$ kΩ

$R_{in} = r_\pi = 5$ kΩ

$A_{vo} = -g_m R_C = -20 \times 10 = -200$ V/V

$R_o = R_C = 10$ kΩ

$A_v = A_{vo} \frac{R_L}{R_L + R_o} = -200 \times \frac{5}{5+10}$

$= -66.7$ V/V

$G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_v = \frac{5}{5+5} \times -66.7$

$= -33.3$ V/V

$\hat{v}_\pi = 5 \text{ mV} \Rightarrow \hat{v}_{sig} = 2 \times 5 = 10$ mV

$\hat{v}_o = 10 \times 33.3 = 0.33$ V

Although a larger fraction of the input signal reaches the amplifier input, linearity considerations cause the output signal to be in fact smaller than in the original design!

Ex: 7.23 Refer to the solution to Exercise 7.21. If $\hat{v}_{sig} = 0.2$ V and we wish to keep $\hat{v}_{gs} = 50$ mV, then we need to connect a resistance $R_s = \frac{3}{g_m}$ in the source lead. Thus,

$R_s = \frac{3}{2 \text{ mA/V}} = 1.5$ kΩ

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

$= -\frac{20\|20}{0.5 + 1.5} = -5$ V/V

$\hat{v}_o = G_v \hat{v}_{sig} = 5 \times 0.2 = 1$ V (unchanged)

Ex: 7.24

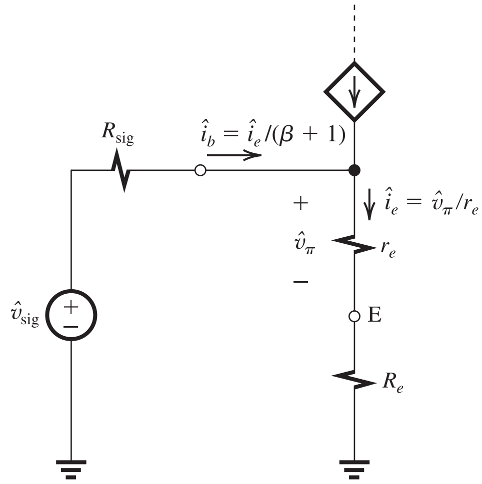
From the following figure we see that

$\hat{v}_{sig} = \hat{i}_b R_{sig} + \hat{v}_\pi + \hat{i}_e R_e$

$= \frac{\hat{i}_e}{\beta + 1} R_{sig} + \hat{v}_\pi + \hat{i}_e R_e$

$= \frac{\hat{v}_\pi}{(\beta+1) r_e} R_{sig} + \hat{v}_\pi + \frac{\hat{v}_\pi}{r_e} R_e$

$\hat{v}_{sig} = \hat{v}_\pi \left(1 + \frac{R_e}{r_e} + \frac{R_{sig}}{r_\pi}\right)$ Q.E.D



For $I_C = 0.5$ mA and $\beta = 100$,

$r_e = \frac{V_T}{I_E} = \frac{\alpha V_T}{I_C} = \frac{0.99 \times 25}{0.5} \simeq 50\ \Omega$

$r_\pi = (\beta + 1) r_e \simeq 5$ kΩ

For $\hat{v}_{sig} = 100$ mV, $R_{sig} = 10$ kΩ and with $\hat{v}_\pi$ limited to 10 mV, the value of R_e required can be found from

$100 = 10\left(1 + \frac{R_e}{50} + \frac{10}{5}\right)$

$\Rightarrow R_e = 350\ \Omega$

$R_{in} = (\beta + 1)(r_e + R_e) = 101 \times (50 + 350)$

$= 40.4$ kΩ

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

$= -100 \frac{10}{10 + 101 \times 0.4} = -19.8$ V/V

Ex: 7.25

$\frac{1}{g_m} = R_{sig} = 100\ \Omega$

$\Rightarrow g_m = \frac{1}{0.1 \text{ k}\Omega} = 10$ mA/V

But

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

Thus,

$10 = \frac{2 I_D}{0.2}$

$\Rightarrow I_D = 1$ mA

$G_v = \frac{R_{in}}{R_{in} + R_{sig}} \times g_m R_D$

$= 0.5 \times 10 \times 2 = 10$ V/V

Ex: 7.26

$I_C = 1 \text{ mA}$

$r_e = \dfrac{V_T}{I_E} \simeq \dfrac{V_T}{I_C} = \dfrac{25 \text{ mV}}{1 \text{ mA}} = 25\ \Omega$

$R_{\text{in}} = r_e = 25\ \Omega$

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

$R_o = R_C = 5\text{ k}\Omega$

$A_v = A_{vo} \dfrac{R_L}{R_L + R_o} = 200 \times \dfrac{5}{5+5} = 100 \text{ V/V}$

$G_v = \dfrac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \times A_v$

$= \dfrac{25}{25 + 5000} \times 100 = 0.5 \text{ V/V}$

Ex: 7.27

$R_{\text{in}} = r_e = 50\ \Omega$

$\Rightarrow I_E = \dfrac{V_T}{r_e} = \dfrac{25 \text{ mV}}{50\ \Omega} = 0.5 \text{ mA}$

$I_C \simeq I_E = 0.5 \text{ mA}$

$G_v = \dfrac{R_C \| R_L}{r_e + R_{\text{sig}}}$

$40 = \dfrac{R_C \| R_L}{(50 + 50)\Omega}$

$R_C \| R_L = 4\text{ k}\Omega$

Ex: 7.28 Refer to Fig. 7.42(c).

$R_o = 100\ \Omega$

Thus,

$\dfrac{1}{g_m} = 100\ \Omega \Rightarrow g_m = 10 \text{ mA/V}$

But

$g_m = \dfrac{2I_D}{V_{OV}}$

Thus,

$I_D = \dfrac{10 \times 0.25}{2} = 1.25 \text{ mA}$

$\hat{v}_o = \hat{v}_i \times \dfrac{R_L}{R_L + R_o} = 1 \times \dfrac{1}{1 + 0.1} = 0.91 \text{ V}$

$\hat{v}_{gs} = \hat{v}_i \dfrac{\dfrac{1}{g_m}}{\dfrac{1}{g_m} + R_L} = 1 \times \dfrac{0.1}{0.1 + 1} = 91 \text{ mV}$

Ex: 7.29

$R_o = 200\ \Omega$

$\dfrac{1}{g_m} = 200\ \Omega$

$\Rightarrow g_m = 5 \text{ mA/V}$

But

$gm = k_n' \left(\dfrac{W}{L}\right) V_{OV}$

Thus,

$5 = 0.4 \times \dfrac{W}{L} \times 0.25$

$\Rightarrow \dfrac{W}{L} = 50$

$I_D = \dfrac{1}{2} k_n' \dfrac{W}{L} V_{OV}^2$

$= \dfrac{1}{2} \times 0.4 \times 50 \times 0.25^2$

$= 0.625 \text{ mA}$

$R_L = 1\text{ k}\Omega$ to $10\text{ k}\Omega$

Correspondingly,

$G_v = \dfrac{R_L}{R_L + R_o} = \dfrac{R_L}{R_L + 0.2}$

will range from

$G_v = \dfrac{1}{1 + 0.2} = 0.83 \text{ V/V}$

to

$G_v = \dfrac{10}{10 + 0.2} = 0.98 \text{ V/V}$

Ex: 7.30

$I_C = 5 \text{ mA}$

$r_e = \dfrac{V_T}{I_E} \simeq \dfrac{V_T}{I_C} = \dfrac{25 \text{ mV}}{5 \text{ mA}} = 5\ \Omega$

$R_{\text{sig}} = 10\text{ k}\Omega \quad R_L = 1\text{ k}\Omega$

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

$= 101 \times (0.005 + 1)$

$= 101.5\text{ k}\Omega$

$G_{vo} = 1 \text{ V/V}$

$R_{\text{out}} = r_e + \dfrac{R_{\text{sig}}}{\beta + 1}$

$= 5 + \dfrac{10{,}000}{101} = 104\ \Omega$

$G_v = \dfrac{R_L}{R_L + r_e + \dfrac{R_{\text{sig}}}{\beta + 1}} = \dfrac{R_L}{R_L + R_{\text{out}}}$

$= \dfrac{1}{1 + 0.104} = 0.91 \text{ V/V}$

$v_\pi = v_{\text{sig}} \dfrac{r_e}{r_e + R_L + \dfrac{R_{\text{sig}}}{\beta + 1}}$

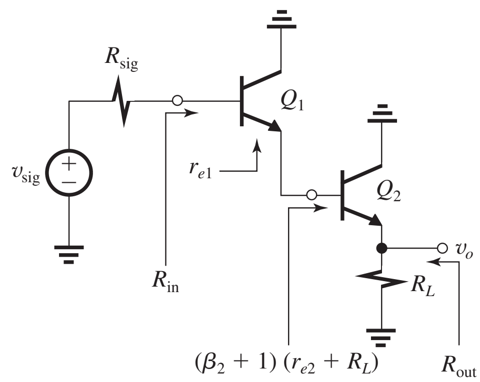
$$\hat{v}_{sig} = \hat{v}_\pi \left[1 + \frac{R_L}{r_e} + \frac{R_{sig}}{(\beta+1)\, r_e}\right]$$

$$\hat{v}_{sig} = 5\left[1 + \frac{1000}{5} + \frac{10{,}000}{101 \times 5}\right] = 1.1 \text{ V/V}$$

Correspondingly,

$$\hat{v}_o = G_v \times 1.1 = 0.91 \times 1.1 = 1 \text{ V}$$

Ex: 7.31



From the figure we can write

$$R_{in} = (\beta_1 + 1)\,[r_{e1} + (\beta_2 + 1)(r_{e2} + R_L)]$$

$$R_{out} = R_L \parallel \left[r_{e2} + \frac{r_{e1} + R_{sig}/(\beta_1 + 1)}{\beta_2 + 1}\right]$$

$$\frac{v_o}{v_{sig}} = \frac{R_L}{R_L + r_{e2} + \dfrac{r_{e1} + R_{sig}/(\beta_1+1)}{\beta_2 + 1}}$$

For $I_{E2} = 5$ mA, $\beta_1 = \beta_2 = 100$, $R_L = 1$ kΩ, and $R_{sig} = 100$ kΩ, we obtain

$$r_{e2} = \frac{25 \text{ mV}}{5 \text{ mA}} = 5\ \Omega$$

$$I_{E1} = \frac{5}{\beta_2 + 1} = \frac{5}{101} \simeq 0.05 \text{ mA}$$

$$r_{e1} = \frac{25 \text{ mV}}{0.05 \text{ mA}} = 500\ \Omega$$

$$R_{in} = 101 \times (0.5 + 101 \times 1.005) = 10.3 \text{ M}\Omega$$

$$R_{out} = 1 \parallel \left[0.005 + \frac{0.5 + (100/101)}{101}\right] \simeq 20\ \Omega$$

$$\frac{v_o}{v_{sig}} = \frac{1}{1 + 0.005 + \dfrac{0.5 + (100/101)}{101}}$$

$$= 0.98 \text{ V/V}$$

Ex: 7.32

$$I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2$$

$$0.5 = \frac{1}{2} \times 1 (V_{GS} - 1)^2$$

$$\Rightarrow V_{GS} = 2 \text{ V}$$

If $V_t = 1.5$ V, then

$$I_D = \frac{1}{2} \times 1 \times (2 - 1.5)^2 = 0.125 \text{ mA}$$

$$\Rightarrow \frac{\Delta I_D}{I_D} = \frac{0.125 - 0.5}{0.5} = -0.75 = -75\%$$

Ex: 7.33

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{5 - 2}{0.5} = 6 \text{ k}\Omega$$

$$\rightarrow R_D = 6.2 \text{ k}\Omega$$

$$I_D = \frac{1}{2} k_n' \frac{W}{L} V_{OV}^2 \Rightarrow 0.5 = \frac{1}{2} \times 1 \times V_{OV}^2$$

$$\Rightarrow V_{OV} = 1 \text{ V}$$

$$\Rightarrow V_{GS} = V_{OV} + V_t = 1 + 1 = 2 \text{ V}$$

$$\Rightarrow V_S = -2 \text{ V}$$

$$R_S = \frac{V_S - V_{SS}}{I_D} = \frac{-2 - (-5)}{0.5} = 6 \text{ k}\Omega$$

$$\rightarrow R_S = 6.2 \text{ k}\Omega$$

If we choose $R_D = R_S = 6.2$ kΩ, then I_D will change slightly:

$$I_D = \frac{1}{2} \times 1 \times (V_{GS} - 1)^2.$$

Also,

$$V_{GS} = -V_S = 5 - R_S I_D$$

Thus,

$$2 I_D = (4 - 6.2 I_D)^2$$

$$\Rightarrow 38.44 I_D^2 - 51.6 I_D^2 + 16 = 0$$

$$\Rightarrow I_D = 0.49 \text{ mA},\ 0.86 \text{ mA}$$

$I_D = 0.86$ results in $V_S > 0$ or $V_S > V_G$, which is not acceptable. Therefore $I_D = 0.49$ mA and

$$V_S = -5 + 6.2 \times 0.49 = -1.96 \text{ V}$$

$$V_D = 5 - 6.2 \times 0.49 = +1.96 \text{ V}$$

R_G should be selected in the range of 1 MΩ to 10 MΩ.

Ex: 7.34

$$I_D = 0.5 \text{ mA} = \frac{1}{2} k_n' \frac{W}{L} V_{OV}^2$$

$$\Rightarrow V_{OV}^2 = \frac{0.5 \times 2}{1} = 1$$

$$\Rightarrow V_{OV} = 1 \text{ V} \Rightarrow V_{GS} = 1 + 1 = 2 \text{ V}$$

$= V_D \Rightarrow R_D = \dfrac{5-2}{0.5} = 6\ \text{k}\Omega$

$\Rightarrow R_D = 6.2\ \text{k}\Omega$ (standard value). For this R_D we have to recalculate I_D:

$$I_D = \frac{1}{2} \times 1 \times (V_{GS} - 1)^2$$

$$= \frac{1}{2}(V_{DD} - R_D I_D - 1)^2$$

$$(V_{GS} = V_D = V_{DD} - R_D I_D)$$

$$I_D = \frac{1}{2}(4 - 6.2 I_D)^2 \Rightarrow I_D \cong 0.49\ \text{mA}$$

$$V_D = 5 - 6.2 \times 0.49 = 1.96\ \text{V}$$

Ex: 7.35 Refer to Example 7.12.

(a) For design 1, $R_E = 3\ \text{k}\Omega$, $R_1 = 80\ \text{k}\Omega$, and $R_2 = 40\ \text{k}\Omega$. Thus, $V_{BB} = 4$ V.

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_1 \| R_2}{\beta + 1}}$$

For the nominal case, $\beta = 100$ and

$$I_E = \frac{4 - 0.7}{3 + \dfrac{40\|80}{101}} = 1.01 \simeq 1\ \text{mA}$$

For $\beta = 50$,

$$I_E = \frac{4 - 0.7}{3 + \dfrac{40\|80}{51}} = 0.94\ \text{mA}$$

For $\beta = 150$,

$$I_E = \frac{4 - 0.7}{3 + \dfrac{40\|80}{151}} = 1.04\ \text{mA}$$

Thus, I_E varies over a range approximately 10% of the nominal value of 1 mA.

(b) For design 2, $R_E = 3.3\ \text{k}\Omega$, $R_1 = 8\ \text{k}\Omega$, and $R_2 = 4\ \text{k}\Omega$. Thus, $V_{BB} = 4$ V. For the nominal case, $\beta = 100$ and

$$I_E = \frac{4 - 0.7}{3.3 + \dfrac{4\|8}{101}} = 0.99 \simeq 1\ \text{mA}$$

For $\beta = 50$,

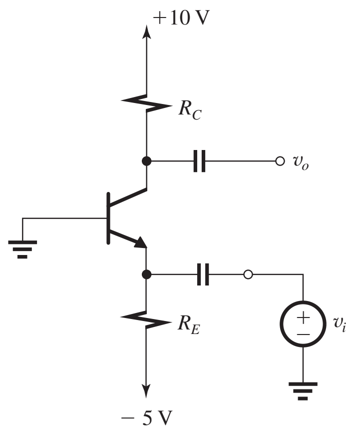
$$I_E = \frac{4 - 0.7}{3.3 + \dfrac{4\|8}{51}} = 0.984\ \text{mA}$$

For $\beta = 150$,

$$I_E = \frac{4 - 0.7}{3.3 + \dfrac{4\|8}{151}} = 0.995\ \text{mA}$$

Thus, I_E varies over a range of 1.1% of the nominal value of 1 mA. Note that lowering the resistances of the voltage divider considerably decreases the dependence on the value of β, a highly desirable result obtained at the expense of increased current and hence power dissipation.

Ex: 7.36 Refer to Fig. 7.55. Since the circuit is to be used as a common-base amplifier, we can dispense with R_B altogether and ground the base; thus $R_B = 0$. The circuit takes the form shown in the figure below.



To establish $I_E = 1$mA,

$$I_E = \frac{5 - V_{BE}}{R_E}$$

$$1\ \text{mA} = \frac{5 - 0.7}{R_E}$$

$$\Rightarrow R_E = 4.3\ \text{k}\Omega$$

The voltage gain $\dfrac{v_o}{v_i} = g_m R_C$, where

$$g_m = \frac{I_C}{V_T} = 40\ \text{mA/V}.$$

To maximize the voltage gain, we select R_C as large as possible, consistent with obtaining a ± 2-V signal swing at the collector. To maintain active-mode operation at all times, the collector voltage should not be allowed to fall below the value that causes the CBJ to become forward biased, namely, -0.4 V. Thus, the lowest possible dc voltage at the collector is $-0.4\ \text{V} + 2\text{V} = +1.6$ V. Correspondingly,

$$R_C = \frac{10 - 1.6}{I_C} \simeq \frac{10 - 1.6}{1\ \text{mA}} = 8.4\ \text{k}\Omega$$

Ex: 7.37 Refer to Fig. 7.56. For $I_E = 1$ mA and $V_C = 2.3$ V,

$$I_E = \frac{V_{CC} - V_C}{R_C}$$

$$1 = \frac{10 - 2.3}{R_C}$$

$$\Rightarrow R_C = 7.7\ \text{k}\Omega$$

Now, using Eq. (7.147), we obtain

$$I_E = \frac{V_{CC} - V_{BE}}{R_C + \dfrac{R_B}{\beta + 1}}$$

$$1 = \frac{10 - 0.7}{7.7 + \dfrac{R_B}{101}}$$

$$\Rightarrow R_B = 162 \text{ k}\Omega$$

Selecting standard 5% resistors (Appendix J), we use

$$R_B = 160 \text{ k}\Omega \qquad \text{and} \qquad R_C = 7.5 \text{ k}\Omega$$

The resulting value of I_E is found as

$$I_E = \frac{10 - 0.7}{7.5 + \dfrac{160}{101}} = 1.02 \text{ mA}$$

and the collector voltage will be

$$V_C = V_{CC} - I_E R_C = 2.3 \text{ V}$$

Ex: 7.38 Refer to Fig. 7.57(b).

$V_S = 3.5$ V and $I_D = 0.5$ mA; thus

$$R_S = \frac{V_S}{I_D} = \frac{3.5}{0.5} = 7 \text{ k}\Omega$$

$V_{DD} = 15$ V and $V_D = 6$ V; thus

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{15 - 6}{0.5 \text{ mA}} = 18 \text{ k}\Omega$$

To obtain V_{OV}, we use

$$I_D = \frac{1}{2} k_n V_{OV}^2$$

$$0.5 = \frac{1}{2} \times 4V_{OV}^2$$

$$\Rightarrow V_{OV} = 0.5 \text{ V}$$

Thus,

$$V_{GS} = V_t + V_{OV} = 1 + 0.5 = 1.5 \text{ V}$$

We now can obtain the dc voltage required at the gate,

$$V_G = V_S + V_{GS} = 3.5 + 1.5 = 5 \text{ V}$$

Using a current of 2 µA in the voltage divider, we have

$$R_{G2} = \frac{5 \text{ V}}{2 \text{ µA}} = 2.5 \text{ M}\Omega$$

The voltage drop across R_{G1} is 10 V, thus

$$R_{G1} = \frac{10 \text{ V}}{2 \text{ µA}} = 5 \text{ M}\Omega$$

This completes the bias design. To obtain g_m and r_o, we use

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.5}{0.5} = 2 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_D} = \frac{100}{0.5} = 200 \text{ k}\Omega$$

Ex: 7.39 Refer to Fig. 7.57(a) and (c) and to the values found in the solution to Exercise 7.38 above.

$$R_{\text{in}} = R_{G1} \| R_{G2} = 5 \| 2.5 = 1.67 \text{ M}\Omega$$

$$R_o = R_D \| r_o = 18 \| 200 = 16.5 \text{ k}\Omega$$

$$G_v = -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m (r_o \| R_D \| R_L)$$

$$= -\frac{1.67}{1.67 + 0.1} \times 2 \times (200 \| 18 \| 20)$$

$$= -17.1 \text{ V/V}$$

Ex: 7.40 To reduce v_{gs} to half its value, the unbypassed R_s is given by

$$R_s = \frac{1}{g_m}$$

From the solution to Exercise 7.38 above, $g_m = 2$ mA/V. Thus

$$R_s = \frac{1}{2} = 0.5 \text{ k}\Omega$$

Neglecting r_o, G_v is given by

$$G_v = -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \times -\frac{R_D \| R_L}{\dfrac{1}{g_m} + R_s}$$

$$= -\frac{1.67}{1.67 + 0.1} \times \frac{18 \| 20}{0.5 + 0.5}$$

$$= -8.9 \text{ V/V}$$

Ex: 7.41 Refer to Fig. 7.58(a). For $V_B = 5$ V and 50-µA current through R_{B2}, we have

$$R_{B2} = \frac{5 \text{ V}}{0.05 \text{ mA}} = 100 \text{ k}\Omega$$

The base current is

$$I_B = \frac{I_E}{\beta + 1} \simeq \frac{0.5 \text{ mA}}{100} = 5 \text{ µA}$$

The current through R_{B1} is

$$I_{R_{B1}} = I_B + I_{R_{B2}} = 5 + 50 = 55 \text{ µA}$$

Since the voltage drop across R_{B1} is $V_{CC} - V_B = 10$ V, the value of R_{B1} can be found from

$$R_{B1} = \frac{10 \text{ V}}{0.055 \text{ µA}} = 182 \text{ k}\Omega$$

The value of R_E can be found from

$$I_E = \frac{V_B - V_{BE}}{R_E}$$

$$\Rightarrow R_E = \frac{5 - 0.7}{0.5} = 8.6 \text{ k}\Omega$$

The value of R_C can be found from

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