INTERNATIONAL SIXTH EDITION

SEDRA/SMITH

INSTRUCTOR'S SOLUTIONS MANUAL FOR
MICROELECTRONIC CIRCUITS

This version of the text has been adapted and customized. Not for distribution in the U.S.A. or Canada.

This Instructor's Solutions Manual contains complete solutions for the 1000+ end-of-chapter problems created specifically for the International Sixth Edition of Sedra/Smith's *Microelectronic Circuits*.

OXFORD
UNIVERSITY PRESS

Oxford University Press, Inc., publishes works that further Oxford University's
objective of excellence in research, scholarship, and education.

Oxford New York
Auckland Cape Town Dar es Salaam Hong Kong Karachi
Kuala Lumpur Madrid Melbourne Mexico City Nairobi
New Delhi Shanghai Taipei Toronto

With offices in
Argentina Austria Brazil Chile Czech Republic France Greece
Guatemala Hungary Italy Japan Poland Portugal Singapore
South Korea Switzerland Thailand Turkey Ukraine Vietnam

Published by Oxford University Press, Inc.
198 Madison Avenue, New York, New York 10016
http://www.oup.com

ISBN: 978-0-19-976570-6

Printing number: 9 8 7 6 5 4 3 2 1

Printed in the United States of America
on acid-free paper

Contents

Preface

This manual contains complete solutions for all exercises and end-of-chapter problems included in the book *Microelectronic Circuits, International Sixth Edition*, by Adel S. Sedra and Kenneth C. Smith.

We are grateful to Mandana Amiri, Shahriar Mirabbasi, Roberto Rosales, Alok Berry, Norman Cox, John Wilson, Clark Kinnaird, Roger King, Marc Cahay, Kathleen Muhonen, Angela Rasmussen, Mike Green, John Davis, Dan Moore, and Bob Krueger, who assisted in the preparation of this manual. We also acknowledge the contribution of Ralph Duncan and Brian Silveira to previous editions of this manual.

Communications concerning detected errors should be sent to the attention of the Engineering Editor, mail to Oxford University Press, 198 Madison Avenue, New York, New York, USA 10016 or e-mail to higher.education.us@oup.com. Needless to say, they would be greatly appreciated.

A website for the book is available at www.oup.com/sedra-xse

Ex: 1.1 When output terminals are open circuited

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

For circuit a. $i_{sc} = \dfrac{v_S(t)}{R_S}$

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

For equivalency

$R_S i_S(t) = v_S(t)$

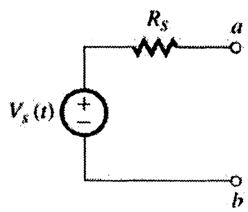


Figure 1.1a

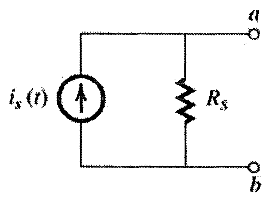
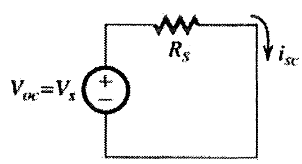


Figure 1.1b

Ex: 1.2

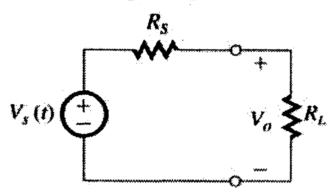


$V_{OC} = 10 \text{ mV}$

$i_{SC} = 10 \ \mu\text{A}$

$R = \dfrac{V}{i} = \dfrac{10 \text{ mV}}{10 \ \mu\text{A}} = 1 \text{ k}\Omega$

Ex: 1.3 Using voltage divider



$v_o(t) = v_S(t) \times \dfrac{R_L}{R_S + R_L}$

Given $v_S(t) = 10 \text{ mV}$ and $R_S = 1 \text{ k}\Omega$

If $R_L = 100 \text{ k}\Omega$

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

If $R_L = 10 \text{ k}\Omega$

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

If $R_L = 1 \text{ k}\Omega$

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

If $R_L = 100 \ \Omega$

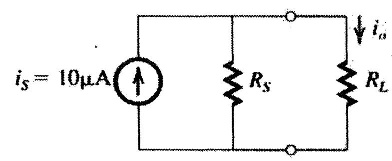
$v_O = 10 \text{ mV} \times \dfrac{100}{100 + 1 \text{ K}} \simeq 0.91 \text{ V}$

80% of source voltage $= 10 \text{ mV} \times \dfrac{80}{100} = 8 \text{ mV}$

If R_L gives 8 mV when $R_S = 1 \text{ k}\Omega$, then

$8 = 10 \times \dfrac{R_L}{1 + R_L} \Rightarrow R_L = 4 \text{ k}\Omega$

Ex: 1.4 Using current divider



$i_O = i_S \times \dfrac{R_S}{R_S + R_L}$

Given $i_S = 10 \ \mu\text{A}$, $R_S = 100 \text{ k}\Omega$

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

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

$\simeq 0.9 \ \mu\text{A}$

80% of source current $= 10 \times \dfrac{80}{100} = 8 \ \mu\text{A}$

If a load R_L gives 80% of the source current, then

$8 \ \mu\text{A} = 10 \ \mu\text{A} \times \dfrac{100}{100 + R_L}$

$\Rightarrow R_L = 25 \text{ k}\Omega$

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

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

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

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

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

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

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

Since it starts with channel 14, it will go from channel 14 to channel 69

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

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

Alteratively,

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

$= \left(\frac{4V}{\sqrt{2}\pi}\right)^2\frac{1}{R} + \left(\frac{4V}{3\sqrt{2}\pi}\right)^2\frac{1}{R} + \left(\frac{4V}{5\sqrt{2}\pi}\right)^2\frac{1}{R} + \ldots$

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

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

$5\frac{8}{\pi^2}\left(1 + \frac{1}{9} + \frac{1}{25} + \frac{1}{49} + \frac{1}{81}\right) = 0.96$

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 distinct values between 0 and +15 V. Thus,

$v_A = 0\text{ V} \Rightarrow D = 0000$

$v_A = 1\text{ V} \Rightarrow D = 0001$

$v_A = 2\text{ V} \Rightarrow D = 0010$

$v_A = 15\text{ V} \Rightarrow D = 1111$

(b) (i) +1 V (ii) +2 V (iii) +4 V (iv) +8 V

(c) The closest discrete value represented by D is 5 V; thus $D = 0101$. The error is -0.2 V or $-0.2/5.2 \times 100 = -4\%$

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

Current gain $= 20\log 1000 = 60\text{ dB}$

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

$= 10\log 10^5 = 50\text{ dB}$

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

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

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

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

Ex: 1.12

$v_o = 1 \times \frac{10}{10^6 + 10} \simeq 10^{-5}\text{ V} = 10\ \mu\text{V}$

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

With the buffer amplifier:

$v_O = 1 \times \frac{R_i}{R_i + R_S} \times A_{vo} \times \frac{R_L}{R_L + R_o}$

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

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

Voltage gain $= \frac{v_O}{v_S} = \frac{0.25\text{ V}}{1\text{ V}} = 0.25\text{ V/V}$

$= -12\text{ dB}$

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

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

$v_i = 0.5\text{ V}$ and

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

Thus,

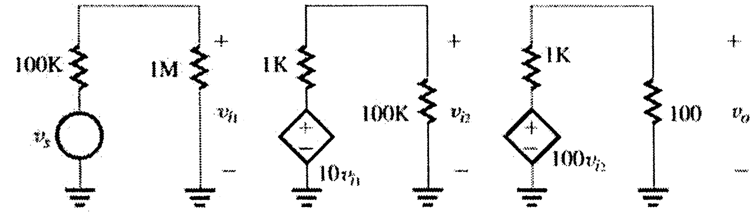
$P_i = 0.5 \times 0.5 = 0.25\ \mu\text{W}$

and,

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

$10\log A_p = 44\text{ dB}$

This figure belongs to Exercise 1.15



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

Output voltage with load connected

$$= A_{v_o} v_i \frac{R_L}{R_L + R_O}$$

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

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

$$P_L = \frac{v_O^2}{R_L} = \left(A_{vo} v_i \frac{R_L}{R_L + R_O}\right)^2 / R_L$$

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

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

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

$10 \log A_p = 44$ dB

Ex: 1.15 Without stage 3 (see figure above)

$$\frac{v_0}{v_S} = \left(\frac{1\ \text{M}}{100\ \text{K} + 1\ \text{M}}\right)(10)\left(\frac{100\ \text{K}}{100\ \text{K} + 1\ \text{K}}\right)$$

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

$$\frac{v_0}{v_S} = (0.909)(10)(0.9901)(100)(0.0909) = 81.8\ \text{V}$$

Ex: 1.16 Given $v_s = 1$ mV

$\frac{v_{i1}}{v_s} = 0.909$ So

$$v_{i1} = 0.909\ v_S = 0.909 \times 1 = 0.909\ \text{mV}$$

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

For $v_s = 1$ mV

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

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

= 818 V/V

For $v_s = 1$ mV

$$v_{i3} = 818\ v_S = 818 \times 1 = 818\ \text{mV}$$

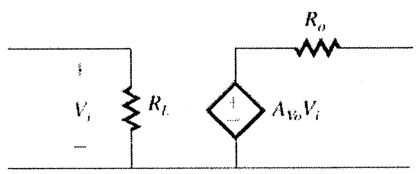
$$\frac{v_{iL}}{v_S} = \frac{v_{iL}}{v_{i3}} \times \frac{v_{i3}}{v_{i2}} \times \frac{v_{i2}}{v_{i1}} \times \frac{v_{i1}}{v_S}$$

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

For $V_s = 1$ mV

$$V_{iL} = 744 \times 1\ \text{mV} = 744\ \text{mV}$$

Ex: 1.17 Using voltage amplifier model, it can be represented as



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

$R_o = 10\ \Omega$

$A_{vo} = A_{v1} \times A_{v2} = 9.9 \times 90.9 = 900$ 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

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

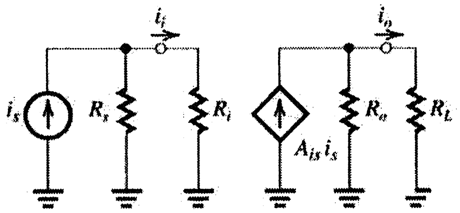
For $R_L = 1000\ \Omega$

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 to 810 V/V

Ex: 1.18



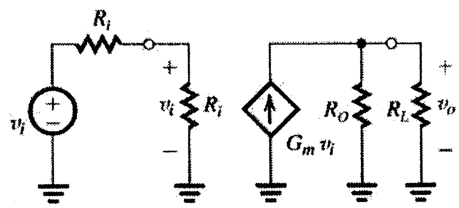
$$i_i = i_S \frac{R_S}{R_S + R_i}$$

$$i_O = A_{is} i_i \frac{R_O}{R_O + R_L} = A_{is} i_S \frac{R_S}{R_S + R_i} \frac{R_O}{R_O + R_L}$$

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



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

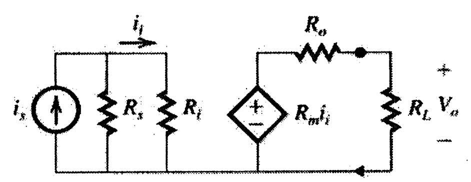
$$v_S = G_m v_i (R_O \parallel R_L)$$

$$= G_m v_S \frac{R_i}{R_i + R_S}(R_O \parallel R_L)$$

Thus,

$$\frac{v_O}{v_S} = G_m \frac{R_i}{R_i + R_S}(R_O \parallel R_L)$$

Ex: 1.20 Using transresistance circuit model the circuit will be



$$\frac{i_i}{i_S} = \frac{R_S}{R_i + R_S}$$

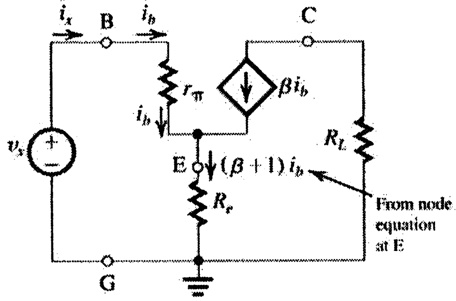
$$V_O = R_m i_i \times \frac{R_L}{R_L + R_O}$$

$$\frac{V_O}{i_i} = R_m \frac{R_L}{R_L + R_O}$$

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



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

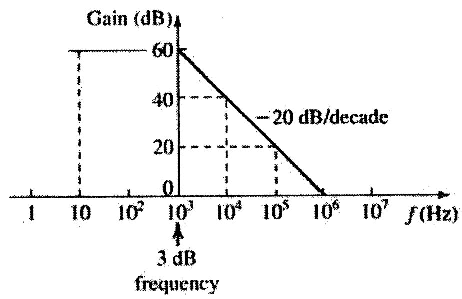
$$= i_b [r_\pi + (\beta + 1) R_e]$$

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

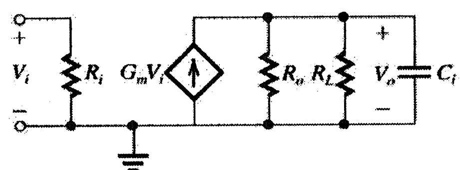
$$R_{in} \equiv \frac{v_x}{i_x} = \frac{v_b}{i_b} = r_\pi + (\beta + 1) R_e$$

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, $\frac{V_O}{V_i} = \frac{G_m}{\frac{1}{R_O} + \frac{1}{R_L}} \frac{1}{1 + \frac{sC_L}{\frac{1}{R_O} + \frac{1}{R_L}}}$

which is of the STC LP type.

$$\text{DC gain} = \frac{G_m}{\frac{1}{R_O} + \frac{1}{R_L}} \geq 100$$

$$\frac{1}{R_O} + \frac{1}{R_L} \le \frac{G_m}{100} = \frac{10}{100} = 0.1 \text{ mA/V}$$

$$\frac{1}{R_L} \le 0.1 - \frac{1}{50} = 0.08 \text{ mA/V}$$

$$R_L \ge \frac{1}{0.08} \text{ k}\Omega = 12.5 \text{ k}\Omega$$

$$\omega_O = \frac{1}{C_L}\left(\frac{1}{R_O} + \frac{1}{R_L}\right) \ge 2\pi \times 100 \text{ kHz}$$

$$C_L \le \frac{\left(\frac{1}{50 \times 10^3} + \frac{1}{12.5 \times 10^3}\right)}{2\pi \times 10^5} = 159.2 \text{ pF}$$

Ex: 1.24 Refer to Fig. E1.23

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

which is a HP STC function.

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

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

Ex: 1.25

T = 50 K

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

$= 7.3 \times 10^{15}(50)^{3/2}\, e^{-1.12/(2 \times 8.62 \times 10^{-5} \times 50)}$

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

T = 350 K

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

$= 7.3 \times 10^{15}(350)^{3/2}\, e^{-1.12/(2 \times 8.62 \times 10^{-5} \times 350)}$

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

Ex: 1.26

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

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: 1.27

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: 1.28

a. υ_n-drift $= -\mu_n E$

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

We use

υ_n-drift $= -\mu_n E$

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

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

b. Time taken to cross 2 μm

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

c. In n-si drift current density J_n in

$J_n = qn\mu_n E$

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

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

d. Drift current $I_n = Aqn\,\upsilon_n$-drift

$= Aqn\mu_n E$

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

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

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

Ex: 1.29 $J_n = q D_n \dfrac{dn(x)}{dx}$

From Figure E1.29

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

$D_n = 35\text{ cm}^3/\text{s} = 35 \times (10^4)^2(\mu\text{m})^2/\text{s}$

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

$\dfrac{dn}{dx} = \dfrac{10^5 - 0}{1} = 10^5\mu\text{m}^{-2}$

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

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

$= 56 \times 10^{-6}\text{ A}/(\mu\text{m})^2$

$= 56\ \mu\text{ A}/(\mu\text{m})^2$

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

$\Rightarrow A = \dfrac{1\text{ mA}}{J_n} = \dfrac{10^3\ \mu A}{56\ \mu A/(\mu\text{m})^2} \simeq 18\ \mu\text{m}^2$

Ex: 1.30

Using equation 1.45

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

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

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

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

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

Ex: 1.31

Equation 3.50

$W = \sqrt{\dfrac{2\epsilon_S}{q}\left(\dfrac{1}{N_A} + \dfrac{1}{N_D}\right)V_O}$

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

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

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

Ex: 1.32

In a p⁺ n diode $N_A >> N_D$

Equation 1.50 $W = \sqrt{\frac{2\epsilon_S}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_O}$

We can neglect the term $\frac{1}{N_A}$ as Compared to $\frac{1}{N_D}$

since $N_A >> N_D$

$$\simeq \sqrt{\frac{2\epsilon_S}{qN_D} \cdot V_O}$$

Equation 1.51 $X_n = W\frac{N_A}{N_A + N_D}$

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

$$= W$$

Equation 1.52 $X_p = W\frac{N_A}{N_A + N_D}$

since $N_A >> N_D$

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

Equation 1.53 $Q_J = Aq\left(\frac{N_A N_D}{N_A + N_D}\right)$

$$W \simeq Aq\frac{N_A N_D}{N_A} \cdot W \text{ since } N_A >> N_D$$

$$\simeq AqN_D W$$

Equation 1.54 $Q_J = A\sqrt{2\epsilon_S q\left(\frac{N_A N_D}{N_A + N_D}\right)V_O}$

$$\simeq A\sqrt{2\epsilon_S q\left(\frac{N_A N_D}{N_A}\right)V_O} \text{ since } N_A >> N_D$$

$$= A\sqrt{2\epsilon_S q N_D V_O}$$

Ex: 1.33

In example 1.29 $N_A = 10^{18}/\text{cm}^3$ and

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

In the n-region of this pn juction diode

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

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

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: 1.34

Equation 1.38 $I_S = Aqn_i^2\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right)$

since $\frac{D_p}{L_p}$ and $\frac{D_n}{L_n}$ here approximately

similar values, if $N_A >> N_D$ 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: 1.35

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

$$= 10^{-4} \times 1.6 \times 10^{-19} \times (1.5 \times 10^1)^2$$

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

$$= 1.45 \times 10^{-14} \text{ A}$$

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

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

$$= 0.2 \text{ mA}$$

Ex: 1.36

$$W = \sqrt{\frac{2\epsilon_S}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_O - V_F)}$$

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

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

Ex: 1.37

$$W = \sqrt{\frac{2\epsilon_S}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_O + V_R)}$$

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

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

Using equation 1.53

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

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

$$= 9.63\ pC$$

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: 1.38

Equation 1.72

$$C_{jo} = A\sqrt{\left(\frac{\epsilon_S q}{2}\right)\left(\frac{N_A N_D}{N_A + N_D}\right)\left(\frac{1}{V_O}\right)}$$

$$= 10^{-4}\sqrt{\left(\frac{1.04 \times 10^{-12} \times 1.6 \times 10^{-19}}{2}\right)}\sqrt{\left(\frac{10^{18} \times 10^{16}}{10^{18} + 10^{16}}\right)\left(\frac{1}{0.814}\right)}$$

$$= 3.2\ pF$$

Equation 1.71

$$C_j = \frac{C_{jO}}{\sqrt{1 + \frac{V_R}{V_O}}}$$

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

$$= 1.72\ pF$$

Ex: 1.39

$$C_d = \frac{dQ}{dV} = \frac{d}{dV}(\tau_T I)$$

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

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

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

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

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

Ex: 1.40

Equation 1.74

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

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

$$= 25\ ns$$

Equation 1.81

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

In example 1.30 $N_A = 10^{18}/\text{cm}^3$,

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

Assuming $N_A >> N_D$

$$\tau_T \simeq \tau_p = 25\ ns$$

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

$$= 96.5\ pF$$

Ex: 2.1

The minimum number of terminals required by a single op amp is five: 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 amp can all share one terminal for positive power supply and one terminal for negative power supply.

Ex: 2.2

Equation are $v_3 = A(v_2 - v_1)$;

$v_{id} = v_2 - v_1$, $v_{icm} = \frac{1}{2}(v_1 + v_2)$

a)

$$v_1 = v_2 - \frac{v_3}{A} = 0 - \frac{2}{10^3} = -0.02 \text{ V} = -2 \text{ mV}$$

$$v_{id} = v_2 - v_1 = 0 - (-0.002) = +0.002 \text{ V}$$
$$= 2 \text{ mV}$$

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

b) $-10 = 10^3(5 - v_1) \Rightarrow v_1 = 5.01$ V

$$v_{id} = v_2 - v_1 = 5 - 5.01 = 0.01 \text{ V} = 10 \text{ mV}$$

$$v_{icm} = \frac{1}{2}(v_1 + v_2) = \frac{1}{2}(5.01 + 5) = 5.005 \text{ V}$$

$\simeq 5$ V

c)

$$v_3 = A(v_2 - v_1) = 10^3(0.998 - 1.002) = -4 \text{ V}$$

$$v_{id} = v_2 - v_1 = 0.998 - 1.002 = -4 \text{ mV}$$

$$v_{icm} = \frac{1}{2}(v_1 + v_2) = \frac{1}{2}(1.002 + 0.998) = 1 \text{ V}$$

d)

$$-3.6 = 10^3[v_2 - (-3.6)] = 10^3(v_2 + 3.6)$$

$$\Rightarrow \sqrt{2} = -3.6036 \text{ V}$$

$$v_{id} = v_2 - v_1 = -3.6036 - (-3.6)$$
$$= -0.0036 \text{ V} = -3.6 \text{ mV}$$

$$v_{icm} = \frac{1}{2}(v_1 + v_2) = \frac{1}{2}[-3.6 + (-3.6)]$$
$$= -3.6 \text{ V}$$

Ex: 2.3

From Figure 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 $G_m = 10$ mA/V and $\mu = 100$ we have:

$A = 100 \times 10 \times 10 = 10^4$ V/V Or equivalently 80 dB

Ex: 2.4

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

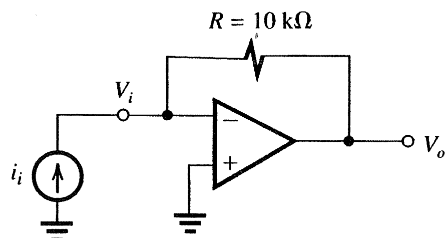
$R_1 = 100$ kΩ and

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

Thus:

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

Ex: 2.5



From Table 1.1 we have:

$R_m = \left.\frac{V_O}{i_i}\right|_{i_o = 0}$, i.e., output is open circuit

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

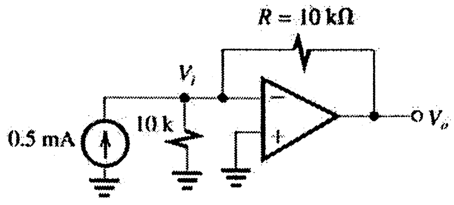
$$V_O = V_i - Ri_i = 0 - Ri_i = -Ri_i$$

$$R_m = \left.\frac{V_O}{i_i}\right|_{i_o = 0} = -\frac{Ri_i}{i_i} = -R \Rightarrow R_m = -R$$
$$= -10 \text{ k}\Omega$$

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

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

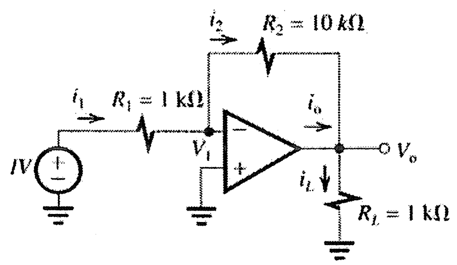
Since we are assuming that the op amp in this transresistance amplifier is ideal, the op amp has zero output resistance and therefore the output resistance of this transresistance amplifier is also zero. That is $R_O = 0\ \Omega$.



Connecting the signal source shown in Figure 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

$$V_O = V_i - R \times 0.5 \text{ mA} = 0 - 10 \text{ K} \times 0.5 \text{ mA} = -5 \text{ V}$$

Ex: 2.6



V_1 is a virtual ground, thus $V_1 = 0$ V

$$i_1 = \frac{1 \text{ V} - V_1}{R_1} = \frac{1-0}{1 \text{ k}\Omega} = 1 \text{ mA}$$

Assuming an ideal op amp, the current flowing into the negative input terminal of the op amp is zero. Therefore, $i_2 = i_1 \Rightarrow i_2 = 1$ mA

$$V_O = V_1 - i_2 R_2 = 0 - 1 \text{ mA} \times 10 \text{ k}\Omega = -10 \text{ V}$$

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

$$i_O = i_L - i_2 = -10 \text{ mA} - 1 \text{ mA} = -11 \text{ mA}$$

$$\text{Voltage gain} = \frac{V_O}{1 \text{ V}} = \frac{-10 \text{ V}}{1 \text{ V}} = -10 \text{ V/V}$$

or 20 dB

$$\text{Current gain} = \frac{i_L}{i_1} = \frac{-10 \text{ mA}}{1 \text{ mA}} = -10 \text{ A/A}$$

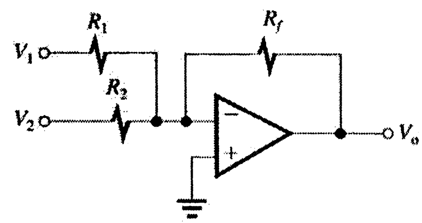
or 20 dB

$$\text{Power gain} = \frac{P_L}{P_I} = \frac{-10(-10 \text{ mA})}{1 \text{ V} \times 1 \text{ mA}} = 100 \text{ W/W}$$

or 20 dB

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

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 $V_O = -(V_1 + 5V_2)$.
We want to have:

$$\frac{R_F}{R_1} = 1 \text{ and } \frac{R_F}{R_2} = 5$$

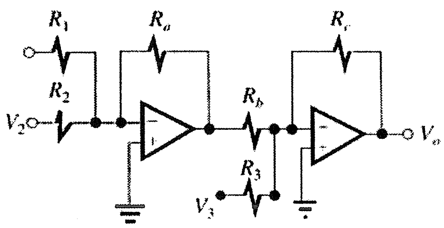
It is also desired that for a maximum output voltage of 10 V the current in the feedback resistor does not exceed 1 mA.
Therefore

$$\frac{10 \text{ V}}{R_f} \le 1 \text{ mA} \Rightarrow R_f \ge \frac{10 \text{ V}}{1 \text{ mA}} \Rightarrow R_f \ge 10 \text{ k}\Omega$$

Let us choose R_f to be 10 kΩ, then

$$R_1 = R_f = 10 \text{ k}\Omega \text{ and } R_2 = \frac{R_f}{5} = 2 \text{ k}\Omega$$

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:
Then we have

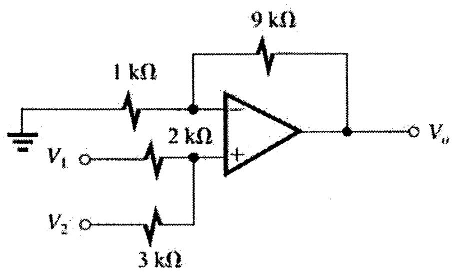
$$R_3 = \frac{R_C}{4} = \frac{10}{4} = 2.5\ \text{k}\Omega$$

$$\left(\frac{R_a}{R_1}\right)\left(\frac{R_C}{R_b}\right) = 2, \Rightarrow \frac{10}{R_1} \times \frac{10}{10} = 2 \Rightarrow R_1 = 5\ \text{k}\Omega$$

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

Ex: 2.9

Using the super position principle, to find the contribution of v_1 to the output voltage v_0, we set $V_2 = 0$



The V_+ (the voltage at the positive input of the op amp is: $V_+ = \frac{3}{2+3}V_1 = 0.6V_1$

Thus

$$V_O = \left(1 + \frac{9\ \text{k}\Omega}{1\ \text{k}\Omega}\right)V_+ = 10 \times 0.6V_1 = 6\ V_1$$

To find the contribution of V_2 to the output voltage V_0 we set $V_1 = 0$.

Then $V_+ = \frac{2}{2+3}V_2 = 0.4\ V_2$

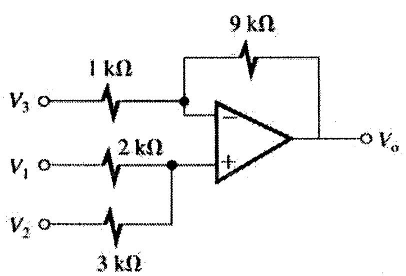
Hence

$$V_O = \left(1 + \frac{9\ \text{k}\Omega}{1\ \text{k}\Omega}\right)V_+ = 10 \times 0.4V_2 = 4V_2$$

Combining the contributions of v1 and v2

To V_O we have $V_O = 6V_1 + 4V_2$

Ex: 2.10



Using the super position principle, to find the contribution of V_1 to V_0 we set $V_2 = V_3 = 0$ Then we have (refer to the solution of exercise 2.9):

$V_O = 6V_1$

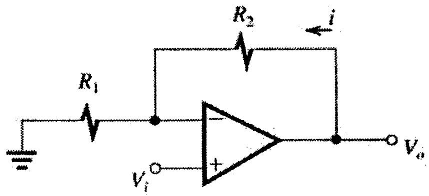
To find the contribution of V_2 to V_0 we set $V_1 = V_3 = 0$, then: $V_O = 4V_2$

To find the contribution of V_3 to V_O we set $V_1 = V_2 = 0$, then

$$V_O = -\frac{9\ \text{k}\Omega}{1\ \text{k}\Omega}V_3 = -9V_3$$

Combining the contributions of V_1, V_2 and V_3 to V_0 we have: $V_O = 6V_1 + 4V_2 - 9V_3$

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 $V_O = 10\ \text{V}$ then it is desired that

$i = 10\ \mu\text{A}$.

Thus,

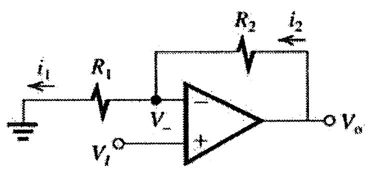
$$i = \frac{10\ \text{V}}{R_1 + R_2} = 10\ \mu\text{A} \Rightarrow R_1 + R_2 = \frac{10\ \text{V}}{10\ \mu\text{A}}$$

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

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

Ex: 2.12

a)



$$V_O = A(V_I - V_-) \Rightarrow V_- = V_I - \frac{V_O}{A}$$

$$i_2 = i_1 \Rightarrow \frac{V_O - V_-}{R_2} = \frac{V_-}{R_1} \Rightarrow \frac{V_O}{R_2} = \left(\frac{1}{R_2} + \frac{1}{R_1}\right)V_-$$

$$V_o = \left(1 + \frac{R_L}{R_1}\right)V_- = \left(1 + \frac{R_L}{R_1}\right)\left(V_I - \frac{V_o}{A}\right) \Rightarrow$$

$$V_O + \frac{1 + R_2/R_1}{A}V_O = (1 + R_2/R_1)V_I$$

$$\frac{V_O}{V_I} = \frac{1 + R_2/R_1}{1 + \frac{1 + R_2/R_1}{A}} \Rightarrow G = \frac{1 + R_2/R_1}{1 + \frac{1 + R_2/R_1}{A}}$$

(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 $G = \dfrac{10}{1 + \frac{10}{A}}$

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

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

For $V_I = 1\text{V}$, $V_O = G \times V_I = 9.901$ 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,

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

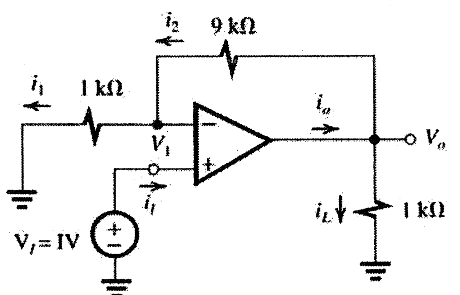
$\simeq 0.1$ mV

Ex: 2.13

$i_I = 0\text{A}$, $V_1 = V_I = 1$ 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,



$$V_O = V_1 + i_2 \times 9\text{ k}\Omega = 1 + 1 \times 9 = 10\text{ V}$$

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

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

$$\frac{V_O}{V_I} = \frac{10\text{ V}}{1\text{ V}} = 10\frac{\text{V}}{\text{V}}\text{ or 20 dB}$$

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

$$\frac{P_L}{P_I} = \frac{V_O \times i_L}{V_I \times I_i} = \frac{10 \times 10}{1 \times 10} = \infty$$

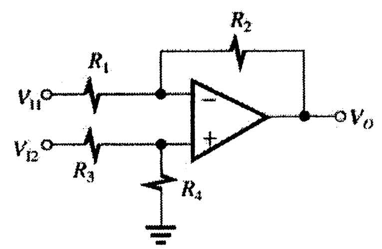
Ex: 2.14

(a) load voltage

$$= \frac{1\text{ k}\Omega}{1\text{ k}\Omega + 1\text{ M}\Omega} \times 1\text{ V} \simeq 1\text{ mV}$$

(b) load voltage = 1V

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) $$A_{cm} = \frac{V_o}{V_{ICM}} = \left(\frac{R_4}{R_4 + R_3}\right)\left(1 - \frac{R_2}{R_1}\frac{R_3}{R_4}\right)$$

$$= \left(\frac{1}{1 + \frac{R_3}{R_4}}\right)\left(1 - \frac{R_2}{R_1}\frac{R_3}{R_4}\right)$$

$$= \frac{\frac{R_4}{R_3} - \frac{R_2}{R_1}}{\frac{R_4}{R_3} + 1}$$

The worst case common-mode gain A_{cm} happens when $|A_{cm}|$ has its maximum value.

If the resistors have 1% tolerance, we have $\dfrac{R_{4nom}(1 - 0.01)}{R_{3nom}(1 + 0.01)} \le \dfrac{R_4}{R_3} \le \dfrac{R_{4nom}(1 + 0.01)}{R_{3nom}(1 - 0.01)}$

where R_{3nom} and R_{4nom} are nominal values for R_3 and R_4 respectively. We have :

$R_{3nom} = 2\text{ k}\Omega$ and $R_{4nom} = 200\text{ k}\Omega$, thus,

$$\frac{200 \times 0.99}{2 \times 1.01} \le \frac{R_4}{R_3} \le \frac{200 \times 1.01}{2 \times 0.99}$$

$$98.02 \le \frac{R_4}{R_3} \le 102.02$$

Simlarly, we can show that

$$98.02 \le \frac{R_2}{R_1} \le 102.02$$

Hence, $-102.02 \le -\frac{R_2}{R_1} \le -98.02$

Therefore,

$$-4 \le \frac{R_4}{R_3} - \frac{R_2}{R_1} \le 4 \Rightarrow \left|\frac{R_4}{R_3} - \frac{R_2}{R_1}\right| \le 4$$

In the worst case

$$\frac{\left|\frac{R_4}{R_3} - \frac{R_2}{R_1}\right|}{1 + \frac{R_4}{R_3}} \le \frac{4}{1 + 98.02} \Rightarrow |A_{cm}| \le 0.04$$

Note that the worst case A_{cm} happens when

$$\frac{R_4}{R_3} = 98.02 \text{ and } \frac{R_2}{R_1} = 102.02$$

The differential gain A_d of the amplifier

is $A_d = \frac{R_2}{R_1}$, therefore, the corresponding value of CMRR for the worst case A_{cm} is :

$$\text{CMRR} = 20 \log\frac{|A_d|}{|A_{cm}|} = 20 \log\frac{102.02}{0.04} \Rightarrow$$

$$\text{CMRR} = 20 \log(2550.5) \simeq 68 \text{ dB}$$

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

$$A_d = \frac{R_2}{R_1} = 10 \text{ and}$$

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

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

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

$$V_{Id} = 10\sin\omega t \text{ mV}$$

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

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

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

$$= 5 - 0.005 \sin\omega t \text{ V}$$

$$v_{I2} = v_{Icm} + \frac{1}{2}v_{ID}$$

$$= 5 + 0.005\sin\omega t \text{ V}$$

$$v_-(\text{Op AmpA}_1) = V_{I1} = 5 - 0.005\sin\omega t \text{ V}$$

$$v_-(\text{Op AmpA}_2) = V_{I2} = 5 + 0.005\sin\omega t \text{ V}$$

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

v_{01} -The to voltage at the output of op amp A.

$$v_{01} = V_{I1} - R_2 \times \frac{V_{Id}}{2R_1}$$

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

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

v_{02} - The voltage at the output of op amp A2

$$V_{02} = v_{I2} + R_2 \times \frac{v_{Id}}{2R_1}$$

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

$$v_+(\text{Op Amp A}_3) = v_{02} \times \frac{R_4}{R_3 + R_4} = v_{02}\frac{10}{10 + 10}$$

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

$$= \frac{1}{2}v_{02} = \frac{1}{2}(5 + 5.005 \sin\omega t)$$

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

$$v_-(\text{Op Amp A}_3) = V_+(\text{Op Amp A}_3)$$

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

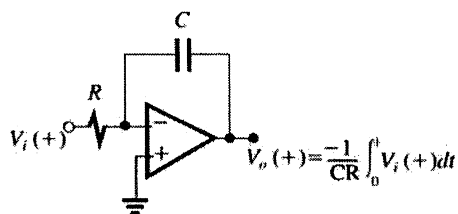
$$v_O = \frac{R_4}{R_3}\left(1 + \frac{R_2}{R_1}\right)v_{Id}$$

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

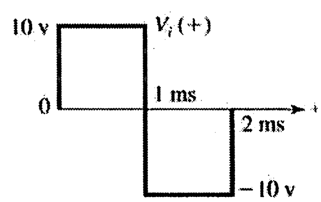
$$= 1(1 + 1000) \times 0.01\sin\omega t$$

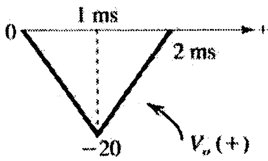
$$10.01 \sin\omega t \text{ V}$$

Ex: 2.18



The waveforms for one period of the input and the output signals are shown below:





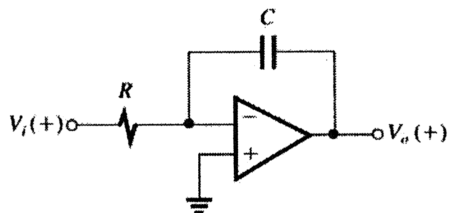
We have

$$-20 = \frac{-1}{CR}\int_0^{1\text{ ms}} 10\, dt$$

$$\Rightarrow -20 = \frac{-1}{CR}\times 10 \times 1\text{ ms}$$

$$CR = \frac{10}{20}\times 1\text{ ms}\times 0.5\text{ ms}$$

Ex: 2.19



The input resistance of this inverting integrator is R_1, therefore, $R = 10\text{ k}\Omega$

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

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

From equation (2.50) the transfer function of this integrator is:

$$\frac{V_O(jw)}{V_i(jw)} = -\frac{1}{jwCR}$$

For $w = 10\text{ rad/s}$ the integrator transfer function has magnitude

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

$$\phi = 90°$$

For $w = 1\text{ rad/s}$ the integrator transfer function has magnitude

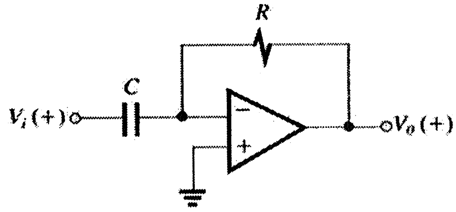
$$\left|\frac{V_O}{V_i}\right| = \frac{1}{10\times 10^{-3}} = 1000\text{ V/V} \text{ and phase}$$

$$\phi = 90°$$

Using equation (2.53) the frequency at which the integrator gain magnitude is unity is

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

Ex: 2.20



$C = 0.01\ \mu\text{F}$ 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 equation (2.57), we know that the transfer function of the differentiator is of the form

$$\frac{V_O(jw)}{V_i(jw)} = -jwCR$$

Thus, for $w = 10\text{ rad/s}$ the differentiator transfer function has magnitude

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

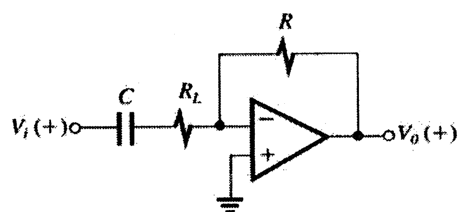
$$\phi = -90°$$

For $w = 10^3\text{ rad/s}$ the differentiator transfer function has magnitude

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

$$\phi = -90°$$

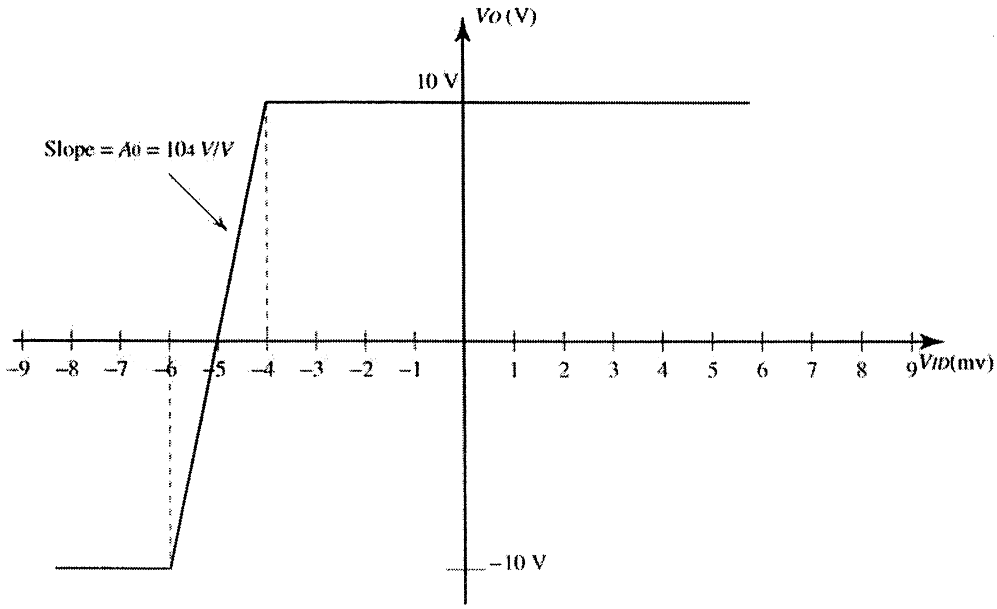
If we add a resistor in series with the capacitor to limit the high frequency gain of the differentiator to 100, the circuit would be:



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

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

Ex: 2.21



$V_O = V_3$

$V_{ID} = V_2 - V_1$

$V_{ID} = V_+ - V_{OS} - V_-$

when $V_+ = V_- = 0$ then

$V_{ID} = 0 - 5\text{ mV} = -5\text{ mV}$. This input offset voltage causes an offset in the voltage transfer characteristic. Rather than passing through the origin, it is now shifted to the left by V_{OS}

Ex: 2.22

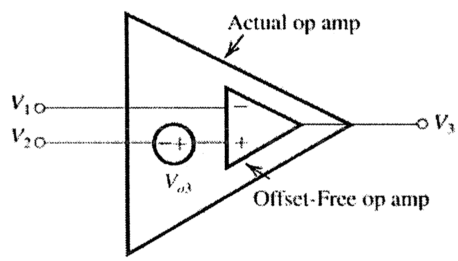
From equation (2.41) we have:

$$f_M = \frac{SR}{2\pi V_{O\max}} = 15.915\text{ kHz} \simeq 15.9\text{ kHz}$$

Using equation (2.42), for an input sinusoid with frequency $f = 5f_M$, the maximum possible amplitude that can be accommodated at the output without incurring SR distortion is:

$$V_O = V_{O\max}\left(\frac{f_M}{5f_M}\right) = 10 \times \frac{1}{5} = 2\text{ V(peak)}$$

Ex: 2.23



$V_O = V_3$

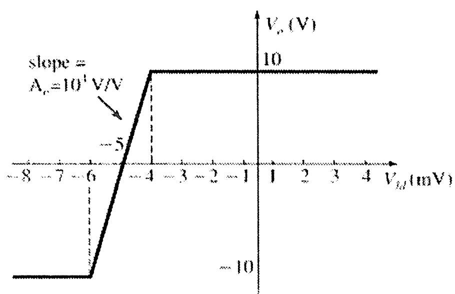
$V_{Id} = V_2 - V_1$

$V_{Id} = V_+ - V_{OS} - V_-$

In order to have zero differential input for the offset-free op amp (i.e., $V_+ - V_- = 0$) we need

$V_{Id} = V_+ - V_- - V_{OS} = 0 - 5\text{ mV} = -5\text{ mV}$

Thus, the transfer characteristic V_O versus V_{Id} is:



Ex: 2.24

From equation(2,44) 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 equation (2.46) the value of resistor R_3 (placed in series with positive input to minimize the output offset voltage) is:

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

$= 9.9 \text{ k}\Omega$

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

With this value of R_3 the new value of the output dc voltage (using equation (2.47))is:

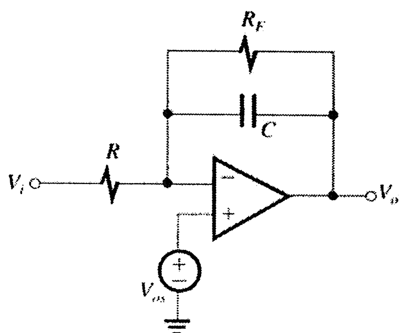
$V_O = I_{OS} R_2 = 10 \text{ nA} \times 10 \text{ k}\Omega \simeq 0.01 \text{ V}$

Ex: 2.25

Using equation (2.54) we have:

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

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



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 equation (2.43), 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 $w = \frac{1}{CR_F}$

We know $RC = 1$ ms and

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

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

$$f = \frac{w}{2\pi} = \frac{1}{2\pi} = 0.16 \text{ Hz}$$

Ex: 2.26

From equation (2.28) we have:

$w_t = A_O w_b \Rightarrow f_t = A_O f_b \Rightarrow f_b = \frac{f_t}{A_O}$, and

we know

$20 \log A_O = 106$ and $f_t = 3$ MHz, therefore $f_b \simeq 15$ Hz

By definition the open-loop gain (in dB) at f_b is:

$A_O(\text{in dB}) - 3 = 106 - 3 = 103 \text{ dB}$

To find the open-loop gain at frequency f we can use equation (2.31) (especially when $f >> f_b$ which is the case in this exercise) and write:

Open-loop gain at $f \simeq 20 \log\left(\frac{f_t}{f}\right)$

Therefore:

Open-loop gain at 300 Hz =

$20 \log\frac{3 \text{ MHz}}{300} = 80 \text{ dB}$

Open-loop gain at 3 kHz =

$20 \log\frac{3 \text{ MHz}}{3 \text{ kHz}} = 60 \text{ dB}$

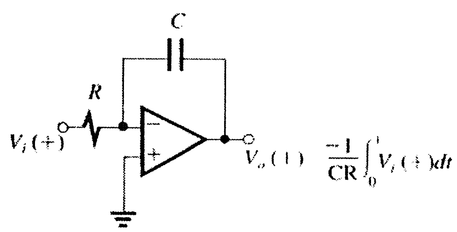
Open-loop gain at 12 kHz =

$20 \log\frac{3 \text{ MHz}}{12 \text{ kHz}} = 48 \text{ dB}$

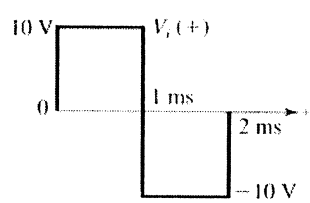
Open-loop gain at 60 kHz =

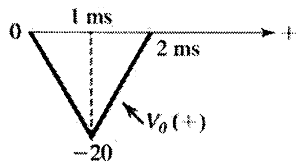
$20 \log\frac{3 \text{ MHz}}{60 \text{ kHz}} = 34 \text{ dB}$

Ex: 2.27



The waveforms for one period of the input and the output signals are shown below:





We have

$$-20 = \frac{-1}{CR}\int_0^{1\text{ ms}} 10\, dt$$

$$\Rightarrow -20 = \frac{-1}{CR} \times 10 \times 1 \text{ ms}$$

$$CR = \frac{10}{20} \times 1 \text{ ms} = 0.5 \text{ ms}$$

Ex: 2.28

Since dc gain of the op amp is much larger than the dc gain of the designed non-inverting amplifier, we can use equation(2.35).
Therefore:

$$f_{3db} = \frac{f_t}{1 + \frac{R_2}{R_1}} \text{ and } 1 + \frac{R_2}{R_1} = 100 \text{ and}$$

$f_t = 2$ MHz

Hence $f_{3db} = \dfrac{2 \text{ MHz}}{100} = 20$ kHz

Ex: 2.29

For the input voltage step of magnitude V the output waveform will still be given by the exponential waveform of equation(2.40)

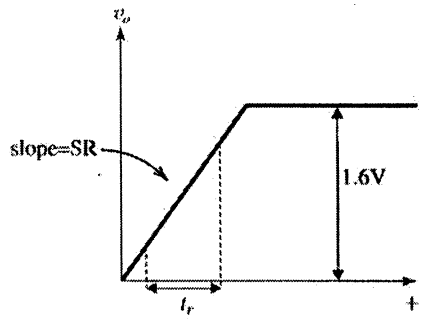
If $w_t V \le SR$

That is $V \le \dfrac{SR}{w_t} \Rightarrow V \le \dfrac{SR}{2\pi f_t}$

$V \le 0.16$ V, thus, the largest possible input voltage step is 0.16 V.
From Appendix F we know that the 10% to 90% rise time of the output waveform of the form of equation (2.40) is $t_r \simeq 2.2\dfrac{1}{w_t}$

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 the output is slew-rate limited and is linearly rising with a slope equal to the slew-rate, as shown in the following figure.



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

$$\Rightarrow t_r = 1.28 \text{ μs}$$

Ex: 2.30

From equation (2.41) we have:

$$f_M = \frac{SR}{2\pi V_{O\max}} = 15.915 \text{ kHz} \simeq 15.9 \text{ kHz}$$

Using equation (2.42), 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:

$$V_O = V_{O\max}\left(\frac{f_M}{5 f_M}\right) = 10 \times \frac{1}{5} = 2 \text{ V (peak)}$$

Ex: 3.1

Refer to Fig 3.3(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 results is the transfer characteristic in Fig E3.1.

Ex: 3.2

see Figure 3.3a and 3.3b

During the positive half of the sinusoid, the diode is forward biased, so it conducts resulting in $v_D = 0$ During the negative half 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 Figure E3.2

Ex: 3.3

$$\hat{i}_D = \frac{\hat{v}_I}{R} = \frac{10\text{ V}}{1\text{ k}\Omega} = 10\text{ mA}$$

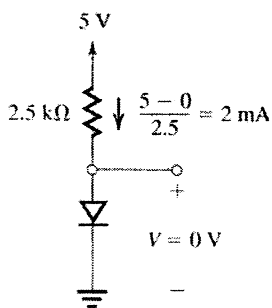
dc component of $v_O = \frac{1}{\pi}\hat{v}_O$

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

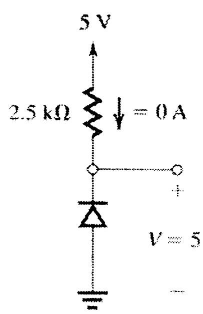
$$= 3.18\text{ V}$$

Ex: 3.4

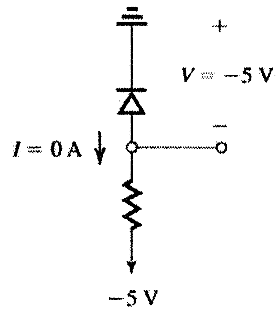
(a)



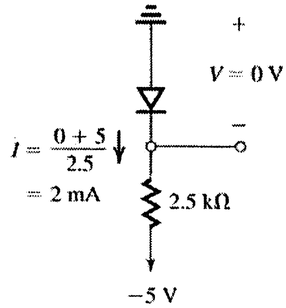
(b)



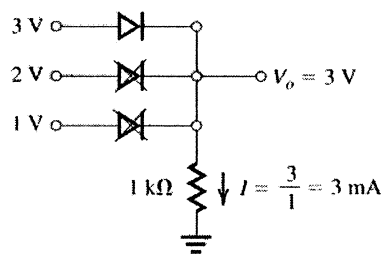
(c)



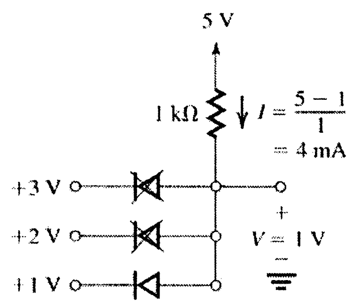
(d)



(e)



(f)



Ex: 3.5

$$V_{avg} = \frac{10}{\pi}$$

$$50 + R = \frac{\frac{10}{\pi} - 0}{1\text{ mA}} = \frac{10}{\pi}\text{ k}\Omega$$

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

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

Now I, the current through each diode is

$$I = I_S e^{V/V_T} = 6.91 \times 10^{-16} e^{0.8/(25 \times 10^{-3})}$$

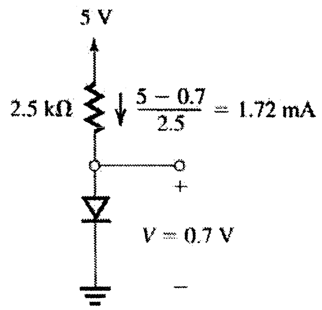
$$= 54.6 \text{ mA}$$

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

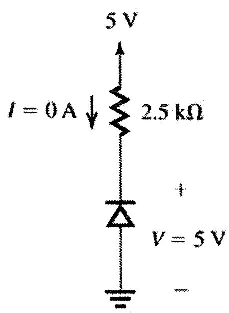
$$= 139\ \Omega$$

Ex: 3.12

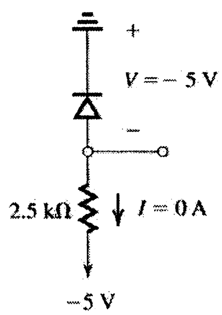
(a)



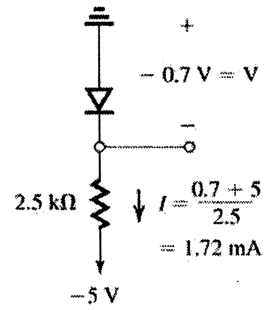
(b)



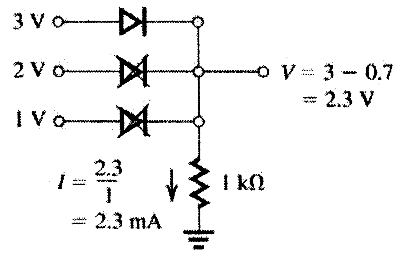
(c)



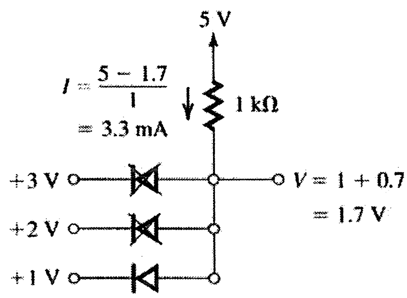
(d)



(e)



(f)



Ex: 3.13

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

$I_D = 0.1$ 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: 3.14

For small signal model, using equation 3.15

$$i_D = I_D + \frac{I_D}{V_T} \cdot v_d$$

$$\Delta i_D = \frac{I_D}{V_T} \cdot \Delta v_d \qquad (1)$$

For exponential model

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

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

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

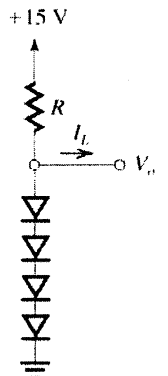
$= i_{D1}(e^{\Delta V/V_T} - 1)$ (2)

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

Using equations (1) and (2) results and using $V_T = 25$ mV

	ΔV(mV)	Δi_D(mA) small signal	Δi_D(mA) expo. 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: 3.15



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

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

∴ 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

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

$I_S = \frac{i_D}{e^{V/V_T}} = \frac{5}{e^{0.75/25 \times 10^{-3}}} = 4.7 \times 10^{-16}$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: 3.16

For a zener diode

$V_O = V_{ZO} + I_Z r_Z$

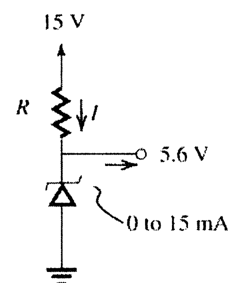
$10 = V_{ZO} + 0.01 \times 50$

$V_{ZO} = 9.5$ V

For $I_Z = 5$ mA

$V_O = 9.5 + 0.005 \times 50 = 9.75$ V

Ex: 3.17



The minimum zener current should be $5 \times I_{ZK} = 5 \times 1 = 5$ mA.

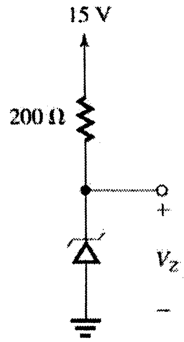
Since the load current can be as large as 15 mA, we should select R so that with $I_L = 15$ mA, a zener current of 5 mA is available. Thus the current should be 20 mA Leading to

$R = \frac{15 - 5.6}{20 \text{ mA}} = 470\ \Omega$

Maximum power dissipated in the diode occurs when $I_L = 0$ is

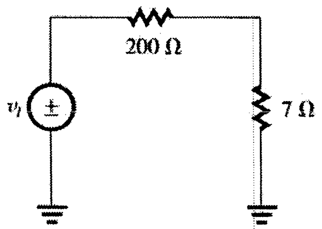
$P_{max} = 20 \times 10^{-3} \times 5.6 = 112$ mV

Ex: 3.18



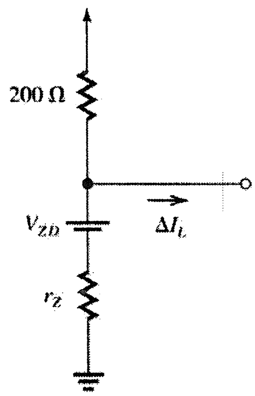
At no load $V_Z = 5.1$ V

FOR LINE REGULATION



$$\text{Line Regulation} = \frac{v_O}{v_i} = \frac{7}{200+7} = 33.8\ \frac{\text{mV}}{\text{V}}$$

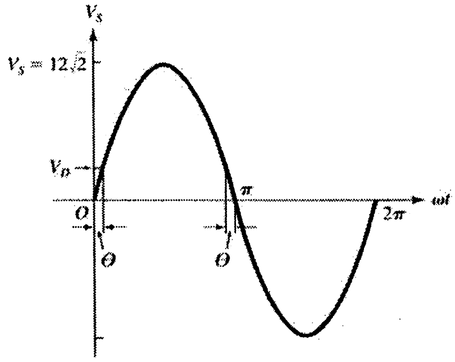
For Load Regualation:



$$\frac{\Delta V_O}{\Delta I_i} = \frac{-\Delta I_i r_Z}{1\ \text{mA}}$$

$$= -7\ \frac{\text{mV}}{\text{mA}}$$

Ex: 3.19



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

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

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

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

$\therefore$ Total conduction angle $= 180 - 2\theta$

$= 175.2°$

$$\text{b. } v_{O,\text{avg}} = \frac{1}{2\pi}\int_{0}^{(\pi-\theta)} (V_S \sin\phi - V_D)\,d\phi$$

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

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

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 occers at the peak diode voltage

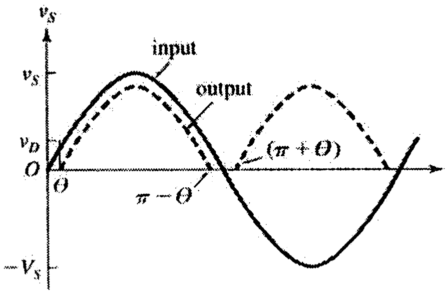
$$\therefore \hat{i}_D = \frac{V_S - V_D}{R} = \frac{12\sqrt{2} - 0.7}{100}$$

$$= 163 \text{ mA}$$

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

$$\simeq 17 \text{ V}$$

Ex: 3.20



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

$$V_{O,avg} = \frac{1}{2\pi}\left[2 \times \int_{\phi}^{(\pi - \phi)} (V_S \sin\phi - V_D) d\phi\right]$$

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

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

c. Peak current occers 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 $V_S = \sqrt{2} \times 12 = 12\sqrt{2}$

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

Non zero 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

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

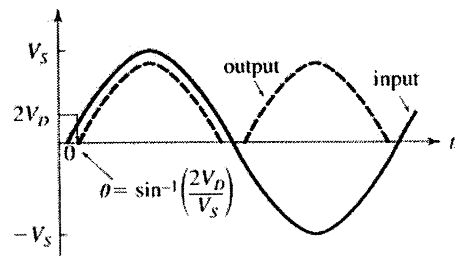
$$= 163 \text{ mA}$$

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

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

$$= 33.2 \text{ V}$$

Ex: 3.21



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

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

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

But $\cos\theta \approx 1$

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

$\pi - 2\theta \approx \pi$

$$\Rightarrow V_{O,avg} = \frac{2V_S}{\pi} - 2V_D$$

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

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

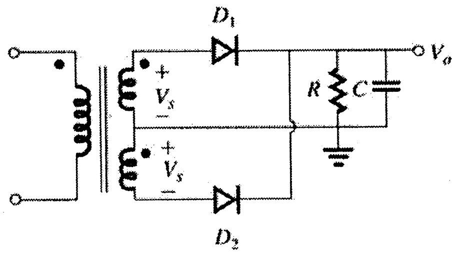
$$= \frac{V_S - 2V_D}{R} = \frac{12\sqrt{2} - 1.4}{100}$$

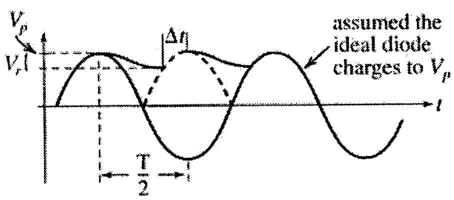
$= 156$ mA

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

Ex: 3.22

Full wave peak Rectifier:





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

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

$V_p - V_r = V_p e^{-\frac{T/2}{RC}}$ ← discharge is only half the period.

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

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

for $CR >> T/2$

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

$$= \frac{V_p}{2fRC} \qquad \text{(a)}$$

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

$Q_{SUPPLIED} = Q_{LOST}$

$i_{cap}\Delta t = CV_r$ SUB (a)

$$(i_{D,av} - I_L)\Delta t = \not{C}\frac{V_p}{2fR\not{C}} = \frac{V_p}{2fR}$$

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

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

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

Note the conduction angle is the same expression as for the half wave rectifier and is given in EQ3.30

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

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

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

Since the output is approximately held at V_p,

$\frac{V_p}{R} \approx I_L$. Thus:

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

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

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:

$$i_D = i_C + i_L$$

$$i_{D,max} = C\frac{dv_S}{dt} + i_L$$

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

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

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

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

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:

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

SUB $\omega = 2\pi f$ sub (a) for f

$$= 2\pi\frac{V_p}{2V_r RC}$$

$$\Rightarrow i_{D,max} = \not{C}\sqrt{\frac{2V_r}{V_p}}\frac{2\pi V_p^2}{2V_r R\not{C}} + I_L$$

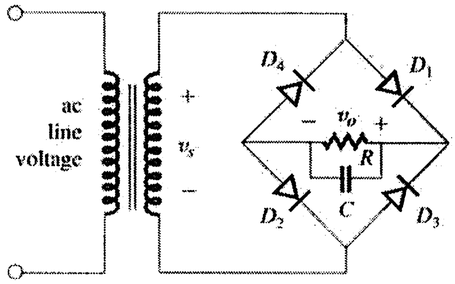
$$= \pi\frac{V_p}{V_r}I_L\sqrt{\frac{2V_r}{V_p}} + I_L$$

$$= I_L\left[1 + \frac{\pi V_p}{V_r}\sqrt{\frac{2V_r}{V_p}}\right]$$

$$= I_L\left[1 + \pi\sqrt{\frac{2V_p}{V_r}}\right]$$

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

Ex: 3.23



The output voltage, v_O, can be expressed as

$v_O = (V_p - 2V_{DO})e^{-t/RC}$

At the end of the discharge interval

$v_O = (V_p - 2V_{DO} - V_r)$

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

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

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

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

$$\Rightarrow V_r = (V_p - 2V_{DO}) \times \frac{T}{2RC}$$

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

$V_{DO} = 0.8$ 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

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

If ripple voltage is included the output voltage is

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

Diode current without taking ripple voltage into

$$\text{consideration} = \frac{12\sqrt{2} - 2 \times 0.8}{100\ \Omega} \simeq 0.15\text{ A}$$

The conduction angle $\omega\Delta t$ can be obtained using equation 4.30

$$\omega\Delta t = \sqrt{\frac{2V_r}{V_p}} = \sqrt{\frac{2 \times 1}{12\sqrt{2} - 2 \times 0.8}} = 0.36$$

rad $= 20.7°$

The average and peak diode currents can be calculated using equations 3.34 and 3.35

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

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

$i_{Dave} = 1.45$ A

$$I_{D\,peak} = 1\left(1 + 2\pi\sqrt{\frac{V_p}{2V_r}}\right)$$

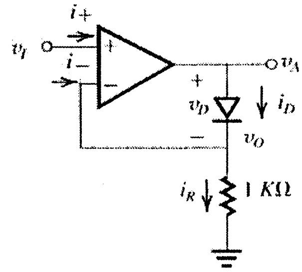
$= 2.74$ A

PIV of the diodes

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

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

Ex: 3.24



The diode has 0.7 V drop at 1 mA current.

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

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

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

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

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

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

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

$V_A = v_D + 10$ mV

$= 0.58 + 0.01$

$= 0.59$ V

For $v_I = 1$ V

$v_O = v_I = 1$ V

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

$v_D = 0.7$ V

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

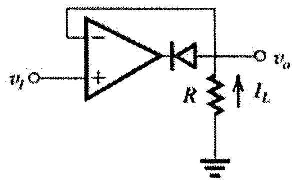
$= 1.7$ V

For $v_I = -1$ V, the diode is cutoff

$\therefore v_O = 0$ V

$V_A = -12$ V because it is ideal amplifier.

Ex: 3.25



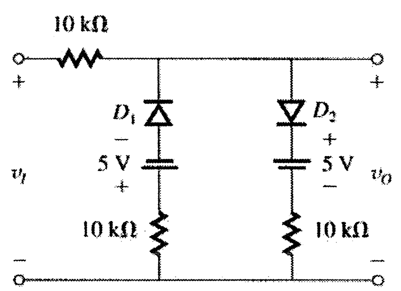
$v_I > 0$ ~ diode is cutoff

$v_O = 0$ V

$v_I < 0$ ~ diode conducts and opamp sinks load current.

$v_O = v_I$

Ex: 3.26



Both diodes are cut-off

for $-5 \leq v_I \leq +5$

and $v_o = v_I$

For $v_I \leq -5$ V

Diode D_1 conducts and

$$v_O = -5 + \frac{1}{2}(+v_I + 5)$$

$$= \left(-2.5 - \frac{v_I}{2}\right)\text{ V}$$

For $v_I \geq 5$ V

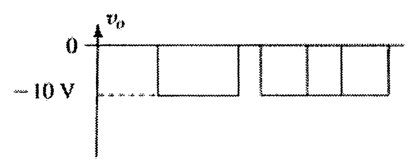
Diode D_2 conducts and

$$v_O = +5 + \frac{1}{2}(v_I - 5)$$

$$= \left(2.5 + \frac{v_I}{2}\right)\text{ V}$$

Ex: 3.27

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: 4.1

$\therefore I_C = I_s e^{v_{BE}/V_T}$

$v_{BE2} - v_{BE1} = V_T \ln\left[\frac{I_{C2}}{I_{C1}}\right]$

$v_{BE2} = 700 + 25\ln\left[\frac{0.1}{1}\right]$

$= 642$ mV

$v_{BE2} = 700 + 25\ln\left[\frac{10}{1}\right]$

$= 758$ mV

Ex: 4.2

$\therefore \alpha = \frac{\beta}{\beta+1}$

$\frac{50}{50+1} < \alpha < \frac{150}{150+1}$

$0.98 < \alpha < 0.993$

Ex: 4.3

$I_C = I_E - I_B$

$= 1.460 \text{ mA} - 0.01446 \text{ mA}$

$= 1.446$ mA

$\alpha = \frac{I_C}{I_E} = \frac{1.446}{1.460} = 0.99$

$\beta = \frac{I_C}{I_B} = \frac{1.446}{0.01446} = 100$

$I_C = I_S e^{v_{BE}/V_T}$

$I_S = \frac{I_C}{e^{v_{BE}/V_T}} = \frac{1.446}{e^{700/25}}$

$= \frac{1.446}{e^{28}}\text{A} = 10^{-15}\text{A}$

Ex: 4.4

$\beta = \frac{\alpha}{1-\alpha}$ 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: 4.5

Given:

$I_S = 10^{-16}$ A, $\beta = 100$, $I_C = 1$ mA

$I_{SE} = I_{SC} + I_{SB} = I_{SC}\left[1 + \frac{1}{\beta}\right]$

$I_{SB} = \frac{I_{SC}}{\beta} = \frac{10^{-16}}{100} = 10^{-18}$ A

$I_{SE} = I_{SC}\left[1 + \frac{1}{\beta}\right] = 10^{-16} \times \frac{101}{100}$

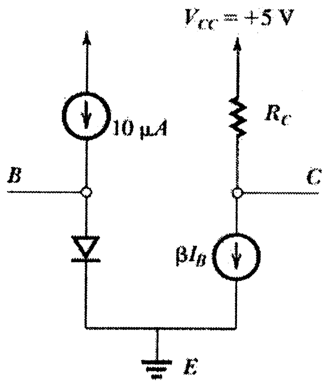
$= 1.01 \times 10^{-16}$ A

$V_{BE} = V_T \ln\left[\frac{I_C}{I_S}\right] = 25\ln\left[\frac{1 \text{ mA}}{10^{-16}}\right]$

$= 25 \times 29.9336$

$= 748$ mV

Ex: 4.6



$v_{BE} = 690$ mV

$I_C = 1$ mA

For active range $V_C \geq V_B$

$R_C(\text{max}) = \frac{V_{CC} - 0.690}{I_C}$

$= \frac{5 - 0.69}{1}$

$= 4.31$ kΩ

Ex: 4.7

$I_S = 10^{-15}$ A

$\text{Area}_C = 100 \times \text{Area}_E$

$I_{SC} = 100 \times I_S = 10^{-13}$ A

Ex: 4.8

$i_C = I_S e^{V_{BE}/V_T} - I_{SC} e^{V_{BC}/V_T}$

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

$$V_{CE} = 25\ln\left[\frac{100}{1}\right] = 115 \text{ mV}$$

Ex: 4.9

$$i_C = I_S e^{V_{BE}/V_T} - I_{SC} e^{V_{BC}/V_T}$$

$$i_b = \frac{I_S}{\beta} e^{V_{BE}/V_T} + I_{SC} e^{V_{BC}/V_T}$$

$$\beta_{\text{forced}} = \left.\frac{i_C}{i_B}\right|_{\text{sat}} < \beta$$

$$= \beta \frac{I_S e^{V_{BE}/V_T} - I_{SC} e^{V_{BC}/V_T}}{I_S e^{V_{BE}/V_T} + \beta I_{SC} e^{V_{BC}/V_T}}$$

$$= \beta \frac{I_S e^{(V_{BE}-V_{BC})/V_T} - I_{SC}}{I_S e^{(V_{BE}-V_{BC})/V_T} + \beta I_{SC}}$$

$$= \beta \frac{e^{V_{CE\text{sat}}/V_T} - I_{SC}/I_S}{e^{V_{CE\text{sat}}/V_T} + \beta I_{SC}/I_S}$$

$$\beta_{\text{forced}} = 100 \frac{e^{200/25} - 100}{e^{200/25} + 100 \times 100}$$

$$= 100 \times 0.2219 \approx 22.2$$

Ex: 4.10

$$I_E = \frac{I_S}{\alpha} e^{V_{BE}/V_T}$$

$$2 \text{ mA} = \frac{51}{50} 10^{-14} e^{V_{BE}/V_T}$$

$$V_{BE} = 25\ln\left[\frac{2}{10^3} \times \frac{50}{51} \times 10^{14}\right]$$

$$= 650 \text{ mV}$$

$$I_C = \frac{\beta}{\beta+1} I_E = \frac{50}{51} \times 2$$

$$= 1.96 \text{ mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{1.96}{50} \Rightarrow 39.2\ \mu\text{A}$$

Ex: 4.11

$$I_C = I_S e^{V_{BE}/V_T} = 1.5 \text{ A}$$

$$\therefore V_{BE} = V_T \ln[1.5 \times 10^{-11}]$$

$$= 25 \times 25.734$$

$$= 643 \text{ mV}$$

Ex: 4.12

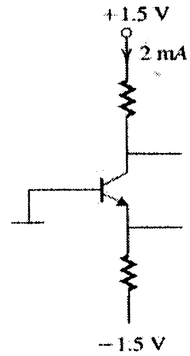


Fig 6.12

$\beta = 100$, $V_{BE} = 0.8$ V at $I_C = 1$ mA

$$V_{BE2} - V_{BE1} = V_T \ln[I_{C2}/I_{C1}]$$

$$= 25 \times 0.693 = 0.01733$$

$$\therefore V_{BE2} = 0.817 \text{ V}$$

$$R_C = \frac{V_{CC} - V_C}{I_C} = \frac{1.5 - 0.5}{2} \text{ k}\Omega$$

$$= 500\ \Omega$$

$$R_E = \frac{V_{EE} - V_{BE}}{I_C} \frac{\beta}{(\beta+1)}$$

$$= \frac{1.5 - 0.817}{2} \times \frac{100}{101} \text{ k}\Omega$$

$$= 338\ \Omega$$

Ex: 4.13

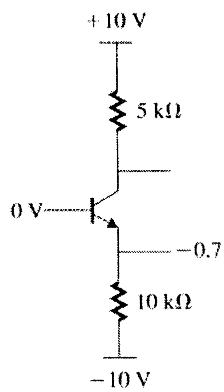


Fig 6.13

$\beta = 50$, $V_{BE} = 0.7$ V

$$V_E = V_B - 0.7 \text{ V}$$

$= 0 - 0.7 = -0.7$ V

$$I_E = \frac{-0.7 + 10}{10\text{ K}}$$

$= 0.93$ mA

$$I_C = \frac{50}{51} I_E = 0.91\text{ mA}$$

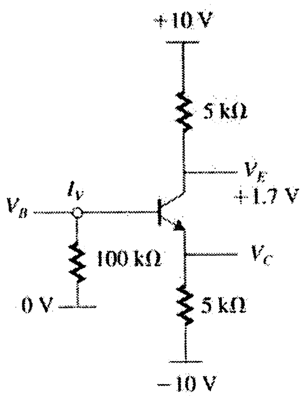
$$V_C = 10 - 0.91 \times 5$$

$= 5.45$ V

$$I_B = \frac{I_C}{\beta} = \frac{0.91}{50}$$

$= 0.0182$ μA

Ex: 4.14



$$I_E = \frac{V_{EE} - V_E}{R_E}$$

$$= \frac{10 - 1.7}{5}$$

$= 1.66$ mA

$$I_B = \frac{V_B - 0}{100\text{ k}\Omega}$$

$= 0.01$ mA

$$I_C = I_E - I_B$$

$= 1.65$ mA

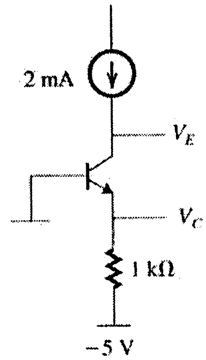
$$\alpha = \frac{I_C}{I_E} = \frac{1.65}{1.66} = 0.99$$

$$\beta = \frac{I_C}{I_B} = \frac{1.65}{0.01} = 165$$

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

$= -10 + 1.65 \times 5 = -1.75$ V

Ex: 4.15



V_{BE} decreases approx 2 mV/°C rise
for 30°C rise

$$\Delta V_{BE} = -2 \times 30$$

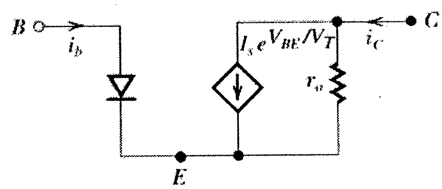
$= -60$ mV

$$\Delta V_E = -60\text{ mV}$$

Since I_E is constant
I_C is constant

$\therefore\ \Delta V_C = 0$ V

Ex: 4.16



$$A + C,\quad i_C = I_S e^{V_{BE}/V_T} + \frac{v_{CE}}{r_O}$$

$$\text{and } r_O = \frac{V_A}{I}$$

$$\therefore\ i_C = I_S e^{V_{BE}/V_T} + \frac{V_{CE} \cdot I_S e^{V_{BE}/V_T}}{V_A}$$

$$= I_S e^{V_{BE}/V_T}\left[1 + \frac{v_{CE}}{V_A}\right]$$

QED

$$i_C = I_S e^{V_{BE}/V_T} + \frac{v_{CE}}{r_O} \text{ in Fig (a)}$$

$$i_B = \frac{I_S}{\beta} e^{V_{BE}/V_T}$$

$$\therefore i_C = \beta i_b + \frac{v_{CE}}{r_O} \text{ as in Fig (b)}$$

QED

Ex: 4.17

$r_o = \frac{V_A}{I_C} \quad \frac{(V)}{(A)}$

I_C(mA)	0.1	1.0	10
r_o	$\frac{100}{0.0001}$	$\frac{100}{0.001}$	$\frac{100}{0.010}$
r_o	$10^6\ \Omega$	$10^5\ \Omega$	$10^4\ \Omega$
r_o	1 MΩ	100 kΩ	10 kΩ

Ex: 4.18

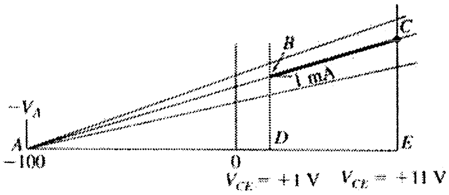


Fig 4.18

By similar triangles ABD v ACE

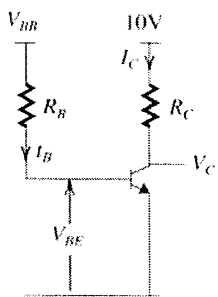
$\frac{1}{r_o} = \frac{\Delta I_C}{\Delta V_{CE}}$

$\frac{BD}{CE} = \frac{AD}{AE}$ or $\frac{1\text{ mA}}{x} = \frac{100+1}{100+11}$

$\Rightarrow x = \frac{1 \times 111}{101} = 1.099\text{ mA}$

$\therefore \approx 1.1\text{ mA}$

Ex: 4.19



$R_C = 10\text{ k}\Omega,\ \beta = 50$

(a) active $V_C = 5$ V

$I_C = \frac{V_{CC} - V_C}{R_C}$

$= \frac{10-5}{10}$

$= 0.5$ mA

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

$= 0.7 + 10 \times 0.01$

$= 0.8$ V

(b) edge of saturation $v_{CE} = 0.3$ V

$I_C = \frac{10-0.3}{10\text{ K}} = \frac{9.7}{10} = 0.97$ mA

$I_C = I_C/\beta = 0.97/50 = 0.0194$ mA

$V_{BB} = 0.7 + 0.0194 \times 10 = 0.894$ V

(c) saturated $V_{CE} = 0.2$ V

$I_C = (10 - 0.2)/10 = 0.98$ mA

$I_B = I_C/\beta F = 0.98/10 = 0.098$ mA

$V_B = 0.7 + 0.098 \times 10 = 1.68$ V

Ex: 4.20

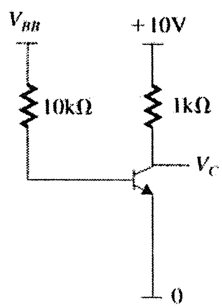


Fig 6.20

For $V_{BB} = 0$

$I_B = 0$

Transistor is OFF

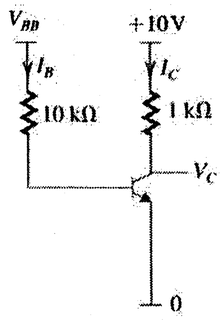
$\therefore I_C = 0$

$V_C = V_{CC} - I_C R_C$

$= +10 - 0$

$= +10$ V

Ex: 4.21



For $V_{BB} = 1.7$ V

$$I_B = \frac{1.7 - 0.7}{10} = 0.1 \text{ mA}$$

$$I_C = \beta I_B$$
$$= 50 \times 0.1 = 5 \text{ mA}$$
$$V_C = 10 - 5 \times 1 \text{ k}\Omega$$
$$= +5 \text{ V} > V_{BE} \text{ (so Active)}$$

(a) edge of saturation $V_{CE} = 0.3$ V

$$R_C = \frac{V_{CC} - V_{CE}}{I_C} = \frac{10 - 0.3}{5} = 1.94 \text{ k}\Omega$$

(b) deep saturation $v_{CE} = 0.2$ V

$I_B = 0.1$ mA (unchanged)

$$I_C = \beta_{\text{Forced}} I_B = 10 \times 0.1 = 1 \text{ mA}$$

$$R_C = \frac{10 - 0.2}{1 \text{ mA}} = 9.8 \text{ k}\Omega$$

Ex: 4.22

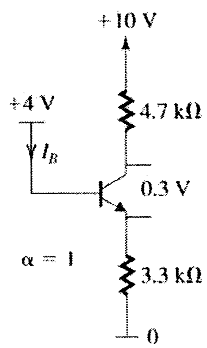


Fig 4.22

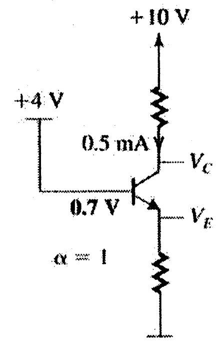
At edge of saturation $v_{CE} = 0.3$ V

$$V_{CC} = I_C R_C + 0.3 + I_E R_E$$
$$\approx I_E [R_C + R_E] + 0.3$$

$$I_E = \frac{10 - 0.2}{4.7 + 3.3} = 1.225 \text{ mA}$$

$$V_{BB} = I_E R_E + 0.7$$
$$= 1.225 \times 3.3 + 0.7$$
$$= 4.7 \text{ V}$$

Ex: 4.23



$$V_E = V_B - 0.7$$
$$= 4 - 0.7 = 3.3 \text{ V}$$

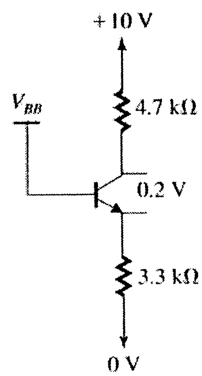
$$R_E = \frac{3.3 \text{ V}}{0.5 \text{ mA}} = 6.6 \text{ k}\Omega$$

$$V_C = V_B + 2 \text{ V}$$
$$= 4 + 2 = +6 \text{ V}$$

$$R_C = \frac{V_{CC} - V_C}{I}$$

$$= \frac{10 - 6}{0.5} = 8 \text{ k}\Omega$$

Ex: 4.24



$\beta_{\text{Forced}} = 5$

Then $I_C = 5\, I_B$

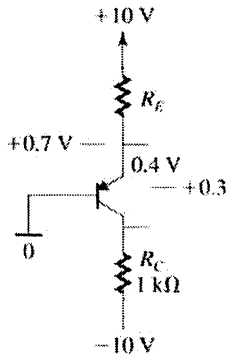
$I_E = 6\, I_B$

$$I_B = \frac{10 - 0.2}{5 \times 4.7 + 6 \times 3.3}$$
$$= 0.226 \text{ mA}$$

$$V_E = 6\, I_B \times 3.3$$
$$= 4.48 \text{ V}$$

$$V_{BB} = V_E + 0.7$$
$$= 5.18 \text{ V}$$

Ex: 4.25



$V_B = 0$
$V_E = +0.7$ V

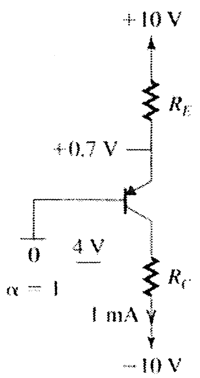
$$I_E = \frac{10 - 0.7}{2}$$

$= 4.65$ mA
$I_C = 0.99\, I_E$

$$R_C = \frac{10 - 0.4 + 0.7}{0.99 \times 4.65}$$

$= 2.2$ kΩ
$[V_C(\max) = 0 + 0.7 - 0.4 = +0.3\text{ V}]$

Ex: 4.26



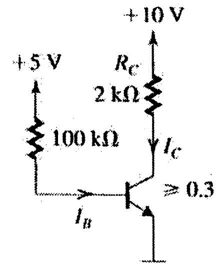
$I_E = I_C$

$$R_E = \frac{10 - 0.7}{1} = 9.3\text{ k}\Omega$$

$V_C = V_B - 4$
$= -4$V

$$R_C = \frac{10 - 4}{1} = 6\text{ k}\Omega$$

Ex: 4.27



$50 \le \beta \le 150$
In active range

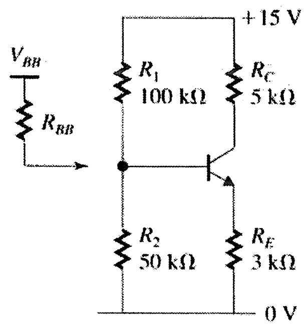
$$I_B = \frac{5 - 0.7}{100\text{ K}} = 0.043\text{ mA}$$

V_C lowest for largest β
$I_C = \beta\, I_B = 150 \times 0.043$ A

$$R_C = \frac{V_{CC} - 0.3}{150 \times 0.043}$$

$= 1.5$ kΩ
For $\beta = 50$
$V_C = 10 - 50 \times 0.043 = 6.78$ V
For $\beta = 150$
$V_C = 0.3$ V

Ex 4.28



$\beta = 50$

$$V_{BB} = \frac{15 \times 50}{150} = 5\text{ V}$$

$R_{BB} = 50 \parallel 100$
$= 100/3$ kΩ

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + [R_{BB}/(\beta + 1)]}$$

$$= \frac{4.3}{3 + \frac{100}{3} \cdot \frac{1}{51}}$$

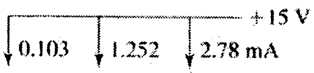
$= 1.18$ mA

$$I_C = I_E \frac{50}{51} = 1.15 \text{ mA}$$

$$\% \text{ change} = \frac{1.28 - 1.15}{1.28}$$

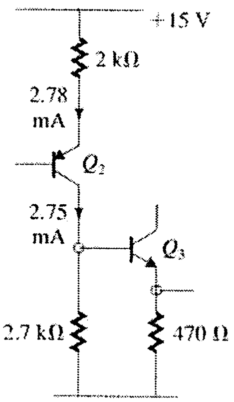
$$\Rightarrow -9.8\%$$

Ex: 4.29



Total current drawn
$= 0.103 + 1.252 + 2.75$ mA
$= 4.135$ mA
Power Consumed $= V \times I$
$= 15 \times 4.135$
$= 62$ mW

Ex: 4.30



$\beta = 100$
I_{E2} unchanged
I_{C2} unchanged
$V_{E3} = V_{C2} - 0.7$ V

$$IE_3 = \frac{VC_2 - 0.7}{0.470}$$

$$= 101\, I_{B3}$$

$$= 101\left[2.75 - \frac{V_{C2}}{2.7}\right]$$

Hence

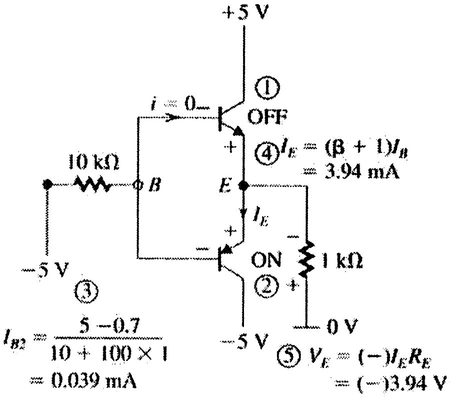
$$V_{C2}\left[\frac{1}{(\beta+1)0.47} + \frac{1}{2.7\text{ k}}\right] = 2.75 + \frac{0.7}{(\beta+1)0.47}$$

$$\Rightarrow V_{C2} = 7.06 \text{ V}$$

$$V_{E3} = V_{C2} - 0.7 = 6.36 \text{ V}$$

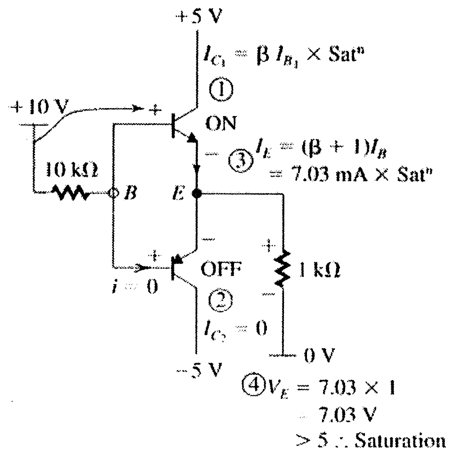
$$I_{C3} = \frac{V_{E3}}{0.47} \times \frac{100}{101} = 13.4 \text{ mA}$$

Ex: 4.31



Ans: $V_E = -3.94$ V

Ex: 4.32



⑤ $V_B = V_E + 0.7$ $\qquad$ $V_E \Rightarrow \frac{V_{CC} - 0.2}{1}$

$= 5.5$ V $\qquad$ $= 4.8$ V

$I_B = \frac{10 - 5.5}{10}$ $\qquad$ $I_E \Rightarrow 4.8$ mA

$= 0.45$ mA

⑥ $I_{C(\text{sat})} = I_E - I_B$ $\qquad$ $V_E \Rightarrow \frac{V_{CC} - 0.2}{1}$

$= 4.8 - 0.45$ $\qquad$ $= 4.8$ V

$= 4.35$ mA $\qquad$ $I_E \Rightarrow 4.8$ mA

⑦ $\beta_{\text{forced}} = \frac{I_C}{I_B}$

$$= \frac{4.35}{0.45} = 9.6 \ll 30$$

Ex: 4.33

$A_V = -\frac{V_{CC} - V_{CE}}{V_T} = \frac{10 - V_{CE}}{0.025} = -320 \text{ V/V}$

$\Rightarrow V_{CE} = 10 - 8 = 2.0 \text{ V}$

$R_C = \frac{10 - V_{CE}}{1 \text{ mA}} = \frac{10 - 2}{1} = 8 \text{ k}\Omega$

V_{CE} Swing $= 2.0 - 0.3 = 1.7 \text{ V}$

$A_V = \frac{\Delta V_{CE}}{\Delta V_{BE}} = -320 = \frac{1.7}{\Delta V_{BE}}$

$\Rightarrow |\Delta V_{BE}| = \frac{1.7}{320} = 5.3 \text{ mV}$

Ex: 4.34

Given: $g_m = \left.\frac{\partial I_C}{\partial V_{BE}}\right|_{i_C = I_C}$

But $I_C = I_S e^{V_{BE}/V_T}$

thus $\frac{\partial I_C}{\partial V_{BE}} = \frac{I_S e^{V_{BE}/V_T}}{V_T}$

$= \frac{I_C}{V_T}$

Ex: 4.35

$g_m = \frac{I_C}{V_T} = \frac{0.5 \text{ mA}}{25 \text{ mV}} = 20 \text{ mA/V}$

Ex: 4.36

$I_C = 0.5$ mA (constant)

$\beta = 50$	$\beta = 200$
$g_m = \frac{I_C}{V_T} = \frac{0.5 \text{ mA}}{25 \text{ mV}}$	
$= 20 \text{ mA / V}$	$= 20 \text{ mA/V}$
$I_B = \frac{I_C}{\beta} = \frac{0.5}{50}$	$= \frac{0.5}{200}$
$= 10\ \mu\text{A}$	$= 2.5 \text{ mA}$
$r_\pi = \frac{\beta}{g_m} = \frac{50}{20}$	$= \frac{200}{20}$
$= 2.5 \text{ k}\Omega$	$= 10 \text{ k}\Omega$

Ex: 4.37

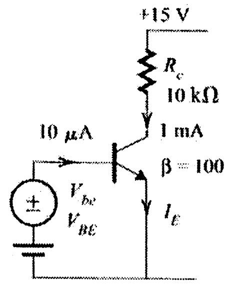
$\beta = 100 \quad I_C = 1 \text{ mA}$

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

$r_\pi = \frac{\beta}{g_m} = \frac{100}{40} = 2.5 \text{ k}\Omega$

$r_e = \frac{r_\pi}{\beta + 1} = 25\ \Omega$

Ex: 4.38



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

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

$= -40 \times 10$

$= -400 \text{ V/V}$

$V_C = V_{CC} - I_C R_C$

$= 15 - 1 \times 10 = 5 \text{ V}$

$N_C(t) = V_C + N_C(t)$

$= (V_{CC} - I_C R_C) + A_V v_{be}(t)$

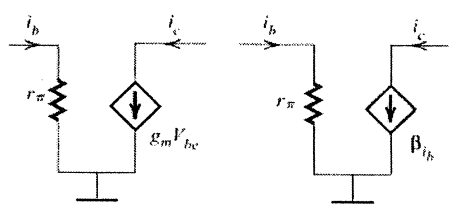
$= (15 - 10) - 400 \times 0.005 \sin\omega t$

$= 5 - 2 \sin \omega t\ (t)$

$i_b(t) = I_B + v_{be}(t)$

$= 10 + 2 \sin \omega t\ (\mu\text{A})$

Ex: 4.39



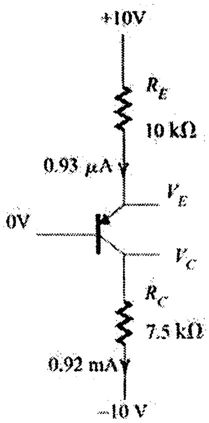
Note: $g_m = \frac{I_C}{V_T}$ and $r_\pi = \frac{\beta}{g_m}$

given $i_C = \beta i_b = (g_m r_\pi) i_b$

$= r_\pi g_m \left(\frac{v_{be}}{r_\pi}\right)$

$= g_m v_{be}$

Ex: 4.40



Change R_C to 7.5 kΩ

$V_C = -10 + 0.92 \times 7.5$

$= -3.1$ V

$$A_V = \frac{v_c}{v_e} = g_m R_C$$

$= 36.8 \times 7.5$

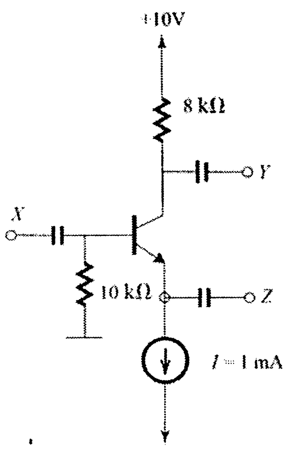
$= 276$ V/V

$\hat{v}_O = A_V v_i$

$= 276 \times \hat{10}$ mV

$= 2.76$ V

Ex: 4.41



$I_E = 1$ mA

$$I_C = \frac{100}{101} = 0.99 \text{ mA}$$

$$I_B = \frac{1}{101} = 0.0099 \text{ mA}$$

$V_C = 10 - 8 \times 0.99 = 2.18$ V

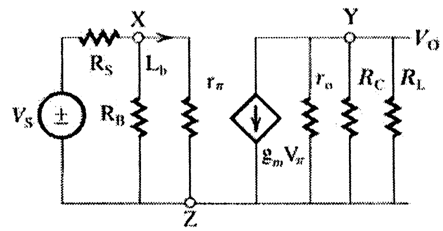
$V_B = -10 \times 0.0099 = -0.099 \approx -0.1$ V

$V_E = -0.1 - 0.7 = -0.8$ V

$$g_m = \frac{I_C}{V_T} = \frac{0.99}{0.025} = 39.6 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{39.6} = 2.53 \text{ k}\Omega$$

$$r_O = \frac{V_A}{I_C} = \frac{100}{0.99} = 101 \approx 100 \text{ k}\Omega$$



$$\frac{v_O}{v_S} = \frac{r_\pi \| R_B}{R_S + r_\pi \| R_B} \cdot (-) g_m (r_O \| R_C \| R_L)$$

$$= \frac{2}{2+2} (-)\ 39.6\ (3.85) = -76.2 \text{ V/ V}$$

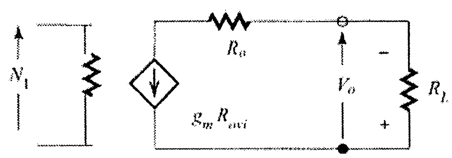
$$\frac{r_O \| R_C \| R_L}{R_C \| R_L} = \frac{3.85}{4.00}$$

thus effect of r_O is $\approx 3.9\%$

Ex (2) **4.41**

$A_{VO} = -g_m (r_O \| R_C)$

$R_O = (r_O \| R_C)$



$$A_V = -\frac{g_m R_O V_1}{V_1} \times \frac{R_L}{R_O + R_L}$$

$$= -g_m \times \frac{R_O R_L}{R_O + R_L}$$

$$= -g_m \times \frac{(r_O \| R_C) R_L}{(r_O \| R_C) + R_L}$$

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

Ex: 4.42

For $I_C = 1$ mA

$$g_m = \frac{I_C}{V_T} = \frac{1 \text{ mA}}{0.025} = 40 \text{ mA / V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40} = 2.5 \text{ k}\Omega$$

$$r_O = \frac{V_A}{I_C} = \frac{100}{1} = 100 \text{ k}\Omega$$

$R_{IN} = r_\pi = 2.5$ kΩ

$A_{VO} = -g_m (r_O \| R_C) = -40(5 \| 100)$

$= -97.6$ V/V

(cont.)

$$\frac{v_1}{v_S} = \frac{R_{IN}}{R_S + R_{IN}} = \frac{2.5}{5+2.5} = \frac{1}{3}$$

$$\frac{v_O}{v_S} = \frac{v_1}{v_S}\cdot\frac{v_O}{v_1} = -\frac{1}{3}\times 97.6 = -32.5 \text{ V/V}$$

$$|v_O| = A_{VO}v_\pi = 32.5 \times \frac{15}{1000} = 0.49 \text{ V}$$

For $I_C = 0.5$ mA and $R_C = 10$ kΩ

$$g_m = \frac{0.5}{0.025} = 20 \text{ mA/V}$$

$$r_\pi = \frac{100}{20} = 5.0 \text{ k}\Omega$$

$$r_O = \frac{100}{0.5} = 200 \text{ k}\Omega$$

$$R_{IN} = r_\pi = 5 \text{ k}\Omega$$

$$A_{VO} = -20(200 \text{ k} \| 10 \text{ k}) = -190.5 \text{ V/V}$$

$$R_O = R_C \| r_O = 10 \text{ k} \| 200 \text{ k} = 9.5 \text{ k}$$

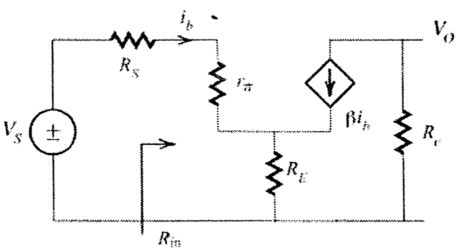
$$A_V = \frac{-190.5\times 5}{5+9.5} = -65.6 \text{ V/V}$$

$$G_V = \frac{v_O}{v_S} = \frac{1}{2}\times 65.6 = -32.8 \text{ V/V}$$

$$\frac{v_1}{v_S} = \frac{5}{5+5} = \frac{1}{2} \Rightarrow \hat{v}_{sig} = 10 \text{ mV}$$

$$|\hat{v}_O| = 32.8 \times 10 \text{ m} = 0.33 \text{ V}$$

Ex: 4.43



$$R_{IN} = \frac{v_b}{i_b} = r_\pi + (\beta+1)R_E$$

$$\frac{V_S}{V_\pi} = \frac{R_S + r_\pi + (\beta+1)R_E}{r_\pi}$$

$$= 1 + \frac{R_S}{r_\pi} + \frac{R_E}{r_\pi/(\beta+1)}$$

$$= 1 + \frac{R_S}{r_\pi} + \frac{R_E}{r_e} \text{ QED}$$

$$\frac{v_S}{v_\pi} = \frac{100}{10} = 1 + 10 \text{ K} + \frac{R_E}{5/101}$$

$$\Rightarrow R_E = \frac{7\times 5}{101} = \frac{5}{01} \approx 0.35 \text{ k}\Omega = 350 \ \Omega$$

$$R_{IN} = 5 \text{ k} + (\beta+1)0.35 \approx 40.4 \text{ k}\Omega$$

$$G_V = \frac{\beta(r_O \| R_C \| R_L)}{R_{sig} + R_{IN}} = \frac{100\times 10}{10+40.4} = -19.8 \text{ V/V}$$

Ex: 4.44

$$g_m = \frac{I_C}{V_T} = \frac{1}{0.025} = 40 \text{ ms}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40} = 2.5 \text{ k}\Omega$$

$$r_e = \frac{r_\pi}{\beta+1} \approx 25 \ \Omega$$

$$R_{IN} = r_e = 25 \ \Omega$$

$$A_{VO} = g_m(r_O \| R_C) \approx g_m R_C = 40\times 5 = 200 \text{ V/V}$$

$$A_V = A_{VO}\times\frac{5}{5+5} = 100 \text{ V/V}$$

$$G_V = \frac{R_{IN}}{R_S + R_{IN}}\cdot A_V = \frac{25}{5000+25}\times 100 = 0.5 \text{ V/V}$$

Ex: 4.45

$R_S = 50$ Ω

$$R_{IN} = r_e = \frac{V_T}{I_E} = \frac{25 \text{ mV}}{I_E} = 50$$

$$\Rightarrow I_E = 25/50 = 0.5 \text{ mA}$$

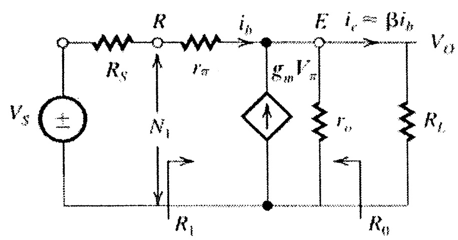
$$A_{VO} = +g_m R_C = 20\times 5 = 100 \text{ V/V}$$

$$G_V = \frac{1}{2}\times A_V = 40 \text{ V/V}$$

$$\Rightarrow A_V = 80 = g_m R_C^*$$

$$\therefore R_C^* = 80/20 = 4 \text{ k}\Omega$$

Ex: 4.46



P Insert 30

$$i_b = \frac{v_1 - v_O}{r_\pi} \text{ and } v_O = +g_m V_\pi R_L$$

$$i_b = \frac{v_i - (g_m V\pi + i_b)R_L}{r_\pi}$$

$$\Rightarrow R_1 = \frac{v_1}{i_b} = r_\pi + (\beta+1)R_L$$

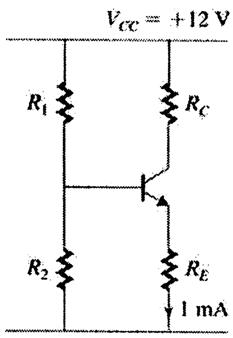
$= 0.5 + 101 \times 1 = 101.5\ k\Omega$

$G_{VO} = 1[R_L \text{ moved}, r_O = \infty]$

$$R_O = \frac{r\pi + R_S}{\beta + 1} = \frac{0.5 + 10}{101} \Rightarrow 104\ \Omega$$

$$G_V = \frac{v_O}{v_S} = \frac{R_L}{R_O + R_S} = \frac{1}{0.104 + 1} = 0.91\ V/V$$

Ex: 4.47



Design 1

$\beta = 100$

$R_E = 3\ k\Omega$

$$R_{BB} = \frac{80 \times 40}{80 + 40} = 26.7\ k\Omega$$

$$V_{BB} = \frac{12 \times 40}{80 + 40} = 4\ V$$

$$I_E = \frac{4 - 0.7}{\frac{26.7}{101} + 3} = 1.01\ mA$$

$\beta = 50$

$$I_E = \frac{3.3}{\frac{26.7}{151} + 3} = 1.04\ mA$$

$$\%\ \text{change} = \frac{1.04 - 0.937}{1} \times 100$$

$= 10.3\ \%$

Design 2

$\beta = 100$

$R_E = 3.3\ k\Omega$

$$R_{BB} = \frac{8 \times 40}{8 + 4} = 2.67\ k\Omega$$

$$V_{BB} = \frac{12 \times 4}{8 + 4} = 4\ V$$

$$I_{EE} = \frac{4 - 0.7}{\frac{26.7}{101} + 3.3} = 0.99\ mA$$

$\beta = 150$

$$I_E = \frac{3.3}{\frac{2.6}{51} + 3.3} = 0.984\ mA$$

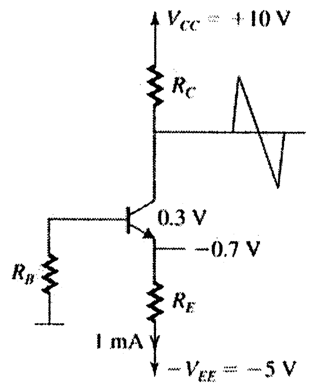
$\beta = 150$

$$I_E = \frac{3.3}{\frac{2.6}{151} + 3.3} = 0.995\ mA$$

$$\% = \frac{0.995 - 0.984}{1} \times 100$$

$= 1.1\ \%$

Ex: 4.48



$$A_V = \frac{I_C R_C}{V_T} \quad I_E \text{ given} \quad \therefore \text{ maximize } R_C$$

$V_C = I_C R_C + 2 + 0.3 + I_E R_E$

$$I_E = \frac{V_{EE} - 0.7}{R_E + R_B/(\beta + 1)} = \frac{4.3}{R_E + R_B/(\beta + 1)} = 1\ mA$$

$\Rightarrow R_E + R_B/(\beta + 1) = 4.3\ k\Omega$

For independence from β, set $R_B = 0$ (OK for C_B)

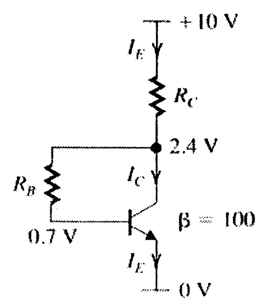
$\Rightarrow R_E = 4.3\ k\Omega$

$V_C(\min) = V_E + 0.3\ V = -0.3\ V$

$VCQ = V_C(\min) + 2V = +10\ V$

$$R_C = \frac{V_{CC} - V_{CQ}}{I_C} = \frac{10 -}{0.9} = 8.48\ k\Omega$$

Ex: 4.49



$V_C = V_E + 0.4 + 2$

$= +2.4\ V$

$$R_C = \frac{V_{CC} - V_C}{1} = \frac{10 - 2.4}{1} = \frac{7.6}{1} = 7.6\ k\Omega$$

$$I_B = \frac{I_E}{\beta + 1} = \frac{1}{101}\ mA$$

(cont.)

$$R_B = \frac{V_C - V_B}{I_B} = 101(2.4 - 0.7) = 171.7\ \text{k}\Omega$$

Using 5% resistors:

$R_C = 7.5\ \text{k}\Omega$ $R_B = 180\ \text{k}\Omega$

$0.7 + I_B R_B + I_E R_C - V_{CC} = 0$

$$I_B = \frac{10 - 0.7}{180 + 7.5(\beta + 1)}$$

$I_B = 9.92\ \mu$

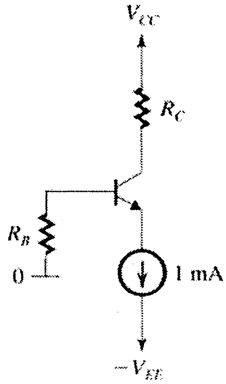
$I_E = 101 \times I_B$

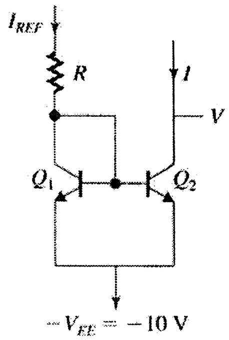
$= 1.002\ \text{mA}$

$V_C = 10 - 7.5(1.002)$

$= 2.5\ \text{V}$

Ex 4.50





$\beta = 100$ $\quad R_B = 100\ \text{k}\Omega$

$R_C = 7.5\ \text{k}\Omega$

$I_B = I_E/(\beta + 1) \approx I_E/100$

$= 0.01\ \text{mA}$

$V_B = 0 - I_B R_B = -1\ \text{V}$

$V_E = V_B - 0.7\ \text{V} = -1.7\ \text{V}$

$$V_C = V_{CC} - \frac{\beta}{\beta + 1} \times 1 \times 7.5 = +2.57\ \text{V}$$

$$R = \frac{V_{CC} - 0.7 + V_{EE}}{I_{REF}} = \frac{19.3}{1} = 19.3\ \text{k}\Omega$$

Ex: 4.51

Refer to Fig E4.51

$I_C = \alpha(1\ \text{m}) \approx 1\ \text{mA}$

$I_B = 0.01\ \text{mA}$

$V_C = 10 - 8\ \text{k}(1\ \text{m}) = +2\ \text{V}$

$V_B = 100\ \text{k} \times (-0.01\ \text{m}) = -1\ \text{V}$

$V_E = -1 - 0.7 = -1.7\ \text{V}$

$\beta = 100$: upper limit $\Rightarrow V_{CC} - V_C = 8\ \text{V}$

lower value $\Rightarrow V_B - V_C' = 0.4\ \text{V}$ (where

$V_C' = -1.4\ \text{V}$)

Swing: $-1.4 - 2 = -3.4$ V

$\beta = 50$: upper still 8 V, lower

$\Rightarrow I_B = 0.0196\ \text{mA}$ so $V_B = -1.96\ \text{V}$

$-1.96\ \text{V} - 0.4 - 2 = -4.4\ \text{V}$

$\beta = 200$: upper still 8V,

lower $\Rightarrow I_B = 0.005\ \text{mA}$ so $V_B = -0.5\ \text{V}$

$-0.5 - 0.4 - 2 = -2.9\ \text{V}$

$V_A = 100\ \text{V}$

$$r_O = \frac{100}{1\ \text{m}} = 100\ \text{k}\Omega$$

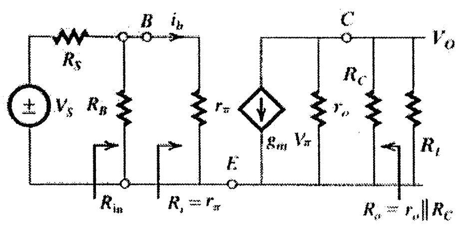
$$g_m = \frac{I_C}{V_T} = \frac{1\ \text{m}}{25\ \text{m}} = 40\ \text{mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40\ \text{m}} = 2.5\ \text{k}\Omega$$

$$r_e = \frac{r_\pi}{(\beta + 1)} \cong 25\ \Omega$$

Ex: 4.52

Example 4.50



$$R_i = \frac{v_b}{i_b} = r_\pi = 2.5\ \text{k}\Omega$$

$R_{IN} = R_B \| r_\pi = 100 \| 2.5 = 2.44\ \text{k}\Omega$

$A_{VO} = -g_m R_C \approx -40 \times 8 = -320\ \text{V/V}$

$R_O = R_C = 8\ \text{k}\Omega$

$A_{VO} = -g_m(r_O \| R_C \| R_L) \approx -40 \times 3.5$

$= -119\ \text{V/V}$

$R_O = r_O \| R_C = 100 \| 8 = 7.4\ \text{k}\Omega$

$A_{VO} = -g_m(r_O \| R_C)$

$= -40 \times 7.4 = -296\ \text{V/V}$

$$G_V = \frac{R_{IN}}{R_S + R_{IN}} A_V \frac{R_C}{R_O + R_L}$$

$$= \frac{2.44}{5 + 2.44}(-216)\frac{5}{7.4 + 5}$$

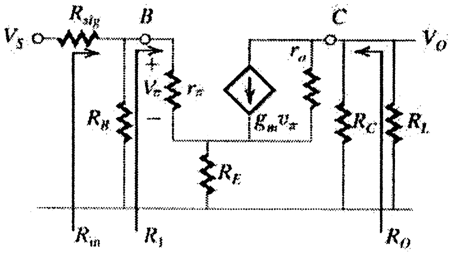
$= -39.1\ \text{V/V}$

$$\hat{v}_S = \frac{R_S + R_{IN}}{R_{IN}} \hat{V} = 15\ \text{mV}$$

$|\hat{v}_O| = G_V |\hat{v}_S|$

$= 39.1 \times 15 = 586\ \text{mV}$

Ex: 4.53



Example 4.50

$g_m = 40$ mA/V $\quad r_\pi = 2.5$ kΩ

$r_o = 100$ kΩ $\quad V_A = 100$ V $\quad R_B = 100$ kΩ

$R_{sig} = 5$ kΩ $\quad R_C = 8$ kΩ $\quad R_L = 5$ kΩ

$R_1 = r_\pi + (\beta + 1)R_E$

$R_{IN} = R_B \| R_1 = 4 \times R_{sig} = 20$ kΩ

$\therefore\ R_E = \dfrac{25 - 2.5}{101} = 0.22$ kΩ $= 223$ Ω

$A_{VO} = \dfrac{-g_m R_C}{1 + g_m R_E} \approx \dfrac{-40(8)}{1 + 40(223)} = -32$ V/V

$R_{out} = 8$ kΩ

$A_V = \dfrac{-R_C \| R_L}{r_e + R_E} = \dfrac{-8\text{ K} \| 5\text{ K}}{25 + 223} = -12.4$ V/V

$G_V = \dfrac{-\beta(R_C \| R_L)}{R_{sig} + (\beta + 1)(r_e + R_E)} = -9.9$ V/V

OR $G_V = \dfrac{R_{IN}}{R_{sig} + R_{IN}} \times A_V = \dfrac{20\text{ K}}{25\text{ K}} \times -12.4$

Note: without R_E: $A_V = -g_m(R_C \| R_L)$

$= -123$ V/V

with R_E:

$\dfrac{V_{sig}}{5\text{ mV}} = \dfrac{5 + 20}{20} = \dfrac{5}{4} \Rightarrow V_{sig} = 6.25$ mV

w/o R_E:

$\dfrac{V_{sig}}{5\text{ mV}} = \dfrac{5 + (2.5 \| 100)}{(2.5 \| 100)} \approx \dfrac{3}{1} \Rightarrow V_S = 15$ mV

$|V_O| = |V_1| \times A_V = 512.4 = 62$ mV

Ex: 4.54

$g_m = 40$ mA/V $\quad V_A = 100$

$r_o = 100$ kΩ $\quad \beta = 100$

$r_\pi = 2.5$ kΩ $\quad \alpha = 0.99$

$r_e = 25$ Ω $\quad I_E = 1$ mA

$R_{IN} = r_e = 25$ Ω

$A_{VO} = +g_m(R_C \| r_O)$

$= 40 \times 10^{-3} \times (8\text{ k} \| 100\text{ k})$

$= -296$ V/V

$R_{out} = R_C \| r_O = 7.4$ kΩ

$A_V = +g_m(R_C \| R_L \| r_O)$

$= 40 \times 3 = 120$ V/V

$\dfrac{r_i}{r_{sig}} = \dfrac{r_e}{R_{sig} + r_e} = \dfrac{25}{5000 + 25}$

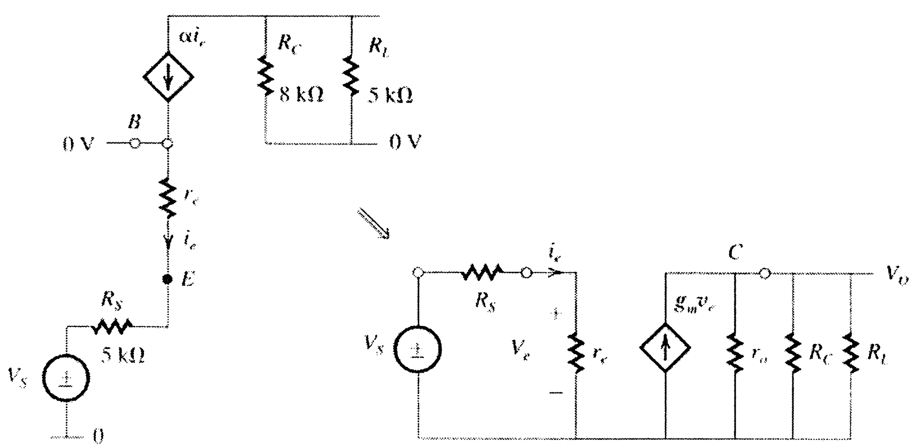
$= 0.005$ V/V

$G_V = \dfrac{\alpha(R_C \| R_L)}{R_{sig} + r_e}$

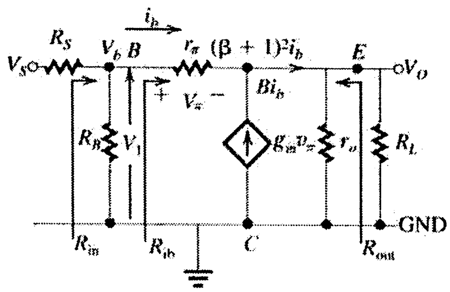
$= 0.6$ V/V

$R_{sig} = \dfrac{\alpha(R_C \| R_L)}{G_V}$

$R_{sig} = 54$ Ω



Ex: 4.55



$I_c = 5$ mA

$$r_\pi = \frac{\beta V_T}{I_C}$$

$$r_\pi = \frac{100(25\text{ m})}{5\text{ m}} = 500\ \Omega$$

$$r_O = \frac{V_A}{I_C} = \frac{100}{5\text{ m}} = 20\text{ k}\Omega$$

$$i_b = \frac{V_b - V_O}{r_\pi} \text{ and } V_O = (\beta+1)i_b(r_O \| R_L)$$

$$\therefore\ i_b = \frac{V_b}{r_\pi} - \frac{i_b(\beta+1)(r_O \| R_L)}{r_\pi}$$

$$\therefore\ R_{ib} = \frac{V_b}{i_b} = r_\pi + (\beta+1)(r_O \| R_L)$$

$$= 0.5 + (101)(20 \| 1)$$

$$= 96.7\text{ k}\Omega$$

$$R_{IN} = R_B \| R_{ib} = 40 \| 96.7 = 28.3\text{ k}\Omega$$

$$G_V = \frac{V_O}{V_S} = \frac{V_1}{V_S} \times \frac{V_O}{V_1}$$

$$= -\frac{R_{IN}}{R_S + R_{IN}} \times \frac{(\beta+1)(r_O \| R_L)}{(R_S \| R_B) + (\beta+1)(r_e + (r_O \|) R_L)}$$

$$= 0.796\text{ V/V}$$

$$G_{VO} = \frac{40}{10+40} \times \frac{20\text{ K}}{\frac{(10\text{ K} \| 40\text{ K})}{101}(5\text{E} + 5 + 20\text{ K})}$$

$$G_{VO} = 0.8\text{ V/V}$$

$$R_{out} = r_O \| (r_e + [R_S \| R_B])/(\beta+1)$$

$$= 20 \| [0.05 + 0.079]\text{ k}\Omega$$

$$= 84\ \Omega$$

$$\hat{V}_O = \frac{\hat{V}_\pi \times (r_O \| r_e)}{r_e} = \frac{0.01 \times 0.95}{0.005} = 1.9\text{ V}$$

For R_L(kΩ)	0.5	1.0	2.0
G_v (V/V)	0.68	0.735	0.765

Ex 4.56 blank

Ex: 5.1

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

$$\mu_n = 450 \text{ cm}^2/\text{VS}$$

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

$$V_{OV} = (v_{GS} - V_t) = 0.5 \text{ V}.$$

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

$L = 0.18$ μm, so $W = 0.93$ μm

Ex: 5.2

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{34.5 \text{ pF/m}}{4 \text{ nm}} = 2.30 \text{ fF}/\mu\text{m}^2$$

$$\mu_n = 550 \text{ cm}^2/\text{VS}$$

$$k'_n = \mu_n C_{ox} = 127 \ \mu\text{A}/\text{V}^2$$

$$I_D = \frac{1}{2} k'_n \frac{W}{L} V_{OV}^2 = 0.2 \text{ mA}, \ \frac{W}{L} = 20$$

$$\therefore V_{OV} = 0.40 \text{ V}.$$

$V_{DS,\min} = V_{OV} = 0.40$ V, for saturation

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 In saturation $v_{DS} \geq V_{OV}$, so $2V_{OV}$

$$I_D = \frac{1}{2} k'_n \frac{W}{L} V_{OV}^2, \text{ so } 4 \ I_D.$$

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

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

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

For $v_{DS} = 0.5 \text{ V} \cdot = V_{OV}$

$$I_D = \frac{1}{2} k'_n \frac{W}{L} V_{OV}^2 = 0.25 \text{ mA}$$

for all $v_{DS} \geq V_{OV} = 0.5$ V.

Ex: 5.6

$$V_A = V'_A L = 50 \times 0.8 = 40 \text{ V},$$

$$\lambda = \frac{1}{V_A} = 0.025 \text{ V}^{-1}$$

$$V_{DS} = 1 \text{ V} > V_{OV} = 0.5 \text{ V}$$

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

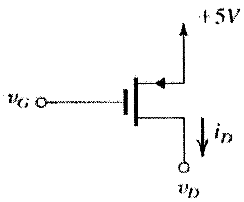
$$I_D = \frac{1}{2} \times 200 \times \frac{16}{0.8} \times 0.5^2 (1 + 0.025 \times .1)$$

$$= 0.51 \text{ mA}$$

$$r_o = \frac{V_A}{I_D} = \frac{40}{0.51} = 78.4 \text{ k}\Omega \simeq 80 \text{ k}\Omega$$

$$r_o = \frac{\Delta V_{DS}}{\Delta I_O} \Rightarrow \Delta I_O = \frac{2 \text{ V}}{80 \text{ K}} = 0.025 \text{ mA}$$

Ex: 5.7



$$V_{tp} = -1 \text{ V}.$$

$$k'_p = 60 \ \mu\text{A}/\text{V}^2$$

$$\frac{W}{L} = 10 \Rightarrow k_p = 600 \ \mu\text{A}/\text{V}^2$$

(a) Conduction occurs for $v_{GS} \leq V_{tp} = -1$ V.

or $v_G \leq V_{tp} + V_s = +4$ V.

(b) Triode region occurs for $v_{GD} \leq V_{tp}$

or $v_G - v_D \leq -1$

or $v_D \geq v_G + 1$

(c) Conversely, for saturation

$v_D \leq v_G + 1$

(d) Given $\lambda \cong 0$

$$I_D = \frac{1}{2} k'_p \frac{W}{L} |V_{OV}|^2 = 75 \ \mu\text{A}$$

$$\therefore |V_{OV}| = 0.5 \text{ V} = -v_{GS} + V_{tp}$$

$$= -v_G + v_S + V_{tp} = 4 - v_G$$

$\therefore v_G = +3.5$ V.

$v_D \le v_G + 1 = 4.5$ V.

(e) For $\lambda = -0.02\ V^{-1}$ and $|V_{OV}| = 0.5$ V.

$I_D = 75\ \mu A$ and $r_o = \frac{1}{|2|I_D} = 667\ k\Omega$

(f) At $V_D = 3$ V.

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

$= 75\ \mu A(1.04) = 78\ \mu A$

At $V_D = 0V$,

$I_D = 75\ \mu A(1.10) = 82.5\ \mu A$

$r_o = \frac{\Delta V_{DS}}{\Delta I_D} = \frac{3V.}{4.5\ \mu A} = 667\ k\Omega$

Ex: 5.8

$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}V_{OV}^2 \Rightarrow 0.3 = \frac{1}{2} \times \frac{60}{1000}$

$\times \frac{120}{3}V_{OV}^2 \Rightarrow$

$V_{OV} = 0.5\ V \Rightarrow V_{GS} = V_{GV} + V_t = 0.5 + 1$

$= 1.5$ V

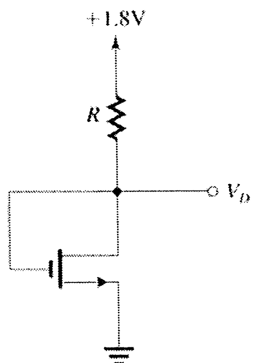
$V_S = -1.5\ V \Rightarrow R_S = \frac{V_S - V_{SS}}{I_D}$

$= \frac{-1.5 - (-2.5)}{0.3}$

$R_S = 3.33\ k\Omega$

$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{2.5 - 0.4}{0.3} = 7\ k\Omega$

Ex: 5.9



$V_{tn} = 0.5$ V.

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

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

$\lambda = 0$

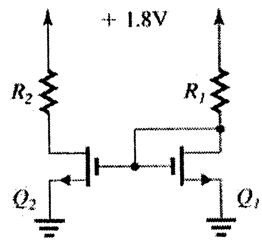
saturation mode $(v_{GD} = 0 < V_{tn})$

$V_D = 0.8\ V. = 1.8 - I_D R_D$

$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_D - V_{tn})^2 = 72\ \mu A$

$\therefore R = \frac{1.8 - 0.8}{72\ \mu A} = 13.9\ k\Omega$

Ex: 5.10



From Exc. 5.9, $V_{GS} = 0.8$ V, $V_{tn} = 0.5$ V,

$V_{OV} = 0.3$ V.

$I_D = 72\ \mu A$ (saturation)

At the triode/saturation boundary

$V_D = V_{OV} = 0.3$ V

$\therefore R_2 = \frac{1.8\ V - 0.3\ V}{72\ \mu A} = 20.8\ k\Omega$

Ex: 5.11

$R_D = 12.4 \times 2 = 24.8\ k\Omega$

$V_{GS} = 5$ V, Assume triode region:

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

$\frac{5 - V_{DS}}{24.8} = 1 \times \left((5 - 1)V_{DS} - \frac{V_{DS}^2}{2}\right)$

$\Rightarrow V_{DS}^2 - 8.08V_{DS} + 0.4 = 0$

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

$I_D = \frac{5 - 0.05}{24.8} = 0.2$ mA

Ex: 5.12

As indicated in Example 3.5

$V_D \ge V_G - V_t$ for the transistor to be in 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

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

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

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

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

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

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

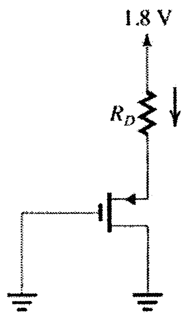
$$R_S = \frac{V_S}{0.32} = 5\text{ k}\Omega$$

$V_{DS} \geq V_{OV} \Rightarrow V_D \geq V_{OV} + V_S \Rightarrow V_D \geq 0.8 + 1.6 = 2.4\text{ V}$

Assume

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

Ex: 5.14



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

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

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

$$V_{GS} = -0.6 + V_{tp} = -1.0\text{ V} = -1.8 + I_D R$$

$$I_D R = 0.8\text{ V. for } V_{OV} = -0.6\text{ V}$$

$$I_D = \frac{1}{2}k_p V_{OV}^2 = 0.1\text{ mA}$$

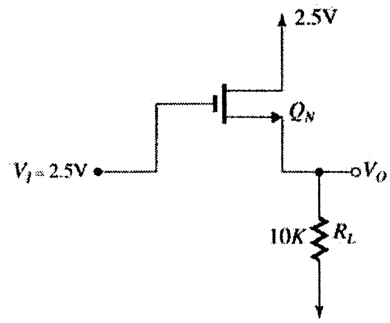
$$\therefore R = 800\ \Omega$$

Ex: 5.15

$v_I = 0$: Since the circuit is perfectly symmetrical $V_o = 0$ and therefore $V_{GS} = 0$ which implies the transistors are turned off and $I_{DN} = I_{DP} = 0$.

$V_I = 2.5\text{ V}$: 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 ($V_{GSP} > 0$)

$$I_{DN} = \frac{1}{2}k_n'\frac{W}{L}(V_{GS} - V_t)^2$$

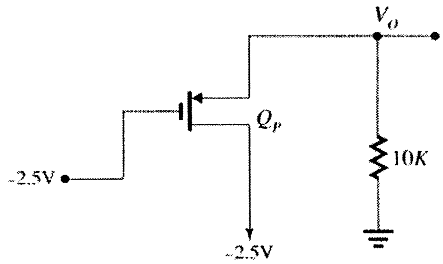


$$I_{DN} = \frac{1}{2} \times 1(2.5 - V_S - 1)^2$$

$$I_{DN} = 0.5(1.5 - V_S)^2$$

Also: $V_S = R_L I_{DN} = 10 I_{DN}$

$$I_{DN} = 0.5(1.5 - 10 I_{DN})^2$$



$$\Rightarrow 100 I_{DN}^2 - 32 I_{DN} + 2.25 = 0 \Rightarrow I_{DN} = 0.104\text{ mA}$$

$$I_{DP} = 0,\ V_O = 10 \times 0.104 = 1.04\text{ V}$$

$V_I = -2.5\text{ V}$: Again if we assume that Q_P is turned on, then $V_o > -2.5$ V and $V_{GS1} < 0$ which implies the NMOS Q_N is turned off.

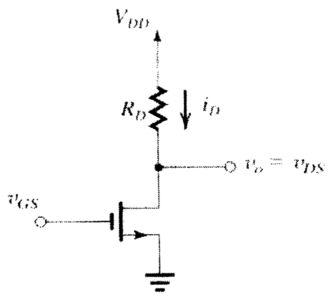
$I_{DN} = 0$

$$I_{DP} = \frac{1}{2}k_n\frac{W}{L}(V_{SG} - |V_t|)^2 = \frac{1}{2} \times 1 \times (v_S + 2.5 - 1)^2$$

$$V_S = -10I_{DP} \Rightarrow 2I_{DP} = (-10I_{DP} + 1.5)^2$$

$$\Rightarrow I_{DP} = 0.104 \text{ mA} \Rightarrow V_O = -10 \times 0.104 = -1.04 \text{ V}$$

Ex: 5.16



$V_{DD} = 1.8$ V

$R_D = 17.5$ kΩ

$V_t = 0.4$ V.

$k_n = 4$ mA / V^2

$\lambda = 0$

(A) Cutoff/Saturation Boundary

$v_{GS} = V_t = 0.4$ V., $v_o = v_{DS} = 1.8$ V.

(B) Saturation/Triode Boundary

$$v_{GD} = v_{GS} - v_o = V_t = 0.4\text{V}.$$

$$\Rightarrow v_{GS} - \left[V_{DD} - \frac{1}{2}k_n(v_{GS} - V_t)^2 R_D\right] = 0.4$$

$$v_{GS} - [1.8 - 35(v_{GS}^2 - 0.8\ v_{GS} + 0.16)] = 0.4$$

$$35v_{GS}^2 - 27v_{GS} + 3.4 = 0$$

$v_{GS} = 0.613$ V., 0.1585

$I_D = 90.7$ μA

$v_O = 0.213$ V.

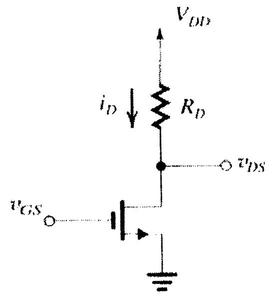
(C) For $v_{GS}|_C = V_{DD} = 1.8$ V., triode,

$V_{OV} = 1.4$ V.

$$r_{DS} = (k_n V_{ov})^{-1} = 179 \ \Omega$$

$$V_O|_C = V_{DS}|_C \cong V_{DD}\frac{r_{DS}}{R_D + r_{DS}} = 18 \text{ mV}.$$

Ex: 5.17



$V_t = 0.4$ V.

$V_{DD} = 1.8$ V.

$V_{GS} = 0.6$ V.

$k'_n = 0.4$ mA / V^2

$\frac{W}{L} = 10$

$R_D = 17.5$ kΩ

(a) $V_{OV} = 0.2$ V.,

$$g_m = k'_n\frac{W}{L}V_{OV} = 800 \ \mu\text{A / V}$$

for $A_V = -g_m R_D = -10$, make

$R_D = 12.5$ kΩ

$v_{GS} = 0.6$ V., $I_D = 0.08$ mA,

$V_{DS} = 0.8$ V.

(b) keep $R_D = 17.5$ kΩ

$$-g_m R_D = -10 \Rightarrow g_m = 571 \ \mu\text{A / V}$$

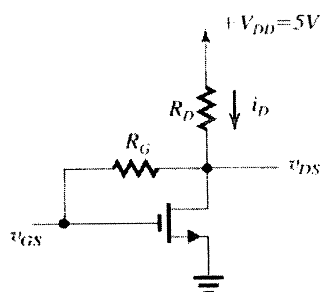
$$= k'_n\frac{W}{L}V_{OV}$$

$\therefore V_{OV} = 0.143$ V.

$v_{GS} = 0.54$ V, $I_D = 0.04$ mA,

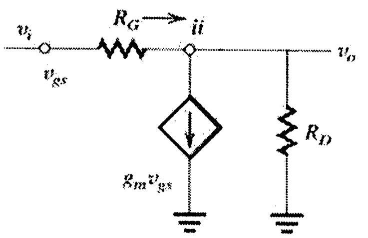
$v_{DS} = 1.1$ V.

Ex: 5.18



$V_t = 0.7$ V.

$k_n = 1$ mA / V^2



Design for $A_v = \frac{v_O}{v_i} = -25$, $R_{in} = 500$ kΩ

$\therefore g_m R_D = 25 = k_n V_{OV} R_D$

$R_{in} = \frac{v_i}{ii} = \frac{v_i}{v_i - v_o} R_G$

$\Rightarrow R_G = 26 R_{in} = 13$ MΩ

$I_D R_D = \left(\frac{1}{2} k_n V_{OV}^2\right) R_D$

$= \frac{1}{2} g_m R_D V_{OV} = 12.5\ V_{OV}$

and

$V_{OV} = V_{DD} - V_t - I_D R_D = 4.3 - 12.5\ V_{OV}$

$\therefore V_{OV} = 0.319$ V.

$g_m = 319\ \mu$A / V

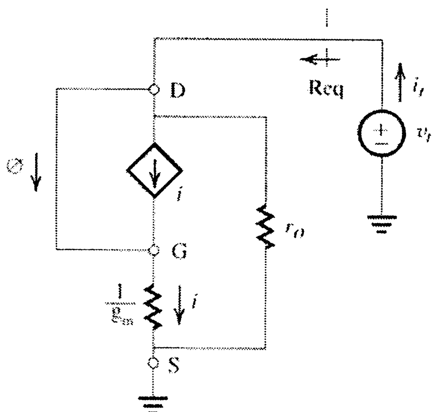
$R_D = 78.5$ kΩ

$V_{DS} = V_{OV} + V_t$

$\hat{v}_{GD} = 0 + 26 \hat{v}_i \le V_t$

$\therefore |\hat{v}_i| < \frac{V_t}{26} = 27$ mV.

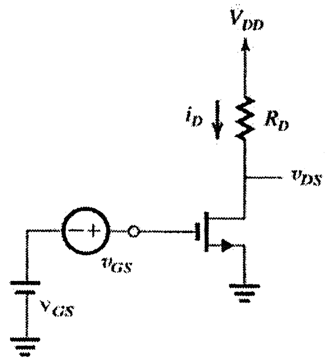
Ex: 5.19



$i_t = \frac{v_t}{r_o} + i = \frac{v_t}{r_o} + g_m v_t$

$\therefore \text{Req} = \frac{v_t}{i_t} r_o \| \frac{1}{g_m}$

Ex: 5.20



$V_{DD} = 5$ V.

$V_{GS} = 2$ V.

$V_t = 1$ V.

$\lambda = 0$

$k_n' = 20\ \mu$A / V^2

$R_D = 10$ kΩ

$\frac{W}{L} = 20$

(a) $V_{GS} = 2V \Rightarrow V_{OV} = 1$ V.

$I_D = \frac{1}{2} k_n' \frac{W}{L} V_{OV}^2 = 200\ \mu$A

$V_{DS} = V_{DD} - I_D R_D = +3$ V

(b) $g_m = k_n' \frac{W}{L} V_{OV} = 400\ \mu$A / V

(c) $A_V = \frac{v_{ds}}{v_{gs}} = -g_m R_D = -4$

(d) $v_{gs} = 0.2 \sin \omega t$ V.

$v_{ds} = -0.8 \sin \omega t$ V.

$v_{DS} = V_{DS} + v_{ds} \Rightarrow 2.2 \le v_{DS} \le 3.8$ V.

(e) Using (5.43)

$i_D = \frac{1}{2} k_n (V_{GS} - V_t)^2$

$+ k_n (V_{GS} - V_t) v_{gs} + \frac{1}{2} k_n v_{gs}^2$

$i_D = 200\ \mu\text{A} + (80\ \mu\text{A}) \sin \omega t$

$+ (8\ \mu\text{A}) \sin^2 \omega t$

$= [200 + 80\ \sin\omega t + (4 - 4\ \cos\omega t)]\mu A$

I_D shifts by 4 μA

$$2HD = \frac{\hat{i}_{2\omega}}{\hat{i}_{\omega}} = \frac{4\ \mu A}{80\ \mu A} = 0.05\ (5\%)$$

Ex: 5.21

$$a)\ g_m = \frac{2I_D}{V_{OV}}\ I_D = \frac{1}{2} \times k_n' \frac{W}{L} V_{OV}^2 = \frac{1}{2} \times 60$$

$$\times 40 \times (1.5 - 1)^2$$

$I_D = 300\ \mu A = 0.3\ mA,\ V_{OV} = 0.5\ V$

$$g_m = \frac{2 \times 0.3}{0.5} = 1.2\ mA/V,$$

$$r_o = \frac{V_A}{I_D} = \frac{15}{0.3} = 50\ k\Omega$$

$$I_D = 0.5\ mA \Rightarrow g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D}$$

$$= \sqrt{2 \times 60 \times 40 \times 0.5 \times 10^3}$$

$g_m = 1.55\ mA/V$

$$r_o = \frac{V_A}{I_D} = \frac{15}{0.5} = 30\ k\Omega$$

Ex: 5.22

$I_D = 0.1\ mA,\ g_m = 1\ mA/V,\ k_n' = 50\mu A/V^2$

$$g_m = \frac{2I_D}{V_{OV}} \Rightarrow V_{OV} = \frac{2 \times 0.1}{1} = 0.2\ V$$

$$I_D = \frac{1}{2} k_n' \frac{W}{L} V_{OV}^2 \Rightarrow \frac{W}{L} = \frac{2I_D}{k_n' V_{OV}^2}$$

$$= \frac{2 \times 0.1}{\frac{50}{1000} \times 0.2^2} = 100$$

Ex: 5.23

$g_m = \mu_n C_{ox} \frac{W}{L} V_{OV}$ 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: 5.24

$$I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{SG} - |V_t|)^2$$

$$= \frac{1}{2} \times 60 \times \frac{16}{0.8} \times (1.6 - 1)^2$$

$I_D = 216\ \mu A$

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 216}{1.6 - 1} = 720\ \mu A/V$$

$= 0.72\ mA/V$

$$\lambda = 0.04 \Rightarrow V_A' = \frac{1}{\lambda} = \frac{1}{0.04} = 25\ V/\mu m$$

$$r_o = \frac{V_A' \times L}{I_D} = \frac{25 \times 0.8}{0.216} = 92.6\ k\Omega$$

Ex: 5.25

$$g_m r_o = \frac{2I_D}{V_{OV}} \times \frac{V_A}{I_D} = \frac{2V_A}{V_{OV}} = A_o$$

$V_A' \times L = V_A$

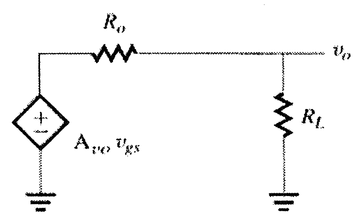
$$L = 0.8\ \mu m \Rightarrow A_o = \frac{2 \times 12.5 \times 0.8}{0.2}$$

$= 100\ V/V$

Ex: 5.26

(5.70) $A_{vo} = -g_m(R_D \| r_O)$

(5.72) $R_O = R_D \| r_O$



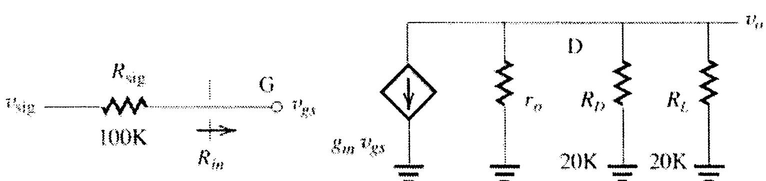
$$A_v = \frac{v_O}{v_{GS}} = A_{vO} \frac{R_L}{R_O + R_L}$$

$$= -g_m R_O \frac{R_L}{R_O + R_L}$$

$\therefore A_v = -g_m(R_O \| R_L) = -g_m(R_D \| r_O \| R_L)$

same as (5.75)

Ex: 5.27



$I_D = 0.25\ \text{mA},\ V_{OV} = 0.25\ \text{V},$

$V_A = 50\ \text{V}$

$r_O = \dfrac{V_A}{I_D} = 200\ \text{k}\Omega$

$g_m = \dfrac{2I_D}{V_{OV}} = 2\ \text{mS}$

$R_{in} = \infty$

$A_{vo} = -g_m(R_D \| r_O) \simeq -g_m R_D = -4$

$R_O = R_D \| r_O \simeq R_D = 20\ \text{k}\Omega$

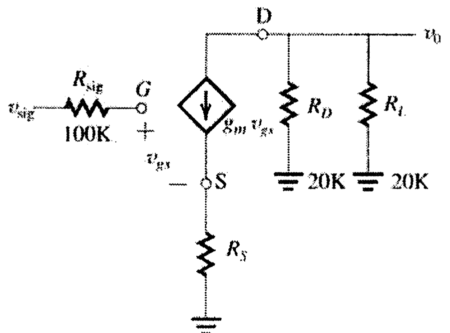
$A_v = G_V = -g_m(R_D \| r_o \| R_L) \simeq$

$-g_m(R_D \| R_L) = -20\ \text{V/V}$

for $\hat{v}_{gs} = (10\%)\ 2V_{OV} = 0.05\ \text{V}.$

$\hat{v}_O = |A_V \hat{v}_{gs}| = 1\ \text{V}.$

Ex: 5.28



Assuming $V_A \to \infty$

From Ex 5.27

$g_m = 2\ \text{mS}$

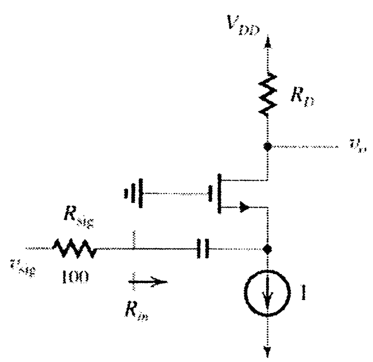
$\dfrac{v_{gs}}{V_{Dis}} = \dfrac{1}{1 + g_m R_S} = \dfrac{50\ \text{mV}}{200\ \text{mV}} \Rightarrow g_m R_S = 3$

$\therefore\ R_S = 1.5\ \text{k}\Omega$

$G_V = A_V = \dfrac{-g_m(R_D \| R_L)}{1 + g_m R_S} = \dfrac{-20}{4} = -5$

$\hat{v}_O = |G_V \hat{v}_{sig}| = 1\text{V}.$

Ex: 5.29



$R_{in} = \dfrac{1}{g_m} = R_{sig} = 100\ \Omega$

$\Rightarrow g_m = 10\ \text{mA/V}$

$g_m = \dfrac{2I_D}{V_{OV}} = \dfrac{2I_D}{0.2\text{V}.} \Rightarrow I_D = 1\ \text{mA}$

$G_V = \dfrac{v_O}{v_{sig}} = \dfrac{R_{in}}{R_{sig} + R_{in}} g_m R_D$

$= \left(\dfrac{1}{2}\right)(10\ \text{mA/V})(2\ \text{k}\Omega)$

$= +10$

Ex: 5.30

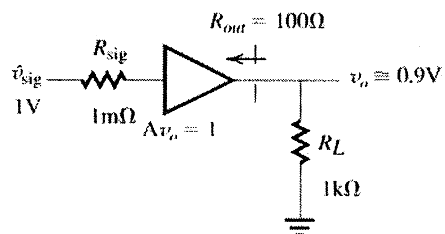
CD amplifier

$R_{out} = \dfrac{1}{g_m} = 100\ \Omega \Rightarrow g_m = 10\ \text{mA/V}$

$g_m = \dfrac{2I_D}{V_{OV}} = \dfrac{2I_D}{0.25\text{V}} \Rightarrow I_D = 1.25\ \text{mA}$

$\hat{v}_O = \hat{v}_{sig} \dfrac{g_m R_L}{1 + g_m R_L} = 0.91\ \text{V}.$

$\hat{v}_{gs} = \hat{v}_{sig} \dfrac{1}{1 + g_m R_L} = 91\ \text{mV}.$



Ex: 5.31

CD (source follower)

$R_{out} = 200\ \Omega = \dfrac{1}{g_m} \Rightarrow g_m = 5\ \text{mA/V}$

$g_m = k_n' \dfrac{W}{L} V_{OV} = (0.4\ \text{mA/V}^2)$

$\left(\dfrac{W}{L}\right)(0.25\ \text{V}) \Rightarrow \dfrac{W}{L} = 50$

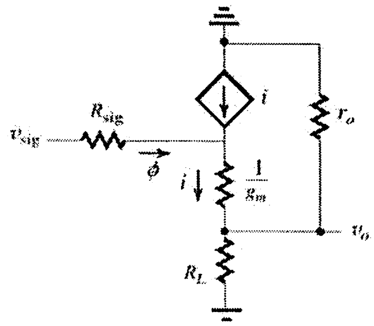
$I_D = \dfrac{1}{2} k_n' \dfrac{W}{L} V_{OV}^2 = 0.625\ \text{mA}$

$G_V = \dfrac{g_m R_L}{1 + g_m R_L}$

for $1\ K < R_L < 10\ K$

$0.83 < G_V < 0.98$

Ex: 5.32



$$A_{vo} = A_v\big|_{R_L \to \infty} = \frac{g_m r_o}{1 + g_m r_o}$$

$$A_{vo} = \frac{r_o}{r_o + \frac{1}{g_m}}$$

$$A_{vo} = \frac{\left(\frac{V_A}{I_D}\right)}{\left(\frac{V_A}{I_D}\right) + \left(\frac{V_{OV}}{2I_D}\right)}$$

$$= \frac{2V_A}{2V_A + V_{OV}} = \left[1 + \frac{V_{OV}}{2V_A}\right]^{-1}$$

for $V_A = 20$ V.

$$A_{vo} = 0.99 = \frac{1}{1 + \frac{V_{OV}}{40}} \Rightarrow V_{OV} = 0.40 \text{ V}.$$

Ex: 5.33

$$I_D = \frac{1}{2}k_n'\frac{W}{L}(V_{GS} - V_t)^2 \Rightarrow 0.5 \text{ mA}$$

$$= \frac{1}{2} \times 1(V_{GS} - 1)^2$$

$V_{GS} = 2$ V.

IF $V_t = 1.5$ V then:

$$I_D = \frac{1}{2} \times 1 \times (2 - 1.5)^2 = 0.125 \text{ mA}$$

$$\Rightarrow \frac{\Delta I_D}{I_o} = \frac{0.5 - 0.125}{0.5} = 0.75 = 75\%$$

Ex: 5.34

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{5 - 2}{0.5} = 6 \text{ k}\Omega$$

$\rightarrow R_D = 6.2$ kΩ

$$I_D = \frac{1}{2}k_n'\frac{W}{L}V_{OV}^2 \Rightarrow 0.5 = \frac{1}{2} \times 1 \times V_{OV}^2$$

$\Rightarrow V_{OV} = 1$ V

$\Rightarrow V_{GS} = V_{OV} + V_t = 1 + 1 = 2$ V

$\Rightarrow V_S = -2$ V

$$R_S = \frac{V_S - V_{SS}}{I_D} = \frac{-2 - (-5)}{0.5} = 6 \text{ k}\Omega$$

$\rightarrow R_S = 6.2$ kΩ

If we choose $R_D = R_s = 6.2$ kΩ then I_D will slightly change:

$I_D = \frac{1}{2} \times 1 \times (V_{GS} - 1)^2$. Also

$V_{GS} = -V_S = 5 - R_S I_D$

$2I_D = (4 - 6.2I_D)^2$

$\Rightarrow 38.44I_D^2 - 51.6I_D^2 + 16 = 0$

$\Rightarrow I_D = 0.49$ mA, 0.86 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

$V_S = -5 + 6.2 \times 0.49 = -1.96$ V

$V_D = 5 - 6.2 \times 0.49 = +1.96$ V

R_G should be selected in the range of 1 MΩ to 10 MΩ to have low current.

Ex: 5.35

$$I_D = 0.5 \text{ mA} = \frac{1}{2}k_n'\frac{W}{L}V_{OV}^2 \Rightarrow V_{OV}^2$$

$$= \frac{0.5 \times 2}{1} = 1 \Rightarrow$$

$V_{OV} = 1 \text{ V} \Rightarrow V_{GS} = 1 + 1 = 2$ V

$$= V_D \Rightarrow R_D = \frac{5 - 2}{0.5} = 6 \text{ k}\Omega$$

$\Rightarrow R_D = 6.2$ kΩ standard value. For this R_D we have to recalculate I_D:

$$I_D = \frac{1}{2} \times 1 \times (V_{GS} - 1)^2$$

$$= \frac{1}{2}(V_{DD} - R_D I_D - 1)^2$$

$(V_{GS} = V_D = V_{DD} - R_D I_D)$

$$I_D = \frac{1}{2}(4 - 6.2I_D)^2 \Rightarrow I_D \cong 0.49 \text{ mA}$$

$V_D = 5 - 6.2 \times 0.49 = 1.96$ V

Ex: 5.36

Using Eq. 3.53

$$I = I_{REF}\frac{(W/L)_2}{(W/L)_1} \Rightarrow I_{REF} = 0.5 \times \frac{1}{5}$$

$\Rightarrow I_{REF} = 0.1$ mA

$$I_{REF} = 0.1 = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_1 V_{OV}^2 \Rightarrow V_{OV}^2$$

$$= \frac{0.1 \times 2}{0.8} = 0.25 \Rightarrow V_{OV} = 0.5 \text{ V}$$

$V_{GS} = V_{OV} + V_t = 1.5$ V

$\Rightarrow V_G = -5 + 1.5 = -3.5$ V

$$R = \frac{V_{GS} - V_G}{I_{REF}} = \frac{5 - (-3.5)}{0.1} = 85\ \text{k}\Omega$$

$$V_{DS2} \geq V_{OV} \Rightarrow V_{DS\min} = V_{OV} = 0.5\ \text{V}$$

$$\Rightarrow V_{D\min} = -4.5\ \text{V}$$

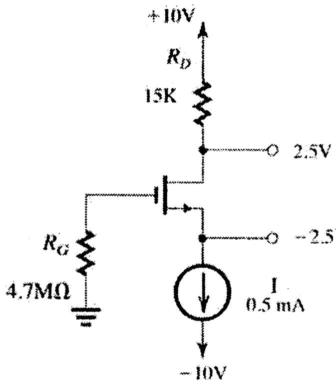
Ex: 5.37

$$V_t = 1.5\ \text{V}$$

$$k_n'\frac{W}{L} = 1\ \text{mA/V}^2$$

$$V_A = 75\text{V}.$$

$$I_D = 0.5\text{mA} = \frac{1}{2}k_n'\frac{W}{L}V_{OV}^2 \Rightarrow V_{OV} = 1.0\ \text{V}.$$



$$V_{GS} = V_t + V_{OV} = 2.5\ \text{V}$$

$$V_G = 0$$

$$V_S = -2.5\ \text{V}.$$

$$V_D = V_{DD} - I_D R_D = +2.5\ \text{V}.$$

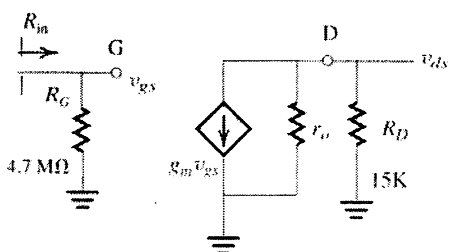
$$g_m = k_n'\frac{W}{L}V_{OV} = 1\ \text{mA/V}$$

$$r_O = \frac{V_A}{I_D} = 150\ \text{k}\Omega$$

$$V_{GD} - \hat{v}_{gd} = V_t$$

$$-\hat{v}_{gd} \cong \hat{v}_d = V_t - V_{GD} = 4.0\ \text{V}.$$

Ex: 5.38



$$g_m = \sqrt{2k_n'\frac{W}{L}I_D} = 1\ \text{mA/V}$$

$$r_O = \frac{V_A}{I_D} = 150\ \text{k}\Omega$$

For $r_O \to \infty$

$$R_{in} = R_G = 4.7\ \text{M}\Omega$$

$$A_{vO} = -g_m R_D = -15$$

$$R_{out} = R_D = 15\ \text{k}\Omega$$

For $r_O = 150\ \text{k}\Omega$, $R_L = 15\ \text{k}\Omega$

$$R_{in} = 4.7\ \text{M}\Omega$$

$$A_{vO} = -g_m(R_D \| r_O) = -13.6$$

$$R_{out} = R_D \| r_O = 13.6\ \text{k}\Omega$$

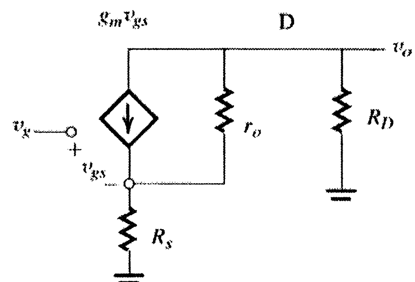
$$G_V = \frac{R_{in}}{R_{in} + R_{sig}}A_{vO}\frac{R_L}{R_L + R_{out}} = -7.0$$

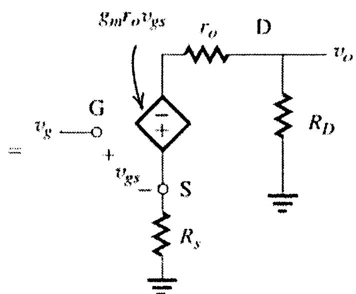
$$v_{DS} = v_O = V_{DS} + v_{ds}$$

$$= 2.5\ \text{V} + G_V(0.4\ \text{V}_{p-p})$$

v_O is a 2.8 V_{p-p} sinusoid superimposed upon a 2.5V d_C voltage.

Ex: 5.39





$$(1)\ v_O = v_{gs}\frac{-g_m r_O R_D}{R_D + r_O + R_S}$$

$$(2)\ v_{gs} = v_g\frac{R_D + r_O + R_S}{R_D + r_O + R_S(1 + g_m r_O)}$$

$$(3)\ v_O = V_g\frac{-g_m r_O R_D}{R_D + r_O + R_S(1 + g_m r_O)}$$

we want

$$\left.\frac{v_O}{v_g}\right|_{R_S} = \frac{1}{3}\left.\frac{v_O}{v_g}\right|_{R_S=0}$$

using (3)

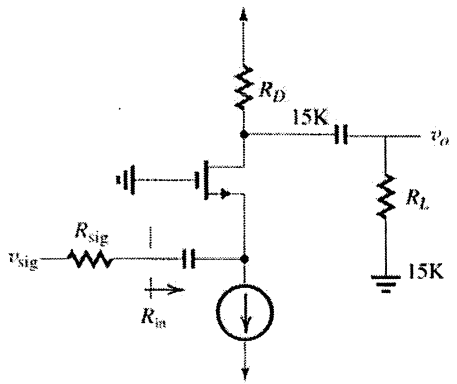
$$\frac{-g_m r_O R_D}{(R_D + r_O) + R_S(1 + g_m r_O)} = \frac{1}{3}\frac{-g_m r_O R_D}{R_D + r_O}$$

$$R_S = \frac{2(R_D + r_O)}{1 + g_m r_O} = 2.185\ \text{k}\Omega$$

based on $R_D = 15\ \text{K}$, $r_O = 150\ \text{K}$,

$g_m = 1\ \text{mS}$

Ex: 5.40



$g_m = 1\ \text{mA/V}$

For $R_{sig} = 50\ \Omega$

$$R_{in} = \frac{1}{g_m} = 1\ \text{k}\Omega$$

$R_{out} = R_D = 15\ \text{k}\Omega$

$A_{vo} = +g_m R_D = +15$

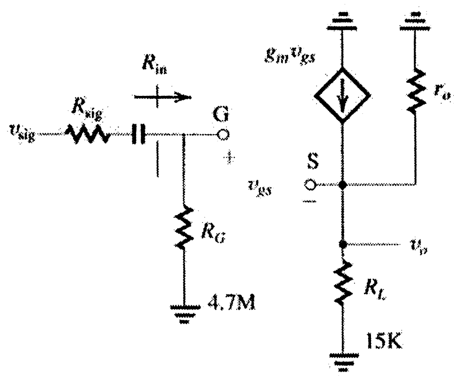
$A_V = g_m(R_D \| R_L) = +7.5$

$$G_V = \frac{R_{in}}{R_{sig} + R_{in}} A_V = 7.1$$

For other R_{sig}

R_{sig}	G_V
1 kΩ	3.75
10 kΩ	0.68
100 kΩ	0.07

Ex: 5.41



$g_m = 1\ \text{mA/V}$

$r_O = 150\ \text{k}\Omega$

$R_{in} = R_G$

$$A_{vo} = \frac{g_m r_O}{1 + g_m r_O}$$

$$A_V = \frac{g_m(r_O \| R_L)}{1 + g_m(r_O \| R_L)}$$

$$R_{out} = \frac{1}{g_m} \| r_O$$

(a)

	$r_o \to \infty$	$r_o = 150\ \text{k}\Omega$
R_{in}	4.7 MΩ	4.7 MΩ
A_{vo}	1.0	0.993
A_v	0.938	0.932
R_{out}	1 kΩ	0.993 kΩ

(b) $G_v = \dfrac{R_{in}}{R_{in} + R_{sig}} A_v = 0.768$

Ex 5.42

See the next page

using eq. (5.107)

$$V_t = V_{to} + r[\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}]$$

$$V_t = 0.8 + 0.4[\sqrt{0.7 + 3} - \sqrt{.7}]$$

$V_t = 1.23$ V

Ex: 5.43

$V_{GS} = +1\text{ V}, V_t = -2\text{ V}$

$V_{GS} - V_t = 3\text{ V}$

TO OPERATE IN SATURATION REGION:

$$V_{DS\,min} = V_{GS} - V_t = 3\text{ V}$$

$$i_D = \frac{1}{2}k_n'\frac{W}{L}(V_{GS} - V_t)^2$$

$$= \frac{1}{2} \times 2 \times 3^2 = 9\text{ mA}$$

Ex: 6A.1 (a) The minimum value of I_n occurs when

$V_{ov} = 0.2$ V and $\frac{W}{L} = 0.1$, that is

$$I_{Dmin} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}V_{OV}^2 \simeq 0.8\ \mu A$$

The maximum value of I_n occurs when

$V_{ov} = 0.4$ V and $\frac{W}{L} = 100$, that is

$$I_{Dmax} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}V_{OV}^2 \simeq 3.1\ mA$$

(b) For a similar range of current in an npn transistor, we have

$$\frac{I_{cmax}}{I_{cmin}} = \frac{3.1\ mA}{0.8\ \mu A} = \frac{I_S e^{V_{BEmax}/V_T}}{I_S e^{V_{BEmin}/V_T}}$$

$$\Rightarrow e^{(V_{BEmax} - V_{BEmin})/V_T} = e^{\Delta V_{BE}/V_T}$$

$$= \frac{3.1\ mA}{0.8\ \mu A}$$

$$\Delta V_{BE} = V_T \ln\left(\frac{3.1\ mA}{0.8\ \mu A}\right) \text{ and } V_T = (25)\ mV$$

$$\Rightarrow \Delta V_{BE} = 207\ mV$$

Ex: 6A.2 For an NMOS Fabricated in the 0.5 µm process, with $\frac{W}{L} = 10$, we want to find the transconductance and the intrinsic gain obtained for the following drain currents: ($L = 0.5$ µm)

$$I_D = (10)\ \mu A,\ g_m = \sqrt{2\ \mu_n C_{ox}\left(\frac{W}{L}\right)I_D}.$$

$$\mu_n C_{ox} = (190)\ \frac{\mu A}{V^2}$$

$$g_m = \sqrt{2 \times 190 \times 10 \times 10} \simeq 0.2\ \frac{mA}{V}$$

$$r_o = \frac{V_A}{I_D} = \frac{V_A' L}{I_D} = \frac{20 \times 0.5}{10\ \mu A} = 1\ M\Omega$$

intrinsic gain

$$= g_m r_o = 0.2\ \frac{mA}{V} \times 1\ M\Omega = 200\ \frac{V}{V}$$

For $I_D = 100$ µA we have:

$$g_m = \sqrt{2\ \mu_n C_{ox}\left(\frac{W}{L}\right)I_D} = \sqrt{2 \times 190 \times 10 \times 100}$$

$$g_m = 0.62\ \frac{mA}{V} \simeq 0.6\ \frac{mA}{V}$$

$$r_o = \frac{V_A' L}{I_D} = \frac{20 \times 0.5}{100\ \mu A} = 100\ k\Omega$$

$$g_m r_o = 0.62\ \frac{mA}{V} \times 100\ k\Omega = 62\ V/V$$

For $I_D = 1$ mA

$$g_m = \sqrt{2\ \mu_n C_{ox}\left(\frac{W}{L}\right)I_D}$$

$$= \sqrt{2 \times 190 \times 10 \times 1} \simeq 2\ \frac{mA}{V}$$

$$r_o = \frac{V_A' L}{I_D} = \frac{20 \times 0.5}{1\ mA} = 10\ k\Omega$$

$$g_m r_o = 2\ \frac{mA}{V} \times 10\ k\Omega = 20\ V/V$$

Ex: 6.A.3 For an NMOS fabricated in the 0.5 µm CMOS technology specified in Table 7.A.1 with $L = 0.5$ µm, $W = 5$ µm, and $V_{OV} = 0.3$ V

We have

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}V_{OV}^2 = \frac{1}{2}\ 190\ \frac{\mu A}{V^2} \times \frac{5}{0.5} \times 0.3^2$$

$$I_D = 85.5\ \mu A$$

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 85.5\ \mu A}{0.3\ V} = 0.57\ mA/V$$

$$r_o = \frac{V_A' L}{I_D} = \frac{20 \times 0.5}{85.5\ \mu A} \simeq 117\ k\Omega$$

$$A_o = g_m r_o = 66.7\ V/V$$

$$C_{gs} = \frac{2}{3}WLC_{ox} + C_{OV}$$

$$= \frac{2}{3} \times 5 \times 0.5 \times 3.8 + 0.4 \times 5$$

$$C_{gs} = 8.3\ fF,\ C_{gd} = C_{OV}W = 0.4 \times 5 = 2\ fF$$

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} = \frac{0.57\ \frac{mA}{V}}{2\pi\ (8.3 + 2)}$$

$$f_T = 8.8\ GHz$$

Ex: 6.1

For this problem, use eq. (6.11

$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right)} \cdot \sqrt{I_D}$$

For $I_D = 10\ \mu A$,

$$g_m = \sqrt{2(387\mu A/V^2)(10)(10\ \mu)} = 0.28\ mA/V$$

using eq. (6.15

$$A_O = V_A' \sqrt{\frac{2\mu_n C_{ox}(WL)}{\sqrt{I_D}}}$$

$$= \frac{5V/\mu m\sqrt{2(387\mu A/V^2)(10)(.36)^2}}{\sqrt{10\ \mu A}}$$

$$A_O = 50\ V/V$$

Since g_m varies with $\sqrt{I_D}$ and A_O with $\frac{1}{\sqrt{I_D}}$

For

$I_D = 100\ \mu A \Rightarrow g_m = 0.28\ m\left(\frac{100}{10}\right)^{\frac{1}{2}} = .89\ mA/V$

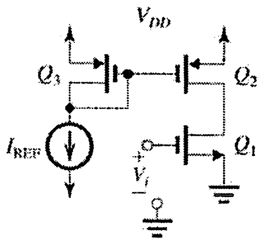
$A_O = 50\left(\frac{10}{100}\right)^{\frac{1}{2}} = 158\ V/V$

For $I_D = 1\ mA$:

$g_m = .28\ mA/V\left(\frac{1}{.010}\right)^{\frac{1}{2}} = 2.8\ mA/V$

$A_O = 50\left(\frac{.010}{1}\right)^{\frac{1}{2}} = 5\ V/V$

Ex: 6.2



Since all transistors have the same

$\frac{W}{L} = \frac{7.2\ \mu m}{0.36\ \mu m}$,

we have

$I_{REF} = I_{D3} = I_{D2} = I_{D1} = 100\ \mu A$

$g_{m1} = \sqrt{2\ \mu_n C_{ox}\left(\frac{W}{L}\right)_1}\ \sqrt{I_{D1}}$

$= \sqrt{2(\ 387\ \mu A/V^2)\left(\frac{7.2}{0.36}\right)(100\ \mu A)}$

$= 1.24\ mA/V$

$r_{o1} = \frac{V_{An}L_1}{I_{D1}} = \frac{5\ V/\mu m\ (0.36\ \mu m)}{0.1\ mA} = 18\ k\Omega$

$r_{o2} = \frac{|V_{Ap}|L_2}{I_{D2}} = \frac{6\ V/\mu m\ (0.36\ \mu m)}{0.1\ mA} = 21.6\ k\Omega$

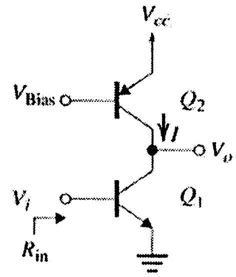
Voltage Gain is

$A_v = -g_m(r_{o1} \| r_{o2})$

$A_v = -(1.24\ mA/V)(18\ k\Omega \| 21.6\ k\Omega)$

$= -12.2\ V/V$

Ex: 6.3



$I_{C1} = I = 100\ \mu A$

$g_{m1} = \frac{I_{C1}}{V_T} = \frac{0.1\ \mu A}{25\ mV} = 4\ mA/V$

$R_{in} = r_{\pi 1} = \frac{\beta_1}{g_{m1}} = \frac{100}{4\ mA/V} = 25\ k\Omega$

$r_{o1} = \frac{V_A}{I} = \frac{50\ V}{0.1\ mA} = 500\ k\Omega$

$r_{o2} = \frac{|V_A|}{I} = \frac{50\ V}{0.1\ mA} = 500\ k\Omega$

$A_o = g_{m1} r_{o1} = (4\ mA/V)(500\ k\Omega) = 2000\ V/V$

$A_v = -g_{m1}(r_{o1} \| r_{o2}) = -(4\ mA/V)$

$(500\ k\Omega \| 500\ k\Omega) = -1000\ V/V$

Ex: 6.4 If L is halved: $L = \frac{0.55\ \mu m}{2}$, and

$|V_A| = |V_A'| \cdot L,$

$|V_A| = 5\ V/\mu m \frac{(0.55\ \mu m)}{2} = 1.375\ V$

$R_o = \frac{|V_A|}{|V_{OV}|/2} \cdot \frac{|V_A|}{I_D} = \frac{2\ (1.375\ V)^2}{(0.3\ V)\ (100\ \mu A)}$

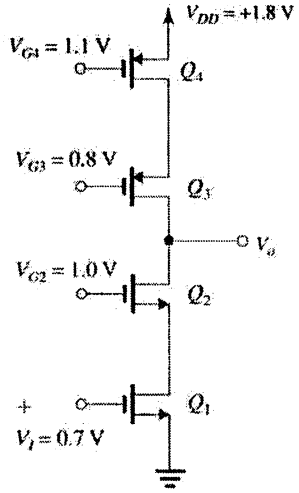
$= 126\ k\Omega$

Since $I_D = \frac{1}{2}(\mu_p C_{ox})\left(\frac{W}{L}\right)|V_{OV}|^2\left(1 + \frac{V_{SD}}{|V_A|}\right)$

$\frac{W}{L} = \frac{2\ (100\ \mu A)}{90\ \mu A/V^2(0.3\ V)^2\left(1 + \frac{0.3\ V}{1.375\ V}\right)}$

$\frac{W}{L} = 20.3$

Ex: 6.5



If all transistors are identical and the gate voltages are fixed, $|V_{OV}| = 0.7 - 0.5 = 0.2$ V

$V_{D1} = V_{S2} = V_{G2} - V_{tn} - V_{OV}$

$= 1.0 - 0.5 - 0.2 = 0.3$ V

the lowest V_{DS2} can go is $|V_{OV}| = 0.2$ V

$\therefore V_{o_{\min}} = V_{DS1} + V_{DS2} = 0.3 + 0.2 = 0.5$ V

Similarly, $V_{SG4} = V_{SG3} = 0.7$ V

$V_{D4} = V_{S3} = V_{G3} + |V_t| + |V_{OV}|$

$= 0.8 + 0.5 + 0.2 = 1.5$ V

V_{SD3} can go as low as $|V_{OV}|$, so

$V_{O_{\max}} = V_{D4} - V_{SD3_{\min}} = 1.5 - 0.2 = 1.3$ V

Ex: 6.6 $g_{m1} = g_{m2} = g_{m3} = g_{m4} = g_m$

$$= \frac{I_D}{\frac{|V_{OV}|}{2}} = \frac{0.2\text{ mA}}{0.2\text{V}/2} = 2 \text{ mA/V}$$

$r_{o1} = r_{o2} = r_{o3} = r_{o4} = r_o$

$$= \frac{|V_A|}{I_D} = \frac{2\text{ V}}{0.2\text{ mA}} = 10\text{ k}\Omega$$

$$R_{on} = (g_{m2}r_{o2})r_{o1} = (2\text{ mA/V})(10\text{ k}\Omega)^2$$

$= 200$ kΩ

$$R_{op} = (g_{m3}r_{o3})(r_{o4}) = (2\text{ mA/V})(10\text{ k}\Omega)^2$$

$= 200$ kΩ

$R_o = R_{on} \| R_{op} = 100$ kΩ

$$Av = -\frac{1}{2}(g_m r_o)^2 = -\frac{1}{2}[(2\text{ mA/V})(10\text{ k}\Omega)]^2$$

$Av = -200$ V/V

Ex: 6.7 $g_m = \dfrac{I_D}{\frac{V_{OV}}{2}} = \dfrac{0.25\text{ mA}}{0.25\text{ V}/2}$

$= 2$ mA/V

$$r_o = \frac{V_A}{I_D} = \frac{5\text{ V}}{0.25\text{ mA}} = 20\text{ k}\Omega$$

(a) From Fig. 6.13

$$R_{in} = \frac{1}{g_m} + \frac{R_L}{(g_m r_o)}$$

$R_L = \infty$:

$$R_{in} = \frac{1}{2\text{ mA/V}} + \frac{R_L}{(2\text{ mA/V})(20\text{ k}\Omega)}$$

$$= 500\ \Omega + \frac{\infty}{40} \rightarrow \infty$$

$R_L = 1$ MΩ:

$$R_{in} = 500\ \Omega + \frac{1\text{ M}\Omega}{40} = 25.5\text{ k}\Omega$$

$R_L = 100$ kΩ:

$$R_{in} = 500\ \Omega + \frac{100\text{ k}\Omega}{40} = 3\text{ k}\Omega$$

$R_L = 20$ kΩ:

$$R_{in} = 500\ \Omega + \frac{20\text{ k}\Omega}{40} = 1\text{ k}\Omega$$

$R_L = 0$:

$$R_{in} = 500\ \Omega + \frac{0}{40} = 0.5\text{ k}\Omega$$

(b) From Fig. 6.13

$R_O = r_o + R_S + (g_m r_o)R_S$

$R_S = 0$:

$R_O = 20\text{ k}\Omega + 0 + (40)(0) = 20\text{ k}\Omega$

$R_S = 1$ kΩ:

$R_O = 20\text{ k}\Omega + 1\text{ k}\Omega + (40)(1\text{ k}\Omega) = 61\text{ k}\Omega$

$R_S = 10$ kΩ:

$R_O = 20\text{ k}\Omega + 10\text{ k}\Omega + (40)(10\text{ k}\Omega) = 430\text{ k}\Omega$

$R_S = 20$ kΩ:

$R_O = 20\text{ k}\Omega + 20\text{ k}\Omega + (40)(20\text{ k}\Omega) = 840\text{ k}\Omega$

$R_S = 100$ kΩ:

$R_O = 20\text{ k}\Omega + 100\text{ k}\Omega + (40)(100\text{ k}\Omega) = 4.12\text{ M}\Omega$

Ex: 6.8 $g_{m1} = g_{m2} = g_m$

$$= \frac{I_D}{\frac{V_{OV}}{2}} = \frac{100\ \mu\text{A}}{0.2\text{ V}/2} = 1\text{ mA/V}$$

$r_{o1} = r_{o2} = r_o$

$= \frac{V_A}{I_D} = \frac{2\ V}{0.1\ mA} = 20\ k\Omega$

so, $(g_m r_o) = 1\ mA/V(20\ k\Omega) = 20$

(a) For $R_L = 20\ k\Omega$,

$$R_{in2} = \frac{R_L + r_{o2}}{1 + g_{m2} r_{o2}} = \frac{20\ k\Omega + 20\ k\Omega}{1 + 20} = 1.9\ k\Omega$$

$\therefore A_{V1} = -g_{m1}(r_{o1} \| R_{in2})$

$= -1\ mA/V(20\ K \| 1.9\ K) = -1.74\ V/V$

or

If we use the approximation of eq. (6.35

$$R_{in2} \simeq \frac{R_L}{g_{m2} r_{o2}} + \frac{1}{g_{m2}} = \frac{20\ k\Omega}{20} + \frac{1}{1\ mA/V}$$

$= 2\ k\Omega$

then,

$A_{V1} = -1\ mA/V(20\ k\Omega \| 2\ k\Omega) = -1.82\ V/V$

Either method is correct.

continuing, from eq. (6.31

$A_V = -gm_1[(gm_2 r_{o2} r_{o1}) \| R_L]$

$A_V = -1\ mA/V\{[(20)(20\ k\Omega)] \| 20\ k\Omega\}$

$= -19.04\ V/V$

$$A_{V2} = \frac{Av}{Av_1} = \frac{-19.04}{-1.82} = 10.5\ V/V$$

(b) Now, for $R_L = 400\ k\Omega$,

$$R_{in2} \simeq \frac{R_L}{g_{m2} r_{O2}} + \frac{1}{g_{m2}} = \frac{400\ k\Omega}{20} + \frac{1}{1\ mA/V}$$

$= 21\ k\Omega$

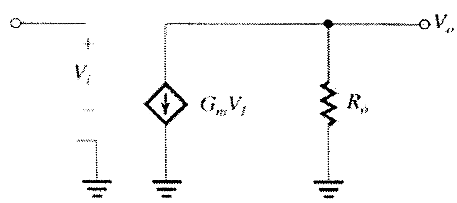
$A_{V1} = -1\ mA/V(20\ k\Omega \| 21\ k\Omega) = -10.2\ V/V$

$A_V = -1\ mA/V\{[(20)(20\ k\Omega)] \| 400\ k\Omega\}$

$= -200\ V/V$

$$A_{V2} = \frac{A_V}{A_{V1}} = \frac{-200}{-10.2} = 19.6\ V/V$$

Ex: 6.9 The circuit of Fig. 6.14 can be modeled as



Where $G_m = \frac{g_m}{1 + g_m Rs}$

and $R_o \simeq (1 + g_m Rs) r_o$

The open-circuit (no load) Voltage gain is

$$Av_o = -G_m Ro = \frac{g_m}{1 + g_m Rs} \cdot (1 + g_m Rs) r_o$$

$= -g_m Ro$

so, the gain remains the same

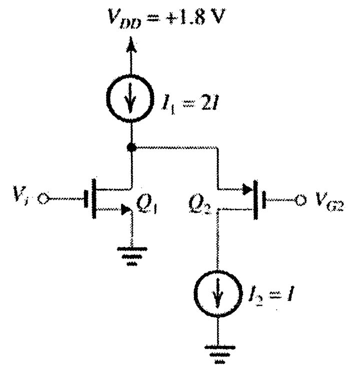
If R_L is connected to the output,

$$Av = \frac{-g_m}{1 + g_m Rs}[(1 + g_m Rs) r_o] \| R_L$$

$$= \frac{-g_m}{1 + g_m Rs} \cdot \frac{(1 + g_m Rs) r_o R_L}{(1 + g_m Rs) r_o + R_L}$$

$$= -(g_m r_o) \frac{R_L}{R_L + (1 + g_m Rs) r_o}$$

Ex: 6.10



(a) $I_{D1} = I$ and $I_{D2} = I$

Since $Vov_1 = Vov_2 = 0.2$ V we have

$$\frac{I_{D2}}{I_{D1}} = \frac{\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_2 V_{OV_2}^2}{\frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 V_{OV_1}^2} = \frac{I}{I} = 1$$

and

$$\frac{k_p'\left(\frac{W}{L}\right)_2}{k_n'\left(\frac{W}{L}\right)_1} = 1 \Rightarrow \left(\frac{W}{L}\right)_2 = \frac{k_n'}{k_p'}\left(\frac{W}{L}\right)_1 = \frac{k_n'}{\frac{k_n'}{4}}\left(\frac{W}{L}\right)_1$$

or

$$\left(\frac{W}{L}\right)_2 = 4\left(\frac{W}{L}\right)_1$$

(b) The minimum voltage allowed across current source I, would be $|Vo\tau| = 0.2$ V if made with a single transistor. If a 0.1 V_{PP} signal swing is to be allowed at the drain of Q_1, the highest dc bias voltage would be

$$V_{DD} - |Vo\tau| - \frac{0.1\ V_{PP}}{2} = 1.8 - 0.2 - \frac{1}{2}(0.1)$$

$= 1.55$ V

(c) $V_{SG2} = |Vo\tau| + |Vtp| = 0.2 + 0.5 = 0.7$ V

V_{GS2} can be set at $1.55 - 0.7 = 0.85$ V

(d) Since current source I_2 is implemented with a cascoded current source similar to Fig.6.10, the minimum voltage required across it for proper operation is $2V_{OV} = 2(0.2\text{ V}) = 0.4\text{ V}$

(e) From parts (c) and (d), the allowable range of signal swing at the output is from 0.4 V to 1.55 V − V_{OV} or 1.35 V.

so, $0.4\text{ V} \le V_O \le 1.35\text{ V}$

Ex:6.11 Referring to fig. 6.19,

$R_{op} = (g_{m3}r_{O3})(r_{O4} \| r_{\pi 3})$ and

$R_{on} = (g_{m2}r_{O2})(r_{O1} \| r_{\pi 2})$

If Q_1 and Q_4 can be selected and biased so that r_{O1} and r_{O4} are very high and have insignificant effect ($r_O >> r_\pi$) then,

$R_{on} = (g_{m2}r_{O2})r_{\pi 2}$

$R_{op} = (g_{m3}r_{O3})r_{\pi 3}$

Since $g_m r_\pi = \beta$,

$R_{on} = \beta_2 r_{O2}$

$R_{op} = \beta_3 r_{O3}$

Since $Av = -g_{m1}(R_{on} \| R_{op})$,

$|Av_{max}| = g_{m1}(\beta_2 r_{O2} \| \beta_3 r_{O3})$

Av_{max} occurs when Q_1 and Q_4 are selected and bias so that r_{O1} and r_{O4} are $>> r_\pi$

Then, $R_{on} = (g_{m2}r_{O2})r_{\pi 2} = \beta_2 r_{O2}$

$R_{on} = 100(25\text{ k}\Omega) = 2.5\text{ M}\Omega$

$R_{op} = (g_{m3}r_{O3})r_{\pi 3} = \beta_3 r_{O3}$

$R_{op} = 50(20\text{ k}\Omega) = 1\text{ M}\Omega$

Finally,

$A_{vmax} = -(8\text{ mA/V})(2.5\text{ M}\Omega \| 1.0\text{ M}\Omega)$

$A_{vmax} = -5714\text{ V/V}$

Ex:6.12 For the npn trasistors,

$$g_{m1} = g_{m2} = \frac{|I_C|}{|V_T|} = \frac{0.2\text{ mA}}{25\text{ mV}} = 8\text{ mA/V}$$

$$r_{\pi 1} = r_{\pi 2} = \frac{\beta}{g_m} = \frac{100}{8\text{ mA/V}} = 12.5\text{ k}\Omega$$

$$r_{O1} = r_{O2} = \frac{|V_A|}{|I_C|} = \frac{5\text{ V}}{0.2\text{ mA}} = 25\text{ k}\Omega$$

From Fig. 6.19,

$R_{on} = (g_{m2}r_{O2})(r_{O1} \| r_{\pi 2})$

$= (8\text{ mA/V})(25\text{ k}\Omega)(25\text{ k}\Omega \| 12.5\text{ k}\Omega)$

$R_{on} = 1.67\text{ M}\Omega$

For the pnp transistors,

$$g_{m3} = g_{m4} = \frac{|I_C|}{V_T} = \frac{0.2\text{ mA}}{25\text{ mV}} = 8\text{ mA/V}$$

$$r_{\pi 3} = r_{\pi 4} = \frac{\beta}{g_m} = \frac{50}{8\text{ mA/V}} = 6.25\text{ k}\Omega$$

$$r_{O3} = r_{O4} = \frac{|V_A|}{|I_C|} = \frac{4\text{ V}}{0.2\text{ mA}} = 20\text{ k}\Omega$$

$R_{op} = (g_{m3}r_{O3})(r_{O4} \| r_{\pi 3})$

$= (8\text{ mA/V})(20\text{ k}\Omega)(20\text{ k}\Omega \| 6.25\text{ k}\Omega)$

$R_{op} = 762\text{ k}\Omega$

$A_v = -g_{m1}(R_{on} \| R_{op})$

$= -(8\text{ mA/V})(1.67\text{ M}\Omega \| 0.762\text{ M}\Omega)$

$A_v = -4.186\text{ V/V}$

Ex:6.13 $g_m = \dfrac{|I_C|}{V_T} = \dfrac{1\text{ mA}}{25\text{ mV}} = 40\text{ mA/V}$

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

$$r_O = \frac{V_A}{I_C} = \frac{10\text{ V}}{1\text{ mA}} = 10\text{ k}\Omega$$

Referring to Fig. 6.20,

$R_o \simeq r_O[1 + g_m(R_e \| r_\pi)]$

$$R_o \simeq 10\text{ k}\Omega\left[1 + 40\frac{\text{mA}}{\text{V}}(0.5\text{ k}\Omega \| 2.5\text{ k}\Omega)\right]$$

$R_o \simeq 176.7\text{ k}\Omega$

without R_e (that is, $R_e = 0$).

$R_o = r_O = 10\text{ k}\Omega$

Ex:6.14 Fig.6.21(a)

$$r_{O1} = r_{O2} = r_O = \frac{V_A}{I} = \frac{5\text{ V}}{0.1\text{ mA}} = 50\text{ k}\Omega$$

$$g_{m1} = \sqrt{2\mu_n C_{ox}(W/L)I_D}$$

$$g_{m1} = \sqrt{2(200\ \mu\text{A/V}^2)(25)(100\ \mu\text{A})}$$

$$g_{m1} = 1\frac{\text{mA}}{\text{V}},\ G_m = g_{m1} = 1\text{ mA/V}$$

$$g_{m2} = \frac{|I_C|}{V_T} = \frac{0.1\text{ mA}}{25\text{ mV}} = 4\text{ mA/V}$$

$$r\pi_2 = \frac{\beta}{g_{m2}} = \frac{100}{4\text{ mA/V}} = 25\text{ k}\Omega$$

Assuming an ideal current source.

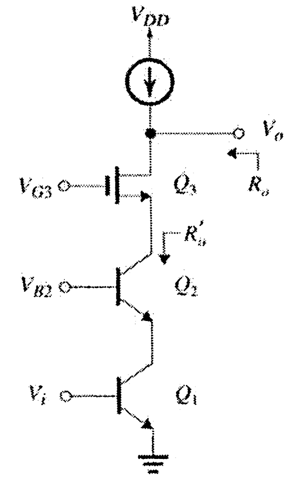
$R_o = (g_{m2}r_{O2})(r_{O1} \| r_{\pi 2})$

$R_o = (4\text{ mA/V})(50\text{ k}\Omega)(50\text{ k}\Omega \| 25\text{ k}\Omega) = 3.33\text{ M}\Omega$

$A_{vo} = -G_m R_O = -(1\text{ mA/V})(3.33\text{ M})$

$= -3.33 \times 10^3\text{ V/V}$

Fig. 7.21 (b)



From part (a),

$g_{m3} = 1$ mA/V

$g_{m1} = g_{m2} = 4$ mA/V

$r_{O3} = r_{O2} = r_{O1} = r_O = 50\ \text{k}\Omega$

$r_{\pi 1} = r_{\pi 2} = r_\pi = 25\ \text{k}\Omega$

$G_m \simeq g_{m1} = 4$ mA/V

From Fig. 6.19 $R_O' = (g_{m2}r_{O2})(r_{O1} \| r_{\pi 2})$

$R_o = (g_{m3}ro_3)R_o'$ so,

$R_o = (1\ \text{mA/V})(50\ \text{k}\Omega)(4\ \text{mA/V})(50\ \text{k}\Omega)$
$(50\ \text{k}\Omega \| 25\ \text{k}\Omega)$

$R_o = 167\ \text{M}\Omega$

$A_{vO} = -g_{m1}R_o = -4\ \text{mA/V}(167\text{M}\Omega)$

$= -668 \times 10^3$ V/V

Ex:6.15 In the current source of Example 6.15 we have $I_O = 100\ \mu\text{A}$ and we want to reduce the change in output current, ΔI_O, corresponding to a 1 V change in output voltage, ΔV_O, to 1% of I_O.

That is $\Delta I_O = \dfrac{\Delta V_O}{ro_2} = 0.01 I_O \Rightarrow \dfrac{1\ \text{V}}{ro_2}$

$= 0.01 \times 100\ \mu\text{A}$

$$ro_2 = \frac{1\ \text{V}}{1\ \mu\text{A}} = 1\ \text{M}\Omega$$

$$ro_2 = \frac{V_A \times L}{I_O} \Rightarrow 1\ \text{M}\Omega = \frac{20 \times L}{100\ \mu\text{A}}$$

$$\Rightarrow L = \frac{100\ \text{V}}{20\ \text{V}/\mu\text{m}} = 5\ \mu\text{m}$$

To keep V_{OV} of the matched transistors the same as that of Example 6.15 $\dfrac{W}{L}$ of the transistor should remain the same. Therefore

$$\frac{W}{5\ \mu\text{m}} = \frac{10\ \mu\text{m}}{1\ \mu\text{m}} \Rightarrow W = 50\ \mu\text{m}$$

So the dimensions of the matched transistors Q_1 and Q_2 should be changed to:

$W = 50\ \mu\text{m}$ and $L = 5\ \mu\text{m}$

Ex:6.16 For the circuit Figure 4.7 we have:

$$I_2 = I_{REF}\frac{(W/L)_2}{(W/L)_1},\ I_3 = I_{REF}\frac{(W/L)_3}{(W/L)_1}$$

and $I_5 = I_4\dfrac{(W/L)_5}{(W/L)_4}$

Since all channel lengths are equal

$L_1 = L_2 = \ldots = L_5 = 1\ \mu\text{m}$

and

$I_{REF} = 10\ \mu\text{A},\ I_2 = 60\ \mu\text{A},\ I_3 = 20\ \mu\text{A},$

$I_4 = I_3 = 20\ \mu\text{A}$ and $I_5 = 80\ \mu\text{A},$

we have:

$$I_2 = I_{REF}\frac{W_2}{W_1} \Rightarrow \frac{W_2}{W_1} = \frac{I_2}{I_{REF}} = \frac{60}{10} = 6$$

$$I_3 = I_{REF}\frac{W_3}{W_1} \Rightarrow \frac{W_3}{W_1} = \frac{I_3}{I_{REF}} = \frac{20}{10} = 2$$

$$I_5 = I_4\frac{W_5}{W_4} \Rightarrow \frac{W_5}{W_4} = \frac{I_5}{I_4} = \frac{80}{10} = 4$$

In order to allow the voltage at the drain of Q_2 to go down to within 0.2 V of the negative supply voltage we need $V_{OV2} = 0.2$ V

$$I_2 = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 V^2{}_{OV_2} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_2 V^2{}_{OV_2}$$

$$60\ \mu\text{A} = \frac{1}{2}200\ \frac{\mu\text{A}}{\text{V}^2}\left(\frac{W}{L}\right)_2 (0.2)^2 \Rightarrow$$

$$\left(\frac{W}{L}\right)_2 = \frac{120}{200 \times (0.2)^2} = 15 \Rightarrow W_2 = 15 \times L_2$$

$$W_2 = 15\ \mu\text{m},\ \frac{W_2}{W_1} = 6 \Rightarrow W_1 = \frac{W_2}{6} = 2.5\ \mu\text{m}$$

$$\frac{W_3}{W_1} = 2 \Rightarrow W_3 = 2 \times W_1 = 5\ \mu\text{m}$$

In order to allow the voltage at the drain of Q_5 to go up to within 0.2 V of positive supply we need

$$V_{OV_5} I_5 = \frac{1}{2}k_p'\left(\frac{W}{L}\right)_5 \Rightarrow V^2{}_{OV2}$$

$$80\ \mu\text{A} = \frac{1}{2}80\frac{\mu\text{A}}{\text{V}^2}\left(\frac{W}{L}\right)_5 (0.2)^2 \Rightarrow$$

$$\left(\frac{W}{L}\right)_5 = \frac{2 \times 80}{80 \times (0.2)^2} = 50 \Rightarrow W_5 = 50\ L_5$$

$W_5 = 50\ \mu\text{m}$

$$\frac{W_5}{W_4} = 4 \Rightarrow W_4 = \frac{50\ \mu\text{m}}{4} = 12.5\ \mu\text{m}$$

Thus:

$W_1 = 2.5\ \mu m$, $W_2 = 15\ \mu m$, $W_3 = 5\ \mu m$

$W_4 = 12.5\ \mu m$ and $W_5 = 50\ \mu m$

Ex:6.17 From equation 6.72 we have:

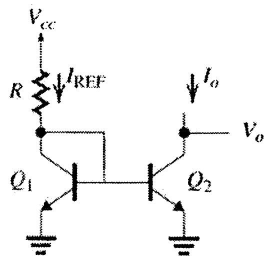
$$I_o = I_{REF}\left(\frac{m}{1+\frac{m+1}{\beta}}\right)\left(1+\frac{V_o - V_{BE}}{V_{A2}}\right)$$

$$I_o = 1\ mA\left(\frac{1}{1+\frac{1+1}{100}}\right)\left(1+\frac{5-0.7}{100}\right) = 1.02\text{ mA}$$

$I_o = 1.02$ mA

$$R_O = r_{O2} = \frac{V_A}{I_O} = \frac{100\ V}{1.02\text{ mA}} = 98\text{ k}\Omega \simeq 100\text{ k}\Omega$$

Ex:6.18



From equation 6.74 we have:

$$I_O = \frac{I_{REF}}{1+(2/\beta)}\left(1+\frac{V_O - V_{BE}}{V_A}\right) \Rightarrow$$

$$0.5\text{ mA} = \frac{I_{REF}}{1+(2/100)}\left(1+\frac{2-0.7}{50}\right) \Rightarrow$$

$$I_{REF} = 0.5\text{ mA}\frac{1.02}{1.026\text{ mA}} = 0.497\text{ mA}$$

$$I_{REF} = \frac{V_{CC} - V_{BE}}{R} \Rightarrow R = \frac{V_{CC} - V_{BE}}{I_{REF}}$$

$$R = \frac{5-0.7}{0.497\text{ mA}} = \frac{4.3}{0.497} 8.65\text{ k}\Omega$$

$V_{Omin} = V_{CESAT} = 0.3$ V

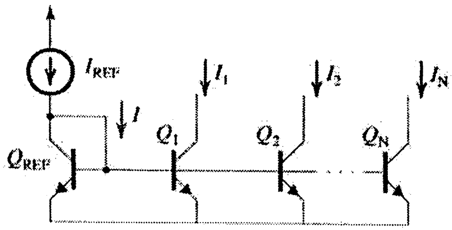
For $V_o = 5$ V, From equation 6.74 we have:

$$I_o = \frac{I_{REF}}{1+(2/\beta)}\left(1+\frac{V_o - V_{BE}}{V_A}\right)$$

$$I_o = \frac{0.497}{1+(2/100)}\left(1+\frac{5-0.7}{50}\right) = 0.53\text{ mA}$$

Ex: 6.19

See next page:



Ignoring the effect of finite output resistances, we have

$$I_1 = I_2 = \ldots = I_N = I_{CQ_{REF}}$$

$$I_{CQ_{REF}} + I = I_{REF} (*)$$

$$I = I_{BQ_{REF}} + I_{B1} + \ldots + I_{BN}$$

$$I = \frac{I_{CQ_{REF}}}{\beta} = \frac{I_{C1}}{\beta} + \ldots + \frac{I_{CN}}{\beta}$$

$$I = I_{CQ_{REF}}\left(\frac{1}{\beta} + \frac{1}{\beta} + \ldots + \frac{1}{\beta}\right)$$

$$I = I_{CQ_{REF}} \frac{N+1}{\beta}$$

From (*) we have:

$$I_{CQ_{REF}} + I = I_{REF} \Rightarrow$$

$$I_{REF} = I_{CQ_{REF}} + I_{CQ_{REF}} \frac{N+1}{\beta}$$

$$\Rightarrow I_{CQ_{REF}} = \frac{I_{REF}}{1 + \frac{N+1}{\beta}}$$

Thus:

$$I_1 = I_2 = \ldots = I_N = \frac{I_{REF}}{1 + \frac{N+1}{\beta}}$$

For an error not exceeding 10% we need:

$$\frac{I_{REF}}{1 + \frac{N+1}{\beta}} \geq I_{REF}(1 - 0.1)$$

$$\frac{I_{REF}}{1 + \frac{N+1}{\beta}} \geq 0.9 I_{REF} \Rightarrow \frac{1}{1 + \frac{N+1}{\beta}} \geq 0.9$$

$$\Rightarrow 1 + \frac{N+1}{\beta} \leq \frac{1}{0.9} \Rightarrow 1 + \frac{N+1}{\beta} \leq 1.11$$

$$\frac{N+1}{\beta} \leq 0.11 \Rightarrow N + 1 \leq 0.11\,\beta \Rightarrow$$

$$N + 1 \leq 11 \Rightarrow N \leq 10$$

The maximum number of outputs for an error not exceeding to be lessthan 10% then we need $N<10$. In this case the maximum number of outputs for and error of less than 10% is $N = 9$.

Ex:6.20 Refering to Fig. 6.32

$I_{D1} = I_{D2} = I_{D3} = I_{D4} = I_{REF} = 100\ \mu A$

Since $I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)V^2_{OV}$

$$V_{OV} = \sqrt{\frac{2I_D}{\mu_n C_{ox}\left(\frac{W}{L}\right)}} = \sqrt{\frac{2(100\ \mu A)}{(387\ \mu A/V^2)\left(\frac{3.6}{0.36}\right)}}$$

$= 0.23$ V

The minimum output voltage is

$V_{tn} + 2V_{ov} = 0.5\ V + 2(0.23\ V) = 096\ V$

To obtain the output resistance, R_O, we need g_{m3}.

$$g_{m3} = \frac{I_{D3}}{V_{OV}/2} = \frac{2(0.1\ mA)}{0.23\ V} = 0.87\ mA/V$$

$$r_{O2} = r_{O3} = \frac{V_A'(L)}{I_D} = \frac{(5V/\mu m)(0.36\ \mu m)}{0.1\ mA}$$

$= 18\ k\Omega$. From eq. 6.77

$R_o = g_{m3}r_{o3}r_{o2} = (0.87\ mA/V)(18\ k\Omega)^2$

$= 282\ k\Omega$

Ex: For the Wilson mirror from the equation (6.80 we have :

$$\frac{I_o}{I_{REF}} = \frac{1}{1 + \frac{2}{\beta(\beta+2)}} = 0.9998$$

Thus $\frac{|I_o - I_{REF}|}{I_{REF}} \times 100 = 0.02\%$

whereas for the simple mirror from equation 6.69 we have :

$$\frac{I_o}{I_{REF}} = \frac{1}{1 + \frac{2}{\beta}} = 0.98$$

Hence $\frac{|I_o - I_{REF}|}{I_{REF}} \times 100 = 2\%$

For the Wilson current mirror we have

$R_o = \frac{\beta r_o}{2} = \frac{100 \times 100\ k\Omega}{2} = 5\ M\Omega$ and for

the simple mirror $R_o = r_o = 100\ k\Omega$

Ex:6.22 For the two current sources designed in Example 6.6
we have :

$g_m = \frac{I_C}{V_T} = \frac{10\ \mu A}{25\ mV} = 0.4\ \frac{mA}{V}$ and

$r_O = \frac{V_A}{I_C} = \frac{100\ V}{10\ \mu A} = 10\ M\Omega,\ r_\pi = \frac{\beta}{g_m} = 250\ k\Omega$

For the current source in Fig6.37awe have

$R_o = r_{o2} = r_o = 10\ M\Omega$

For the current source in Fig.6.37b from equation 6.98 we have:

$R_o \simeq [1 + g_m(R_E \| r_\pi)]r_o$

In Example 6.6 $R_E = R_3 = 11.5\ k\Omega$,

therefore,

$$R_o \simeq \left[1 + 0.4\ \frac{mA}{V}(11.5\ k\Omega \| 250\ k\Omega)\right]10\ M\Omega$$

$\Rightarrow R_o = 54\ M\Omega$

Ex: 7.1

Referring to Fig 7.3

If R_D is doubled to 5 K,

$$V_{D1} = V_{D2} = V_{DD} - \frac{I}{2}R_D$$

$$= 1.5 - \frac{0.4\text{ mA}}{2}(5\text{ K}) = 0.5\text{ V}$$

$$V_{CM_{max}} = V_t + V_D = 0.5 + 0.5 = +1.0\text{ V}$$

Since the currents I_{D1}, and I_{D2} are still 0.2 mA each,

$$V_{GS} = 0.82\text{ V}$$

So, $V_{CM_{min}} = V_{SS} + V_{CS} + V_{GS}$

$$= -1.5\text{ V} + 0.4\text{ V} + 0.82\text{ V} = -0.28\text{ V}$$

So, the common-mode range is

−0.28 V to 1.0 V

Ex: 7.2

(a) The value of v_{id} that causes Q_1 to conduct the entire current is $\sqrt{2}\,V_{OV}$

$$\rightarrow \sqrt{2} \times 0.316 = 0.45\text{ V}$$

then, $V_{D1} = V_{DD} - I \times R_D$

$$= 1.5 - 0.4 \times 2.5 = 0.5\text{ V}$$

$$V_{D2} = V_{DD} = +1.5\text{ V}$$

(b) For Q_2 to conduct the entire current:

$$v_{id} = -\sqrt{2}\,V_{OV} = -0.45\text{ V}$$

then,

$$V_{D1} = V_{DD} = +1.5\text{ V}$$

$$V_{D2} = 1.5 - 0.4 \times 2.5 = 0.5\text{ V}$$

(c) Thus the differential output range is:

$V_{D2} - V_{D1}$: from $1.5 - 0.5 = +1$ V

to $0.5 - 1.5 = -1$ V

Ex: 7.3

Refer to answer table for Exercise7.3where values were obtained in the following way:

$$V_{OV} = \sqrt{I/KW/L} \rightarrow \frac{W}{L} = \frac{I}{KV_{OV}^2}$$

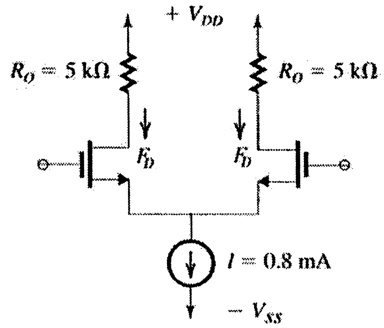
$$g_m = \frac{I}{V_{OV}}$$

$$\left(\frac{v_{id}/2}{V_{OV}}\right)^2 = 0.1 \rightarrow v_{id} = 2\,V_{OV}\sqrt{0.1}$$

Ex: 7.4

$$I_D = \frac{I}{2} = \frac{0.8\text{ mA}}{2} = 0.4\text{ mA}$$

$$I_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)(V_{OV})^2 \text{ So that}$$



$$V_{OV} = \sqrt{\frac{2I_D}{k_n'\left(\frac{W}{L}\right)}} = \sqrt{\frac{2(0.4\text{ mA})}{0.2(\text{mA}/\text{V}^2)(100)}} = 0.2\text{ V}$$

$$g_m = \frac{I_D}{V_{OV}/2} = \frac{0.4\text{ mA}(2)}{0.2\text{ V}} = 4\text{ mA/V}$$

$$r_O = \frac{V_A}{I_D} = \frac{20\text{ V}}{0.4\text{ mA}} = 50\text{ k}\Omega$$

$$A_d = g_m(R_D \| r_O)$$

$$A_D = (4\text{ mA/V})(5\text{ K} \| 50\text{ K}) = 18.2\text{ V/V}$$

Ex: 7.5

With $I = 200\ \mu$A. for all transistors,

$$I_D = \frac{I}{2} = \frac{200\ \mu\text{A}}{2} = 100\ \mu\text{A}$$

$$L = 2(0.18\ \mu\text{m}) = 0.36\ \mu\text{m}$$

$$r_{O_1} = r_{O2} = r_{O3} = r_{O4} = \frac{|V_A'|L}{I_D}$$

$$= \frac{(10\text{ V}/\mu\text{m})(0.36\ \mu\text{m})}{0.1\text{ mA}} = 36\text{ k}\Omega$$

Since $I_{D1} = I_{D2} = \frac{1}{2}\mu_A C_{ox}\left(\frac{W}{L}\right)V_{OV}^2$,

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = \frac{2I_D}{\mu_A C_{ox}(V_{OV})^2}$$

$$\frac{2(100\ \mu\text{A})}{(400\ \mu\text{A/V}^2)(0.2\text{ V})^2} = 12.5$$

$$\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = \frac{2I_D}{\mu_A C_{ox}|V_{OV}|^2}$$

$$\frac{2(100\ \mu\text{A})}{(100\ \mu\text{A/V}^2)(0.2)^2} = 50$$

$$g_m = \frac{I_D}{|V_{OV}|/2} = \frac{(100\ \mu\text{A})(2)}{0.2\text{ V}} = 1\text{ mA/V},$$

so,

$$A_D = g_{m1}(r_{O1} \| r_{O3}) = 1(\text{mA/V})(36\text{ K} \| 36\text{ K})$$

$$= 18\text{ V/V}$$

Ex 7.6

$L = 2(0.18\ \mu m) = 0.36\ \mu m$

All $r_O = \dfrac{|V_A'| \cdot L}{|I_D|}$

The drain current for all transistors is

$I_D = \dfrac{I}{2} = \dfrac{200\ \mu A}{2} = 100\ \mu A$

$r_O = \dfrac{(10\ V/\mu m)(0.36\ \mu m)}{0.1\ mA} = 36\ k\Omega$

Refering to Fig7.12(a).

Since $I_D = \frac{1}{2}\mu_A C_{ox}\left(\frac{W}{L}\right)(V_{OV})^2$ for all NMOS transistors

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = \left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4$$

$$= \frac{2\ I_D}{\mu_n C_{ox}(V_{OV})^2} = \frac{2(100\ \mu A)}{400\ \mu A/V^2(0.2\ V)^2} = 12.5$$

$$\left(\frac{W}{L}\right)_5 = \left(\frac{W}{L}\right)_6 = \left(\frac{W}{L}\right)_7 = \left(\frac{W}{L}\right)_8$$

$$= \frac{2\ I_D}{\mu_P C_{ox}(V_{OV})^2} = \frac{2(100\ \mu A)}{100\ \mu A/V^2(0.2\ V)^2} = 50$$

For all transistors,

$$g_m = \frac{|I_D|}{|V_{OV}|/2} = \frac{(0.1\ mA)(2)}{(0.2\ V)} = 1\ mA/V$$

From Fig.7.12(b),

$R_{on} = (g_{m3}\ r_{O3})r_{O1} = (1\ mA/V)(36\ k)^2$

$= 1.296\ M\Omega$

$R_{op} = (g_{m5}\ r_{O5})r_{O7} = (1\ mA/V)(36\ k)^2$

$= 1.296\ M\Omega$

Using eq.(7.38

$A_d = g_{m1}\ (R_{on} \| R_{op})$

$= (1\ mA/V)1.296(\ M\Omega \|\ 1.296\ M\Omega)$

$= 648\ V/V$

Ex: 7.7

The transconductance for each transistor is

$g_m = \sqrt{2\ \mu_n C_{ox}(W/L) I_D}$

$I_D = \dfrac{I}{2} = \dfrac{0.8\ mA}{2} = 0.4\ mA$

from eq(7.35 the differential gain for matched R_D values is $A_d = \dfrac{V_{O2} - V_{O1}}{V_{id}} = g_m R_D$

If we ignore the 1% here,

$A_d = g_m R_D = (4\ mA/V)(5\ K) = 20\ V/V$

From eq. (7.49

$$A_{CM} = \frac{V_{od}}{V_{icm}} = \pm\frac{\Delta R_D}{2\ R_{SS}} = \frac{(0.01)(5\ K)}{2(25\ K)} = 0.001\ V/V$$

$$CMRR(dB) = 20\ \log 10 \frac{|A_d|}{|A_{CM}|} = 20\ \log 10\left(\frac{20}{0.001}\right)$$

$= 86\ dB$

Ex: 7.8

From Exercise 7.7

$W/L = 100, \mu_n C_{ox}(0.2\ mA/V^2)$,

$I_D = \dfrac{I}{2} = \dfrac{0.8\ mA}{2} = 0.4\ mA$

$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_D}$

$= \sqrt{2(0.2\ mA/V^2)(100)(0.4\ mA)}$

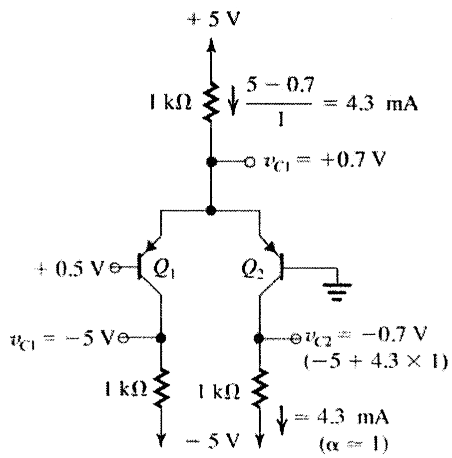
$g_m = 4\ mA/V$

using eq. (7.64 and the fact that $R_{SS} = 25\ k\Omega$

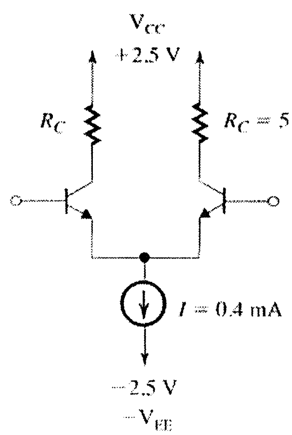
$$CMRR = \frac{(2\ g_m R_{SS})}{\left(\frac{\Delta g_m}{g_m}\right)} = \frac{2(4\ mA/V)(25\ K)}{0.01} = 20,000$$

$CMRR(dB) = 20\log_{10}(20{,}000) = 86\ dB$

Ex: 7.9



Ex: 7.10



$I_{C1} = I_{C2} = I_{E1} = I_{E2} = \frac{I}{2} = \frac{0.4 \text{ mA}}{2}$

$= 0.2$ mA

From eq. 7.66

$V_{CM\,max} \simeq V_C + 0.4$ V

$= V_{CC} - I_C R_C + 0.4$ V

$= 2.5 - 0.2$ mA$(5$ K$) + 0.4$ V $= +1.9$ V

From eq. 7.67

$V_{CM\,min} = -V_{EE} + V_{CS} + V_{BE}$

$V_{CM\,min} = -2.5$ V $+ 0.3$ V $+ 0.7$ V $= -1.5$ V

Input range is -1.5 V to $+1.9$ V

Ex: 7.11

Substituting $i_{E1} + i_{E2} = I$ in Eqn.7.70 yields

$$i_{E1} = \frac{I}{1 + e^{(v_{B2} - v_{B1})/V_T}}$$

$$0.99\,I = \frac{I}{1 + e^{(v_{B2} - v_{B1})/V_T}}$$

$$v_{B1} - v_{B2} = -V_T \ln\left(\frac{1}{0.99} - 1\right)$$

$= -25\ln(1/99)$

$= 25\ln(99) = 115$ mV

Ex: 7.12

(a) The DC current in each transister is 0.5 mA. Thus V_{BE} for each will be

$$V_{BE} = 0.7 + 0.025\ln\left(\frac{0.5}{1}\right)$$

$= 0.683$ V

$\Rightarrow vE = 5 - 0.683 = +4.317$ V

(b) $g_m = \frac{IC}{VT} = \frac{0.5}{0.025} = 20\ \frac{\text{mA}}{\text{V}}$

(c) $i_{C1} = 0.5 + g_{m1}\Delta v_{BE1}$

$= 0.5 + 20 \times 0.005\text{Sin}(2\pi \times 1000t)$

$= 0.5 + 0.1\text{Sin}(2\pi \times 1000t)$, mA

$i_{C2} = 0.5 - 0.1\text{Sin}(2\pi \times 1000t)$, mA

(d)

$v_{C1} = (V_{CC} - I_C R_C) - 0.1 \times Rc\text{Sin}(2\pi \times 1000t)$

$= (15 - 0.5 \times 10) - 0.1 \times 10\text{Sin}(2\pi 1000t)$

$= 10 - 1\text{Sin}(2\pi \times 1000t)$, V

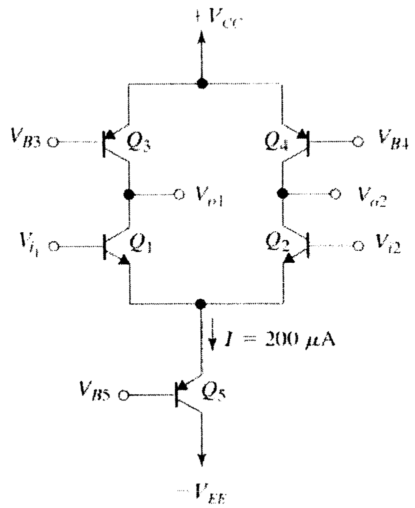
$v_{C2} = 10 + 1\text{Sin}(2\pi \times 1000t)$, V

(e) $v_{C2} - v_{C1} = 2 \cdot \text{Sin}(2\pi \times 1000t)$, V

(f) Voltage gain $= \frac{v_{C2} - v_{C1}}{v_{B1} - v_{B2}}$

$= \frac{2\text{V Peak}}{0.1\text{V Peak}} = 200$ V/V

Ex: 7.13



$I = 200\ \mu$A

Since $\beta \gg 1$,

$I_{C1} \approx I_{C2} \approx \frac{I}{2} = \frac{200\ \mu\text{A}}{2} = 100\ \mu$A

$g_{m1} = g_{m2} = g_m = \frac{|I_C|}{V_T} = \frac{100\ \mu\text{A}}{25 \text{ mV}} = 4$ mA / V

$R_{C1} = R_{C2} = R_C = r_O = \frac{|V_A|}{I_C}$

$= \frac{10 \text{ V}}{100\ \mu\text{A}} = 100$ kΩ

$R_{EE} = \frac{V_A}{I} = \frac{10 \text{ V}}{200\ \mu\text{A}} = 50$ kΩ

$r_{e_1} = r_{e_2} = r_e = \frac{V_T}{I_E} = \frac{25 \text{ mV}}{0.1 \text{ mA}} = 0.25$ kΩ

Since $R_0 >> r_e$,

$|A_d| \simeq$

$\frac{R_C \parallel r_O}{r_e} = \frac{100 \text{ K} \parallel 100 \text{ K}}{0.25 \text{ K}} = 200$ V/V

$R_{id} = 2r_\pi \quad r_\pi = \frac{\beta}{g_m} = \frac{100}{4 \text{ mA/V}} = 25$ kΩ

$R_{id} = 2(25$ K$) = 50$ K

If the total load resistance is assumed to be mismatched by 1%,

$|A_{cm}| = \frac{\Delta R_C}{2R_{EE}} = \frac{(0.01)(100 \text{ K})}{2(50 \text{ K})} = 0.01$

$\text{CMRR(dB)} = 20\log_{10}\left|\frac{A_d}{A_{cm}}\right| = 20\log_{10}\left|\frac{200}{0.01}\right|$

$= 86$ dB

Note: If only the load transistors are mismatched, and since $\alpha \simeq 1$,

$$V_{O1} = -\frac{R_C \| V_O}{2R_{EE} + r_e} V_{icm} = -\frac{(100\text{ K} \| 100\text{ K})V_{icm}}{2(50\text{ K}) + 0.25\text{ K}}$$

$= -0.499\ V_{icm}$

$$V_{O2} \simeq \frac{-[(R_C + \Delta R_C) \| r_O]V_{icm}}{2R_{EE} + r_e}$$

$$= -\frac{[(1.01)100\text{ K}] \| 100\text{ K}}{2(50\text{ K}) + 0.25\text{ K}} \cdot V_{icm} = 0.501 V_{icm}$$

$$\text{CMRR} = \frac{|A_d|}{|A_{cm}|} = \frac{200}{0.501 - 0.499}$$

$= 100,000 \rightarrow 100$ dB

Using eq. 7.103

$$R_{icm} = \beta R_{EE} \cdot \frac{1 + \frac{R_C}{\beta r_O}}{1 + \frac{R_C + 2R_{EE}}{r_O}} = (100)(50\text{ K})$$

$$\cdot \frac{1 + \frac{100\text{ K}}{100(100\text{ K})}}{1 + \frac{100\text{ K} + 2(50\text{ K})}{100\text{ K}}}$$

$R_{icm} \simeq 1.68\ \text{M}\Omega$

Ex: 7.14

From Exercise 7.4

$V_{ov} = 0.2$ V

Using Equ. 7.108 we obtain V_{os} due to $\Delta R_D / R_D$ as:

$$V_{OS} = \left(\frac{V_{OV}}{2}\right) \cdot \left(\frac{\Delta R_D}{R_D}\right)$$

$$= \frac{0.2}{2} \times 0.02 = 0.002\text{ V} \quad \text{i.e } 2\text{ mV}$$

To obtain V_{os} due to $\frac{\Delta W / L}{W / L}$

Use Eqn. (7.113

$$V_{OS} = \left(\frac{V_{OV}}{2}\right)\left(\frac{\Delta W / L}{W / L}\right)$$

$$\rightarrow V_{OS} = \left(\frac{0.2}{2}\right) \times 0.02 = 0.002$$

$\rightarrow 2$ mV

The offset voltage arising from ΔVt is obtained from Eqn. (7.116

$V_{os} = \Delta Vt = 2$ mV

Finally, from Eqn. 7.117 the total input offset is:

$$V_{OS} =$$

$$\left[\left(\frac{V_{OV}}{2}\frac{\Delta R_D}{R_D}\right)^2 + \left(\frac{V_{OV}}{2}\frac{\Delta W / L}{W / L}\right)^2 + (\Delta V_t)^2\right]^{1/2}$$

$$= \sqrt{(2 \times 10^{-3})^2 + (2 \times 10^{-3})^2 + (2 \times 10^{-3})^2}$$

$$= \sqrt{3 \times (2 \times 10^{-3})^2}$$

$= 3.46$ mV

Ex: 7.15

From Eqn. 7.127

$$V_{OS} = V_T \sqrt{\left(\frac{\Delta R_C}{R_C}\right)^2 + \left(\frac{\Delta I_S}{I_S}\right)^2}$$

$$= 25\sqrt{(0.02)^2 + (0.1)^2}$$

$= 2.5$ mV

$$I_B = \frac{100}{2(\beta + 1)} = \frac{100}{2 \times 101} \simeq 0.5\ \mu\text{A}$$

$$I_{OS} = I_B\left(\frac{\Delta\beta}{\beta}\right)$$

$= 0.5 \times 0.1\ \mu\text{A} = 50$ nA

Ex: 7.16

$$(W/L)_n \times \mu_n C_{ox} \quad 0.2\text{ m} \times 100 = 20\text{ m}\frac{\text{A}}{\text{V}}$$

$$(W/L)p \times \mu p C_{ox} = 0.1\text{ m} \times 200 = 20\text{ m}\frac{\text{A}}{\text{V}}$$

Since all transistors have the same drain current ($I/2$) and the name product $W/L \times \mu C_{ox}$ then all transconductances g_m are identical.

$$|V_{OV}| = \sqrt{\frac{I_D}{20\text{ mA/V}}} = \sqrt{\frac{0.8\text{ mA}}{20\text{ mA/V}}} = 0.2\text{ V}$$

thus,

$$g_m = \frac{I_D}{V_{OV}} = \frac{(0.8\text{ mA}/2)}{0.2\text{ V}} = 4\text{ m}\frac{\text{A}}{\text{V}}$$

From Eqn. (7.138

$G_m = g_m = 4$ mA / V

$R_O = r_{O2} \| r_{O4}$

$$r_{O2} = \frac{V_{An}}{I_{D2}} = \frac{20}{(0.8\text{ m}/2)} = 50\text{ k}\Omega$$

$$r_{O4} = \frac{V_{Ap}}{I_{D4}} = \frac{20}{(0.8\text{ m}/2)} = 50\text{ k}\Omega$$

thus,

$R_O = 50 \| 50 = 25\text{ k}\Omega$

From Eqn. (7.141

$$A_d = G_m R_O = 4\frac{\text{mA}}{\text{V}} \times 25\text{ k}\Omega = 100\frac{\text{V}}{\text{V}}$$

From Eqn. (7.148a

$$A_{cm} \simeq \frac{1}{2g_{m3}R_{SS}} = \frac{1}{2 \times 4 \times 25} = 0.005\text{ V/V}$$

$$CMRR = \frac{|A_d|}{|A_{cm}|} = \frac{100}{0.005} = 20,000$$

$\rightarrow 86$ dB

Ex: 7.17

From Eqn. (7.156 $G_m = g_m$

$$g_m \simeq \frac{I/2}{V_T} = \frac{(0.8\text{ mA}/2)}{25\text{ mV}} = 16\frac{\text{mA}}{\text{V}}$$

From Eqn. (7.159

$R_O = r_{O2} \| r_{O4}$

$= \frac{V_A}{I_{C2}} \| \frac{V_A}{I_{C4}} \simeq \frac{1}{2}\frac{V_A}{I/2}$

$= \frac{100\text{ V}}{0.8\text{ mA}} = 125\text{ k}\Omega$

$A_d = G_m \times R_O = 16 \times 125 = 2000\ \frac{\text{V}}{\text{V}}$

From Eqn. (7.162

$R_{id} = 2 \times r_\pi$

$\simeq 2 \times \frac{V_T}{(I/2)}\beta_n = \frac{2 \times 25\text{ m} \times 160}{(0.8\text{ m}/2)}$

$= 20\text{ k}\Omega$

For a simple current mirror the output resistance (thus R_{EE}) is r_o

$\rightarrow R_{EE} = \frac{V_A}{I} = \frac{100\text{ V}}{0.8\text{ mA}} = 125\text{ k}\Omega$

From Eqn. (7.167

$A_{cm} = \frac{-r_{O4}}{\beta_3 R_{EE}}$

$A_{cm} = \frac{-2 \times 125\text{ K}}{160 \times 125\text{ K}}$

$A_{cm} = -.0125\frac{\text{V}}{\text{V}}$

$C_{MRR} = \left|\frac{2000}{.0125}\right|$

$C_{MRR} = 160,000$

$20\log_{10}(160,000) = 104\text{ dB}$

Ex: 7.18

$G_m = gm_{1,2} = \frac{I/2}{V_T} = \frac{1\text{ m}/2}{25\text{ m}} = 20\text{ m}\frac{\text{A}}{\text{V}}$

$r_{O4} = r_{O5} = \frac{V_A}{I/2} = \frac{100\text{ V}}{0.5\text{ mA}} = 200\text{ k}\Omega$

$\rightarrow R_{O4} = \beta_4 r_{O4} = 50 \times 200\text{ K} = 10\text{ M}\Omega$

$R_{O5} = \beta_5\frac{r_{O5}}{2} = 100 \times \frac{200\text{ K}}{2} = 10\text{ M}\Omega$

From Eqn. (7.174

$R_O = \left[\beta_4 r_{O4} \| \beta_5\frac{r_{O5}}{2}\right]$

$= (10 \| 10)\text{ M}\Omega = 5\text{ M}\Omega$

$A_d = g_m \times R_o = 20 \times 5000 = 10^5\text{ V/V}$

i.e. 100 dB

Ex: 7.19

Refer to Fig (7.41

(a) Using Eqn. (7.178

$I_6 = \frac{(W/L)_6}{(W/L)_4}(I/2)$

$\Rightarrow 100 = \frac{(W/L)_6}{100} \times 50$

thus, $(W/L)6 = 200$

Using Eqn. (7.179

$I_7 = \frac{(W/L)_7}{(W/L)_5}(I)$

$\Rightarrow 100 = \frac{(W/L)_7}{200} \times 100$

thus, $(W/L)_7 = 200$

(b) For Q_1,

$I = \frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_1 V_{OV1}^2$

$\Rightarrow V_{OV1} = \sqrt{\frac{50}{\frac{1}{2} \times 30 \times 200}} = 0.129\text{ V}$

Similarly for Q_2, $V_{ov2} = 0.129\text{ V}$

For Q_6,

$100 = \frac{1}{2} \times 90 \times 200\ V_{OV6}^2$

$\Rightarrow V_{OV6} = 0.105\text{ V}$

(c) $g_m = \frac{2I_D}{V_{OV}}$

	I_D	V_{OV}	g_m
Q_1	50 μA	0.129 V	0.775 mA.V
Q_2	50 μA	0.129 V	0.775 mA/V
Q_6	100 μA	0.105 V	1.90 mA/V

(d) $r_{o2} = 10/0.05 = 200\text{ k}\Omega$

$r_4 = 10/0.05 = 200\text{ k}\Omega$

$r_6 = 10/0.1 = 100\text{ k}\Omega$

$r_7 = 10/0.1 = 100\text{ k}\Omega$

(e) Eqn. (7.176

$A_1 = -g_{m1}(r_{O2} \| r_{O4})$

$= -0.775\ (200 \| 200) = -77.5\ \frac{\text{V}}{\text{V}}$

Eqn. (7.177

$A_2 = -g_{m6}(r_{O6} \| r_{O7})$

$= -95\text{ V/V}$

Overall voltage gain is:

$A_1 \times A_2 = 77.5 \times 95 = 7363\text{ V/V}$

Ex: 7.20

Referring to Fig.7.42 all I_D values are the same.

so, $V_{GS13} = V_{GS12} + I_B R_B$

Using the equation developed in the text,

$$R_B = \frac{2}{\sqrt{2\mu_n C_{OX}\left(\frac{W}{L}\right)_{12} I_B}} \cdot \left(\sqrt{\frac{\left(\frac{W}{L}\right)_{12}}{\left(\frac{W}{L}\right)_{13}}} - 1\right)$$

$$R_B = \frac{2}{\sqrt{2\ (90\ \mu\text{A}/\text{V}^2)(80)(10\ \mu\text{A})}} \cdot \left(\sqrt{\frac{80}{20}} - 1\right)$$

$= 5.27\text{ k}\Omega$

$$g_{m12} = \frac{2}{R_B}\left(\sqrt{\frac{\left(\frac{W}{L}\right)_{12}}{\left(\frac{W}{L}\right)_{13}}}-1\right)$$

$$g_{m12} = \frac{2}{5.27\text{ K}}\cdot\left(\sqrt{\frac{80}{20}}-1\right) = 0.38\text{ mA/V}$$

Ex 7.21

$I_D = 90\ \mu A$

$\mu_n C_{ox} = 160\ \mu A/V^2$

$\mu_p C_{ox} = 40\ \mu A/V^2$

For Q_8 and Q_9 : $W/L = 40/0.8$

(as given in Example 7.5)

$$|V_{OV}| = \sqrt{\frac{2I_D}{\mu p C_{ox}(W/L)}}$$

$$\rightarrow |V_{OV}|_{8,9} = \sqrt{\frac{2\times 90\ \mu}{40\ \mu \times \frac{40}{0.8}}} = 0.3\text{ V}$$

then,

$$g_{m8,9} = \frac{2I_D}{|V_{OV}|} = \frac{2\times 90\ \mu A}{0.3\text{ V}}$$

$= 0.6$ mA/V

Since g_m of Q_{10}, Q_{11} and Q_{13} are identical to g_m of Q_8 and Q_9 then:

$V_{ov13} = 0.3$ V

Thus, for Q_{13}

$$(0.3)^2 = \frac{2\times 90\ \mu}{160\ \mu\ (W/L)_{13}}$$

$$\rightarrow (W/L)_{13} = 12.5$$

i.e. (10 / 0.8)

Since Q_{12} is 4 times as wide as Q_{13}, then

$$\left(\frac{W}{L}\right)_{12} = \frac{4\times 10}{0.8} = \frac{40}{0.8}$$

$$R_B = \frac{2}{\sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right)_{12} I_B}}\cdot\left(\sqrt{\frac{(W/L)_{12}}{(W/L)_{13}}}-1\right)$$

$$= \frac{2}{\sqrt{2\times 160\ \mu\times\frac{40}{0.8}\times 90\ \mu}}\cdot\left(\sqrt{\frac{40/0.8}{12.5}}-1\right)$$

$$\rightarrow R_B = 1.67\text{ k}\Omega$$

The voltage drop on R_B is:

$1.67\text{ k}\Omega \times 90\ \mu A = 150$ mV

$$V_{OV12} = \sqrt{\frac{2\times 90\ \mu}{160\ \mu\times\frac{40}{0.8}}} = 0.15\text{ V}$$

$V_{ov12} = V_{GS12} - V_{tn}$

$V_{GS12} = 0.15 + 0.7 = 0.85$ V

thus, $V_{G12,13} = V_{GS12} + I_B R_B - V_{SS}$

$= 0.85 + 0.15 - 2.5$

$= -1.5$ V

$V_{OV11} = |V_{OV8}| = 0.3$ V

$\rightarrow V_{GS11} = 0.3 + 0.7 = 1$ V

$V_{G11} = -1.5 + 1 = -0.5$ V

Finally,

$V_{G8} = V_{DD} - V_{SG8} = +2.5 + (-0.3 - 0.8)$

$= +1.4$ V

Ex: 7.22

$R_{in} = 20.2\text{ k}\Omega$

$A_{vo} = 8513$ V/V

$R_o = 152\ \Omega$

With $R_s = 10\text{ k}\Omega$ and $R_L = 1\text{ k}\Omega$

$$A_V = \frac{20.2}{20.2+10}\times 8513\times\frac{1}{(1+0.152)}$$

$= 4943$ V/V

Ex 7.23

$$\frac{i_{e8}}{i_{b8}} = \beta_8 + 1 = 101$$

$$\frac{i_{b8}}{i_{c7}} = \frac{R_5}{R_5+R_{i4}} = \frac{15.7}{15.7+303.5} = 0.0492$$

$$\frac{i_{c7}}{i_{b7}} = \beta_7 = 100$$

$$\frac{i_{b7}}{i_{c5}} = \frac{R_3}{R_3+R_{i3}} = \frac{3}{3+234.8} = 0.0126$$

$$\frac{i_{c5}}{i_{b5}} = \beta_5 = 100$$

$$\frac{i_{b5}}{i_{c2}} = \frac{R_1+R_2}{R_1+R_2+R_{i2}} = \frac{40}{40+5.05} = 0.8879$$

$$\frac{i_{c2}}{i_1} = \beta_2 = 100$$

Thus the overall current gain is:

$$\frac{i_{e8}}{i_1} = 101\times 0.0492\times 100\times 0.0126\times 100..$$

$\times\ 0.8879 \times 100$

$= 55993$ A/A

and the overall voltage gain is

$$\frac{V_O}{V_{id}} = \frac{R_6}{R_{i1}}\cdot\frac{i_{e8}}{i_1}$$

$$= \frac{3}{20.2}\times 55593 = 8256\text{ V/V}$$

Ex: 8.1

$$A_M = \frac{-R_G}{R_G + R_{sig}} \times g_m(R_L \| R_D)$$

$$= -\frac{10}{10+0.1} \times 2 \times \frac{10\text{ K}}{2}$$

$A_M = -9.9$ V/V

$$f_{P1} = \frac{1}{2\pi C_{C1}(R_G + R_{sig})}$$

$$= \frac{1}{2\pi \times 1\ \mu \times (10 + 0.1\text{ M})} = 0.016\text{ Hz}$$

$$f_{P2} = \frac{1}{2\pi C_S / g_m} = \frac{1}{2\pi \times 1\ \mu / 2\text{ m}} = 318\text{ Hz}$$

$$f_{P3} = \frac{1}{2\pi C_{C2}(R_L + R_D)} = \frac{1}{2\pi 1\ \mu \times (10 + 10)}$$

$= 8$ Hz

$f_L \simeq f_{P2} = 318$ Hz

Ex: 8.2

$C_{C1} = C_E = C_{C2} = 1\ \mu$F

$$g_m = 40\frac{\text{mA}}{\text{V}} \rightarrow I_C = 40\text{ m} \times 25\text{ m} = 1\text{ mA}$$

$$r_\pi = 2.5\text{ k}\Omega = \frac{\beta}{g_m} \Rightarrow \beta = 100$$

$$r_e = \frac{V_T}{I_E} = \frac{25\text{ mV}}{1\text{ mA}} = 25\ \Omega$$

$$f_{P1} = \frac{1}{2\pi C_{C1}[R_B \| r_\pi + R_{sig}]}$$

$$= \frac{1}{2\pi 1\mu[100\text{ K} \| 2.5\text{ K} + 5\text{ K}]}$$

$f_{P1} = 21.4$ Hz

$$f_{P2} = \frac{1}{2\pi \cdot C_E\left[r_e + \frac{R_B \| R_{sig}}{\beta + 1}\right]}$$

$$f_{P2} = \frac{1}{2\pi \cdot 1\mu\left[25 + \frac{100\text{ K} \| 5\text{ K}}{101}\right]}$$

$f_{P2} = 2.2$ KHz

$$f_{P3} = \frac{1}{2\pi \cdot C_{C2} \cdot (R_C + R_L)}$$

$$= \frac{1}{2\pi \cdot 1\mu(8\text{ K} + 5\text{ K})}$$

$f_{P3} = 12.2$ Hz

Ex: 8.3

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.45 \times 10^{-11}}{10 \times 10^{-9}}$$

$$= 3.45 \times 10^{-3}\text{F/m}^2 = 3.45\text{ fF}/\mu\text{m}^2$$

$$C_{OV} = WL_{OV}C_{ox} = 10 \times 0.05 \times 3.45$$

$= 172$ fF

$$C_{gs} = \frac{2}{3}WLC_{ox} + C_{OV}$$

$$= \frac{2}{3} \times 10 \times 1 \times 3.45 + 1.72 = 24.72\text{ fF}$$

$C_{gd} = C_{OV} = 1.72$ fF

$$C_{sb} = \frac{C_{sbo}}{\sqrt{1 + \frac{V_{SB}}{V_O}}} = \frac{10}{\sqrt{1 + \frac{1}{0.6}}} = 6.1\text{ fF}$$

$$C_{db} = \frac{C_{dbo}}{\sqrt{1 + \frac{V_{DB}}{V_O}}} = \frac{10}{\sqrt{1 + \frac{2+1}{0.6}}} = 4.1\text{ fF}$$

Ex: 8.4

Peak current occurs At $V_I = V_{th} = 5$ V

$$i\text{ Peak} = \frac{1}{2}K_n'\left(\frac{W}{L}\right)_n (V_{th} - V_{tn})^2$$

$$= \frac{1}{2} \times 20 \times 20(5-2)^2 = 1800$$

Ex: 8.5

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

$$C_{de} = \tau_F \cdot g_m = 20 \times 10^{-12} \times 40 \times 10^{-3}$$

$= 0.8$ pF

$C_{je} = 2\ C_{jeo} = 2 \times 20 = 40$ fF

$C_\pi = C_{de} + C_{je} = 0.84$ pF

$$C\mu = \frac{C_{\mu O}}{\left(1 + \frac{V_{CB}}{V_{OC}}\right)^{m_{CBJ}}}$$

$$= \frac{20\text{ fF}}{\left(1 + \frac{2}{0.5}\right)^{0.33}} = 12\text{ fF}$$

$$f_T = \frac{g_m}{2\pi(C\pi + C\mu)}$$

$$= \frac{40 \times 10^{-3}}{2\pi(0.84 + 0.012) \times 10^{-12}} = 7.47\text{ GHz}$$

Ex: 8.6

$$|h_{fe}| \simeq \frac{f_T}{f} \rightarrow 10 = \frac{f_T}{50}$$

$\Rightarrow f_T = 500$ MHz

$$f_T = \frac{g_m}{2\pi(C\pi + C\mu)}$$

$$C\pi + C\mu = \frac{40 \times 10^{-3}}{2\pi \times 500 \times 10^6} = 12.7\text{ pF}$$

$C\pi = 12.7 - C\mu = 12.7 - 2 = 10.7$ pF

Ex: 8.7 Diffusion component of $C\pi$ at I_c of 1 mA

$= 10.7 - 2 = 8.7$ pF

Since C_{de} is proportional to I_C, then:

$C_{de}\,(I_C = 0.1 \text{ mA}) = 0.87 \text{ pF}$
$C\pi\,(I_C = 0.1 \text{ mA}) = 2.87 \text{ pF}$

$$f_T(I_C = 0.1 \text{ mA}) = \frac{g_m}{2\pi(C\pi + C\mu)}$$
$$= \frac{4 \times 10^{-3}}{2\pi(2.87 + 2) \times 10^{-12}}$$
$$= 130.7 \text{ MHz}$$

Ex: 8.8

$$A_M = -\frac{R_G}{R_G + R_{sig}} g_m R_L'$$

$R_L' = 7.14 \text{ k}\Omega,\ g_m = 1 \text{ mA/V}$
$R_{sig} = 10 \text{ k}\Omega$

$$A_M = \frac{-4.7 \text{ M}\Omega}{(4.7 + 0.01) \text{ M}\Omega} \times 1 \times 7.14$$
$$= -7.12 \text{ V/V}$$

$$f_H = \frac{1}{2\pi C_{in}(R_{sig}||R_G)} \quad C_{in} = 4.26 \text{ pF}$$

$$f_H = \frac{1}{2\pi \times 4.26(10 \text{ K} \| 4.7 \text{ M})} = 3.7 \text{ MHz}$$

Ex: 8.9

$C_{gs} = 1 \text{ pF}$

$C_{eq} = (1 + g_m R_L')C_{gd} = (1 + 1 \times 7.14)$

$C_{gd} = 8.14 C_{gd}$

$$f_T \geq 1 \text{ MHz} \Rightarrow \frac{1}{2\pi C_{in}(R_{sig}||R_G)} \geq 1 \text{ MHz}$$

$C_{in} = C_{gs} + C_{eq} = 1 \text{ pF} + 8.14\, C_{gd}(\text{PF})$

$$\frac{1}{2\pi(1 + 8.14C_{gd})\text{pF}(100 \text{ K} \| 4.7 \text{ M})} \geq 1 \text{ MHz}$$

$\Rightarrow 1.63 \geq 1 + 8.14 C_{gd}$

$C_{gd} \leq 0.077 \text{ pF}$ or $C_{gd} \leq 77 \text{ fF}$

Ex: 8.10

① $A_v = -39/2 = -19.5 \text{ V/V}$

$$A_M = \frac{-R_B}{R_B + R_{sig}} \cdot \frac{r_\pi \cdot g_m \cdot R_L'}{r_\pi + r_X + (R_B + R_{sig})}$$

$$A_M = \frac{-100}{100 + 5} \cdot \frac{2.5 \times 40 \cdot 10^{-3} \times R_L'}{2.5 + 0.05 + (100 \| 5)}$$
$$= -0.013 \times R_L'$$

$\Rightarrow R_L' = 1.5 \text{ k}\Omega = r_o \| R_C \| R_L$

$1.5 \text{ k}\Omega = (100 \| 8 \| R_L) \text{ k}\Omega$
$= 7.4 \text{ k} \| R_L$
$\rightarrow R_L = 1.9 \text{ k}\Omega$

② $$f_H = \frac{1}{2\pi C_{in} \cdot R_{sig}'} \quad R_{sig}' = 1.65 \text{ k}\Omega$$

$C_{in} = C\pi + C\mu(1 + g_m R_L')$

$C_{in} = 7 + 1\,(1 + 40 \times 10^{-3} + 1.5 + 10^3)$
$= 68 \text{ pF}$

$$\Rightarrow f_H = \frac{1}{2\pi\, 68\text{p} \cdot 1.65 \text{ K}} = 1.42 \text{ MHz}$$

Ex: 8.11 Using equations 8.61 and 8.63 we can write the general form of the transfer function of a direct-coupled amplifier as:

$$A(s) = \frac{A_{DC}}{1 + \frac{s}{2\pi f_{3dB}}} \quad \text{where } A_{DC} \text{ is the DC gain}$$

of the amplifier and f_{3dB} is the upper 3dB frequency of the amplifier.
In this case we have $A_{DC} = 1000$ and $f_{3dB} = 100 \text{ KHz} = 10^5 \text{ Hz}$

$$\text{Therefore } A(s) = \frac{1000}{1 + \frac{s}{2\pi \times 10^5}}$$

Ex: 8.12
For this amplifier we have:

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

By definition at $\omega = \omega_H$ we have

$$|H(j\omega_H)|^2 = \frac{A_M^2}{2} \Rightarrow$$

$$\frac{A_M^2}{\left(1 + \left(\frac{\omega_H}{\omega_{P1}}\right)^2\right)\left(1 + \left(\frac{\omega_H}{\omega_{P2}}\right)^2\right)} = \frac{A_M^2}{2} \Rightarrow$$

$$\left[1 + \left(\frac{\omega_H}{\omega_{P1}}\right)^2\right]\left[1 + \left(\frac{\omega_H}{\omega_{P2}}\right)^2\right] = 2$$

If $\omega_{P2} = K\omega_{P1}$ and $\omega_H = 0.9\,\omega_{P1}$, then

$$\left[1 + \left(\frac{0.9\omega_{P1}}{\omega_{P1}}\right)^2\right]\left[1 + \left(\frac{0.9\omega_{P1}}{K\omega_{P1}}\right)^2\right] = 2$$

$$(1 + 0.9^2)\left(1 + \left(\frac{0.9}{\text{K}}\right)^2\right) = 2$$

$$1 + \left(\frac{0.9}{\text{K}}\right)^2 = 1.1 \Rightarrow \left(\frac{0.9}{\text{K}}\right)^2 = 0.1 \Rightarrow \text{K} = 2.78$$

If $\omega_H = 0.99\,\omega_{P1}$, then :

$$\left[1 + \left(\frac{0.99\omega_{P1}}{\omega_{P1}}\right)^2\right]\left[1 + \left(\frac{0.99\omega_{P1}}{\text{K}\omega_{P1}}\right)^2\right] = 2$$

$$(1 + 0.99^2)\left(1 + \left(\frac{0.99}{\text{K}}\right)^2\right) = 2 \Rightarrow$$

$$1 + \left(\frac{0.99}{\text{K}}\right)^2 = 1.01 \Rightarrow \left(\frac{0.99}{\text{K}}\right)^2 = 0.01 \Rightarrow$$

$\text{K} = 9.88$

Ex: 8.13

From Exercise 8.12 we have:

$$\left[1+\left(\frac{\omega_H}{\omega_{P1}}\right)^2\right]\left[1+\left(\frac{\omega_H}{\omega_{P2}}\right)^2\right] = 2 \text{ and}$$

$$\omega_{P2} = K\omega_{P1}$$

$$K = 1 \Rightarrow \left[1+\left(\frac{\omega_H}{\omega_{P1}}\right)^2\right]\left[1+\left(\frac{\omega_H}{\omega_{P2}}\right)^2\right] = 2$$

$$1+\left(\frac{\omega_H}{\omega_{P1}}\right)^2 = \sqrt{2} \Rightarrow \left(\frac{\omega_H}{\omega_{P1}}\right)^2 = \sqrt{2}-1$$

$$\omega_H = \sqrt{\sqrt{2}-1}\quad \omega_{P1} = 0.64\,\omega_{P1} \text{ (exact value)}$$

(note that in this case the zeros are at $S = \infty$) we have :

$$\omega_H = 1/\sqrt{\frac{1}{\omega_{P1}^2}+\frac{1}{\omega_{P2}^2}} = 1/\sqrt{\frac{1}{\omega_{P1}^2}+\frac{1}{K^2\omega_{P1}^2}}$$

$$\omega_H = \omega_{P1}/\sqrt{1+\frac{1}{K^2}}$$

For $K = 1 \Rightarrow \omega_H = \frac{1}{\sqrt{2}}\omega_{P1} = 0.71\,\omega_{P1}$

For the case of $K = 2$, the exact value of ω_H can be found from the following equation:

$$\left[1+\left(\frac{\omega_H}{\omega_{P1}}\right)^2\right]\left[1+\left(\frac{\omega_H}{K\omega_{P1}}\right)^2\right] = 2$$

Assuming $\frac{\omega_H}{\omega_{P1}} = X$ we have

$$(1+X^2)\left(1+\frac{X^2}{K^2}\right) = 2 \Rightarrow$$

$$\frac{1}{K^2}X^4 + \left(1+\frac{1}{K^2}\right)X^2 + 1 = 2 \Rightarrow$$

$$X^4 + (K^2+1)X^2 - K^2 = 0 \Rightarrow$$

$$X^2 = \frac{-(K^2+1)+\sqrt{(K^2+1)^2+4K^2}}{2}$$

$$\frac{\omega_H}{\omega_{P1}} = \sqrt{\frac{-(K^2+1)+\sqrt{(K^2+1)^2+4K^2}}{2}} \quad (*)$$

For $K = 2 \Rightarrow \frac{\omega_H}{\omega_{P1}} = 0.84 \Rightarrow \omega_H = 0.84\omega_{P1}$

In this case, the approximate value of ω_H is:

$$\omega_H = \omega_{P1}/\sqrt{1+\frac{1}{K^2}} = 0.89\omega_{P1}$$

For $K = 4$, using equation (*), the exact value of ω_H is:

$\omega_H = 0.95\,\omega_{P1}$

In this case, the approximate value of ω_H is :

$$\omega_H = \omega_{P1}/\sqrt{1+\frac{1}{K^2}} = 0.97\omega_{P1}$$

Ex: 8.14

We have $A_M = -10.8$ V/V and $f_H \simeq 128.3$ KHz, therefore, the gain-bandwidth product is:

$10.8 \times 128.3 = 1.3856 \text{ MHz} \simeq 1.39 \text{ MHz}$

Now we want to find the value of R_L' that will result in $f_H = 180$ KHz. We have:

$$\tau_{gs} + \tau_{gd} = \frac{1}{\omega_H} = \frac{1}{2\pi f_H}$$

$$\tau_{gs} + \tau_{gd} = \frac{1}{2\pi \times 180 \text{ KHz}} = 884.2 \text{ nsec}$$

$$\tau_{gs} = 80.8 \text{ nsec} \Rightarrow \tau_{gd} = 884.2 - 80.8$$

$$\tau_{gd} = 803.4 \text{ nsec}$$

$$\tau_{gd} = R_{gd}C_{gd} = (R' + R_L' + g_m R_L' R')C_{gd}$$

$$R' = R_{in} \| R_{sig} = 80.8 \text{ k}\Omega,\ g_m = 4\ \frac{\text{mA}}{\text{V}},$$

$C_{gd} = 1$ pF

Thus

$$803.4 \text{ nsec} = (80.8 \text{ k}\Omega + R_L' + 323.2R_L') + 1 \text{ pF}$$

$$\Rightarrow 324.2R_L' = \frac{803.4 \text{ nsec}}{1 \text{ pF}} - 80.8 \text{ k}\Omega$$

$$\Rightarrow R_L' = \frac{722.6 \text{ k}\Omega}{324.2} = 2.23 \text{ k}\Omega$$

$$\Rightarrow R_L' = 2.23 \text{ k}\Omega$$

For this value of R_L' we have

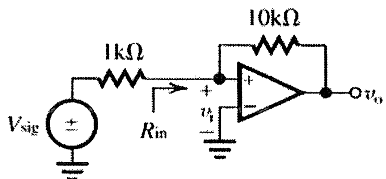
$$A_M = -\frac{R_{in}}{R_{in}+R_{sig}}(g_m R_L')$$

$$A_M = -\frac{420}{420 \times 100} \times 4 \times 2.23 = -7.2 \text{ V/V}$$

Therefore, the gain-bandwidth product is:

$7.2 \times 180 \text{ KHz} = 1.296 \text{ MHz} \simeq 1.3 \text{ MHz}$

Ex: 8.15



Using Miller's theorem we have

$$R_{in} = \frac{10 \text{ k}\Omega}{A+1},\ V_i = \frac{R_{in}}{R_{in}+1 \text{ k}\Omega}V_{sig} \text{ and}$$

$V_o = -AV_i$

Assuming $V_{sig} = 1$ V we have

A(V/V)	$R_{in}(\Omega)$	V_i(mV)	V_o(V)	V_o/V_{sig} $\left(\frac{V}{V}\right)$
10	909	476	4.76	4.76
100	99	90	–9	–9
1000	9.99	9.9	–9.9	–9.9
10000	1	0.999	–9.99	–9.99

Ex:8.16 Refering to the solution of Example 8.10 the value of f_H determined by the exact analysis is:

$f_H = f_{P1} = 143.4$ MHz

Also,

$A_M = -g_m \cdot R_L' = -1.25 \times 10 = -12.5$ V/V

Therefore the gain-bandwidth product (f_t) is:

$f_t = 143.4 \times 12.5 = 1.79$ GHz

Since f_t is less than $f_{P2} = 2.44$ GHz and $f_z = 40$ GHz, therefore it is a good approximation of the unity gain frequency.

Ex: Referring to the solution of Example 8.10 if a load resistor is connected at the output halving the value of R_L', then we have

$R_L' = \frac{r_{O1} \| r_{O2}}{2}$ and therefore

$$|A_M| = g_m \frac{r_{O1} \| r_{O2}}{2} = 1.25 \times \frac{10}{2} = 6.25 \text{ V/V}$$

Using equation 8.92 and assuming $f_H \simeq f_{P1}$, we have:

$$f_H \simeq \frac{1}{2\pi \cdot [[C_{gs} + C_{gd}(1 + g_m R_L')] \cdot R_{sig}' + (C_L + C_{gd})R_L']}$$

$$f_H \simeq \frac{1}{2\pi[[20f + 5f(1 + 1.25 \times 5)] \cdot 10 \text{ K} + (25f + 5f) \times 5 \text{ K}]}$$

$f_H \simeq 223$ MHz

$f_T = |A_M| \cdot f_H = 6.25 \times 223 = 1.4$ GHz

Ex:8.18 Referring to the solution of Example 8.10

$g_{m1} = \frac{2I_{D1}}{V_{OV1}}$ is I_D is increased by 4 and V_{ov} by 2

then :

$$g_m = \frac{2(4I_{D1})}{(2V_{OV1})} = 2g_{m1} = 2 \times 1.25 \frac{\text{mA}}{\text{V}}$$

$$= 2.50 \frac{\text{mA}}{\text{V}}$$

To calculate R_L'

If $R_{L1}' = r_{OQ1} \| r_{OQ2} = 10$ kΩ in example 9.10

Since $r_O = \frac{V_A}{I_D} \rightarrow$ increasing I_D by 4 reduces both r_{OQ1} and r_{OQ2} by 4

Thus :

$$r_{OQ1} \| r_{OQ2} = 10 \text{ K} \rightarrow \frac{r_{OQ1}}{4} \| \frac{r_{OQ2}}{4} = \frac{1}{4}(r_{OQ1} \| r_{OQ2})$$

$$R_L' = \frac{1}{4} \times 10 \text{ K} = 2.5 \text{ k}\Omega$$

$$|A_M| = g_m \cdot R_L' = 2.5 \times 2.5$$

$$= 6.25 \text{ A/A}$$

Using equation 8.93 and assuming $f_H \simeq f_{P1}$ we have:

$$f_H = \frac{1}{2\pi\{[C_{gs} + C_{gd}(1 + g_m R_L')]R_{sig} + (C_L + C_{gd})R_L'\}}$$

$$f_H = \frac{1}{2\pi\{[20 \text{ f} + 5 \text{ f}(1 + 6.25)]10 \text{ K} + (25 + 5) \text{ f} \times 2.5 \text{ K}}$$

$f_H = 250$ MHz $\Rightarrow$ $f_{P1} \simeq f_H = 250$ MHz

$f_t \simeq |A_M| \cdot f_H = 6.25 \times 250 = 1.56$ GHz

Ex:8.19

$$r_{onpn} = \frac{V_{An}}{I} = \frac{130 \text{ V}}{1 \text{ mA}} = 130 \text{ k}\Omega$$

$$r_{opnp} = \left|\frac{V_{Ap}}{I}\right| = \frac{50 \text{ V}}{1 \text{ mA}} = 50 \text{ k}\Omega$$

$$R_L' = r_{onpn} \| r_{opnp} = 130 \text{ k}\Omega \| 50 \text{ k}\Omega$$

$$R_L' = 36 \text{ k}\Omega$$

$$g_m = \frac{I}{V_T} = \frac{1 \text{ mA}}{25 \text{ mV}} = 40 \frac{\text{mA}}{\text{V}}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{200}{40 \frac{\text{mA}}{\text{V}}} = 5 \text{ k}\Omega$$

(a) From equation 8.97 we have:

$$A_M = -\frac{r_\pi}{R_{sig} + r_x + r_\pi}(g_m R_L')$$

$$= -\frac{5}{36 + 0.2 + 5}(40 \times 36 \text{ k}\Omega) \simeq -175 \frac{\text{V}}{\text{V}}$$

$$A_M = -175 \frac{\text{V}}{\text{V}}$$

(b) Using Miller's theorem we have:

$$C_{in} = C_\pi + C_\mu(1 + g_m R_L')$$

$$= 16 \text{ pF} + 0.3 \text{ pF}(1 + 40 \times 36) = 448 \text{ pF}$$

$$C_{in} = 448 \text{ pF}$$

$$f_H \simeq \frac{1}{2\pi C_{in} R_{sig}'} = \frac{1}{2\pi C_{in}[r_\pi \| (R_{sig} + r_x)]}$$

$$f_H = \frac{1}{2\pi \times 448 \text{ pF}\underbrace{[5 \| (36 + 0.2)]}_{\simeq 4.3 \text{ k}\Omega}} = 82.6 \text{ kHz}$$

(c) Using the method of open-circuit time constants, from equation 8.100 we have:

$$\tau_H = C_\pi R_{sig}' + C_\mu[(1 + g_m R_L')R_{sig}' + R_L'] + C_L R_L'$$

We have $R_{sig}' = r_\pi \| (R_{sig} + r_x) \simeq 4.3$ kΩ

$R_L' = r_{onpn} \| r_{opnp} = 36$ kΩ

Thus:

$\tau_H = 16 \times 4.3 + 0.3[(1 + 40 \times 36)4.3 + 36] + 5 \times 36$

$\tau_H = 2.12$ nsec

$$f_H = \frac{1}{2\pi\tau_H} \simeq 75.1 \text{ kHz}$$

(d) Using equations 8.102, 8.103 and 8.104 we have:

$$f_Z = \frac{1}{2\pi}\frac{g_m}{C_\mu} = \frac{1}{2\pi}\frac{40\ \frac{\text{mA}}{\text{V}}}{0.3\ \text{pF}} = 21.2 \text{ GHz}$$

$$f_{p1} \simeq \frac{1}{2\pi[C_\pi + C_\mu(1 + g_m R_L')]R_{sig}' + (C_L + C_\mu)R_L'}$$

$\Rightarrow f_{p1} = 75.1$ kHz

$$f_{p2} \simeq \frac{1}{2\pi}\frac{[C_\pi + C_\mu(1 + g_m R_L')]R_{sig}' + (C_L + C_\mu)R_L'}{[C_\pi(C_L + C_\mu) + C_L C_\mu]R_{sig}' R_L}$$

$f_{p2} = 25.2$ MHz

Since $f_{p1} << f_z$ and $f_{p1} << f_{p2}$, thus $f_H \simeq f_{p1} = 75.1$ KHz

(e) $f_t \simeq |A_M| f_H = 175 \times 75.1 \text{ kHz} = 13.1$ MHz

$f_t = 13.1$ MHz

Ex:8.20 Referring to the solution of Example 8.11 we have $f_T = |A_M| \cdot f_H$, since $|A_M|$ remains the same as that of the example, to place f_t at 2 GHz we need

$$2 \text{ GHz} = f_T = |A_M| \cdot f_H = \frac{|A_M|}{2\pi(C_L + C_{gd})R_L'}$$

$$\Rightarrow C_L = \frac{|A_M|}{2\pi R_L' \cdot f_T} - C_{gd}$$

$$= \frac{12.5}{2\pi \times 10 \text{ k}\Omega \times 2 \text{ GHz}} - 5 \times \text{fF}$$

$\Rightarrow C_L = 94.5$ fF

Ex:8.21 For a CS amplifier fed with $R_{sig} = 0$ we know that:

$$f_t = \frac{g_m}{2\pi(C_L + C_{gd})}$$

and $f_z = \dfrac{g_m}{2\pi C_{gd}}$

Therefore,

$$\frac{f_z}{f_t} = \frac{g_m/(2\pi C_{gd})}{g_m/[2\pi(C_L + C_{gd})]} = \frac{C_L + C_{gd}}{C_{gd}}$$

$$\frac{f_z}{f_t} = \frac{C_L}{C_{gd}} + 1 \Rightarrow \frac{f_z}{f_t} = 1 + \frac{C_L}{C_{gd}}$$

Ex:8.22 $R_L = 500$ kΩ, and from Example 8.12

$g_m = 1.25$ mA/V, $r_o = 20$ kΩ,

$C_{gs} = 20$ fF, $C_{gd} = 5$ fF $C_L = 15$ fF,

$R_{sig} = 10$ kΩ, $R_L = 20$ kΩ.

$$R_{in} = \frac{1}{g_m} + \frac{R_L}{g_m r_o} = \frac{1}{1.25 \text{ m}} + \frac{500 \text{ K}}{1.25 \times 20}$$

$= 20.8$ kΩ

$$G_v = \frac{R_L}{R_{sig} + R_{in}} = \frac{500}{10 + 20.8} = 16.2 \text{ V/V}$$

To obtain f_H:

$R_{gs} = R_{sig} \| R_{in} = 10 \text{ K} \| 20.8 \text{ K} = 6.75$ kΩ

$R_{gd} = R_L \| R_O$

$R_O = r_O + R_{sig} + (g_m r_O) \cdot R_{sig} = 280$ K

(same as in Eq. 8.12)

$R_{gd} = 500 \text{ K} \| 280 \text{ K} = 179.5$ kΩ

$\tau_H = C_{gs} \cdot R_{gs} + (C_{gd} + C_L) \cdot R_{gd}$

$= 20 \text{ f} \times 6.75 \text{ K} + (5 \text{ f} + 15 \text{ f}) \times 179.5 \text{ K}$

$\tau_H = 0.135 \text{ ns} + 3.59 \text{ ns} = 3.72$ ns

Thus, $f_H = \dfrac{1}{2\pi T_H} = 42.7$ MHz

Ex:8.23 a) Low-frequency gain

A_V: $g_m r_O 40$; $R_L = r_O$

CS − Amplifier: $A_V = -g_m(R_L \| r_O)$

Since $= R_L = r_O \rightarrow$

$$A_V = -\frac{1}{2}(g_m r_O) = -\frac{1}{2} \times 40 = -20 \text{ V/V}$$

CASCODE Amplifier:

$A_V = -g_m(R_O \| R_L) = -g_m(R_O \| r_O)$

where $R_O = r_{O2} + r_{O1} + (g_{m2} r_{O2}) r_{O1}$

since $r_{O2} = r_{O1} = r_O$ and $g_{m2} = g_{m1} = g_m$

$R_O = 2r_O + (g_m r_O) \cdot r_O = r_O(2 + g_m r_O)$

$= 42 r_O$

$\Rightarrow A_V = -g_m(42 r_O \| r_O) \simeq -g_m \cdot r_O$

$= -40$ V/V

$$\frac{A_{V\text{ CASCODE}}}{A_{VCS}} = \frac{-40}{-20} = 2$$

b) f_H: Neglect components of τ_H that do not include R_{sig}; also $C_{gd} = 0.25\ C_{gs}$

CS - Amplifier:

$$\tau_H = C_{gs} \cdot R_{sig} + C_{gd}[(1 + g_m \cdot R_L')R_{sig} + R_L'] + (C_L + C_{ds})R_L'$$

where: $R_L' = r_O \| r_L = \dfrac{r_O}{2}$

$$\Rightarrow \tau_H = C_{gs} \cdot R_{sig} + C_{gd}\left[\left(1 + \frac{g_m r_O}{2}\right)R_{sig}\right]$$

since $C_{gd} = 0.25\ C_{gs}$ and $g_m r_O = 40$

$\Rightarrow \tau_H = C_{gs} \cdot R_{sig} + 0.25 \times C_{gs} \times 21 \times R_{sig}$

$= R_{sig} \times C_{gs} \times 6.25$

CASCODE - Amplifier:

Using Eq8.118 and neglecting the terms that do not include R_{sig}

$\tau_H = R_{sig}[C_{gs} + C_{gd}(1 + g_m R_{d1})]$

$R_{d1} = r_O \| \left(\frac{r_O + R_L}{g_m r_O}\right) = r_O \| \frac{2r_O}{g_m r_O}$

$= r_O \| \frac{r_O}{20} \simeq \frac{r_O}{20}$

$\rightarrow \tau_H = R_{sig}\left[C_{gs} + 0.25 \times C_{gs}\left(1 + \frac{g_m r_O}{20}\right)\right]$

$= R_{sig} \cdot C_{gs} \times 1.75$

$\frac{f_{H\ CASCODE}}{f_{H\ CS}} = \frac{\tau_{cs}}{\tau_{CASCODE}}$

$= \frac{R_{sig} \cdot C_{gs} \times 6.25}{R_{sig} \cdot C_{gs} \times 1.75} = 3.6$

c) $f_T = |A_V| \cdot f_H$

$\frac{f_{T\ CASCODE}}{f_{T\ CS}} = \left(\frac{|A_V|_{CASCODE}}{|A_V|_{CS}}\right) \times \left(\frac{f_{H\ CASCODE}}{f_{H\ CS}}\right)$

$= 2 \times 3.6$

$= 7.2$

Ex:8.24 Referring to the solution of Exercise8.19 we have:

$g_m = 40 \frac{mA}{V}$ and $r_\pi = 5\ k\Omega$

Note that for the cascode amplifier considered in this exercise:

$r_{\pi 1} = r_{\pi 2} = r_\pi = 5\ k\Omega$

$g_{m1} = g_{m2} = g_m = 40 \frac{mA}{V}$

$R_{in} = r_{\pi 1} + r_x = 5\ k\Omega + 0.2\ k\Omega = 5.2\ k\Omega$

$A_o = g_m \cdot r_o = 40 \times 130 = 5200\ V/V$

$R_{o1} = r_{o1} = r_o = 130\ k\Omega$

$R_{in2} \simeq r_{e2} \cdot \frac{r_{o2} + R_L}{r_{o2} + \frac{R_L}{\beta + 1}} = \frac{5\ K}{200 + 1}$

$\times \frac{130 + 50}{130 + \frac{50}{201}}$

$R_{in2} \simeq 35\ \Omega$

$R_o \simeq \beta_2 r_{O2} = 200 \times 130\ k\Omega = 26\ M\Omega$

$A_M = \frac{-r_\pi}{r_\pi + r_x + R_{sig}} \cdot g_m(\beta r_o \| R_L)$

$A_M \simeq -242 \frac{V}{V}$

To calculate f_H we use the method of open-circuit time constants. From Figure8.30we have:

$R'_{sig} = r_{\pi 1}\|(r_{x1} + R_{sig}) = 5\ K\|(0.2 + 36)$

$R'_{sig} = 4.4\ k\Omega$

$R_{\pi 1} = R'_{sig} = 4.4\ k\Omega$

$R_{O1} = r_{O1} \| R_{in2} = r_O \| \left[r_{e2}\left(\frac{r_{O2} + R_L}{r_{O2} + \frac{R_L}{\beta_2 + 1}}\right)\right]$

$R_{O1} = 130\ K \| 35\ \Omega \simeq 35\ \Omega$

$R_{\mu 1} = R'_{sig}(1 + g_{m1} R_{O1}) + R_{O1}$

$R_{\mu 1} = 10.6\ k\Omega$

$\tau_H = C_{\pi 1} \cdot R_{\pi 1} + C_{\mu 1} \cdot R_{\mu 1} + (C_{cs1} + C_{\pi 2})$

$R_{O1} + (C_L + C_{cs2} + C_{\mu 2}) \cdot (R_L \| R_O)$

$\tau_H = 16p \times 4.4\ K + 0.3\ p \times 10.6\ K + (0 + 16\ p)$

$\times 35 + (5\ p + 0 + 0.3\ p)(50\ K \| 26\ M)$

$\tau_H = 339\ ns$

$f_H = \frac{1}{2\pi\tau_H} = \frac{1}{2\pi \times 339\ ns} \simeq 469\ KHz$

$f_T \simeq |A_M| \cdot f_H = 242 \times 469\ KHz$

$\simeq 113.5\ MHz$

Compared to the CE amplifier in Exercise 8.19 $|A_M|$ has increased from 175 V / V to 242 V / V, f_H has increased from 75.1 KHz to 469 KHz and f_t has increased from 13.1 MHz to 113.5 MHz

To increase f_H to 1 MHz we need:

$\tau_H = \frac{1}{2\pi f_H} = 159\ ns$, thus

$16\ p \times 4.4\ K + 0.3\ p \times 10.6\ K + 16\ p \times 35$

$+ (C_L + 0.3\ p) \cdot (50\ K \| 26\ M) = 159\ ns$

$\Rightarrow C_L = 1.4\ pf$

Ex:8.25 $R'_L = R_L \| r_o = 20\ K \| 20\ K$

$= 10\ K$

From Eq.8.121 we have:

$A_M = \frac{g_m R'_L}{1 + g_m R'_L} = \frac{1.25 \times 10}{1 + 1.25 \times 10} = 0.93 \frac{V}{V}$

$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} = \frac{1}{2\pi} \times \frac{1.25\ m}{(20\ f + 5\ f)}$

$= 8\ GHz$

$f_z = \frac{1}{2\pi} \cdot \frac{g_m}{C_{gs}} = \frac{1}{2\pi} \cdot \frac{1.25\ m}{20\ f} \simeq 10\ GHz$

$R_{gd} = R_{sig} = 10\ K$

$R_{gs} = \frac{R_{sig} + R'_L}{1 + g_m \cdot R'_L} = \frac{10\ K + 10\ K}{1 + 1.25 \times 10}$

$= 1.48\ k\Omega$

Ex:8.28

$$f_Z = \frac{1}{2\pi \cdot C_{SS} \cdot R_{SS}}$$

$$= \frac{1}{2\pi \cdot (0.4\ \text{p})25\ \text{K}} = 15.9\ \text{MHz}$$

Ex:8.29 For a loaded bipolar differential amplifier:

$$A_d = \frac{1}{2} g_m \cdot r_O$$

where,

$$g_m = \frac{I/2}{V_T} = \frac{0.5\ \text{mA}}{25\ \text{mV}} = 20\ \text{mA/V}$$

$$r_O = \frac{V_A}{I/2} = \frac{100\ \text{V}}{0.5\ \text{mA}} = 200\ \text{k}\Omega$$

$$\Rightarrow A_d = \frac{1}{2} \times 20\ \frac{\text{mA}}{\text{V}} \times 200\ \text{k}\Omega$$

$$= 2000\ \text{V/V}$$

The dominant pole is set by the output load capacitance

$$f_z = \frac{1}{2\pi \cdot C_L (r_{O2} \| r_{O4})}$$

$$= \frac{1}{2\pi \times 2\ \text{pF} \times (200\ \text{K} \| 200\ \text{K})\Omega}$$

$$= 0.796\ \text{MHz} \simeq 0.8\ \text{MHz}$$

Ex:8.30 (a)

$$A_M = -g_m \times R'_L = -g_m(R_L \| r_o)$$

$$A_M = -2\ \frac{\text{mA}}{\text{V}} \times (20\ \text{k}\Omega \| 20\ \text{k}\Omega) = -20\ \frac{\text{V}}{\text{V}}$$

To calculate τ_H using the method of open-circuit time-constants we can employ Eq (8.84

$$\tau_H = C_{gs} \cdot R_{sig} + C_{gd}[R_{sig}(1 + g_m R'_L) + R'_L] + C_L \cdot R'_L$$

$$\tau_H = 20\ \text{f} \times 20\ \text{K} + 5\ \text{f}[20\ \text{K}(1 + 20) + 10\ \text{K}] + 5\ \text{f} \times 10\ \text{K}$$

$$\tau_H = 2.6\ \text{ns} \Rightarrow f_H = \frac{1}{2\pi\tau_H} = 61.2\ \text{MHz}$$

The gain-bandwidth product is:

$$\text{GBP} = 20 \times 61.2\ \text{M} = 1.22\ \text{GHz}$$

(b) With source degeneration of $R_S = \frac{2}{g_m}$

$$R_O = r_O[1 + g_m R_S] = 3 r_O$$

$$R_O = 3 \times 20\ \text{k}\Omega = 60\ \text{k}\Omega$$

$$A_M = -g_m r_O \times \frac{R_L}{R_L + R_O} = -2 \times 20 \times \frac{20}{20 + 60} = -10\ \frac{\text{V}}{\text{V}}$$

$$G_m = \frac{g_m}{1 + g_m R_S} = \frac{g_m}{1 + 2} = \frac{g_m}{3} = \frac{2}{3}\ \frac{\text{mA}}{\text{V}}$$

Using Eq 8.153 to 8.157 we have:

$$R'_L = R_L \| R_O = 20\ \text{K} \| 60\ \text{K} = 15\ \text{k}\Omega$$

$$R_{gd} = R_{sig}(1 + G_m R'_L) + R'_L = 235\ \text{k}\Omega$$

$$R_{gs} \simeq \frac{R_{sig} + R_S}{1 + g_m R_S \times \dfrac{r_O}{r_O + R_L}} = \frac{R_{sig} + R_S}{1 + 2 \times \dfrac{20}{20 + 20}}$$

$$= \frac{R_{sig} + R_S}{2}$$

$$R_S = \frac{2}{g_m} = 1\ \text{k}\Omega \Rightarrow R_{gs} = \frac{20 + 1}{2} = 10.5\ \text{k}\Omega$$

$$\tau_H = C_{gs} R_{gs} + C_{gd} \cdot R_{gd} + C_L R'_L$$

$$= 20\ \text{f}(10.5\ \text{K} + 5\ \text{f} \times 235\ \text{K} + 5\ \text{f} \times 15\ \text{K})$$

$$\tau_H = 1.46\ \text{ns} \Rightarrow f_H = \frac{1}{2\pi\tau_H} = 109\ \text{MHz}$$

$$GBP = 10 \times 109\ \text{MHz} \simeq 1.1\ \text{GHz}$$

Ex:8.31

$$R_{in} = (\beta_1 + 1)(r_{e1} + r_{e2})$$

Since in this case $r_{e1} = r_{e2} = r_e$ and $\beta_1 = \beta_2 = \beta$ we have

$$R_{in} = r_\pi + r_\pi = 2 r_\pi = \frac{2\beta V_T}{I_C} \simeq 10\ \text{k}\Omega$$

we have:

$$\frac{V_O}{V_{Sig}} = \frac{1}{2}\left(\frac{R_{in}}{R_{in} + R_{Sig}}\right) g_m R_L$$

$$\frac{V_O}{V_{Sig}} = \frac{1}{2}\left(\frac{10}{10 + 10}\right) \frac{V_T}{I_C} R_L = 50\ \frac{\text{V}}{\text{V}}$$

we have:

$$f_{P1} = \frac{1}{2\pi\left(\dfrac{C_\pi}{2} + C_\mu\right)(R_{sig} \| 2 r_\pi)}$$

$$f_{P1} = \frac{1}{2\pi\left(\dfrac{6\ \text{pF}}{2} + 2\ \text{pF}\right)(10\ \text{K} \| 10\ \text{K})}$$

$$\simeq 6.4\ \text{MHz}$$

we have:

$$f_{P2} = \frac{1}{2\pi C_\mu R_L} = \frac{1}{2\pi \times 2\ \text{pF} \times 10\ \text{K}}$$

$$\simeq 8\ \text{MHz}$$

Therefore, the transfer function of this CC-CB amplifier is:

$$A(s) = \frac{A_M}{\left(1 + \dfrac{s}{2\pi f_{P1}}\right)\left(1 + \dfrac{s}{2\pi f_{P2}}\right)}$$

$$|A(s)|_{s = j\omega_H} = \frac{|A_M|}{\sqrt{2}} \text{ or } |A(s)|^2_{s = j\omega_H} = \frac{A_M^2}{2}$$

Thus:

$$\frac{A_M^2}{\left(1+\frac{(2\pi f_M)^2}{(2\pi f_{P1})^2}\right)\left(1+\frac{(2\pi f_M)^2}{(2\pi f_{P2})^2}\right)} = \frac{A_M^2}{2}$$

$$\left(1+\frac{f_M^2}{f_{P1}^2}\right)\left(1+\frac{f_M^2}{f_{P2}^2}\right) = 2$$

Solving this equation for f_H we have:

$f_H \simeq 4.6$ MHz

Using the approximate formula, we have:

$$f_H \simeq \frac{1}{\sqrt{\frac{1}{f_{P1}^2}+\frac{1}{f_{P2}^2}}} \simeq 5 \text{ MHz}$$

Ex:8.32 From Eq 8.178

$$\omega_t = \frac{G_{m1}}{C_C} \text{ from Example 7.4}$$

$$G_{m1} = G_{m1,2} = 0.3 \text{ mA/V}$$

thus, for $f_T = 10$ MHz:

$$C_C = \frac{0.3 \text{ mA/V}}{2\pi \times 10 \times 10^6} = 4.8 \text{ pF}$$

From Eqn. (8.173

$$f_Z = \frac{G_{m2}}{2\pi \cdot C_C} \quad G_{m2} = g_{m6} = 0.6 \text{ mA/V}$$

$$\Rightarrow f_Z = \frac{0.6 \text{ mA/V}}{2\pi \times 4.8 \text{ pF}} = 20 \text{ MHz}$$

From Eqn. (8.177

$$f_{P2} = \frac{G_{m2}}{2\pi \cdot C_2} = \frac{0.6 \text{ mA/V}}{2\pi \times 2 \text{ pF}} = 48 \text{ MHz}$$

Ex:8.33 To obtain Req:

$$\text{Req} = R_2 \parallel r_{O2} \parallel r_{\pi 5}$$

$$R_2 = 20 \text{ k}\Omega$$

$$r_{O2} = \frac{V_A}{I_{C2}} \simeq \frac{100 \text{ V}}{0.25 \text{ mA}} = 400 \text{ k}\Omega$$

$$r_{\pi 5} = (\beta+1)\frac{V_T}{I_5} = 101 \times \frac{25 \text{ mV}}{1 \text{ mA}}$$

$$= 2525 \ \Omega$$

Thus,

$$\text{Req} = 20 \text{ K} \parallel 400 \text{ K} \parallel 2525 = 2.2 \text{ k}\Omega$$

To obtain Ceq :

$$Ceq = C_{\mu 2} + C_{\pi 5} + C_{\mu 5}(1 + g_{m5}R_{L5})$$

$$C_{\mu 2} = C_{\pi 5} = 2 \text{ pF}$$

$$R_{L5} \simeq R_3 = 3 \text{ k}\Omega$$

$$g_{m5} = \frac{I_5}{V_T} = \frac{1 \text{ mA}}{25 \text{ mV}} = 40\frac{\text{mA}}{\text{V}}$$

$$C_{\pi 5} + C_{\mu 5} = \frac{g_{m5}}{2\pi f_T}$$

$$\Rightarrow C_{\pi 5} = \frac{40 \text{ m}}{2\pi \times 400 \text{ m}} - 2 \text{ p} = 14 \text{ pF}$$

thus,

$$Ceq = 2 \text{ pF} + 14 \text{ pF} + 2 \text{ pF}(1 + 40 \times 3)$$

$$= 258 \text{ pF}$$

Finally,

$$f_P = \frac{1}{2\pi \cdot Req \cdot Ceq}$$

$$= \frac{1}{2\pi \times 2.2 \text{ K} \times 258 \text{ p}}$$

$$= 280 \text{ KHz}$$

Ex:9 . 1 (c) $A = 100$ V/V and $A_f = 10$ V/V

$$A_f = \frac{A}{1+\beta A} \Rightarrow \beta = \frac{1}{A_f} - \frac{1}{A} = \frac{1}{10} - \frac{1}{100} = 0.09$$

$\beta = 0.09$

since: $1 + \frac{R_2}{R_1} = \frac{1}{\beta}$

$$\Rightarrow \frac{R_2}{R_1} = \frac{1}{0.09} - 1 = 10.11$$

(d) The amount of feed-back is:
$1 + A\beta = 1 + 100 \times 0.09 = 10$ which is 20 dB
(e) For $V_S = 1$ V; $V_O = A_f V_S = 10 \times 1 = 10$ V

$$V_f = \beta \cdot V_O = 0.09 \times 10 = 0.9 \text{ V}$$

$$V_i = \frac{V_O}{A} = \frac{10}{100} = 0.1 \text{ V}$$

(f) If A decreases by 20%:
$A = 0.8 \times 100 = 80$ V/V

$$A_f = \frac{80}{1 + 80 \times 0.09} = 9.7561$$

$\Delta A_f = 10 - 9.7561 \rightarrow 2.44\%$ of $A_f = 10$

Ex:9 . 2 (c) $A = 10^4$ V/V and $A_f = 10^3$

$$A_f = \frac{A}{1+\beta A} \Rightarrow \beta = \frac{1}{A_f} - \frac{1}{A} = \frac{1}{10^3} - \frac{1}{10^4}$$

$= 9 \times 10^{-4}$

$$\Rightarrow \frac{R_2}{R_1} = \frac{1}{\beta} - 1 = 110.1$$

(d) The amount of feed-back is:
$1 + A\beta = 1 + 10^4 \times 9 \times 10^{-4} = 10$ which is 20 dB
(e) For $V_S = 0.01$ V:

$$V_O = A_f \cdot V_S = 10^3 \times 0.01 = 10 \text{ V}$$

$$V_f = \beta \cdot V_O = 9 \times 10^{-4} \times 10 = 0.009 \text{ V}$$

$$V_i = \frac{V_O}{A} = \frac{10}{10^4} = 0.001 \text{ V}$$

Ex:9 . 3 $\frac{dA_f}{A_f} = 0.1\%$ and $\frac{dA}{A} = 10\%$

$$\frac{dA_f}{A_f} = \left(\frac{1}{1+A\beta}\right) \cdot \frac{dA}{A} \Rightarrow 0.01 = \frac{1}{1+A\beta}$$

$A_f = \frac{A}{1+A\beta}$ and the largest close-loop gain possible occurs when $A = 1000$ V/V

$\Rightarrow A_f = 0.01 \times 1000 = 10$ V/V

If three of these amplifiers are cascaded:
$A_{TOT} = A_{f1} \times A_{f2} \times A_{f3} = 1000$ V/V and the total variability is:

$$\frac{dA_1}{A_1} + \frac{dA_2}{A_2} + \frac{dA_3}{A_3} = 0.3\% \text{ maximum}$$

Ex:9 . 4 For Example 7.1
$A_O \approx 6000$, $\beta = 10^{-3}$

$(1 + A\beta) = (1 + (6 \times 10^3) \times 10^{-3}) = 7$

$\therefore f_{Hf} = f_H(1 + A\beta) = 1 \times 7 = 7$ kHz

Ex:9 . 5

$$V_o = V_s\frac{A_1A_2}{1+A_1A_2\beta} + V_n\frac{A_1}{1+A_1A_2\beta} = V_{sf} + V_{nf}$$

$$= \frac{(1 \times 100) \times V_S}{1 + (100 \times 1) \times 1} + \frac{1 \times V_n}{1 + (100 \times 1) \times 1}$$

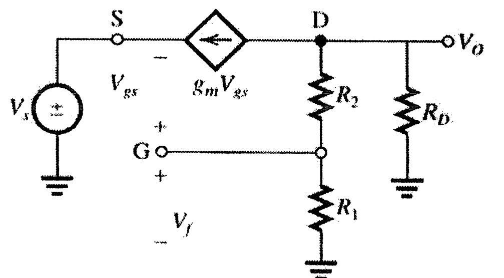
$= 0.99 + 0.0099$

Thus, $V_{sf} \approx 1$ V and $V_{nf} \approx 0.01$ V

New S/N ratio $= 100/1$

an improvement of $20 \log(100/1) = 40$ dB

Ex:9 . 6 Replacing the amplifier by its small signal model



Open-loop gain: without R_2 and R_1 ang the gate grounded:

$V_O = -g_m V_{gs} \times R_D$

$V_{gs} = -V_S \Rightarrow A = g_m R_D$

Feed-back factor:

$$\beta = \frac{V_f}{V_O} \Rightarrow V_f = \frac{R_1}{R_1 + R_2} \cdot V_O \rightarrow \beta = \frac{R_1}{R_1 + R_2}$$

Closed-loop gain A_f

$$A_f = \frac{V_O}{V_S}$$

$$V_O = -g_m V_{gs} \times \{(R_1 + R_2) \parallel R_D\}$$

$$= -g_m V_{gs} \cdot \frac{(R_2 + R_1)R_D}{R_2 + R_1 + R_D}$$

but $R_2 + R_1 >> R_D$ $\;R_2 + R_1 + R_D \simeq R_2 + R_1$

$$\rightarrow V_O = \left(-g_m V_{gs} \cdot \frac{(R_2 + R_1)R_D}{R_2 + R_1}\right)$$

$$= -g_m V_{gs}, R_D$$

$$-V_{gs} = V_S - V_f = V_S - \frac{R_1 V_O}{R_1 + R_2}$$

$$\Rightarrow V_O = g_m R_D \left\{ V_S - \frac{R_1 V_O}{R_1 + R_2} \right\}$$

$$\Rightarrow V_O \left\{ 1 + \frac{g_m R_D R_1}{R_1 + R_2} \right\} = g_m R_D V_S$$

Thus:

$$A_f = \frac{V_O}{V_S} = \frac{g_m R_D}{1 + g_m R_D R_1 / (R_1 + R_2)}$$

if $A \cdot \beta >> 1 \Rightarrow (g_m R_D) \cdot R_1 / (R_1 + R_2) >> 1$

$$A_f = \frac{g_m R_D}{g_m R_D R_1 / (R_1 + R_2)} = \frac{R_1 + R_2}{R_1}$$

$$= 1 + \frac{R_2}{R_1}$$

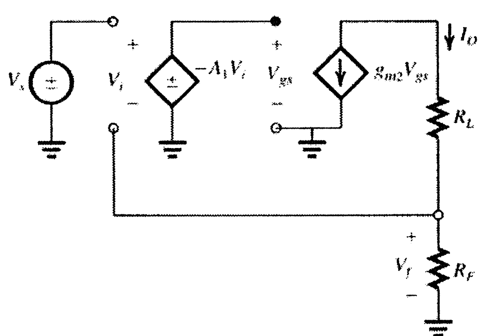
Ex:9.7 From Example 9.2 we know that:

$$A_f = \frac{-g_{m2} R_D}{1 + \dfrac{g_{m2} R_D}{1 + \dfrac{R_F}{R_M}}}$$ where $-g_{m2} R_D$ is the open-loop gain

if loop-gain $A\beta >> 1 \Rightarrow \dfrac{g_{m2} R_D}{1 + \dfrac{R_F}{R_M}} >> 1$

thus: $A_f \cong \dfrac{-g_{m2} R_D}{\dfrac{g_{m2} R_D}{\left(1 + \dfrac{R_F}{R_M}\right)}} \cong -\left(1 + \dfrac{R_F}{R_M}\right)$

Ex: 9.8 The equivalent small-signal model for Fig 9.10 b) is:



Open-loop gain: $V_s \equiv V_i$

$I_o = -g_{m2} V_{gs}$, and $V_{gs} = -A_1 V_i$

$$\Rightarrow I_o = g_{m2}(A_1 V_i) \rightarrow A = \frac{I_o}{V_i} = A_1 g_{m2}$$

$$\beta = \frac{V_f}{I_O}$$

$$V_f = I_O \cdot R_f \rightarrow \frac{V_f}{I_O} = R_f \Rightarrow \beta = R_f$$

Closed-loop gain: $A_f = \dfrac{I_O}{V_S}$

$I_O = A_1 g_{m2} V_i$ and $V_i = V_S - V_F$

$I_O = A_1 g_{m2}\{V_S - V_f\} = A_1 g_{m2}\{V_S - I_O R_F\}$

$\Rightarrow I_O(1 + R_F A_1 g_{m2}) = A_1 g_{m2} \cdot V_S$

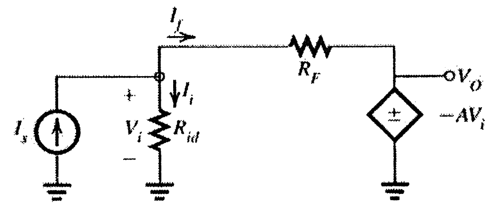
$A_f = \dfrac{I_O}{V_S} = \dfrac{A_1 g_{m2}}{1 + R_F A_1 g_{m2}}$ which is the same as $A_f = \dfrac{A}{1 + \beta A}$

If $A\beta >> 1 \Rightarrow R_F A_1 g_{m2} >> 1$ and

$$A_f \simeq \frac{A_1 g_{m2}}{R_F A_1 g_{m2}}$$

$$\rightarrow A_f \simeq \frac{1}{R_F}$$

Ex:9.9 The equivalent small-signal circuit for Fig 9.11b)



$$V_O = -AV_i \rightarrow V_i = \frac{-V_O}{A}$$

$$I_S = I_i + I_f \qquad I_i = \frac{V_i}{R_{id}} = \frac{-V_O}{AR_{id}} \qquad (1)$$

$$I_f = \frac{V_i - V_O}{R_F} = \frac{-V_O}{AR_F} - \frac{V_O}{R_F}$$

$$= -V_O\left(\frac{1}{AR_F} + \frac{1}{R_F}\right) \qquad (2)$$

$$(1) + (2): I_S = -V_O\left\{\frac{1}{AR_{id}} + \frac{1}{AR_F} + \frac{1}{R_F}\right\}$$

$$= \frac{-V_O}{R_F}\left\{\frac{1}{AR_{id}} + \frac{1}{A} + 1\right\}$$

$$\Rightarrow \frac{V_O}{I_S} = \frac{-R_F}{\left(1 + \dfrac{1}{A} + \dfrac{R_F}{AR_{id}}\right)}$$

if $A >> 1$ and $AR_{id} >> R_F$

$$\Rightarrow 1 + \frac{1}{A} + \frac{R_F}{AR_{id}} \simeq 1 \text{ and } A_f \simeq -R_F$$

Ex: 9.10

From Example 7.1

$A_0 \approx 6000,\ \beta = 10^{-3}$

$(1 + A\beta) = (1 + (6 \times 10^3) \times 10^{-3}) = 7$

$\therefore f_{Hf} = f_H(1 + A\beta) = 1 \times 7 = 7\ \text{kHz}$

Ex: 9.11

$I_{E1} = I_{E2} = 0.5\text{mA}$

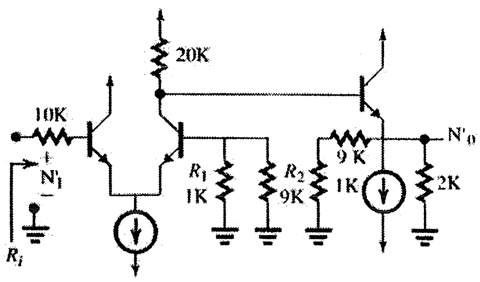
$V_{C2} = 10.7 - 0.5 \times 20 = +0.7v$

$V_o = 0.7 - V_{BE3} = 0$

$I_{E3} = 5\ \text{mA}$

$r_{e1} = r_{e2} = V_A / I = 50\Omega,\ r_{e3} = 5\Omega$

A-Circuit:



$$A = \frac{V_o'}{V_1'} = \frac{[20 \| (\beta_2 + 1)(r_{e3} + 2 \| 10)]}{r_{e1} + r_{e2} + \dfrac{10}{\beta_1 + 1} + \dfrac{(1 \| 9)}{\beta_2 + 1}} \times$$

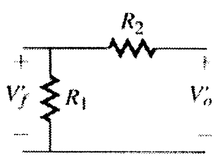
$$\frac{(2 \| 10)}{r_{e3} + (2 \| 10)} = 85.7\ \text{V/V}$$

$R_i = R_S + (\beta + 1)(r_{e1} + r_{e2}) + R_E \| R_4$

$= 10 + 101(50 + 50) + (1 \| 9) = 21\ \text{k}\Omega$

$$R_0 = 2 \| 10 \| \left[r_{e3} + \frac{20}{\beta_2 + 1}\right] = 181\ \Omega$$

B-Circuit:



$\beta = V_f' / V_o'$

$$= \frac{1}{9 + 1} = 0.1\text{V/V}$$

$$A_f = \frac{V_o}{V_S} = \frac{A}{1 + A\beta} = \frac{85.7}{1 + 85.7 \times 0.1} = 8.96\text{V/V}$$

$R_{if} = R_i(1 + A\beta) = 21 \times 9.57 = 201\ \text{k}\Omega$

$R_{iN} = R_{if} - R_S = 201 - 10 = 191\ \text{k}\Omega$

$$R_{of} = (R_{out} \| R_L) = \frac{R_o}{1 + A\beta} = \frac{181}{9.57} = 18.8\ \Omega$$

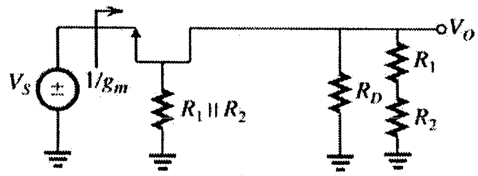
$\Rightarrow R_{out} = 19.1\ \Omega$

Ex: 9.12 The feed-back network is composed of the voltage-driver resistors R_1 and R_2

a) The loading effect of the feed-back network at the input is: $R_1 \| R_2$

b) The loading effect of the feed-back network at the output is: $R_1 + R_2$

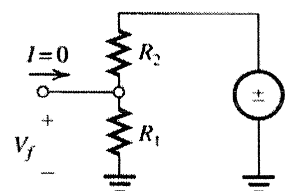
The A circuit is:



For the *CG* amplifier:

$A = g_m[R_D \| (R_1 + R_2)]$

To obtain β:



$$\beta = \frac{V_F}{V_O} = \frac{R_1}{R_1 + R_2}$$

$$A_f = \frac{A}{1 + A\beta}\ \text{Substituting:}$$

$$A_f = \frac{g_m R_D}{1 + \dfrac{R_D(1 + g_m R_1)}{R_1 + R_2}}$$

if $R_1 + R_2 >> R_D$ we obtain the same result as in Exercise 10.6

From the A circuit:

$$R_i = 1/g_m \Rightarrow R_{in} = \frac{1}{g_m}(1 + A\beta)$$

$$R_D = R_D \| (R_1 + R_2) \Rightarrow R_{out} = \frac{(R_D \| R_1 + R_2)}{1 + A\beta}$$

(c) $R_i = R_S \parallel R_F$

Following the procedure used in Example 9.7

$$R_{if} = \frac{R_i}{1 + A\beta} \Rightarrow \frac{1}{R_{if}} = \frac{1}{R_i} + \frac{A\beta}{R_i}$$

$$\frac{1}{R_{if}} = \frac{1}{R_i} + \frac{(R_S \parallel R_F)g_m(r_O \parallel R_F)}{(R_S \parallel R_F) \cdot R_F}$$ if we cal

$$\mu' = g_m(r_O \parallel R_F)$$

$$\Rightarrow \frac{1}{R_{if}} = \frac{1}{R_i} + \frac{\mu'}{R_F} \text{ or } R_{if} = R_i \parallel \frac{R_F}{\mu'}$$

Substituting for $R_i = R_S \parallel R_F$:

$$R_{if} = R_S \parallel R_F \parallel \frac{R_F}{\mu'}$$

$$= R_S \parallel \frac{R_F}{(1 + \mu')}$$

Since

$$R_{if} = R_S \parallel R_{in} \rightarrow R_{in} = \frac{R_F}{1 + \mu'}$$

$$= \frac{R_F}{1 + g_m(r_O \parallel R_F)}$$

(d) $R_O = r_O \parallel R_F$

Following the procedure used in Example 9.7

$$R_{of} = \frac{R_O}{1 + A\beta} \Rightarrow \frac{1}{R_{of}} = \frac{1}{R_O} + \frac{A\beta}{R_O}$$

$$\frac{1}{R_{of}} = \frac{1}{R_O} + \frac{(R_S \parallel R_F)g_m(r_O \parallel R_F)}{R_F \cdot (r_O \parallel R_F)}$$ if we call

$$\mu' = g_m(R_S \parallel R_F)$$

$$R_{of} = R_O \parallel \frac{R_F}{\mu'}$$

Substituting for

$$R_O = r_O \parallel R_F: R_{of} = r_O \parallel R_F \parallel \frac{R_F}{\mu'}$$

$$R_{of} = r_O \parallel \frac{R_F}{1 + \mu'}$$

Since: $R_{of} = R_{out} \parallel R_L$ and $R_L = \infty$

$$\Rightarrow R_{out} = r_O \parallel \frac{R_F}{1 + g_m(R_S \parallel R_F)}$$

(e) For $g_m = 5\ \frac{\text{mA}}{\text{V}}$ $r_O = 20\ \text{k}\Omega$

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

$R_S = 1\ \text{k}\Omega$

$$A = -(1\text{ K} \parallel 10\text{ K}) \cdot 5\text{ m}(20\text{ K} \parallel 10\text{ K})$$
$$= -30.3\ \text{k}\Omega$$

$$\beta = -1/R_F = -1/10\text{ K} = -0.1\ \text{mA/V}$$

$$A\beta = -30.3 \times -0.1 = 3.03$$

$$A_f = \frac{A}{1 + A\beta} = \frac{-3.03\text{ K}}{1 + 3.03} = -7.52\ \text{k}\Omega$$

$$R_i = R_S \parallel R_F = 1 \parallel 10 = 909\ \Omega$$

$$R_O = r_O \parallel R_F = 20 \parallel 10 = 6.67\ \text{k}\Omega$$

$$R_{in} = \frac{10\text{ K}}{1 + 5\text{ m}(20\text{ K} \parallel 10\text{ K})} = 291\ \Omega$$

$$R_{if} = \frac{R_i}{1 + A\beta} = \frac{909}{4.03} = 225.6\ \Omega$$

$$R_{of} = \frac{R_O}{1 + A\beta} = \frac{6.67\text{ K}}{4.03} = 1.66\ \text{k}\Omega$$

$$R_{out} = 20\text{ K} \parallel \frac{10\text{ K}}{1 + 5\text{ m}(1\text{ K} \parallel 10\text{ K})} = 1.66\ \text{k}\Omega$$

Ex: 9.16 $\mu = 100$

$R_S = \infty$ $r_{O1} = 1\ \text{K}\Omega$ $R_1 = 10\ \text{K}\Omega$

$R_2 = 90\ \text{k}\Omega$ $g_m = 5\ \text{mA/V}$

$r_O = 20\ \text{k}\Omega$

Refer to Example 9.8

$R_i = 100\text{ K}$, unchanged

$$A = -\mu \cdot \frac{R_i}{R_1 \parallel R_2} = -100 \cdot \frac{100}{10 \parallel 90}$$

$$= -1.11 \times 10^3\ \text{A/A}$$

$\beta = -0.1\ \text{A/A}$, unchanged

$A\beta = 111$

$$A_f = \frac{-1.11 \times 10^3}{1 + 111} = -9.91\ \text{A/A}$$

$$R_{in} = \frac{90\text{ K}}{100} = 900\ \Omega$$

$R_O = 900\ \text{K}\Omega$, unchanged

$R_{out} = (1 + 111).\ 900\text{ K} = 100\ \text{M}\Omega$

Ex: 9.17 If $R_1 = 0 \Rightarrow \beta = \frac{R_1}{R_1 + R_2} = -1$

All of I_O is fed-back.

$\Rightarrow$ if $A\beta \gg 1 \rightarrow$ ideal

$$A_f = -\frac{1}{\beta} = 1\ \text{A/A}$$

$$R_i = R_S \parallel R_{id} \parallel R_1 = \infty \parallel \infty \parallel R_1 = R_1$$

$$R_O = r_{O2} + (R_1 \parallel 0) + g_m r_{O2}(R_1 \parallel 0) = r_{O2}$$

Replacing R_2 for 0 in Eq 9.69

$$A = \frac{-\mu R_i r_{o2}}{\frac{1}{g_m} \times r_{o2}} = -\mu g_m R_i = -\mu g_m R_1$$

$$A_f = \frac{A}{1 + A\beta} = \frac{-\mu \cdot g_m \cdot R_1}{1 + \mu g_m \cdot R_1}.$$

From Eq 9.77

$$R_{out} = \mu \cdot \frac{R_1}{R_1} \cdot g_m r_{o2} \cdot R_1 = \mu g_m r_{o2} \cdot R_1$$

To obtain R_{in}:

$$R_{if} = \frac{R_i}{1 + A\beta} = \frac{R_1}{1 + \mu g_m R_1}$$

$$R_{in} = \frac{1}{\frac{1}{R_{if}} - \frac{1}{R_S}}$$

$$R_S = \infty \rightarrow R_{in} = \frac{R_1}{1 + \mu g_m R_1} = \frac{1}{\frac{1}{R_1} + \mu g_m}$$

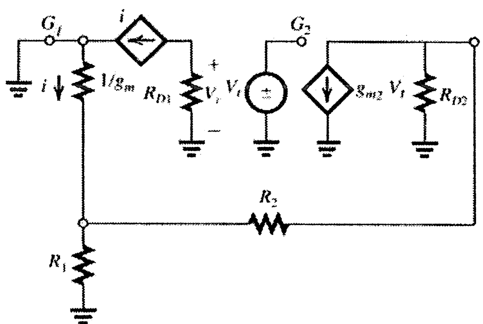
Since $\mu g_m \gg \frac{1}{R_1} \Rightarrow R_{in} = 1/\mu g_m$

Ex:9.18 Small-signal equivalent circuit:

$$\frac{-V_r}{V_t} = \frac{g_{m2} \cdot R_{D2}}{R_{D2} + R_2 + R_1 \parallel 1/g_{m1}} \cdot \left(\frac{R_1}{R_1 + 1/g_{m1}}\right) \cdot R_{D1}$$

$$A\beta = \frac{4\text{ m} \times 10\text{ K}}{(10\text{ K} + 9\text{ K} + 1\text{ K} \parallel 1/4\text{ m})} \cdot \left(\frac{1\text{ K}}{1\text{ K} \parallel 1/4\text{ m}}\right) \cdot 10\text{ K} = 16.66$$

Compared to 17.39 obtained in Example 9.4



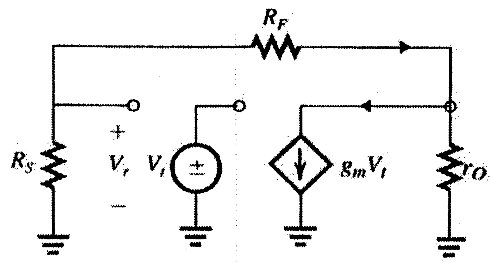
Ex 9.19

$$V_x = \frac{-g_m r_o}{r_o + R_F + R_S} \cdot R_S \cdot V_t$$

$$\frac{-V_x}{V_t} = A\beta = \frac{g_m r_o}{r_o + R_F + R_S} \cdot R_S$$

$$A\beta = \frac{5\text{ m} \times 20\text{ K} \times 1\text{ K}}{20\text{ K} + 10\text{ K} + 1\text{ K}} = 3.22$$

as compared to 3.03 obtained in Exercise 9.15



Ex 9.20 $A(j\omega) = \left(\frac{10}{1 + j\omega/10^4}\right)^3$

Thus $\phi = -3\tan^{-1}(\omega/10^4)$

At $\omega_{180°}, \phi = 180° \Rightarrow \tan^{-1}(\omega_{180°}/10^4) = 60°$

$(\omega_{180}/10^4) = \sqrt{3} \Rightarrow \omega_{180} = \sqrt{3} \times 10^4$ rad|s

Amplifier stable if $|A\beta| < 1$ at $\omega_{180°}$

When $|A\beta| = 1$: $\beta_{cr} = \frac{1}{|A(j\omega_{180})|}$

$$\therefore \beta_{cr} = \frac{1}{1000/(1 + (\sqrt{3})^2)^{3/2}} = 0.008$$

Ex:9.21 Pole is shifted by factor $(1 + A_o\beta)$

$= 1 + 10^5 \times 0.01 = 1001$

$f_{pf} = f_p(1 + A_o\beta) = 100 \times 1001 = 100.1\text{kHz}$

For closed loop gain = 1, $\beta = 1$

$f'_{pf} = f'_p(1 + A_o\beta) = 10^5(1001) = 10^7$ Hz

Ex:9.22 From Eq. 9.92 Poles will coincide when

$(\omega_{P1} + \omega_{P2})^2 - 4(1 + A_o\beta)\ \omega_{P1}\omega_{P2} = 0$

Using

$A_o = 100,\ \omega_{P1} = 10^4,\ \omega_{P2} = 10^6$ rad|s

$(10^4 + 10^6)^2 - 4(1 + 100\beta) \times 10^{10} = 0$

$1 + 100\beta = (1.01)^2 \times 100/4$

$\Rightarrow \beta = 0.245$

Corresponding $Q = 0.5$

For maximally flat response $Q = 0.707$ and

$$\frac{1}{\sqrt{2}} = \frac{\sqrt{(1 + 100\beta) \times 10^{10}}}{10^4 + 10^6} \Rightarrow \beta = 0.5$$

Corresponding gain is

$$A = \frac{A}{1 + A_o\beta} = \frac{100}{1 + 100 \times 0.5} = 1.96\ \text{V/V}$$

Ex9.23 Closed loop poles are found using

$$1 + A(s)\beta = 0$$

$$1 + \frac{10^3}{(1 + S/10^4)^3}\beta = 0$$

$$(1 + S/4)^3 + 10^3\beta = 0$$

$$\frac{S^3}{10^{12}} + \frac{3S^2}{10^8} + \frac{3S^1}{10^4} + (1 + 100\beta) = 0$$

$$= S_n^3 + 3S_n + 3S_n + (1 + 100\beta) = 0 \text{ for}$$

$$S_n = \frac{S}{10^4}$$

Roots of this cubic equation are:

$$(-1 - 10\beta^{1/3}), -1 + 5\beta^{1/3} \pm j\,5\sqrt{3}\beta^{1/3}$$

Amplifier becomes unstable when complex poles are on $j\omega$ axis ie. when $\beta = \beta_{cr}$

$$10\beta_{cr}^{1/3} = \frac{1}{\cos 60^\circ} = 2 \Rightarrow \beta_{cr} = 0.008$$

Ex: 9.24 $A = \dfrac{A_O}{1 + j\dfrac{\omega}{\omega_p}} = \dfrac{A_O}{1 + j\,f/f_p}$

$$= \frac{10^5}{1 + j\,f/10}$$

$$\beta = 0.01 \quad |A\beta| = \frac{10^5 \times 0.01}{\sqrt{1 + f^2/100}} = 1$$

thus $1 + f^2/100 = 10^6 \Rightarrow f = 10^4$ Hz

At $f = 10^4$ Hz

$$\phi = -\tan^{-1}(10^4/10) \approx -90^\circ$$

making phase margin $180 - 90 = 90^\circ$

Ex:9.25 From Eqn 9.105

$|A_f(j\omega_2)| = \dfrac{1/\beta}{|1 + e^{-j\theta}|}$ and $\dfrac{1}{\beta} \approx$ low frequency gain $\theta = 180^\circ -$ Phase margin

For $PM = 30^\circ, \theta = 150^\circ$

$$|A_f(j\omega_1)| / (1/\beta) = 1.93$$

For $PM = 60^\circ, \theta = 120^\circ$

$$|A_f(j\omega_2)| / (1/\beta) = 1.0$$

For $PM = 90^\circ,\ \theta = 90^\circ$

$$|A_f(j\omega_{ar})| / (1/\beta) = 0.707$$

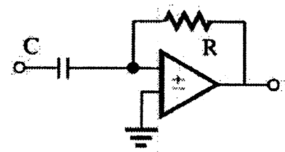
Ex:9.26 $\beta = \dfrac{1/SC}{R + 1/SC} = \dfrac{1}{1 + SCR}$

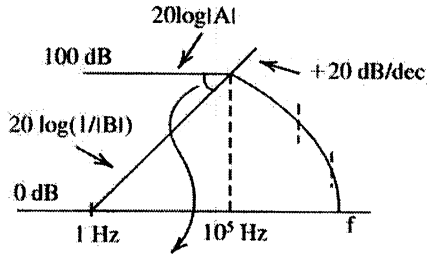
$$\left|\frac{1}{\beta}\right| = \sqrt{1 + (\omega CR)^2}$$

$$\therefore \frac{1}{2\pi CR} \leq 1 \text{ Hz}$$

$$CR \leq \frac{1}{2\pi}$$

Thus $CR \geq 0.1595$.



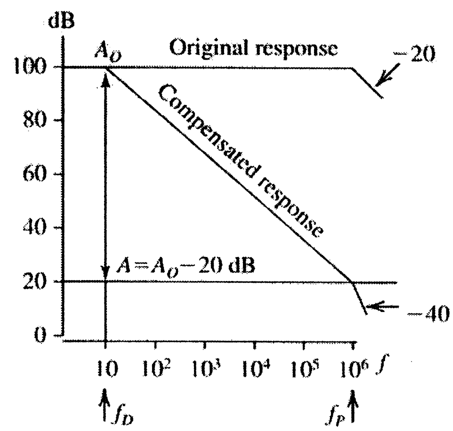


Rate of closure = 20 dB/dec

Ex:9.27 Must place new dominant pole at

$$f_D = \frac{f_P}{A} = \frac{10^6}{10^4}$$

$\therefore f_D = 100$ Hz



Ex: 9.28 The pole must be moved f_{P1} to f_D where

$$f_D = \frac{\text{Frequency of 2nd pole}}{A_O \div A_F}$$

$$= \frac{10 \times 10^6}{10^4} \quad \leftarrow (100 \text{ dB} - 20 \text{ db})$$

$$= 10^3 \text{ Hz}$$

The capacitance at the controlling node must be increased by same factor as f is lowered.

$\therefore C_{new} = C_{old} \times 1000$

Ex 13.1

For Q_1

$$I = \frac{V_{CC} - V_{CEsat}}{R_L} = \frac{15 - 0.2}{1\ k\Omega}$$

$I = 14.8$ mA

$$R = \frac{-V_D - (-V_{CC})}{14.8} = \frac{-0.7 - (-15)}{14.8}$$

$= 0.97\ k\Omega$

$v_{omax} = V_{CC} - V_{CEsat}$
$= 15 - 0.2$
$= 14.8$ V

$v_{omin} = -V_{CC} + V_{CEsat}$
$= -15 + 0.2$
$= -14.8$

Output signal swing is from 14.8 V to −14.8 V

Maximum emitter current $= 2I = 2 \times 14.8$
$= 29.6$ mA

Ex 13.2

At $v_o = -10$ V, the load current is −10 mA and the emitter current of Q_1 is $14.8 - 10 = 4.8$ mA.

Thus, $v_{BE1} = 0.6 + 0.025 \ln\left(\frac{14.8}{1}\right)$

$= 0.64$ V

Thus, $v_I = -10 + 0.64 = -9.36$ V

At $v_o = 0$ V, $i_L = 0$ and $i_{E1} = 14.8$ mA

Thus, $v_{BE1} = 0.6 + 0.025 \ln\frac{4.8}{1}$

$= 0.67$ V

$v_I = +0.67$ V

At $v_o = +10$ V, $i_L = 10$ mA and $i_{E1} = 24.8$ mA

Thus, $v_{BE1} = 0.6 + 0.025 \ln(24.8)$

$= 0.68$ V

$v_I = 10.68$ V

To calculate the incremental voltage gain we use

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + r_{e1}}$$

At $v_o = -10$ V, $i_{E1} = 4.8$ mA and

$$r_{e1} = \frac{25}{4.8} = 5.2\ \Omega$$

Thus, $\frac{v_o}{v_i} = \frac{1}{1 + 0.0052} = 0.995$ V / V

Similarly, at $v_o = 0$ V, $r_{e1} = \frac{25}{14.8} = 1.7\ \Omega$

and, $\frac{v_o}{v_i} = \frac{1}{1 + 0.0017} = 0.998$ V / V

At $v_o = +10$ V, $i_{E1} = 24.8$ mA and $r_{e1} = 1\ \Omega$

Thus, $\frac{v_o}{v_i} = \frac{1}{1 + 0.001} = 0.999$ V / V

Ex 13.3

a. $P_L = \frac{(\hat{V}_o/\sqrt{2})^2}{R_L} = \frac{(8/\sqrt{2})^2}{100} = 0.32$ W

$P_s = 2V_{cc} \times I = 2 \times 10 \times 100 \times 10^{-3}$
$= 2$ W

Efficiency $\eta = \frac{P_L}{P_S} \times 100$

$= \frac{0.32}{2} \times 100$

$= 16\%$

Ex 13.4

(a) $P_L = \frac{1}{2}\frac{\hat{V}_o^2}{R_L}$

$= \frac{1}{2}\frac{(4.5)^2}{4} = 2.53$ W

(b) $P_+ = P_- = V_{CC} \times \frac{1}{\pi}\frac{\hat{V}_o}{R_L}$

$= 6 \times \frac{1}{\pi} \times \frac{4.5}{4} = 2.15$ W

(c) $\eta = \frac{P_L}{P_S} \times 100 = \frac{2.53}{2 \times 2.15} \times 100$

$= 59\%$

(d) Peak input currents $= \frac{1}{\beta + 1}\frac{\hat{V}_o}{R_L}$

$= \frac{1}{51} \times \frac{4.5}{4}$

$= 22.1$ mA

(e) Using Eq. 10.22

$$P_{DNmax} = P_{DPmax} = \frac{V_{CC}^2}{\pi^2 R_L}$$

$$= \frac{6^2}{\pi^2 \times 4} = 0.91\ W$$

Ex 13.5

(a) The quiescent power dissipated in each transistor $= I_Q \times V_{cc}$

Total power dissipated in the two transistors
$= 2I_Q \times V_{cc}$
$= 2 \times 2 \times 10^{-3} \times 15$
$= 60$ mW

(b) I_Q is increased to 10 mA

At $V_o = 0$, $i_N = i_P = 10$ mA

From equation 13.31

$$R_{out} = \frac{V_T}{i_P + i_N} = \frac{25}{10 + 10} = 1.25\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{out}} = \frac{100}{100 + 1.25}$$

$\frac{v_o}{v_i} = 0.988$ at $v_o = 0$ V

At $v_o = 10$ V,

$$i_L = \frac{10\text{ V}}{100\ \Omega} = 0.1\text{ A} = 100\text{ mA}$$

use equation 13.27 to calculate i_N

$i_N^2 - i_N i_L - I_Q^2 = 0$

$i_N^2 - 100\, i_N - 10^2 = 0$

$\Rightarrow i_N = 99.99$ mA

using equation 13.26

$$i_P = \frac{I_Q^2}{I_N} \simeq 1\text{ mA}$$

$$R_{out} = \frac{V_T}{i_N + i_P} = \frac{25}{99.99 + 1} \simeq 0.2475\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{out}} = \frac{100}{100 + 0.2475} \simeq 1$$

$$\%\text{ change} = \frac{1 - 0.988}{1} \times 100 = 1.2\%$$

In example 13.5 $I_Q = 2$ mA, and for $v_o = 0$

$$R_{out} = \frac{V_T}{i_N + i_P} = \frac{25}{2 + 2} = 6.25\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{out}} = \frac{100}{100 + 6.25} = 0.94$$

$v_o = 10$ V

$$I_L = \frac{10\text{ V}}{100\ \Omega} = 100\text{ mA}$$

Again calculate i_N (for $I_Q = 2$ mA) using equation 13.27 $i_N = 99.96$ mA

$$i_P = \frac{I_Q^2}{I_N} = \frac{2^2}{99.96} = 0.04\text{ mA}$$

$$R_{out} = \frac{V_T}{i_N + i_P} = \frac{25}{99.6 + 0.04} = 0.25\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{out}} \simeq 1$$

$$\%\text{ Change} = \frac{1 - 0.94}{1} \times 100 = 6\%$$

For $I_Q = 10$ mA, change is 1.2%

For $I_Q = 2$ mA, change is 6%

(c) The quiesent power dissipated in each transistor $= I_Q \times V_{CC}$

Total power dissipated $= 2 \times 10 \times 10^{-3} \times 15$

$= 300$ mW

Ex 13.6

From example 13.4 $V_{CC} = 15$ V, $R_L = 100\ \Omega$

Q_N and Q_P matched and $I_S = 10^{-13}$ A and $\beta = 50$,

$I_{Bias} = 3$ mA

For $v_o = 10$ V, $I_L = \frac{10}{100} = 0.1$ A

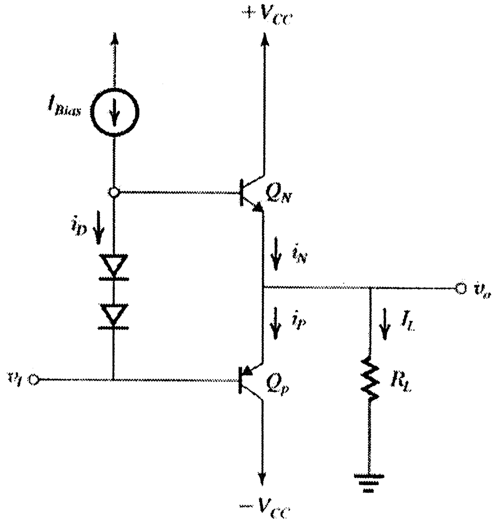
As a first approximation $i_N \simeq 0.1$ A, $i_P = 0$, $i_{BN} \simeq$

$$\frac{0.1\text{ A}}{50 + 1} \simeq 2\text{ mA}$$

$i_D = I_{Bias} - i_{BN} = 3 - 2 = 1$ mA

$$V_{BB} = 2\, V_T \ln\left(\frac{10^{-3}}{\frac{1}{3} \times 10^{-13}}\right)$$

This $\frac{1}{3}$ is because biasing diodes have $\frac{1}{3}$ area of the output devices.



But $V_{BB} = V_{BEN} + V_{BEP} =$ (1)

$$V_T \ln\left(\frac{i_N}{I_S}\right) + V_T \ln\left(\frac{i_N - i_L}{I_S}\right)$$

$$= V_T \ln\left[\frac{i_N(i_N - i_L)}{I_S^2}\right] \quad (2)$$

Equating equations 1 and 2

$$2V_T \ln\left(\frac{10^{-3}}{\frac{1}{3} \times 10^{-13}}\right) = V_T \ln\left(\frac{i_N - i_L}{I_S^2}\right)$$

$$\left(\frac{10^{-3}}{\frac{1}{3} \times 10^{-13}}\right)^2 = \frac{i_N(i_N - 0.1)}{(10^{-13})^2}$$

$i_N(i_N - 0.1) = 9 \times 10^{-6}$

If i_N is in mA, then

$i_N(i_N - 100) = 9$

$i_N^2 - 100\, i_N - 9 = 0$

$\Rightarrow i_N = 100.1$ mA

$i_P = i_N - i_L = 0.1$ mA

For $v_O = -10$ V and $i_L = \frac{-10}{100} = -0.1$ A

$= -100$ mA

As a first approximation assume $i_P \cong 100$ mA.

$i_N \simeq 0$ since $i_N = 0$, current through diodes $= 3$ mA

$$\therefore V_{BB} - 2V_T \ln\left(\frac{3\times 10^{-3}}{\frac{1}{3}\times 10^{-13}}\right) \quad (3)$$

But $V_{BB} = V_T \ln\left(\frac{i_N}{10^{-13}}\right) + V_T \ln\left(\frac{i_P}{10^{-13}}\right)$

$$= V_T \ln\left(\frac{i_P - i_L}{10^{-13}}\right) + V_T \ln\left(\frac{i_P}{10^{-13}}\right) \quad (4)$$

Here $i_L = 0.1$ A

Equating equations 3 and 4

$$2V_T \ln\left(\frac{3\times 10^{-3}}{\frac{1}{3}\times 10^{-13}}\right) =$$

$$V_T \ln\left(\frac{i_P - 0.1}{10^{-13}}\right) + V_T \ln\left(\frac{i_P}{10^{-13}}\right)$$

$$\left(\frac{3\times 10^{-3}}{\frac{1}{3}\times 10^{-13}}\right)^2 = \frac{i_P(i_P - 0.1)}{(10^{-13})^2}$$

$i_P(i_P - 0.1) = 81\times 10^{-6}$

Expressing currents in mA

$i_P(i_P - 100) = 81$

$i_P^2 - 100\, i_P - 81 = 0$

$\Rightarrow i_P = 100.8$ mA

$i_N = i_P - i_L = 0.8$ mA

Ex 13.7

$\Delta I_C = g_m \times 2$ mV / °C × 5 °C, mA

where g_m is in mA / mV

$$g_m = \frac{10 \text{ mA}}{25 \text{ mV}} = 0.4 \text{ mA / mV}$$

Thus, $\Delta I_C = 0.4\times 2\times 5 = 4$ mA

Ex 13.8

Refer to Fig. 10.14

(a) To obtain a terminal voltage of 1.2 V, and since β_1 is very large, it follows, that $V_{R1} = V_{R2} = 0.6$ V.

Thus $I_{C1} = 1$ mA

$$I_R = \frac{1.2 \text{ V}}{R_1 + R_2} = \frac{1.2}{2.4} = 0.5 \text{ mA}$$

Thus, $I = I_{C1} + I_R = 1.5$ mA

(b) For $\Delta V_{BB} = +50$ mV:

$V_{BB} = 1.25$ V $\quad I_R = \frac{1.25}{2.4} = 0.52$ mA

$$V_{BE} = \frac{1.25}{2} = 0.625 \text{ V}$$

$$I_{C1} = 1\times e^{\Delta V_{BE}/V_T} = e^{0.025/0.025}$$

$= 2.72$ mA

$I = 2.72 + 0.52 = 3.24$ mA

For $\Delta V_{BB} = +100$ mV

$V_{BB} = 1.3$ V $\quad I_R = \frac{1.3}{2.4} = 0.54$ mA

$$V_{BE} = \frac{1.3}{2} = 0.65 \text{ V}$$

$$I_{C1} = 1\times e^{\Delta V_{BE}/V_T} = 1\times e^{0.05/0.025}$$

$= 7.39$

$I = 7.39 + 0.54 = 7.93$ mA

For $\Delta V_{BB} = +200$ mV:

$V_{BB} = 1.4$ V $\quad I_R = \frac{1.4}{2.4} = 0.58$ mA

$V_{BE} = 0.7$ V

$I_{C1} = 1\times e^{0.1/0.025} = 54.60$ mA

$I = 54.60 + 0.58 = 55.18$ mA

For $\Delta V_{BB} = -50$ mV

$V_{BB} = 1.15$ V $\quad I_R = \frac{1.15}{2.4} = 0.48$ mA

$$V_{BE} = \frac{1.15}{2}$$

$= 0.575$

$I_{C1} = 1\times e^{-0.025/0.025} = 0.37$ mA

$I = 0.48 + 0.37 = 0.85$ mA

For $\Delta V_{BB} = -100$ mV:

$V_{BB} = 1.1$ V $\quad I_R = \frac{1.1}{2.4} = 0.46$ mA

$V_{BE} = 0.55$ V

$I_{C1} = 1\times e^{-0.05/0.025} = 0.13$ mA

$I = 0.46 + 0.13 = 0.59$ mA

For $\Delta V_{BB} = -200$ mV:

$V_{BB} = 1.0$ V $\quad I_R = \frac{1}{2.4} = 0.417$ mA

$V_{BE} = 0.5$ V

$I_{C1} = 1\times e^{-0.1/0.025} = 0.018$ mA

$I = 0.43$ mA

Ex 13.9

Using equation 13.43

$$I_Q = I_{\text{Bias}} \frac{(W/L)_n}{(W/L)_1}$$

$$1 = 0.2\,\frac{(W/L)_n}{(W/L)_P}$$

$$\frac{(W/L)_n}{(W/L)_1} = 5$$

$$Q_1:\ I_{\text{Bias}} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_1 (V_{GS} - V_{tn})^2$$

$$0.2 = \frac{1}{2}\times 0.250\left(\frac{W}{L}\right)_1 (0.2)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_1 = 40$$

Q_2: $I_{Bias} = \frac{1}{2} k_p'\left(\frac{W}{L}\right)_2 (V_{GS} - |V_t|)^2$

$$0.2 = \frac{1}{2} \times 0.100 \times \left(\frac{W}{L}\right)_2 \times (0.2)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_2 = 100$$

Q_N: $I_Q = \frac{1}{2} k_n'\left(\frac{W}{L}\right)_N (V_{GS} - V_t)^2$

$$1 = \frac{1}{2} \times 0.250 \times \left(\frac{W}{L}\right)_N 0.2^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_N = 200$$

Q_P: $I_Q = \frac{1}{2} k_p'\left(\frac{W}{L}\right)_P (V_{GS} - |V_t|)^2$

$$1 = \frac{1}{2} \times 0.100 \times \left(\frac{W}{L}\right)_P \times 0.2^2$$

$$\left(\frac{W}{L}\right)_P = 500$$

Now $V_{GG} = V_{GS1} + V_{GS2}$

$$= (V_{ov1} + V_t) + (V_{ov2} + |V_t|)$$
$$= (0.2 + 0.5) + (0.2 + 0.5)$$
$$= 1.4\text{ V}$$

Ex 13.10

$I_N = i_{Lmax} = 10\text{ mA}$

$$\therefore 10 = \frac{1}{2} k_n' \left(\frac{W}{L}\right)_n V_{ov}^2$$

$$10 = \frac{1}{2} \times 0.250 \times 200 \times V_{ov}^2$$

$$\Rightarrow V_{ov} = 0.63\text{ V}$$

Using equation 13.46

$$V_{omax} = V_{DD} - V_{ov}|_{Bias} - V_{tn} - V_{ovN}$$
$$= 2.5 - 0.2 - 0.5 - 0.63$$
$$= 1.17\text{ V}$$

Ex 13.11

New values of W/L are

$$\left(\frac{W}{L}\right)_p = \frac{2000}{2} = 1000$$

$$\left(\frac{W}{L}\right)_N = \frac{800}{2} = 400$$

$$I_Q = \frac{1}{2} k_p'\left(\frac{W}{L}\right)_p V_{ov}^2$$

$$1 \times 10^{-3} = \frac{1}{2} \times 0.1 \times 10^{-3} \times 1000 \times V_{ov}^2$$

$$\Rightarrow V_{ov} = 0.14\text{ V}$$

Gain Error =

$$-\frac{V_{ov}}{4\mu I_Q R_L} = -\frac{0.14}{4 \times 10 \times 1 \times 10^{-3} \times 100}$$
$$= -0.035$$

Gain Error = $-0.035 \times 100 = 3.5\%$

$$g_{mn} = g_{mp} = \frac{2I_Q}{V_{ov}} = \frac{2 \times 1 \times 10^{-3}}{0.14}$$
$$= 14.14\text{ mA/V}$$

$$R_{out} = \frac{1}{\mu(g_{mp} + g_{mn})} =$$

$$\frac{1}{10 \times (14.14 + 14.14) \times 10^{-3}}$$
$$\simeq 3.5\ \Omega$$

Ex 13.12

See solution on next page

Ex 13.12

Need to prove when $V_{o2} = 4\,I_Q R_L$ then $V_{GSN2} = V_{tn}$

Assume Q_N off ($V_{GSN} = V_{tn}$) so $i_{N2} = 0$ and

$i_{p2} = i_{L2}$

$$i_{p2} = i_{L2} = \frac{V_{O2}}{R_L} = 4I_Q$$

$$4I_Q = \frac{1}{2}k'_p\left(\frac{W}{L}\right)_p(V_{SGP2} - |V_{tp}|)^2$$

$$\sqrt{4\left(\frac{1}{2}k'_p\left(\frac{W}{L}\right)_p(V_{SGPQ} - |V_{tp}|)^2\right)}$$

$$= \sqrt{\frac{1}{2}k'_p\left(\frac{W}{L}\right)_p(V_{SGP2} - |V_{tp}|)^2}$$

$$2(V_{SGPQ} - |V_{tp}|) = (V_{SGP2} - |V_{tp}|)$$

$$V_{SGP2} = 2V_{SGPQ} - 2|V_{tp}| + |V_{tp}|$$

$$= 2V_{SGPQ} - |V_{tp}| \quad (1)$$

Find V_{i2} for the gate voltage, V_{GP2}:

$$V_{GP2} = (V_{DD} - V_{SGPQ}) + \mu(V_{O2} - V_{i2})$$

$$(V_{GP2} - V_{DD}) = -V_{SGPQ} + \mu(V_{O2} - V_{i2})$$

$$[V_{GSP2}\text{ OR}] - V_{SGP2} = -V_{SGPQ} + \mu(V_{O2} - V_{i2})$$

using (1):

$$-2V_{SGPQ} + |V_{tp}| = -V_{SGPQ} + \mu(V_{O2} - V_{i2})$$

$$\mu(V_{i2} - V_{O2}) = -V_{SGPQ} + 2V_{SGPQ} - |V_{tp}|$$

$$V_{i2} = +V_{O2} + \frac{(V_{SGPQ} - |V_{tp}|)}{\mu} = V_{O2} + \frac{V_{OVQ}}{\mu}$$

Plug this value for V_{i2} into the value for V_{GN2}

and show $V_{GSN2} = V_{tN}$

$$(-V_{SS} + V_{GSNQ}) + \mu(V_{O2} - V_{i2}) = V_{GN2} - (-V_{SS})$$

$$V_{GSNQ} + \mu\left(V_{O2} - V_{O2} - \frac{V_{OVQ}}{\mu}\right) = V_{GSN2}$$

where

$$V_{OVQ} = (V_{GSNQ} - V_{tn}) = (V_{SGPQ} - |V_{tp}|)$$

$$V_{GSNQ} - V_{GSNQ} + V_{tn} = V_{GSN2} \text{ Q.E.D.}$$

Same proof for p transistor.

Ex: 10.1

$V_{ICM(max)} \leq V_{DD} - |V_{OV5}| - |V_{tp}| - |V_{OV1}|$

$\leq +1.65 - 0.3 - 0.5 - 0.3$

$\leq +0.55\text{ V}$

$V_{ICM(min)} \geq -V_{SS} + V_{OV3} + V_{tn} - |V_{tp}|$

$\geq -1.65 + 0.3 + 0.5 - 0.5$

$\geq -1.35\text{ V}$

$V_{0(min)} \leq V_{DD} - |V_{OV7}|$

$\leq +1.65 - 0.5$

$\leq +1.15\text{V}$

$V_{0(min)} \geq -V_{SS} + V_{OV6}$

$\geq -1.65 + 0.5$

$\geq -1.15\text{V}$

Ex: 10.2

$|V_A| = 30\text{V},\ I_6 = 0.5\text{ mA},$

$V_{OV1} = 0.2\text{V},\ V_{OV6} = 0.5\text{ V}$

$I = K(V_{OV})^2$

For $Q_6: 0.5 = K(0.5)^2 \Rightarrow K = 2\text{ mA/V}^2$

For $Q_2: I_2 = 2(0.2)^2 \Rightarrow I_2 = 0.8\text{ mA}$

$$g_m = \frac{I}{V_{OV}} \Rightarrow g_{m2} = \frac{0.8}{0.2} = 4\text{ mA/V}$$

$$\Rightarrow g_{m6} = \frac{0.5}{0.5} = 1\text{ mA/V}$$

$$r_o = \frac{V_A}{I} \Rightarrow r_{o2} = \frac{20}{0.8} = 25\text{ k}\Omega$$

$$\Rightarrow r_{o6} = r_{o7} = \frac{20}{0.5} = 40\text{ k}\Omega$$

$A_1 = -g_{m2}r_{o2} = -4 \times 25 = -100\text{ V/V}$

$A_2 = -g_{m6}r_{o6} = -1 \times 40 = -40\text{ V/V}$

$A = A_1A_2 = (-100)(-40) = +4000\text{ V/V}$

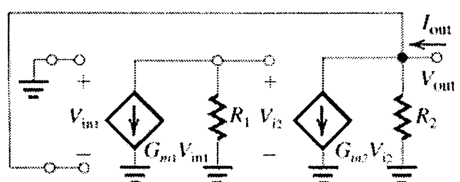
$$R_o = (r_{o6} \| r_{o7}) = \frac{40\text{k}}{2} = 20\text{ k}\Omega$$

Ex: 10.3

The small-signal equivalent circuit for the op-amp in Fig. 10.3 on page of the Text is redrawn below for a unity-gain buffer.

From Eq10.8,10.7,10.14,10.15on page of the Text : $G_{m1} = g_{m1}\ G_{m2} = g_{m6}$

$R_1 = r_{o2} \| r_{o4}\ R_2 = r_{o6} \| r_{o7}$



From the above we can write :

$$I_{out} = G_{m2}V_{i2} + \frac{V_{out}}{R_2}\ \text{where}$$

$V_{i2} = -G_{m1}V_{in1}R_1$ and

$V_{in1} = -V_{out} \Rightarrow V_{i2} = G_{m1}R_1V_{out}$ therefore :

$$I_{out} = g_{m6}g_{m1}R_1V_{out} + \frac{V_{out}}{R_2}$$

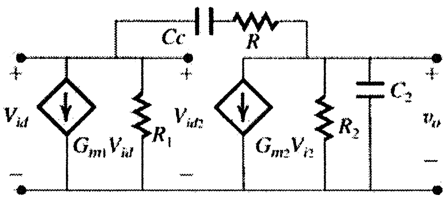
$$I_{out} = V_{out}\left(g_{m6}g_{m1}R_1 + \frac{1}{R_2}\right)\text{or}$$

$$R_o = \frac{1}{g_{m6}g_{m1}(r_{o2} \| r_{o4}) + \dfrac{1}{r_{o6} \| r_{o7}}}$$

Since $r_{o6} \| r_{o7}$ is huge, we can neglect $\dfrac{1}{r_{o6} \| r_{o7}}$ and have :

$$R_o \approx \frac{1}{g_{m6}g_{m1}(r_{o2} \| r_{o4})}$$

Ex: 10.4



$G_{m1} = 1\text{ mA/V}\ \ G_{m2} = 2\text{ mA/V}$

$C_2 = 1P$

$r_{o2} = r_{o4} = 100\text{ K}, r_{o6} = r_{o7} = 40\text{ K}$

$$\text{(a) } f_t = \frac{G_{m1}}{2\pi C_C} = \frac{1\text{ mA/V}}{2\pi C_C} = 100\text{ MHz}$$

$\Rightarrow C_C = 1.6\text{ pF}$

$A_1 = -G_{m1}R_1 = (1 \times 10^{-3})(r_{o2} \| r_{o4})$

$= (1 \times 10^{-3})(100\text{ K}/2) = -50\text{ V/V}$

$A_2 = -G_{m2}R_2 = (2 \times 10^{-3})(r_{o6} \| r_{o7})$

$= (2 \times 10^{-3})(40(\text{ K})/2) = -40\text{ V/V}$

$A = A_1 \cdot A_2 = (-50)(-40) = +2000$

$f_p = f_t/A = 100 \times 10^6/2 \times 10^3 = 50\text{ KHz}$

(b) to move zero to $S = \infty$

$$R = \frac{1}{G_{m2}} = \frac{1}{2 \times 10^{-3}} = 500\ \Omega$$

$$f_{p2} \approx \frac{G_{m2}}{2\pi C_2} = \frac{0.2 \times 10^{-3}}{2\pi 10^{-9}} = 318 \times 10^6 \text{ HZ}$$

$$\theta = \tan^{-1}\frac{f_t}{f_P} = \tan^{-1}\frac{100 \times 10^6}{318 \times 10^6} = 17.4^\circ$$

$$PM = 90 - \theta = 72.6^\circ$$

Ex: 10.5

Find SR for $f_t = 100$ MHz

$V_{OV1} = 0.2$ V

$SR = 2\pi f_t V_{OV} = 2\pi \times 100 \times 10^6 \times 0.2$

$= 125.67 \approx 126$ V / μS

$SR = \frac{I}{C_C} \Rightarrow I = SR \times C_C$

$\therefore I = 126 \times 10^6 \times 1.6 \times 10^{-12}$

$= 200\ \mu$A

Ex: 10.6

$V_{ICM(\max)} \leq V_{DD} - V_{OV9} + V_{tn}$

$\leq +1.65 - 0.3 + 0.5 = +1.85$ V

$V_{ICM(\min)} \geq -V_{SS} + V_{OV11} + V_{OV1} + V_{tn}$

$\geq -1.65 + 0.3 + 0.3 + 0.5 = -0.55$ V

$V_{o(\max)} \leq V_{DD} - |V_{OV9}| - |V_{OV}|$

$\leq +1.65 - 0.3 - 0.3 = +1.05$ V

$V_{o(\min)} \geq -V_{SS} + V_{OV11} + V_{OV1} + V_{tn}$

$\geq -1.66 + 0.3 + 0.3 + 0.5 = -0.55$ V

Ex: 10.7

$|V_A| = 20$ V, $V_{OV} = 0.2$V, $I = 100\ \mu$A

$$G_m = \frac{2I}{V_{OV}} = \frac{2 \times 100 \times 10^{-6}}{0.2} = 1.0 \text{ mA / V}$$

$$r_o = \frac{V_A}{I} = \frac{20 \times 10^6}{100} \Rightarrow 200 \text{ k}\Omega$$

$R_O = [g_{m4}r_{o4}(r_{o2} \| r_{o10})] \| [g_{m6}r_{o6}r_{o5}]$

$= g_m r_o^2\left[\frac{1}{2}(1 \| 2)\right]$

$= 1.0 \times 200^2 \times 1/3 \times 10^6 = 13.33$ MΩ

$A = G_m R_o = 1.0 \times 10^{-3} \times 13.33 \times 10^6$

$= 13.33 \times 10^3$ V / V

Ex: 10.8

Given : all $V_{OV} = 0.3$ V, $|V_T| = 0.7$ V

$V_{DD} = V_{SS} = 2.5$V

(a) $V_{IC(\max)}$ for NMOS

$V_{ICM(\max)_N} \leq V_{DD} - V_{OV} + V_T$

$\leq +2.5 - 0.3 + 0.7 = +2.9$ V

$V_{ICM(\min)_N} \geq -V_{SS} + V_{OV} + V_{OV} + V_T$

$\geq -2.5 + 0.3 + 0.3 + 0.7 = -1.2$ V

$\therefore -1.2V \leq (V_{ICM})_N \leq +2.9$V

(b) By Sym.

-2.9 V $\leq (V_{ICM})_P \leq +1.2$ V

(c) -1.2 V $\leq (V_{ICM})_{\text{BOTH}} \leq +1.2$ V

(d) -2.9 V $\leq (V_{ICM})_{\text{overall}} \leq +2.9$ V

Ex: 10.9

$I_1 = \frac{1}{2}K(W/L)(V_{GS1} - V_T)^2$

$I_2 = \frac{1}{2}K(W4/L)(V_{GS2} - V_T)^2$

For $I_1 = I_2$:

$(V_{GS1} - V_T)^2 = 4(V_{GS2} - V_T)^2$

i.e., $V_{GS1} - V_T = 2(V_{GS2} - V_T)$

or $V_{GS1} = 2V_{GS2} - V_T$

Ex: 10.10

npn : $I_S = 10^{-14}$A, $\beta = 200$, $V_A = 125$ V

pnp : $I_S = 10^{-14}$A, $\beta = 50$, $V_A = 50$ V

$I = I_S e^{V_{BE}/V_T}$

$\Rightarrow V_{BE} = V_T \ln\frac{I}{I_S}$

$$V_{BE} = 25 \text{ mV} \ln\frac{10^{-3}}{10^{-14}} = 633 \text{ mV}$$

$g_m = \beta / r_E = 200/5\text{k} = 40$ mA / v

$r_\pi \approx \beta_{re} \approx 200 \times 25 \Rightarrow 5$ kΩ

$$r_e = \frac{V_T}{I} = \frac{25\text{mV}}{1\text{mA}} = 25\ \Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{125\text{V}}{1\text{mA}} = 125 \text{ k}\Omega$$

Ex: 10.11

$I = I_S e^{V_B/V_T} \Rightarrow V_{BE} = V_T \ln(I/I_S)$

and $I_3 = I_4$, $I_1 = I_2$

From ect : $V_{BE1} + V_{BE2} = V_{BE3} + V_{BE4}$

$$V_T \ln\left[\frac{I_1}{I_{S1}}\right] + V_T \ln\left[\frac{I_2}{I_{S2}}\right] = V_T \ln\left[\frac{I_3 I_4}{I_{S3} I_{S4}}\right]$$

$$\therefore \ln\left[\frac{I_1^2}{I_{S1} \cdot I_{S2}}\right] = \ln\left[\frac{I_3^2}{I_{S3} I_{S4}}\right]$$

$$\therefore I_3 = I_1\left[\frac{I_{S3} I_{S4}}{I_{S1} I_{S2}}\right]^{\frac{1}{2}}$$

Ex: 10.12

$V_{BE} = 0.7$ V for $I_C = 1$ mA for $Q11$

$I_C = 10\ \mu$A for $Q10$

$$V_{BE10} = 0.7 + V_t \ln\left[\frac{10\ \mu A}{1\ mA}\right] = 0.585\ V$$

Voltage across $R_4 = V_{BE10} - V_{BE11}$

$= 0.7 - 0.585 = 0.115$ V

$$\Rightarrow I_{R4} = \frac{V_{R4}}{R_4} \Rightarrow R_4 = \frac{0.115\ V}{10\ \mu A} \Rightarrow 11.5\ k\Omega$$

Ex: 10.13

$V_{ICM(max)} = V_{DD} - V_{BE8} - V_{1sat} + V_{BE}$

$= +15 - 0.6 - 0.3 + 0.6$

$= +14.7$ V

$V_{ICM(min)} = -V_{SS} + V_{BE5} + V_{BE7} + V_{3sat} + V_{BE1}$

$= -15 + 0.6 + 0.6 + 0.3 + 0.6$

$= -12.9$ V

(neglecting R_1 & R_2 drops)

Ex: 10.14

Assume Q_{18}, Q_{19} (now diode connected transistors) have normal area

Q_{14}, Q_{20} have area = 3 * normal

$$I_{14} = 0.25 I_{REF}\sqrt{\frac{I_{S14} \cdot I_{S20}}{I_{S18} \cdot I_{S19}}}$$

$$I_{14} = 180\ \mu\sqrt{\frac{3I}{I} \cdot \frac{3I}{I}}$$

$$I_{14} = 180\ \mu \times 3 = 540\ \mu A$$

Ex: 10.15

Assume $I_{C7} \approx I_{C5} \approx I_{C6} = 9.5\ \mu$A

(a) $V_{B6} = I_E(R_2 + r_{e6}) = i_e(1 + 2.63)$

$= 3.63 I_3$

(b) $I_{E7} = \dfrac{V_{B6}}{R_3} + I_{B5} + I_{B6}$

$= \dfrac{V_{B6}}{R_3} + \dfrac{2I_E}{\beta + 1} = \dfrac{3.63 I_E}{50} + \dfrac{2I_E}{201}$

$= 0.08 I_E$

(c) $I_{B7} = \dfrac{V_{E7}}{\beta + 1} \approx \dfrac{0.08 I_E}{201} \approx 0.0004 I_E$

(d) $V_{B7} = V_{B6} + I_{E7} r_{e7}$

$= 3.63 I_E + 0.08 I_E \times \dfrac{25\ mV}{9.5\ \mu A}$

$= 3.84 k\Omega \times I_E$

(e) $R_{in} = \dfrac{(\beta + 1)}{\beta}\dfrac{V_{B7}}{I_E} \approx 3.84\ k\Omega$

Ex:

See Fig 10.22 on page of the Text, Let $R_1 = R$, $R_2 = R + \Delta R$ Assume $\beta >> 1$ and $r_{e5} = r_{e6}$, then

$V_{B5} = V_{B6} = i(r_{e5} + R_1) = i(r_{e6} + R_2)$

$$\therefore i_{C6} = i\frac{r_{e5} + R}{r_{e5} + R + \Delta R}$$

$i_o = i_{C6} - i = i$

$$\therefore i_6 = i\frac{r_{e5} + R}{r_{e5} + R + \Delta R} - i = i\frac{\Delta R}{r_{e5} + R + \Delta R}$$

$$\Rightarrow \epsilon_m = \frac{\Delta R}{r_{e5} + R + \Delta R}$$

For $\dfrac{\Delta R}{R} = 0.02$:

$$\epsilon_m = \frac{0.02R}{R + 0.02R + r_{e5}} = \frac{0.02}{1.02 + \frac{r_{e5}}{R}}$$

Substituting $R = 1\ k\Omega$ and $r_e = 2.63\ k\Omega$ for 741 op-amp, we have

$$\epsilon_m = \frac{0.02}{1.02 + \frac{2.63}{1}} = 5.5 \times 10^{-3}$$

Ex: 10.17

From Fig.10.23 on page of the Text:

$R_o = R_{o9} \parallel R_{o10}$

$$R_{o9} = r_{o9} = \frac{V_A}{I} = \frac{50}{19 \times 10^{-6}} = 2.63\ M\Omega$$

$$R_{o10} = r_{o10}(1 + g_{m10}(r_{\pi 10} \parallel R_4)) = \frac{125}{19 \times 10^{-6}}$$

$$\left(1 + \frac{19 \times 10^{-6}}{25 \times 10^{-3}}\left(\frac{200 \times 25 \times 10^{-3}}{19 \times 10^{-6}} \parallel 5 \times 10^3\right)\right)$$

$R_{o10} = 31.1\ M\Omega$

$R_o = 2.63 \parallel 31.1 = 2.42\ M\Omega$

Ex: 10.18

From Eq.10.93 we have: $G_{mcm} = \dfrac{\epsilon_m}{2R_o}$ From Ex.10.16 and 10.17 in the Text, we have:

$\epsilon_m = 5.5 \times 10^{-3}$, $R_o = 2.43\ M\Omega$

Hence:

$$G_{mcm} = \frac{5.5 \times 10^{-3}}{2 \times 2.43 \times 10^6} = 1.13 \times 10^{-6}\ mA/V$$

From Eq.10.95 we have:

$CMRR = 2g_{m1}(R_{o9} \parallel R_{o10}) / \epsilon_m$

$$CMRR = \frac{2\left(\frac{9.5 \times 10^{-6}}{25 \times 10^{-3}}\right)\left(\frac{2.63\ \mu \times 31.1\ \mu}{2.63\ \mu + 31.1\ \mu}\right)}{5.5 \times 10^{-3}}$$

1.68×10^5 or 104.5 dB

If the common-mode feedback is not present, as explained in the text, common-mode transconductance and common-mode gain are both reduced by a factor of β_p. Hence,

$$CMRR = \frac{1.68 \times 10^5}{50} = 3360 \text{ or}$$

$$CMRR = 70.5 \text{ dB}$$

Ex: 10.19

$\beta_{16} = \beta_{17} = 200$

$$r_{e16} = \frac{25 \text{ mV}}{16.2\ \mu\text{A}} = 1.54 \text{ k}\Omega$$

$$r_{e17} = \frac{25 \text{ mV}}{0.55 \text{ mA}} = 45.5\ \Omega$$

$R_8 = 100\ \Omega$, $R_9 = 50 \text{ k}\Omega$

Substituting into Eq. (8.77

$$R_{i2} = 201[1.54 + 50 \| (201 \times 0.0455)]$$

$$\simeq 4 \text{ M}\Omega$$

Ex: 10.20

$$i_{c17} = \frac{\beta}{\beta+1} \cdot \frac{V_{b17}}{r_{e17} + R_8} \simeq \frac{V_{b17}}{45.5 + 100} = \frac{V_{b17}}{145.5}$$

$$V_{b17} = V_{i2}\frac{(R_9 \| R_{i17})}{(R_9 \| R_{i17}) + r_{e16}}$$

needs $R_{i17} = (\beta + 1)(r_{e17} + R_8)$

$$= 201(45.5 + 100) = 29.2 \text{ k}\Omega$$

$\therefore V_{b17} \simeq V_{i2} \times 0.92$

Ex: 10.21

$R_{o2} = R_{o13B} \| R_{o17}$

where $R_{o13B} = r_{o13B} = \dfrac{50\text{V}}{0.55 \text{ mA}} = 90.9 \text{ k}\Omega$

$$R_{o17} = r_{o17}(1 + g_{m17}(R_8 \| r_{\pi17}))$$

$$r_{o17} = \frac{125\text{V}}{0.55 \text{ mA}} = 227.3 \text{ k}\Omega$$

$$g_{m17} = \frac{0.55 \text{ mA}}{0.025 \text{ mV}} = 22 \text{ mA/V}$$

$$r_{\pi17} = \frac{\beta}{g_m} = \frac{200}{22} = 9.09 \text{ k}\Omega$$

$R_8 = 100\ \Omega$

Thus $R_{o17} \Rightarrow 722 \text{ k}\Omega$

Hence $R_{o2} = 90.9 \| 722k \simeq 81 \text{ k}\Omega$

Ex: 10.22

$$\frac{I_t}{V_t} = \frac{1}{18.8} + 6.6 \times 0.917 = 0.05 + 6.05$$

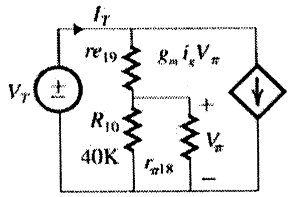
$$= 6.11$$

open-circuit voltage gain

$$(A_2)_{oc} = -G_{m2} R_{02}$$

$$= -6.5 \times 8.1 = -526.5 \text{ V/V}$$

Ex: 10.23



$$r_{e19} = \frac{25 \text{ mV}}{16\ \mu\text{A}}$$

$$= 1.56 \text{ K}$$

$$r_{\pi18} = \frac{200}{40 \times 0.165}$$

$$= 30.3 \text{ k}\Omega$$

$$I_T = \frac{V_T}{r_{e19} + (R_{10} \| r_{\pi18})} + \frac{g_{m18} V_T (R_{10} \| r_{\pi18})}{r_{e19} + (R_{10} \| r_{\pi18})}$$

$$\therefore I_T = V_T\left[\frac{1}{18.8 \text{ K}} + \frac{6.6 \times 0.917}{18.8 \text{ K}}\right]$$

$$= V_T[0.05 + 6.05]$$

$$\Rightarrow R_T \equiv \frac{V_T}{I_T} = 163\ \Omega$$

Ex: 10.24

$$R_O \simeq r_{e14} + \frac{\left[R_{18,19} + r_{e23} + \dfrac{R_{O2}}{\beta_{23} + 1}\right]}{\beta_{14} + 1}$$

$$R_O \simeq \frac{0.025}{0.005} + \frac{\left(163 + \dfrac{25 \text{ M}}{180\ \mu} + \dfrac{81 \text{ K}}{51}\right)}{201}$$

Assuming $\beta_{23} = 50$ and $\beta_{14} = 200$ and $I_{c13A} = 180\ \mu\text{A}$ from Table

$$R_O \simeq \frac{5 + (163 + 139 + 1588)}{201} = 5 + 94$$

$R_O \simeq 14.4\ \Omega$

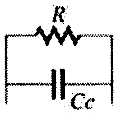
Ex: 10.25

$SR = 0.63\ V/\mu S$

using eq.

$$f_n = \frac{SR}{2\pi V_{O\,max}} = \frac{0.63}{2\pi(10) \times 1 \times 10^{-6}} = 10\ \text{kHz}$$

Ex: 10.26



$A_o = 2.43147 \times 10^5$

$G_{m1} = \frac{1}{5.26} \times 10^{-3}$

$\therefore A_o = G_{m1} R$

$\therefore R = A_o / G_{m1} \Rightarrow 1279\ \text{MHz}$

Ex: 10.27

$SR = \frac{W_t}{a}$ where

$a = \frac{G_{m1}}{2I} \Rightarrow SR = \frac{2I}{G_{m1}} \times w_t$

with R_E inserted in emitters of Q_3, Q_4

$$G_{m1} = 2 \times \frac{1}{4r_e + 2R_E} = \frac{1}{2r_e + R_E}$$

$$= \frac{1}{2 \times \frac{0.025\ \text{mV}}{I} + R_E} = \frac{I}{2r_T + IR_E}$$

for $I = 9.5 \times 10^{-6}$ A

$$R_E = \frac{0.050}{9.5 \times 10^{-6}} = 5.26\ \text{k}\Omega$$

now $SR = \frac{2Iwt}{I} \times (2V_T + IR_E)$

$= 4[V_T + I_{RE}/2]^{wt}$ QED

new C_c : $\frac{G'_{m1}}{C_c} = \frac{G_{m1}}{2C_c}$

$\therefore$ C_c must be reduce × factor of 2

$C_{c\,new} = \frac{C_{c\,old}}{2} = \frac{30}{2} = 15$ pF

Gain A α G_{m1} ∴ A also halved

$A_{new} = A_{old} - 6$ dB $= 101.7$ dB

$f_p = f_t/\text{A} = f_t$ has been halved

$f_{p\,new} = 2 \times f_{p\,old} = 8.2$ Hz

Ex: 10.28

using eq. (10.129

$I = \frac{V_T}{R_2}\ln\left(\frac{I_{S2}}{I_{S1}}\right)$ where $V_T = 25$ mV

$R_3 = R_4 = \frac{0.2}{10\ \mu} = 20,000\ \Omega$

$R_2 = \frac{V_T}{I}\ln\left(\frac{I_{S2}}{I_{S1}}\right)$

$R_2 = \frac{25\ \text{m}}{10\ \mu}\ln(2) = 1,733\ \Omega$

Ex: 10.29

use $R_3 = R_4 = 20\ k\Omega$

and $I = 10\ \mu A$ from Exercise 10.28

For $I_8 = 10\ \mu A = I$, then $\left(\frac{W}{L}\right)_8 = \left(\frac{W}{L}\right)_3$

For $I_9 = 20\ \mu A = 2I$, then $\left(\frac{W}{L}\right)_9 = 2\left(\frac{W}{L}\right)_3$

For $I_{10} = 5\ \mu A = \frac{I}{2}$, then $\left(\frac{W}{L}\right)_{10} = \frac{1}{2}\left(\frac{W}{L}\right)_3$

Since V_S has to equal the original $(V_{CC} - I * R_4) = V_{CC} - 0.2$ so R_8, R_9, and R_{10} can be found by

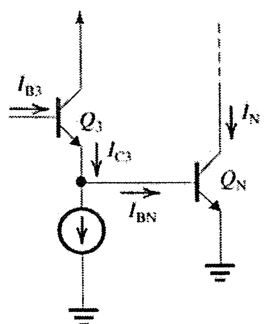
$$R_8 = \frac{0.2}{10\ \mu} = 20\ k\Omega$$

$$R_9 = \frac{0.2}{20\ \mu} = 10\ k\Omega$$

$$R_{10} = \frac{0.2}{5\ \mu} = 40\ k\Omega$$

Ex: 10.30

(a) Find $\frac{i_N}{i_{B3}}$ for (V_{IN})



Assume

$i_{C3} \approx i_{BN}$

$i_{B3} \leq \frac{i_{C3}}{\beta_N}$

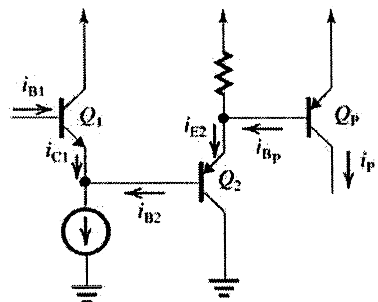
$i_{C3} \approx i_{BN} = \frac{i_N}{\beta_N}$

$$\therefore \frac{i_N}{i_{B1}} = \frac{i_N}{\left(\frac{i_N}{\beta_N}\right)\left(\frac{1}{\beta_N}\right)} = \beta_N^2$$

Find $\frac{i_P}{i_{B1}}$ for (V_{IP})

Assume $i_{BP} \approx i_{E2}$ and $i_{C1} \approx i_{B2}$

$$\therefore \frac{i_P}{i_{B1}} = \frac{i_P}{\left(\frac{i_P}{\beta_P}\right)\left(\frac{1}{\beta_P}\right)\left(\frac{1}{\beta_N}\right)} = \beta_P^2 \cdot \beta_N$$



(b) $i_{B3} = \frac{i_N}{\beta_N^2}$ (Assume $\beta_N \approx 40$)

$$i_{B3} = \frac{10\ m}{(40)^2} = 6.25\ \mu A$$

$i_{B1} = \frac{i_P}{\beta_P^2 \beta_N}$ (Assume $\beta_P \approx 10$)

$$i_{B1} = \frac{10\ m}{(10)^2 \cdot 40} = 2.5\ \mu A$$

Ex: 11.1

$A = -20 \log |T|$ [dB]

$\|T\| =$	1	0.99	0.9	0.8	0.7	0.5	0.1	0
$A \simeq$	0	0.1	1	2	3	6	20	∞

Ex: 11.2

$A_{max} = 20 \log 1.05 - 20 \log 0.95 = 0.9$ dB

$A_{min} = 20 \log\left[\frac{1}{0.001}\right] = 40$ dB

Ex: 11.3

$$T(s) = k\frac{(s+j2)\ (s-j2)}{\left(s+\frac{1}{2}+j\sqrt{\frac{3}{2}}\right)\left(s+\frac{1}{2}-j\sqrt{\frac{3}{2}}\right)}$$

$$= k\frac{(s^2+4)}{s^2+s+\frac{1}{4}+\frac{3}{4}}$$

$$= k\frac{(s^2+4)}{s^2+s+1}$$

$$T(o) = k\frac{4}{1} = 1$$

$$k = \frac{1}{4}$$

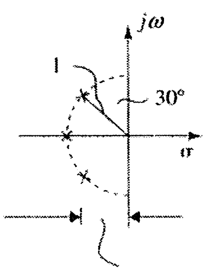
$$\therefore T(s) = \frac{1}{4}\frac{(s^2+4)}{s^2+s+1}$$

Ex: 11.4

$$T(s) = k\frac{s(s^2+4)}{(s+0.1+j8)\ (s+0.1-j8)}$$
$$(s+0.1+j1.2)\ (s+0.1-j1.2)$$

$$= k\frac{s(s^2+4)}{(s^2+0.23+0.65)\ (s^2+0.23+1.45)}$$

Ex: 11.5



$\omega_0/2Q = 1\text{Cos}60 = 1/2$

As shown, the pair of computex poles has $\omega_0 = 1$ and $Q = 1$

$$\omega_O/zQ = 1\cos 60 = \frac{1}{2}$$

$$\frac{1}{2Q} = \frac{1}{2}$$

$$Q = 1$$

$$\therefore T(s) = k\frac{1}{(s+1)\ (s^2+s+s+1)}$$

since $T(0) = 1, k = 1$

$$\text{Thus: } T(s) = \frac{1}{(s+1)\ (s^2+s+1)}$$

$$T(j\omega) = \frac{1}{\sqrt{1+\omega^2}\sqrt{(1-\omega^2)^2+\omega^2}}$$

$$= \frac{1}{\sqrt{(1-\omega^4)\ (1-\omega^2)+\omega^2\ (1+\omega^2)}}$$

$$= \frac{1}{\sqrt{1-\omega^4-\omega^2+\omega^6+\omega^2+\omega^4}}$$

$$\frac{1}{\sqrt{1+\omega^6}} \text{ Q.E.D}$$

$$\text{Thus: } \frac{1}{\sqrt{2}} = \frac{1}{(1+\omega_{3dB}^6)^{\frac{1}{2}}} \Rightarrow \omega_{3dB} = 1 \text{ rad/s}$$

$$A(3) = -20 \log\frac{1}{\sqrt{1+3^6}} = 28.6 \text{ dB}$$

Ex: 11.6

$$\epsilon = \sqrt{10^{\frac{A_{max}}{10}}-1} = \sqrt{10^{\frac{1}{10}}-1} = 0.5088$$

$$|T(j\omega)| = \frac{1}{\sqrt{1+\epsilon^2\left(\frac{\omega}{\omega_p}\right)^{2N}}}$$

$$A(\omega_s) = -20 \log|T(j\omega_s)|$$

$$= 10 \log\left[1+\epsilon^2\left(\frac{\omega_s}{\omega_p}\right)^{2N}\right]$$

Thus, $10 \log[1+0.5888^2 \times 1.5^{2N}] \geq 30$

$N = 10$ LHS $= 29.35$ dB

$N = 11$ LHS $= 32.87$ dB

$\therefore$ Use $N = 11$ and obtain

$A_{min} = 32.87$ dB

For A_{min} to be exactly 30 dB

$10 \log[1+\epsilon^2 \times 1.5^{22}] = 30$

$\epsilon \Rightarrow 0.3654 \Rightarrow A_{max} + 20 \log\sqrt{1+0.3654^2}$
$= 0.54$ dB

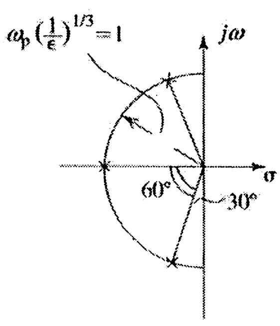
Ex: 11.7

The real pole is at $s = -1$

The complex conjugate poles are at

$$s = 2\cos 60° \pm j\sin 60°$$

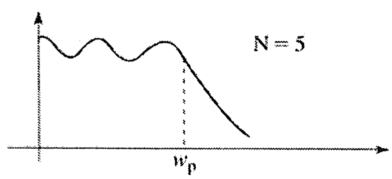
$$= -0.5 \pm j\sqrt{\frac{3}{2}}$$



$$T(s) = \frac{1}{(s+1)\left(s+0.5+j\sqrt{\frac{3}{2}}\right)\left(s+0.5-j\sqrt{\frac{3}{2}}\right)}$$

$$= \frac{1}{(s+1)(s^2+s+1)} \text{ for } DC_{gain} = 1$$

Ex: 11.8



$$|T(j\omega)| = \frac{1}{\sqrt{1+\epsilon^2\cos^2\left[N\cos^{-1}\left(\frac{\omega}{\omega_p}\right)\right]}}$$

for $\omega < \omega_p$.

Peaks are obtained when

$$\cos^2 5\left[N\cos^{-1}\left(\frac{\omega}{\omega_p}\right)\right] = 0$$

$$\cos^2 5\left[5\cos^{-1}\left(\frac{\omega}{\omega_p}\right)\right] = 0$$

$$5\cos^{-1}\left(\frac{\omega}{\omega_p}\right) = (2k+1)\frac{\pi}{2}, k = 0, 1, 2$$

$$\therefore \hat{\omega} = \omega_p \text{Cos}\left[\frac{(2k+1)\pi}{10}\right], k = 0, 1, 2$$

$$\hat{\omega}_1 = \omega_p \text{Cos}\left(\frac{\pi}{10}\right) = 0.95\omega_p$$

$$\hat{\omega}_2 = \omega_p \text{Cos}\left(\frac{3}{10}\pi\right) = 0.59\omega_p$$

$$\hat{\omega}_3 = \omega_p \text{Cos}\left(\frac{5}{10}\pi\right) = 0$$

Valleys are obtained when

$$\text{Cos}^2\left[N\text{Cos}^{-1}\left(\frac{\omega}{\omega_p}\right)\right] = 1$$

$$5\text{Cos}^{-1}\left(\frac{\omega}{\omega_p}\right) = k\pi, k = 0, 1, 2$$

$$\therefore \hat{\omega} = \omega_p \text{Cos}\left(\frac{k\pi}{5}\right), k = 0, 1, 2$$

$$\hat{\omega}_1 = \omega_p \text{Cos}0 = \omega_p$$

$$\hat{\omega}_2 = \omega_p \text{Cos}\frac{\pi}{5} = 0.81\omega_p$$

$$\hat{\omega}_3 = \omega_p \text{Cos}\frac{2\pi}{5} = 0.31\omega_p$$

Ex: 11.9

$$\epsilon = \sqrt{10^{\frac{A_{max}}{10}} - 1} = \sqrt{10^{\frac{0.5}{10}} - 1} = 0.3493$$

$$A(\omega_s) = 10\log\left[1+\epsilon^2\cosh^2\left(N\cosh^{-1}\frac{\omega_s}{\omega_p}\right)\right]$$

$$= 10\log[1+0.3493^2\cosh^2(7\cosh^{-1}2)]$$

$$= 64.9 \text{ dB}$$

For $A_{max} = 1$ dB, $\epsilon = \sqrt{10^{0.1}-1} = 0.5088$

$$A(\omega_s) = 10\log[1+0.5088^2\cosh^2(7\cosh^{-1}2)]$$

$$= 68.2 \text{ dB}$$

This is an increase of 3.3 dB

Ex: 11.10

$$\epsilon = \sqrt{10^{\frac{1}{10}} - 1} = 0.5088$$

(a) For the Chebyshev Filter:

$$A(\omega_S) = 10\log[1+0.5088^2\cosh^2(N\cosh^{-1}1.5)]$$

$$\geq 50 \text{ dB}$$

$N = 7.4 \therefore$ choose $N = 8$

Excess Attenuation =

$$10\log[1+0.5088^2\cosh^2(8\cosh^{-1}1.5)] - 50$$

$$= 55 - 50 = 5 \text{ dB}$$

(b) For a Butterworth Filter

$\epsilon = 0.5088$

$$A(\omega_s) = 10\log\left[1+\epsilon^2\left(\frac{\omega_s}{\omega_p}\right)^{2N}\right]$$

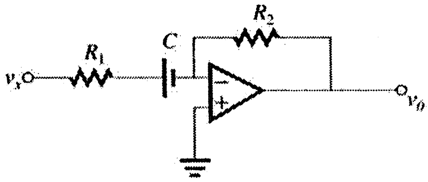
$$= 10\log[1+0.5088^2(1.5)^{2N}] \geq 50$$

$N = 15.9 \therefore$ choose $N = 16$

Excess attenuation =

$$10\log([1+0.5088^2(1.5)^{32}] - 50) = 0.5 \text{ dB}$$

Ex: 11.11



$10^4 = \frac{1}{CR_1}$ $R_1 = 10\ \text{k}\Omega$

$C = 0.01\ \mu\text{F}$

$\text{H.F. Gain} = \frac{-R_2}{R_1} = -10$

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

Ex: 11.12

Refer to Fig. 11.14

$\omega_0 = \frac{1}{CR} = 10^3\ \text{rad/s}$

For R arbitrarily selected to be

$10\ \text{k}\Omega\ C = \frac{1}{10^3 \times 10^4} = 0.1\ \mu\text{F}$

The two resistors labelled R_1 can also be selected to be $10\ \text{k}\Omega$ each.

Ex: 11.13

$T(s) = \frac{\omega_0^2}{s + s\sqrt{2\omega_0} + \omega_0^2}$ (for dc gain = 1)

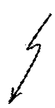
$|T(j\omega)| = \frac{\omega_0^2}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\omega_0^2\,\omega^2)}}$

$= \frac{\omega_0^2}{\sqrt{\omega_0^4 + \omega^4}}$

$= \frac{\omega_0^2}{\sqrt{1 + \left(\frac{\omega}{\omega_0}\right)^4}}$

At $\omega = \omega_0$, $|T| = \frac{1}{\sqrt{2}}$ which is 3 dB below the value at dc(unity) Q.E.D.

Ex: 11.14



This $T(s) = \frac{10^4 s}{s^2 + 10^4 s + 10^{10}}$

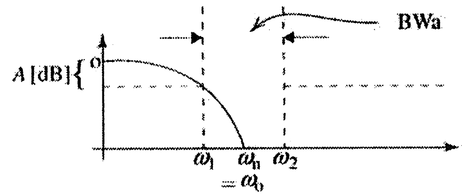
$\omega_0 = 10^5\ \text{rad/s}$

$\frac{\omega_0}{Q} = 10^3\text{rad/s}$

selected to yeild a centre. Frequency gain of 10.

Ex: 11.15

(a)



$T(S) = \frac{s^2 + \omega_O^2}{s^2 + s\,\omega_O/Q + \omega_O^2}$

$|T(j\omega)| = \frac{\omega_O^2 - \omega^2}{\sqrt{(\omega_O^2 - \omega^2)^2 + \frac{\omega^2\omega_O^2}{Q^2}}}$

$= \frac{1}{\sqrt{1 + \frac{\omega_O^2\omega^2}{(\omega_O^2 - \omega^2)^2 Q^2}}}$

for any two frequencies ω_1 and ω_2 at which $|T|$ is the same

$\frac{\omega_1^2\omega_O^2}{(\omega_O^2 - \omega_1^2)^2} = \frac{\omega_2^2\,\omega_O^2}{(\omega_O^2 - \omega_2^2)^2}$

$\omega_1(\omega_O^2 - \omega_2^2) = \omega_2(\omega_O^2 - \omega_1^2)$

$\Rightarrow \omega_1\omega_2 = \omega_O^2 \quad (1)$

Now to obtain attenuation $\geq$ A dB at ω_1 and ω_2 where $\omega_2 - \omega_1 = Bw_a$

$10 \log\left[1 + \frac{\omega_O^2\omega_1^2}{(\omega_O^2 - \omega_1^2)^2 Q^2}\right] \geq A$

$\frac{\omega_1\omega_O}{\omega_O^2 - \omega_1^2}\,\frac{1}{Q} \geq \sqrt{10^{A/10} - 1}$ SUB (1)

$\frac{\omega_1\omega_O}{\omega_1\omega_2 - \omega_1^2}\,\frac{1}{Q} \geq \sqrt{10^{A/10} - 1}$

$\frac{\omega_O}{\omega_2 - \omega_1}\,\frac{1}{Q} \geq \sqrt{10^{A/10} - 1}$

$\frac{\omega_O}{BW_a}\,\frac{1}{Q} \geq \sqrt{10^{A/10} - 1}$

$\Rightarrow Q \leq \frac{\omega_O}{BW_a\sqrt{10^{A/10} - 1}}$ Q.E.D.

(b) For $A = 3$ dB

$Q = \frac{\omega_O}{BW_3\sqrt{10^{0.3} - 1}} = \frac{\omega_O}{BW_3}$

OR $BW_3 = \omega_O/Q$ Q.E.D.

Ex: 11.16

From Fig10.16(e)

$$\omega_{max} = \omega_O\sqrt{\frac{(\omega_n/\omega_O)^2\left(1-\frac{1}{2Q^2}\right)-1}{(\omega_n/\omega_o)^2+\frac{1}{2Q^2}-1}}$$

For $\omega_o = 1$ rad/s, $\omega_n = 1.2$ rad/s $Q = 10$

$$\text{dc gain} = |a_2|\left(\frac{\omega_n^2}{\omega_o^2}\right) = 1$$

$$|a_2| = \omega_o^2/\omega_n^2 = \frac{1}{1.44}$$

$$\omega_{max} = 1\sqrt{\frac{1.44\left(1-\frac{1}{200}\right)-1}{1.44+\frac{1}{200}-1}}$$

$= 0.986$ rad/s

$$|T(j\omega_{max})| = \frac{a_2|(\omega_n^2-\omega_{max}^2)|}{\sqrt{(\omega_n^2-\omega_{max}^2)^2+\left(\frac{\omega_o\omega_{max}}{Q}\right)^2}}$$

$= 3.17$

$$|T(j\infty)| = Q_2 = \frac{1}{1.44} = 0.69$$

Ex: 11.17

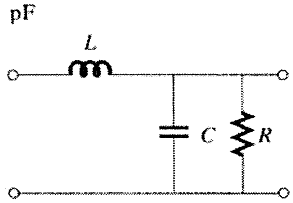
Maximally flat $\Rightarrow Q = \frac{1}{\sqrt{2}}$

$\omega_o = 2\pi \times 100 \times 10^3$

Arbitrarily selecting R = 1 kΩ

$$Q = \omega_o CR \Rightarrow C = \frac{1}{\sqrt{2}\times 2\pi 10^5 \times 10^3}$$

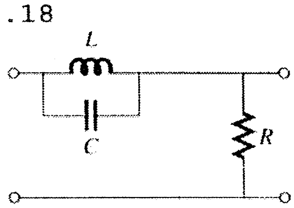
$= 1125$ pF



Also $Q = \frac{R}{\omega_o L}$

$$\therefore L = \frac{R}{\omega_o Q} = \frac{10^3}{2\pi 10^5 \times \frac{1}{\sqrt{2}}} = 2.25 \text{ mH}$$

Ex: 11.18



From Exercise 11.16above 3dB bandwidth

$= \omega_o/Q$

$2\pi 10 = 2\pi 60/Q \Rightarrow Q = 6$

$Q = \omega_o CR$

$6 = 2\pi 60 \times C \times 10^4 \Rightarrow C = 1.6\mu F$

$$Q = \frac{R}{\omega_o L}$$

$$L = \frac{R}{\omega_o Q} = \frac{10^4}{2\pi 60 \times 6} = 4.42 \text{ H}$$

Ex: 11.19

$f_o = 10$ kHz $\Delta f_{3dB} = 500$ Hz

$$Q = \frac{f}{\Delta f_{3dB}} = \frac{10^4}{500} = 20$$

Using the data at the top of Table 11.1

$C_A = C_6 = 1.2$ nF

$$R_1 = R_2 = R_3 = R_5 = \frac{1}{\omega_o C}$$

$$= \frac{1}{2\pi 10^4 \times 1.2 \times 10^{-9}} = 13.26 \text{ k}\Omega$$

$$R_6 = Q/\omega_{oC} = \frac{20}{2\pi 10^4 \times 1.2 \times 10^{-9}} = 265 \text{ k}\Omega$$

Now using the data in Table11.1for the bandpass case

K = centre-frequency gain = 10

$1 + r_2/r_1 = 10$

Selecting $r_1 = 10$ kΩ then$r_2 = 90$ kΩ

Ex: 11.20

Eq (16.25) ~ $\omega_p = 2\pi 10^4$

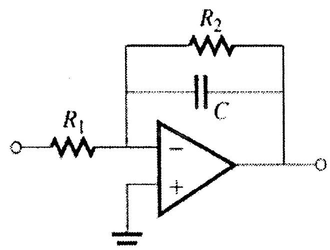
$$T(s) = \frac{\omega_p^5}{8.1408(s+0.2895\omega_p)} \times$$

$$\frac{1}{(s^2+s0.4684\omega_p+0.4293\omega_p^2)} \times$$

$$\frac{1}{(s^2+s0.1789\omega_p+0.9883\omega_p^2)}$$

The circuit consists of 3 sections in cascade:

(a) First order section



the number coefficient was set so that the dc gain =1.

$$T(s) = \frac{-0.2895\omega_p}{s+0.2895\omega_p}$$

Let $R_1 = 10\ k\Omega$

dc gain $= R_2/R_1 = 1 = R_2 = 10\ k\Omega$

as $j\omega \to \infty$

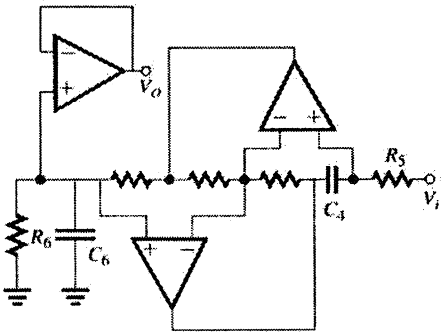
$$|T(j\omega)| \to \frac{0.2985\omega_p}{\omega} = \frac{1}{\omega C R_1}$$

$$C = \frac{1}{0.2895 \times 2\pi 10^4 \times 10^4} = 5.5\ nF$$

(b) Second-Order section with transfer function:

$$T(s) = \frac{0.4295\omega_p^2}{s^2 + 0.4684\omega_p + 0.4293\omega_p^2}$$

where the numerator coefficient was selected to yield a dc gain of unity



Select $R_1 = R_2 = R_3 = R_5 = 10\ k\Omega$

$$\Rightarrow C = \frac{1}{\sqrt{0.4293} \times 2\pi 10^4 \times 10^4} = 2.43\ nF$$

$C_4 = C_6 = C = 2.43nF$

$$Q = \frac{\sqrt{0.4293}\omega_p}{0.4684\omega_p} = 1.4 \Rightarrow R_6 = \frac{Q}{\omega_0 C} = 14\ k\Omega$$

(c) Second-Order Section with Transfer-function:

$$T(s) = \frac{0.9883\omega^2{}_p}{s^2 + s0.1789\omega_p + 0.9883\omega^2{}_p}$$

The circuit is similar to that in (b) above but with

$R_1 = R_2 = R_3 = R_5 = 10\ k\Omega$

$$C_4 = C_6 = \frac{1}{\omega_0 \times 10^4} = \frac{1}{\sqrt{0.9883} \times 2\pi 10^4 \times 10^4}$$

$= 1.6\ nF$

$$Q = \frac{\sqrt{0.9883}}{0.1789} = 5.56$$

Thus $R_6 = Q/\omega_0 C = 55.6\ k\Omega$

Placing the three sections in cascade, i.e. connecting the output of the first-order section to the input of the second-order section in (b) and the output of of section (b) to the input of (c) results in the overall transfer function in eq. 11.25

Ex: 11.21

Refer to the KHN circuit in Fig. 11.24 Choosing $C = 1nF$

$$R = \frac{1}{\omega_0 C} = \frac{1}{2\pi 10^4 \times 10^{-9}} = 15.9\ k\Omega$$

Using Eq. 11.62 and selecting $R_1 = 10\ k\Omega$

$R_f = R_1 = 10\ k\Omega$

Using Eq. 11.63 and setting $R_2 = 10\ k\Omega$

$R_3 = R_2(2Q - 1) = 10(2 \times 2 - 1) = 30\ k\Omega$

$$\text{High freuency gain} = K = 2 - \frac{1}{Q} = 1.5\ V/V$$

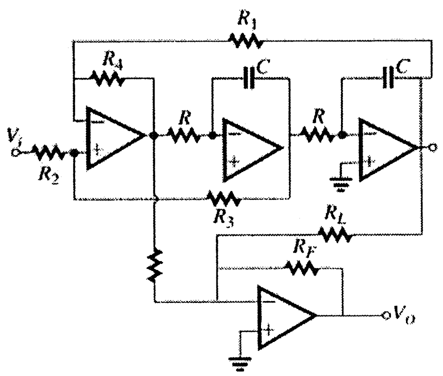
The transfer function to the output of the first integrator is

$$\frac{V_{np}}{V_i} = -\frac{1}{SCR} = \frac{V_{np}}{V_i} = \frac{sK/(CR)}{s^2 + s\frac{\omega_0}{Q} + \omega^2{}_0}$$

Thus the centre-frequency gain

$$= \frac{K\ Q}{CR\omega_0} = KQ = 1.5 \times 2 = 3\ V/V$$

Ex: 11.22



$$\frac{V_o}{V_i} = -K\frac{(R_F/R_H)s^2 + (R_F/R_L)\omega^2{}_o}{s^2 + s\omega_o/Q + \omega^2{}_o}$$

given $C = 1nF$ $R_L = 10\ k\Omega$

$$R = \frac{1}{\omega_{oc}} = \frac{1}{2\pi 5 \times 10^3 \times 10^{-9}} = 31.83\ k\Omega$$

$R_1 = 10\ k\Omega \Rightarrow R_F = 10\ k\Omega$

$R_2 = 10\ k\Omega \Rightarrow R_3 = R_2(2Q - 1)$

$= 10(10 - 1) = 90\ k\Omega$

$$\frac{R_H}{R_L}\omega_o{}^2 = \omega_n{}^2 \Rightarrow R_H = 10\left(\frac{8}{5}\right)^2 = 25.6\ k\Omega$$

$$\text{DC gain} = K\frac{R_F}{R_L} = \left(2 - \frac{1}{Q}\right)\frac{R_F}{R_L} = 3$$

$$R_F = \frac{3 \times 10}{2 - 1/5} = 16.7\ k\Omega$$

Ex: 11.23

Refer to Fig.16.25(b)

$$CR = \frac{1}{\omega_0} \Rightarrow C = \frac{1}{2\pi 10^3 \times 10^4} = 1.59 \text{ nF}$$

$$R_d = QR = 20 \times 10 = 200 \text{ k}\Omega$$

Centre frequency gain = $KQ = 1$

$$\therefore K = \frac{1}{Q} = \frac{1}{20}$$

$$R_g = R/K = 20R = 200 \text{ k}\Omega$$

Ex: 11.24

Refer to Fig11.26and Table 11.2

$$C = 10 \text{ nF}$$

$$R = \frac{1}{\omega_o C} = \frac{1}{10^4 \times 10 \times 10^{-9}} = 10 \text{ k}\Omega$$

$$QR = 5 \times 10 = 50 \text{ k}\Omega$$

$$C_1 = C \times \text{flat gain} = 10 \times 1 = 10 \text{ nF}$$

$$R_1 = \infty$$

$$R_2 = \frac{R}{\text{gain}} = R/1 = 10 \text{ k}\Omega$$

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

$$R_3 = \frac{Q_r}{\text{gain}} = \frac{5 \times 10}{1} = 50 \text{ k}\Omega$$

Ex: 11.25

From eq (11.76

$$CR = \frac{2Q}{\omega_o} = \frac{2 \times 1}{10^4} = 2 \times 10^4 \text{s}$$

For $C = C_1 = C_2 = \text{lnF}$

$$R = \frac{2 \times 10^{-4}}{10^{-9}} = 200 \text{ k}\Omega$$

Thus $R_3 = 200 \text{ k}\Omega$

From eq. (11.75

$$m = 4Q^2 = 4$$

Thus, $R_4 = \frac{R}{M} = \frac{200}{4} = 50 \text{ k}\Omega$

Ex: 11.26

The transfer function of the feedback network is given in Fig. (11.28a.The poles are the roots of the denominator polynomial,

$$s^2 + s\left(\frac{1}{C_1R_3} + \frac{1}{C_2R_3} + \frac{1}{C_1R_4}\right) + \frac{1}{C_1C_2R_3R_4} = 0$$

For $C_1 = C_2 = 10^{-9}$ F, $R_3 = 2 \times 10^5\ \Omega$,

$R_4 = 5 \times 10^4\ \Omega$,

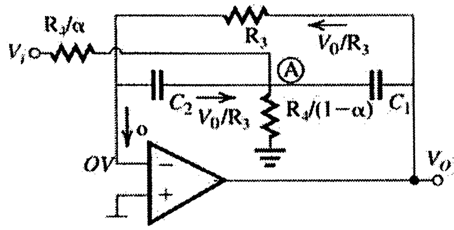
$$s^2 + s\left(\frac{2}{10^{-9} \times 2 \times 10^5} + \frac{1}{10^{-9} \times 5 \times 10^4}\right) + \frac{1}{10^{-18}10^{10}} = 0$$

$$s^2 + s(3 \times 10^4) + 10^8 = 0$$

$$s = \frac{-3 \times 10^4 \pm \sqrt{9 \times 10^8 - 4 \times 10^8}}{2}$$

$$= -0.382 \times 10^4 \text{ and } -2.618 \times 10^4 \ \frac{\text{rad}}{\text{s}}$$

Ex:11.27



$$V_A = O - \frac{V_O}{SC_2R_3}$$

ΣI at (A)

$$\frac{V_O}{R_3} + SC_1(V_O - V_A) + \frac{-V_A}{R_y/(1-\alpha)}$$

$$+ \frac{V_i - V_A}{R_y/\alpha} = 0$$

$$\frac{V_O}{R_3} + SC_1V_O + \frac{SC_1V_O}{SC_2R_3} + \frac{(1-\alpha)V_O}{SC_2R_3R_4} + \frac{\alpha V_i}{R_4}$$

$$+ \frac{\alpha V_O}{SC_2R_3R_4} = 0$$

$$\frac{V_O}{V_i} = \frac{-\alpha/R_4}{SC_1 + 1/R_3 + \frac{C_1}{C_2R_3} + \frac{1}{SC_2R_3R_4}}$$

$$= \frac{-S\alpha/(C_1R_4)}{S^2 + S\left(\frac{1}{C_1R_3} + \frac{1}{C_2R_3}\right) + \frac{1}{C_1C_2R_3R_4}}$$

This is a bandpass function whose poles are identical to the zeros of $t(s)$ in Fig. (11.28a).

For $C_1 = C_2 = 10^{-9}$ F, $R_3 = 2 \times 10^5\ \Omega$ & $R_4 = 5 \times 10^4\ \Omega$

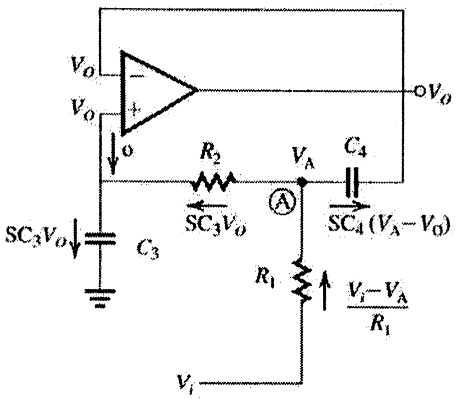
$$\frac{V_O}{V_i} = \frac{-S \times 2 \times 10^4 \times \alpha}{S^2 + S \times 10^4 + 10^8}$$

For unity centre-frequency gain

$$2 \times 10^4 \times \alpha = 10^4 \Rightarrow \alpha = 0.5$$

Thus $\frac{R_4}{\alpha} = 100 \text{ k}\Omega$; $\frac{R_4}{1-\alpha} = 100 \text{ k}\Omega$

Ex: 11.28



$V_A = V_o + SC_3 V_o R_2$
$= V_o(1 + SC_3 R_2)$
ΣI at (A)

$$SC_3V_O - \frac{V_i}{R_1} + \frac{V_O}{R_1} + \frac{V_O}{R_1}SC_3R_2 + V_OSC_4(SC_3R_2)$$

$$\frac{V_i}{R_1} = V_O\left[S^2C_3C_4R_2 + \frac{SC_3R_2}{R_1} + SC_3 + \frac{1}{R_L}\right]$$

$$\frac{V_O}{V_i} = \frac{1/C_3C_4R_1R_2}{S^2 + S\frac{1}{C_4R_2}\left(1 + \frac{R_2}{R_1}\right) + \frac{1}{C_3C_4R_1R_2}}$$

$$\omega_O = \frac{1}{\sqrt{C_3C_4R_1R_2}} \text{ as in Eq. (16.77)}$$

$$Q = \frac{1}{\sqrt{C_3C_4R_1R_2}} \frac{C_4}{\left(\frac{1}{R_1} + \frac{1}{R_2}\right)} \text{ as in Eq (11.78}$$

D.C. gain = 1 Q.E.D.

Ex: 11.29

From Fig 11.34(c)
$R_1 = R_2 = R = 10\ \text{k}\Omega$
$CR = 2Q/\omega_o$

$$C = \frac{2Q}{\omega_O R} = \frac{2/\sqrt{2}}{2\pi(4 \times 10^3)10^4} = 5.63 \text{ nF}$$

$$m = 4Q^2 = 4\left(\frac{1}{2}\right) = 2$$

$C_4 = 2.81$ nF

Ex: 11.30

Refer to the results in Example 11.2
(a) $\Delta R_3/R_3 = +2\%$

$$S_{R3}^{\omega_o} = -1/2 \Rightarrow \frac{\Delta\omega_O}{\omega_O} = -\frac{1}{2} \times 2 = -1\%$$

$$S_{R3}^{Q} = -\frac{1}{2} \Rightarrow \Delta Q/Q = \frac{1}{2} \times 2 = 1\%$$

(b) $\Delta R_4/R_4 = 2\%$

$$S_{R_4}^{\omega_o} = -\frac{1}{2} \Rightarrow \frac{\Delta\omega_O}{\omega_O} = -1\%$$

$$S_{R_4}^{Q} = -\frac{1}{2} \Rightarrow \frac{\Delta Q}{Q} = -\frac{1}{2} \times 2 = -1\%$$

(c) Combining the results in (a) & (b)

$$\frac{\Delta\omega_O}{\omega_O} = -1 - 1 = -2\%$$

$$\frac{\Delta Q}{Q} = 1 - 1 = 0\%$$

(d) using the results in (c) for both resistors being 2% high we have:

$$\frac{\Delta\omega_O}{\omega_O} = S_{C1}^{\omega_o}\frac{\Delta C_1}{C_1} + S_{C2}^{\omega_o}\frac{\Delta C_2}{C_2} - 2$$

$$= -\frac{1}{2}(-2) + \frac{-1}{2}(-2) - 2$$

$$= 2 - 2 = 0\%$$

$$\frac{\Delta Q}{Q} = S_{C1}^{Q}\frac{\Delta C_1}{C} + S_{C2}^{Q}\frac{\Delta C_2}{C_2} + 0$$

$$= 0(-2) + (0)(-2) + 0 = 0\%$$

Ex: 11.31

From Eq (11.96 & (11.97

$C_3 = C_4 = \omega_O T_C C$

$$= 2\pi 10^4 \times \frac{1}{200 \times 10^3} \times 20$$

$= 6.283$ pF

From Eq. (11.99

$$C_5 = \frac{C_4}{Q} = \frac{6.283}{20} = 0.314 \text{ pF}$$

From Eq (11.100

$$\text{Centre-frequency gain} = \frac{C_6}{C_5} = 1$$

$C_6 = C_5 = 0.314$ pF

Ex: 11.32

$R_p = \omega_O L Q_O = 2\pi 10^6 \times 3.2 \times 10^{-6} \times 150 = 3\ \text{k}\Omega$

$R = R_L \| r_O \| R_p = 2\ \text{k}\Omega \Rightarrow R_L = 15\ \text{k}\Omega$

Ex: 11.33

$Q = (R_1 \| R_{in})/\omega_O L$

$$= \frac{10^3 \| 10^3}{(2\pi \times 455 \times 10^3) \times 5 \times 10^{-6}} = 35$$

$BW = f_O/Q = 455/35 = 13$ KHz

$$C_1 + C_{in} = \frac{1}{\omega_O^2 L}$$

$$= \frac{1}{(2\pi \times 455 \times 10^3)^2 \times 5 \times 10^{-6}}$$

$= 24.47$ nF

$C_1 = 24.47 - 0.2 = 24.27$ nF

Ex: 11.34

To just meet specifications

$$Q = \frac{f_O}{BW} = \frac{455}{10} = 45.5$$

$$\therefore \frac{R_1 \| n^2 R_{in}}{\omega_O L} = 45.5$$

$$R_1 \| n^2 R_{in} = 45.5 \times 455 \times 10^3 \times 5 \times 10^{-6}$$

$$= 650\ \Omega$$

$$n^2 R_{in} = 1.86\ \text{k}\Omega$$

$$n = \sqrt{\frac{1.86}{1}} = 1.36$$

$$C_1 + \frac{C_{in}}{n^2} = \frac{1}{\omega_O^2 L} = 24.47$$

$$C_1 = 24.36\ \text{nF}$$

At resonance, the voltage developed across R_1 is $I(R_1 \| n^2 R_{in})$. Thus, $V_{De} = IR/n$ &

$I_C = g_m V_{De} = g_m IR/n$, here

$$\frac{I_C}{I} = g_m R/n = \frac{40 \times 0.65}{1.36} = 19.1 \frac{\text{A}}{\text{A}}$$

Ex: 11.35

$$200 = f_O/Q\sqrt{2^{1/2} - 1} \qquad \text{Eq (16.110)}$$

$$\frac{f_O}{Q} = 310.8\ \text{kHz}$$

$$C = \frac{1}{\omega_O^2 L} = \frac{1}{(2\pi \times 10.7 \times 10^6)^2 \times 3 \times 10^{-6}}$$

$$= 73.7\ \text{pF}$$

$$\frac{\omega_O}{Q} = \frac{1}{C_R}$$

$$R = \frac{1}{73.7 \times 10^{-12} \times 2\pi \times 310.8 \times 10^3}$$

$$= 6.95\ \text{k}\Omega$$

Ex: 11.36

$$f_{O1} = f_O + \frac{2\pi B}{2\sqrt{2}} \qquad \text{Eq(16.115)}$$

$$= 10.7\ \text{MHz} + \frac{200}{2\sqrt{2}}\ \text{kHz} = 10.77\ \text{MHz}$$

$$B_1 = B/\sqrt{2} = 200/\sqrt{2} = 141.4\ \text{KHz}$$

$$f_{O2} = f_O - \frac{2\pi B}{2\sqrt{2}} \qquad \text{Eq(16.116)}$$

$$= 10.7\ \text{MHz} - 200/2\sqrt{2} = 10.63\ \text{MHz}$$

$$B_2 = \frac{200}{\sqrt{2}} = 141.4\ \text{KHz}$$

For stage 1

$$C = \frac{1}{\omega_{O1}^2 L} = \frac{1}{(2\pi\ 10.77 \times 10^6)^2 \times 3 \times 10^{-6}}$$

$$= 72.8\ \text{pF}$$

$$R = \frac{1}{CB_1} = \frac{1}{72.8 \times 10^{-12} \times 141.4 \times 2\pi\ 10^3}$$

$$= 15.5\ \text{k}\Omega$$

For stage 2

$$C = \frac{1}{\omega_{O2}^2 L} = \frac{1}{(2\pi\ 10.63 \times 10^6)^2 \times 3 \times 10^{-6}}$$

$$= 74.7\ \text{pF}$$

$$R = \frac{1}{CB_2} = \frac{1}{74.7 \times 10^{-12} \times 141.4 \times 2\pi\ 10^3}$$

$$= 15.1\ \text{k}\Omega$$

Ex: 11.37

Gain of stagger-tuned amplifier at f_O is proportional to

$$\frac{1}{\sqrt{2}} R_{stage1} \times \frac{1}{\sqrt{2}} R_{stage2}$$

$$= \frac{1}{2} \times 15.5 \times 15.1 = 117$$

Gain of synchronous-tuned amplifier at to

$$\alpha\ R_{stage1} \times R_{stage2}$$

$$= 6.95 \times 6.95$$

$$= 48.3$$

$$\therefore \text{Ratio} = \frac{117}{48.3} = 2.42$$

Ex: 12.1

Pole frequency f_o = 1 kHz

$$\text{Centre frequency gain} = \frac{1}{\text{AMPLIFIER GAIN}}$$

$$= \frac{1}{2}\text{V/V}$$

Ex: 12.2

$$L_+ = V^{R_1/R_5} + V_D\left(1 + \frac{R_4}{R_5}\right)$$

$$= 15\left(\frac{3}{9}\right) + 0.7\left(1 + \frac{3}{9}\right)$$

$$= 5 + 0.93 = +5.93 \text{ V}$$

$$L_- = -V\frac{R_3}{R_2} - V_D\left(1 + \frac{R_3}{R_2}\right)$$

$$= -15 \times \frac{3}{9} - 0.7\left(1 + \frac{3}{9}\right)$$

$$= -5.93 \text{ V/V}$$

$$\text{Limiter gain} = \frac{-R_f}{R_1} = \frac{-60}{30}$$

$$= -2\text{V/V}$$

Thus limiting occurs at $\frac{\pm 5.93}{2}$

$= \pm 2.97$ V

Slope in the limiting regions

$$= \frac{-R_f \| R_4}{R_1} = -\frac{60 \| 3}{30} = -0.095 \frac{\text{V}}{\text{V}}$$

Ex: 12.3

$$\text{(a) } L(s) = \left(1 + \frac{R_2}{R_1}\right)\frac{Z_P}{Z_P + Z_S}$$

$$= \left(1 + \frac{R_2}{R_1}\right)\left(\frac{1}{1 + Z_S Y_P}\right)$$

$$= \left(1 + \frac{20.3}{10}\right)\left(\frac{1}{1 + \left(R + \frac{1}{SC}\right)\left(\frac{1}{R} + SC\right)}\right)$$

$$= \frac{3.03}{3 + SCR + \frac{1}{SCR}}$$

where R = 10 kΩ and C = 16 nF

Thus

$$L(s) = \frac{3.03}{3 + S16 \times 10^{-5} + \frac{1}{S \times 16 \times 10^{-5}}}$$

The closed loop poles are found by setting $L(s) = 1$, that is, they are the values of s, satifiying

$$3 + S \times 16 \times 10^{-5} + \frac{1}{S \times 16 \times 10^{-5}} = 3.03$$

$$\Rightarrow S = \frac{10^5}{16}(0.015 \pm j)$$

(b) The frequency of oscillation is (10^5/16) rad/s or 1 kHz

(c) Refer to fig. 12.5At the positine peak $\hat{V}_O$, the voltage at node b will be one diode drop (0.7 V) above the voltage V_1 which is about 1/3 of V_o; thus $V_b = 0.7 + \hat{v}_O/3$. Now if we neglect the current through D_2 in comparison with the currents through R_5 and R_6 we find that

$$\frac{\hat{V}_O - V_b}{R_5} = \frac{V_b - (-15)}{R_6}$$

Thus,

$$\frac{\hat{V}_O - V_b}{1} = \frac{V_b + 15}{3}$$

$$\hat{V}_O = \frac{4}{3}V_b + 5$$

$$\hat{V}_O = \frac{4}{3}\left(0.7 + \frac{\hat{V}_O}{3}\right) + 5$$

$$\Rightarrow \hat{V}_O = 10.68 \text{ V}$$

from symmetry, we see that the negative peak is equal to the positive peak. Thus the output peak-to-peak voltage is 21.36 V

Ex: 12.4

a) for oscillations to start, $R_2/R_1 = 2$ thus the potentiometer should be set so that its resistance to ground is 20 kΩ

$$\text{(b) } f_o = \frac{1}{2\pi RC} = \frac{1}{2\pi 10 \times 10^3 \times 16 \times 10^{-9}}$$

$$= 1 \text{ kHz}$$

Ex: 12.5

Working from the output back to the input and continuing the equations we get I

$$I = \frac{V_O}{R_f} + \frac{V_O}{SCR_fR} + \frac{V_O}{SCR_fR} + \frac{1}{SCR}$$

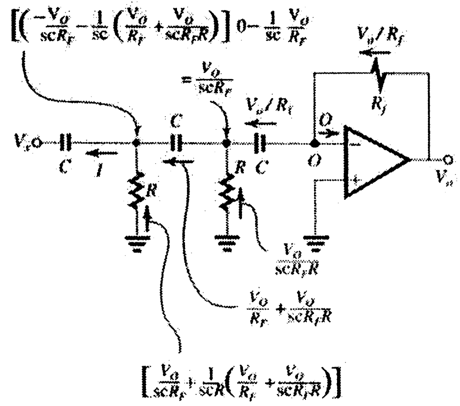
$$\left(\frac{V_O}{R_f} + \frac{V_O}{SCR_fR}\right)$$

$$V_x = \frac{-V_O}{SCR_f} - \frac{1}{SC}\left(\frac{V_O}{R_f} + \frac{V_O}{SCR_fR}\right) - \frac{I}{SC}$$

$$V_x = \frac{-V_O}{SCR_f}\left(2 + \frac{1}{SCR}\right)$$

$$\frac{-V_O}{SCR_f}\left[1 + \frac{1}{SCR} + \frac{1}{SCR} + \frac{1}{SCR}\left(1 + \frac{1}{SCR}\right)\right]$$

$$= \frac{-V_O}{SCR_f}\left(3 + \frac{4}{SCR} + \frac{1}{S^2C^2R^2}\right)$$



Thus:

$$\frac{V_O}{V_x} = \frac{-SCR_f}{3 + \frac{4}{SCR} + \frac{1}{S^2C^2R^2}}$$

$$\frac{V_O}{V_x}(j\omega) = \frac{-j\omega CR_f}{4 + j\left(3\omega CR - \frac{1}{\omega CR}\right)}$$

Ex: 12.6

The circuit will oscillate at the value of ω that makes $\frac{V_O}{V_x}(j\omega)$ a real number.

It follows that ω_o is obtained from

$$3\omega_0 CR = \frac{1}{\omega_0 CR} \Rightarrow \omega_0 = \frac{1}{\sqrt{3}CR}$$

$$\text{Thus, } f_o = \frac{1}{2\pi\sqrt{3} \times 16 \times 10^{-9} \times 10 \times 10^3}$$

$$= 574.3 \text{ Hz}$$

For oscillations to begin, the magnitude of $\frac{V_O}{V_x}(j\omega)$ should equal to (or greater than) unity, that is

$$\frac{\omega_0^2 C^2 RR_f}{4} \ge 1$$

Thus the minimum value of R_f is

$$R_f = \frac{4}{\omega_0^2 C^2 R} = \frac{4\text{ R}}{\omega_0^2 C^2 R^2} = \frac{4\text{ R}}{\frac{1}{3}}$$

$$= 12 \text{ R or } 120 \text{ k}\Omega$$

Ex: 12.7

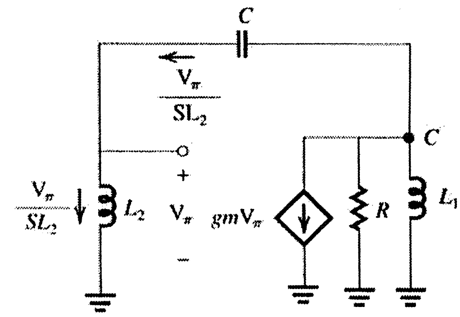
$$\omega_0 = \frac{1}{CR} \Rightarrow CR = \frac{1}{2\pi 10^3}$$

For $C = 16$ nF $R = 10$ kΩ

∴ the output is twice as large as the voltage across the resonator, the peak-to-peak amplitude is

$$\frac{4\text{ V}}{\pi} = \frac{4(2 \times 1.4)}{\pi} = 3.6 \text{ V}$$

Ex: 12.8



$$V_c = V_\pi + \frac{V_\pi}{SL_2} \cdot \frac{1}{SC} = V_\pi\left(1 + \frac{1}{S^2CL_2}\right)$$

Node equation at collector:

$$\frac{V_\pi}{SL_2} + g_m V_\pi + \frac{V_c}{R} + \frac{V_c}{SL_1} = 0$$

$$\frac{V_\pi}{SL_2} + g_m V_\pi + \frac{V_\pi}{R}\left(1 + \frac{1}{S^2CL_2}\right)$$

$$+ \frac{V_\pi}{S_4}\left(1 + \frac{1}{S^2CL_2}\right) = 0$$

Since $V_\pi \neq D$, (oscillations have started) it can be eliminated resulting in

$$S^3 L_1 L_2 C\left(g_m + \frac{1}{R}\right) + S^2(L_1C + L_2C)$$

$$+ S\frac{L_1}{R} + 1 = 0$$

Substituting $S = j\omega$

$$[1 - \omega^2 C(L_1 + L_2)] + j\omega$$

$$\left[\frac{L_1}{R} - \left(g_m + \frac{1}{R}\right) \times \omega^2 L_1 L_2 C\right] = 0$$

$$R_E = 0 \Rightarrow \omega_0 = \frac{1}{\sqrt{C(L_1 + L_2)}} \text{ Q.E.D.}$$

$$I_m = 0 \Rightarrow g_m R + 1 = \frac{1}{\omega_0^2 L_2 C}$$

$$= \frac{L_1 + L_2}{L_2}$$

$$\Rightarrow g_m R = L_1 / L_2$$

for oscillations to start

$g_m R > L_1 / L_2$ Q.E.D.

Ex: 12.9

$$R = \frac{Q}{\omega_0} \| R_L \| r_O$$

$$= \frac{100}{10^6 \times 10^{-8}} \| 2 \times 10^3 \| 100 \times 10^3$$

$$= 10 \| 2 \| 100 = 1.64 \text{ k}\Omega$$

$$\frac{C_2}{C_1} = g_m R = 40 \times 1.64 = 65.6$$

$C_2 = 65.6 \times 0.01 = 0.66\ \mu\text{F}$

$$L = \frac{1}{\omega_0^2 \frac{C_1 C_2}{C_1 + C_2}}$$

$$= \frac{1}{10^{12} \times \frac{0.01 \times 0.66 \times 10^{-6}}{0.01 + 0.66}} \cong 100\ \mu\text{A}$$

Ex: 12.10

from Eq (12.24

$$f_S = \frac{1}{2\pi\sqrt{LC_s}} = \frac{1}{2\pi\sqrt{0.52 \times 0.012 \times 10^{-12}}}$$

$= 2.015$ MHz

from Eq (12.25

$$f_P = \frac{1}{2\pi\sqrt{L\frac{C_S C_P}{C_n + C_p}}}$$

$$= \frac{1}{2\pi\sqrt{0.52 \times \frac{0.012 \times 4 \times 10^{-12}}{0.012 + 4}}}$$

$= 2.018$ MHz

$$Q = \frac{\omega_o L}{r} \cong \frac{\omega_S L}{r}$$

$$= \frac{2\pi \times 2.015 \times 10^6 \times 0.52}{120}$$

$\cong 55,000$

Ex: 12.11

$V_{TH} = V_{TL} = \beta\ |L \pm|$

$$5 = \frac{R_1}{R_1 + R_2} \times 13$$

$$\frac{R_2}{R_1} = 1.6$$

$R_2 = 16\ \text{k}\Omega$

Ex: 12.12

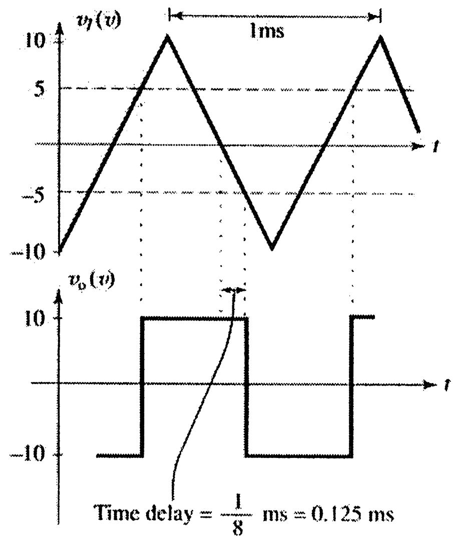
$$V_{TH} - V_{TL} = \frac{R_1}{R_2}|L|$$

$$5 = \frac{R_1}{R_2} \times 10$$

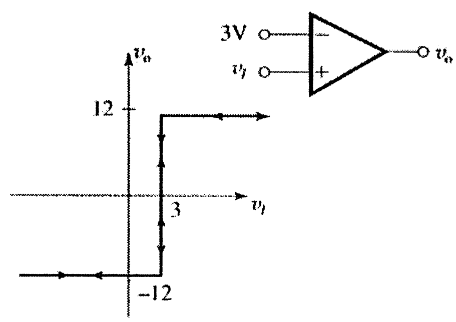
$R_2 = 2R_1$

Possible choice $R_1 = 10\ \text{k}\Omega \quad R_2 = 20\ \text{k}\Omega$

Ex: 12.13



Ex: 12.14



A comparator with a threshold of 3 V and output levels of ± 12 V

Ex: 12.15

$$|V_T| = \frac{100}{2} = 50\ \text{mV}$$

$$50 \times 10^{-3} = 10\frac{R_1}{R_2}$$

$$\frac{R_2}{R_1} = \frac{10}{0.06}$$

$R_2 = 200\ R_1$

for $R_1 = 1\ \text{k}\Omega \quad R_2 = 200\ \text{k}\Omega$

Ex: 12.16

$$\beta = \frac{R_1}{R_1 + R_2} = \frac{100}{100 + 1000} = 0.091\ \frac{\text{V}}{\text{V}}$$

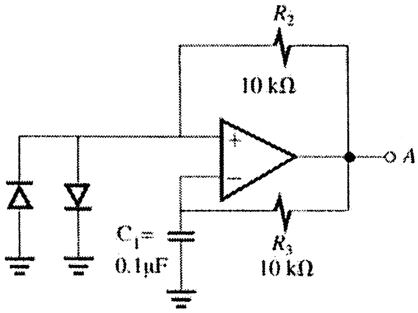
$$T = 2\tau \ln\frac{1+\beta}{1-\beta}$$

$$2 \times 0.01 \times 10^{-6} \times 10^{6} \times \ln\left(\frac{1.091}{1-0.091}\right)$$

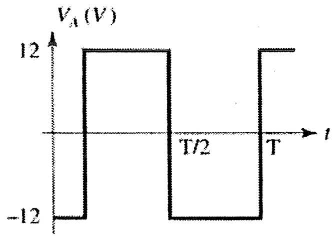
$$= 0.00365 \text{ s}$$

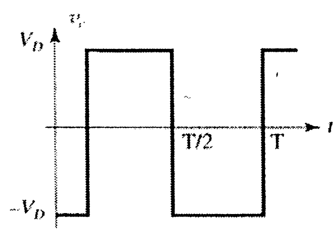
$$f_o = \frac{1}{T} = 274 \text{ Hz}$$

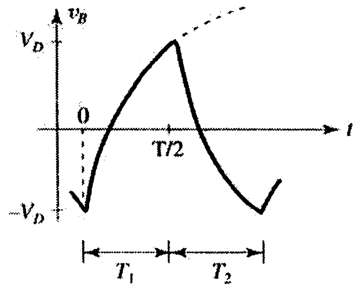
Ex: 12.17



$$T_1 = T_2 = T/2$$







During T_1

$$V_B(t) = 12 - (12 + V_D)e^{-t/\tau}$$

$$V_B = V_D \text{ at } t = T/2$$

$$V_D = 12 - (12 + V_D)e^{-T/2\tau}$$

$$T = 2\tau \ln\left(\frac{12 + V_D}{12 - V_D}\right)$$

$$= 2 \times 0.1 \times 10^{-6} \times 10 \times 10^{3} \times \ln\left(\frac{12 + V_D}{12 - V_D}\right)$$

$$f = \frac{1}{T} = \frac{500}{\ln\left(\frac{12 + V_D}{12 - V_D}\right)}$$

$$f|_{25^\circ C} = \frac{500}{\ln\left(\frac{12.7}{11.3}\right)}$$

$$= 4281 \text{ Hz}$$

At 0°C, $V_D = 0.7 + .05 = 0.75$ V

$$f|_{0^\circ C} = \frac{500}{\ln\left(\frac{12.75}{11.25}\right)} = 3,995 \text{ Hz}$$

At 50°C, $V_D = 0.7 - 0.05 = 0.65$ V

$$f|_{50^\circ C} = \frac{500}{\ln\left(\frac{12.65}{11.35}\right)} = 4,611 \text{ Hz}$$

At 100°C, $V_D = 0.7 - 0.15 = 0.55$ V

$$f|_{100^\circ C} = \frac{500}{\ln\left(\frac{12.55}{11.45}\right)} = 5,451 \text{ Hz}.$$

Ex: 12.18

To obtain a triangular waveform with 10-V peak-to-peak amplitute we should have

$$V_{TH} = -V_{TL} = 5 \text{ V}$$

But $V_{TL} = -L + \frac{R_1}{R_2}$

Thus $-5 = -10 \times \frac{10}{R_2}$

$$R_2 = 20 \text{ k}\Omega$$

For 1 kHz frequency, T = 1ms
Thus,

$$T/2 = 0.5 \times 10^{-3} = CR\frac{V_{TH} - V_{TL}}{4}$$

$$= 0.01 \times 10^{-6} \times R \times 10/10$$

$$R = 50\ \text{k}\Omega$$

Ex: 12.19

Using Eq (12.37

$$100 \times 10^{-6} = 0.1 \times 10^{-6} \times R_3 \ln\left(\frac{12.7}{10.8}\right)$$

$$R_3 = 6171\ \Omega$$

Ex: 12.20

$$T = 1.1CR \Rightarrow R = T/1.1C = 9.1\ \text{k}\Omega$$

Ex: 12.21

$$T = 0.69C(R_A + 2R_B)$$

$$\frac{1}{100 \times 10^3} = 0.69 \times 10^3 \times 10^{-12}(R_A + 2R_B)$$

$$\Rightarrow R_A + 2R_B = \frac{1}{0.69 \times 10^{-4}} = 14.49\ \text{k}\Omega\ (1)$$

Using Eq (13.45)

$$0.75 = \frac{A + R_B}{R_A + 2R_B}$$

$$R_A + R_B = 0.75 \times 14.44 = 10.88\ \text{k}\Omega \quad (2)$$

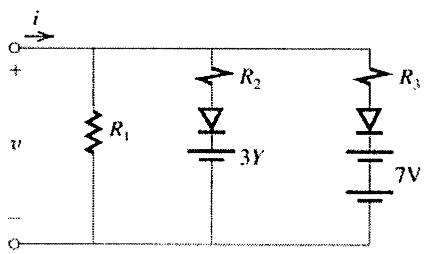
$$(1) - (2) \Rightarrow R_B = 3.61\ \text{k}\Omega$$

Now, substituting into (2)

$$R_A = 7.27\ \text{k}\Omega$$

Use 7.2 kΩ and 3.6 kΩ, standard 5% resistors.

Ex: 12.22



$$i = 0.1\ v^2$$

At $v = 2$ V, $i = 0.4$ mA

$$\text{Thus } R_1 = \frac{2}{0.4} = 5\ \text{k}\Omega$$

For $3V \leq V \leq 7V$

$$i = \frac{v}{R_1} + \frac{v - 3}{R_2}$$

To obtain a perfect match at $V = 4$ V (i.e. to obtain $i = 1.6$ mA)

$$1.6 = \frac{4}{5} + \frac{4 - 3}{R_2}$$

$$R_2 = 1.25\ \text{k}\Omega$$

for $v \geq 7V$

$$i = \frac{v}{R_1} + \frac{v - 3}{R_2} + \frac{v - 7}{R_3}$$

To obtain a perfect match at $v = 8V$ we must have to select R_3 so that $i = 6.4$ mA,

$$6.4 = \frac{8}{5} + \frac{8 - 3}{1.25} + \frac{8.7}{R_3}$$

$$\Rightarrow R_3 = 1.25\ \text{k}\Omega$$

At $v = 3$ V, the circuit provides .

$$i = \frac{3}{5} = 0.6\ \text{mA while ideally}$$

$i = 0.1 \times 9 = 0.9$ mA . Thus the error is -0.3 mA.

* At V = 5V, the circuit provides

$$i = \frac{5}{5} + \frac{5 - 3}{1.25} = 2.6\ \text{mA , while ideally}$$

$i = 0.1 \times 25 = 2.5$ mA . Thus the error is $+0.1$ mA.

* At $v = 7$ V, the circuit provides

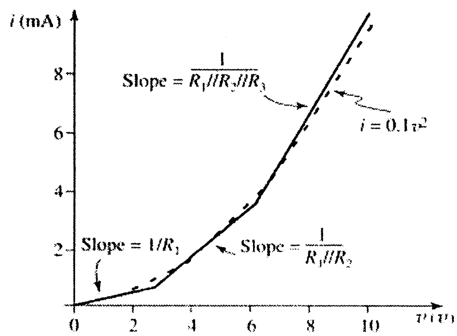
$$i = \frac{7}{5} + \frac{7 - 3}{1.25} = 4.6\ \text{mA , while ideally. Thus}$$

the error is -0.3 mA

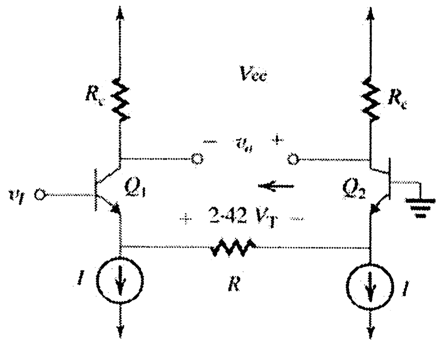
* At $v = 10V$, the circuit provides,

$$i = \frac{10}{6} + \frac{10 - 3}{1.25} + \frac{10 - 7}{1.25} = 10\ \text{mA , while}$$

ideally $i = 10$ mA. Thus the error is 0 A.



Ex: 12.23



$$I_{e_1} = I + (2.42\, V_T)/R$$

$$= I\left[1 + \frac{2.42\, V_T}{I_R}\right]$$

$$= I\left[1 + \frac{2.42\, V_T}{2.5\, V_T}\right]$$

$$= I\left(1 + \frac{2.42}{2.5}\right)$$

$$I_{c_1} \cong I\left(1 + \frac{2.42}{2.5}\right)$$

$$I_{c_2} \cong I\left(1 - \frac{2.42}{2.5}\right)$$

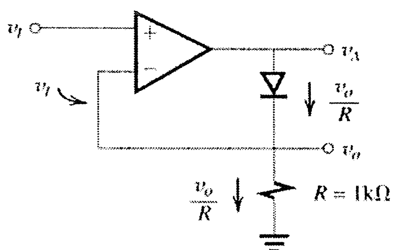
$$v_O = (V_{cc} - I_{c2}R_c) - (V_{cc} - I_{c1}R_c)$$

$$= (I_{c1} - I_{c2})R_c$$

$$= IR_c \times 2 \times \frac{2.42}{2.5}$$

$$= 0.25 \times 10 \times 2 \times \frac{2.42}{2.5} = 4.84 \text{ V}$$

Ex: 12.24



$\therefore$ The opamp is ideal $v_o = v_I$ for $v = > 0$.

$v_I = 10 \text{ mV} \quad v_O = 10 \text{ mV}$

$$i_D = \frac{10 \text{ mV}}{R} = 10\ \mu\text{A}$$

Given $\Rightarrow i_D = 1 \text{ mA} \quad 0.1 \text{ mA} \quad 10\ \mu\text{A}$

$v_D = 0.7 \text{ V} \quad 0.6 \text{ V} \quad 0.5 \text{ V}$

Thus, $v_D = 0.5$ V so

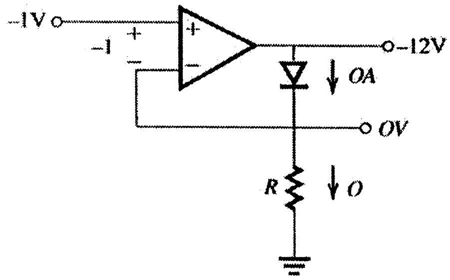
$v_A = v_O + v_D = 0.51$ V

$v_I = 1 \text{ V} \Rightarrow v_O = 1$ V

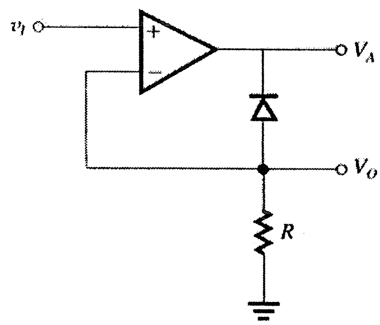
$i_D = 1$ mA, $v_D = 0.7$ V $v_A = 1.7$ V

$v_I = -1$ V ~ The negative feedback loop is not operative.

$v_o = 0 \text{ V} \; v_A = -12$ V



Ex: 12.25



For the diode to conduct and close the negative feedback loop, v_o must be negative, in which case, the negative feedback causes a virtual short circuit to appear between the input terminals of the op amp and thus $v_o = v_I$ For positive v_I, the op amp saturates in the positive saturation level. The diode will be cut off and $v_D = 0$.

In summary

$v_o = 0$ for $v_I \geq 0$

$v_o = v_I$ for $v_I \leq 0$

Ex: 12.26

Refer to Fig. 12.34

For $v_I = +1$ V:

D_2 will conduct and close the negative feedback loop around the op amp. $v\_ = 0$, the current through R_1 and D_2 will be 1 mA. Thus the voltage at the op amp output, $v_A = -0.7$ V which will set

D_1 off and no current will flow through R_2. Thus
$v_D = 0$ V

For $v_I = -10$ mV

D_1 will conduct through R_2 & R_1 to v_I. The negative feedback loop of the op amp will thus be closed and a virtual ground will appear at the inverting input terminal. D_2 will be cutoff. The current through R_1, R_2 and D_1 will be

$\frac{10\text{ mV}}{1\text{ k}\Omega} = 10\ \mu\text{A}$. Thus the diode, D_1, voltage will be 0.5 V.

$v_o = 0 + 10\ \mu\text{A} \times 10\text{ k}\Omega = +0.1$ V

$v_A = v_{D1} + v_o = 0.5 + 0.1 = 0.6$ V

For $v_I = -1$ V

This is similar to the case when $v_I = -10$ mV. The current through R_1, R_2, D_1 will be

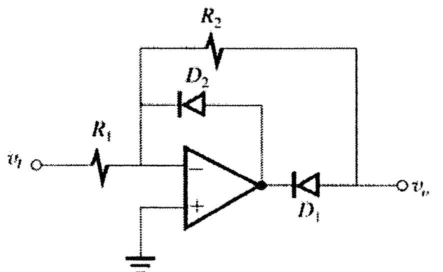
$$I = \frac{1}{1\text{ k}\Omega} = 1\text{ mA}$$

$\therefore\ v_{D1} = 0.7$ V

$v_O = 0 + 1\text{mA} \times 10\text{ k}\Omega = 10$ V

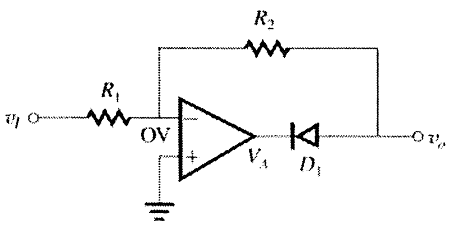
$v_A = 10 + v_{D1} = 10.7$ V

Ex: 12.27



$v_I > 0$

Current flows from v_I through R_1, R_2, D_2 into the output terminal of the opamp. v_0 goes negative and is thus off. The following circuit results:



$$\frac{v_0}{v_I} = \frac{-R_2}{R_1}$$

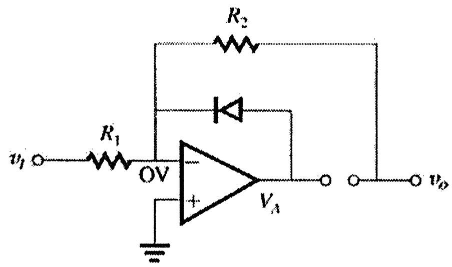
$v_I < 0$ ~ D_1 on

~ v_0 goes the & forms D_1 off

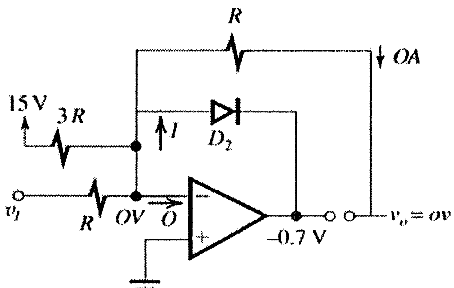
~ no current flows through

$R_2 = v_0 = 0$ V

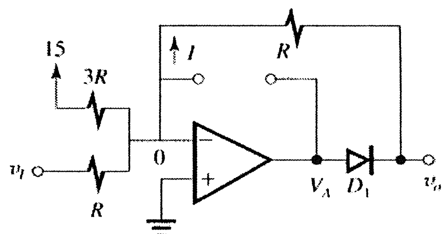
~ $V_A = 0.7$ V



Ex: 12.28



$VI > 0$ - Equivalant Circuit
~ D_2 on , D_1 off



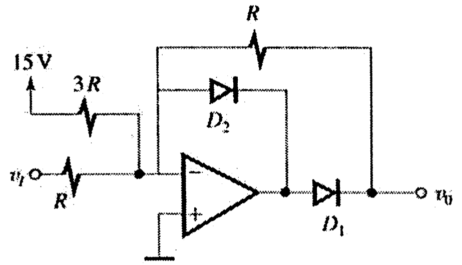
$$I = \frac{15}{3R} + \frac{v_I}{R}$$

As v_I goes negative, the above circuit holds so that $v_0 = 0$. This occurs as the 15 V supply sources the current I even for small negative v_I. This situation remains the case until $I = 0$

$$\therefore\ \frac{15}{3R} + \frac{v_I}{R} = 0$$

$v_I = -5$ V

$v_I < -5$ V ~ D_2 off D_1 -on



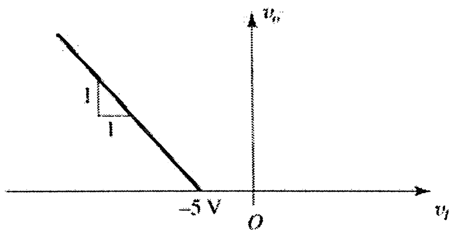
$v_0 = 0 - IR$

$= 0 - \left(\frac{15}{3R} + \frac{v_I}{R}\right)R$

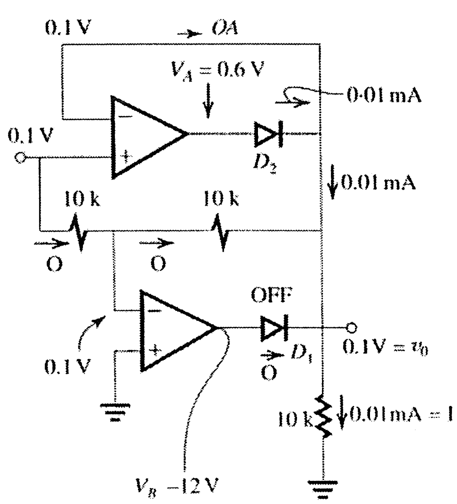
$= -v_I - 5$

note $v_A = v_0 + 0.7 = -v_I - 4.3 > 0$

$\therefore\ v_{D2} = 0 - V_A < 0 - D_2$ off!



Ex: 12.29



a) $v_I = 0.1$ V

NB

for all circuits, currents are given in mA, resistance in kΩ & voltages in V.

b) $v_I = 1$ V ~ similar to the circuit in (a) but with all of the undergrounded opamp input terminals at $v_I = 1$ V

$v_0 = 1$ V

$I = 1 / 10\ \text{k}\Omega = 0.1$ mA

$v_A = 1 + U_{D2}$

$= 1 + 0.7 + 0.1 \log\left(\frac{0.1}{1}\right)$

$= 1.6$ V

(c)

$v_I = 10$ V ~ similar to (a) & (b)

~ all input terminals (not grounded) of opamps is equal to 10 V.

$v_0 = 10$ V

$I = \frac{10}{10} = 1$ mA ~ diode voltages = 0.7 V

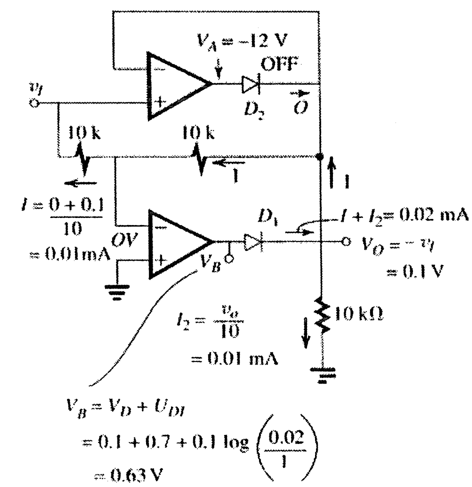
$V_A = v_0 + U_{D2} = 10 + 0.7 = 10.7$ V

d) $v_I = 0.1$ V

$V_B = V_D + V_{D1}$

$= 0.1 + 0.7 + 0.1 \log\left(\frac{0.02}{1}\right)$

$= 0.63$ V



(e) $v_I = -1$ V - use circuit in (d)

$I = 0.1$ mA

$V_0 = -v_I = 1$ V

$I_2 = 0.1$ mA

$I_{D1} = I + I_2 = 0.2$ mA

$V_B = V_0 + V_{D1}$

$= 1 + 0.7 + 0.1 \log\left(\frac{0.2}{1}\right)$

$= 1.63$ V

(f) $v_I = -10$ V use circuit (d)

$I = .0$ mA

$v_0 = -v_1 = 10$ V

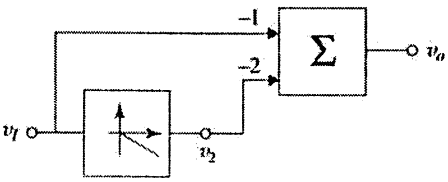
$I_2 = 1.0$ mA

$I_m = 2$ mA

$$V_B = V_0 + V_{D1} = 10 - 0.7 + 0.1\ \log\left(\frac{2}{1}\right)$$

$= 10.73$ V

Ex: 12.30



For $v_I \geq 0$, i.e. $v_I = |v_I|$,

$v_2 = -|v_I|$ and

$v_0 = -|v_I| - 2 \times -|v_I| = +|v_I|$

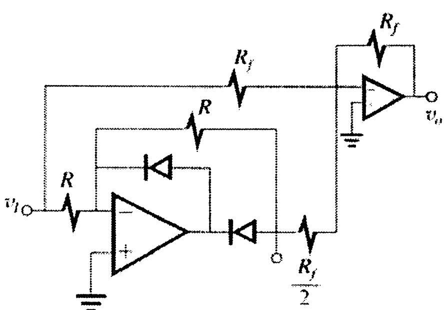
For $v_I \leq 0$, i.e. $v_I = -|v_I|$

$v_2 = 0$, $v_0 = -|x - |v_I||$

$= +|v_I|$

Thus, the block diagram implements the absolute value operation.

Using the circuits of Fig(12.34 a), with the diodes reversed, to implement the half-wave rectifier, and a weighted summer results in the circuit shown below.



Use $R = R_f = 10\ k\Omega$

Ex: 12.31

v_A is a sinusoid of 5-V rms (peak voltage of $5\sqrt{2}$) The average current through the meter will be $\frac{2}{\pi} \times \frac{5\sqrt{2}}{R}$. To obtain full-scale leading. This current must be equal to 1 mA. Thus $\frac{2}{\pi} \times \frac{5\sqrt{2}}{R} =$ 1 mA, which leads to $R = 4.5\ k\Omega$

V_c will be maximum when V_A is at its positive peak, i.e. $v_A = 5\sqrt{2}$ V. At this value of VA, we obtain

$v_c = V_{D1} + V_M + V_{D3} + V_R$ where

$V_{D1} = V_{D3} \cong 0.7$ V and

$$V_M = \frac{5\sqrt{2}}{4.5} \times 0.05 = 0.08 \text{ V}$$

Thus

$V_c|_{max} = 0.7 + 0.8 + 0.7 + 5\sqrt{2} = 8.55$ V

Similarly we can calculate :

$v_c|_{min} = -8.55$ V

Ex 13.1

For Q_1

$$I = \frac{V_{CC} - V_{CEsat}}{R_L} = \frac{15 - 0.2}{1\ k\Omega}$$

$I = 14.8$ mA

$$R = \frac{-V_D - (-V_{CC})}{14.8} = \frac{-0.7 - (-15)}{14.8}$$

$= 0.97\ k\Omega$

$v_{omax} = V_{CC} - V_{CEsat}$
$= 15 - 0.2$
$= 14.8$ V

$v_{omin} = -V_{CC} + V_{CEsat}$
$= -15 + 0.2$
$= -14.8$

Output signal swing is from 14.8 V to -14.8 V

Maximum emitter current $= 2I = 2 \times 14.8$
$= 29.6$ mA

Ex 13.2

At $v_o = -10$ V, the load current is -10 mA and the emitter current of Q_1 is $14.8 - 10 = 4.8$ mA.

Thus, $v_{BE1} = 0.6 + 0.025\ \ln\left(\frac{14.8}{1}\right)$

$= 0.64$ V

Thus, $v_I = -10 + 0.64 = -9.36$ V

At $v_o = 0$ V, $i_L = 0$ and $i_{E1} = 14.8$ mA

Thus, $v_{BE1} = 0.6 + 0.025\ \ln\frac{4.8}{1}$

$= 0.67$ V

$v_I = +0.67$ V

At $v_o = +10$ V, $i_L = 10$ mA and $i_{E1} = 24.8$ mA

Thus, $v_{BE1} = 0.6 + 0.025\ \ln(24.8)$

$= 0.68$ V

$v_I = 10.68$ V

To calculate the incremental voltage gain we use

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + r_{e1}}$$

At $v_o = -10$ V, $i_{E1} = 4.8$ mA and

$$r_{e1} = \frac{25}{4.8} = 5.2\ \Omega$$

Thus, $\frac{v_o}{v_i} = \frac{1}{1 + 0.0052} = 0.995$ V / V

Similarly, at $v_o = 0$ V, $r_{e1} = \frac{25}{14.8} = 1.7\ \Omega$

and, $\frac{v_o}{v_i} = \frac{1}{1 + 0.0017} = 0.998$ V / V

At $v_o = +10$ V, $i_{E1} = 24.8$ mA and $r_{e1} = 1\ \Omega$

Thus, $\frac{v_o}{v_i} = \frac{1}{1 + 0.001} = 0.999$ V / V

Ex 13.3

a. $P_L = \frac{(\hat{V}_o/\sqrt{2})^2}{R_L} = \frac{(8/\sqrt{2})^2}{100} = 0.32$ W

$P_S = 2\,V'_{CC} \times I = 2 \times 10 \times 100 \times 10^{-3}$
$= 2$ W

Efficiency $\eta = \frac{P_L}{P_S} \times 100$

$= \frac{0.32}{2} \times 100$

$= 16\%$

Ex 13.4

(a) $P_L = \frac{1}{2}\frac{\hat{V}_o^2}{R_L}$

$= \frac{1}{2}\frac{(4.5)^2}{4} = 2.53$ W

(b) $P_+ = P_- = V_{CC} \times \frac{1}{\pi}\frac{\hat{V}_o}{R_L}$

$= 6 \times \frac{1}{\pi} \times \frac{4.5}{4} = 2.15$ W

(c) $\eta = \frac{P_L}{P_S} \times 100 = \frac{2.53}{2 \times 2.15} \times 100$

$= 59\%$

(d) Peak input currents $= \frac{1}{\beta + 1}\frac{\hat{V}_o}{R_L}$

$= \frac{1}{51} \times \frac{4.5}{4}$

$= 22.1$ mA

(e) Using Eq. 10.22

$$P_{DNmax} = P_{DPmax} = \frac{V_{CC}^2}{\pi^2 R_L}$$

$$= \frac{6^2}{\pi^2 \times 4} = 0.91\ W$$

Ex 13.5

(a) The quiescent power dissipated in each transistor $= I_Q \times V_{CC}$

Total power dissipated in the two transistors
$= 2I_Q \times V_{CC}$
$= 2 \times 2 \times 10^{-3} \times 15$
$= 60$ mW

(b) I_Q is increased to 10 mA

At $V_o = 0$, $i_N = i_P = 10$ mA

From equation 13.31

$$R_{out} = \frac{V_T}{i_P + i_N} = \frac{25}{10 + 10} = 1.25\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{out}} = \frac{100}{100 + 1.25}$$

$\frac{v_o}{v_i} = 0.988$ at $v_o = 0$ V

At $v_o = 10$ V,

$$i_L = \frac{10\ \text{V}}{100\ \Omega} = 0.1\ \text{A} = 100\ \text{mA}$$

use equation 13.27 to calculate i_N

$i_N^2 - i_N i_L - I_Q^2 = 0$

$i_N^2 - 100\, i_N - 10^2 = 0$

$\Rightarrow i_N = 99.99$ mA

using equation 13.26

$$i_P = \frac{I_Q^2}{I_N} \simeq 1\ \text{mA}$$

$$R_{out} = \frac{V_T}{i_N + i_P} = \frac{25}{99.99 + 1} \simeq 0.2475\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{out}} = \frac{100}{100 + 0.2475} \simeq 1$$

$$\%\ \text{change} = \frac{1 - 0.988}{1} \times 100 = 1.2\%$$

In example 13.5 $I_Q = 2$ mA, and for $v_o = 0$

$$R_{out} = \frac{V_T}{i_N + i_P} = \frac{25}{2 + 2} = 6.25\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{out}} = \frac{100}{100 + 6.25} = 0.94$$

$v_o = 10$ V

$$I_L = \frac{10\ \text{V}}{100\ \Omega} = 100\ \text{mA}$$

Again calculate i_N (for $I_Q = 2$ mA) using equation 13.27 $i_N = 99.96$ mA

$$i_P = \frac{I_Q^2}{I_N} = \frac{2^2}{99.96} = 0.04\ \text{mA}$$

$$R_{out} = \frac{V_T}{i_N + i_P} = \frac{25}{99.6 + 0.04} = 0.25\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{out}} \simeq 1$$

$$\%\ \text{Change} = \frac{1 - 0.94}{1} \times 100 = 6\%$$

For $I_Q = 10$ mA, change is 1.2%

For $I_Q = 2$ mA, change is 6%

(c) The quiesent power dissipated in each transistor $= I_Q \times V_{CC}$

Total power dissipated $= 2 \times 10 \times 10^{-3} \times 15$
$= 300$ mW

Ex 13.6

From example 13.4 $V_{CC} = 15$ V, $R_L = 100\ \Omega$

Q_N and Q_P matched and $I_S = 10^{-13}$ A and $\beta = 50$, $I_{Bias} = 3$ mA

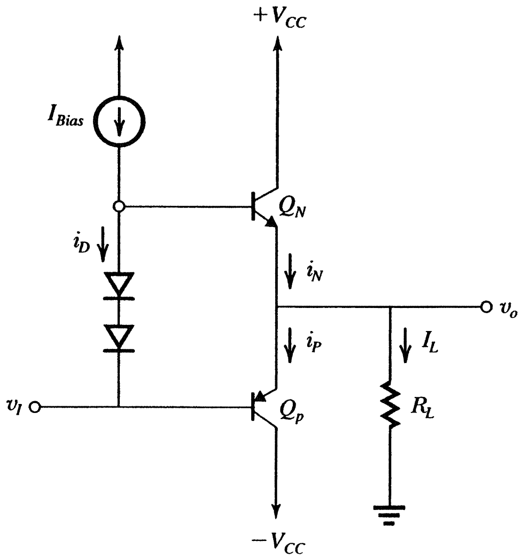
For $v_o = 10$ V, $I_L = \frac{10}{100} = 0.1$ A

As a first approximation $i_N \simeq 0.1$ A, $i_P = 0$, $i_{BN} \simeq \frac{0.1\ \text{A}}{50 + 1} \simeq 2$ mA

$i_D = I_{Bias} - i_{BN} = 3 - 2 = 1$ mA

$$V_{BB} = 2\, V_T \ln\left(\frac{10^{-3}}{\frac{1}{3} \times 10^{-13}}\right)$$

This $\frac{1}{3}$ is because biasing diodes have $\frac{1}{3}$ area of the output devices.



But $V_{BB} = V_{BEN} + V_{BEP} =$ (1)

$$V_T \ln\left(\frac{i_N}{I_S}\right) + V_T \ln\left(\frac{i_N - i_L}{I_S}\right)$$

$$= V_T \ln\left[\frac{i_N(i_N - i_L)}{I_S^2}\right] \quad (2)$$

Equating equations 1 and 2

$$2V_T \ln\left(\frac{10^{-3}}{\frac{1}{3} \times 10^{-13}}\right) = V_T \ln\left(\frac{i_N - i_L}{I_S^2}\right)$$

$$\left(\frac{10^{-3}}{\frac{1}{3} \times 10^{-13}}\right)^2 = \frac{i_N(i_N - 0.1)}{(10^{-13})^2}$$

$i_N(i_N - 0.1) = 9 \times 10^{-6}$

If i_N is in mA, then

$i_N(i_N - 100) = 9$

$i_N^2 - 100\, i_N - 9 = 0$

$\Rightarrow i_N = 100.1$ mA

$i_P = i_N - i_L = 0.1$ mA

For $v_O = -10$ V and $i_L = \frac{-10}{100} = -0.1$ A
$= -100$ mA

As a first approximation assume $i_P \cong 100$ mA, $i_N \simeq 0$ since $i_N = 0$, current through diodes $= 3$ mA

$$\therefore V_{BB} - 2V_T\ln\left(\frac{3\times10^{-3}}{\frac{1}{3}\times10^{-13}}\right) \qquad (3)$$

But $V_{BB} = V_T\ln\left(\frac{i_N}{10^{-13}}\right) + V_T\ln\left(\frac{i_P}{10^{-13}}\right)$

$$= V_T\ln\left(\frac{i_P - i_L}{10^{-13}}\right) + V_T\ln\left(\frac{i_P}{10^{-13}}\right) \quad (4)$$

Here $i_L = 0.1$ A

Equating equations 3 and 4

$$2V_T\ln\left(\frac{3\times10^{-3}}{\frac{1}{3}\times10^{-13}}\right) =$$

$$V_T\ln\left(\frac{i_P - 0.1}{10^{-13}}\right) + V_T\ln\left(\frac{i_P}{10^{-13}}\right)$$

$$\left(\frac{3\times10^{-3}}{\frac{1}{3}\times10^{-13}}\right)^2 = \frac{i_P(i_P-0.1)}{(10^{-13})^2}$$

$i_P(i_P - 0.1) = 81\times10^{-6}$

Expressing currents in mA

$i_P(i_P - 100) = 81$

$i_P^2 - 100\,i_P - 81 = 0$

$\Rightarrow i_P = 100.8$ mA

$i_N = i_P - i_L = 0.8$ mA

Ex 13.7

$\Delta I_C = g_m \times 2\text{ mV}/°\text{C}\times 5\ °\text{C}$, mA

where g_m is in mA / mV

$$g_m = \frac{10\text{ mA}}{25\text{ mV}} = 0.4\text{ mA/mV}$$

Thus, $\Delta I_C = 0.4\times2\times5 = 4$ mA

Ex 13.8

Refer to Fig. 10.14

(a) To obtain a terminal voltage of 1.2 V, and since β_1 is very large, it follows, that $V_{R1} = V_{R2} = 0.6$ V.

Thus $I_{C1} = 1$ mA

$$I_R = \frac{1.2\text{ V}}{R_1 + R_2} = \frac{1.2}{2.4} = 0.5\text{ mA}$$

Thus, $I = I_{C1} + I_R = 1.5$ mA

(b) For $\Delta V_{BB} = +50$ mV:

$V_{BB} = 1.25$ V $\quad I_R = \frac{1.25}{2.4} = 0.52$ mA

$$V_{BE} = \frac{1.25}{2} = 0.625\text{ V}$$

$$I_{C1} = 1\times e^{\Delta V_{BE}/V_T} = e^{0.025/0.025}$$

$= 2.72$ mA

$I = 2.72 + 0.52 = 3.24$ mA

For $\Delta V_{BB} = +100$ mV

$V_{BB} = 1.3$ V $I_R = \frac{1.3}{2.4} = 0.54$ mA

$$V_{BE} = \frac{1.3}{2} = 0.65\text{ V}$$

$$I_{C1} = 1\times e^{\Delta V_{BE}/V_T} = 1\times e^{0.05/0.025}$$

$= 7.39$

$I = 7.39 + 0.54 = 7.93$ mA

For $\Delta V_{BB} = +200$ mV:

$V_{BB} = 1.4$ V $\quad I_R = \frac{1.4}{2.4} = 0.58$ mA

$V_{BE} = 0.7$ V

$I_{C1} = 1\times e^{0.1/0.025} = 54.60$ mA

$I = 54.60 + 0.58 = 55.18$ mA

For $\Delta V_{BB} = -50$ mV

$V_{BB} = 1.15$ V $\quad I_R = \frac{1.15}{2.4} = 0.48$ mA

$$V_{BE} = \frac{1.15}{2}$$

$= 0.575$

$I_{C1} = 1\times e^{-0.025/0.025} = 0.37$ mA

$I = 0.48 + 0.37 = 0.85$ mA

For $\Delta V_{BB} = -100$ mV:

$V_{BB} = 1.1$ V $I_R = \frac{1.1}{2.4} = 0.46$ mA

$V_{BE} = 0.55$ V

$I_{C1} = 1\times e^{-0.05/0.025} = 0.13$ mA

$I = 0.46 + 0.13 = 0.59$ mA

For $\Delta V_{BB} = -200$ mV:

$V_{BB} = 1.0$ V $\quad I_R = \frac{1}{2.4} = 0.417$ mA

$V_{BE} = 0.5$ V

$I_{C1} = 1\times e^{-0.1/0.025} = 0.018$ mA

$I = 0.43$ mA

Ex 13.9

Using equation 13.43

$$I_Q = I_{\text{Bias}}\frac{(W/L)_n}{(W/L)_1}$$

$$1 = 0.2\,\frac{(W/L)_n}{(W/L)_P}$$

$$\frac{(W/L)_n}{(W/L)_1} = 5$$

$$Q_1:\ I_{\text{Bias}} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_1(V_{GS} - V_{tn})^2$$

$$0.2 = \frac{1}{2}\times0.250\left(\frac{W}{L}\right)_1(0.2)^2$$

$$\Rightarrow\left(\frac{W}{L}\right)_1 = 40$$

Q_2: $I_{\text{Bias}} = \frac{1}{2} k_P'\left(\frac{W}{L}\right)_2 (V_{GS} - |V_t|)^2$

$$0.2 = \frac{1}{2} \times 0.100 \times \left(\frac{W}{L}\right)_2 \times (0.2)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_2 = 100$$

Q_N: $I_Q = \frac{1}{2} k_n'\left(\frac{W}{L}\right)_N (V_{GS} - V_t)^2$

$$1 = \frac{1}{2} \times 0.250 \times \left(\frac{W}{L}\right)_N 0.2^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_N = 200$$

Q_P: $I_Q = \frac{1}{2} k_p'\left(\frac{W}{L}\right)_P (V_{GS} - |V_t|)^2$

$$1 = \frac{1}{2} \times 0.100 \times \left(\frac{W}{L}\right)_P \times 0.2^2$$

$$\left(\frac{W}{L}\right)_P = 500$$

Now $V_{GG} = V_{GS1} + V_{GS2}$

$= (V_{ov1} + V_t) + (V_{ov2} + |V_t|)$

$= (0.2 + 0.5) + (0.2 + 0.5)$

$= 1.4$ V

Ex 13.10

$I_N = i_{L\max} = 10$ mA

$$\therefore 10 = \frac{1}{2} k_n' \left(\frac{W}{L}\right)_n V_{ov}^2$$

$$10 = \frac{1}{2} \times 0.250 \times 200 \times V_{ov}^2$$

$$\Rightarrow V_{ov} = 0.63 \text{ V}$$

Using equation 13.46

$V_{o\max} = V_{DD} - V_{ov}|_{\text{Bias}} - V_{tn} - V_{ovN}$

$= 2.5 - 0.2 - 0.5 - 0.63$

$= 1.17$ V

Ex 13.11

New values of W/L are

$$\left(\frac{W}{L}\right)_P = \frac{2000}{2} = 1000$$

$$\left(\frac{W}{L}\right)_N = \frac{800}{2} = 400$$

$$I_Q = \frac{1}{2} k_p'\left(\frac{W}{L}\right)_P V_{ov}^2$$

$$1 \times 10^{-3} = \frac{1}{2} \times 0.1 \times 10^{-3} \times 1000 \times V_{ov}^2$$

$$\Rightarrow V_{ov} = 0.14 \text{ V}$$

Gain Error =

$$-\frac{V_{ov}}{4\mu I_Q R_L} = -\frac{0.14}{4 \times 10 \times 1 \times 10^{-3} \times 100}$$

$= -0.035$

Gain Error $= -0.035 \times 100 = 3.5\%$

$$g_{mn} = g_{mp} = \frac{2I_Q}{V_{ov}} = \frac{2 \times 1 \times 10^{-3}}{0.14}$$

$= 14.14$ mA/V

$$R_{\text{out}} = \frac{1}{\mu(g_{mp} + g_{mn})} =$$

$$\frac{1}{10 \times (14.14 + 14.14) \times 10^{-3}}$$

$\simeq 3.5\ \Omega$

Ex 13.12

See solution on next page

Ex 13.12

Need to prove when $V_{o2} = 4\,I_Q R_L$ then $V_{GSN2} = V_{tn}$

Assume Q_N off ($V_{GSN} = V_{tn}$) so $i_{N2} = 0$ and

$i_{p2} = i_{L2}$

$$i_{p2} = i_{L2} = \frac{V_{O2}}{R_L} = 4I_Q$$

$$4I_Q = \frac{1}{2}k_p'\left(\frac{W}{L}\right)_p (V_{SGP2} - |V_{tp}|)^2$$

$$\sqrt{4\left(\cancel{\frac{1}{2}}\cancel{k_p'}\left(\cancel{\frac{W}{L}}\right)_p (V_{SGPQ} - |V_{tp}|)^2\right)}$$

$$= \sqrt{\cancel{\frac{1}{2}}\cancel{k_p'}\left(\cancel{\frac{W}{L}}\right)_p (V_{SGP2} - |V_{tp}|)^2}$$

$$2(V_{SGPQ} - |V_{tp}|) = (V_{SGP2} - |V_{tp}|)$$

$$V_{SGP2} = 2V_{SGPQ} - 2|V_{tp}| + |V_{tp}|$$

$$= 2V_{SGPQ} - |V_{tp}| \qquad (1)$$

Find V_{i2} for the gate voltage, V_{GP2}:

$$V_{GP2} = (V_{DD} - V_{SGPQ}) + \mu(V_{O2} - V_{i2})$$

$$(V_{GP2} - V_{DD}) = -V_{SGPQ} + \mu(V_{O2} - V_{i2})$$

$$[V_{GSP2}\ \text{OR}] - V_{SGP2} = -V_{SGPQ} + \mu(V_{O2} - V_{i2})$$

using (1):

$$-2V_{SGPQ} + |V_{tp}| = -V_{SGPQ} + \mu(V_{O2} - V_{i2})$$

$$\mu(V_{i2} - V_{O2}) = -V_{SGPQ} + 2V_{SGPQ} - |V_{tp}|$$

$$V_{i2} = +V_{O2} + \frac{(V_{SGPQ} - |V_{tp}|)}{\mu} = V_{O2} + \frac{V_{OVQ}}{\mu}$$

Plug this value for V_{i2} into the value for V_{GN2}

and show $V_{GSN2} = V_{tN}$

$$(-\cancel{V_{SS}} + V_{GSNQ}) + \mu(V_{O2} - V_{i2}) = V_{GN2} - (-\cancel{V_{SS}})$$

$$V_{GSNQ} + \cancel{\mu}\left(\cancel{V_{O2}} - \cancel{V_{O2}} - \frac{V_{OVQ}}{\cancel{\mu}}\right) = V_{GSN2}$$

where

$$V_{OVQ} = (V_{GSNQ} - V_{tn}) = (V_{SGPQ} - |V_{tp}|)$$

$$\cancel{V_{GSNQ}} - \cancel{V_{GSNQ}} + V_{tn} = V_{GSN2}\ \text{Q.E.D.}$$

Same proof for p transistor.

Ex 13.13

$T_J - T_A = \theta_{JA} P_D$

$200 - 25 = \theta_{JA} \times 50$

$$\theta_{JA} = \frac{175}{50} = 3.5°C/W$$

But, $\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA}$

$3.5 = 1.4 + 0.6 + \theta_{SA}$

$\Rightarrow \quad \theta_{SA} = 1.5°C/W$

$T_J - T_C = \theta_{JC} \times P_D$

$T_C = T_J - \theta_{JC} \times P_D$

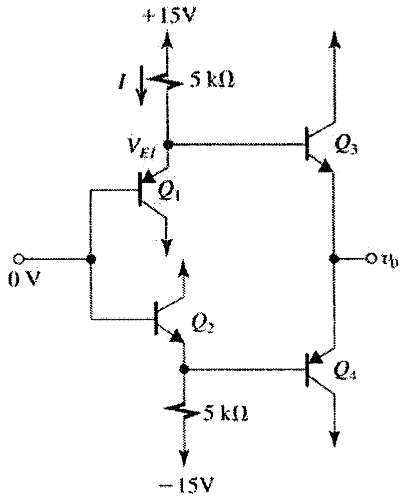
$= 200 - 1.4 \times 50$

$= 130° C$

Ex 13.14

(a) From symmetry we see that all transistors will conduct equal currents and have equal V_{BE}'s Thus.

$v_o = 0\text{ V}$



If $V_{BE} \simeq 0.7$ V Then

$$V_{E1} = 0.7 \text{ V and } I_1 = \frac{15 - 0.7}{5} = 2.86 \text{ mA}$$

If we neglect I_{B3} then

$I_{C1} \simeq 2.86$ mA

At this current, V_{BE} is given by

$$V_{BE} = 0.025 \ln\left(\frac{2.86 \times 10^{-3}}{3.3 \times 10^{-14}}\right) \simeq 0.63 \text{ V}$$

Thus $V_{E1} = 0.63$ V and $I_1 = 2.87$ mA

No more iterations are required and

$i_{C1} = i_{C2} = i_{C3} = i_{C4} \simeq 2.87$ mA

(b) For $v_I = +10$ V:

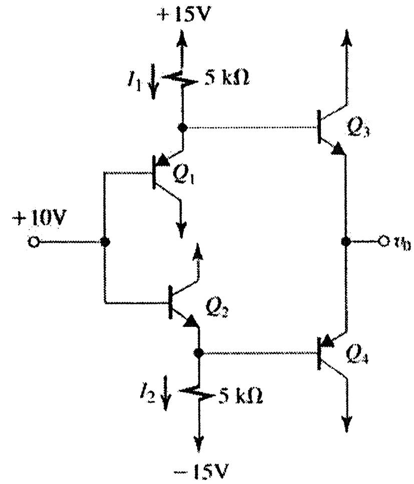
To start the iterations let $V_{BE1} \simeq 0.7$ V

Thus,

$V_{E1} = 10.7$ V

and,

$$I_1 = \frac{15 - 10.7}{5} = 0.86 \text{ mA}$$



Neglecting I_{B3},

$I_{C1} \simeq I_{E1} \simeq I_1 = 0.86$ mA

But at this current

$$V_{BE1} = V_T \ln\left(\frac{I_{C1}}{I_S}\right)$$

$$= 0.025 \ln\left(\frac{0.86 \times 10^{-3}}{3.3 \times 10^{-14}}\right)$$

$= 0.6$ V

Thus, $V_{E1} = +10.6$ V and $I_1 = 0.88$ mA No further iterations are required and $I_{C1} \simeq 0.88$ mA.

To find I_{C2} we use an identical procedure :

$V_{BE2} \simeq 0.7$ V

$V_{E2} = 10 - 0.7 = +9.3$ V

$$I_2 = \frac{9.3 - (-15)}{5} = 4.86 \text{ mA}$$

$$V_{BE2} = 0.025 \ln\left(\frac{4.86 \times 10^{-3}}{3.3 \times 10^{-14}}\right)$$

$= 0.643$ V

$V_{E2} = 10 - .643 = +9.357$

$I_2 = 4.87$ mA

$I_{C2} \simeq 4.87$ mA

Finally,

$$I_{C3} = I_{C4} = 3.3 \times 10^{-14} e^{V_{BE}/V_T}$$

Where

$$V_{BE} = \frac{V_{E1} - V_{E2}}{2} = 0.62 \text{ V}$$

Thus, $I_{C3} = I_{C4} = 1.95$ mA

The symmetry of the circuit enables us to find the values for $v_I = -10$ V as follows:

$I_{C1} = 4.87$ mA $I_{C2} = 0.88$ mA

$I_{C3} = I_{C4} = 1.95$ mA

For $v_I = +10$ V, $v_o = V_{E1} - V_{BE3}$

$= 10.6 - 0.62 = +9.98$ V

For $v_I = -10$ V, $v_o = V_{E1} - V_{BE3}$

$= -9.357 - 0.62 = -9.98$ V

(c)For $v_I = +10$ V,

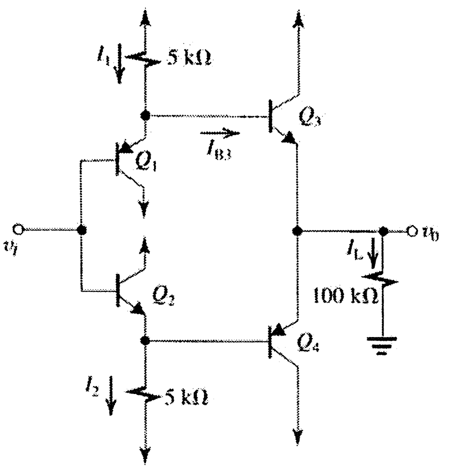
$v_O \simeq 10$ V

$I_L \simeq 100$ mA

$I_{C3} \simeq 100$ mA

$$I_{B3} = \frac{100}{201}$$

$\simeq 0.5$ mA



Assuming that V_{BE1} has not changed much from 0.6 V, then

$V_{E1} \simeq 10.6$ V

$$I_1 = \frac{15 - 10.6}{5} = 0.88 \text{ mA}$$

$I_{E1} = I_1 - I_{B3} = 0.88 - 0.5 = 0.38$ mA

$I_{C1} \simeq 0.38$ mA

$$V_{BE1} = 0.025 \ln\left(\frac{0.38 \times 10^{-3}}{3.3 \times 10^{-14}}\right)$$

$= 0.58$ V

$V_{E1} = 10.88$ V

$$I_1 = \frac{15 - 10.58}{5} = 0.88 \text{ mA}$$

Thus, $I_{C1} \simeq 0.30$ mA

Now for Q_2 we have:

$V_{BE2} = 0.643$ V

$V_{E2} = 10 - 0.643 = 9.357$

$I_2 = 4.87$ mA

$I_{B4} \simeq 0$

$I_{C2} \simeq 4.87$ mA (as in (b))

Assuming that $I_{C3} \simeq 100$ mA,

$$V_{BE3} = 0.025 \ln\left(\frac{100 \times 10^{-3}}{3.3 \times 10^{-14}}\right)$$

$= 0.72$ V

Thus, $v_o = V_{E1} - V_{BE3}$

$= 10.58 - 0.72 = +9.86$ V

$V_{BE4} = v_o - V_{E2}$

$= 9.86 - 9.36 = 0.5$ V

Thus, $I_{C4} = 3.3 \times 10^{-14} e^{0.5/0.025}$

$\simeq 0.02$ mA

For symmetry we find the value for the case $v_I = -10$ V as.

$I_{C1} = 4.87$ mA $I_{C2} = 0.38$ mA

$I_{C3} = 0.02$ mA $I_{C4} = 100$ mA

$v_o = -9.86$ V.

Ex 13.15

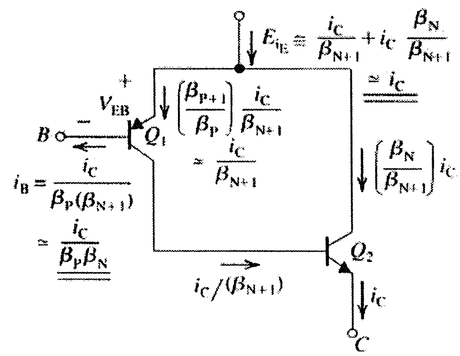
For Q_1:

$$i_{C1} = I_{SP}\, e^{v_{EB}/V_T}$$

$$\frac{i_C}{\beta_N + 1} = I_{SP}\, e^{v_{EB}/V_T}$$

$$i_C \simeq \beta_N I_{SP}\, e^{v_{EB}/V_T}$$

Thus, Effective scale current $= \beta_N I_{SP}$



(b) Effective current gain $= \frac{i_C}{i_B} = \beta_P\, \beta_N$

$= 20 \times 50 = 1000$

$100 \times 10^{-3} = 50 \times 10^{-14}\, e^{v_{EB}/0.025}$

$v_{EB} = 0.025 \ln (2 \times 10^{11})$

$= 0.651$ V

Ex 13.16

See Figure 13.34

When $V_{R_{E5}} = 150 \times 10^{-3} \times R_{E1}$, then $I_{C5} = I_{bias}$ $= 2$ mA

$$V_{BE5} = V_T \ln\left(\frac{I_{C5}}{I_S}\right)$$

$$= 25 \times 10^{-3} \ln\left(\frac{2 \times 10^{-3}}{10^{-14}}\right)$$

$= 0.651$ V

$150 \times 10^{-3} R_{E1} = 0.651$

$R_{E1} = 4.34\ \Omega$

If peak output current = 100 mA

$V_{BE5} = R_{E1} \times 100\text{ mA} = 4.34 \times 100 \times 10^{-3}$
$= 0.434$ V

$$i_{C5} = I_S e^{V_{BE5}/V_T}$$

$$= 10^{-14} e^{0.434/25 \times 10^{-3}}$$

$$\simeq 0.35\ \mu\text{A}$$

Ex 13.17

Total current out of mode B $= \frac{2v_i}{R_3} + \frac{v_o}{R_2}$

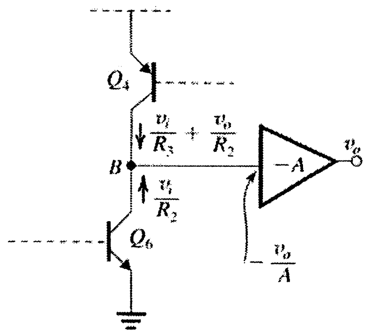
Thus

$$\left(\frac{2v_i}{R_3} + \frac{v_o}{R_2}\right) R = -\frac{v_o}{A}$$

$$\Rightarrow v_o\left(\frac{1}{A} + \frac{R}{R_1}\right) = -\frac{2R}{R_3} v_i$$

$$\frac{v_o}{v_i} = \frac{-\frac{2R}{R_3}}{\frac{1}{A} + \frac{R}{R_1}}$$

$$= \frac{-2R_2/R_3}{1 + (R_2/AR)} \qquad \text{Q.E.D}$$



For $AR >> R_2$

$$\frac{v_o}{v_i} \simeq -\frac{2R_2}{R_3}$$

Ex 13.18

$$P_{D\max} = \frac{T_{J\max} - T_A}{\theta_{JA}}$$

$$= \frac{150 - 50}{35} = 2.9\text{ W}$$

Ex 13.19

For Fig. 10.32 we see that for $P_{dissipation}$ to be less than 2.9 W, a maximum supply voltage of 20V is called for. The 20-V-supply curve intersects the 3% distoration line at a point for which the output power is 4.2 W. Since

$$P_L = \frac{(\hat{V}_o/\sqrt{2})^2}{R_L}$$

Thus $\hat{V}_o = \sqrt{4.2 \times 2 \times 8} = 8.2$ V

or 16.4 V peak-to-peak

Ex 13.20

Voltage gain = 2 K

where $K = \frac{R_4}{R_3} = 1 + \frac{R_2}{R_1} = 1.5$

Thus, $A_v = 3$ V/V

Input resistance $= R_3 = 10\text{ k}\Omega$

Peak-to-Peak $v_o = 3 \times 20 = 60$ V

Peak load current $= \frac{30\text{ V}}{8\ \Omega} = 3.75$ A

$$P_L = \frac{(30/\sqrt{2})^2}{8} = 56.25\text{ W}$$

Ex 13.21

We wish to value

$$\frac{\partial V_{GG}}{\partial T} = -3 - 3 = -6\text{ mV/°C}$$

but From Eq. 10.58

$$\frac{\partial V_{GG}}{\partial T} = \left(1 + \frac{R_3}{R_4}\right)\frac{\partial V_{BE6}}{\partial T}$$

$$\text{Thus } -6 = \left(1 + \frac{R_3}{R_4}\right) \times -2$$

$$\Rightarrow \frac{R_3}{R_4} = 2$$

Ex 13.22

Refer to Figure 13.44

$$I_{DN} = I_{DP} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(|V_{GS}| - V_t)^2$$

$$100 \times 10^{-3} = \frac{1}{2} \times 2(|V_{GS}| - 3)^2$$

$$0.1 = (|V_{GS}| - V_t)^2$$

$$\Rightarrow V_{GS} = 3.32\text{ V}$$

$V_{GG} = 2V_{GS} = 6.64$ V

$$R = \frac{V_{GG}}{20\text{ mA}} = \frac{6.64}{20 \times 10^{-3}} = 3.32\ \Omega$$

Using equation

$$V_{GG} = \left(1 + \frac{R_3}{R_4}\right)V_{BE6} + \left(1 + \frac{R_1}{R_2}\right)V_{BE5} - 4V_{BE}$$

$$6.64 = (1 + 2) \times 0.7 + \left(1 + \frac{R_1}{R_2}\right) \times 0.7 - 4 \times 0.7$$

$$\Rightarrow \frac{R_1}{R_2} \simeq 9.5$$

Ex: 14.1

In the low-ouput state, the transistor is on and

$$R_{on} = r_{DS} \simeq \frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_t)}$$

Therefore, the current drawn from the supply in this state can be calculated as:

$$I_{DD} = \frac{V_{DD}}{R_D + r_{DS}} = 50\ \mu A \Rightarrow R_D + r_{DS}$$

$$= \frac{2.5\ V}{50\ \mu A} = 50\ k\Omega$$

Also: $V_{OL} = V_{DD}\frac{r_{DS}}{R_D + r_{DS}}$

Substituting for

$$R_D + r_{DS} : 0.1 = 2.5\frac{r_{DS}}{50\ k\Omega} \Rightarrow r_{DS} = 2\ k\Omega$$

and hence: $R_D = 48\ k\Omega$

To obtain $\frac{W}{L}$, we use:

$$r_{DS} = \frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_t)} \Rightarrow \frac{W}{L}$$

$$= \frac{1}{2\times 10^3 \times 125\times 10^{-6}\times(2.5 - 0.5)}$$

$$\therefore \frac{W}{L} = 2$$

When the switch is closed or in low-output state, the current drawn from the supply is 50 μA.

$$P_{DD} = V_{DD}I_{DD} = 2.5\times 50\times 10^{-6} = 125\mu w$$

When the switch is open, no current is drawn from the supply: $P_{DD} = 0$

Ex: 14.2

When input is low, the output is high and equal to V_{OH}. In this case, the switch is connected to R_{C2}, therefore the current through R_{C1} is zero. Hence, $V_{OH} = V_{CC} = 5V$.

When the input is high, the output is low and equal to V_{OL}. The switch is connected to R_{C1}. Hence

$$V_{OL} = V_{CC} - R_{C1}I_{EE} = 5 - 2\times 1 = 3V$$

Ex: 14.3

To determine $\frac{W}{L}$, we use: $K_n R_D = \frac{1}{V_x}$ and substitute $V_x = 0.089V$, $R_D = 10^{k\Omega}$, $k_n' = 300\ \mu A/V^2$:

$$300\times 10^{-6}\times\frac{W}{L}\times 10\times 10^3 = \frac{1}{0.089} \Rightarrow \frac{W}{L} = 3.75$$

Noise margins stay unchanged, because $V_{OL}, V_{OH}, V_{IL}, V_{IH}$ only depend on V_{DD}, V_t, and V_x. Since V_x has not changed, noise margins stay the same.

Inorder to calculate the power dissipation, we need to first recalculate

$$I_{DD}: I_{DD} = \frac{V_{DD} - V_{OL}}{R_D} = \frac{1.8 - 0.12}{10\ k\Omega} = 168\ \mu A$$

$$P_{DD} = V_{DD}I_{DD} = 1.8\times 168\ \mu A = 302.4\ \mu W$$

$$P_{Daverage} = \frac{1}{2}P_{DD} = 151\ \mu W$$

Note that keeping V_x unchanged resulted in higher power consumption, but noise margins stayed the same.

Ex: 14.4

To determine V_x, we use:

$K_n R_a = \frac{1}{V_x}$ and with $R_D = 10\ k\Omega$ and K_n unchanged:

$$\frac{V_{x2}}{V_{x1}} = \frac{R_{D1}}{R_{D2}} \Rightarrow V_x = 0.089\times\frac{25}{10} = 0.22V$$

To calculate the new noise margins, we have to find $V_{OH}, V_{IH}, V_{IL}, V_{OL}$.

$V_{OH} = V_{DD} = 1.8\ V$ unchanged

$$V_{IL} = V_t + V_x = 0.5 + 0.22 = 0.72\ V$$

$$V_{IH} = V_t + 1.63\sqrt{V_{DD}V_x} - V_x$$

$$= 0.5 + 1.63\sqrt{1.8\times 0.22} - 0.22 = 1.31V$$

$$V_{OL} = \frac{V_{DD}}{1 + \frac{V_{DD} - V_t}{V_x}} = \frac{1.8}{1 + \frac{1.8 - 0.5}{0.22}} = 0.26\ V$$

$$NM_H = V_{OH} - V_{IH} = 1.8 - 1.31 = 0.49\ V$$

$$NM_L = V_{IL} - V_{OL} = 0.72 - 0.26 = 0.46\ V$$

The power dissipation becomes:

$$P_{d\ average} = \frac{1}{2}P_D = \frac{1}{2}V_{DD}I_{DD} = \frac{1}{2}V_{DD}\frac{V_{DD} - V_{OL}}{R_D}$$

$$P_{d\ average} = \frac{1}{2}\times 1.8\times\frac{1.8 - 0.26}{10\ k\Omega} = 139\ \mu W$$

Note that keeping $\frac{W}{L}$ unchanged resulted in lower noise margins and higher power dissipation.

Ex: 14.5

$$k_r = \sqrt{\frac{(W/L)_1}{(W/L)_2}} = \sqrt{\frac{3}{1/3}} = 3$$

From Eq. 14.20: $V_{OH} = V_{DD} - V_t = 1.3$ V unchanged

From Eq. 14.28

$$V_{OL} \cong \frac{(V_{DD} - V_t)^2}{2k^2_r(V_{DD} - 2V_t)} = \frac{(1.8 - 0.5)^2}{2 \times 3^2(1.8 - 2 \times 0.5)}$$

$= 0.12$ V

From Eq. 14.22 $V_{IL} = V_t = 0.5$ V unchanged.

From Eq. 14.23

$$V_M = \frac{V_{DD} + (k_r - 1)V_t}{k_r + 1} = \frac{1.8 + (3 - 1)0.5}{3 + 1}$$

$= 0.7$ V

From Eq. 14.26 together with setting $\frac{dv_o}{dv_I} = -1$:

$$2k_r^2\left[(v_I - v_t)v_O - \frac{1}{2}v^2{}_O\right] = (V_{DD} - v_I - v_O)^2$$

$$2k_r^2\left[v_O + (v_I - v_t)\frac{dv_O}{dv_I} - v_O\frac{dv_O}{dv_I}\right]$$

$$= -2(V_{DD} - V_t - v_O)\frac{dv_O}{dv_I}$$

Now if we substitute for $\frac{dv_O}{dv_I} = -1$ then:

$$k_r^2[v_{OL} - v_{IH} + v_t - v_{OL}] = +V_{DD} - V_t - V_{OL}$$

$$\therefore 3^2[0.12 - V_{IH} + 0.5 + 0.12] = 1.8 - 0.5 - 0.12$$

$$9[0.74 - V_{IH}] = 1.18 \Rightarrow V_{IH} = 0.61\text{V}$$

$$NM_H = V_{OH} - V_{IH} = 1.3 - .61 = .69 \text{ V}$$

$$NM_L = V_{IL} - V_{OL} = .5 - .12 = .38 \text{ V}$$

Ex: 14.6

The inverter area is approximately

$A = W_1L_1 + W_2L_2$ Since $\frac{W_1}{L_1} = K_r$ and $\frac{W_2}{L_2} = \frac{1}{K_r}$, we have $W_1 = k_rL_1$, and $L_2 = k_rW_2$. Assuming $k_r > 1$, we have $L_1 = d$ and $W_2 = L$.

Thus:

$$A = k_rL_1L_1 + W_2krW_2 = k_rL^2{}_1 + k_rW^2{}_2$$

$$= k_rd^2 + k_rd^2 = 2k_rd^2$$

Ex: 14.7

From Eq. 14.36 we have: $P_{dyn} = fCV_{DD}{}^2$

$$P_{dyn} = 100 \times 10^6 \times 100 \times 10^{-15} \times 1.8^2$$

$= 32.4 \times 10^{-6} = 32.4$ μw

Ex: 14.8

$$P_{dyn} \alpha C_x V^2{}_{DD} \Rightarrow \frac{P_{dyn1}}{P_{dyn2}} = \frac{C_1V^2{}_{DD1}}{C_2V^2{}_{DD2}}$$

$$= \frac{0.5}{0.13} \times \frac{5^2}{1.2^2} = 66.73 \simeq 66.8$$

Ex: 14.9

$$V_o(t) = V_o(\infty) - (V_o(\infty) - V_o(0^+))e^{-t/\tau}$$

$$\frac{V_{DD}}{2} = V_{DD} - (V_{DD} - O)e^{-t_{PLH}/\left(\frac{V_{DD}}{I}\right)\cdot C}$$

$$\ln\left(-\frac{1}{2}\right) = \frac{(-t_{PLH})}{\frac{V_{DD} \cdot C}{I}}$$

$$\therefore t_{PLH} = \frac{V_{DD} \cdot C}{I} \cdot 0.69$$

for $t_{PLH} = 10$ psec. with $C = 10$ fF and $V_{DD} = 1.8$ V

$$I = \frac{1.8 \cdot 10f}{10\text{ P}} \cdot 0.69 = 1.2 \text{ mA}$$

Ex: 14 .10

For t_{PLH} the output starts at V_{OL} and goes to V_{OH} through the Pu which is 20 kΩ :

$$V_O(t) = V_O(\infty) - (V_O(\infty) - V_O(O^+))e^{-t/\tau}$$

$$\frac{1}{2}(V_{OH} + V_{OL}) = V_{OH} - (V_{OH} - V_{OL})e^{-t_{PLH}/\tau}$$

$$\frac{\left(-\frac{1}{2}V_{OH} + \frac{1}{2}V_{OL}\right)}{-(V_{OH}) + V_{OL}} = e^{-t_{PLH}/\tau}$$

$$\tau\left(-\ln\left(\frac{1}{2}\right)\right) = t_{PLH}$$

$t_{PLH} = 0.69$ R.C $= 0.69$ (20 K) (10f) $= 138$ pSec

For t_{PHL}, the output starts at V_{OH} and goes to V_{OL} through P_O which is 10 kΩ .

$$\frac{1}{2}(V_{OH} + V_{OL}) = V_{OL} - (V_{OL} - V_{OH})e^{-t_{PHL}/\tau}$$

$$\frac{\left(\frac{1}{2}V_{OH} + \frac{1}{2}V_{OL} - \frac{2}{2}V_{OL}\right)}{-V_{OL} + V_{OH}} = e^{-t_{PHL}/\tau}$$

$$\tau\left(-\ln\left(\frac{1}{2}\right)\right) = t_{PHL}$$

$$t_{PHL} = 0.69.\text{R.C} = 0.69 \times 10 \text{ K} \times 10f = 69 \text{ psec}$$

$$t_P = \frac{1}{2}(t_{PHL} + t_{PLH}) = \frac{1}{2}(138 \text{ p} + 69 \text{ p}) = 10^4 \text{ psec}$$

Ex: 14.11

$V_O(t) = V_O(\infty) - [V_O(\infty) - V_O(O^+)]e^{-t/\tau}$

$V_O(t) = O - [V_{DD} - O]e^{-t/(2\,\mathrm{K} \cdot 100\,f) = \tau}$

t_f is when voltage is $\approx .1V_{DD}$

$.1V_{DD} = -V_{DD}e^{-(0 - t_f)/\tau}$

$-\ln(.1) = t\dfrac{t_f}{\tau}$

$2.3 \cdot \tau \cong t_f$

$t_f \approx 2.3 \cdot 2\,\mathrm{K} \cdot 100\,f = 0.46$ nsec

Ex: 14.12

a) From Eq. 14.58

$$V_M = \frac{r(V_{DD} - |V_{tp}|) + V_{tn}}{r+1} \text{ or}$$

$$0.6 = \frac{r(1.2 - 0.4) + 0.4}{1 + r} \Rightarrow 0.6 + 0.6r$$

$$= 0.8r + 0.4 \Rightarrow r = 1$$

$$r = \sqrt{\frac{\mu_p w_p}{\mu_n w_n}} = \sqrt{\frac{1}{4} \times \frac{w_p}{w_n}} = 1 \Rightarrow \frac{w_p}{w_n} = 4$$

$$\Rightarrow (w_p = 4 \times 0.13\ \mu\text{m} = 0.52\ \mu\text{m})$$

b) $V_{OH} = V_{DD} = 1.2\text{V},\ V_{OL} = 0\ \text{V}$

$$V_{IH} = \frac{1}{8}(5V_{DD} - 2V_t) = \frac{1}{8}(5 \times 1.2 - 2 \times 0.4)$$

$$= 0.65\text{V}$$

$$V_{IL} = \frac{1}{8}(3V_{DD} + 2V_t) = \frac{1}{8}(3 \times 1.2 + 2 \times 0.4)$$

$$= 0.55\ \text{V}$$

$$NM_H = V_{OH} - V_{IH} = 1.2 - 0.65 = 0.55\ \text{V}$$

$$NM_L = V_{IL} - V_{OL} = 0.55\ \text{V}$$

c) The output resistance of the inverter in the low-output state is:

$$r_{DSN} = \frac{1}{\mu_n C_{ox}\left(\frac{W}{L}\right)_n (V_{DD} - V_{tn})}$$

$$= \frac{1}{430 \times 10^{-6} \times 1(1.2 - 0.4)}$$

$$= 2.9\ \text{k}\Omega$$

Since Q_N and Q_P are matched, the output resistance in the high-output state is the same:

$$r_{DSP} = r_{DSN} = 2.9\ \text{k}\Omega$$

d) For $\left(\frac{W}{L}\right)_p = \left(\frac{W}{L}\right)_n = 1.0$, we have

$$r = \sqrt{\frac{1}{4} \times 1} = 0.5,$$

hence: $V_M = \dfrac{0.5(1.2 - 0.4) + 0.4}{1 + 0.5} = 0.53\ \text{V}$

Ex: 14.13

Using Eq. 14.58 and 14.59

$$V_M = \frac{r(V_{DD} - |V_{tp}| + V_{tn})}{r+1} \Rightarrow 2.5$$

$$= \frac{r(5-1)+1}{r+1} \Rightarrow r = 1$$

$$r = \sqrt{\frac{\mu_p w_p}{\mu_n w_n}} \Rightarrow \frac{w_p}{w_n} = \frac{1}{1/2} = 2$$

When $V_I = V_{DD}$ and $V_O = 0.2\text{V}$, Q_N operates in triode region and hence the circuit is given as:

$$i_D = k_n'\left(\frac{W}{L}\right)_n\left[(V_i - V_{tn})V_O - \frac{1}{2}V_o^2\right]$$

$$\Rightarrow 0.2 \times 10^{-3} = 50 \times 10^{-6} \times \left(\frac{W}{L}\right)_n$$

$$\left[(5-1)0.2 - \frac{1}{2} \times 0.2^2\right] \Rightarrow \left(\frac{W}{L}\right)_n = 5$$

From above: $w_p = 2w_n \Rightarrow \left(\frac{W}{L}\right)_p = 10$

Ex: 14.14

Using Eqs.14.63 to 14.67 we have:

$$t_{PHL} = \frac{\alpha_n C}{k_n'\left(\frac{W}{L}\right)_n V_{DD}},$$

$$\alpha_n = 2\Big/\left[\frac{7}{4} - \frac{3V_{tn}}{V_{DD}} + \left(\frac{V_{tn}}{V_{DD}}\right)^2\right]$$

$$= 2\Big/\left[\frac{7}{4} - \frac{3 \times 0.5}{1.8} + \left(\frac{0.5}{1.8}\right)^2\right] = 1.99$$

Noting that $V_{tn} = |V_{tp}|$, then $\alpha_n = \alpha_p = 1.99$

$$t_{PHL} = \frac{1.99 \times 10 \times 10^{-15}}{300 \times 10^{-6} \times 1.5 \times 1.8} = 24.7\text{ps}$$

$$t_{PLH} = \frac{\alpha_p C}{k_p'\left(\frac{W}{L}\right)_p V_{DD}} \text{ or}$$

$$\frac{t_{PLH}}{t_{PHL}} = \frac{k_n'\left(\frac{W}{L}\right)_n}{k_p'\left(\frac{W}{L}\right)_p} \Rightarrow t_{PLH} = 24.6 \times 4 \times \frac{1.5}{3}$$

$$= 49.4\ \text{ps}$$

$$t_p = \frac{1}{2}(t_{PLH} + t_{PHL}) = \frac{1}{2}(24.7 + 49.4) = 37\text{ps}$$

Ex: 14.15

From Eq.14.68 we have:

$t_{PHL} = 0.69 R_N C$ and if we substitute for R_N from Eq.14.70 i.e. $R_N = \dfrac{12.5}{\left(\frac{W}{L}\right)_n}$ kΩ then:

$$t_{PHL} = 0.69 \times \frac{12.5}{\left(\frac{W}{L}\right)_n} \times 10^3 \times \text{C} = \frac{8625\text{C}}{\left(\frac{W}{L}\right)_n} \text{ or}$$

$$50 \times 10^{-12} = \frac{8625 \times 20 \times 10^{-15}}{\left(\frac{W}{L}\right)_n}$$

$$\therefore \left(\frac{W}{L}\right)_n = 3.5$$

Similarly, using Eqs.14.69 and 14.71 we obtain:

$$t_{PLH} = 0.69R_p C = 0.69 \times 30 \times 10^3 \frac{C}{\left(\frac{W}{L}\right)_p}$$

or

$$t_{PLH} = 20.7 \times 10^3 \frac{C}{\left(\frac{W}{L}\right)_p} \Rightarrow 50 \times 10^{-12}$$

$$= 20.7 \times 10^3 \times \frac{20 \times 10^{-15}}{\left(\frac{W}{L}\right)_p} \Rightarrow \left(\frac{W}{L}\right)_p = 8.3$$

Ex: 14.16

t_{PHL} and t_{PLH} are proportional to C

$$\therefore t_{PHL} = t_{PHL} - \text{orginal} * \frac{C_{new}}{C_{old}}$$

and

$$t_{PHL} = t_{PLH} - \text{original} * \frac{C_{new}}{C_{old}}$$

$$C_{new} = C_{old} + .1\text{p} = 6.25\text{f} + .1\text{p}$$

$$C_{new} = .10625 \text{ pF}$$

$$t_p = \frac{1}{2}(t_{PHL} + t_{PLH}) = t_{pOLD} * \frac{C_{new}}{C_{old}}$$

$$t_p = 28\text{p} * \frac{.10625\text{p}}{6.25\text{f}} = 476 \text{ psec}$$

Ex: 14.17

W_P is reduced from 1.125 μm to 0.375 μm

$$\therefore \frac{0.375}{1.125} \times 100 = 33\% \text{ reduction}$$

$$C_{gd2} = C_{gd1} = 0.3375 \text{ fF}$$

$$C_{g3} = C_{g4} = 0.7875\text{fF}$$

$$C = (4 \times 0.3375\text{f}) + 1\text{f} + 1\text{f} + (2 \times .7875\text{f}) + .2\text{f}$$

$$= 4.225 \text{ fF}$$

$$t_{PHL} = 24.6 \times 10^{-12} \times \left(\frac{4.225f}{6.25f}\right) = 16.6 \text{ psec}$$

$$t_{PLH} = 31.5 \times 10^{-12} \times \left(\frac{4.225f}{6.25f}\right) = 21.3 \text{ psec}$$

$$t_p = \frac{1}{2}(t_{PHL} + t_{PLH}) = \frac{1}{2}(16.6\text{p} + 21.3\text{p}) = 19 \text{ psec}$$

Ex: 14.18

$$f_{max} = \frac{1}{2t_p} = \frac{1}{2(28 \times 10^{-12})} = 17.9 \text{ GHz}$$

The minimum period at which the inverter can reliability operate is

$T_{min} = t_{PHL} + t_{PLH}$. Thus,

$$F_{max} = \frac{1}{T_{min}} = \frac{1}{t_{PHL} + t_{PLH}} = \frac{1}{2t_p} = \frac{1}{2 \times 28}$$

$= 17.96$ Hz

Ex: 14.19

a) As mentioned on page of the Text, C_{int} is the contribution of intrinsic capacitances of Q_N and Q_P. Therefore,

$$C_{int} = 2e_{gd1} + 2C_{gd2} + C_{db} + C_{db2}$$

$$\therefore C_{int} = 2 \times 0.1125 + 2 \times 0.3375 + 1 + 1 = 2.9 \text{ fF}$$

$$C_{ext} = Cg_3 + Cg_4 + C_w = 0.7875 + 2.3625 + 0.2$$

$= 3.35$fF

b) From Eq. 14.79 we have:

$$t_p = 0.69\left(R_{eq}C_{at} + \frac{1}{S}R_{eq}C_{ext}\right)$$ The extrinsic

part of t_p is: $0.69\frac{1}{S}R_{eq}C_{ext}$ and in order to reduce the extrinsic part by a factor of 2, S has to be increased by a factor of 2. Note that $S = \frac{R_{eq}}{R_{eq}}$. Therefore, R_{eq} has to be reduced by a factor of 2 or equivalently $\left(\frac{W}{L}\right)_n$ and $\left(\frac{W}{L}\right)_p$ have to be increased by factor of 2.

c) From Eq. 14.79

$$= 0.69\left(R_{eq0}C_{int\phi} + \frac{1}{S}R_{eq\phi}C_{ext}\right). \text{Hence,}$$

$$\frac{t_{pnew}}{t_{pold}} = \frac{C_{int} + C_{at}/s}{C_{int} + C_{ext}}$$

$$\text{For } S = 2 : t_{pnew} = \frac{2.9 + 3.35/2}{2.9 + 3.35} \times 28 \text{ ps}$$

$= 20.5$ ps

d) $A = W \times L$ and since $\left(\frac{W}{L}\right)$ is doubled and L is constant, then A or area is also doubled.

Ex: 14.20

Using Eq. 14.35

$$P_{dyn} = fCV_{DD}^2 = 1 \times 10^9 \times 6.25 \times 10^{-15} \times 2.5^2$$

$= 39.1$ µw

The maximum possible operating frequency is:

$$f_{max} = \frac{1}{2t_p}. \text{ Hence,}$$

$$PDP = P_{dyn} \times t_p = f_{max}CV^2_{DD} \times t_p$$

$$= \frac{1}{2t_p} \times C \times V^2_{DD} \times t_p = \frac{CV^2_{DD}}{2}$$

$$= \frac{6.25 \times 10^{-15} \times 2.5^2}{2} = 19.5 \text{ fF/J}$$

Ex: 14.21

a) For NMOS devices:

$$\frac{W}{L} = n = \frac{0.18}{0.18} \times 1.5 = \frac{0.27}{0.18}$$

For PMOS devices:

$$\frac{W}{L} = 4p = \frac{0.18}{0.18} \times 4 \times 3 = \frac{2.16}{0.18}$$

b) For NMOS devices:

$$\frac{W}{L} = 4n = \frac{0.18}{0.18} \times 4 \times 1.5 = \frac{1.08}{0.18}$$

For PMOS devices:

$$\frac{W}{L} = p = \frac{0.18}{0.18} \times 3 = \frac{0.54}{0.18}$$

Ex: 14.22

(a) The minimum current available to charage a load capacitance is that provided by a single PMOS device. The maximum current available to charge a load capacitance is that provided by four PMOS transistors. Thus, the ratio is 4.

(b) There is only one possible configuration (or path) for capacitor discharge. Thus the minimum and maximum currents are the same

$\Rightarrow$ ratio is 1.

Ex: 14.23

Since dynamic power dissipation is scaled by $\frac{1}{S^2}$

and propagation delay is scaled by $\frac{1}{S}$, hence, PDP

is scaled by $\frac{1}{S^2} \times \frac{1}{S} = \frac{1}{S^3} = \frac{1}{8}$ So PDP

decreases by a factor of 8.

Ex: 14.24

If V_{DD} and Vt are kept constant, the entries in Table 14.2 that change are as follows:

Obviously, V_{DD} and V_t do not scale by $\frac{1}{S}$ any-more. They are kept constant!

$t_p \propto \frac{\alpha C}{k' V_{DD}}$ since $\alpha \propto \frac{V_t}{V_{DD}}$, thus α remains

unchanged, while C is scaled by $\frac{1}{S}$, and K' is

scaled by S, therefore t_p is scaled by $\frac{1/S}{S} = \frac{1}{S^2}$

Energy/Switching cycle, i.e., CV^2_{DD}, is scaled by $\frac{1}{S}$

$P_{dyn} \propto \frac{CV^3_{DD}}{2t_p}$ and thus is scaled by $\frac{1/S}{1/S^2} = S$

thus P_{dyn} increases.

The power density, i.e., $\frac{P_{dyn}}{\text{deive area}}$ is scaled

by $\frac{S}{1/S^2} = S^3$

Ex: 14.25

Using Eq. 14.94 we have:

$$V_{DSat} = \frac{L}{\mu_n} v_{sat} = \frac{0.25 \times 10^{-6}}{400 \times 10^{-4}} \times 10^7 \times 10^{-2}$$

$= 0.63\text{V}$

Ex: 14.26

For the NMOS transistor, $V_{GS} = 1.2$ V results in $V_{GS} - V_{tn} = 1.2 - 0.4 = 0.8$ V which is greater than $V_{Dsat} = 0.34$ V. Also, $V_{DS} = 1.2$ V is greater than V_{Dsat}, thus both conditions in Eq. 14.101 are satisfied and the NMOS transistor will be operating in the velocity-saturation region and thus i_D is given by Eq. 14.100

$$i_D = 430 \times 10^{-6} \times 1.5 \times 0.34\left(1.2 - 0.4 - \frac{1}{2} \times 0.34\right)$$

$(1 + 0.1 \times 1.2) = 154.7\ \mu\text{A}$

if velocity-saturation-were absent, the current would be:

$$i_D = \frac{1}{2} \times 430 \times 10^{-6} \times 1.5(1.2 - 0.4)^2$$

$\times (1 + 0.1 \times 1.2) = 231.2\ \mu\text{A}$

Saturation is obtained over the range

$V_{DS} = 0.34\text{V}$ to 1.2V compared to

$V_{DS} = V_{OV} = (1.2 - 0.4) = 0.8$ V to 1.2 V

in the absence of velocity saturation.

For the PMOS transistor, we see that since $|V_{GS}| - |V_{tp}| = 0.8$ V and $|V_{DS}| = 1.2$ V are both larger than $|V_{Dsat}| = 0.6$ V the device will be operating in velocity saturation and

$$i_D = 110 \times 10^{-6} \times 1.5 \times 0.6\left(1.2 - 0.4 - \frac{1}{2} \times 0.6\right)$$

$(1 + 0.1 \times 1.2) = 55.4\ \mu\text{A}$

$0.6 \le V_{DS} \le 1.2$ V

without velocity saturation

$$i_D = \frac{1}{2} \times 110 \times 1.5 \times 0.6(1.2 - 0.4)^2(1 + 0.1 \times 1.2)$$

$= 59.1\ \mu\text{A}$

$V_{ov} \le V_{DS} \le 1.2$ V or $0.8\text{V} \le V_{DS} \le 1.2\text{V}$

Note that the velocity saturation reduces the NMOS current by 33% and the PMOS current by ~ 7%.

Ex: 14.27

a) Using Eq. 14.102 we have

$i_D = I_{se} V_{GS} / nV_T$

Thus, $\log i_D = \log I_S + \dfrac{V_{GS}}{nV_T} \log(e)$

Therefore, the slope of the straight line representing subthreshold conduction is given by:

$\dfrac{nV_T}{\log(e)} = 2.3nV_T$

b) $V_T = 25\text{ mV}$ for $i_D = 100\text{ nA}$

at $V_{GS} = .21\text{V}$

$100n = Ise^{.21/1.22(25m)}$

$I_s = .1\text{ nA}$

$i_D = .1ne^{0/nV_T} = .1\text{nA}$

c) For $V_{GS} = 0$, $i_D = .1\text{nA}$

$I_{total} = 500 \times 10^6 \times .1 \times 10^{-9} = 50\text{ mA}$

$P_{diss} = I_{total} \times V_{DD} = 50\text{ m} \times 1.2 = 60\text{ mW}$

15.1

$(W/L)_n = 1.5 \ (W/L)_p = 0.32$

$t_{PLH} = 0.5$ ns

$t_{PLH} = 0.03$ ns

THE NOISE MARGINS WILL NOT CHANGE

15.2

Using eq. 15.11

$$V_{OL} = (V_{DD} - V_t)\left[1 - \sqrt{1 - \frac{1}{\gamma}}\right] = (2.5 - 0.5) \times \left[1 - \sqrt{1 - \frac{1}{4}}\right]$$

$V_{OL} = 0.27$ V

using eq. 15.13 and 15.14

$$NM_L = V_t - (V_{DD} - V_t)\left[1 - \sqrt{1 - \frac{1}{\gamma} - \frac{1}{\sqrt{\gamma(\gamma+1)}}}\right]$$

$$NM_L = 0.5 - (2)\left[1 - \sqrt{1 - \frac{1}{4} - \frac{1}{\sqrt{4(5)}}}\right] = 0.7 \text{ V}$$

$$NM_H = (V_{DD} - V_t)\left(1 - \frac{2}{\sqrt{3\gamma}}\right) = (2) \times \left(1 - \frac{2}{\sqrt{3.4}}\right) = 0.85 \text{ V}$$

$$\gamma = \frac{\mu_n C_{ox}\left(\frac{W}{L}\right)_n}{\mu_p C_{ox}\left(\frac{W}{L}\right)_p} = \frac{115\ \mu\left(\frac{0.375}{0.25}\right)}{30\ \mu\left(\frac{W}{L}\right)_p} = 4$$

$$\therefore \left(\frac{W}{L}\right)_p = 1.44$$

using eq. 15.12

$$I_{stat} = \frac{1}{2}(30\ \mu)(1.44)(2.5 - 0.5)^2 = 86.4\ \mu\text{A}$$

$$P_D = I_{stat}V_{DD} = 86.4\ \mu\ 2.5 = 0.22 \text{ mW}$$

using eq 15.15 and 15.16

$$\alpha_p = 2\Big/\left[\frac{7}{4} - 3\left(\frac{0.5}{2.5}\right) + \left(\frac{0.5}{2.5}\right)^2\right] = 1.68$$

$$t_{PLH} = \frac{1.68 \times 7 \times 10^{-15}}{30 \times 10^{-6} \times 1.44 \times 2.5} = 0.11 \text{ nsec}$$

using eq. 15.17 and 15.18

$$\alpha_n = 2\Big/\left[1 + \frac{3}{4}\left(1 - \frac{1}{\gamma}\right) - \left(3 - \frac{1}{\gamma}\right)\left(\frac{0.5}{2.5}\right) + \left(\frac{0.5}{2.5}\right)^2\right]$$

$= 1.9$

$$t_{PHL} = \frac{1.9 \times 7 \times 10^{-15}}{115 \times 10^{-6} \times \left(\frac{.375}{.25}\right) \times 2.5} = 0.03 \text{ nsec}$$

$$t_p = \frac{1}{2}(t_{PHL} + t_{PLH}) = \frac{1}{2}(.11\text{n} + 0.03\text{n}) = 0.07 \text{ nsec}$$

15.3

$$V_t = V_{to} + \gamma(\sqrt{V_{OH} + 2\phi_f} - \sqrt{2\phi_f})$$

since $V_{OH} = V_{DD} - V_t$,

$$V_t = V_{to} + \gamma(\sqrt{V_{DD} - V_t + 2\phi_f} - \sqrt{2\phi_f})$$

Substituting values, we get

$$V_t = 0.5 + 0.3\text{V}^{1/2}$$

$$(\sqrt{1.8\text{ V} - V_t + 0.85\text{ V}} - \sqrt{0.85\text{ V}})$$

$$V_t = 0.5 + 0.3\text{V}^{1/2}$$

$$\sqrt{2.65\text{V} - V_t} - 0.3\text{V}^{1/2}\sqrt{0.85\text{V}}$$

$$V_t - 0.223 = 0.3\sqrt{2.65 - V_t}$$

Squaring both sides yields

$$V_t^2 - 0.446V_t + 0.05 = 0.09(2.65 - V_t)$$

so that, $V_t^2 - 0.356V_t - 0.189 = 0$

Solving this quadratic equation, yields one practical value for V_t:

$V_t = 0.648$ V

$V_{OH} = V_{DD} - V_t = 1.8\text{ V} - 0.648\text{ V}$

$= 1.15$ V

15.4

(a) Referring to Fig 15.12 without loading,

$V_{OH} \to 5$ V

$V_{OL} \to 0$ V

(b) Referring to Fig.15.12 (a),

$$i_{DN}(\text{o}) = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_n(V_{DD} - V_{to})^2$$

$$= \frac{1}{2}(50\ \mu\text{A}/\text{V}^2)\left(\frac{4\ \mu\text{m}}{2\ \mu\text{m}}\right)(5\text{ V} - 1\text{ V})^2 = 800\ \mu\text{A}$$

$$i_{DP}(\text{o}) = \frac{1}{2}k_P'\left(\frac{W}{L}\right)_p(V_{DD} - V_{to})^2$$

$$= \frac{1}{2}(20\mu\text{A}/\text{V}^2)\left(\frac{4}{2}\right)(5\text{V} - 1\text{V})^2 = 320\ \mu\text{A}$$

Capacitor current is

$$i_C(o) = i_{DN}(\text{o}) + i_{DP}(\text{o}) = 800\mu\text{A} + 320\ \mu\text{A}$$

$= 1120\ \mu$A

To obtain $i_{DN}(t_{PLH})$, we note that this situation is identical to that in Example 15.2 and we can use the result of part (c):

$i_{DN}(t_{PLH}) = 50\ \mu$A

$$i_{DP}(t_{PLH}) = k_P'\left(\frac{W}{L}\right)_P \times \gamma$$

$$\left[(V_{DD} - V_{to})\frac{V_{DD}}{2} - \frac{1}{2}\left(\frac{V_{DD}}{2}\right)^2\right]$$

$= (20\ \mu A/V^2)\left(\frac{4}{2}\right)\left[(5\ V - 1\ V)\left(\frac{5\ V}{2}\right) - \frac{1}{2}\left(\frac{5\ V}{2}\right)^2\right]$

$= 275\ \mu A$

Thus, $i_C(t_{PLH}) = 50\mu A + 275\mu A = 325\ \mu A$

$i_C|_{av} = \frac{1}{2}(1120\mu A + 325\mu A) = 722.5\ \mu A$

$$t_{PLH} = \frac{C\left(\frac{V_{DD}}{2}\right)}{i_C|_{av}} = \frac{70(10^{-15})F\left(\frac{5\ V}{2}\right)}{722.5(10^{-6})A}$$

$= 0.24$ ns

(c) Referring to Fig.15.12(b),

$i_{DN}(o) = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_n(V_{DD} - V_{to})^2$

$= \frac{1}{2}(50\mu A/V^2)\left(\frac{4}{2}\right)(5\ V - 1\ V)^2 = 800\ \mu A$

$i_{DP}(o) = \frac{1}{2}k_P'\left(\frac{W}{L}\right)_p(V_{DD} - V_{to})^2$

$= \frac{1}{2}(20\mu A/V^2)\left(\frac{4}{2}\right)(5V - 1V)^2 = 320\mu A$

$i_C(o) = i_{DN}(o) + i_{DP}(o) = 800\mu A + 320\mu A$

$= 1120\mu A$

$i_{DD}(t_{PHL}) = k_n'\left(\frac{W}{L}\right)_n \times$

$\left[(V_{DD} - V_{to})\frac{V_{DD}}{2} - \frac{1}{2}\left(\frac{V_{DD}}{2}\right)^2\right]$

$= 50\ \mu A/V^2\left(\frac{4}{2}\right)\left[(5\ V - 1\ V)\left(\frac{5\ V}{2}\right) - \frac{1}{2}\left(\frac{5\ V}{2}\right)^2\right]$

$= 688\mu A$

To find $i_{DP}(t_{PHL})$, we first determine V_{tp} when $v_o = \frac{V_{DD}}{2}$ which corresponds to $V_{SG} = \frac{V_{DD}}{2}$

$|V_{tp}| = V_{to} + \gamma\left[\sqrt{\frac{V_{DD}}{2} + 2\phi_f} - \sqrt{2\phi_f}\right]$

$= 1\ V + 0.5\ V^{1/2}\left[\sqrt{\frac{5\ V}{2} + 0.6\ V} - \sqrt{0.6\ V}\right] = 1.49\ V$

Thus, $i_{DP}(t_{PHL}) = \frac{1}{2}k_P'\left(\frac{W}{L}\right)_p\left[\frac{V_{DD}}{2} - |V_{tp}|\right]^2$

$= \frac{1}{2}(20\mu A/V^2)\left(\frac{4}{2}\right)\left[\frac{5V}{2} - 1.49V\right]^2 = 20\ \mu A$

$i_C(t_{PHL}) = i_{DN}(t_{PHL}) + i_{DP}(t_{PHL})$

$= 688\ \mu A + 20\ \mu A = 708\ \mu A$

$i_C|_{av} = \frac{1120\ \mu A + 708\ \mu A}{2} = 914\ \mu A$

So,

$$t_{PHL} = \frac{C\left(\frac{V_{DD}}{2}\right)}{i_C|_{av}} = \frac{70(10^{-15})F\left(\frac{5V}{2}\right)}{914(10^{-6})A} = 0.19\text{ ns}$$

Q_p will turn off when $V_o = |V_{tp}|$ where

$|V_{tp}| = V_{to} + \gamma[\sqrt{V_{DD} - |V_{tp}| + 2\phi_f} - \sqrt{2\phi_f}]$

Solving for $|V_{tp}|$,

$|V_{tp}| = 1V + 0.5V^{1/2}$

$[\sqrt{5\ V - |V_{tp}| + 0.6\ V} - \sqrt{0.6\ V}]$

$|V_{tp}| - 0.613V = 0.5V^{1/2}\sqrt{5.6V - |V_{tp}|}$

squaring both sides and setting one side equal to zero, we have the quadratic equation,

$|V_{tp}|^2 - 0.976|V_{tp}| - 1.024V^2 = 0$

solving, we get $|V_{tp}| = 1.6\ V$

(d)

$t_p = \frac{1}{2}(t_{PLH} + t_{PHL}) = \frac{1}{2}(0.24\text{ ns} + 0.19\text{ ns})$

$\simeq 0.22$ ns

15.5

$R_{TG_{AV}} = \frac{R_{TG1} + R_{TG2}}{2} = \frac{4.5\ k\Omega + 6.5\ k\Omega}{2}$

$= 5.5k\Omega$

$t_{PLH} = 0.69RC = 0.69(5.5k\Omega)(70)(10^{-15})F$

$t_{PLH} = 0.27$ns which is close to the value of 0.24ns obtained in Exercise 15.14

15.6

$\left(\frac{W}{L}\right)_n = \left(\frac{W}{L}\right)_p = 1.5$

Using Eq. 15.36

$R_{TG} \approx \frac{12.5}{(W/L)_n} = \frac{12.5}{1.5} = 8.3\ k\Omega$

15.7

Using Eq.14.71

$R_{P1} = \frac{30}{\left(\frac{W}{L}\right)_p}\ k\Omega = \frac{30}{(2)}\ k\Omega = 15\ k\Omega$

with Eq. 15.36 we see that

$R_{TG} = \frac{12.5}{\left(\frac{W}{L}\right)_n}\ k\Omega = \frac{12.5}{(1)}\ k\Omega = 12.5\ k\Omega$

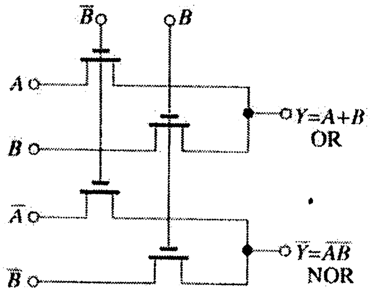
Using Eq.15.38

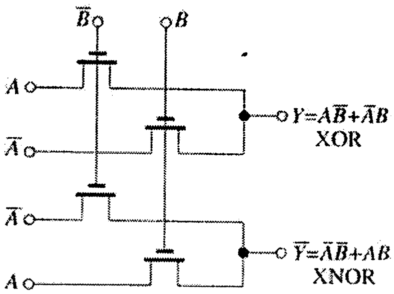
$t_p = 0.69[(C_{out1} + C_{TG1})R_1 + (C_{in2} + C_{TG2}) \times (R_1 + R_2)$

$= 0.69[(10fF + 5fF)(15k\Omega) + (10fF + 5fF) \times (15\ k\Omega + 12.5\ k\Omega)]$

$t_p = 0.64$ ns

15.8





15.9

Since $i_D(V_{DD}) = \frac{1}{2}(\mu_n C_{ox})\left(\frac{W}{L}\right)_{eq}(V_{DD} - V_t)^2$.

doubling $\left(\frac{W}{L}\right)$ will double $\left(\frac{W}{L}\right)_{eq}$ and $i_D(V_{DD})$

so $i_D(V_{DD}) = 2(76.1\ \mu A) = 152.2\ \mu A$

This new $\left(\frac{W}{L}\right)_{eq}$ will also double $i_D\left(\frac{V_{DD}}{2}\right)$:

$$i_D\left(\frac{V_{DD}}{2}\right) = 2(68.9\mu A) = 137.8\ \mu A$$

This doubles I_{av} to $2(72.5\ \mu A) = 145\ \mu A$
the new t_{PHL} is

$$t_{PHL} = \frac{C\left(V_{DD} - \frac{V_{DD}}{2}\right)}{I_{av}}$$

$$= \frac{30(10^{-15})F(1.8V - 0.9V)}{145(10^{-6})A} = 0.19 \text{ ns}$$

15.10

Refer to Fig. E15.10

(a) $\left(\frac{W}{L}\right)_{eq1} = \frac{1}{2}\left(\frac{W}{L}\right) = \frac{1}{2} \times \frac{4}{2} = 1$

$$\left(\frac{W}{L}\right)_{eq2} = \frac{1}{2}\left(\frac{W}{L}\right) = \frac{1}{2} \times \frac{4}{2} = 1$$

(b) $i_{D1}(v_{I1} = V_{DD}) = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_{eq1}(V_{DD} - V_t)^2$

$$= \frac{1}{2} \times 50 \times 1(5 - 1)^2$$

$$= 400\mu A$$

$$i_{D1}(v_{Y1} = V_t) = k_n'\left(\frac{W}{L}\right)_{eq1}\left[(V_{DD} - V_t)V_t - \frac{1}{2}v_t^2\right]$$

$$= 50 \times 1\left[(5 - 1)1 - \frac{1}{2} \times 1\right]$$

$$= 175\mu A$$

$$i_{D1}|_{av} = \frac{400 + 175}{2} = 288\mu A$$

(c) $i_{D1}|_{av}\Delta t = C_{L1}\,\Delta v_{Y1}$

$$\Delta t = \frac{C_{L1}(V_{DD} - V_t)}{i_{D1}|_{av}} = \frac{40 \times 10^{-15} \times 4}{288 \times 10^{-6}}$$

$$= 0.56 \text{ ns}$$

(d) Following the hint we assume that Q_{eq} remains saturated during Δt.

$$i_{D2}|_{av} = i_{D2}(v_{Y1} = 3V) = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_{eq2}(3 - 1)^2$$

$$i_{D2}|_{av} = \frac{1}{2} \times 50 \times 1(3 - 1)^2$$

$$= 100\mu A$$

(e) $\Delta v_{Y2} = -\frac{i_{D2}|_{av} \cdot \Delta t}{C_{L2}}$

$$= -\frac{100 \times 10^{-6} \times 0.56 \times 10^{-9}}{40 \times 10^{-15}}$$

$$= -1.4 \text{ V}$$

Thus, v_{Y2} decrease to 3.6 V.

15.11

$V_{OH} = 0$

$V_{OL} = -0.88$ V

SHOULD BE SHIFTED BY -0.88 V

$V_{OH} = -0.88$V AFTER SHIFTING

$V_{OL} = -1.76$V AFTER SHIFTING

15.12

Refer to Fig. 15.12 Neglecting the base current of Q_1, the current through R_1, D_1, D_2 and R_2 is

$$I = \frac{5.2 - V_{D1} - V_{D2}}{R_1 + R_2}$$

$$= \frac{5.2 - 0.75 - 0.75}{0.907 + 4.98} = 0.6285 \text{ mA}$$

Thus, $V_B = -I_{R1} = -0.57$ V

$V_R = V_B - V_{BE1} = -0.57 - 0.75 = -1.32$ V

15.13

Refer to Fig. 15.26

$$I_E = \frac{V_R - V_{BE}|_{QR} - (-V_{EE})}{R_E}$$

$$= \frac{-1.32 - 0.75 + 5.2}{0.779} \simeq 4 \text{ mA}$$

$V_C|_{QR} = -\gamma \times 4 \times R_{C2} \cong -4 \times 0.245 = -1$ V.

$V_C|_{Q_A Q_B} = 0$V (because the current through R_{C1} is zero)

15.14

Refer to Fig. 15.28

For $V_I = V_{IL}$, $I_{QR} = 99\, I_{QA}$,

$$I_E = \frac{-1.32 - V_{BE|QR} + 5.2}{0.779}$$

Assume $V_{BE}|_{QR} = 0.75$V, $I_E = 4.018$ mA

$I_{QR} \simeq 0.99 \times 4.018 = 3.98$ mA

Thus a better estimate of $V_{BE}|_{QR}$ is

$$V_{BE}|_{QR} = 0.75 + 0.025\ln\left(\frac{3.98}{1}\right)$$

$= 0.785$ V

and correspondingly,

$$I_E = \frac{-1.32 - 0.785 + 5.2}{0.779} = 3.97 \text{ mA}$$

For $V_I = -1.32$V, $I_{QR} = I_{QA} = I_E/2$,

$$I_E = \frac{-1.32 - 0.75 + 5.2}{0.779} = 4.018 \text{ mA}$$

Thus a better estimate for $V_{BE}|_{QR}$ is

$$V_{BE}|_{QR} = 0.75 + 0.025\ \ln\left(\frac{2.009}{1}\right)$$

$= 0.767$ V

and correspodingly,

$I_E = 4.00$ mA

For $V_I = V_{IH} = -1.205$ V,

$I_{QA} = 99 I_{QR}$,

$$I_E = \frac{-1.205 - 0.75 + 5.2}{0.779} = 4.166 \text{ mA}$$

Thus a better estimate for $V_{BE}|_{QA}$ is

$$V_{BE}|_{QA} = 0.75 + 0.025\ln\left(\frac{0.99 \times 4.166}{1}\right)$$

$= 0.788$ V.

and correspondingly

$$I_E = \frac{-1.205 - 0.788 + 5.2}{0.799} = 4.12 \text{ mA}$$

At $V_I = V_R \cdot I_{QR} = \frac{1}{2} I_E = 2$ mA

Thus, $V_C|_{QR} = -2 \times 0.245 = -0.49$ V

$v_{OR} = -0.49 - 0.75 = -1.24$ V

$$I_E|_{Q2} = \frac{-1.24 + 2}{0.05} = 15.2 \text{ mA}$$

A better estimate for $V_{BE}|_{Q2}$ is

$$V_{BE}|_{Q2} = 0.75 + 0.025\ln\left(\frac{15.2}{1}\right)$$

$= 0.818$ V

Thus a better estimate for v_{OR} is

$v_{OR} = -0.49 - 0.818 = -1.31$ V

15.15

REFER TO FIG. 15.32for

$V_I = V_{IH} = -1.205$

The value of I_E we found in Exercise 15.14to be 4.12 mA. The $V_C|_{QR} \simeq -0.22 \times 4.12$

$= -0.906$ V

$v_{NOR} \simeq -0.906 - 0.75 = -1.656$ V

$$I|_{Q3} = \frac{-1.656 + 2}{0.05} = 6.88 \text{ mA}$$

A better estimate for $V_{BE}|_{Q3}$ is

$$V_{BE}|_{Q3} = 0.75 + 0.025\ln\left(\frac{6.88}{1}\right)$$

$= 0.798$ V

and correspondingly

$V_{NOR} = -0.906 - 0.798 = -1.704$ V

(b)For $v_I = V_{OH} = -0.88$ V,

$$I_E \simeq \frac{-0.88 - 0.75 + 5.2}{0.779} = 4.58 \text{ mA}$$

A better estimate for $V_{BE}|_{QA}$ is

$$V_{BE}|_{QA} = 0.75 + 0.025\ln\left(\frac{4.58}{1}\right) = 0.788 \text{ V}$$

$$\text{Thus}, I_E = \frac{-0.88 - 0.788 + 5.2}{0.779} = 4.53 \text{ mA}$$

$V_C|_{QA} = -0.22 \times 4.53 = -1$ V

$V_{NOR} = -1 - 0.75 = -1.75$ V

$$I|_{RT} = \frac{-1.75 + 2}{0.05} = 5 \text{ mA}$$

$$V_{BE}|_{Q3} = 0.75 + 0.025\ln\left(\frac{5}{1}\right)$$

$= 0.79$ V

$V_{NOR} = -1 - 0.79 = -1.79$ V

(c) The input resistance into the base of Q_3 is

$(\beta + 1)[r_{e3} + R_T]$

$$= 101\left[\frac{25}{5} + 50\right] = 5.55 \text{ k}\Omega$$

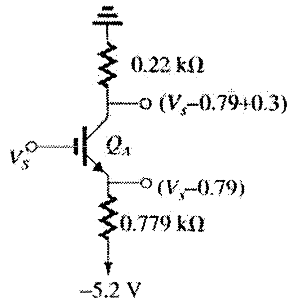
$$\frac{V_C|_{QA}}{V_i} = -\frac{(5.55\ k\Omega \parallel 0.22\ k\Omega)}{r_e|_{QA} + R_E}$$

$$= \frac{-5.55 \parallel 0.22}{\left(\frac{25}{4.53} + 771\right) \times 10^{-3}} = -0.269$$

$$\frac{v_{NOR}}{v_C|_{QA}} = \frac{50\ \Omega}{50\ \Omega + 5\ \Omega} = 0.909$$

Thus, $\frac{v_{NOR}}{v_C|_{QA}} = -0.269 \times 0.909 = -0.24\,V/V$

d) See figure below. Assume $V_{BE} \approx 0.79\,V$



(because the current will be 4 to 5 mA). At the range of saturation,

$I_C = \alpha I_E = 0.99 I_E$

Thus, $\frac{0 - V_s + 0.79 - 0.3}{0.22} = 0.99 \times$

$\frac{V_s - 0.79 + 5.2}{0.779}$

$\Rightarrow V_S = -0.58\ V$

15.16

Refer to Fig. 15.26 For the reference circuit, the current through R_1, D_1, D_2, and R_2

is $\frac{5.2 - 2 \times 0.75}{4.98 + 0.907} = 0.629\ mA$

$V_B|_{Q1} = -0.57\ V$

$V_R = -0.57 - 0.75 = -1.32\ V$

$I_E|_{Q1} = \frac{-1.32 + 5.2}{6.1} = 0.636\ mA$

Thus the reference circuit draws a current of $(0.629 + 0.636) = 1.265$ mA from the 5.2 V supply. It follows that the power dissipated in the reference circuit is $1.265 \times 5.2 = 6.6$ mW. Since the reference circuit supplies four gates, the dissipation attributed to a gate is $\frac{6.6}{4} = 1.65$ mW

In addition, the gate draws a current $I_E \approx 4$ mA from the 5.2V supply. Thus the total power dissipation / gate is

$P_D = 4 \times 5.2 + 1.65 = 22.4\ mW$

Ex 16.1

Refer to Fig.16.5(a)

when $v_\phi = v_s = \frac{V_{DD}}{2}$ then Q_{eq} will be saturatted $v_{\bar{Q}} = \frac{V_{DD}}{2}$ and Q_2 will be in triode

$$Q_{eq}: \left(\frac{W}{L}\right) = \frac{1}{2}\left(\frac{W}{L}\right)_{5,6}$$

$$\frac{1}{2}k_n'\left(\frac{W}{L}\right)_{eq}\left(\frac{V_{DD}}{2} - V_t\right)^2 = \frac{1}{2}k_p'\left(\frac{W}{L}\right)_2$$

$$\left[(V_{DD} - V_t)\frac{V_{DD}}{2} - \frac{1}{2}\left(\frac{V_{DD}}{2}\right)^2\right]$$

From Example 16.1

$k_n' = 4k_p' = 300\ \mu A/V^2$;

$|V_t| = 0.5$; $V_{DD} = 1.8$

$$\frac{1}{2}(300 \times 10^{-6})\left(\frac{1}{2}\right)\left(\frac{W}{L}\right)_5\left(\frac{1.8}{2} - 0.5\right)^2$$

$$= \frac{1}{2}\left(\frac{300\ \mu}{4}\right)\left(\frac{1.08}{0.18}\right)\left[(1.8 - 0.5)\left(\frac{1.8}{2}\right) - \frac{1}{2}(.9)^2\right]$$

$$(12 \times 10^{-6})\left(\frac{W}{L}\right)_5 = 172 \times 10^{-6}$$

$$\left(\frac{W}{L}\right)_5 = 14.3 \cong \frac{2.6\ \mu m}{0.18\ \mu m}$$

Ex 16.2

Bits for row address:

$2^M = 1,024$

$\log_2(2^M) = \log_2(1,024)$

$\mu * \log_2(2) = \log_2(1,024)$

$$\mu = \frac{\log_2(1,024)}{\log_2(2)} = 10$$

Bits for column address:

$2^N = 128$

$$N = \frac{\log_2(128)}{\log_2(2)} = 7$$

Bits for block address:

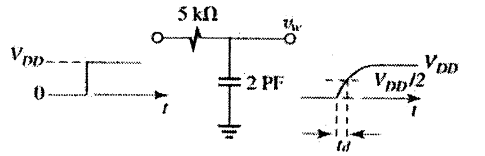
$2^{Bits} = 32$

$$Bits = \frac{\log_2(32)}{\log_2(2)} = 5$$

Ex 16.3

$v_w = V_{DD}(1 - e^{-t/CR})$

$$\frac{V_{DD}}{2} = V_{DD}(1 - e^{-t_d/CR})$$



$t_d = CR\ln 2$

$= 2 \times 10^{-12} \times 5 \times 10^3 \times 0.69$

$= 6.9$ ns

Ex 16.4

$$\left.\frac{\left(\frac{W}{L}\right)_a}{\left(\frac{W}{L}\right)_n}\right|_{max} = \frac{1}{\left(1 - \frac{V_{tn}}{V_{DD} - V_{tn}}\right)^2} - 1$$

$$\left.\left(\frac{W}{L}\right)_a\right|_{max} = 1.5 \times \left[\frac{1}{\left(1 - \frac{0.5}{1.8 - 0.5}\right)^2} - 1\right] = 2.5$$

$$\Rightarrow \left(\frac{W}{L}\right)_a \leq 2.5$$

Ex 16.5

$\Delta t = \frac{C_B \times \Delta V}{I_5}$: To find I_5, we use

$$I_5 = \frac{1}{2}(\mu_n C_{ox})\left(\frac{W}{L}\right)(V_{DD} - V_{tn} - V_{\bar{Q}})^2$$

(a) $\left(\frac{W}{L}\right)_a = 2.5$

$$I_5 = \frac{1}{2} \times 300 \times 10^{-6} \times 2.5 \times (1.8 - 0.5 - 0.5)^2$$

$= 240\ \mu A$

$$\Delta t = \frac{2 \times 10^{-12} \times 0.2}{240 \times 10^{-6}} = 1.7 \text{ ns}$$

(b) $\left(\frac{W}{L}\right)_a = 1.5$

$$I_5 = \frac{1}{2} \times 300 \times 10^{-6} \times 1.5 \times (1.8 - 0.5 - 0.5)^2$$

$= 144\ \mu A$

$$\Delta t = \frac{2 \times 10^{-12} \times 0.2}{144\ \mu A} = 2.8 \text{ ns}$$

or: $\Delta t\ \alpha\ \frac{1}{I_5}\ \alpha\ \frac{1}{\left(\frac{W}{L}\right)_a}$ therefore,

$$\Delta t = 1.7 \text{ ns} \times \frac{2.5}{1.5} = 2.8 \text{ ns}$$

Ex 16.6

$$\left(\frac{W}{L}\right)_p \leqslant \left(\frac{W}{L}\right)_a \times \frac{\mu_n}{\mu_p}\left[1 - \left(1 - \frac{V_{tn}}{V_{DD} - V_{tn}}\right)^2\right]$$

$$\left(\frac{W}{L}\right)_p \leqslant \left(\frac{W}{L}\right)_a \times 4 \times \left[1 - \left(1 - \frac{0.5}{1.8 - 0.5}\right)^2\right]$$

$$\left(\frac{W}{L}\right)_p \leqslant 2.5\left(\frac{W}{L}\right)_a \text{ or}$$

$$\left(\frac{W}{L}\right)_p \leqslant 2.5 \times 2.5 \Rightarrow \left(\frac{W}{L}\right)_p \leqslant 6.25$$

For minimum area: select

$W_n = W_p = W_a = 0.18\mu m$

Ex 16.7

From Eqs.16.14 and 16.15 we have:

$\Delta V_{(1)} \simeq$

$$\frac{C_S}{C_B} \times \frac{V_{DD}}{2} = \frac{30 \times 10^{-15}}{0.3 \times 10^{-12}} \times \frac{1.2}{2} = 6.0 \text{ mV}$$

$\Delta V_{(0)} \simeq$

$$-\frac{C_S}{C_B} \times \frac{V_{DD}}{2} = \frac{-30 \times 10^{-15}}{0.3 \times 10^{-12}} \times \frac{1.2}{2} = -0.06 \text{ V}$$

$$= -60 \text{ mV}$$

Ex 16.8

Area of the storage array

$= 64 \times 1024 \times 1024 \times 2 = 134217728 \ \mu m^2$

$= 134.2 \text{ mm}^2$ or equivalently

$= 11.6 \text{ mm} \times 11.6 \text{ mm}$

Total chip area

$= 1.3 \times 134.2 = 174.46 \text{ mm}^2 = 13.2 \times 13.2 \text{ mm}^2$

Ex 16.9

Refer to Example 16.2

Since Δt is proportional to $\tau = \frac{C}{G_m}$, we can reduce Δt by a factor of 2 by decreasing τ by the same factor. $\Delta t \ \alpha \ \tau \ \alpha \ \frac{1}{G_m}$

Hence, G_m has to be doubled. $G_m = g_{mn} + g_{mp}$ and both g_{mn} and g_{mp} have to be increased by a factor of 2. The increase in g_m can be achieved by increasing the correspondng $\frac{W}{L}$, thus:

$$\left(\frac{W}{L}\right)_n = 2 \times \frac{0.54}{0.18} = 6$$

$$\left(\frac{W}{L}\right)_p = 2 \times \frac{2.16}{0.18} = 24$$

Ex 16.11

From Eq.16.18 $\Delta t = \frac{CV_{DD}}{I}$ or

$$I = \frac{CV_{DD}}{\Delta t} = \frac{50^{pF} \times 1.8}{0.5 \text{ ns}} = 180 \ \mu A$$

$$P = V_{DD}I = 1.8 \times 180 \ \mu A = 324 \ \mu W$$

Ex 16.12

Refer to Fig. 13.26

Our decoder is an extension of that show:

We have M bits is the address (as opposed to 3) and correspondingly there will be 2^M word lines. Now, each of the 2^M word lines is connected to M NMOS devices and to one PMOS transistor. Thus the total number of devices required is

$$M2^M(\text{NMOS}) + 2^M(\text{PMOS})$$

$$= 2^M(M + 1)$$

Ex 16.13

Refer to Fig.13.28 Our tree decoder will have 2^N bit lines. Thus it will have N levels: At the first levels there will be 2 transistors, at the second 2^2,..., at the Nth level there will be 2^N transistors. Thus the total number of transistors, can be find as

$$\text{Number} = 2 + 2^2 + 2^3 + \cdots + 2^N$$

$$= 2\underbrace{(1 + 2 + 2^2 + \cdots + 2^{N-1})}$$

Geometric series r = 2

$$\text{Sum} = \frac{r^N - 1}{r - 1} = \frac{2^N - 1}{2 - 1}$$

$$= 2^N - 1$$

Thus,

Number $= 2(2^N - 1)$

Ex 16.14

$$f = \frac{1}{2 \times 5t_p}$$

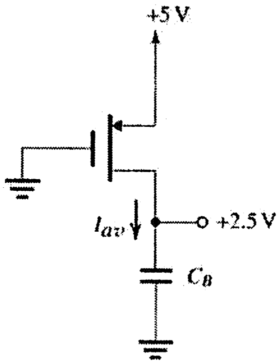
$$= \frac{1}{2 \times 5 \times 10^{-9}} = 100 \text{ MHz}$$

Ex 16.15

(a) $I_{av} = k_p'\left(\frac{W}{L}\right)_p\left[(5-1)2.5 - \frac{1}{2}2.5^2\right]$

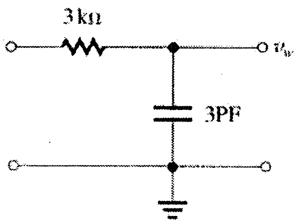
$= 20 \times \frac{24}{2}[10 - 3.125]$

$= 1.65$ mA



Thus, $t_{Charging} = \frac{2 \times 10^{-12} \times 2}{1.65 \times 10^{-3}} = 6.1$ ns

(b)

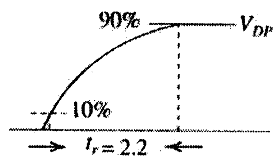


$t_r \simeq 2.2\tau$

$= 2.2 \times 3 \times 10^{-12} \times 3 \times 10^3$

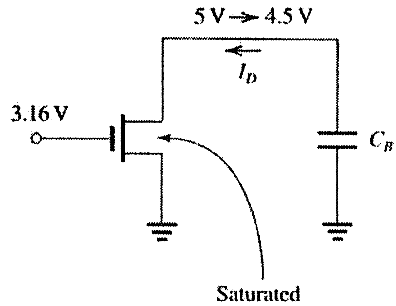
$= 19.8$ ns

(c) In one time-constant the voltage reached is



$V_{DD}(1 - e^{-1}) = 0.632V_{DD}$

$= 3.16$ V



$I_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_n(3.16 - 1)^2$

$= \frac{1}{2} \times 50 \times \frac{6}{2} \times 2.16^2$

$= 0.35$ mA

$\Delta t = \frac{C_B \Delta V}{I_D}$

$= \frac{2 \times 10^{-12} \times 0.5}{0.35 \times 10^{-3}} = 2.9$ ns

1.1

(a) $I = \frac{V}{R} = \frac{10\ \text{V}}{1\ \text{k}\Omega} = 10\ \text{m}A$

(b) $R = \frac{V}{I} = \frac{10\ \text{V}}{1\ \text{mA}} = 10\ \text{k}\Omega$

(c) $V = IR = 10\ \text{mA} \times 10\ \text{k}\Omega = 100\ \text{V}$

(d) $I = \frac{V}{R} = \frac{10\ \text{V}}{100\ \Omega} = 0.1\ A$

Note: Volts, milliamps, and kilo-ohms constitute a consistent set of units.

1.2

(a) $V = IR = 10\ \text{m}A \times 1\ \text{k}\Omega = 10\ \text{V}$

$P = I^2R = (10\ \text{mA})^2 \times 1\ \text{k}\Omega = 100\ \text{mW}$

(b) $R = V/I = 10\ \text{V}/1\ \text{mA} = 10\ \text{k}\Omega$

$P = VI = 10\ \text{V} \times 1\ \text{mA} = 10\ \text{mW}$

(c) $I = P/V = 1\ \text{W}/10\ \text{V} = 0.1\ \text{A}$

$R = V/I = 10\ \text{V}/0.1\ \text{A} = 100\ \Omega$

(d) $V = P/I = 0.1\ \text{W}/10\ \text{mA}$

$= 100\ \text{mW}/10\ \text{mA} = 10\ \text{V}$

$R = V/I = 10\ \text{V}/10\ \text{mA} = 1\ \text{k}\Omega$

(e) $P = I^2R \Rightarrow I = \sqrt{P/R}$

$I = \sqrt{1000\ \text{mW}/1\ \text{k}\Omega} = 31.6\ \text{mA}$

$V = IR = 31.6\ \text{mA} \times 1\ \text{k}\Omega = 31.6\ \text{V}$

Note: V, mA, kΩ, and mW constitute a consistent set of units.

1.3

Thus, there are 17 possible resistance values.

1.4

Shunting the 10 kΩ by a resistor of value of R result in the combination having a resistance R_{eq},

$$R_{eq} = \frac{10\,R}{R + 10}$$

Thus, for a 1% reduction,

$$\frac{R}{R+10} = 0.99 \Rightarrow R = 990\ \text{k}\Omega$$

For a 5% reduction,

$$\frac{R}{R+10} = 0.95 \Rightarrow R = 190\ \text{k}\Omega$$

For a 10% reduction,

$$\frac{R}{R+10} = 0.90 \Rightarrow R = 90\ \text{k}\Omega$$

For a 50% reduction,

$$\frac{R}{R+10} = 0.50 \Rightarrow R = 10\ \text{k}\Omega$$

Shunting the 10 kΩ by

(a) 1MΩ result in

$$R_{eq} = \frac{10 \times 1000}{1000 + 10} = \frac{10}{1.01} = 9.9\ \text{k}\Omega,$$

a 1% reduction;

(b) 100 kΩ results in

$$R_{eq} = \frac{10 \times 100}{100 + 10} = \frac{10}{1.1} = 9.09\ \text{k}\Omega,$$

a 9.1% reduction;

(c) 10 kΩ results in

$$R_{eq} = \frac{10}{10 + 10} = 5\ \text{k}\Omega,$$

a 50% reduction.

1.5

$$V_O = V_{DD}\frac{R_2}{R_1 + R_2}$$

To find R_O, we short circuit V_{DD} and look back into node X,

$$R_O = R_2 \parallel R_1 = \frac{R_1R_2}{R_1 + R_2}$$

1.6

Use voltage divider to find V_o

$$V_o = 9\frac{3.3}{3.3 + 6.8} = 2.94\ \text{V}$$

Equivalent output resistance R_O is

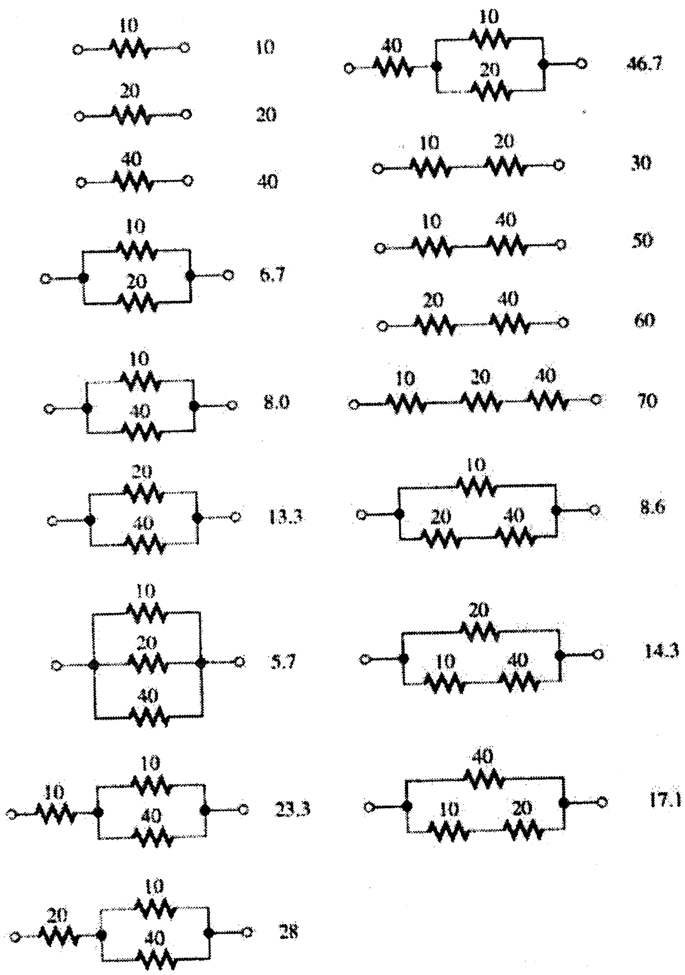
$$R_O = (3.3\ \text{k}\Omega \parallel 6.8\ \text{k}\Omega) = 2.22\ \text{k}\Omega$$

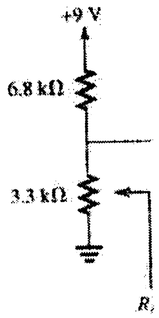
The extreme values of V_o for ±5 % tolerance resistor are

$$V_{O-min} = 9\frac{3.3(1-0.05)}{3.3(1-0.05) + 6.8(1+0.05)}$$

$$= 2.75\ \text{V}$$

This figure is for 1.3



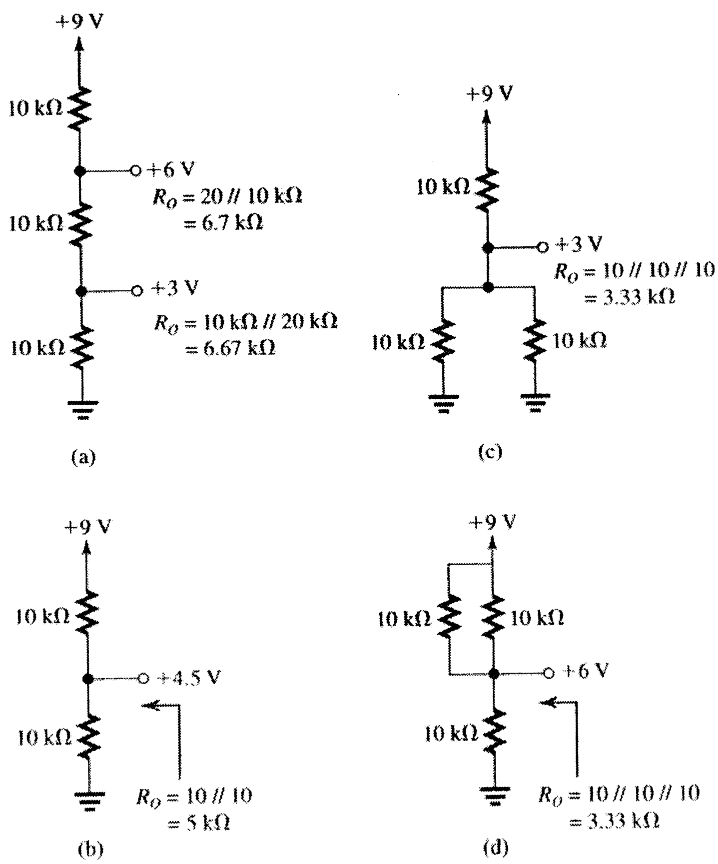


$$V_{O\ max} = 9\frac{3.3(1+0.05)}{3.3(1+0.05)+6.8(1-0.05)}$$
$$= 3.14\ V$$

The extreme values of R_O for ±5% tolerance resistors are

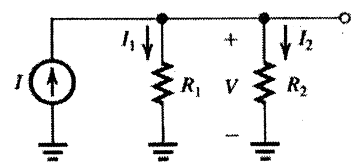
$$R_{O-min} = \frac{3.3(1-0.05)\times 6.8(1-0.05)}{3.3(1-0.05)+6.8(1-0.05)}$$
$$= 2.11\ k\Omega$$
$$R_{O-max} = \frac{3.3(1+0.05)\times 6.8(1+0.05)}{3.3(1+0.05)+6.8(1+0.05)}$$
$$= 2.33\ k\Omega$$

1.7



Voltage generated
+3V (two ways: (a) and (c) with (c) having lower output resistance)
+4.5 V (b)
+6V (two ways: (a) and (d) with (d) having a lower output resistance)

1.8



$$V = I(R_1 \parallel R_2)$$
$$= I\frac{R_1 R_2}{R_1 + R_2}$$
$$I_1 = \frac{V}{R_1} = I\frac{R_2}{R_1+R_2}$$
$$I_2 = \frac{V}{R_2} = I\frac{R_1}{R_1+R_2}$$

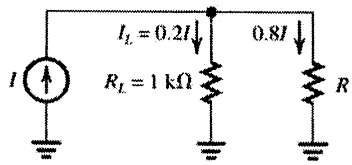
1.9

Connect a resistor R in parallel with R_L.

To make $I_L = 0.2I$ (and thus the current through R, $0.8I$), R should be such

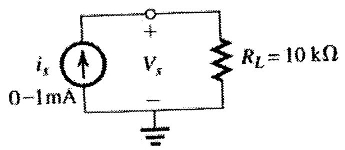
$0.2I \times 1\ \text{k}\Omega = 0.8IR$

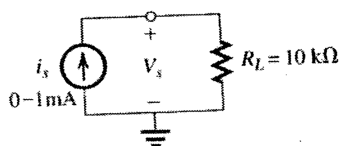
$\Rightarrow R = 250\ \text{k}\Omega$



1.10

For $R_L = 10\ \text{k}\Omega$, when signal source generates 0 – 1 mA, a voltage of 0 – 10 V may appear across the source





To limit $V_S \leq 1$ V, the net resistance has to be ≤ 1 kΩ. To achieve this we have to shunt R_L with a resistor R so that $(R \parallel R_L) \leq 1$ kΩ.

$R \parallel R_L \leq 1$ kΩ.

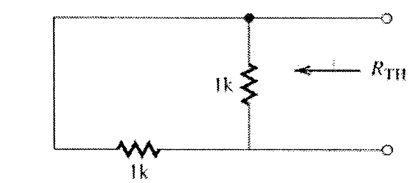
$$\frac{RR_L}{R + R_L} \leq 1\ \text{k}\Omega$$

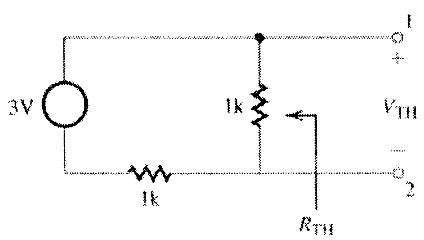
For $R_L = 10$ K

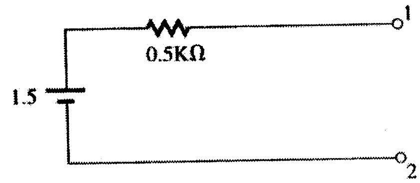
$R \simeq 1.11$ kΩ

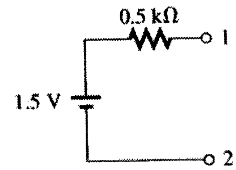
The resulting circuit needs only one additional resistance of 1.11 kΩ in parallel with R_l so that $V_S \leq 1$ V

1.11







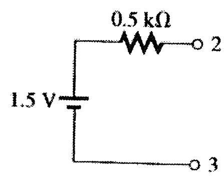


(a)

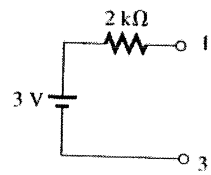
$$V_{TH} = 3\left(\frac{1\ \text{k}}{1\ \text{k} + 1\ \text{k}}\right) = 1.5\ \text{V}$$

$R_{TH} = 1\ \text{k} \parallel 1\ \text{k} = 0.5\ \text{k}$

Same procedure is used for b) & c)

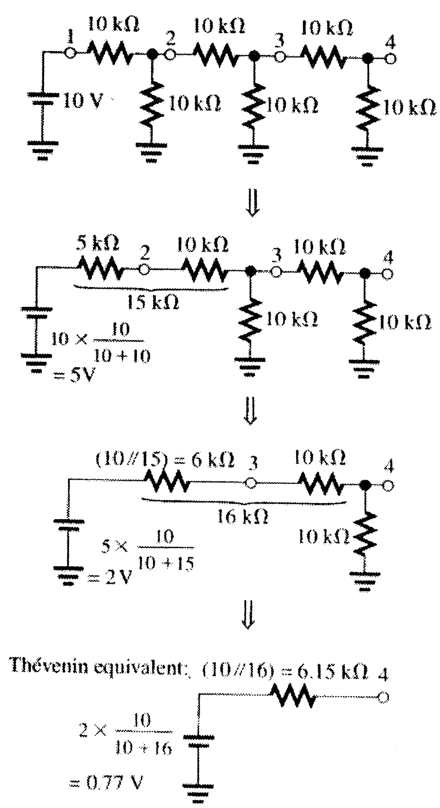


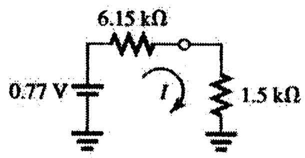
(b)



(c)

1.11





Now, when a resistance of 1.5 kΩ is connected between 4 and ground,

$$I = \frac{0.77}{6.15 + 1.5}$$

$= 0.1$ mA

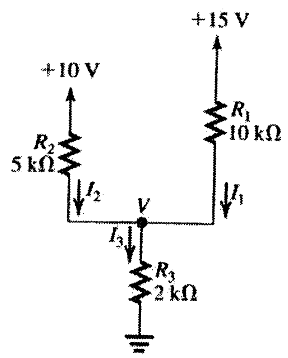
1.12

(a) Node equation at the common mode yields

$I_3 = I_1 + I_2$

Using the fact that the sum of the voltage drops across R_1 and R_3 equals 15 V, we write

$$15 = I_1R_1 + I_3R_3$$
$$= 10I_1 + (I_1 + I_2) \times 2$$
$$= 12I_1 + 2I_2$$



That is,

$12I_1 + 2I_2 = 15$ (1)

Similarly, the voltage drops across R_2 and R_3 add up to 10 V, thus

$$10 = I_2R_2 + I_3R_3$$
$$= 5I_2 + (I_1 + I_2) \times 2$$

which yields

$2I_1 + 7I_2 = 10$ (2)

Equations (1) and (2) can be solved together by multiplying (2) by 6,

$12I_1 + 42I_2 = 60$ (3)

Now, subtracting (1) from (3) yields

$40I_2 = 45$

$\Rightarrow I_2 = 1.125$ mA

Substituting in (2) gives

$$2I_1 = 10 - 7 \times 1.125 \text{ mA}$$
$$\Rightarrow I_1 = 1.0625 \text{ mA}$$
$$I_3 = I_1 + I_2$$
$$= 1.0625 + 1.1250$$
$$= 1.1875 \text{ mA}$$
$$V = I_3R_3$$
$$= 1.1875 \times 2 = 2.3750 \text{ V}$$

To summarize:

$I_1 \simeq 1.06$ mA $\quad I_2 \simeq 1.13$ mA

$I_3 \simeq 1.19$ mA $\quad V \simeq 2.38$ V

(b) A node equation at the common node can be written in terms of V as

$$\frac{15 - V}{R_1} + \frac{10 - V}{R_2} = \frac{V}{R_3}$$

Thus,

$$\frac{15 - V}{10} + \frac{10 - V}{5} = \frac{V}{2}$$
$$\Rightarrow 0.8 \text{ V} = 3.5$$
$$\Rightarrow V = 2.375 \text{ V}$$

Now, I_1, I_2, and I_3 can be easily found as

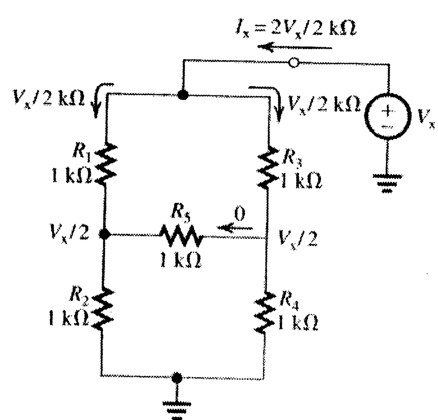
$$I_1 = \frac{15 - V}{10} = \frac{15 - 2.375}{10}$$
$$= 1.0625 \text{ mA} \simeq 1.06 \text{ mA}$$
$$I_2 = \frac{10 - V}{5} = \frac{10 - 2.375}{5}$$
$$= 1.125 \text{ mA} \simeq 1.13 \text{ mA}$$
$$I_3 = \frac{V}{R_3} = \frac{2.375}{2} = 1.1875 \text{ mA} \simeq 1.19 \text{ mA}$$

Method (b) is much preferred; faster, more insightful and less prone to errors. In general, one attempts to identify the least possible number of variables and write the corresponding minimum number of equations.

1.13

From the symmetry of the circuit, there will be no current in R_5. (Otherwise the symmetry would be violated.) Thus each branch will carry a current $V_x/2$ kΩ and I_x will be the sum of the two current,

$$I_x = \frac{2V_x}{2 \text{ k}\Omega} = \frac{V_x}{1 \text{ k}\Omega}$$



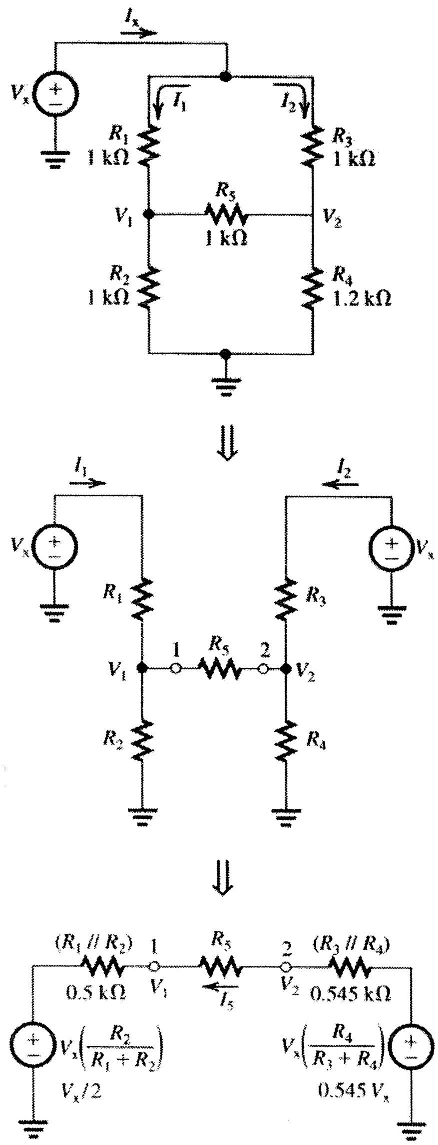
Thus,

$$R_{eq} = \frac{V_x}{I_x} = 1\ \text{k}\Omega$$

Now, if R_4 is raised to 1.2 kΩ the symmetry will be broken. To find I_x we use Thévenin's theorem as follows:

$$I_5 = \frac{0.545V_x - 0.5V_x}{0.5 + 1 + 0.545} = 0.022V_x$$

$$V_1 = \frac{V_x}{2} + 0.022\ V_x \times 0.5$$



$$= 0.5V_x \times 1.022 = 0.511V_x$$

$$V_2 = V_1 + I_5R_5 = 0.533V_x$$

$$I_1 = \frac{V_x - V_2}{1\ \text{k}\Omega} = 0.489\ V_x$$

$$I_2 = \frac{V_x - V_2}{1\ \text{k}\Omega} = 0.467V_x$$

$$I_x = I_1 + I_2 = 0.956V_x$$

$$\Rightarrow R_{eq} = \frac{V_x}{I_x} = 1.05\ \text{k}\Omega$$

1.14

(a) $Z = 1\ \text{k}\Omega$ at all frequencies

(b) $Z = 1/j\omega C = -j\dfrac{1}{2\pi f \times 10 \times 10^{-9}}$

At $f = 60$ Hz, $Z = -j265\ \text{k}\Omega$

At $f = 100$ kHz, $Z = -j159\ \Omega$

At $f = 1$ GHz, $Z = -j0.016\ \Omega$

(c) $Z = 1/j\omega C = -j\dfrac{1}{2\pi f \times 2 \times 10^{-12}}$

At $f = 60$ Hz, $Z = -j1.33\ \text{G}\Omega$

At $f = 100$ kHz, $Z = -j0.8\ \text{M}\Omega$

At $f = 1$ GHz, $Z = -j79.6\ \Omega$

(d) $Z = j\omega L = j2\pi fL = j2\pi f \times 10 \times 10^{-3}$

At $f = 60$ Hz, $Z = j3.77\ \Omega$

At $f = 100$ kHz, $Z = j6.28\ \text{k}\Omega$

At $f = 1$ GHz, $Z = j62.8\ \Omega$

(e) $Z = j\omega L = j2\pi fL = j2\pi f(1 \times 10^{-9})$

$f = 60$ Hz, $Z = j3.77 \times 10^{-7} = j0.377\ \mu\Omega$

$f = 100$ kHz,

$Z = j6.28 \times 10^{-4} = j0.628\ \text{m}\Omega$

$f = 16$ Hz, $Z = j62.8\ \Omega$

1.15

(a) $Z = R + \dfrac{1}{j\omega C}$

$$= 10^3 + \frac{1}{j2\pi \times 10 \times 10^3 \times 10 \times 10^{-9}}$$

$$= (1 - j1.59)\ \text{k}\Omega$$

(b) $Y = \dfrac{1}{R} + j\omega C$

$$= \frac{1}{10^3} + j2\pi \times 10 \times 10^3 \times 0.01 \times 10^{-6}$$

$$= 10^{-3}(1 + j0.628)\ \Omega$$

$$Z = \frac{1}{Y} = \frac{1000}{1 + j0.628}$$

$$= \frac{1000(1 - j0.628)}{1 + 0.628^2}$$

$$= (717.2 - j45.04)\ \Omega$$

(c) $Y = \dfrac{1}{R} + j\omega C$

$$= \frac{1}{100 \times 10^3} + j2\pi \times 10 \times 10^3 \times 100 \times 10^{-12}$$

$$= 10^{-5}(1 + j0.628)$$

$$Z = \frac{10^5}{1 + j0.628}$$

$$= (71.72 - j450.4)\ \text{k}\Omega$$

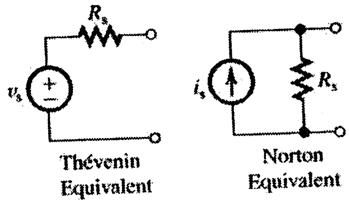
(d) $Z = R + j\omega L$

$$= 100 + j2\pi \times 10 \times 10^3 \times 10 \times 10^{-3}$$

$$= 100 + j6.28 \times 100$$

$$= (100 + j628)\ \Omega$$

1.16



$v_{OC} = v_S$

$i_{SC} = i_S$

$v_S = i_S R_S$

Thus,

$$R_S = \frac{v_{OC}}{i_{SC}}$$

(a) $v_S = v_{OC} = 10 \text{ V}$

$i_s = i_{SC} = 100\ \mu A$

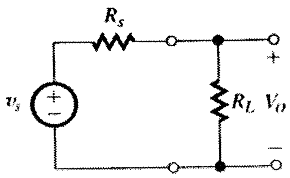
$$R_s = \frac{v_{OC}}{i_{SC}} = \frac{10 \text{ V}}{100\ \mu A} = 0.1 \text{ M}\Omega = 100 \text{ k}\Omega$$

(b) $v_S = v_{OC} = 0.1 \text{ V}$

$i_S = i_{SC} = 10\ \mu A$

$$R_S = \frac{v_{OC}}{i_{SC}} = \frac{0.1 \text{ V}}{10\ \mu A} = 0.01 \text{ M}\Omega = 10 \text{ k}\Omega$$

1.17



$$\frac{v_O}{v_s} = \frac{R_L}{R_L + R_S}$$

$$v_O = v_S / \left(1 + \frac{R_S}{R_L}\right)$$

Thus,

$$\frac{v_S}{1 + \frac{R_S}{100}} = 30$$

and

$$\frac{v_S}{1 + \frac{R_S}{10}} = 10$$

Dividing (1) by (2) gives

$$\frac{1 + (R_S/10)}{1 + (R_S/100)} = 3$$

$\Rightarrow R_S = 28.6 \text{ k}\Omega$

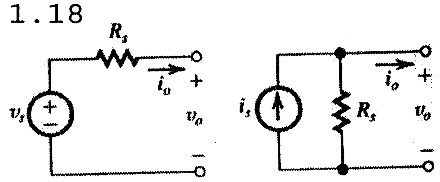
Substituting in (2) gives

$v_s = 38.6 \text{ mV}$

The Norton current i_s can be found as

$$i_s = \frac{v_S}{R_S} = \frac{38.6 \text{ mV}}{28.6 \text{ k}\Omega} = 1.35\ \mu A$$

1.18

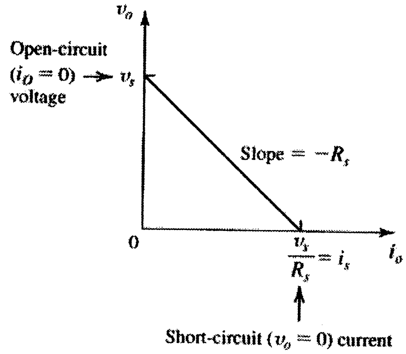


$v_O = v_s - i_O R_s$

$v_O = (i_s - i_O) R_s$

$= i_s R_s - i_O R_s$

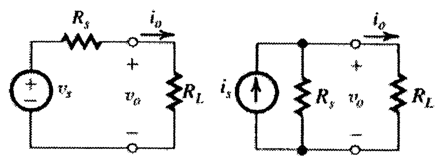
$v_O = v_s - i_O R_s$



1.19

(1) 1.26

(2)



R_L represents the input resistance of the processor

For $v_O = 0.9\ v_s$

$$0.9 = \frac{R_L}{R_L + R_S} \Rightarrow R_L = 9R_S$$

For $i_o = 0.9\ i_s$

$$0.9 = \frac{R_S}{R_S + R_L} \Rightarrow R_L = R_S / 9$$

1.20

Case	ω (rad/s)	f (Hz)	T (s)
a	6.28×10^{9}	1×10^{9}	1×10^{-9}
b	1×10^{9}	1.59×10^{8}	6.28×10^{-9}
c	6.28×10^{10}	1×10^{10}	1×10^{-10}
d	3.77×10^{2}	60	1.67×10^{-2}
e	6.28×10^{3}	1×10^{3}	1×10^{-3}
f	6.28×10^{6}	1×10^{6}	1×10^{-6}

1.21

(a) $V_{peak} = 117 \times \sqrt{2} = 165$ V

(b) $V_{rms} = 33.9 \times \sqrt{2} = 24$ V

(c) $V_{peak} = 220 \times \sqrt{2} = 311$ V

(d) $V_{peak} = 220 \times \sqrt{2} = 311$ kV

1.22

(a) $v = 10 \sin (2\pi \times 10^4 t)$, V

(b) $v = 120\sqrt{2} \sin (2\pi \times 60)$, V

(c) $v = 0.1 \sin(1000t)$, V

(d) $v = 0.1 \sin (2\pi \times 10^{+3} t)$, V

1.23

The two harmonics have the ratio 126/98 = 9/7. Thus, these are the 7th and 9th harmonics. From Eq. 1.2 we note that the amplitudes of these two harmonics will have the ratio 7 to 9, which is confirmed by the measurement reported. Thus the fundamental will have a frequency of 98/7 or 14 kHz and peak amplitude of 63 × 7 = 441 mV. The rms value of the fundamental will be $441 / \sqrt{2} = 312$ mV. To find the peak-to-peak amplitude of the square wave we note that $4V / \pi = 441$ mV. Thus,

Peak-to-peak amplitude

$$= 2V = 441 \times \frac{\pi}{2} = 693 \text{ mV}$$

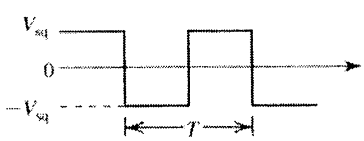
$$\text{Period } T = \frac{1}{f} = \frac{1}{14 \times 10^3} = 71.4\ \mu s$$

1.24

To be barely audible by a relatively young listener, the 5th harmonic must be limited to 20 kHz; thus the fundamental will be 4 kHz. At the low end, hearing extends down to about 20 Hz. For the fifth and higher to be audible the fifth must be no lower than 20 Hz. Correspondingly, the fundamental will be at 4 Hz.

1.25

If the amplitude of the square wave is V_{sq} then the power delivered by the square wave to a resistance R will be V_{sq}^2 / R. If this power is to equal that delivered by a sine wave of peak amlitude $\hat{V}$ then



$$\frac{V_{sq}^2}{R} = \frac{(\hat{V} / \sqrt{2})^2}{R}$$

Thus, $V_{sq} = \hat{V} / \sqrt{2}$. This result is independant of frequency.

1.26

Decimal	Binary
0	0
5	101
8	1000
25	11001
57	111001

1.27

b_3	b_2	b_1	b_0	Value Represented
0	0	0	0	+0
0	0	0	1	+1
0	0	1	0	+2
0	0	1	1	+3
0	1	0	0	+4
0	1	0	1	+5
0	1	1	0	+6
0	1	1	1	+7
1	0	0	0	−0
1	0	0	1	−1
1	0	1	0	−2
1	0	1	1	−3
1	1	0	0	−4
1	1	0	1	−5
1	1	1	0	−6
1	1	1	1	−7

Note that there are two possible representation of zero: 0000 and 1000. For a 0.5-V step size, analog signals in the range ±3.5 V can be represented

Input	Steps	Code
+2.5 V	+5	0101
−3.0 V	−6	1110
+2.7	+5	0101
−2.8	−6	1110

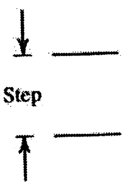
1.28

(a) For N bits there will be 2^N possible levels, from 0 to V_{FS}. Thus there will be $(2^N - 1)$ discrete steps from 0 to V_{FS} with the step size given by

$$\text{Step size} = \frac{V_{FS}}{2^N - 1}$$

This is the analog change corresponding to a change in the LSB. It is the value of the resolution of the ADC.

(b) The maximum error in conversion occurs when the analog signal value is at the middle of a step. Thus the maximum error is



$$\frac{1}{2} \times \text{step size} = \frac{1}{2}\frac{V_{FS}}{2^N - 1}$$

This is known as the quantization error.

(c) $\frac{10\ V}{2^N - 1} \leq 5\ \text{mV}$

$2^N - 1 \geq 2000$

$2^N \geq 2001 \Rightarrow N = 11,$

For $N = 11$

$$\text{Resolution} = \frac{10}{2^{11} - 1} = 4.9\ \text{mV}$$

$$\text{Quantization error} = \frac{4.9}{2} = 2.4\ \text{mV}$$

1.29

There will be 44,100 samples per second with each sample represented by 16 bits. Thus the through-put or speed will be $44{,}100 \times 16 = 7.056 \times 10^5$ bits per second.

1.30

(a) $A_v = \frac{v_O}{v_i} = \frac{10\ V}{100\ mV} = 100\ V/V$

or, 20 log 100 = 40 dB

$A_i = \frac{i_O}{i_i} = \frac{v_O/R_L}{i_i} = \frac{10\ V/100\ \Omega}{100\ \mu A} = \frac{0.1\ A}{100\ \mu A}$

$= 1000$ A/A

or, 20 log 1000 = 60 dB

$A_P = \frac{v_O i_O}{v_i i_i} = \frac{v_O}{v_i} \times \frac{i_O}{i_i} = 100 \times 1000$

$= 10^5$ W/W

or 10 log 10^5 = 50 dB

(b) $A_v = \frac{v_O}{v_i} = \frac{2\ V}{10\ \mu V} = 2 \times 10^5\ V/V$

or, 20 log 2×10^5 = 106 dB

$A_i = \frac{i_O}{i_i} = \frac{v_O/R_L}{i_i} = \frac{2\ V/10\ k\Omega}{100\ nA}$

$= \frac{0.2\ mA}{100\ nA} = \frac{0.2 \times 10^{-3}}{100 \times 10^{-9}} = 2000\ A/A$

or 20 log A_i = 66 dB

1.31

$A_P = \frac{v_O i_O}{v_i i_i} = \frac{v_O}{v_i} \times \frac{i_O}{i_i}$

$= 2 \times 10^5 \times 2000$

$= 4 \times 10^8$ W/W

or 10 log A_P = 86 dB

(c) $A_v = \frac{v_O}{v_i} = \frac{10\ V}{1\ V} = 10\ V/V$

or, 20 log 10 = 20 dB

$A_i = \frac{i_O}{i_i} = \frac{v_O/R_L}{i_i} = \frac{10\ V/10\ \Omega}{1\ mA}$

$= \frac{1\ A}{1\ mA} = 1000\ A/A$

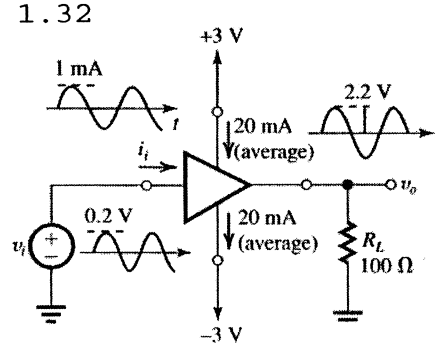
or, 20 log 1000 = 60 dB

$A_P = \frac{v_O i_O}{v_i i_i} = \frac{v_O}{v_i} \times \frac{i_O}{i_i}$

$= 10 \times 1000 = 10^4$ W/W

or 10 $\log_{10} A_P$ = 40 dB

1.32



$A_v = \frac{v_O}{v_i} = \frac{2.2}{0.2}$

$= 11$ V/V

or 20 log 11 = 20.8 dB

$A_i = \frac{i_O}{i_i} = \frac{2.2\ V/100\ \Omega}{1\ mA}$

$= \frac{22\ mA}{1\ mA} = 22\ A/A$

or, 20 log A_i = 26.8 dB

$A_p = \frac{p_O}{p_i} = \frac{(2.2/\sqrt{2})^2/100}{\frac{0.2}{\sqrt{2}} \times \frac{10^{-3}}{\sqrt{2}}}$

$= 242$ W/W

or, 10 log A_p = 23.8 dB

Supply power = 2 × 3 V × 20 mA = 120 mW

Output power =

$\frac{v_{orms}^2}{R_L} = \frac{(2.2/\sqrt{2})^2}{100\ \Omega} = 24.2\ \text{mW}$

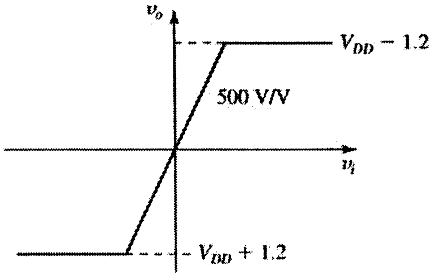
Input power $= \frac{24.2}{242} = 0.1$ mW (negligible)

Amplifier dissipation ≃ Supply power − Output power

$= 120 - 24.2 = 95.8$ mW

$$\text{Amplifier efficiency} = \frac{\text{Output power}}{\text{Supply power}} \times 100$$

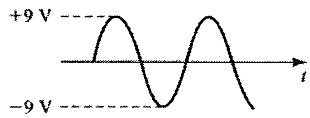
$= \frac{24.2}{120} \times 100 = 20.2\%$



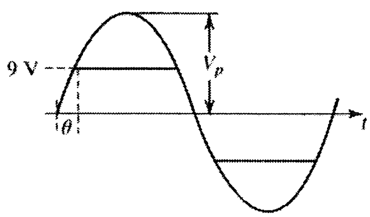
For $V_{DD} = 15$ V, the largest undistorted sine-wave output is of 13.8-V peak amplitude or 9.8 V_{rms}. The input needed is 9.8 V/500 = 19.6 mV_{rms}.

1.33

(a) For an output whose extremes are just at the edge of clipping, i.e., an output of 9-V_{peak}, the input must have 9 V/1000 = 9 mV_{peak}.

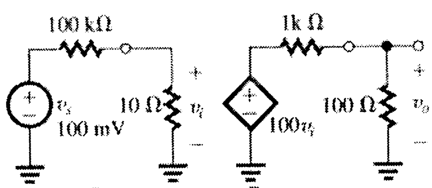


(b) For an output that is clipping 90% of the time, $\theta = 0.1 \times 90° = 9°$ and V_P sin $9° = 9\ V \Rightarrow V_P = 57.5\ V$ which of course does not occur as the output saturates at ± 9 V. To produce this result, the input peak must be 57.5/1000 = 57.5 mV.



(c) For an output that is clipping 99% of the time,
$\theta = 0.01 \times 90° = 0.9°$
$V_P \sin 0.9° = 9$ V
$\Rightarrow V_P = 573$ V and the input must be 573 V/1000 or 0.573 V_{peak}.

1.34



$$\frac{v_O}{v_S} = \frac{R_i}{R_i + R_S} \times A_{v_o} \times \frac{R_L}{R_L + R_O}$$

(a) $$\frac{v_O}{v_S} = \frac{10R_S}{10R_S + R_S} \times A_{v_o} \times \frac{10R_O}{10R_O + R_O}$$

$$= \frac{10}{11} \times 10 \times \frac{10}{11} = 8.26\ V/V$$

or, 20 log 8.26 = 18.3 dB

(b) $$\frac{v_O}{v_S} = \frac{R_S}{R_S + R_S} \times A_{v_o} \times \frac{R_O}{R_O + R_O}$$

$= 0.5 \times 10 \times 0.5 = 2.5$ V/V

or, 20 log 2.5 = 8 dB

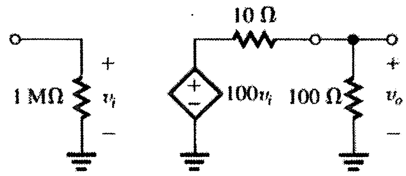
(c)

$$\frac{v_O}{v_S} = \frac{R_S/10}{(R_S/10) + R_S} \times A_{v_o} \times \frac{R_O/10}{(R_O/10) + R_O}$$

$$= \frac{1}{11} \times 10 \times \frac{1}{11} = 0.083\ V/V$$

or 20 log 0.083 = −21.6 dB

1.35



$20 \log A_{v_o} = 40\ \text{dB} \Rightarrow A_{vO} = 100\ V/V$

$$A_v = \frac{v_O}{v_i}$$

$$= 100 \times \frac{100}{100 + 10}$$

$= 90.9$ V/V

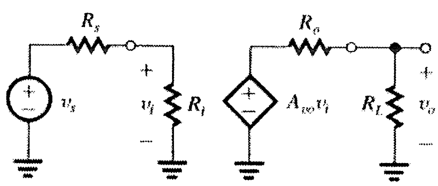
or, 20 log 90.9 = 39.1 dB

$$A_P = \frac{v_O^2 / 100\ \Omega}{v_i^2 / 1\ \text{M}\Omega} = A_v^2 \times 10^4 = 8.3 \times 10^7 W/W$$

or 10 log (8.3×10^7) = 79.1 dB.

For a peak output sine-wave current of 100 Ω, the peak output voltage will be 100 mA × 100 Ω = 10 V. Correspondingly v_i will be a sine wave with a peak value of 10 V/A_v = 10/90.9 or an rms value of $10/(90.9 \times \sqrt{2}) = 0.08$ V.

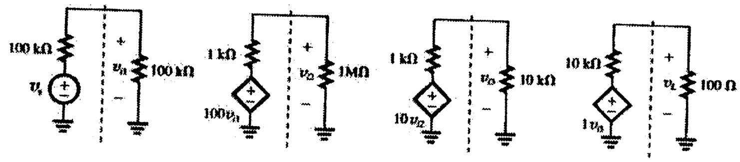
Corresponding output power =
$(10/\sqrt{2})^2 / 100\ \Omega$
$= 0.5$ W



$$\frac{v_O}{v_S} = \frac{10\ \text{k}\Omega}{10\ \text{k}\Omega + 100\ \text{k}\Omega} \times 1000 \times \frac{100\ \Omega}{100\ \Omega + 1\ \text{k}\Omega}$$

$$= \frac{10}{110} \times 1000 \times \frac{100}{1100} = 8.26\ V/V$$

This figure is for 1.37



1.36

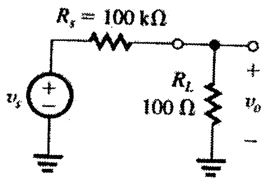
The signal loses about 90% of its strength when connected to the amplifier input (because $R_i = R_s/10$). Also, the output signal of the amplifier loses approximately 90% of its strength when the load is connected (because $R_L = R_o/10$). Not a good design! Nevertheless, if the source were connected directly to the load,

$$\frac{v_O}{v_S} = \frac{R_L}{R_L + R_S}$$

$$= \frac{100\ \Omega}{100\ \Omega + 100\ \text{k}\Omega}$$

$$\simeq 0.001\ \text{V/V}$$

$R_S = 100\ \text{k}\Omega$



which is clearly a much worse situation. Indeed inserting the amplifier increases the gain by a factor 8.3/0.001 = 8300.

1.37

In example 1.3 when the first and the second stages are interchanged, the circuit looks like the figure above

$$\frac{v_{i1}}{v_S} = \frac{100\ \text{k}\Omega}{100\ \text{k}\Omega + 100\ \text{k}\Omega} = 0.5\ \text{V/V}$$

$$A_{v1} = \frac{v_{i2}}{v_{i1}} = 100 \times \frac{1\ \text{M}\Omega}{1\ \text{M}\Omega + 1\ \text{k}\Omega}$$

$= 99.9$ V/V

$$A_{v2} = \frac{v_{i3}}{v_{i2}} = 10 \times \frac{10\ \text{k}\Omega}{10\ \text{k}\Omega + 1\ \text{k}\Omega}$$

$= 9.09$ V/V

$$A_{v3} = \frac{v_L}{v_{i3}} = 1 \times \frac{100\ \Omega}{100\ \Omega + 10\ \Omega} = 0.909\ \text{V/V}$$

$$\text{Total gain} = A_v = \frac{v_L}{v_{i1}} = A_{v1} \times A_{v2} \times A_{v3}$$

$= 99.9 \times 9.09 \times 0.909 = 825.5$ V/V

The voltage gain from source to load is

$$\frac{v_L}{v_S} = \frac{v_L}{v_{i1}} \times \frac{v_{i1}}{v_S} = A_v \cdot \frac{v_{i1}}{v_S}$$

$= 825.5 \times 0.5$

$= 412.7$ V/V

The overall voltage has reduced appreciably. It is due to the reason because the input impedance of the first stage, R_{in}, is comparable to the source resistance R_s. In example 1.3 the input impedance of the first stage is much larger than the source resistance

1.38

a. Case S-A-B-L

$$\frac{V_O}{V_S} = \frac{V_O}{V_{ib}} \times \frac{V_{ib}}{V_{ia}} \times \frac{V_{ia}}{V_S} =$$

$$\left(1 \times \frac{100}{100 + 100}\right) \times \left(100 \times \frac{100}{100 + 10}\right) \times \left(\frac{10}{100 + 10}\right)$$

$\frac{V_O}{V_S} = 4.13$ V/V and gain in dB 20 log 4.1 =

12.32 dB (See figure below)

b. Case S-B-A-L

$$\frac{V_O}{V_S} = \frac{V_O}{V_{ia}} \cdot \frac{V_{ia}}{V_{ib}} \cdot \frac{V_{ib}}{V_S}$$

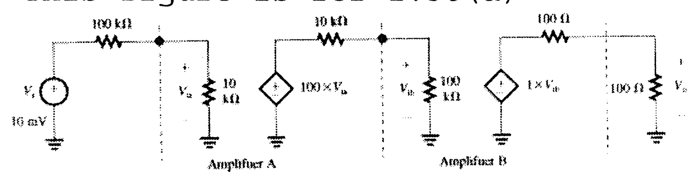
$$= \left(100 \times \frac{100}{100 + 10\ \text{K}}\right) \times \left(1 \times \frac{10\ \text{K}}{10\ \text{K} + 100}\right) \times$$

$$\left(\frac{100\ \text{K}}{100\ \text{K} + 100}\right)$$

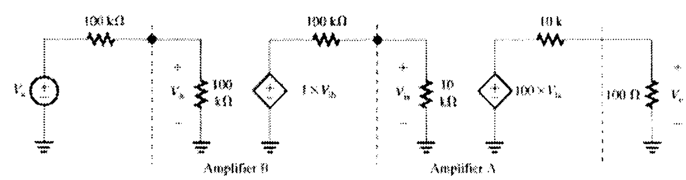
$\frac{V_O}{V_S} = 0.49\ V/S$ and gain in dB is 20 log 0.49 =

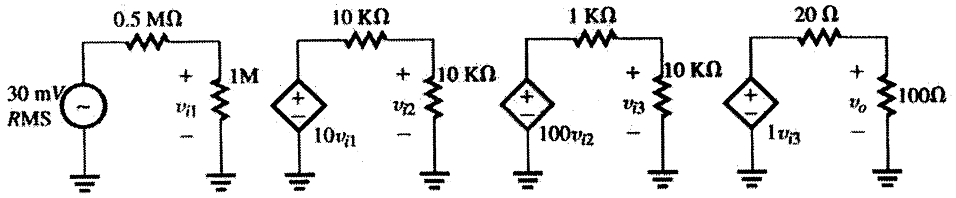
−6.19 dB case a is preferred as it provides higher voltage gain.

This figure is for 1.38(a)



This figure is for 1.38(b)

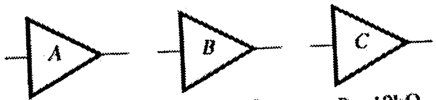




This figure is for 1.39

1.39

Deliver 0.5W to a 100Ω load
Source is 30mV RMS with 0.5MΩ source resistance. Choose from 3 amplifiers types



R_i= 1MΩ	R_i= 10kΩ	R_i= 10kΩ
A_v= 10 v/v	A_v= 100 v/v	A_v= 1 v/v
R_o= 10kΩ	R_o= 1kΩ	R_o= 20Ω

Choose order to eliminate loading on input and output
A - 1st-to minimize loading on 0.5 MΩ source
B - 2nd-to boost gain
C - 3rd - to minimize loading at 100Ω output.
(See figure below)

$$\frac{v_O}{v_S} = \frac{2\ V}{30mV} = 235.7 < \left(\frac{1\mu}{0.5\mu + 1\mu}\right)(10)$$

$$\left(\frac{10}{10+10}\right)(100)\left(\frac{10}{10+1}\right)(1)\left(\frac{100}{20+100}\right)$$

235.7 < 253.6

$$v_O = (253.6)(30\text{mV}) = 7.61\text{v RMS}$$

$$P = \frac{v_O^2}{R_L} = \frac{(7.61)^2}{100} = 0.58\ \text{W}$$

1.40

(a) Required voltage gain $= \frac{v_O}{v_S}$

$$= \frac{3\ \text{V}}{0.01\ \text{V}} = 300\ \text{V/V}$$

(b) The smallest R_i allowed is obtained from

$$0.1\ \mu A = \frac{10\ \text{mV}}{R_S + R_i} \Rightarrow R_S + R_i = 100\ \text{k}\Omega$$

Thus $R_i = 90$ kΩ.
For $R_i = 90$ kΩ, $i_i = 0.1$ μA peak, and

Overall current gain $= \frac{v_O / R_L}{i_i}$

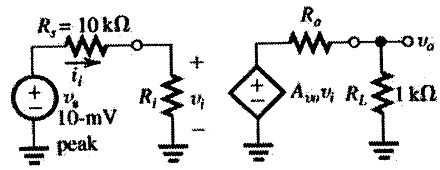
$$= \frac{3\ \text{mA}}{0.1\ \mu A} = 3 \times 10^4\ \text{A/A}$$

Overall power gain $= \frac{v_{O rms}^2 / R_L}{v_{s(rms)} \times i_{i(rms)}}$

$$= \frac{\left(\frac{3}{\sqrt{2}}\right)^2 / 1000}{\left(\frac{10 \times 10^{-3}}{\sqrt{2}}\right) \times \left(\frac{0.1 \times 10^{-6}}{\sqrt{2}}\right)}$$

$= 9 \times 10^6$ W/W
(This takes into acct. the power dissipated in the internal resistance of the source.)

(c) If (A_{v_o} v_i) has its peak value limited to 5 V, the largest value of R_o is found from



$$= \times \frac{R_L}{R_L + R_O} = 3 \Rightarrow R_O = \frac{2}{3}R_L = 667\ \Omega$$

(If R_o were greater than this value, the output voltage across R_L would be less than 3 V.)

(d) For R_i = 90 kΩ and R_o = 667 Ω, the required value A_{vo} can be found from

$$300\ \text{V/V} = \frac{90}{90+10} \times A_{v_o} \times \frac{1}{1+0.667}$$

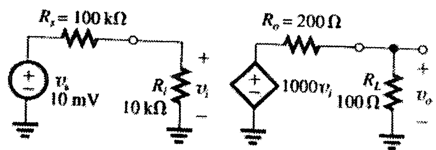
$$\Rightarrow A_{v_o} = 555.7\ \text{V/V}$$

(e) R_i = 100 kΩ (1 × 10^5 Ω)
R_o = 100 Ω (1 × 10^2 Ω)

$$300 = \frac{100}{100+10} \times A_{v_o} \times \frac{1000}{1000+100}$$

$$\Rightarrow A_{v_o} = 363\ \text{V/V}$$

1.41



(a)

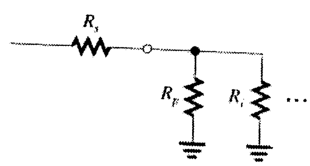
$$v_O = 10\ \text{mV} \times \frac{10}{10+100} \times 1000 \times \frac{100}{100+200}$$

$= 303$ mV

(b) $\frac{v_O}{v_S} = \frac{303\ \text{mV}}{10\ \text{mV}} = 30.3\ \text{V/V}$

(c) $\frac{v_O}{v_i} = 1000 \times \frac{100}{100+200} = 333.3\ \text{V/V}$

(d)



Connect a resistance R_P in parallel with the input and select its value from

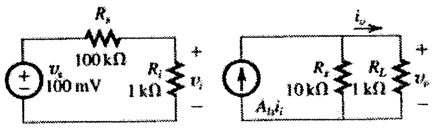
$$\frac{(R_P \parallel R_i)}{(R_P \parallel R_i) + R_S} = \frac{1}{2}\frac{R_i}{R_i + R_S}$$

$$\Rightarrow 1 + \frac{R_S}{R_P \parallel R_i} = 22 \Rightarrow R_P \parallel R_i = \frac{R_S}{21} = \frac{100}{21}$$

$$\Rightarrow \frac{1}{R_P} + \frac{1}{R_i} = \frac{21}{100}$$

$$R_P = \frac{1}{0.21 - 0.1} = 9.1\ \text{k}\Omega$$

1.42



(a) Current gain $= \frac{i_O}{i_i}$

$$= A_{is}\frac{R_O}{R_O + R_L}$$

$$= 100\frac{10}{11}$$

$$= 90.9\frac{\text{A}}{\text{A}} = 39.2\ \text{dB}$$

(b) Voltage gain $= \frac{v_O}{v_S}$

$$= \frac{i_O}{i_i}\frac{R_S}{R_S + R_i}$$

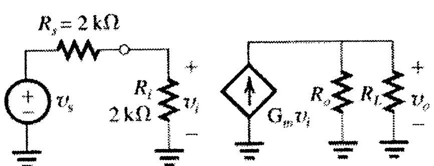
$$= 90.9 \times \frac{1}{101}$$

$$= 0.9\ \text{V/V} = -0.9\ \text{dB}$$

(c) Power gain $= A_P = \frac{v_O i_O}{v_S i_i}$

$$= 0.9 \times 90.9$$
$$= 81.8\ \text{W/W} = 19.1\ \text{dB}$$

1.43



$G_m = 40$ mA/V
$R_o = 20$ kΩ
$R_L = 1$ kΩ

$$v_i = v_S\frac{R_i}{R_S + R_i}$$

$$= v_S\frac{2}{2+2} = \frac{v_S}{2}$$

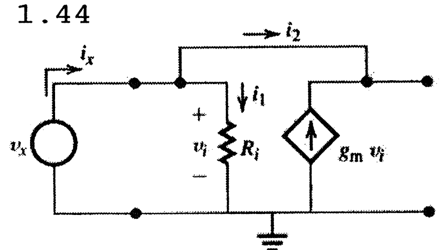
$$v_O = G_m v_i(R_L \parallel R_O)$$

$$= 40\frac{20 \times 1}{20 + 1}v_i$$

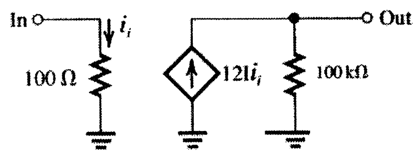
$$= 40\frac{20}{21}\frac{v_S}{2}$$

Overall voltage gain $\equiv \frac{v_O}{v_S} = 19.05$ V / V

1.44



$$\left.\begin{array}{l} i_x = i_1 + i_2 \\ i_1 = v_i / R_i \\ i_2 = g_m + v_i \\ v_i = V_x \end{array}\right\} \quad \begin{array}{l} i_x = v_x / R_i + g_m v_x \\ i_x = v_x + \left(\frac{1}{R_i} + g_m\right) \\ \frac{v_x}{i_x} = \frac{1}{1/R_i + g_m} \\ \quad = \frac{R_x}{1 + g_m R_i} = R_{in} \end{array}$$



1.45

Transresistance amplifier

To limit Δv_o to 10% corresponding to R_s varying in the range 1 to 10 kΩ, we select R_i sufficiently low;

$$R_i \le \frac{R_{s\min}}{10}$$

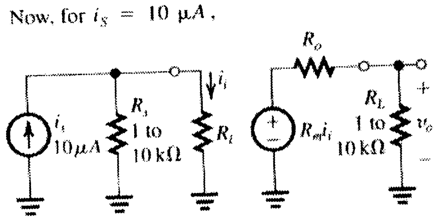
Thus, $R_i = 100\ \Omega$

To limit Δv_o to 10% while R_L varies over the range 1 to 10 kΩ, we select R_o sufficiently low;

$$R_O \le \frac{R_{L\min}}{10}$$

Thus, $R_O = 100\ \Omega$

Now, for $i_S = 10\ \mu A$,

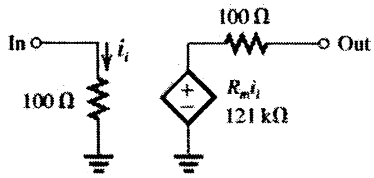


$$v_{O\min} = 10^{-5}\frac{R_{s\min}}{R_{s\min}+R_i}R_m\frac{R_{L\min}}{R_{L\min}+R_O}$$

$$1 = 10^{-5}\frac{1000}{1000+100}R_m\frac{1000}{1000+100}$$

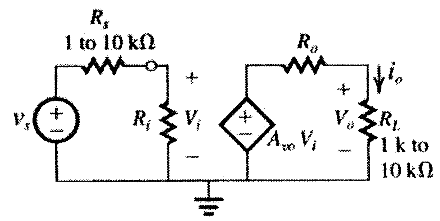
$$\Rightarrow R_m = 1.21 \times 10^5$$

$$= 121 \text{ k}\Omega$$



1.46

Voltage Amplifier



For R_s varying in the range 1 K to 10 kΩ and Δi_o variation limited to 10%, select R_i to be sufficiently large:

$R_i \geq 10\ R_{S\max}$

$R_i = 10 \times 10\text{ k}\Omega = 100\text{ k}\Omega = 1 \times 10^5\ \Omega$

For R_L varying in the range 1 to 10 kΩ, the load current variation limited to 10%, select R_o sufficiently low:

$$R_O \leq \frac{R_{L\max}}{10}$$

$$R_O = \frac{1\text{ k}\Omega}{10} = 100\ \Omega = 1 \times 10^2\ \Omega$$

Now find A_{vo}

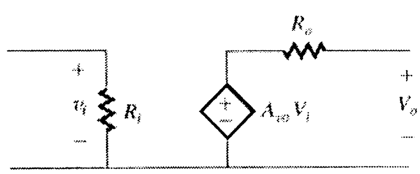
$$i_{o\min} = 10\text{ mV} \times \frac{R_i}{R_i + R_{S\max}} \times A_{vo}\frac{1}{R_O + R_{L\max}}$$

$$1 \times 10^{-3} = 10 \times 10^{-3} \times \frac{100\text{ k}\Omega}{100\text{ k}\Omega + 10\text{ k}\Omega}$$

$$\times A_{vo} \times \frac{1}{100\ \Omega + 10\text{ k}\Omega}$$

$$1 \times 10^{-3} = 10 \times 10^{-3} \times \frac{100}{110} \times A_{vo} \times \frac{1}{1100}$$

$A_{vo} = 121$ V/V



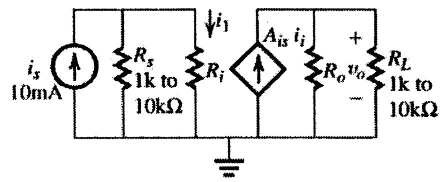
Voltage amplifier equivalent circuit is

$R_i = 1 \times 10^5\ \Omega$, $A_{vo} = 121$ V/V and

$R_O = 1 \times 10^2\ \Omega$

1.47

Current Amplifier



For R_s varying in the range 1 kΩ to 10 kΩ range and load voltage variation limited to 10%, select R_i to be sufficiently low:

$$R_i \leq \frac{R_{S\min}}{10}$$

$$R_i = \frac{1\text{ k}\Omega}{10} = 100\ \Omega = 1 \times 10^2\ \Omega$$

For R_L varying in the range 1 kΩ to 10 kΩ and load voltage variation limited to 10%, R_o is selected sufficiently large:

$R_o \geq 10\ R_{L\max}$

$R_o = 10 \times 10\text{ k}\Omega$

$= 100\text{ k}\Omega = 1 \times 10^5\ \Omega$

Now we find A_{is}

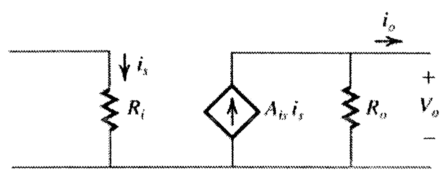
$$V_{O\min} = 10\ \mu A \times \frac{R_{S\min}}{R_{S\min} + R_i} \times A_{is} \times R_O \| R_{L\min}$$

$$= 10 \times 10^{-6}\frac{R_{S\min}}{R_{S\min}+R_i} \times A_{is}\frac{R_O R_{L\min}}{R_O + R_{L\min}}$$

$$= 10 \times 10^{-6}\frac{1\text{ k}\Omega}{1\text{ k}\Omega + 100\ \Omega} \times A_{is}\frac{100\text{ K} \times 1\text{ K}}{100\text{ K} + 1\text{ K}}$$

$\Rightarrow A_{is} = 111.1$ A/A

Current amplifier equivalent circuit is



$R_i = 1 \times 10^2\ \Omega$, $A_{is} = 111.1$ A/s,

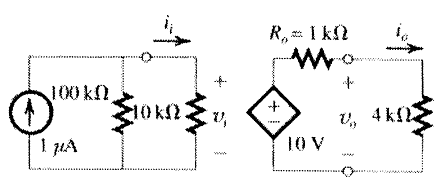
$R_O = 1 \times 10^5\ \Omega$

1.48

$$R_O = \frac{\text{Open-circuit output voltage}}{\text{Short-circuit output current}} = \frac{10\text{ V}}{10\text{ mA}}$$

$= 1\text{ k}\Omega$

$$v_O = 10 \times \frac{4}{1+4} = 8\text{ V}$$



$$A_v = \frac{v_O}{v_I} = \frac{8}{1\times10^{-3}\times(100\,\|\,10)\times10^3}$$

$=888$ V/V or 58.9 dB

$$A_i = \frac{i_o}{i_i} = \frac{v_O/R_L}{10^{-3}\times\frac{100}{100+10}} = \frac{8/(4\times10^3)}{10^{-3}\times\frac{100}{110}}$$

$=$ 2200 A/A or 66.8 dB

$$A_i = \frac{v_O^2/R_L}{i_i^2 R_i} = \frac{8^2/(4\times10^3)}{\left(10^{-3}\times\frac{100}{100+10}\right)^2 10\times10^3}$$

$= 19.36\times10^5$ W/W or 62.9 dB

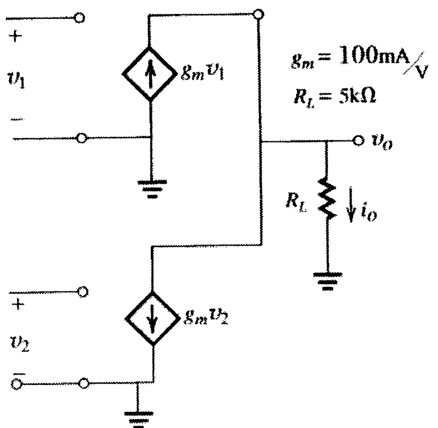
$$\text{Overall current gain} = \frac{i_o}{1\ \mu A}$$

$$= \frac{v_O/R_L}{1\ \mu A} = \frac{8/(4\times10^3)}{10^{-3}}$$

$=$ 2000 A/A or 66 dB

1.49

Using the voltage divider rule



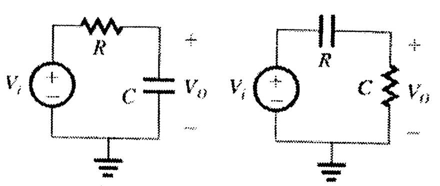
a. $i_o = g_m v_1 - g_m v_2$

$v_O = i_o R_L = g_m R_L (v_1 - v_2) = v_0$

b. $v_1 = v_2 \therefore v_0 = 0V$

$$\left.\begin{matrix} v_1 = 1.01 \\ v_2 = 0.99 \end{matrix}\right\} \therefore v_0 = 10V$$

1.50



(a) (b)

for (a) $V_0 = V_I\left(\frac{1/SC}{1/SC + R}\right)$

$$\frac{V_0}{V_I} = \frac{1}{1+SCR}$$

where k = 1

$\omega_0 = \frac{1}{RC}$ from table 1.2 it is low pass.

for (b) $V_0 = V_I\left(\frac{R}{R+\frac{1}{SC}}\right)$

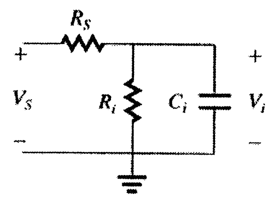
$$\frac{V_0}{V_I} = \frac{SRC}{1+SCR}$$

$$\frac{V_0}{V_I} = \frac{S}{S+\frac{1}{RC}}$$

where k = 1

$\omega_0 = \frac{1}{RC}$ from table 1.2 it is high pass.

1.51



$$\frac{V_i}{V_S} = \frac{\dfrac{R_i\frac{1}{sC_i}}{R_i+\frac{1}{sC_i}}}{R_S + \left(\dfrac{R_i\frac{1}{sC_i}}{R_i+\frac{1}{sC_i}}\right)} = \frac{\dfrac{R_i}{1+sC_iR_i}}{R_S+\left(\dfrac{R_i}{1+sC_iR_i}\right)}$$

$$= \frac{R_i}{R_S + sC_iR_iR_s + R_i}$$

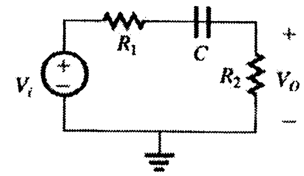
$$\frac{V_i}{V_S} = \frac{R_i}{(R_S+R_i)+sC_iR_iR_S} = \frac{\dfrac{R_i}{(R_S+R_i)}}{1+S\left(\dfrac{C_iR_iR_S}{R_S+R_i}\right)}$$

Where $K = \frac{R_i}{(R_S+R_i)}$

$\omega = \frac{R_S+R_i}{C_iR_iR_S}$ from table 1.2 low pass for given values $\omega_0 = 12.5$ MHz

1.52

Using the voltage-divider rule.



$$T(s) = \frac{V_O}{V_i} = \frac{R_2}{R_2 + R_1 + \frac{1}{sC}}$$

$$T(s) = \left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{s}{s + \frac{1}{C(R_1 + R_2)}}\right)$$

which is from Table 1.2 is of the high-pass type with

$$K = \frac{R_2}{R_1 + R_2} \quad \omega_0 = \frac{1}{C(R_1 + R_2)}$$

As a further verification that this is a high-pass network and $T(s)$ is a high-pass transfer function, we assume as $s \Rightarrow 0$, $T(s) \Rightarrow 0$; and as $s \to \infty$, $T(s) = R_2/(R_1 + R_2)$. Also, from the circuit observe as $s \to \infty$, $(1/sC) \to 0$ and $V_O/V_i = R_2/(R_1 + R_2)$. Now, for $R_1 = 10\ \text{k}\Omega$, $R_2 = 40\ \text{k}\Omega$, and $C = 0.1\ \mu F$.

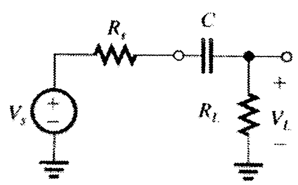
$$f_o = \frac{\omega_0}{2\pi} = \frac{1}{2\pi \times 0.1 \times 10^{-6}(10 + 40) \times 10^3}$$

$$= 31.8\ \text{Hz}$$

$$|T(j\omega_0)| = \frac{K}{\sqrt{2}} = \frac{40}{10 + 40}\frac{1}{\sqrt{2}} = 0.57\ \text{V/V}$$

1.53

Using the voltage divider rule,



$$\frac{V_O}{V_S} = \frac{R_L}{R_L + R_S + \frac{1}{sC}}$$

$$= \frac{R_L}{R_L + R_S}\frac{s}{s + \frac{1}{C(R_L + R_S)}}$$

which is of the high-pass STC type (see Table 1.2) with

$$K = \frac{R_L}{R_L + R_S} \qquad \omega_0 = \frac{1}{C(R_L + R_S)}$$

For $f_o \le 10$ Hz

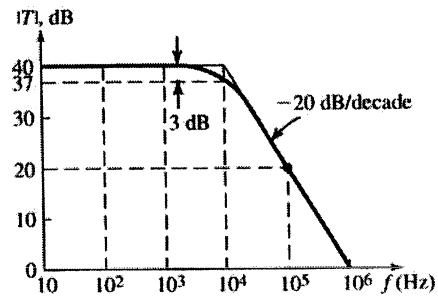
$$\frac{1}{2\pi C(R_L + R_S)} \le 10$$

$$\Rightarrow C \ge \frac{1}{2\pi \times 10(20 + 5) \times 10^3}$$

Thus, the smallest value of C that will do the job is $C = 0.64\ \mu F$.

1.54

The given measured data indicate that this amplifier has a low-pass STC frequency response with a low-frequency gain of 40 dB, and a 3-dB frequency of 10^4 Hz. From our knowledge of the Bode plots for low-pass STC networks (Figure 1.23a) we can complete the Table entries and sketch the amplifier frequency response



f(Hz)	|T|(dB)	$\angle T(°)$
0	40	0
100	40	0
1000	40	0
10^4	37	−45°
10^5	20	−90°
10^6	0	−90°

1.55

Since the overall transfer function is that of three identical STC LP circuits in cascade (but with no loading effects since the buffer amplifiers have input and zero output resistances) the overall gain will drop by 3 dB below the value at dc at the frequency for which the gain of each STC circuit is 1 dB down. This frequency is found as follows: The transfer function of each STC circuit is

$$T(s) = \frac{1}{1 + \frac{s}{\omega_0}}$$

where

$$\omega_0 = 1/CR$$

Thus,

$$|T(j\omega)| = \frac{1}{\sqrt{1 + \left(\frac{\omega}{\omega_0}\right)^2}}$$

$$20\log\frac{1}{\sqrt{1 + \left(\frac{\omega_{1dB}}{\omega_0}\right)^2}} = -1$$

$$\Rightarrow 1 + \left(\frac{\omega_{1dB}}{\omega_0}\right)^2 = 10^{0.1}$$

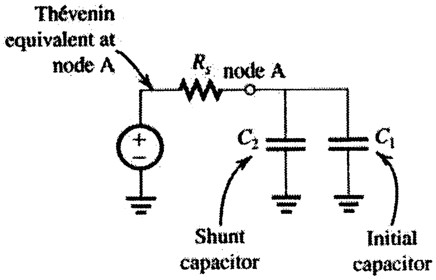
$$\omega_{1dB} = 0.51\omega_0$$

$$\omega_{1dB} = 0.51/CR$$

1.56

$R_S = 100\text{ k}\Omega$, since the 3-dB frequency is reduced by a very high factor (from 6 MHz to 120 kHz) C_2 must be much larger than C_1. Thus, neglecting C_1 we find C_2 from

$$120\text{ kHz} \simeq \frac{1}{2\pi C_2 R_S}$$



$$= \frac{1}{2\pi C_2 \times 10^5}$$

$$\Rightarrow C_2 = 13.3\text{ pF}$$

If the original 3-dB frequency (6 MHz) is attributable to C_1 then

$$6\text{ MHz} = \frac{1}{2\pi C_1 R_S}$$

$$\Rightarrow C_1 = \frac{1}{2\pi \times 6 \times 10^6 \times 10^5}$$

$$= 0.26\text{ pF}$$

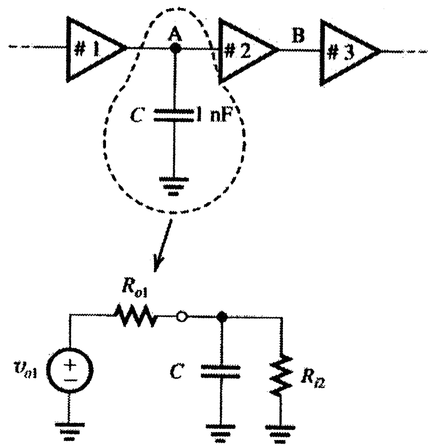
1.57

Since when C is connected the 3-dB frequency is reduced by a large factor, the value of C must be much larger than whatever parasitic capacitance originally existed at node A (i.e., between A and ground). Furthermore, it must be that C is now the dominant determinant of the amplifier 3-dB frequency (i.e., it is dominating over whatever may be happening at node B or anywhere else in the amplifier). Thus, we can write

$$150\text{ kHz} = \frac{1}{2\pi C(R_{o1} \| R_{i2})}$$

$$\Rightarrow (R_{o1} \| R_{i2}) = \frac{1}{2\pi \times 150 \times 10^3 \times 1 \times 10^{-9}}$$

$$= 1.06\text{ k}\Omega$$



Now $R_{i2} = 100\text{ k}\Omega$.

Thus $R_{o1} = 1.07\text{ k}\Omega$

Similarly, for node B,

$$15\text{ kHz} = \frac{1}{2\pi C(R_{o2} \| R_{i3})}$$

$$\Rightarrow R_{o2} \| R_{i3} = \frac{1}{2\pi \times 15 \times 10^3 \times 1 \times 10^{-9}}$$

$$= 10.6\text{ k}\Omega$$

$R_{o2} = 11.9\text{ k}\Omega$

She should connect a capacitor of value C_p to node B where C_p can be found from,

$$10\text{ kHz} = \frac{1}{2\pi C_p(R_{o2} \| R_{i3})}$$

$$\Rightarrow C_p = \frac{1}{2\pi \times 10 \times 10^3 \times 10.6 \times 10^3}$$

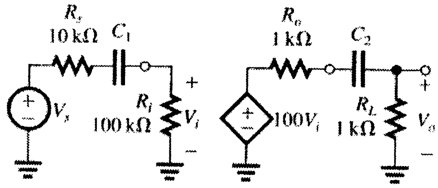
$= 1.5\text{ nF}$

Note that if she chooses to use node A she would need to connect a capacitor 10 times larger!

1.58

For the input circuit, the corner frequency f_{01} is found from

$$f_{01} = \frac{1}{2\pi C_1(R_S + R_i)}$$



For $f_{01} \leq 100\text{ Hz}$,

$$\frac{1}{2\pi C_1(10 + 100) \times 10^3} \leq 100$$

$$\Rightarrow C_1 \geq \frac{1}{2\pi \times 110 \times 10^3 \times 10^2} = 1.4 \times 10^{-8}$$

Thus we select $C_1 = 1 \times 10^{-7}\ F = 0.1\ \mu F$.

The actual corner frequency resulting from C_1 will be

$$f_{o1} = \frac{1}{2\pi \times 10^{-7} \times 110 \times 10^3} = 14.5\ \text{Hz}$$

For the output circuit,

$$f_{o2} = \frac{1}{2\pi C_2 (R_O + R_L)}$$

For $f_{o2} \leq 100$ Hz.

$$\frac{1}{2\pi C_2 (1+1) \times 10^3} \leq 100$$

$$\Rightarrow C_2 \geq \frac{1}{2\pi \times 2 \times 10^3 \times 10^2} = 0.8 \times 10^{-6}$$

Select $C_2 = 1 \times 10^{-6} = 1\ \mu F$

This will place the corner frequency at

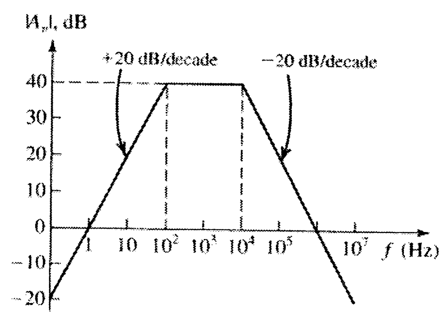
$$f_{02} = \frac{1}{2\pi \times 10^{-6} \times 2 \times 10^3} = 80\ \text{Hz}$$

$$T(s) = 100 \frac{s}{\left(1 + \frac{s}{2\pi f_{01}}\right)\left(1 + \frac{s}{2\pi f_{02}}\right)}$$

1.59

The LP factor $1/(1 + jf/10^4)$ results in a Bode plot like that in Fig. 1.23(a) with the 3dB frequency $f_O = 10^4$ Hz. The high-pass factor $1/(1 + 10^4/jf)$ results in a Bode plot like that in Fig.1.24(a) with the 3dB frequency $f_O = 10^4$ Hz.

The Bode plot for the overall transfer function can be obtained by summing the dB values of the two individual plots and then raising the resulting plot vertically by 40 dB (corresponding to the factor 100 in the numerator). The result is as follows:



f = 10 10^2 10^3 10^4 10^5 10^6 10^7 (Hz)

$|A_v| \simeq$ 20 40 40 40 20 0 −20 (dB)

↑ 37 ↑ 37

Better approximation
(3-dB frequencies)
Bandwidth = $10^4 - 10^2$ = 9900 Hz

1.60

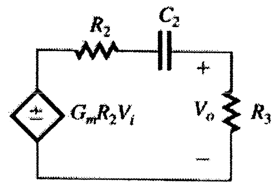
$$T_i(s) = \frac{V_i(s)}{V_S(s)} = \frac{1/sC_1}{1/sC_1 + R_1} = \frac{1}{sC_1R_1 + 1}$$

LP

3 dB frequency

$$= \frac{1}{2\pi C_1 R_1} = \frac{1}{2\pi 10^{-11} 10^6} = 15.9\ \text{Hz}$$

For $T_O(S)$, the following quivalent circuit can be used:



$$T_O(S) = -G_m R_2 \frac{R_3}{R_2 + R_3 + 1/sC_2}$$

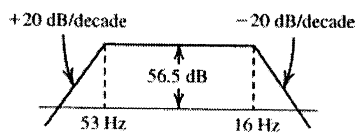
$$= -G_m(R_2 \| R_3) \frac{S}{S + \frac{1}{C_2(R_2 + R_3)}}$$

$$\text{3 dB frequency} = \frac{1}{2\pi C_2 (R_2 + R_3)}$$

$$= \frac{1}{2\pi 100 \times 10^{-9} \times 30 \times 10^3} = 53\ \text{Hz}$$

$$\therefore T(S) = T_i(S) T_O(S)$$

$$= \frac{1}{1 + \frac{S}{2\pi \times 15.9 \times 10^3}} \times -666.7 \times \frac{S}{S + (2\pi \times 53)}$$



Bandwidth = 16 kHz − 53 Hz ≃ 16 Hz

1.61

$$V_i = V_S \frac{R_i}{R_S + R_i}$$

a) To satisfy constraint (1), namely

$$V_i \geq \left(1 + \frac{x}{100}\right) V_S$$

We substitute in Eq.(1) to obtain

$$\frac{R_i}{R_S + R_i} \geq 1 - \frac{x}{100}$$

Thus

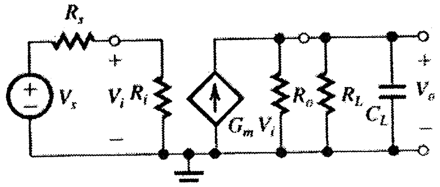
$$\frac{R_S + R_i}{R_i} \le \frac{1}{1 - \frac{x}{100}}$$

$$\frac{R_S}{R_i} \le \frac{1}{1 - \frac{x}{100}} - 1 = \frac{\frac{x}{100}}{1 - \frac{x}{100}}$$

which can be expressed as

$$\frac{R_i}{R_S} \ge \frac{1 - \frac{x}{100}}{\frac{x}{100}}$$

resulting in



$$R_i \ge R_S\left(\frac{100}{x} - 1\right)$$

b) The 3-dB frequency is determined by the parallel RC circuit at the output

$$f_O = \frac{1}{2\pi}\omega_O = \frac{1}{2\pi}\frac{1}{C_L(R_L \parallel R_O)}$$

Thus,

$$f_O = \frac{1}{2\pi C_L}\left(\frac{1}{R_L} + \frac{1}{R_O}\right)$$

To obtain a value for f_O greater than a specified value f_{3dB} we select R_O so that

$$\frac{1}{2\pi C_L}\left(\frac{1}{R_L} + \frac{1}{R_O}\right) \ge f_{3dB}$$

$$\frac{1}{R_L} + \frac{1}{R_O} \ge 2\pi C_L f_{3dB}$$

$$\frac{1}{R_O} \ge 2\pi C_L f_{3dB} - \frac{1}{R_L}$$

$$R_O \le \frac{1}{2\pi f_{3dB} + C_L - \frac{1}{R_L}} \qquad (2)$$

c) To satisfy constraint (3), we first determine the dc gain as

$$\text{dc gain} = \frac{R_i}{R_S + R_i} G_m(R_O \parallel R_L)$$

For the dc gain to be greater than a specified value A_O,

$$\frac{R_i}{R_S + R_i} G_m(R_O \parallel R_L) \ge A_O$$

The first factor on the LHS is (from constaint (1)) greater or equal to $(1 - x/100)$. Thus

$$G_m \ge \frac{A_O}{\left(1 - \frac{x}{100}\right)(R_O \parallel R_L)} \qquad (3)$$

Substituting $R_S = 10\ \text{k}\Omega$ and $x = 20\%$ in (1) results in

$$R_S \ge 10\left(\frac{100}{20} - 1\right) = 40\ \text{k}\Omega$$

Substituting $f_{3dB} = 3$ MHz, $C_L = 10$ pF and RL = 10 kΩ in Eq. (2) result in

$$R_O \le \frac{1}{2\pi \times 3 \times 10^6 \times 10 \times 10^{-12} - \frac{1}{10^4}}$$

$$= 11.3\ \text{k}\Omega$$

Substituting $A_o = 80$, $x = 20\%$, $R_L = 10\ \text{k}\Omega$, and $R_o = 11.3\ \text{k}\Omega$, eq. (3) results in

$$G_m \ge \frac{80}{\left(1 - \frac{20}{100}\right)(10 \parallel 11.3) \times 10^3} = 18.85\ \text{mA/V}$$

If the more practical value of $R_o = 10\ \text{k}\Omega$ is used then

$$G_m \ge \frac{80}{\left(1 - \frac{20}{100}\right)(10 \parallel 10) \times 10^3} = 20\ \text{mA/V}$$

1.62

Using the voltage-divider rule we obtain

$$\frac{V_O}{V_i} = \frac{Z_2}{Z_1 + Z_2}$$

where

$$Z_1 = R_1 \parallel \frac{1}{sC_1} \text{ and } Z_2 = R_2 \parallel \frac{1}{sC_2}.$$

It is obviously more convenient to work in terms of admittances. Therefore we express V_o/V_i in the alternate form

$$\frac{V_O}{V_i} = \frac{Y_1}{Y_1 + Y_2}$$

and substitute $Y_1 = (1/R_1) + sC_1$ and $Y_2 = (1/R_2) + sC_2$ to obtain

$$\frac{V_O}{V_i} = \frac{\frac{1}{R_1} + sC_1}{\frac{1}{R_1} + \frac{1}{R_2} + s(C_1 + C_2)}$$

$$= \frac{C_1}{C_1 + C_2} \frac{s + \frac{1}{C_1 R_1}}{s + \frac{1}{(C_1 + C_2)}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)}$$

This transfer function will be independent of frequency (s) if the second factor reduces to unity.

This in turn will happen if

$$\frac{1}{C_1R_1} = \frac{1}{C_1+C_2}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)$$

which can be simplified as follows

$$\frac{C_1+C_2}{C_2} = R_1\left(\frac{1}{R_1}+\frac{1}{R_2}\right) \qquad (1)$$

$$1+\frac{C_2}{C_1} = 1+\frac{R_1}{R_2}$$

or

$$C_1R_1 = C_2R_2$$

When this condition applies, the attenuator is said to be compensated, and its transfer function is given by

$$\frac{V_O}{V_i} = \frac{C_1}{C_1+C_2}$$

which, using Eq. (1) can be expressed in the alternate form

$$\frac{V_O}{V_i} = \frac{1}{1+\frac{R_1}{R_2}} = \frac{R_2}{R_1+R_2}$$

Thus when the attenuator is compensated ($C_1R_1 = C_2R_2$) its transmission can be determined either by its two resistors R_1, R_2 or by its two capacitors. C_1, C_2, and the transmission is *not* a function of frequency.

1.63

The HP STC circuit whose response determines the frequency response of the amplifier in the low-frequency range has a phase angle of 11.4° at $f = 100$ Hz. Using the equation for $\angle T(j\omega)$ from Table 1.2 we obtain

$$\tan^{-1}\frac{f_o}{100} = 11.4° \Rightarrow f_o = 20.16 \text{ Hz}$$

The LP STC circuit whose response determines the amplifier response at the high-frequency end has a phase angle of $-11.4°$ at $f = 1$ kHz. Using the relationship for $\angle T(j\omega)$ given in Table 1.2 we obtain for the LP STC circuit.

$$-\tan^{-1}\frac{10^3}{f_o} = -11.4° \Rightarrow f_o = 4959.4 \text{ Hz}$$

At $f = 100$ Hz the drop in gain is due to the HP STC network, and thus its value is

$$20\log\frac{1}{\sqrt{1+\left(\frac{20.16}{100}\right)^2}} = -0.17 \text{ dB}$$

Similarly, at $f = 1$ kHz the drop in gain is caused by the LP STC network. The drop in gain is

$$20\log\frac{1}{\sqrt{1+\left(\frac{1000}{4959.4}\right)^2}} = -0.17 \text{ dB}$$

The gain drops by 3 dB at the corner frequencies of the two STC networks, that is, at $f = 20.16$ Hz and $f = 4959.4$ Hz.

1.64

Using the expression in (3.2) using $B = 7.3\times10^{15}\text{ Cm}^{-3}\text{K}^{-3/2}$; $k = 8.62\times10^{-5}\text{eV/K}$; $E_g = 1.12$ V, we have:

$T = -70°C = 203$ K:

$$n_i = 2.67\times10^4\text{ cm}^{-3};\ \frac{n_i}{N} = 5.33\times10^{-19}$$

That is, one out of every 5.33×10^{18} silicon atoms is ionized at this temperature.

$T = 0°C = 273$ K:

$$n_i = 1.52\times10^9\text{ cm}^{-3};\ \frac{n_i}{N} = 3.05\times10^{-14}$$

$T = 20°C = 293$ K:

$$n_i = 8.60\times10^9\text{ cm}^{-3};\ \frac{n_i}{N} = 1.72\times10^{-13}$$

$T = 100°C = 373$ K:

$$n_i = 1.43\times10^{12}\text{ cm}^{-3};\ \frac{n_i}{N} = 2.87\times10^{-11}$$

$T = 125°C = 398$ K:

$$n_i = 4.72\times10^{12}\text{ cm}^{-3};\ \frac{n_i}{N} = 9.45\times10^{-11}$$

1.65

Hole concentration in intrinsic $S_i = n_i$

$$n_i = BT^{3/2}e^{-E_g/KT}$$

$$= 7.3\times10^{15}(300)^{3/2}e^{-1.12/(2\times8.62\times10^{-5}\times300)}$$

$$= 1.5\times10^{10}\text{ holes/cm}^3$$

In phosphorus doped *Si*, hole concentration drops below intrinsic level by a factor of 10^7

∴ Hole concentration in *P* doped *Si* is

$$P_n = \frac{1.5\times10^{10}}{10^7} = 1.5\times10^3\text{ cm}^{-3}$$

Phosphorus doped *Si*, so

$$n_n = N_D \quad p_n n_n = n_i^2$$

$$n_n = n_i^2/p_n = \frac{(1.5\times10^{10})^2}{1.5\times10^3}$$

1.66

$$N_D = n_n = 1.5\times10^{17}\ P\text{ atoms/cm}^3$$

$$T = 27°C = 273+27 = 300\text{ K}$$

At 300 K, $n_i = 1.5\times10^{10}/\text{cm}^3$

Phosphorous doped *Si*

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

$$p_n \cong \frac{n_i^2}{N_D} = \frac{(1.5\times10^{10})^2}{10^{16}} = 2.25\times10^4\times\text{cm}^3$$

Hole concentration $= p_n = 2.25\times10^4/\text{cm}^3$

$T = 125°C = 273+125 = 398$ K

At 398 K, $n_i = BT^{3/2}e^{-Eg/(2KT)}$

$= 7.3 \times 10^{15} \times (398)^{3/2} e^{-1.12/(2 \times 8.62 \times 10^{-5} \times 398)}$

$= 4.72 \times 10^{12}/cm^3$

$p_n \cong \frac{n_i^2}{N_D} = 2.23 \times 10^9/cm^3$

At 398 K, hole concentration

$p_n = 2.23 \times 10^9/cm^3$

1.67

(a) The resistivity of silicon is given For intrinsic silicon,

$p = n = n_i = 1.5 \times 10^{10}\ cm^{-3}$

Using $\mu_n = 1350\ cm^2/Vs$ and

$\mu_p = 480\ cm^2/Vs$, we have:

$\rho = 2.28 \times 10^5\ \Omega$-cm.

Using $R = \rho \cdot \frac{L}{A}$ with $L = 0.01$ cm and

$A = 3 \times 10^{-8}\ cm^2$, we have

$R = 7.59 \times 10^9\ \Omega$.

(b) $n_n \approx N_D = 10^{16}\ cm^{-3}$:

$p_n = \frac{n_i^2}{n_n} = 2.25 \times 10^4\ cm^{-3}$

Using $\mu_n = 1110\ cm^2/Vs$ and

$\mu_p = 400\ cm^2/Vs$, we have:

$\rho = 0.56\ \Omega$-cm; $R = 18.8\ k\Omega$.

(c) $n_n \approx N_D = 10^{18}\ cm^{-3}$;

$p_n = \frac{n_i^2}{n_n} = 2.25 \times 10^2\ cm^{-3}$

Using $\mu_n = 1110\ cm^2/Vs$ and

$\mu_p = 400\ cm^2/Vs$, we have:

$\rho = 5.63 \times 10^{-3}\ \Omega$-cm; $R = 188\ \Omega$.

As expected, since ND is increased by 100, the resistivity decreases by the same factor.

(d) $p_p \approx N_A = 10^{16}\ cm^{-3}$; $n_p = \frac{n_i^2}{n_n}$

$= 2.25 \times 10^4\ cm^{-3}$

$\rho = 1.56\ \Omega$-cm; $R = 52.1\ k\Omega$

(e) Since ρ is given to be $2.8 \times 10^{-6}\ \Omega$-cm, we directly calculate $R = 9.33 \times 10^{-2}\ \Omega$.

1.68

$J_{drift} = q(n\mu_n + p\mu_p)E$

Here $n = N_D$ and since it is η - *Si*, one can assume $p << n$ and ignore the term $p\mu_p$ Also

$E = \frac{1\ V}{10\ \mu m} = \frac{1\ V}{10 \times 10^{-4} cm} = 10^3\ V/cm$

Need $J_{drift} = 1\ mA/\mu m^2 = q N_D \mu n E$

$\frac{10^{-3} A}{10^{-8} cm^2} = 1.6 \times 10^{-19} N_D \times 1350 \times 10^3$

$\Rightarrow N_D = 4.63 \times 10^{17}/cm^3$

1.69

$p_{no} = \frac{n_i^2}{N_D} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4/cm^3$

From Figure p3.10

$\frac{dp}{dx} = -\frac{10^8 p_{no} - p_{no}}{W} \cong -\frac{10^8 p_{no}}{0.1 \times 10^{-4}}$

since $0.1\ \mu m = 0.1 \times 10^{-4}$ cm

$\frac{dp}{dx} = \frac{10^8 \times 2.25 \times 10^4}{0.1 \times 10^{-4}}$

$= 2.25 \times 10^{17}$

Hence

$J_p = -qD_p\frac{dp}{dx}$

$= -1.6 \times 10^{-19} \times 12 \times (-2.25 \times 10^{17})$

$= 0.432\ A/cm^2$

1.70

$N_A = N_D = 10^{16}\ cm^{-3}$ and $n_i = 1.5 \times 10^{10}\ cm^{-3}$ we have $V_o = 695$ mV. Using (3.26) and $\epsilon_s = 11.7 \times 8.85 \times 10^{-14}$ F/cm, we have $W = 4.24 \times 10^{-5}$ cm $= 0.424\ \mu m$. The extension of the depletion width into the n and p regions is given in (3.27) and (3.28) respectively:

$x_n = W \cdot \frac{N_A}{N_A + N_D} = 0.212\ \mu m$

$x_p = W \cdot \frac{N_D}{N_A + N_D} = 0.212\ \mu m$

Since both regions are doped equally, the depletion region is symmetric.

Using (3.29) and $A = 10^{-6}\ cm^2$ the charge magnitude on each side of the junction is:

$Q_J = 3.39 \times 10^{-14}$ C.

1.71

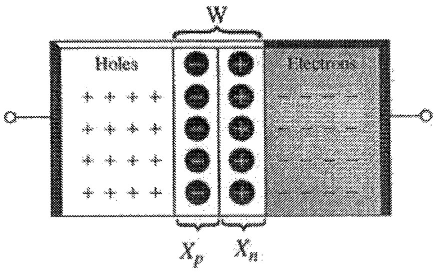
V_T at 300° K = 25.8 mV

built in voltage V_o

$$V_o = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = 25.8 \times 10^{-13}$$

$$\ln\left(\frac{10^{16} \times 10^{15}}{(1.5 \times 10^{10})^2}\right)$$

= 0.633 V



Depletion with

$$W = \sqrt{\frac{2\epsilon s}{q}\left(\frac{1}{N_A} + \frac{1}{N_O}\right) V_O} \leftarrow \text{equation 3.26}$$

$$W = \sqrt{\frac{2 \times 1.04 \times 10^{-17}}{1.6 \times 10^{-19}}\left(\frac{1}{10^6} + \frac{1}{10^{15}}\right) \times 0.633}$$

$= 0.951 \times 10^{-4}$cm = 0.951 μm

to find X_n and X_p

$$X_n = W\frac{N_A}{N_A + N_D} = 0.951 \times \frac{10^{16}}{10^{16} + 10^{15}}$$

= 0.8642 μm

$$X_p = W\frac{N_D}{N_A + N_D} = 0.951 \times \frac{10^{15}}{10^{16} + 10^{15}}$$

= 0.8642 μm

to calculate charge stored on either side

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

$= 400\ \mu m^2 = 400 \times 10^{-8} cm^2$

$$= 400 \times 10^{-8} \cdot 1.6 \times 10^{-19}\left(\frac{10^{16} \cdot 10^{15}}{10^{16} + 10^{15}}\right).$$

$$= 0.951 \times 10^{-4}$$

Hence,

$Q_J = 5.53 \times 10^{-14}$ C

1.72

Charge stored $Q_J = qAXN$

Here X = 0.1 μm = 0.1×10^{-4} cm

A = 10 μm × 10 μm = 10×10^{-4} cm × 10×10^{-4} cm

$= 100 \times 10^{-8}$ cm^2

So, $Q_J = 1.6 \times 10^{-19} \times 100 \times 10^{-8} \times 0.1 \times 10^{-4} \times 10^{16}$

=16 fC

1.73

$$V_O = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

If N_A or N_D is increased by a factor of 10, then new value of V_O will be

$$V_O = V_T \ln\left(\frac{10\, N_A N_D}{n_i^2}\right)$$

The change in the value of V_O is

$$= \frac{\ln(10)}{\ln\left(\frac{N_A N_D}{n_i^2}\right)}$$

1.74

with $N_A = 10^{16}$ cm^{-3}, $N_D = 10^{16}$ cm^{-3}, and $n_i = 1.5 \times 10^{10}$, we have V_O = 635 mV.

and V_R = 5 V, we have

$W = 2.83 \times 10^{-4}$ cm = 2.83 μm.

with A = 4×10^{-6} cm², we have

$Q_J = 4.12 \times 10^{-14}$ C.

1.75

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

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

$$= W_O\sqrt{1 + \frac{V_R}{V_O}}$$

$$\therefore \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right) V_O} = W_O$$

$$Q_j = A\sqrt{2\epsilon_s q\left(\frac{N_A N_D}{N_A + N_D}\right) \cdot (V_O + V_R)}$$

$$= A\sqrt{2\epsilon_s q\left(\frac{N_A N_D}{N_A + N_D}\right) V_O \cdot \left(1 + \frac{V_R}{V_O}\right)}$$

$$= A\sqrt{2\epsilon_s q\left(\frac{N_A N_D}{N_A + N_D}\right) V_O \cdot \left(1 + \frac{V_R}{V_O}\right)}$$

$$= Q_{JO}\sqrt{1 + \frac{V_R}{V_O}}$$

$$\because A\sqrt{2\epsilon_s q\left(\frac{N_A N_D}{N_A + N_D}\right) V_O} = Q_{JO}$$

1.76

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

$A = 200\ \mu m^2 = 200 \times 10^{-8}$ cm^2

$$I_s = 200 \times 10^{-8} \times 1.6 \times 10^{-19} \times (1.5 \times 10^{10})^2$$

$$\frac{10}{5 \times 10^{-4} \times 10^{17}} + \frac{18}{10 \times 10^{-14} \times 10^{16}}$$

$= 1.44 \times 10^{-6}$ A

$$I \cong I_s e^{V/V_T}$$
$$= 1.44 \times 10^{-16} \times e^{700/25.9}$$
$$\cong 79\ \mu A$$

1.77

$$n_i = BT^{3/2} e^{-E_G/(2KT)}$$

At 300 K,

$$n_i = 7.3 \times 10^{15} \times (300)^{3/2} \times e^{-1.12/\left(2 \times 8.62 \times 10^{-5} \times 300\right)}$$
$$= 1.4939 \times 10^{10}/\text{cm}^2$$
$$n_i^2(\text{at } 300\text{ K}) = 2.232 \times 10^{20}$$

At 305 K,

$$n_i = 7.3 \times 10^{15} \times (305)^{3/2} \times e^{-1.12/\left(2 \times 8.62 \times 10^{-5} \times 305\right)}$$
$$= 2.152 \times 10^{10}$$
$$n_i^2(\text{at } 305\text{ K}) = 4.631 \times 10^{20}$$

so $\dfrac{n_i^2(\text{at } 305\text{ K})}{n_i^2(\text{at } 300\text{ K})} = 2.152$

1.78

$$I = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)(e^{V/V_T} - 1)$$

So $I_p = Aqn_i^2 \dfrac{D_p}{L_pN_D}(e^{V/V_T} - 1)$

$$I_n = Aqn_i^2 \frac{D_n}{L_nN_A}(e^{V/V_T} - 1)$$

For $p^+ - n$ junction $N_A >> N_D$

$\therefore I \simeq I_p = Aqn_i^2 \dfrac{D_p}{L_pN_D}(e^{V/V_T} - 1)$

For this case

$$I_s \simeq Aqn_i^2 \frac{D_p}{L_pN_D} = 10^4 \times 10^{-8}\text{ cm}^2 \times 1.6 \times 10^{-19}$$
$$\times (1.5 \times 10^{10})^2 \frac{10}{10 \times 10^{-4} \times 10^{16}}$$
$$= 3.6 \times 10^{-15}\text{ A}$$
$$I = I_s(e^{V/V_T} - 1) = 0.5 \times 10^{-3}$$
$$3.6 \times 10^{-15}\left(e^{V/\left(25.9 \times 10^{-3}\right)} - 1\right) = 0.5 \times 10^{-3}$$
$$\Rightarrow V = 0.6645\text{ V}$$

$$C_j = \frac{C_{jo}}{\left(1 + \frac{V_R}{V_O}\right)^m}$$

For $V_R = 1$ V, $C_j = \dfrac{0.6\text{ pF}}{\left(1 + \frac{1}{0.75}\right)^{\frac{1}{3}}}$

$$= 0.45\text{ pF}$$

For $V_R = 10$ V, $C_j = \dfrac{0.6\text{ pF}}{\left(1 + \frac{10}{0.75}\right)^{\frac{1}{3}}}$

$$= 0.25\text{ pF}$$

1.80

$$C_d = \left(\frac{\tau_T}{V_T}\right)I$$
$$10\text{ pF} = \left(\frac{\tau_T}{25.9 \times 10^{-3}}\right) \times 1 \times 10^{-3}$$
$$\tau_T = 10 \times 10^{-12} \times 25.9$$
$$= 259\text{ pS}$$

For I = 0.1 mA

$$C_d = \left(\frac{\tau_T}{V_T}\right) \times I$$
$$= \left(\frac{259 \times 10^{-12}}{25.9 \times 10^{-3}}\right) \times 0.1 \times 10^{-3}$$
$$= 1\text{ pF}$$

1.81

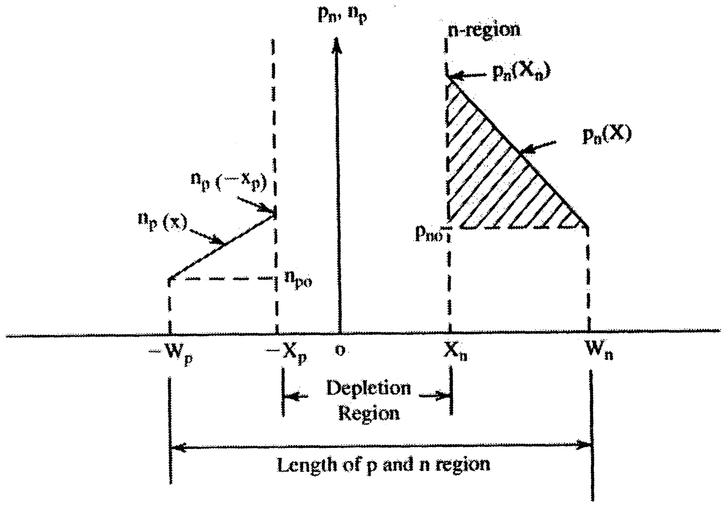
$$\tau_p = \frac{L_p^2}{D_p} = \frac{(10 \times 10^{-4})^2}{10}$$

note $1\,\mu\text{m} = 10^{-4}\text{cm}$

$$= 100\text{ ns}$$
$$Q_P = \tau_P I_P$$
$$= 100 \times 10^{-9} \times 0.2 \times 10^{-3}$$
$$= 20 \times 10^{-12}\text{ C}$$
$$C_d = \left(\frac{\tau_P}{V_T}\right)I$$
$$= \left(\frac{100 \times 10^{-9}}{25.9 \times 10^{-3}}\right) \times 0.2 \times 10^{-3}$$
$$= 772\text{ pF}$$

1.82

a.



b. The current $I = I_p + I_n$
Find current component I_p

$$p_n(x_n) = p_{no}e^{V/V_T} \text{ and } p_{no} = \frac{n_i^2}{N_D}$$

$$I_p = AJ_p = AqD_p\frac{dp}{dx}$$

$$\frac{dp}{dx} = \frac{p_n(x_n) - p_{no}}{W_n - X_n} = \frac{p_{no}e^{V/V_T} - p_{no}}{W_n - X_n}$$

$$= p_{no}\frac{(e^{V/V} - 1)}{W_n - X_n}$$

$$= \frac{n_i^2(e^{V/V_T} - 1)}{N_D(W_n - X_n)}$$

$$\therefore I_p = AqD_p\frac{dp}{dx}$$

$$= Aqn_i^2\frac{D_p}{(W_n - X_n)N_D} \times (e^{V/V_T} - 1)$$

Similarly

$$I_n = Aqn_i^2\frac{D_n}{(W_p - X_p)N_A} \times (e^{V/V_T} - 1)$$

$$I = I_p + I_n$$

$$= Aqn_i^2\left[\frac{D_p}{(W_n - X_n)N_D} + \frac{D_n}{(W_p - X_p)N_A}\right]$$

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

The excess change, Q_p, can be obtained by multiplying the area of the sheded triangle of the $p_n(x)$ distibution graph by Aq.

$$Q_p = Aq \times \frac{1}{2}[p_n(X_n) - p_{no}](W_n - X_n)$$

$$= \frac{1}{2}Aq[p_{no}e^{V/V_T} - p_{no}](W_n - X_n)$$

$$= \frac{1}{2}Aqp_{no} + (e^{V/V_T} - 1)(W_n - X_n)$$

$$= \frac{1}{2}Aq\frac{ni^2}{N_D}(W_n - X_n)(e^{V/V_T} - 1)$$

$$= \frac{1}{2}\frac{(W_n - X_n)^2}{D_p} \cdot I_p$$

$$\simeq \frac{1}{2}\frac{W_n^2}{D_p} \cdot I_p \text{ for } W_x >> X_p$$

c. $C_d = \dfrac{dQ}{dV} = \tau_T\dfrac{dI}{dV}$

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

$$\frac{dI}{dV} = \frac{I_Se^{V/V_T}}{V_T}$$

$$\simeq \frac{I}{V_T}$$

so $C_d \cong \tau_T \cdot \dfrac{I}{V_T}$

d. $C_d = \dfrac{1}{2}\dfrac{W_n^2}{10}\dfrac{1 \times 10^{-3}}{25.9 \times 10^{-3}} = 8 \times 10^{-12}$ F

Solve for W_n

$W_n = 63.25\ \mu m$

2.1

$v_o = A v_+ \Rightarrow A = \frac{4}{4/1001} = 1001$

$v_+ = v_I \frac{1k\Omega}{1M\Omega + 1k\Omega} = \frac{4}{1001}\ V$

2.2

The voltage at the positive input has to be −3.000V.

$v_+ = -3.020\ V$, $A = \frac{v_o}{(v_+ - v_-)} = \frac{-2}{-3.020-(-3)} = 100$

2.3

#	v_1	v_2	$v_d = v_2 - v_1$	v_o	v_o/v_d
1	0.00	0.00	0.00	0.00	–
2	1.00	1.00	0.00	0.00	–
3	(a)	1.00	(b)	1.00	
4	1.00	1.10	0.10	10.1	101
5	2.01	2.00	−0.01	−0.99	99
6	1.99	2.00	0.01	1.00	100
7	5.10	(c)	(d)	−5.10	

experiments 4,5,6 show that the gain is approximately 100 V/V. The missing entry for experiment #3 can be predicted as follows:

(b) $v_d = \frac{v_o}{A} = \frac{1.00}{100} = 0.01$ V.

(a) $v_1 = v_2 - v_d = 1.00 - 0.01 = 0.99$ V

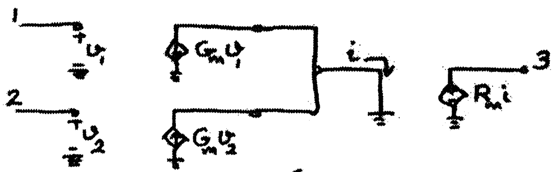
The missing entries for experiment #7:

(d) $v_d = \frac{-5.10}{100} = -0.051$ V

(c) $v_2 = v_1 + v_d = 5.10 - 0.051 = 5.049$ V

All the resluts seen to be reasonable.

2.4



$A = G_m R_m = 100 \times 10^{-3} \times 10^{6} = 100{,}000\ V/V$

2.5

$v_{CM} = 1\, v \,\text{Sin}\,(2\pi 60)t = \frac{1}{2}(v_1 + v_2)$

$v_d = 0.01\ \text{Sin}\,(2\pi 1000)t = v_1 - v_2$

$v_1 = v_{CM} - v_d/2 = \text{Sin}(120\pi)t - 0.005\ \text{Sin}\ 2000\pi t$

$v_2 = v_{CM} + v_d/2 = \text{Sin}\ 120\pi t + 0.005\ \text{Sin}\ 2000\pi t$

2.6

Circuit	v_o/v_i (V/V)	R_{in} (kΩ)
a	$\frac{-100}{10} = -10$	10
b	−10	10
c	−10	10
d	−10	10

virtual ground no current in 10 kΩ

2.7

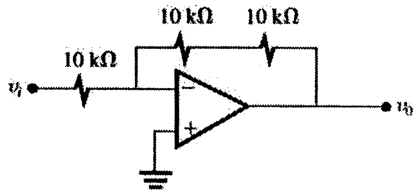
closed loop gain = −1 V/V. for $v_i = 5V \Rightarrow v_o = -5$ V

Gain would be in the range of $\frac{-0.95}{1.05}$ to $\frac{-1.05}{0.95}$: $-0.9 < G < -1.1$

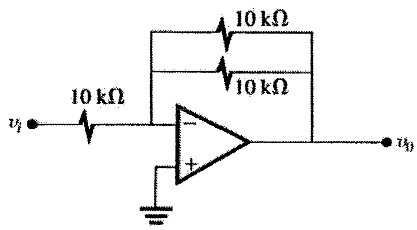
for $v_i = 5 \Rightarrow -4.5 < v_o < -5.5\,V$

2.8

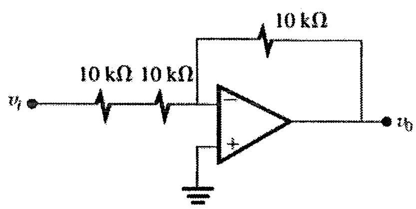
There are four possibilities:



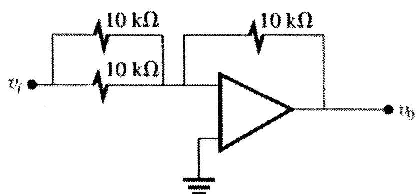
$\frac{v_o}{v_i} = -2$ V/V $R_{in} = 10$ kΩ



$\frac{v_o}{v_i} = -0.5$ V/V $R_{in} = 10$ kΩ



$\frac{v_o}{v_i} = -0.5$ V/V $R_{in} = 20$ kΩ



$\frac{v_o}{v_i} = -2$ V/V $R_{in} = 5$ kΩ

2.9

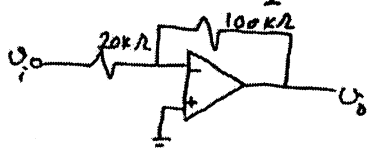
a. G = −1 V/V
b. G = −10 V/V
c. G = −0.1 V/V
d. G = −100 V/V
e. G = −10 V/V

2.10

$\frac{v_o}{v_i} = -5 = \frac{-R_2}{R_1} \Rightarrow R_2 = 5R_1$

$R_1 + R_2 = 120\,k\Omega \Rightarrow 5R_1 + R_1 = 120\,K\Omega \Rightarrow$

$R_1 = 20\,K\Omega \Rightarrow R_2 = 100\,k\Omega$



2.11

$20\log|G| = 26\,dB \Rightarrow G = -19.95\ V/V = \frac{v_o}{v_i} = -\frac{R_2}{R}$

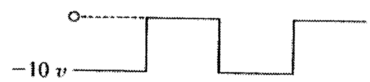
$\Rightarrow R_2 = 19.95 R_1 \leq 10\,M\Omega$

For largest possible input resistance, select

$R_2 = 10\,M\Omega \Rightarrow R_1 \simeq 500\,K\Omega$

$R_{in} = 500\,K\Omega$

2.12



$G = \frac{v_o}{v_i} = \frac{-R_2}{R_1} = \frac{-100}{10} = -10$

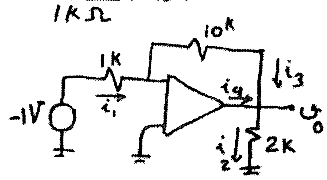
$v_{low} = 10$ V, $v_{high} = 0$, $v_{avg} = -5$ V

2.13

$\frac{v_o}{v_i} = -\frac{R_2}{R_1} \Rightarrow v_o = -1 \times -\frac{10\,k\Omega}{1\,K\Omega} = 10\,V$

$i_2 = \frac{v_o}{2\,K\Omega} = 5\,mA$

$i_1 = i_3 = \frac{v_o}{10\,K\Omega} = 1\,mA$



$i_4 = i_2 - i_3 = 4\,mA$ This additional current comes from the output of the op amp.

2.14

$$|Gain| = \frac{R_2}{R_1} = \frac{R_2(1+x/100)}{R_1(1+x/100)} \simeq \frac{R_2}{R_1}\left(1 \pm \frac{2x}{100}\right)$$

for small x

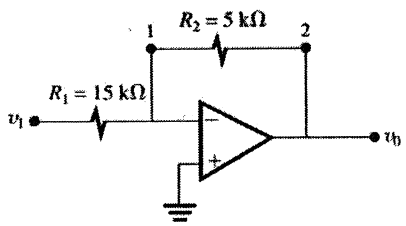
$\Rightarrow 2x\%$ is the tolerance on the closed loop gain (G).

$G = -100\ V/V$, $x = 5 \Rightarrow -110 < G < -90$

or more precisely: $-100 \times \frac{105}{95} < G < -100\,\frac{95}{105}$

$-110.5 < G < -90.5$

2.15



$$G = \frac{v_o}{v_i} = \frac{-R_2}{R_1} \Rightarrow \frac{R_2}{R_1} = \frac{5}{15}$$

$v_1 = 0V$, $\quad v_2 = v_o = 5V$

For $\pm 1\%$ on R_1, R_2: $R_1 = 15 \pm 0.15\ k\Omega$

$R_2 = 5 \pm 0.05\ k\Omega$

$$v_o = v_i\frac{-R_2}{R_1} = 15\frac{R_2}{R_1} \Rightarrow 15 \times \frac{4.95}{15.15}$$

$$\le v_o \le 15 \times \frac{5.05}{14.85}$$

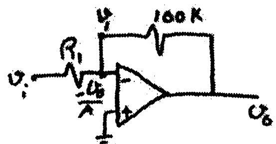
$$\Rightarrow 4.9\ V \le v_o \le 5.1\ V$$

For $v_i = -15 \pm 0.15\ V$ $\quad 14.85 \times \frac{4.95}{15.15}$

$$\le v_o \le 15.15 \times \frac{5.05}{14.85}$$

$$\Rightarrow 4.85\ v \le v_o \le 5.15\ V$$

2.16



$$v_1 = \frac{-v_o}{A} = -\frac{v_o}{200}$$

$$\frac{v_o}{v_i} = -50\ V/V$$

$$\frac{v_i - \left(\frac{-v_o}{A}\right)}{R_1} = \frac{\left(\frac{-v_o}{A} - v_o\right)}{100k\Omega} \Rightarrow R_1 = 100K \times \frac{\frac{v_o}{200} - \frac{v_o}{50}}{\frac{-v_o}{200} - v_o}$$

$$\Rightarrow R_1 = 100K \times \frac{3}{201} = 1.49\,k\Omega$$

Shunt Resistor R_a : $R_a \,//\, 2k\Omega = 1.49K$

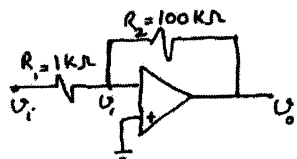
$$\frac{R_a \times 2}{R_a + 2} = 1.49 \Rightarrow R_a = 5.84\,k\Omega$$

2.17

ⓐ

$$\frac{v_o}{v_i} = \frac{-R_2}{R_1} \Rightarrow -100\ V/V = \frac{-R_2}{1K\Omega} \Rightarrow R_2 = 100\,k\Omega$$

ⓑ $A = 1000\ V/V$



$$v_1 = \frac{-v_o}{A}$$

$$\frac{v_i - v_1}{R_1} = \frac{v_1 - v_o}{R_2}$$

$$\frac{v_o}{v_i} = \frac{-R_2/R_1}{1 + (1 + \frac{R_2}{R_1})/A} = \frac{-100}{1 + \frac{101}{1000}} = -90.8\ V/V$$

$$\Rightarrow \frac{v_o}{v_i} = 90.8\ V/V$$

ⓒ Assume $R_1' = R_x \,//\, R_1$ when $R_1 = 1k\Omega$

$$\frac{v_o}{v_i} = -100\ V/V$$

$$\frac{v_i - v_1}{R_1'} = \frac{v_1 - v_o}{R_2} \Rightarrow R_1' = R_2 \times \left(\frac{-v_o}{100} - \frac{-v_o}{1000}\right) \Big/ \left(\frac{-v_o}{1000} - v_o\right)$$

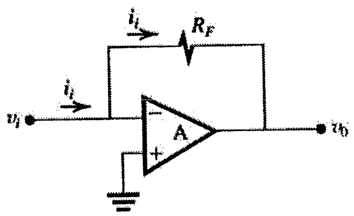
$$R_1' = \frac{1 - 0.1}{1.001} = 0.899\,k\Omega = \frac{R_1 R_x}{R_1 + R_x} = \frac{R_x}{1 + R_x}$$

$$\Rightarrow R_x = 8.9\,k\Omega \simeq 8.87\,k\Omega \pm 1\%$$

2.18

Voltage of the inverting input terminal will vary from $\frac{-10V}{1000}$ to $\frac{+10V}{1000}$. Thus the virtual ground will depart from the ideal voltage of zero by a maximum of ±10mV.

2.19



a) For A = ∞: $v_i = 0$

$v_o = -i_i R_F$

$$R_m = \frac{v_o}{i_i} = -R_F$$

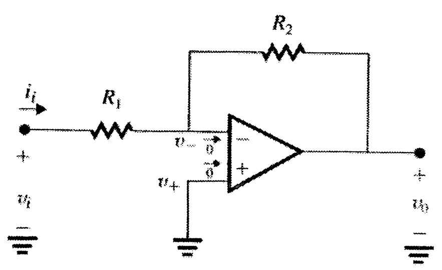
$$R_{in} = \frac{v_i}{i_i} = 0$$

b) For A-finite: $v_i = -\frac{v_o}{A}$, $v_o = v_i - i_i R_F$

$$\Rightarrow v_o = \frac{-v_o}{A} - i_i R_F \Rightarrow R_m = \frac{v_o}{i_i} = -\frac{R_F}{1 + \frac{1}{A}}$$

$$R_i = \frac{v_i}{i_i} = \frac{R_F}{1 + A}$$

2.20



$v_o = -Av_- = v_- - i_i R_2$

$i_i R_2 = v_-(1 + A)$

$$v_- = \frac{i_i R_2}{1 + A}$$

Again $v_i = i_i R_1 + v_-$

$$= i_i R_1 + i_i \frac{R_2}{1 + A}$$

$$\text{So } R_{in} = \frac{v_i}{i_i} = R_1 + \frac{R_2}{A + 1}$$

2.21

$$R_1' = R_1 \parallel R_c \qquad G' = \frac{-R_2/R_1'}{1 + \frac{1 + R_2/R_1'}{A}}$$

In order for $G' = G$:

$$G = \frac{-R_2/R_1'}{1 + \frac{1 + R_2/R_1'}{A}} = \frac{-R_2}{R_1}$$

$$R_1' = \frac{R_1 R_c}{R_1 + R_c}$$

$$\Rightarrow \frac{R_1 + R_c}{R_1 R_c} = \frac{1}{R_1}\left(1 + \frac{R_2 \frac{(R_1 + R_c)}{R_1 R_c}}{A}\right)$$

$$(R_1 + R_c)A = AR_c + R_c + \frac{R_2}{R_1}(R_1 + R_c)$$

$$R_1 A = R_c + GR_1 + GR_c$$

$$\frac{R_c}{R_1} = \frac{A - G}{1 + G}$$

2.22

$$G = \frac{-R_2/R_1}{1 + \frac{1 + R_2/R_1}{A}} \qquad G_{nominal} = \frac{-R_2}{R_1}$$

$$\epsilon = \left| \frac{G - G_{nominal}}{G_{nominal}} \right| = \left| \frac{G}{G_{nominal}} - 1 \right|$$

$$\epsilon = \left| \frac{1}{1 + \frac{1 + R_2/R_1}{A}} - 1 \right| = \left| \frac{-\frac{1 + R_2/R_1}{A}}{1 + \frac{1 + R_2/R_1}{A}} \right| = \frac{1}{\frac{A}{1 + \frac{R_2}{R_1}} + 1}$$

which can be rearranged to yield:

$$\frac{A}{1 + \frac{R_2}{R_1}} + 1 = \frac{1}{\epsilon} \Rightarrow A = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{1}{\epsilon} - 1\right)$$

$$\text{or } A = (1 - G_{nominal})\left(\frac{1}{\epsilon} - 1\right)$$

For $G_{nominal} = -100$ V/V and $\epsilon = 10\% = 0.1$

$$A = (1 + 100)\left(\frac{1}{0.1} - 1\right) = 909 \text{ V/V}$$

This is the minimum required value for A.

2.23

(a) $\frac{\Delta|G|/|G|}{\Delta A/A} = \frac{1 + R_2/R_1}{A}$

(b) $\frac{\Delta|G|}{G} = 0.5\%,\ \frac{\Delta A}{A} = 50\%,\ \frac{R_2}{R_1} = 100$

$$\frac{0.005}{.5} = \frac{1+100}{A}$$

$$A = \frac{101(.5)}{(.005)} = 10.1\ \text{k}$$

2.24

$$\frac{v_o}{v_i} = -\frac{R_2}{R_1}\left(1 + \frac{R_4}{R_2} + \frac{R_4}{R_3}\right)$$

For $R_1 = R_2 = R_4 = 1\,M\Omega \Rightarrow \frac{v_o}{v_i} = -(1 + 1 + \frac{1}{R_3})$

a) $\frac{v_o}{v_i} = -10\ V/V \Rightarrow 10 = 2 + \frac{1}{R_3} \Rightarrow R_3 = \frac{1}{8}\,M\Omega = 125\ k\Omega$

b) $\frac{v_o}{v_i} = -100\ V/V \Rightarrow 100 = 2 + \frac{1}{R_3} \Rightarrow R_3 = \frac{1}{98}\,M\Omega = 10.2\ k\Omega$

c) $\frac{v_o}{v_i} = -2\ V/V \Rightarrow 2 = 2 + \frac{1}{R_3} \Rightarrow R_3 = \infty$; eliminate R_3.

2.25

$R_2/R_1 = 1000,\ R_2 = 100\ \text{k}\Omega \Rightarrow R_1 = 1000\ \Omega$

a) $R_{in} = R_1 = 100\ \Omega$

b) $\frac{v_O}{v_I} = \frac{-R_2}{R_1}\left(1 + \frac{R_4}{R_2} + \frac{R_4}{R_3}\right) = -1000$

If $R_2 = R_1 = R_4 = 100\ \text{K} \Rightarrow R_3 = \frac{100\ \text{K}}{1000 - 2} \simeq$

$100\ \Omega$

$R_{in} = R_1 = 100\ \text{k}\Omega$

2.26

$v_x = 0 - i_1 R_2$, $i_1 = \frac{v_I}{R_1} \Rightarrow v_x = -v_I \frac{R_2}{R_1}$

$$\frac{v_x}{v_I} = -\frac{R_2}{R_1}$$

$$v_x = v_o \frac{R_2 \| R_3}{R_2 \| R_3 + R_4} = v_o \frac{R_2 R_3}{R_2 R_3 + R_4 R_2 + R_4 R_3}$$

$$\frac{v_o}{v_x} = \frac{R_2 R_3 + R_2 R_4 + R_3 R_4}{R_2 R_3} = 1 + \frac{R_4}{R_3} + \frac{R_4}{R_2}$$

$$\frac{v_o/v_x}{v_I/v_x} = \frac{v_o}{v_I} = \frac{(1 + R_4/R_3 + R_4/R_2)}{-R_1/R_2} \Rightarrow$$

$$\frac{v_o}{v_I} = -\frac{R_2}{R_1}\left(1 + \frac{R_4}{R_3} + \frac{R_4}{R_2}\right)$$

2.27

a) $R_1 = R$

$R_2 = (R \parallel R) + \frac{R}{2} = \frac{R}{2} + \frac{R}{2} = R$

$R_3 = (R_2 \parallel R) + \frac{R}{2} = (R \parallel R) + \frac{R}{2} = R$

$R_4 = (R_3 \parallel R) + \frac{R}{2} = (R \parallel R) + \frac{R}{2} = R$

b) $v = RI = RI_1 \Rightarrow I_1 = I$

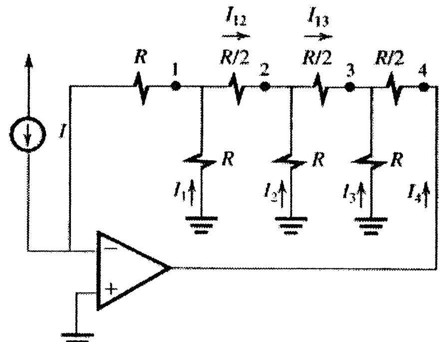
$I_{12} = I + I = 2I \Rightarrow v_1 + 2I \times \frac{R}{2} = RI_2$

$RI + RI = RI_2 \Rightarrow I_2 = 2I$

$I_{13} = I_2 + I_{12} = 4I \Rightarrow v_2 + 4I \times \frac{R}{2} = RI_3$

$R \times 2I + 4I \times \frac{R}{2} = RI_3 \Rightarrow I_3 = 4I,$

$I_4 = -(4I + 4I)\ I_4 = 8I$



c) $v_1 = I_1 R = -IR$

$v_2 = -I_2 R = -2IR$

$v_3 = -I_3 R = -4IR$

$v_4 = -I_3 R + I_4 \frac{R}{2} = -4IR - 8I\frac{R}{2} = -8IR$

2.28

a) $I_1 = \frac{1V}{10k\Omega} = 0.1mA$

$I_2 = I_1 = 0.1\ mA$, $I_2 \times 10k\Omega = I_3 \times 100\Omega \Rightarrow I_3 = 10^{mA}$

$v_x = 10mA \times 100\Omega = 1V$

b) $v_x = R_L I_L + v_o$, $I_L = I_2 + I_3 = 10.1mA$

$1V = R_L \times 10.1mA + v_o$

$R_L = \frac{1 - v_o}{10.1} \Rightarrow R_{Lmax} = \frac{1 - v_{omin}}{10.1} = \frac{14}{10.1}$

$R_{Lmax} =$

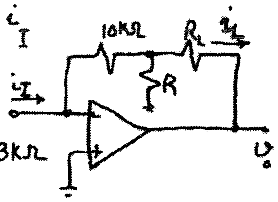
c) $100\Omega \leqslant R_L \leqslant 1k\Omega$

I_L stays fixed at 10.1mA

$v_o = v_x - R_L I_L = 1 - R_L \times 10.1 \Rightarrow -9.1^V \leqslant v_o \leqslant -0.01^V$

2.29

a) $\frac{i_L}{i_i} = 20 \Rightarrow i_L = 20 i_I$



$-10k\Omega \times i_I = R(i_I - i_L)$

$R = \frac{10k\Omega \times i_I}{20i_I - i_I} = 0.53k\Omega$

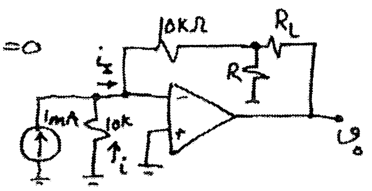
b) $R_L = 1k\Omega$ $-12^V \leqslant v_o \leqslant 12^V$

$v_o = R_L i_L + 10k\Omega \times i_I = i_I (1k\Omega \times \frac{i_L}{i_I} + 10^{k\Omega})$

$v_o = i_I (1 \times 20 + 10) = 30 i_I$

$i_I = \frac{v_o}{30} \Rightarrow \frac{-12}{30} \leqslant i_I \leqslant \frac{12}{30} \Rightarrow -0.4_{mA} \leqslant i_I \leqslant 0.4_{mA}$

c) $R_I = \frac{v_I}{i_I} = \frac{0}{i_I} = 0$



$v_I = 0 \Rightarrow i = 0$

$\Rightarrow i_I = 1mA$

From part a: $i_L = 20 \times i_I = 20\ mA$

2.30

$R_I = 100\ k\Omega - 10 \leq \frac{v_o}{v_i} \leq -1\ \frac{V}{V}$

$R_i = R_1 = 100\ k\Omega$

$$\frac{v_o}{v_i} = \frac{-R_2}{R_1}\left(\frac{R_4}{R_3} + \frac{R_4}{R_2} + 1\right)$$

$$R_4 = 0 \Rightarrow \frac{v_o}{v_i} = \frac{-R_2}{R_1} = -1 \Rightarrow R_2 = 100\ k\Omega$$

$$R_4 = 10\ k\Omega \Rightarrow \frac{v_o}{v_i} = -10$$

$$= -1 \times \left(\frac{10\ k\Omega}{R_3} + \frac{10\ k\Omega}{100\ k\Omega} + 1\right)$$

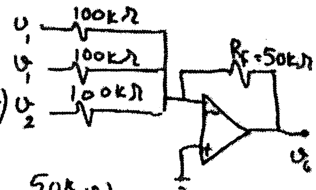
$$+10 = \left(\frac{10}{R_3} + 1.1\right) \Rightarrow R_3 = 1.12\ k\Omega$$

Potentiometer in the middle:

$$\frac{v_o}{v_i} = -1\left(\frac{5}{5 + R_3} + \frac{5}{100} + 1\right)$$

$$\frac{v_o}{v_i} = -1.87\ V/V$$

2.31



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

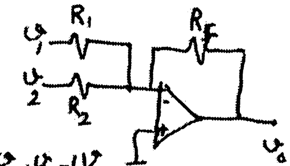
$v_o = -\left(\frac{50k}{100k} v_1 + \frac{50k}{100k} v_1 + \frac{50k}{100k} v_2\right)$

$v_o = -\left(v_1 + \frac{v_2}{2}\right)$ $v_1 = 3, v_2 = -3 \Rightarrow v_o = -1.5V$

2.32

we choose the weighted summer configuration

$v_o = -\left[4v_1 + \frac{v_2}{3}\right]$



$i_1 = \frac{v_1}{R_1}$ $\quad i_2 = \frac{v_2}{R_2}$

$i_1, i_2 \leq 0.1\ mA$ for $v_1, v_2 = 1V$

$R_1, R_2 \geq 10k\Omega$

$\frac{R_F}{R_1} = 4$, if $R_1 = 10k\Omega \Rightarrow R_F = 40k\Omega$

$\frac{R_F}{R_2} = \frac{1}{3} \Rightarrow R_2 = 120k\Omega$

2.33

$v_o = -(2v_1 + 4v_2 + 8v_3)$

$R_1, R_2, R_3 \geq 10\ k\Omega$

$\frac{R_F}{R_1} = 2,\ \frac{R_F}{R_2} = 4\ \frac{R_F}{R_3} = 8$

$R_3 = 10\ k\Omega \Rightarrow R_F = 80\ k\Omega$

$R_2 = 20\ k\Omega$

$R_1 = 40\ k\Omega$

2.34

The output signal should be:

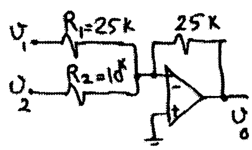
$v_o = -5\sin\omega t - 5$

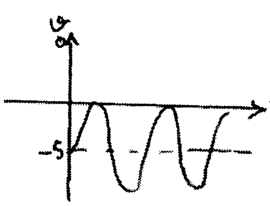
if we assume : $v_1 = 5\sin\omega t$, $v_2 = 2V$ $\Big\}\ v_o = -(v_1 + 2.5v_2)$

In a weighted summer configuration:

$\frac{R_F}{R_1} = +1$ $\qquad \frac{R_F}{R_2} = 2.5$

$R_2 = 10k\Omega \Rightarrow R_F = 25K = R_1$





2.35

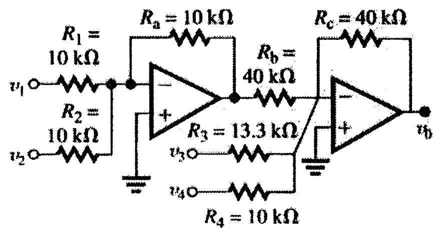
$v_o = v_1 + 2v_2 - 3v_3 - 4v_4$:

For a weighted summer circuit:

$$v_o = v_1\frac{R_aR_c}{R_1R_b} + v_2\frac{R_aR_c}{R_2R_3} - v_3\frac{R_c}{R_3} - v_4\frac{R_c}{R_4}$$

$$\frac{R_a}{R_1}\frac{R_c}{R_b} = 1,\ \frac{R_a}{R_2}\frac{R_c}{R_b} = 1,\ \frac{R_c}{R_3} = 3,\ \frac{R_c}{R_4} = 4$$

assume:



$R_4 = 10\ k\Omega \Rightarrow R_c = 40\ k\Omega \Rightarrow R_3 = \frac{40}{3}$

$= 13.3\ k\Omega$

$\frac{R_a}{R_1} \times \frac{40}{R_b} = 1\ \ \frac{R_a}{R_2} \times \frac{40}{R_b} = 1$

$R_b = 40\ k\Omega$, $\qquad R_1 = R_2 = R_a = 10\ k\Omega$

2.36

$v_1 = 3\sin(2\pi \times 60t) + 0.01\sin(2\pi \times 1000t)$

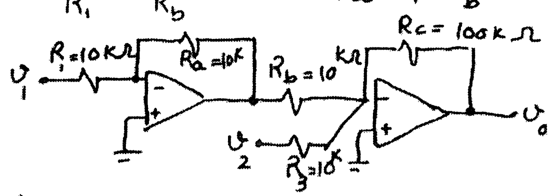
$v_2 = 3\sin(2\pi \times 60t) - 0.01\sin(2\pi \times 1000t)$

we want to have : $v_o = 10v_1 - 10v_2$

$v_o = v_1\frac{R_a}{R_1}\frac{R_c}{R_b} - v_3\frac{R_c}{R_3}$

$\frac{R_a}{R_1}\frac{R_c}{R_b} = 10$, $\frac{R_c}{R_3} = 10$, if $R_3 = 10^{k\Omega} \Rightarrow R_c = 100^{k\Omega}$

$\Rightarrow \frac{R_a}{R_1} \times \frac{100^{k\Omega}}{R_b} = 10 \Rightarrow R_a = R_1 = R_b = 10k\Omega$



$v_o = 10v_1 - 10v_2 = 10 \times 0.02\ \sin 2\pi \times 1000t$

$v_o = 0.2\sin(2\pi \times 1000t)$ $\quad -0.2^V \leq v_o \leq 0.2^V$

2.37

This is a weighted summer circuit:

$$v_o = -\left(\frac{R_F}{R_0}v_0 + \frac{R_F}{R_1}v_1 + \frac{R_F}{R_2}v_2 + \frac{R_F}{R_3}v_3\right)$$

we may write: $v_0 = 5v \times a_0$, $v_2 = 5v \times a_2$; $v_1 = 5v \times a_1$, $v_3 = 5v \times a_3$

$$v_o = -R_F\left(\frac{50}{80\text{ k}\Omega} + \frac{5}{40\text{ k}\Omega}a_1 + \frac{5}{20\text{ k}\Omega}a_2 + \frac{5}{10\text{ k}\Omega}a_3\right)$$

$$v_o = -R_F\left(\frac{a_0}{16} + \frac{a_1}{8} + \frac{a_2}{4} + \frac{a_3}{2}\right)$$

$$v_o = -\frac{R_F}{16}(2^0a_0 + 2^1a_1 + 2^2a_2 + 2^3a_3)$$

2.38

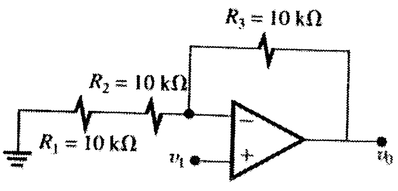
a) $\frac{v_o}{v_i} = 1 = 1 + \frac{R_2}{R_1} \Rightarrow R_2 = 0,\ R_1 = 10\text{k}\Omega$

b) $\frac{v_o}{v_i} = 2 = 1 + \frac{R_2}{R} \Rightarrow R_1 = R_2 = 10\text{k}\Omega$

c) $\frac{v_o}{v_i} = 101\ V/V = 1 + \frac{R_2}{R_1} \Rightarrow$ if $R_1 = 10\text{k}\Omega \Rightarrow R_2 = 1\text{M}\Omega$

d) $\frac{v_o}{v_i} = 100\ V/V = 1 + \frac{R_2}{R_1} \Rightarrow$ if $R_1 = 10\text{k}\Omega \Rightarrow R_2 = 990\text{ k}\Omega$

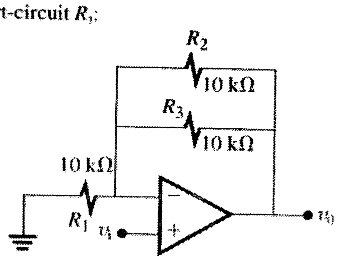
2.39



Short-circuit R_2:

$$\frac{v_o}{v_i} = 2$$

Short-circuit R_1:



$$\frac{v_o}{v_i} = 1$$

2.40

$v_+ = v_- = v_o = R \times i$, $i = 100\ \mu$A when

$v = 10$V

$$\Rightarrow R = \frac{10}{0.1\text{ mA}} = 100\text{ k}\Omega$$

As indicated, i only depends on R and v and the meter resistance does not affect i.

2.41

$v_o = v_{I1} + 3v_{I2} - 2(v_{I3} + 3v_{I4})$

$\frac{R_F}{R_{N3}} = 2$ if $R_{N3} = 10\text{ k}\Omega \Rightarrow R_F = 20\text{ k}\Omega$

$\frac{R_F}{R_{N4}} = 6 \Rightarrow R_{N4} = \frac{20}{6} = 3.3\text{ k}\Omega$

$R_N = R_{N3} \parallel R_{N4} = 10\text{ K} \parallel 3.3\text{ k} = 2.48\text{ k}\Omega$

$\left(1 + \frac{R_F}{R_N}\right)\frac{R_P}{R_o} = 1 \Rightarrow \left(1 + \frac{20}{2.48}\right)\frac{R_P}{R_{P1}}$

$= 1 \Rightarrow 9.06\ R_P = R_{P1}$

$R_P = R_{P1} \parallel R_{P2} \parallel R_{P3} \Rightarrow R_P$

$$= \frac{1}{\frac{1}{R_{P1}} + \frac{1}{R_{P2}} + \frac{1}{R_{P0}}}$$

$\left(1 + \frac{R_F}{R_N}\right)\frac{R_P}{R_{P2}} = 3 \Rightarrow 9.06\frac{R_P}{R_{P2}} = 3 \Rightarrow R_{P2} \simeq 3R_P$

$R_{P1} \parallel R_{P2} = \frac{9 \times 3R_P}{9 + 3} = 2.25R_P.$

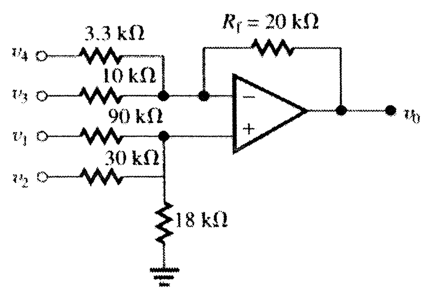
$R_P = 2.25R_P \parallel R_{P0}$

$\Rightarrow R_P + R_{PO} = 2.25\ R_{PO} \Rightarrow R_{PO} = 1.8\ R_P$

$R_P = 10\text{ k}\Omega \Rightarrow R_{PO} = 18\text{ k}\Omega$

$R_{P1} = 9 \times 10\text{ k} = 90\text{ k}\Omega$

$R_{P2} = 3 \times 10\text{ k} = 30\text{ k}\Omega$



2.42

$$v_+ = v_I \frac{R_4}{R_3 + R_4} = v$$

$$\frac{v}{R_1} = \frac{v_o - v_-}{R_2} \Rightarrow v_o = v_-\left(1 + \frac{R_2}{R_1}\right)$$

From the two above equations:

$$\frac{v_o}{v_I} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) = \frac{1 + R_2/R_1}{1 + R_3/R_4}$$

2.43

Setting $v_2 = 0$, we obtain the output component due to v_1 as:

$v_{o1} = -20\ v$

Setting $v_1 = 0$, we obtain the output component due to v_2 as:

$$v_{O2} = v_2\left(1 + \frac{20R}{R}\right)\left(\frac{20R}{20R + R}\right) = 20\ v_2$$

The total output voltage is:

$v_o = v_{o1} + v_{o2} = 20\,(v_2 - v_1)$

For $v_1 = 10 \text{Sin}\, 2\pi \times 60t - 0.1\ \text{Sin}\,(2\pi \times 1000\ t)$

$v_2 = 10 \text{Sin}\, 2\pi \times 60t + 0.1\ \text{Sin}\,(2\pi \times 1000\ t)$

$v_o = 4 \text{Sin}\,(2\pi \times 1000\ t)$

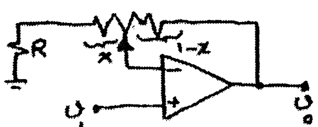
2.44

$$\frac{v_o}{v_I} = 1 + \frac{R_2}{R_1} = 1 + \frac{(1-x)}{x} = 1 + \frac{1}{x} - 1 = \frac{1}{x}$$

$0 < x \leq 1 \Rightarrow 1 \leq \frac{v_o}{v_I} < \infty$

if we add a resistor on the ground path:

$$\frac{v_o}{v_I} = 1 + \frac{(1-x) \times 10K}{x \times 10K + R}$$

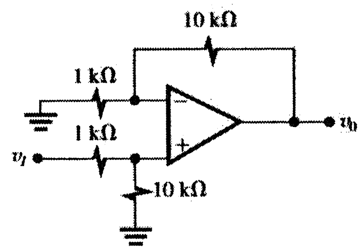


$\text{Gain}_{max} = 21$ when

$x = 0 \Rightarrow 21 = 1 + \frac{10K}{R}$

$\Rightarrow R = \frac{10K}{20} = 0.5\,K\Omega$

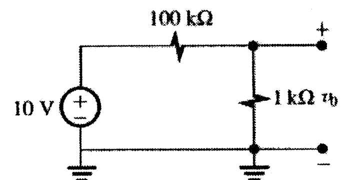
2.45



$$v_O = v_I \frac{10}{1 + 10}\left(1 + \frac{10}{1}\right)$$

$$v_O = 10\ v_I$$

2.46



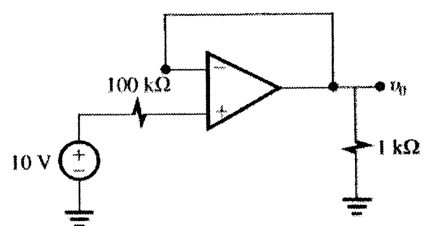
a) Source is connected directly.

$$v_O = 10 \times \frac{1}{101} = 0.099\ \text{V}$$

$$i_L = \frac{v_O}{1\ \text{k}\Omega} = \frac{0.099}{1} = 0.099\ \text{mA}$$

Current supplied by the source is 0.099 mA.

b) inserting a buffer



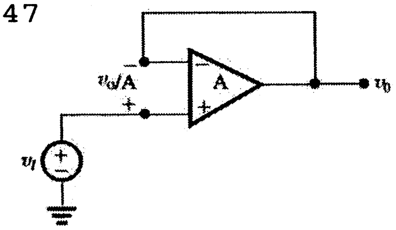
$$v_O = 10\ \text{V}$$

$$i_L = \frac{10\ \text{V}}{1\ \text{K}} = 10\ \text{mA}$$

current supplied by the source is 0.

The load current i_L comes from the power supply of the op-amp.

2.47



$$v_O = v_I - \frac{v_O}{A}$$

$$\frac{v_O}{v_I} = \frac{1}{1+\frac{1}{A}}$$

error of Gain magnitude

$$\frac{\left|\frac{v_O}{v_I} - 1\right|}{1} = -\frac{1}{A+1}$$

$A\left(\frac{V}{V}\right)$	1000	100	10
$\frac{V_O}{V_i}\left(\frac{V}{V}\right)$	0.999	0.990	0.909
Gain error	−0.1%	−1%	−9.1%

2.48

$A = 50$ V/V $\quad 1 + \frac{R_2}{R_1} = 10$ V/V

if $R_1 = 10\ \text{k}\Omega \Rightarrow R_2 = 90\ \text{k}\Omega$

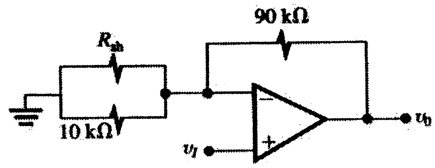
$$G = \frac{v_O}{v_I} = \frac{1+\frac{R_2}{R_1}}{1+\frac{1+R_2/R_1}{A}}$$

$$G = \frac{1+98/10}{1+\frac{1+90/10}{50}} = \frac{10}{1.2} = 8.33\ \text{V/V}$$

In order to compensate the gain drop, we can shunt a resistor with R_1.
Compensated:

$$R_{sh}:\ 10 = \frac{1+\left(\frac{90}{10}+\frac{90}{R_{sh}}\right)}{1+\frac{1+\frac{90}{10}+\frac{90}{R_{sh}}}{50}} \Rightarrow$$

$$10 \times (510R_{sh} + 90R_{sh} + 900)$$
$$= 50 \times (10R_{sh} + 90R_{sh} + 900)$$
$$100R_{sh} = 3600 \Rightarrow R_{sh} = 36\ \text{k}\Omega$$



If A = 100 then:

$$G_{\text{uncompensated}} = \frac{1+\frac{90}{10}}{1+\frac{1+90/10}{100}} = \frac{10}{1.1} = 9.09\ \text{V/V}$$

$$G_{\text{compensated}} = \frac{1+\frac{90}{10}+\frac{90}{36}}{1+\frac{1+\frac{90}{10}+\frac{90}{36}}{100}}$$

$$= \frac{125}{1.125} = 11.1\ \text{V/V}$$

2.49

$$G = \frac{G_O}{1+\frac{G_O}{A}},\ \frac{G_O - G}{G_O} \times 100 = \frac{G_O/A \times 100}{1+\frac{G_O}{A}} \le x$$

$$\text{or } \frac{1+\frac{G_O}{A}}{\frac{G_O}{A}} \ge \frac{100}{x} \Rightarrow \frac{A}{G_O} \ge \underbrace{\left(\frac{100}{x} - 1\right)}_{F}$$

$$\Rightarrow A \ge G_O F \text{ where } F = \frac{100}{x} - 1 \simeq \frac{100}{x}$$

x	0.01	0.1	1	10
F	10^4	10^3	10^2	10

Thus for:

$x = 0.01$:						
	G_O (V/V)	1	10	10^2	10^3	10^4
	A(V/V)	10^4	10^5	10^6	10^7	10^8

(10^7, 10^8: too high to be practical)

$x = 0.1$:						
	G_O (V/V)	1	10	10^2	10^3	10^4
	A(V/V)	10^3	10^4	10^5	10^6	10^7

$x = 1$:						
	G_O (V/V)	1	10	10^2	10^3	10^4
	A(V/V)	10^2	10^3	10^4	10^5	10^6

$x = 10$:						
	G_O (V/V)	1	10	10^2	10^3	10^4
	A(V/V)	10	10^2	10^3	10^4	10^5

2.50

for non-inverting amplifier

$$G = \frac{G_O}{1+\frac{G_O}{A}} \quad , \epsilon = \frac{G_O - G}{G_O} \times 100$$

for inverting amplifier

$$G = \frac{G_O}{1+\frac{1-G_O}{A}} \quad , \epsilon = \frac{G_O - G}{G_O} \times 100$$

case	G_O (V/V)	A(V/V)	G (V/V)	ϵ%
a	–1	10	–0.83	16
b	1	10	0.91	9
c	–1	100	–0.98	2
d	10	10	5	50
e	–10	100	–9	10
f	–10	1000	–9.89	1.1
g	+1	2	0.67	33

2.51 when potentiometer is set to the bottom:

$$v_O = v_+ = -15 + \frac{30 \times 20}{20+100+20} = -10.714 \text{ V}$$

when set to the top:

$$v_O = -15 + \frac{30 \times 20}{20+100+20} = 10.714 \text{ V}$$

$$\Rightarrow -10.714 \le v_O \le +10.714$$

pot has 20 turn, each turn:

$$\Delta v_O = \frac{2 \times 10.714}{20} = 1.07 \text{ V}$$

2.52

Notice that we have : $\frac{R_4}{R_3} = \frac{R_2}{R_1} = \frac{100}{10}$.

therefore

$$v_o = \frac{R_2}{R_1} v_{Id} \Rightarrow A = \frac{R_2}{R_1} = 10 \text{ V/V}$$

$$R_{id} = 2R_1 = 20\text{k}\Omega$$

If $\frac{R_2}{R_1}$, $\frac{R_4}{R_3}$ were different by 1% :

$$\frac{R_2}{R_1} = 0.99\frac{R_4}{R_3}$$

2.53

If we assume $R_3 = R_1$, $R_4 = R_2$, then

$$R_{id} = 2R_1 \Rightarrow R_1 = \frac{20}{2} = 10\text{ k}\Omega$$

a) $A_d = \frac{R_2}{R_1} = 1 \text{ V/V} \Rightarrow R_2 = 10\text{ k}\Omega$

$R_1 = R_2 = R_3 = R_4 = 10\text{ k}\Omega$

b) $A_d = \frac{R_2}{R_1} = 2 \text{ V/V} \Rightarrow R_2 = 20\text{ k}\Omega = R_4$

$R_1 = R_3 = 10\text{ k}\Omega$

c) $A_d = \frac{R_2}{R_1} = 100 \text{ V/V} \Rightarrow R_2 = 1\text{ M}\Omega = R_4$

$R_1 = R_3 = 10\text{ k}\Omega$

d) $A_d = \frac{R_2}{R_1} = 0.5 \text{ V/V} \Rightarrow R_2 = 5\text{ k}\Omega = R_4$

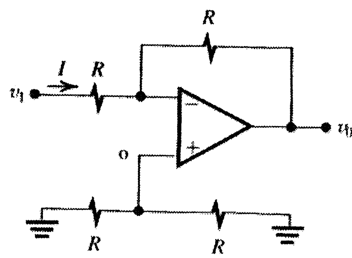
$R_1 = R_3 = 10\text{ k}\Omega$

2.54

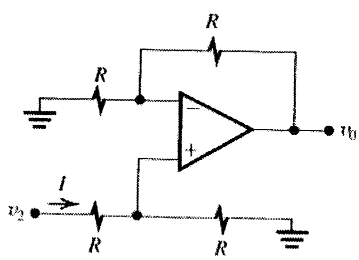
Considering that $v_- = v_+$:

$$v_1 + \frac{v_O - v_1}{2} = \frac{v_2}{2} \Rightarrow v_O = v_2 - v_1$$

v_1 only: $R_I = \frac{v_1}{I} = R$



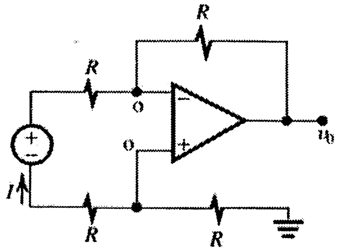
v_2 only: $R_I = \frac{v_2}{I} = 2R$



v_S between 2 terminals:

$$R_I = \frac{v}{I} = 2R$$

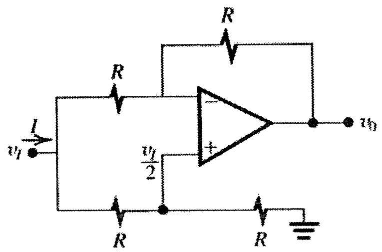
$$v_+ = v_- = 0$$



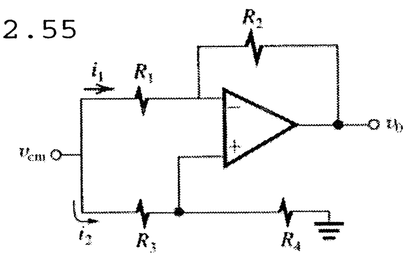
v_3 connected to both v_1 & v_2:

$$R_I = \frac{v}{I} = R$$

$$v_+ = v_- = \frac{v_I}{2}$$



2.55



$$v_+ = v_{cm}\frac{R_4}{R_3 + R_4}$$

$$v_+ = v_-$$

$$i_2 = \frac{v_{cm}}{R_3 + R_4}$$

$$i_1 = \frac{v_{cm}}{R_1} - \frac{v_{cm}}{R_3 + R_4}\frac{R_4}{} = \frac{1}{R_1} = \frac{v_{cm}}{R_1}\frac{R_3}{R_3 + R_4}$$

$$i = i_1 + i_2 = \frac{v_{cm}}{R_1}\frac{R_3}{R_3 + R_4} + \frac{v_{cm}}{R_3 + R_4}$$

if we replace $\frac{R_4}{R_3}$: with $\frac{R_2}{R_1}$: $\left(\frac{R_4}{R_3} = \frac{R_2}{R_1}\right)$

$$\frac{1}{R_I} = \frac{1}{R_1 + R_2} + \frac{1}{R_3 + R_4}$$

$$\Rightarrow R_5 = (R_1 + R_2) \parallel (R_3 + R_4)$$

2.56

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

The worst case is when A_{cm} has its maximum value.

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

Max A_{cm} $\Rightarrow$ $\frac{R_3}{R_4}$ has to be at its minimum value and also $\frac{R_2}{R_1}$ has to be minimum.

$$\frac{100-x}{100+x} \leq \frac{R_3}{R_4} \leq \frac{100+x}{100-x} \qquad \frac{100-x}{100+x} \leq \frac{R_2}{R_1} \leq \frac{100+x}{100-x}$$

so if $\frac{R_3}{R_4} = \frac{100-x}{100+x}$ & $\frac{R_2}{R_1} = \frac{100-x}{100+x}$

$$A_{cm\,Max} = \frac{1}{\frac{100-x}{100+x} + 1}\left(1 - \frac{100-x}{100+x}\frac{100-x}{100+x}\right)$$

$$A_{cm}Max = \frac{1}{200}\frac{(100+x)^2 - (100-x)^2}{100+x} = \frac{2x}{100+x} \simeq \frac{x}{50}$$

x	0.1	1	5
$A_{cm\,Max}$	0.002	0.02	0.1

$CMRR = 20\log\left|\frac{A_d}{A_{cm}}\right|$. Now we have to calculate A_d based on values we chose for $R_1 - R_4$ that gave us $A_{cm\,Max}$.

$R_2 = R_3 = 100 - x$ $\qquad$ $R_1 = R_4 = 100 + x$

$v_O = v_{O1} + v_{O2}$ by applying superposition

$$v_O = -\frac{R_2}{R_1}v_1 + v_2\frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)$$

$$v_O = -\frac{100-x}{100+x}v_1 + v_2\frac{100+x}{200}\left(1 + \frac{100-x}{100+x}\right)$$

$$v_O = -\frac{100-x}{100+x}v_1 + v_2$$

if we consider $\frac{100-x}{100+x} \simeq 1 \Rightarrow \frac{v_O}{v_{id}} \simeq 1$ $\qquad$ Cont.

$$CMRR = 20\log\frac{A_d}{A_{cm}} = 20\log\frac{1}{x/50} = 20\log\frac{50}{x}$$

x	0.1	1	5
CMRR	54db	34db	20db

2.57

$$A_{cm} = \frac{R_4}{R_3+R_4}\left(1-\frac{R_2R_3}{R_1R_4}\right)$$

In order to calculate A_d, we use Superposition principle:

$$v_O = v_{01} + v_{02} = \frac{-R_2}{R_1}v_1 + v_2\frac{R_4}{R_3+R_4}\left(1+\frac{R_2}{R_1}\right)$$

then replace $v_1 = v_{cm} - \frac{v_d}{2}$

$$v_2 = v_{cm} + \frac{v_d}{2}$$

$$v_O = -\frac{R_2}{R_1}v_{cm} + \frac{R_2}{R}v_{d/2} + v_{cm}$$

$$\frac{1+\frac{R_2}{R_1}}{1+\frac{R_3}{R_4}} + \frac{v_O}{2}\,\frac{1+R_2/R_1}{1+\frac{R_3}{R_4}}$$

$$v_O = \underbrace{\frac{R_2}{2R_1}\left[1+\frac{R_1/R_2+1}{R_3/R_4+1}\right]}_{Ad}v_d + \frac{R_2}{R_1}\left[-1+\frac{R_1/R_2+1}{R_3/R_4+1}\right]v_{cm}$$

$$CMRR = 20\log\left|\frac{A_d}{A_{cm}}\right| = 20\log\frac{\frac{R_2}{2R_1}\left[1+\frac{R_1/R_2+1}{R_3/R_4+1}\right]}{\frac{1}{\frac{R_3}{R_4}+1}\left(1-\frac{R_2R_3}{R_1R_4}\right)}$$

$$CMRR = 20\log\left|\frac{\frac{1}{2}\frac{R_2}{R_1}\left[2+\frac{R_1}{R_2}+R_3/R_4\right]}{1-\frac{R_2}{R_1}\cdot\frac{R_3}{R_4}}\right|$$

$$CMRR = 20\log\left|\frac{1+\frac{1}{2}\frac{R_1}{R_2}+\frac{1}{2}\frac{R_3}{R_4}}{\frac{R_1}{R_2}\cdot\frac{R_3}{R_4}}\right|$$

for worst case, minimum CMRR we have co maximize the denominator, which means:

$R_1 = R_{1n}(1+\epsilon)$ $\quad R_3 = R_{gn}(1-\epsilon)$

$R_2 = R_{2n}(1-\epsilon)$ $\quad R_4 = R_{gn}(1+\epsilon)$

also $\frac{R_{2n}}{R_{1n}} = \frac{R_{gn}}{R_{3n}} = K$

$$CMRR = 20\log\left|k\frac{1+\frac{1}{2}\frac{1}{K}\frac{1+\epsilon}{1-\epsilon}+\frac{1}{2}\frac{1}{K}\frac{1-\epsilon}{1+\epsilon}}{\frac{1+\epsilon}{1-\epsilon}-\frac{1-\epsilon}{1+\epsilon}}\right|$$

$$CMRR = 20\log\left|\frac{k(1-\epsilon^2)+(1+\epsilon^2)}{4\epsilon}\right| \simeq$$

$$20\log\left|\frac{k+1}{4\epsilon}\right|$$

for $\epsilon^2 \ll 1$.

if $k = A_{d\,ideal} = 100$, $\epsilon = 0.01$

$$CMRR = 20\log\frac{101}{0.04} = 68\text{ db}$$

2.58

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

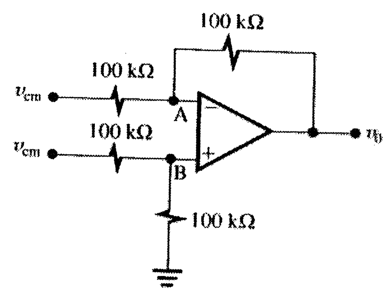
$$= \frac{100}{100+100}\left(1-\frac{100.100}{100.100}\right)$$

$A_{cm} = 0$

Refer to 2.17: $\frac{R_2}{R_1} = \frac{R_4}{R_3}$

$$\Rightarrow A_d = \frac{R_2}{R_1} = 1$$

b) Since $A_{cm} = 0$,



then if we apply V_{cm} to V_{I1} and V_{I2}, $v_o = 0$.

Therefore, $V_A = v_{cm}\frac{100}{100+100}$

$$V_A = \frac{v_{cm}}{2}$$

Similarly, $v_B = \frac{v_{cm}}{2}$

we know $V_A = V_B$ and $-2.5 \le v_A \le 2.5$

$\Rightarrow -5 \le v_{cm} \le 5$

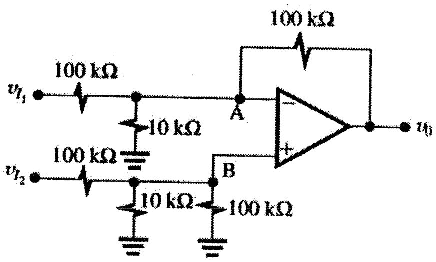
c) we aply the Superposition principle to calculate A_d.

v_{o1} is the output voltage when $v_{I2} = 0$

v_{o2} is the output voltage when $v_{I1} = 0$

$v_o = v_{o1} + v_{o2}$

$$v_{o1} = \frac{-R_2}{R_1} v_{I1} = -v_{I1}$$



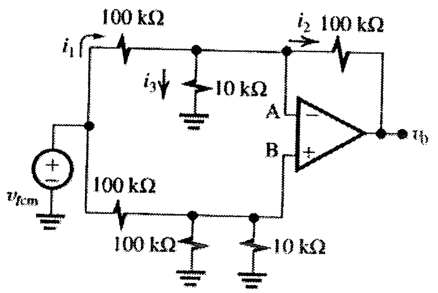
$$v_{o2} = v_{I2} \frac{100\text{ k}\Omega \parallel 10\text{ k}\Omega}{100\text{ k}\Omega \parallel 10\text{ k}\Omega + 100}$$

$$\left(1 + \frac{100\text{ k}\Omega}{100\text{ k}\Omega \parallel 10\text{ k}\Omega}\right)$$

$v_{o2} = v_{I2} \times 1$

$$\Rightarrow v_o = v_{o1} + v_{o2} = -v_{I1} + v_{I2} \Rightarrow A_d = 1$$

Now we calculate A_{cm}:



$$v_B = v_{ICM} \frac{100\text{ k}\Omega \parallel 10\text{ k}\Omega}{100\text{ k}\Omega \parallel 10\text{ k}\Omega + 100\text{ k}\Omega},\ v_A = v_B$$

$$i_1 = \frac{v_{ICM} - v_A}{100\text{ k}\Omega}$$

$v_o = v_A - 100\text{ k}\Omega \times i_2$ and

$$i_2 = i_1 - i_3 = i_1 - \frac{v_A}{10\text{ k}\Omega}$$

$v_o = v_A - 100\text{ k}\Omega \times i_1 + 10 \times v_A$

$v_o = v_A - v_{ICM} + v_A + 10 \times v_A$

$v_A = v_B \Rightarrow v_o$

$$= v_{ICM}\left(-1 + 12\frac{100\text{ k}\Omega \parallel 10\text{ k}\Omega}{(100\text{ k}\Omega \parallel 10\text{ k}\Omega) + 100\text{ k}\Omega}\right)$$

$$\frac{v_o}{v_{ICM}} = A_{cm} = 0$$

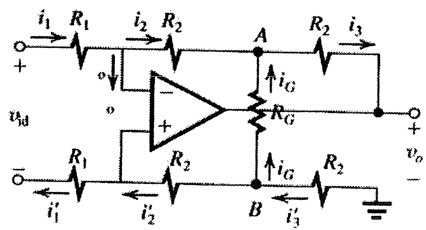
Now we calculate v_{ICM} range:

$-2.5 \le v_B \le 2.5 \Rightarrow$

$$-2.5 < v_{ICM} \times \frac{100\text{ k}\Omega \parallel 10\text{ k}\Omega}{(100\text{ k}\Omega \parallel 10\text{ k}\Omega) + 100\text{ k}\Omega} < 2.5$$

$-30\text{ V} \le v_{ICM} \le 30\text{ V}$

2.59



$v_+ = v_-$ so we can consider v_+, v_- a virtual short: $i_1 = v_{Id}/2R_1 \Rightarrow i_2 = \dfrac{v_{id}}{2R_1}$

$$i_1' = i_2' = \frac{v_{id}}{2R_1}$$

then:

$$i_2 R_2 + v_{AB} + i_2' R_2 = 0 \Rightarrow v_{AB} = \frac{-v_{id}}{R_1} R_2$$

$$i_G = \frac{v_{id}}{R_G} \times \frac{R_2}{R_1}$$

$$i_3 = i_2 + i_G = \frac{v_{id}}{2R_1} + \frac{v_{id}}{R_G}\frac{R_2}{R_1}$$

$$i_3' = i_G + i_2' = i_3$$

$$\Rightarrow v_o = -[i_3' R_2 + v_{BA} + i_3 R_2]$$

$$v_o = -[2i_3 R_2 + v_{BA}]$$

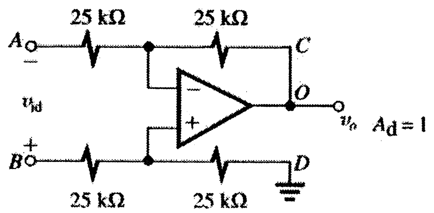
$$v_o = -\left[\frac{2v_{id}}{2R_1}R_2 + 2v_{id}\frac{R_2}{R_1}\frac{R_2}{R_G} + \frac{v_{id}}{R_1}R_2\right]$$

$$\frac{v_o}{v_{id}} = A_d = -2\frac{R_2}{R_1}\left[1 + \frac{R_2}{R_G}\right]$$

2.60

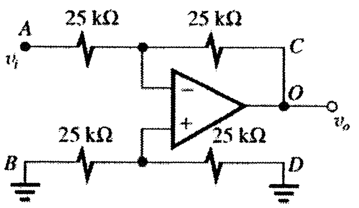
a) $A_d = \frac{R_2}{R_1} = 1$. Connect c and o together

a)

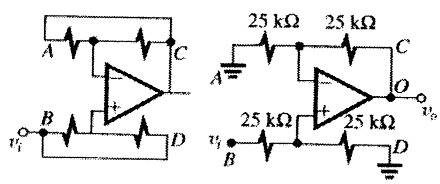


b) $\frac{v_o}{v_i} = -1$ V/V

i)

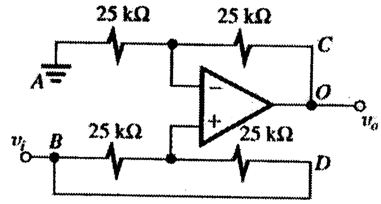


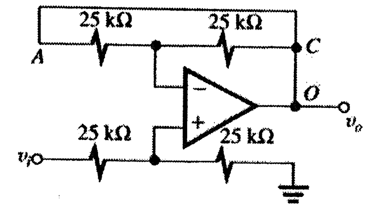
ii) $\frac{v_o}{v_i} = +1$ V/V



The circuit on the left ideally has infinite input resistance

iii) $\frac{v_o}{v_i} = +2$ V/V



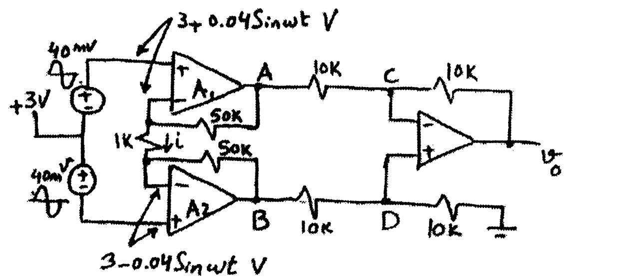


iv) $\frac{v_o}{v_i} = +\frac{1}{2}$ V/V

$$v_+ = \frac{v_i}{2} = v_o$$

$$\Rightarrow \frac{v_o}{v_i} = \frac{1}{2}$$

2.61



$$i = \frac{3 + 0.04\sin\omega t - (3 - 0.04\sin\omega t)}{1K} = 0.08\sin\omega t, \text{mA}$$

$$v_A = 3 + 0.04\sin\omega t + 50K \times i = 3 + 4.04\sin\omega t, \text{ V}$$

$$v_B = 3 - 0.04\sin\omega t - 50K \times i = 3 - 4.04\sin\omega t, \text{ V}$$

$$v_C = v_D = \frac{1}{2}v_B = 1.5 - 2.02\sin\omega t, \text{ V}$$

$$v_o = v_B - v_A = -8.08\sin\omega t, \text{ V}$$

2.62 a.

The gain of the first stage is: $\left(1+\frac{R_2}{R_1}\right)=101$ If the opamps of the first stage saturate at ± 14 V:

$-14\text{ V} \le v_1 \le +14\text{ V} \Rightarrow -14\text{ V} \le 101\ v_{icm} \le +14\text{ V}$

$\Rightarrow -0.14\text{ V} \le v_{icm} \le 0.14\text{ V}$

As explained in the text, the disadvantage of circuit in Fig. 2.20a is that v_{ICM} is amplified by a gain equal to $v_{icm}\left(1+\frac{R_2}{R_1}\right)$ in the first stage and therefore a very small v_{icm} range is acceptable to avoid saturation.

b) In Fig. 2.20b, when v_{icm} is applied, v_- for both A_1 & A_2 is the same and therefore no current flows through $2R_1$. This means voltage at the output of A_1 and A_2 is the same as v_{icm}.

$-14 \le v_o \le 14 \Rightarrow -14 \le v_{icm} \le 14$

This circuit allow for bigger range of v_{icm}.

2.63

$A_d=\frac{R_4}{R_3}\left(1+\frac{R_2}{R_1}\right)=\frac{100K}{100K}\left(1+\frac{100k}{5K}\right)=21\ V/V$

$A_{cm}=0$

$CMRR=20\log\left|\frac{A_d}{A_{cm}}\right|=\infty$

If all resistors are ±1% :

$A_d \simeq 21$

In order to calculate A_{cm}, apply V_{cm} to both inputs and note that V_{cm} will appear at both output terminals of the first stage. Now we can evaluate v_o by analyzing the second stage as was done in problem 2.65. In P2.65 we showed that if each 100K resistor has $\pm x\%$ tolerance, A_{cm} of the differential amplifier is: $A_{cm}=\frac{v_o}{v_{cm}}=\frac{x}{50}$. Therefore the overall A_{cm} is also $\frac{x}{50}$.

$x=1 \Rightarrow A_{cm}=\frac{1}{50}=0.02$

$CMRR=20\log\frac{21}{0.02}=\underline{60db}$

If $2R_1=1k\Omega$: $A_d=\frac{R_4}{R_3}\left(1+\frac{R_2}{R_1}\right)=201\ V/V$

$A_{cm}=0.02$ unchanged

$CMRR=20\log\frac{201}{0.02}=\underline{80db}$

Conclusion: Large CMRR can be achieved by having relatively large A_d in the first stage.

2.64

$A_{d(2)}$ of the second stage is $\frac{R_4}{R_3}=0.5$

$R_4=100\text{ k}\Omega, R_3=200\text{ k}\Omega$

we use a series configuration of R_{1F} and R_1 (Pot): $R_1=100\text{ k}\Omega$Pot (Fixed)

Minimum gain =

$$\left(1+\frac{R_2}{R_1}\right)=0.5\left(1+\frac{R_2}{\frac{100\text{ K}+R_1}{2}}\right)$$

$$1 \le A_d \le 100 \Rightarrow 1 = 0.5\left(1+\frac{2R_2}{R_{1F}+100\text{ k}\Omega}\right)$$

$$\Rightarrow R_{1F}+100 = 2R_2 \qquad (1)$$

$$\text{Maximum gain} = 100 = 0.5\left(1+\frac{R_2}{R_{1F}/2}\right) \Rightarrow$$

$$2R_2 = 199\ R_{1F} \qquad (2)$$

$$(1),(2) \Rightarrow R_{1F} = 0.505\text{ k}\Omega \simeq 0.5\text{ k}\Omega$$

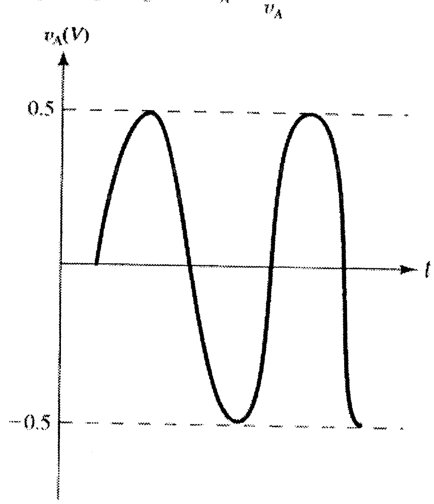
$$R_2 = 50.25\text{ k}\Omega \simeq 50\text{ k}\Omega$$

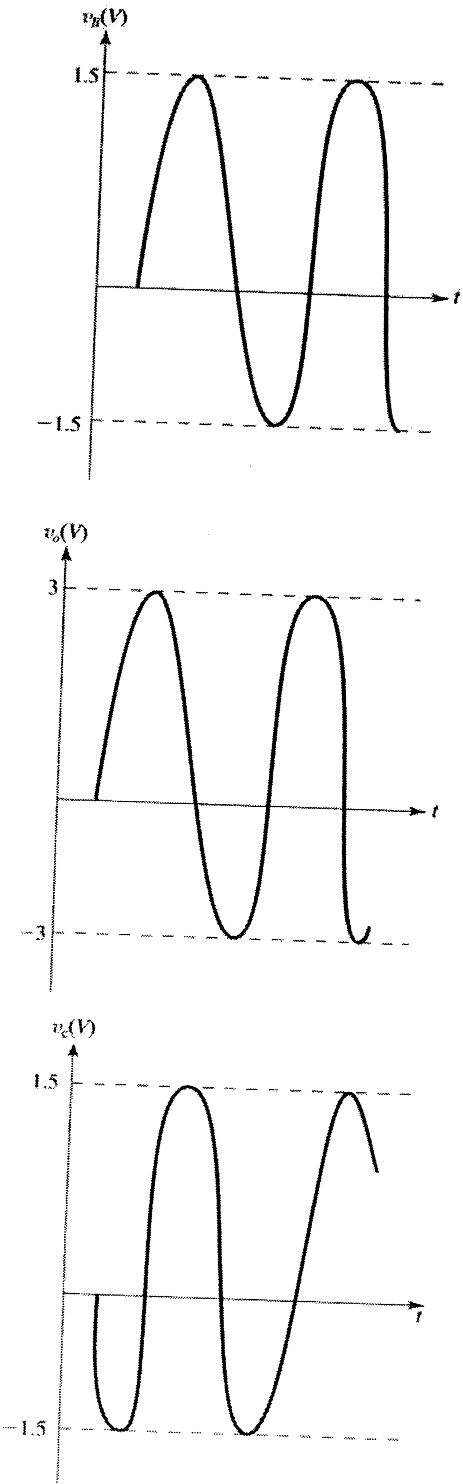
2.65

a) $\frac{v_B}{v_A}=1+\frac{20}{10}=3$ V/V,

$\frac{v_C}{v_A}=-\frac{30}{10}=-3$ V/V

b) $v_o=v_B-v_C=6V_A \Rightarrow \frac{v_o}{v_A}=6$ V/V

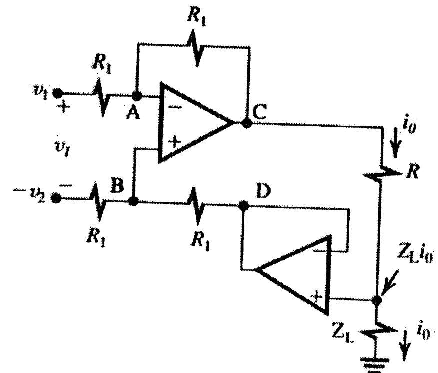




c) v_B and v_C can be ±14 V or 28 V P-P.
$-28 \le v_o \le 28$ or 56 VP-P.

$$v_{orms} = 19.8 \text{ V} = \frac{28}{\sqrt{2}}$$

2.66



Since the inputs of the op-amp do not draw any current, v_I appears across R_1

$$i_o = \frac{v_I}{R}$$

$v_D = Z_L i_o$

we use superposition:

$v_I = v_1 - v_2$

$$v_1 \text{ only: } V_B = \frac{V_O}{2} = \frac{z_L i_{o1}}{2}$$

$$\frac{v_1 - \frac{z_L i_{o1}}{2}}{R_1} = \frac{\frac{z_L i_{o1}}{2} - i_{o1}(z_L + R)}{R_1}$$

$$\Rightarrow v_1 = i_{o1} R \Rightarrow i_{o1} = \frac{v_1}{R}$$

Now if only $(-v_2)$ is applied:

$$v_B = \frac{-v_2 + z_L i_{o2}}{2}, \quad v_A = \frac{i_{o2} \times (R + z_L)}{2}$$

$$v_A = v_B \Rightarrow -v_2 + z_L i_{o2} = i_{o2} R + i_{o2} z_L$$

$$-v_2 = i_{o2} R \Rightarrow i_{o2} = \frac{-V_2}{R}$$

The total current due to both sources is:

$$i_o = i_{o1} + i_{o2} = \frac{v_1}{R} - \frac{v_2}{R} = \frac{v_I}{R}$$

The circuit has ideally infinite input resistance, and if requires that both terminals of Z_L be available, while the other circuit has finite input resistance with one side of Z_L grounded.

2.67

$$\frac{V_o}{V_i} = \frac{-1}{sCR} = \frac{-1}{j\omega CR} = \frac{1}{-j\omega \times 10\times10^{-9} \times 100\times10^{3}}$$

$$\frac{V_o}{V_i} = -\frac{10^3}{j\omega}$$

a) $\frac{V_o}{V_i} = 1 \Rightarrow \omega = 1\,\text{KRad/s} \Rightarrow f = 159\,\text{HZ}$

b) $\frac{1}{j}$ indicates $90°$ lag, but since its $\frac{-1}{j}$, it results in output leading the input by $90°$

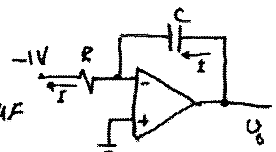
c) $\frac{V_o}{V_i} = \frac{-10^3}{j\omega}$ if frequency if lowered by a factor of 10, then the output would in crease by a factor of 10.

d) The phase doesnot change and the output still leads the input by $90°$

2.68

$R_{in} = R = 100K\Omega$

$CR = 1S \Rightarrow C = \frac{1}{100\times10^3} = 10\mu F$

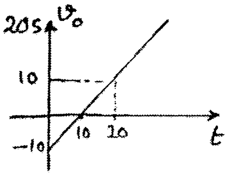


with a $-1V$ dc input applied, the capacitor charges with a constant current:

$I = \frac{1V}{R} = 0.01\,mA$ and its voltage rises linearly:

$$V_o(t) = -10 + \frac{1}{C}\int_0^t I\,dt = -10 + \frac{I}{C}t = -10 + \frac{t}{RC}$$

the voltage reaches $0V$ at $t = 10RC = 10s$ and it reaches $10V$ at $t = 20s$



2.69

$|T| = \frac{1}{\omega RC}$ if $|T| = 100$ V/V for $f = 1$ kHz, then for $|T| = 1$ V/V, f has to be 1 kHz × 100 = 100 kHz.

Also

$$RC = \frac{1}{\omega T} = \frac{1}{2\pi \times 1\text{ kHz} \times 100} = 1.59\ \mu s$$

2.70

$R_{in} = R$, Thus $R = 100$ kΩ.

$$|T| = \frac{1}{\omega RC} = 1 \text{ at } \omega = \frac{1}{RC}.$$

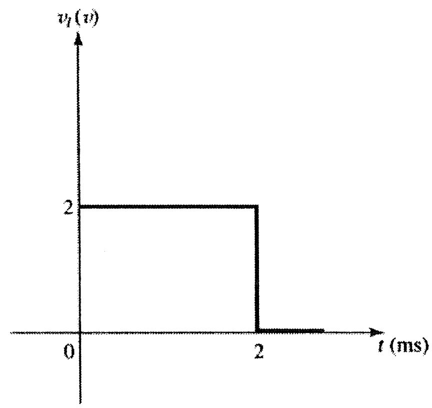
$$\omega = 1000\text{ rad/s} = \frac{1}{RC} \Rightarrow C = \frac{1}{1000 \times 100^2} = 10\text{mF}$$

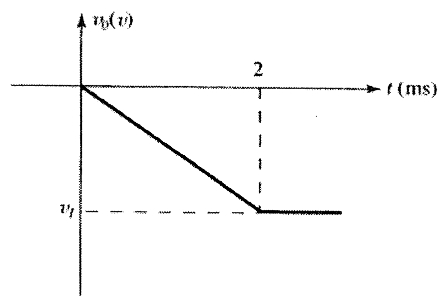
with a 2V-2ms pulse at the input, the output falls linearly until $t = 2$ms at which

$$v_o = v_I,\ v_o = \frac{-I}{C}t = \frac{-2}{RC}t = -2t \text{ Volts}$$

where t in ms

Thus $v_I = -4$ V





with $V_I = 2\sin 1000t$ applied at the input,

$$v_o(t) = 2 \times \frac{1}{1000 \times 10^{-3}} \sin(1000t + 90°)$$

$$v_o(t) = 2\sin(1000t + 90°)$$

2.71

$R_{in} = R = 20\ \text{k}\Omega$

$|T| = \dfrac{1}{\omega RC} = 1$ at

$\omega = 2\pi \times 10\ \text{kHz} \Rightarrow C = \dfrac{1}{2\pi \times 10\ \text{kHz} \times 20\ \text{K}}$

$C = 0.796\ \text{nF}$

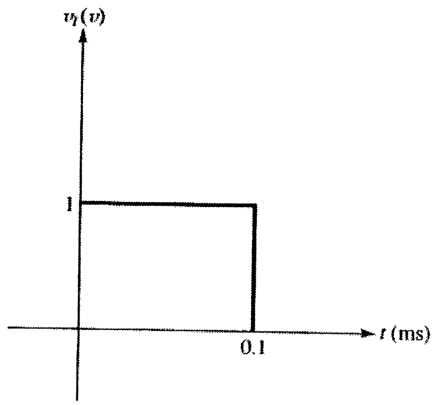
$\dfrac{v_o}{v_i} = \dfrac{R_F/R}{1 + S\,CR_F}$ and the finite dc gain is $\dfrac{-R_F}{R}$.

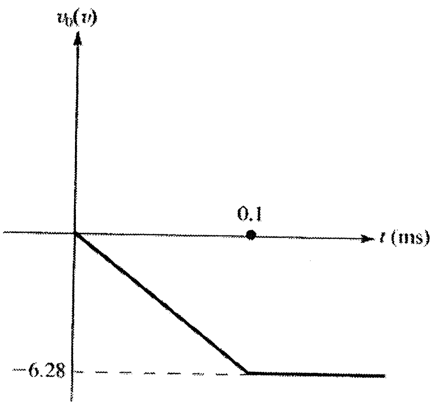
There fore for 40db gain or equivalently 100 V/V we have: $\dfrac{-R_F}{R} = -100$ V/V

$\Rightarrow R_F = 100 \times 20\ \text{k} = 2\ \text{M}\Omega$

The corner frequency $\dfrac{1}{C\ \ /R_F}$ is:

$\dfrac{1}{0.796\text{m} \times 2\text{M}} = 628\ \text{Hz}$





a) when no R_F

$v_o(t) = \dfrac{-1}{RC}\displaystyle\int_0^t 1.\text{dt} = -62.8t \quad 0 \le t \le 0.1\ \text{ms}$

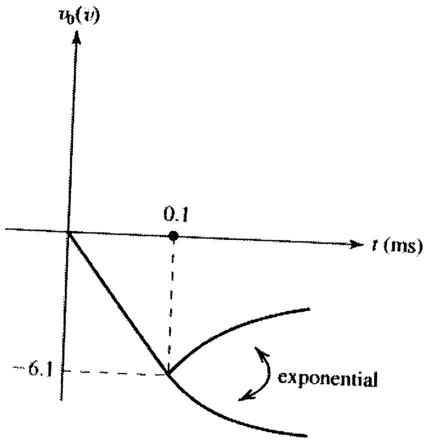
$v_o(0.1) = -6.28\ \text{V}$

b) with R_F: $v_o(t) = v_o(\infty)(i - e^{-t/CR_F})$

(Refer to pg. 112)

$v_o(\infty) = -1 \times R_F = -\dfrac{1\ \text{V}}{20\ \text{K}} \times 2\ \text{M} = -100\ \text{V}$

$v_o(t) = -100(1 - e^{-t/1.5})$

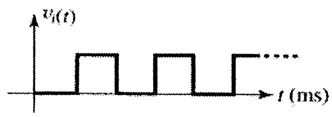


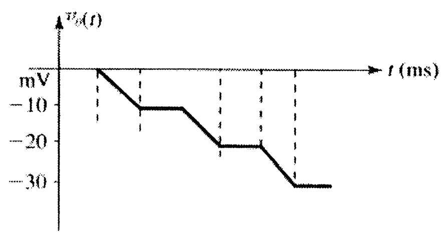
2.72

Each pulse lowers the output voltage by:

$\Delta v_o = \dfrac{1}{RC}\displaystyle\int_0^{10\text{ms}} 1.\text{dt} = \dfrac{10\ \mu\text{s}}{RC} = \dfrac{10\ \mu\text{s}}{1\ \text{ms}} = 10\ \text{mV}$

Therefore a total of 100 pulses are required to cause a change of 1 V in $v_o(t)$.

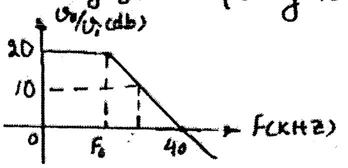




2.73

$$\frac{V_o}{V_i} = -\frac{Z_2}{Z_1} = -\frac{Y_1}{Y_2} = -\frac{1/R_1}{1/R_2 + SC} = -\frac{R_2/R_1}{1+SCR_2}$$

which is an STC LP circuit with a dc gain of $-\frac{R_2}{R_1}$ and a 3-db frequency $\omega_0 = \frac{1}{CR_2}$.
The input resistance equal to R_1. So for:
$R_i = 1K \Rightarrow R_1 = 1K\Omega$ and for dc gain of 20db or 10 : $\frac{R_2}{R_1} = 10 \Rightarrow R_2 = 10\ K\Omega$
for 3db frequency of 4KHZ: $\omega_0 = 2\pi \times 4 \times 10^3 = \frac{1}{CR_2}$
$\Rightarrow C \approx 4nF$
the unity gain frequency is (odb) is 40 KHZ



2.74

$$\frac{v_O}{v_i}(s) = -sRC = -s \times 0.01 \times 10^{-6} \times 10 \times 10^3$$

$$= -10^{-4}s$$

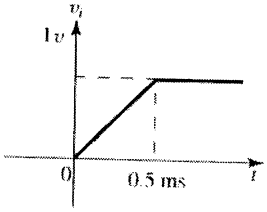
$$\frac{v_O}{v_i}(jw) = -jw \times 10^{-4} \Rightarrow \left|\frac{v_O}{v_i}\right| = -w \times 10^{-4}$$

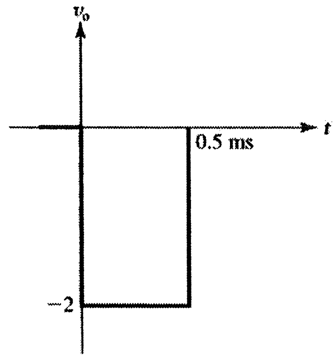
$$\Rightarrow \left|\frac{v_O}{v_i}\right| = 1 \text{ when } w = 10^4 \text{rad/s}$$

or $f = 1.59$ kHz
for an input 10 times this frequency, the output will be 10 times as large as the input: 10V peak-to-peak. The (-j) indicates that the output lags the input by 90°. Thus

$$v_O(t) = -5 \sin(10^5 t + 90°) \text{ Volts}$$

2.75





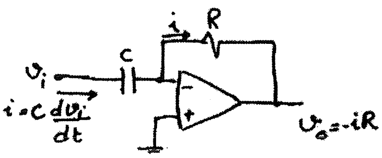
$$v_O = -CR\frac{dv_i}{dt}$$

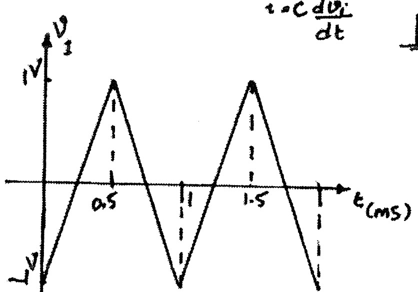
therefore:
For $0 \le t \le 0.5$:

$$v_O = -1\text{ms} \times \frac{1\text{ V}}{0.5\text{ ms}} = -2\text{ V}$$

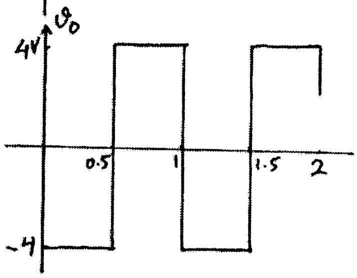
and $v_O = 0$ otherwise

2.76





$\text{Slope} = \frac{2V}{0.5ms} = 4\ V/ms$



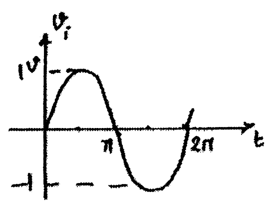
$$C\frac{dV_i}{dt} = 0.1 \times 10^{-6} \times \frac{4}{10^{-3}} = 0.4mA$$

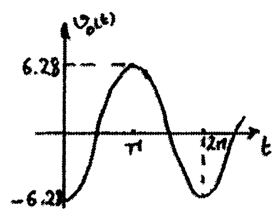
Thus the peak value of the output square wave is $0.4\,mA \times 10\,k\Omega = 4V$. The frequency of the output is the same as the input (1KHz).
The average value of the output is 0.
To increase the value of the output to 10V, R has to be increased to $\frac{10}{4} = 2.5$, i.e $25^{k\Omega}$.

When a 1-KHz, 1V peak input sine wave is applied
$v_i = \sin(2\pi \times 1000\,t)$
a sinusoidal signal appears at the output.
It can be determined by one of the following methods.

a) $v_O(t) = -RC\frac{dv_i}{dt} = -0.1 \times 10^{-6} \times 10 \times 10^{3}\frac{dv_i}{dt} = -10^{-3}\frac{dv_i}{dt}$
$v_O(t) = -10^{-3} \times 2\pi \times 1000 \times \cos(2\pi \times 1000\,t)$
$v_O(t) = -2\pi\cos(2\pi \times 1000\,t)$

Thus the peak amplitude is 6.28V and the negative peaks occur at $t = 0, \frac{2\pi}{2\pi \times 1000}, \ldots$





b) $\frac{v_o}{v_i} = -sRC \Rightarrow \frac{v_o}{v_i}(j\omega) = -j\omega RC \Rightarrow v_o(t) = -j\omega RC\, v_i(t)$

the output is inverted and has 90° phase shift, due to (−j) factor.
$v_o(t) = -(\omega RC) \times 1\,\sin(2\pi \times 1000t + 90^\circ)$
$v_o(t) = -6.28\,\sin(2\pi \times 1000t + 90^\circ)$
$v_o(t) = -6.28\,\cos(2\pi \times 1000\,t)$
Same as before.

c) The peaks of the output waveform are equal to RC×(maximum slope of input wave). Since the maximum slope occurs at the zero crossings, its value is $2\pi \times 1000$. Thus the peak output $= 2\pi \times 1000 \times RC = 6.28V$
The negative peak occurs at $\omega t = 0, 2\pi, \ldots$

2.77

$RC = 10^{-3}$s when
$C = 10\text{mF} \Rightarrow R = 100\text{ k}\Omega$

$$\frac{v_O}{v_i} = -\text{sRC},\ \frac{v_O}{v_i}(jw) = -jwRC$$

$\varphi = -90°$ always

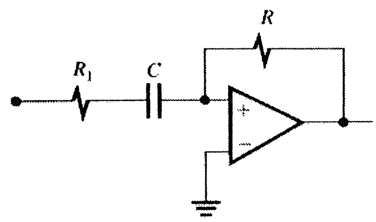
$$\left|\frac{v_O}{v_i}\right| = 1 \Rightarrow w = \frac{1}{\text{unity }RC} = 1\text{krad/s}$$

Gain is 10 times the unity gain, when = the frequency is 10 times the unity gain frequency. Similarly for $w = \frac{1}{10}$ krad/s, gain is 0.1 V/V. (for $w = 10$ krad/s, gain = 10 V/V)
for high frequency C is short circuited,

$$\frac{v_O}{v_i} = \frac{-R}{R_1} = -100 \Rightarrow R_1 = 1\text{ k}\Omega$$

$$\frac{v_O}{v_i} = \frac{-RCs}{R_1Cs + 1} = \frac{-10^{-3}s}{10^{-5}s + 1}$$

$\Rightarrow w_{3db} = 100$ krad/s or
$f_{3db} = 15.9$ kHz



for unity gain:
$|10^{-3}s| = |10^{-5}s + 1| \Rightarrow w_H = 1.01$ krad/s

if $w = 10.1$krad/s: $\left|\frac{v_O}{v_i}\right| = \frac{10.1}{1.01} = 10,$

$\varphi = -95.77°$

2.78

$\frac{v_o}{v_i} = -\frac{Z_2}{Z_1} = \frac{-R_2}{R_1 + \frac{1}{sC}} = \frac{-\left(\frac{R_2}{R_1}\right)s}{s + \frac{1}{R_1 C}}$ which is the

transfer function of an STC HP filter with a high frequency gain $K = -\frac{R_2}{R_1}$ and a 3-db frequency $\omega_0 = \frac{1}{R_1 C}$

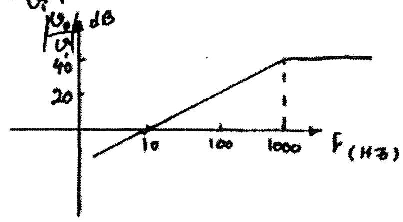
The high-frequency input impedance approaches R_1. (as $\frac{1}{j\omega C}$ becomes negligibly small) So we can select $R_1 = 10k\Omega$

To Obtain a high-frequency gain of 40db (i.e. 100) : $\frac{R_2}{R_1} = 100 \Rightarrow R_2 = 1M\Omega$.

For a 3-db frequency of 1000 Hz:

$\frac{1}{R_1 C} = 2\pi \times 1000 \Rightarrow C = 15.9nF$

from the Bode-diagram below, we see that $\left|\frac{v_o}{v_i}\right|$ reduces to unity at $f = 0.01 f_0 = 10 Hz$



2.79

$$\frac{v_O}{v_i} = -\frac{Z_2}{Z_1} = -\frac{1}{Z_1 Y_2} = -\frac{1}{\left(R_1 + \frac{1}{sC_1}\right)\left(\frac{1}{R_2} + sC_2\right)}$$

$$\frac{v_O}{v_i} = -\frac{R_2 / R_1}{\left(1 + \frac{1}{R_1 C_1 s}\right)(1 + sR_2C_2)}$$

$$\frac{v_O}{v_i}(jw) = \frac{-R_2/R_1}{\left(1 + \frac{1}{jwR_1C_1}\right)(1 + jwR_2C_2)}$$

$$= \frac{-R_2/R_1}{\left(1 + \frac{w_1}{jw}\right)\left(1 + j\frac{w}{w_2}\right)}$$

where $w_1 = \frac{1}{R_1C_1}$, $w_2 = \frac{1}{R_2C_2}$

a) for $w = w_1 << w_2$

$$\frac{v_O}{v_i}(jw) \simeq \frac{-R_2/R_1}{\left(1 + \frac{w}{jw}\right)} \simeq \frac{-R_2R_1}{w_1/jw} \simeq -j\frac{R_2}{R_1}\frac{w}{w_1}$$

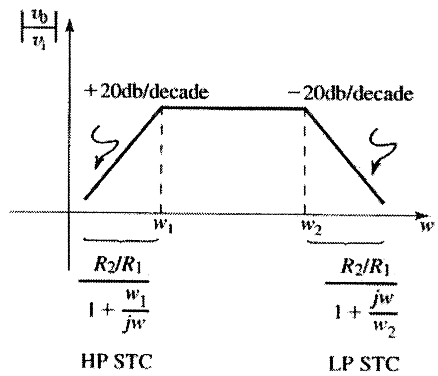
b) for $w_1 << w << w_2$

$$\frac{v_O}{v_i}(jw) \simeq -\frac{R_2}{R_1}$$

c) for $w >> w_2$ and $w_2 >> w_1$:

$$\frac{v_O}{v_i}(jw) \simeq \frac{-R_2R_1}{1 + jw/w_2} \simeq \frac{-R_2R_1}{jw/w_2} = j\left(\frac{R_2}{R_1}\right)\left(\frac{w_2}{w}\right)$$

from the results of a), b) and c) we can draw the Bode-plot:



Design: $\frac{R_2}{R_1} = 1000$ (60 dB gain in the mid-frequency range)

R_{in} for $w >> w_1$

$= R_1 = 1\ k\Omega \Rightarrow R_2 = 1\ M\Omega$

$f_1 = 100\ Hz \Rightarrow w_1 = 2\pi \times 100 = \frac{1}{R_1C_1}$

$\Rightarrow C_1 = 1.59\ \mu F$

$f_2 = 10\ Hz \Rightarrow w_2 = 2\pi \times 10 \times 10^3 = \frac{1}{R_1C_1}$

$\Rightarrow C_2 = 15.9\ pF$

2.80

$v_{OS} = \pm 2\text{ mV}$

$v_O = 0.01\sin\omega t \times 200 + v_{OS} \times 200$

$= 2\sin\omega t \pm 0.4\text{ V}$

2.81

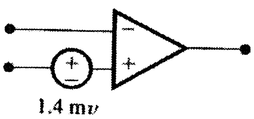
Output DC offset, $v_{OS} = 3\text{mV} \times 1000 = 3\text{V}$

Therefore the maximum amplitude of an input sinusoid is the one that results in an output peak amplitude of $13 - 3 = 10\text{V} \Rightarrow v_i = \frac{10}{1000} = 10\text{ mV}$

If the amplifier is capacity coupled, then:

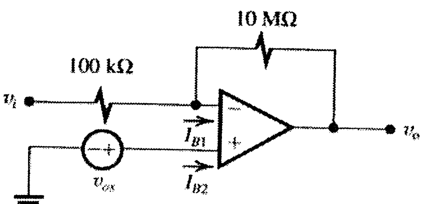
$v_{i\,max} = \frac{13}{1000} = 13\text{mV}$

2.82



$$v_{OS} = \frac{1.4}{100} = 1.4\text{ mV}$$

2.83



a) $I_B = (I_{B1} + I_{B2})/2$

open input:

$v_O = v_+ + R_2 I_{B1} = v_{OS} + R_2 I_{B1}$

$9.31 = v_{OS} + 10000 I_{B1}$ (1)

input connected to ground:

$$v_O = v_+ + R_2\left(I_{B1} + \frac{v_{OS}}{R_1}\right)$$

$$= v_{OS}\left(1 + \frac{R_2}{R_1} + R_2 I_{B1}\right)$$

$9.09 = v_{OS} \times 101 + 10000\, I_{B1}$ (2)

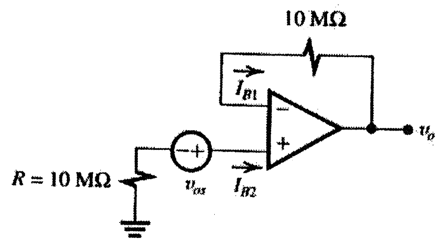
(1), (2)

$\Rightarrow 100 v_{OS} = -0.22 \Rightarrow v_{OS} = -2.2\text{ mV}$

$\Rightarrow I_{B1} = 930\text{ nA}$

$I_B \simeq I_{B1} = 930\text{ nA}$

b) $v_{OS} = -2.2\text{ mV}$



c) In this case, Since R is too large, we may ignore v_{OS} compare to the voltage drop across R. $v_{OS} << RI_B$, Also Eq 2.46 holds:

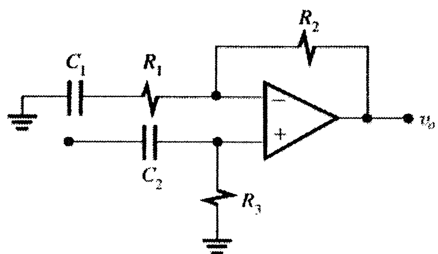
$R_3 = R_1 \| R_2$

therefore from Eq. 2.47:

$v_O = I_{OS} \times R_2 \Rightarrow I_{OS} = \frac{0.8}{10\text{ M}\Omega}$

$I_{OS} = -80\text{ nA}$

2.84



$R_2 = R_3 = 100\text{ k}\Omega$

$1 + \frac{R_2}{R_1} = 200$

$R_1 = \frac{100\text{ k}}{199} = 502\ \Omega$

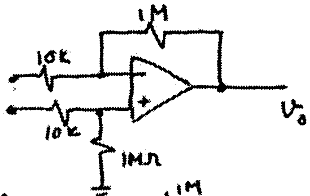
$\frac{1}{R_1 C_1} = 2\pi \times 100 \Rightarrow C_1 = \frac{1}{500 \times 2\pi \times 100}$

$= 3.18\ \mu\text{F}$

$\frac{1}{R_3 C_2} = 2\pi \times 10 \Rightarrow C_2 = \frac{1}{100\text{ K} \times 2\pi \times 100}$

$= 0.16\ \mu\text{F}$

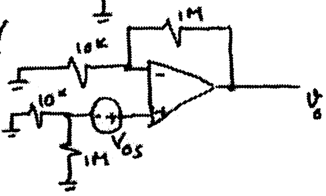
2.85



The output component due to V_{OS} is :

$V_{O1} = V_{OS}(1 + \frac{1M}{10K})$

$V_{O1} = 4(1+100) = 404mV$



The output component due to I_B or input bias current is :

$I_{B_1} = I_B + \frac{I_{OS}}{2}$, $I_{B2} = I_B - \frac{I_{OS}}{2}$

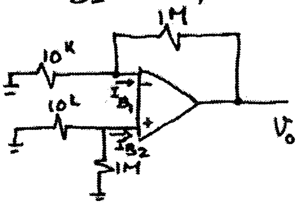
$I_{B_1} = 0.3 + \frac{0.05}{2} = 0.325\mu A$ $\quad I_{B2} = 0.275\,\mu A$

$V_+ = -I_{B_2} \times (10^K \| 1M)$

$V_+ = -2.72mV$

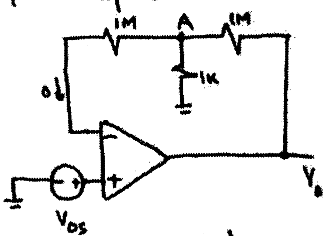
$V_{O2} = V_+ + (1^M \times (I_{B_1} + \frac{V_+}{10k}))$

$V_{O2} = 50mV$



The worst case (largest) DC offset voltage at the output is $404 + 50 = 454mV$

for capacitively coupled input:



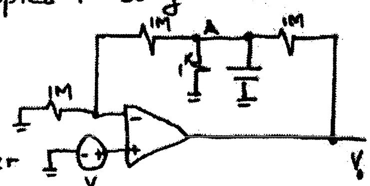
$V_+ = V_- = V_{OS}$

$V_A = V_{OS}$

$V_O = V_A + 1M \times \frac{V_{OS}}{1K}$

$V_O = 1001\,V_{OS} = \pm 4.004V$

for capacitively coupled 1K to ground:



$V_+ = V_- = V_{OS}$

$V_A = 2V_{OS}$

$V_O = 3V_{OS} = \pm 12mV$

This is much smaller than capacitvely coupled input case.

2.87

At 0°C, we expect

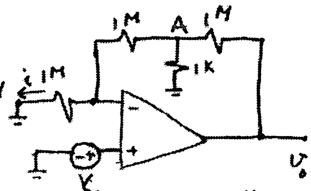
$\pm 10 \times 25 \times 1000\ \mu = \pm 250\ \text{mV}$

At 75°C, we expect

$\pm 10 \times 50 \times 1000\ \mu = \pm 500\ \text{mV}$

We expect these quantities to have opposite polarities.

2.86



$V_- = V_+ = V_{OS} \Rightarrow V_A = 2V_{OS} = 8mV$

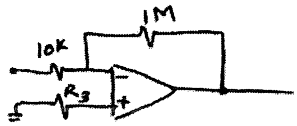
$i = \frac{V_{OS}}{1M} = V_{OS}\ (\mu A)$

$V_O = V_A + 1M \times (i + \frac{V_A}{1K})$

$V_O = 2V_{OS} + 1M\,(\frac{V_{OS}}{1M} + \frac{2V_{OS}}{1K}) = 2003\,V_{OS} = 2003 \times 4^{mV} = 8V$

$V_O = 8V$

2.88

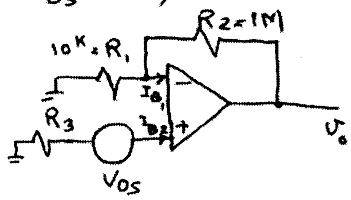


$R_3 = R_1 \| R_2 = 9.9K\Omega$

(Refer to 2.46)

$V_O = I_{OS} R_2$ $\quad$ Eq. 2.47

$V_O = 0.21 = I_{OS} \times 1^M \Rightarrow I_{OS} = 0.21\,\mu A$



If $V_{OS} = 1mV$

$V_+ = -I_{B2} R_3 \mp V_{OS}$

$$I_{B_1} = \frac{R_3 I_{B_2} \pm V_{os}}{R_1} + \frac{0.21 + R_3 I_{B_2} \pm V_{os}}{R_2}$$

$$I_{B_1} = R_3 I_{B_2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \pm V_{os}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

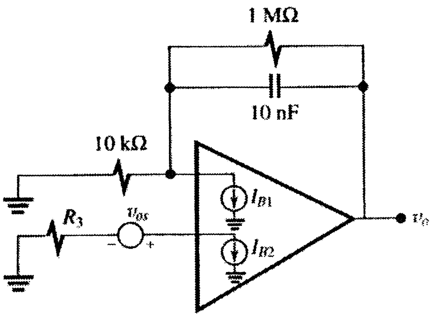
$$\frac{1}{R_3} = \frac{1}{R_1} + \frac{1}{R_2} \Rightarrow I_{B_1} - I_{B_2} = \pm V_{os}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\Rightarrow I_{os} = \pm\frac{1\,mV}{9.9K} = \pm 0.1\,\mu A$$

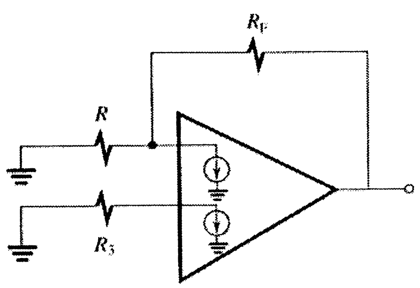
If we apply the same current as I_{os} to the other end of R_3, then it will cancel out the offset current effect on the output. $\pm 0.1 \mu A$

2.89

a) To compensate for the effect of dc bias current I_B, we can consider the following model



$R_3 = R \| R_F = 10\,k\Omega \| 1\,M\Omega \Rightarrow R_3 = 9.9\,k\Omega$



b) the dc output voltage of the integrator when the input is grounded is: $V_O = V_{OS}\left(1 + \frac{R_F}{R}\right) + I_{OS}R_F$

$$V_O = 3\,mV\left(1 + \frac{1\,M\Omega}{10\,k\Omega}\right) + 10\,nA \times 1\,M\Omega$$

$= 0.303\,V + 0.01\,V$

$V_O = 0.313\,V$

2.90

$w_t = A_O w_b$

$\Rightarrow f_t = A_O f_b$

A_O	f_b(Hz)	f_t(Hz)
10^5	10^2	10^7
10^6	1	10^6
10^5	10^3	10^8
10^7	10^{-1}	10^6
2×10^5	10	2×10^6

2.91 $A = \frac{A_o}{1 + j\,\omega/\omega_b} \Rightarrow |A| = \frac{|A_o|}{\sqrt{1 + \left(\frac{f}{f_b}\right)^2}}$

$A_o = 86\,db$, $A = 40\,db$ @ $f = 100\,KHz$

$$20\log\sqrt{1 + \left(\frac{f}{f_b}\right)^2} = 20\log\frac{|A_o|}{|A|} = 20\log A_o - 20\log A$$

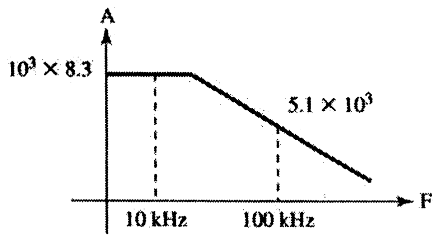
$= 86 - 40 = 46\,db$

$1 + \left(\frac{100\,KHz}{f_b}\right)^2 = (199.5)^2 \Rightarrow f_b = 0.501\,KHZ$

$f_b = 501\,HZ$

$f_t = A_o f_b = \underbrace{1.995 \times 10^4}_{86db} \times 501 = 9.998\,MHZ \simeq 10\,MHZ$

2.92



$A_O = 8.3 \times 10^3$ V/V

Eq. 2.25: $A = \dfrac{A_O}{1 + j\dfrac{f}{f_b}}$

$f_t = A_O f_b$

$5.1 \times 10^3 = \dfrac{8.3 \times 10^3}{\sqrt{1 + \left(\dfrac{100\text{ kH}}{f_b}\right)^2}} \Rightarrow 1 + \left(\dfrac{100\text{ kHz}}{f_b}\right)^2$

$= 2.65$

$f_b = 60.7$ kHz

$f_t = A_O f_b = 8.3 \times 10^3 \times 60.7\text{kHz} = 503$ MHz

2.93

we have:

$A_O(\text{db}) = 20\text{ dB} + \text{A(db)}$

$20\text{ db} = 20\log 10 \Rightarrow A_O = 10\text{A}$

a) $A_O = 10 \times 3 \times 10^5 = 3 \times 10^6$ Hz V/V

$\text{A} = \dfrac{A_O}{1 + jf/f_b} \Rightarrow \left|1 + j\dfrac{f}{f_b}\right| = \dfrac{A_O}{A} = 10 \Rightarrow$

$\dfrac{6 \times 10^2}{f_b} = \sqrt{99}$

$\Rightarrow f_b = 60.3$ Hz

$f_t = A_O f_b = 3 \times 10^6 \times 60.3 = 180.9$ MHz

b)

$A = 50 \times 10^5 \times 10\text{ V/V} \Rightarrow A_O = 10 \times 50 \times 10^5$

$= 50 \times 10^6$ V/V

$\left|1 + \dfrac{jf}{f_b}\right| = \dfrac{A_O}{\text{A}} = 10 \Rightarrow \dfrac{10\text{ Hz}}{f_b} = \sqrt{99} \Rightarrow f_b = 1\text{ Hz}$

$f_t = A_O f_b = 50$ MHz

c) $A = 1500\text{ V/V} \Rightarrow A_O = 1500$ V/V

$\left|1 + \dfrac{jf}{f_b}\right| = 10 \Rightarrow \dfrac{0.1 \times 10^9}{f_b} = \sqrt{99} \Rightarrow f_b = 10\text{ kHz}$

$f_b = 15000 \times 10\text{ K} = 150$ MHz

d) $A_O = 10 \times 100 = 1000$ V/V

$\left|1 + \dfrac{jf}{f_b}\right| = 10 \Rightarrow \dfrac{0.1 \times 10^9}{f_b} = \sqrt{99} \Rightarrow f_b = 10\text{ MHz}$

$f_t = 1000 \times 10\text{ MHz} = 10$ GHz

e) $A = 25\text{ V/mV} \times 10 = 25 \times 10^4$ V/V

$\left|1 + \dfrac{jf}{f_b}\right| = 10 \Rightarrow \dfrac{2.5\text{ kHz}}{f_b} = \sqrt{99} \Rightarrow f_b = 2.51\text{ kHz}$

$f_t = A_O f_b = 25 \times 10^4 \times 2.51 \times 10^3 = 627.5$ MHz

2.95

$G_{\text{Nom}} = -\dfrac{R_2}{R_1} = -20 \quad A_O = 10^4$ V/V

$f_t = 10^6$ Hz

$w_{3\text{db}} = \dfrac{w_t}{1 + R_2 R_1} = \dfrac{2\pi \times 10^6}{1 + 20}$

$= 2\pi \times 47.6$ kHz

$f_{3\text{db}} = 47.6$ kHz

$\dfrac{v_O}{v_i} \simeq \dfrac{-R_2/R_1}{1 + \dfrac{s}{w_t\left(1 + \dfrac{R_2}{R_1}\right)}} = \dfrac{-20}{1 + \dfrac{215}{2\pi \times 10^6}}$

$f = 0.1 f_{3\text{db}} \Rightarrow \left|\dfrac{v_O}{v_i}\right| = \dfrac{-20}{\sqrt{1 + (0.1)^2}} = 19.9$ V/V

$f = 10 f_{3\text{db}} \Rightarrow \left|\dfrac{v_O}{v_i}\right| = \dfrac{-20}{\sqrt{1 + 100}} = 19.9$ V/V

2.96

$1 + \dfrac{R_2}{R_1} = 100\text{ V/V}, \quad f_t = 20\text{ MHZ}$

$f_{3db} = \dfrac{f_t}{1 + \dfrac{R_2}{R_1}} = 200\text{ KHZ}$

$G(jw) = \dfrac{100}{1 + j\,f/f_{3db}} \Rightarrow \varphi = -\tan^{-1}\dfrac{f}{f_{3db}} =$

$\varphi = -6° \Rightarrow f = f_{3db} \times \tan 6° = 21\text{ KHZ}$

$\varphi = -84° \Rightarrow f = f_{3db} \times \tan 84° = 1.9\text{ MHZ}$

2.96

a) $\frac{R_2}{R_1} = -100$ V/V , $f_{3db} = 100$ kHz

$w_t = w_{3db}\left(1 + \frac{R_2}{R_1}\right) \Rightarrow f_t = 100\text{ k} \times 101 = 10.1$ MHz

b) $1 + \frac{R_2}{R_1} = 100$ V/V, $f_{3db} = 100$ kHz

$f_t = f_{3db}\left(1 + \frac{R_2}{R_1}\right) = 10$ MHz

c) $1 + \frac{R_2}{R_1} = 2$ V/V, $f_{3db} = 10$ kHz

$f_t = 10\text{ MHz} \times 2 = 20$ MHz

d) $-\frac{R_2}{R_1} = -2$ V/V, $f_{3db} = 10$ kHz

$f_t = 10\text{ MHz}(1 + 2) = 30$ MHz

e) $-\frac{R_2}{R_1} = -1000$ V/V, $f_{3db} = 20$ kHz

$f_t = 20\text{ kHz}(1 + 100) = 20.02$ MHz

f) $1 + \frac{R_2}{R_1} = 1$ V/V, $f_{3db} = 1$ MHz

$f_t = 1\text{M} \times 1 = 1$MHz

g) $-\frac{R_2}{R_1} = -1$, $f_{3db} = 1$ MHz

$f_t = 1\text{ M}(1 + 1) = 2$ MHz

2.97

$1 + \frac{R_2}{R_1} = 100$ V/V $\quad f_{3db} = 8$ kHz

$f_t = 8 \times 100 = 800$ kHz

for $f_{3db} = 20$ kHz : $G_o = \frac{800}{20} = 40$ V/V

2.98

$f_{3db} = f_t = 1$ MHz

$$|G| = \frac{1}{\sqrt{1 + \left(\frac{f}{f_{3db}}\right)^2}} = \frac{1}{\sqrt{1 + f^2}} \quad f_{in}\text{ MHz}$$

$|G| = 0.99 \Rightarrow f = 0.142$ MHz

The follower behaves like a low-pass STC circuit with a time constant $\tau = \frac{1}{2\pi \times 10^6} = \frac{1}{2\pi}$ µs

$t_r = 2.2\tau = 0.35$ µs (Refer to Appendix F)

2.99

a) Assume two identical stages, each with a gain function: $G = \frac{G_O}{1 + j\frac{w}{w_1}} = \frac{G_O}{1 + jf/f_1}$

$$G = \frac{G_O}{\sqrt{1 + \left(\frac{f}{f_1}\right)^2}}$$

overall gain of the cascade is $\frac{G_O^2}{\sqrt{1 + \left(\frac{f}{f_1}\right)^2}}$

The gain will drop by 3db when:

$1 + \left(\frac{f_{3db}}{f_1}\right)^2 = \sqrt{2}$, Note $3\text{db} = 20\log\sqrt{2}$

$f_{3db} = F_1\sqrt{\sqrt{2} - 1}$

b) 40 db = 20 log $G_O \Rightarrow G_O = 100 = 1 + \frac{R_2}{R_1}$

$$f_{3db} = \frac{f_t}{1 + \frac{R_2}{R_1}} = \frac{1\text{ MHz}}{100} = 10\text{ kHz}$$

c) Each stage should have 20db gain or

$1 + \frac{R_2}{R_1} = 10$ and therefore a 3db frequency of:

$f_1 = \frac{10^6}{10} = 10^5$ Hz .

The overall $f_{3db} = 10^5\sqrt{\sqrt{2} - 1} = 64.35$ kHz which is 6 time greater than the bandwidth achieved using single op amp.
(case b above)

2.100

$f_t = 100 \times 5 = 500$ MHz if single op-amp is used.

with op-amp that has only $f_t = 40$ MHz , the possible closed 100 p gain at 5 MHz is:

$|A| = \frac{40}{5} = 8$ V/V

To obtain a overall gain of 100, three such amplifier cascaded, would be required. Now, if each of the 3 stages, has a low-frequency (d) closed loop gain K, then its 3-db frequency will $\frac{40}{k}$ MHz .

Thus for each stage the closed loop gain is:

$$|G| = \frac{k}{\sqrt{1+\left(\frac{f}{\frac{40}{k}}\right)^2}}$$

which at $f = 5$ MHz becomes:

$$|G_{5MHz}| = \frac{k}{\sqrt{1+\left(\frac{k}{8}\right)^2}}$$

The overall gain of 100: $100 = \left[\frac{k}{\sqrt{1+\left(\frac{k}{8}\right)^2}}\right]^3$

$k = 5.7$

Thus for each cascade stage: $f_{3db} = \frac{40}{5.7}$

$f_{3db} = 7$ MHz

The 3-db frequency of the overall amplifier f_1, can be calculated as:

$$\left[\frac{5.7}{\sqrt{1+\left(\frac{f}{7}\right)^2}}\right]^3 = \frac{(5.7)^3}{\sqrt{2}} \Rightarrow f_1 = 3.6 \text{ MHz}$$

2.101

a) $\frac{R_2}{R_1} = k,\ f_{3db} = \frac{f_t}{1+\frac{R_2}{R_1}} = \frac{f_t}{1+k}$

GBP = Gain × f_{3db}

$$GBP = k\frac{f_t}{1+k}$$

b) $1+\frac{R_2}{R_1} = k\ \ f_{3db} = \frac{f_t}{k}$

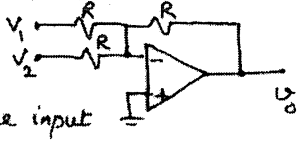
$$GBP = k\frac{f_t}{k} = f_t$$

The non-inverting amplifier realizes a higher GBP and it's independent of k.

2.102

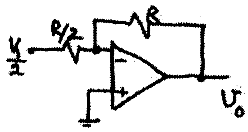
To find f_{3db} we use superposition:

Set $V2 = 0$



Now using Thevenin's Theorem to simplify the input circuit results in:

$$\frac{V_o}{V_1/2} = \frac{-R/R/2}{1+S\frac{1+R/R/2}{\omega_t}}$$



Thevenin's equivalent

which gives:

$$\frac{V_o}{V_1} = \frac{-1}{1+S/(\omega_t/3)}$$

$f_{3db} = \frac{f_t}{3}$. Similar results can be obtained for $\frac{V_o}{V_2}$.

2.103

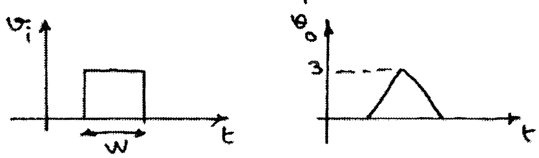
The peak value of the largest possible sine wave that can be applied at the input without output clipping is: $\frac{\pm 12\text{V}}{100} = 0.12\text{V} = 120$ mV rms

value $= \frac{120}{\sqrt{2}} = 85$ mV

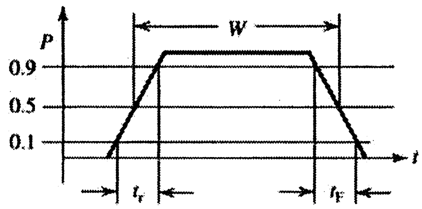
2.104

The output is triangular with the slew rate of 20V/μs. In order to reach 3V, it takes $\frac{3}{20}$ μs = 0.15 μs = 150ns.

Therefore the minimum pulse width is 150 ns.



2.105



$W = 2\ \mu s$

$t_r + t_F = 0.2\ W = 0.4\ \mu s$

$t_r = t_F = 0.2\ \mu s$

$$SR = \frac{(0.9 - 0.1)P}{t_r} = \frac{0.8 \times 10}{0.2} = 40\ V/\mu s$$

2.106

Slope of the triangle wave $= \frac{20\ V}{T/2} = SR$

Thus $\frac{20}{T} \times 2 = 10\ V/\mu s$

$\Rightarrow T = 4\ \mu s$ or $f = \frac{1}{T} = 250\ kHz$

For a sine wave $v_o = v_o \sin(2\pi \times 250 \times 10^3 t)$

$$\left.\frac{dv_o}{dt}\right|_{max} = 2\pi \times 250 \times 10^3\ \hat{v}_o = SR$$

$$\Rightarrow \hat{v}_o = \frac{10 \times 10^6}{2\pi \times 10^3 \times 250} = 6.37\ V$$

2.107

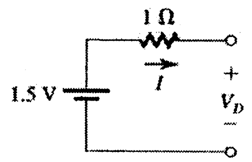
$$v_o = 10\sin\omega t \Rightarrow \frac{dv_o}{dt} = 10\omega\cos\omega t \Rightarrow \left.\frac{dv_o}{dt}\right|_{max} = 10\ \omega$$

The highest frequency at which this output is possible is that for which:

$$\left.\frac{dv_o}{dt}\right|_{max} = SR \Rightarrow 10\omega_{max} = 60 \times 10^{+6} \Rightarrow \omega_{max} = 6 \times 10^5$$

$\Rightarrow f_{max} = 45.5\ kHz$

3.1



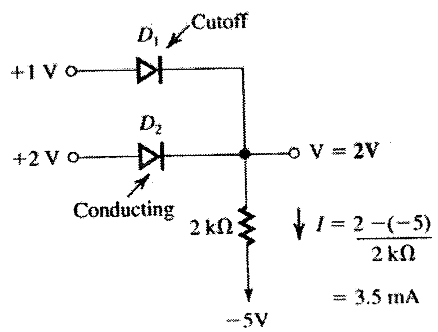
The diode can be reverse-biased and thus no current would flow, or forward-biased where current would flow.

(a) Reverse biased I = OA $V_D = 1.5$ V

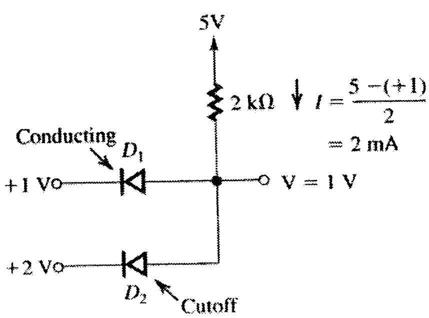
(b) Foward biased $I = 1.5$ A $V_D = 0$ V

3.2

(a)

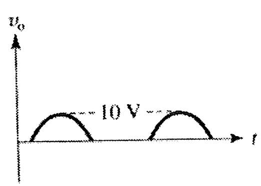


(b)



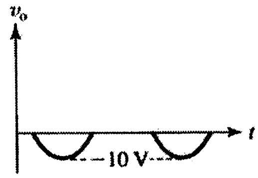
3.3

(a)



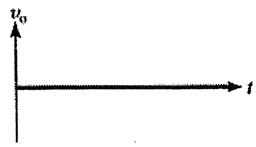
$V_{p+} = 10$ V $V_{p-} = 0$ V
$f = 1\ kH_3$

(b)



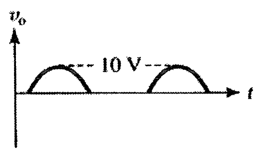
$V_{p+} = 0$ V $V_{p-} = -10$ V
$f = 1\ kH_3$

(c)



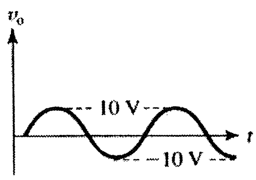
$v_O = 0$ V
Neither D_1 nor D_2 conducts so there is no output.

(d)



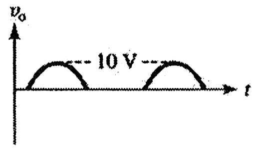
$V_{p+} = 10$ V $V_{p-} = 0$ V $f = 1\ kH_3$
Both D_1 and D_2 conduct when $V_I > 0$

(e)



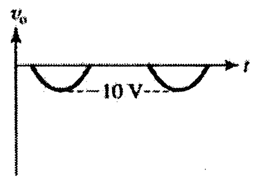
$V_{p+} = 10$ V $V_{p-} = -10$ V $f = 1\ kH_3$
D_1 conducts when $v_I > 0$ and D_2 conducts when $v_I < 0$. Thus the output follows the input.

(f)



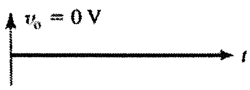
$V_{p+} = 10\text{ V}$ $V_{p-} = 0\text{ V}$ $f = 1\text{ kH}_3$
$-D_1$ is cutoff when $v_I < 0$

(g)



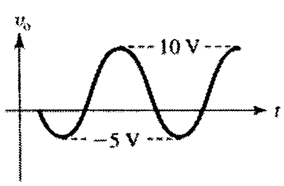
$V_{p+} = 0\text{ V}$ $V_{p-} = -10\text{ V}$ $f = 1\text{ kH}_3$
D_1 shorts to ground when $v_I > 0$ and is cut off when $v_I < 0$ whereby the output follows v_I.

(h)



$v_O = 0\text{ V}$ – The output is always shorted to ground as D_1 conducts when $v_I > 0$ and D_2 conducts when $v_I < 0$.

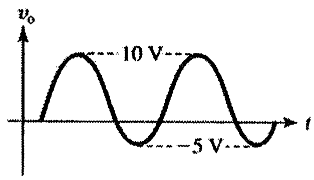
(i)



$V_{p+} = 10\text{ V}$ $V_{p-} = -5\text{ V}$ $f = 1\text{ kH}_3$
When $v_I > 0$, D_1 is cutoff and v_O follows v_I
When $v_I < 0$, D_1 is conducting and the circuit becomes a voltage divider where the negative peak is

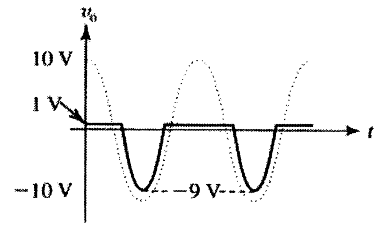
$$\frac{1\text{ k}\Omega}{1\text{ k}\Omega + 1\text{ k}\Omega} \bullet -10\text{ V} = -5\text{ V}$$

(j)



$V_{p+} = 10\text{ V}$ $V_{p-} = -5\text{ V}$ $f = 1\text{ kH}_3$
When $v_I > 0$, the output follows the input as D_1 is conducting.
When $v_I < 0$, D_1 is cut off and the circuit becomes a voltage divider.

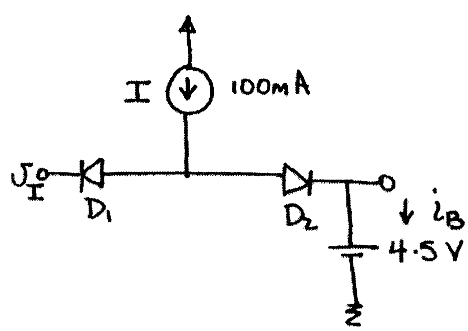
(k)

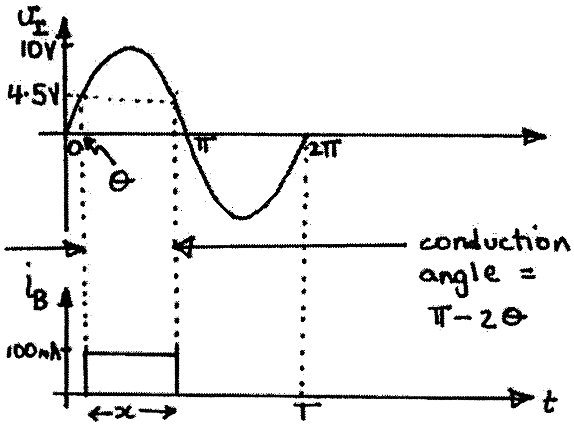


$V_{p+} = 1\text{ V}$ $V_{p-} = -9\text{ V}$ $f = 1\text{ kH}_3$
When $v_I > 0$, D_1 is cutoff and D_2 is conducting. The output becomes 1 V.
When $v_I < 0$, D_1 is conducting and D_2 is cutoff.
The output becomes:-

$$v_O = v_I + 1\text{V}$$

3.4





- When $v_I < 4.5V$ D_1 conducts and D_2 is cutoff so $i_B = 0A$. For $v_I > 4.5V$ D_2 conducts and D_1 is cut off thus disconnecting the input v_I. All of the current then flows through the battery.

$$10 \sin\theta = 4.5 \text{ V}$$
$$\theta = \sin^{-1}(4.5/10)$$
conduction angle = $\pi - 2\theta$

Fraction of cycle that $i_B = \underline{100\text{mA}}$ is given by:-

$$x = \frac{\pi - 2\theta}{2\pi} = 0.35$$

$$i_{B\,avg} = \frac{1}{T}\int_T i_B\, dt$$
$$= \frac{1}{T}\left[100 \cdot 0.35T\right]$$
$$= \underline{\underline{35\text{mA}}}$$

If v_I is reduced by 10% the peak value of i_B remains the same

$$i_{B\,peak} = \underline{100\text{mA}}$$

but the fraction of the cycle for conduction changes

$$x = \frac{\pi - 2\theta}{2\pi} = \frac{\pi - 2\sin^{-1}(4.5/9)}{2\pi}$$
$$= \frac{1}{3}$$

Thus:

$$i_{B\,avg} = \frac{1}{T}\left[100 \cdot \frac{T}{3}\right]$$
$$= \underline{\underline{33.3\text{ mA}}}$$

3.5

$$\frac{5-0}{R} \leq 0.1\text{ mA}$$

$$R \geq 5/0.1 = \underline{\underline{50\text{k}\Omega}}$$

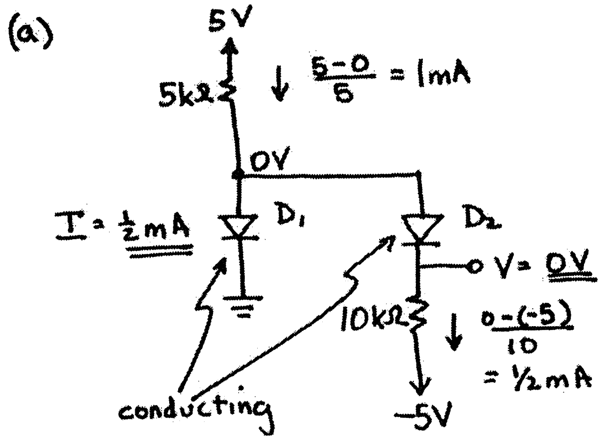
3.6

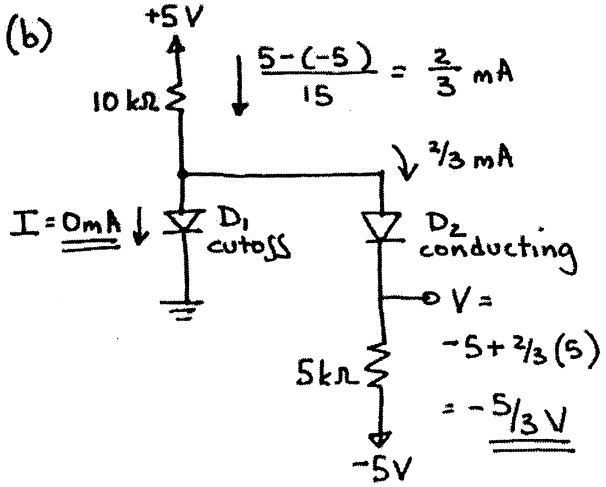
The maximum input current occurs when one input is low and the other two are high.

$$\frac{5-0}{R} \leq 0.1\text{ mA}$$

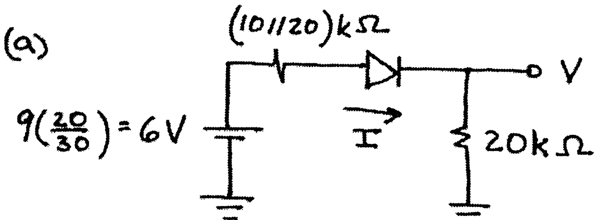
$$R \geq 50\text{ k}\Omega$$

3.7



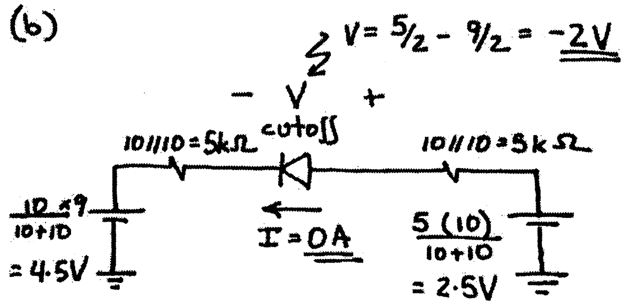


3.8



$$I = \frac{6}{(10/\!/20)+20} = 0.225\,mA$$

$$V = \frac{20}{(10/\!/20)+20} \times 6 = 4.5V$$



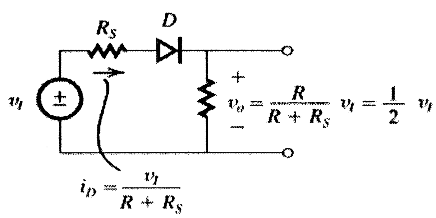
3.9

$R \geq \frac{120\sqrt{2}}{50} \geq 3.4\ k\Omega$

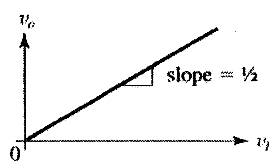
The largest reverse voltage appearing across the diode is equal to the peak input voltage

$120\sqrt{2} = 169.7\ V$

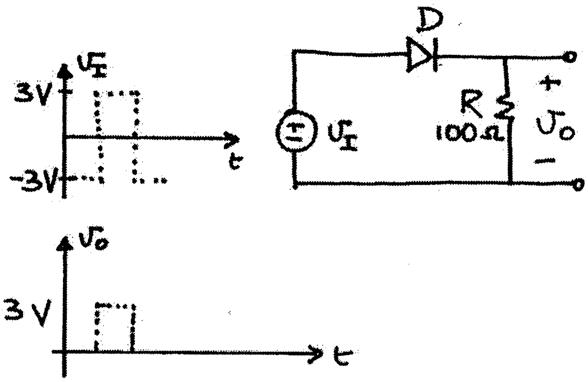
3.10



D starts to conduct when $v_I > 0$



3.11



$v_{O,peak} = 3V$

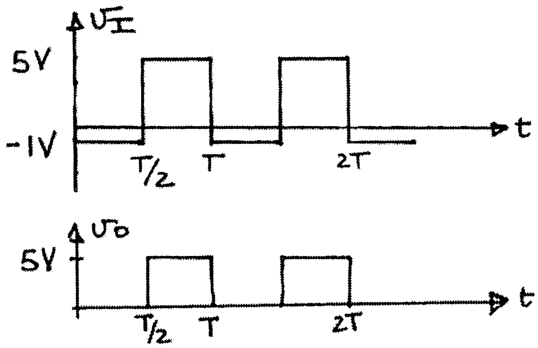
$$v_{O,avg} = \frac{1}{T}\int v_O \, dt = \frac{1}{T}\left[3\frac{T}{2}\right] = 3/2 \text{ V}$$

$i_{D,peak} = 3/100 = 30 \text{ mA}$

$i_{D,avg} = \frac{3/2}{100} = 15 \text{ mA}$

The maximum reverse diode voltage is 3 V

3.12



$v_{O,peak} = 5V$

$v_{O,avg} = 2.5V$

$i_{D,peak} = \frac{v_{O,peak}}{100} = 50 \text{mA}$

$i_{D,avg} = i_{D,peak}/2 = 25 \text{mA}$

maximum reverse voltage = 1V

3.13

V	RED	GREEN	
3 V	ON	OFF	- D_1 conducts
0	OFF	OFF	- No current flows
–3 V	OFF	ON	- D_2 conducts

3.14

$i_1 = I_s e^{0.7/V_T} = 10^{-3}$

$i_2 = I_s e^{0.5/V_T}$

$\frac{i_2}{i_1} = \frac{i_2}{10^{-3}} = e^{\frac{0.5-0.7}{0.025}}$

$i_2 = 0.335 \ \mu\text{A}$

3.15

$i = I_s e^{v/nV_T} = I_s e^{0.7/0.025} = 5(10^{-3})$

$I_s = 5(10^{-3}) e^{-0.7/0.025} = 3.46 \times 10^{-15} \text{A}$

v	i
0.71 V	7.46 mA
0.8 V	273.21 mA
0.69 V	3.35 mA
0.6 V	91.65 μA

Let $i_1 = I_s e^{v_1/0.025}$

$i_2 = 10 i_1 = I_s e^{v_2/0.025}$

$\frac{i_2}{i_1} = 10 = e^{\frac{v_2 - v_1}{0.025}}$

$\therefore \Delta v = v_2 - v_1 = 57.56 \text{mV}$

3.16

To calculate I_S use

$$I_S = I e^{-V/nV_T} = I e^{-V/n \times 0.025}$$

To calculate the voltage at 1% of the measured current use

$i_2 = 0.01 i_1$ so,

$$\frac{i_2}{i_1} = 0.01 = e^{\frac{V_2 - V_1}{nV_T}}$$

$$V_2 = V_1 + nV_T \ln 0.01$$
$$= V + n(0.025)\ln(0.01)$$

V [V]	I	I_S n=1 [A]	I_S n=2 [A]	V n=1 [V]	V n=2 [V
0.7	1A	6.91×10^{-13}	8.32×10^{-7}	0.585	0.470
0.650	1mA	5.11×10^{-15}	2.26×10^{-9}	0.535	0.420
0.650	10μA	5.11×10^{-17}	2.26×10^{-11}	0.535	0.420
0.7	10mA	6.91×10^{-15}	8.32×10^{-9}	0.584	0.470

3.17

Let $I_1 = I_S e^{V_1/nV_T}$ and

$$I_2 = I_S e^{V_2/nV_T} = I_1/10$$

Calculate n by :-

$$\frac{I_2}{I_1} = e^{\frac{V_2 - V_1}{nV_T}}$$

$$n = \frac{1}{V_T}\left[\frac{V_2 - V_1}{\ln I_2/I_1}\right] = \frac{1}{0.025}\left[\frac{V_2 - V_1}{\ln 0.1}\right]$$

Calculate I_S by :-

$$I_S = I_1 e^{-V_1/nV_T}$$

Calculate the diode voltage at $10I_1$ by :- $V_3 = nV_T \ln \frac{10I_1}{I_S}$

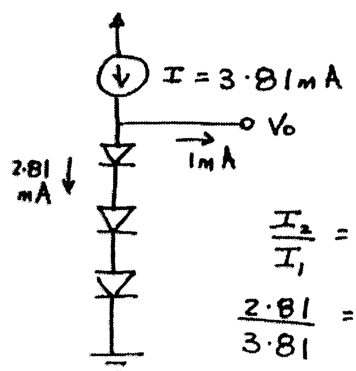
I	V_1 [V]	V_2 [V]	n	I_S [A]	V_3 [V]
10mA	0.7	0.6	1.737	10^{-9}	0.8
1mA	0.7	0.6	1.737	10^{-10}	0.8
10A	0.8	0.7	1.737	10^{-7}	0.9
1 mA	0.7	0.58	2.085	1.47×10^{-9}	0.82
10μA	0.7	0.64	1.042	2.15×10^{-17}	0.7

3.18

∴ The voltage across each diode is $V_0/3$

$$I = I_S e^{\frac{V_0/3}{nV_T}} = 10^{-14} e^{\frac{2/3}{0.025}}$$

$= \underline{3.81 mA}$

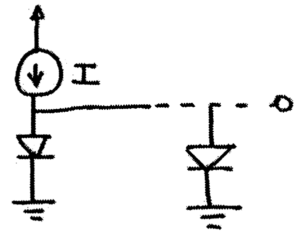


$$\frac{I_2}{I_1} = e^{\frac{(V_2 - V_1)/3}{0.025}}$$

$$\frac{2.81}{3.81} = e^{\frac{(V_2 - 2)/3}{0.025}}$$

$$\Delta V = V_2 - 2 = \underline{-22.8 mV}$$

3.19



With one diode the current through it is

$$I = I_s e^{V_1/nV_T}$$

With two diodes in parallel, the current splits between each diode so that the diodes each has half the current

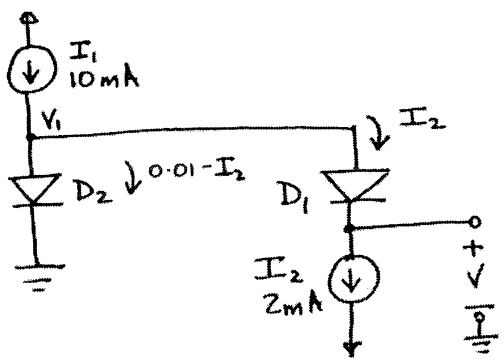
$$\frac{I}{2} = I_s e^{V_2/nV_T}$$

$$\therefore \frac{I/2}{I} = e^{\frac{V_2 - V_1}{nV_T}}$$

The change in voltage is

$$\Delta V = V_2 - V_1 = nV_T \ln\left(\frac{1}{2}\right) = \underline{\underline{-17.3\,mV}}$$

3.20



The current through D_1 is

$$10 I_s e^{\frac{V_1 - V}{nV_T}} = I_2 \quad (A)$$

The current through D_2 is

$$I_s e^{\frac{V_1}{nV_T}} = 0.01 - I_2$$

$$I_s = (0.01 - I_2) e^{\frac{-V_1}{nV_T}} \quad (B)$$

(B) → (A)

$$10(0.01 - I_2) e^{\frac{-V}{nV_T}} = I_2$$

$$V = -V_T \ln\left(\frac{I_2}{10(0.01 - I_2)}\right)$$

$$= 0.025 \ln\left(\frac{2}{10(8)}\right) = \underline{\underline{92.2\,mV}}$$

For $V = 50\,mV$

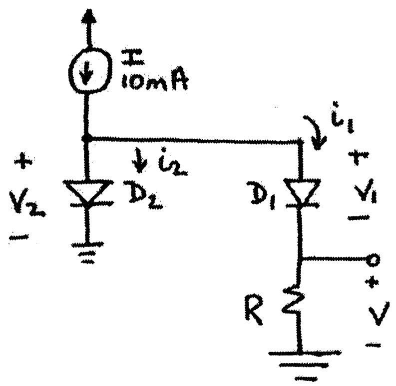
$$-V_T \ln\left(\frac{I_2}{10(10 - I_2)}\right) = 50 \times 10^{-3}$$

$$I_2 = 10(10 - I_2) e^{-2}$$

$$I_2(1 + 10e^{-2}) = 100 e^{-2}$$

$$I_2 = \underline{\underline{5.75\,mA}}$$

3.21



Given for each diode

$i = I_S e^{V/nV_T} \Rightarrow 10\times10^{-3} = I_S e^{0.7/n\times0.025}$ ①

$100\times10^{-3} = I_S e^{0.8/n\times0.025}$ ②

②/① $10 = e^{0.1/n(0.025)}$

$n = 1.737$

$V = V_2 - V_1 = nV_T \ln(i_2/i_1) = 80\text{mV}$

$1.737(25\times10^{-3})\ln\left(\frac{0.01-i_1}{i_1}\right) = 80$

$i_1 = 1.4\ mA$

$R = 80/i_1 = 80/1.4 = \underline{57.1\Omega}$

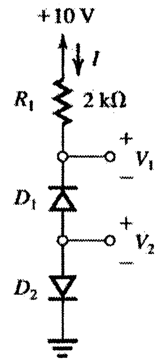
3.22

For a diode conducting a constant current, the diode voltage decreases by approximately 2 mV per increase of 1° C.

$T = -20°C$ corresponds to a temperature decrease of 40° C, which results in an increase of the diode voltage by 80 mV. Thus $V_D = 770$ mV.

$T = +70°$ C corresponds to a temperature increase of 50° C, which results in a decrease of the diode voltage by 100 mV. Thus $V_D = 590$ mV.

3.23



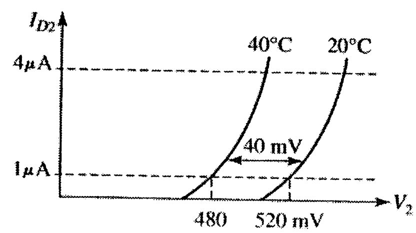
At 20°C:

$V_{R1} = V_2 = 520$ mV

$R_1 = 520$ kΩ

$I = \frac{520\text{ mV}}{520\text{ k}\Omega} = 1\ \mu\text{A}$

At 40°C, $I = 4\ \mu$A



$V_2 = 480 + 2.3 \times 1 \times 25 \log 4$

$= 514.6$ mV

$V_{R1} = 4\ \mu\text{A} \times 520\text{ k}\Omega = 2.08$ V

At 0°C, $I = \frac{1}{4}\ \mu$A

$V_2 = 560 - 2.3 \times 1 \times 25 \log 4$

$= 525.4$ mV

$V_{R1} = \frac{1}{4} \times 520 = 0.13$ V

3.24

The voltage drop = 700 − 580 = 120 mV
Since the diode voltage decreases by approximately 2 mV for every 1°C increase in temperature, the junction temperature must have increased by

$$\frac{120}{2} = \underline{\underline{60\,°C}}$$

Power being dissipated =

$$580 \times 10^{-3} \times 15 = \underline{\underline{8.7\,W}}$$

Thermal Resistance = temperature rise/watt

$$= 60/8.7 = \underline{\underline{6.9\,°C/W}}$$

3.25

$$i = I_S\, e^{v/nV_T}$$

$$10 = I_S\, e^{0.8/2(0.025)}$$

$$I_S = 1.12 \times 10^{-6}\ A$$

For current varying between $i_1 = 0.5\,mA$ to $i_2 = 1.5\,mA$, the voltage varies from

$$v_1 = 2(0.025)\ln\left(\frac{0.5 \times 10^{-3}}{1.12 \times 10^{-6}}\right) = \underline{\underline{0.305\,V}}$$

to:

$$v_2 = 2(0.025)\ln\left(\frac{1.5 \times 10^{-3}}{1.12 \times 10^{-6}}\right) = \underline{\underline{0.360\,V}}$$

∴ the voltage decreases by approximately 2 mV for every 1°C increase in temperature, the voltage may vary by ∓50 mV for the ±25°C temperature variation.

3.26

$$i = I_S\, e^{v/nV_T}$$

$$\frac{I_{S2}}{I_{S1}} = \frac{1}{0.1 \times 10^{-3}} = 10^4$$

For identical currents

$$I_{S1}\, e^{v_1/nV_T} = I_{S2}\, e^{v_2/nV_T}$$

$$e^{\frac{v_1 - v_2}{nV_T}} = 10^4$$

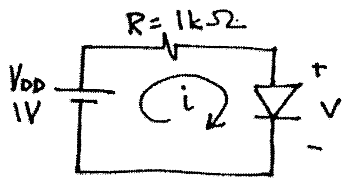
$$v_1 - v_2 = nV_T \ln 10^4$$

$$= 25 \times 10^{-3} \ln 10^4$$

$$= \underline{+0.23\,V}$$

I.E. THE VOLTAGE DIFFERENCE BETWEEN THE TWO DIODES IS +0.23 V INDEPENDENT OF THE CURRENT.
HOWEVER, SINCE THE TWO CURRENTS CAN VARY BY A FACTOR OF 3 (0.5 mA TO 1.5 mA) THE DIFFERENCE VOLTAGE WILL BE:
$0.23\,V \pm nV_T \ln 3 = 0.23\,V \pm 2.75\,mV$
SINCE TEMPERATURE CHANGE AFFECTS BOTH DIODES SIMILARLY THE DIFFERENCE VOLTAGE REMAINS CONSTANT.

3.27

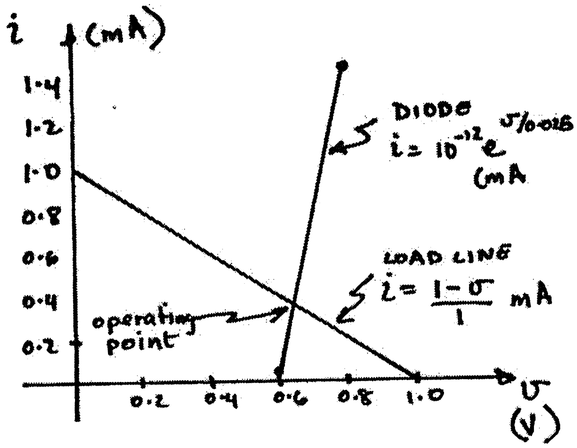


$$i = 10^{-15}\, e^{v/V_T}$$
where $n = 1$

$v = 0.7\,V \quad i = 1.45\,mA$

$v = 0.6\,V \quad i = 0.026\,mA$

A sketch of the graphical construction to determine the operating point is shown below.



From the above sketch we see that the operating point must lie between $v = 0.6$ and $0.7\,V$ and $i \approx 0.3$ to $0.4\,mA$. To find the point more accurately an enlarged graph is plotted.

For $i = 0.3\,mA = 10^{-12} e^{v/0.025}$

$\Rightarrow v = 660.7\,mV$

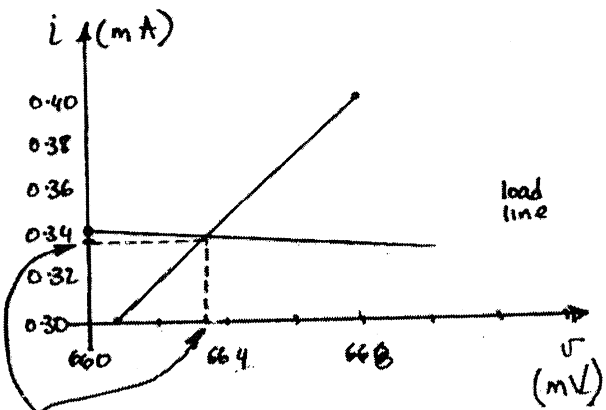
For $i = 0.4\,mA = 10^{-12} e^{v/0.025}$

$\Rightarrow v = 667.9\,mV$

For the load line:

$v = 660\,mV \Rightarrow i = 0.34\,mA$

$v = 670\,mV \Rightarrow i = 0.33\,mA$



Graphical Point $\quad i = 0.337\,mA$

$v = 663.4\,mV$

Comparing the graphical results to the exponential model gives:

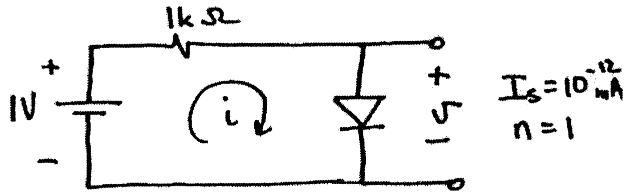
At $i = 0.337\,mA = 10^{-12} e^{v/0.025}$

$\Rightarrow v = 663.6\,mV$

which is only $(663.6 - 663.4) = \underline{0.2\,mV}$ greater than the value found graphically!

3.28

Iterative Analysis:



#1 $\quad v = 0.7\,V \qquad i = \frac{1-0.7}{1} = 0.3\,mA$

#2 $\quad v = 0.25\ln\left(\frac{0.3}{10^{-12}}\right) = 0.6607\,V$

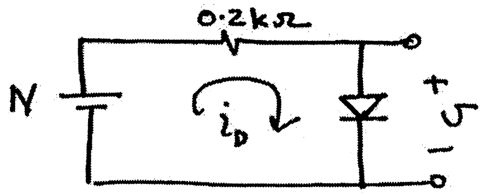
$i = \frac{1-0.6607}{1} = 0.3393\,mA$

#3 $\quad v = 0.25\ln\left(\frac{0.3393}{10^{-12}}\right) = \underline{\underline{0.6638\,V}}$

$i = \frac{1-0.6638}{1} = \underline{\underline{0.3362}}$

∴ i did not change by much stop here.

3.29



(a) $i_D = \dfrac{1-0.7}{0.2} = \underline{\underline{1.5mA}}$

(b) Iterative Analysis given $v_D = 0.7V$ at $i_D = 1mA$

#1 $v = 0.7V$ $\quad i_D = \dfrac{1-0.7}{0.2} = 1.5mA$

#2 $\because\ i = I_S e^{v/nV_T}$ $\quad n=2$

$$\frac{i_2}{i_1} = e^{\frac{v_2 - v_1}{0.05}}$$

thus $v_2 = v_1 + 0.05 \ln i_2/i_1$

$\therefore$ for $i = 1.5$ mA

$v = 0.7 + 0.05 \ln \frac{1.5}{1}$ $= 0.720V$ $\quad$ & $i_D = \dfrac{1-0.720}{0.2} = 1.4mA$

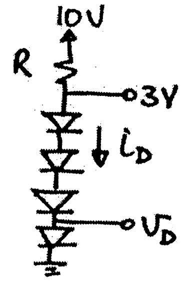
#3

$v = 0.720 + 0.05 \ln\left(\frac{1.4}{1.5}\right) = 0.716V$ $\quad$ & $i_D = \dfrac{1-0.716}{0.2} = 1.42mA$

#4

$v = 0.716 + 0.05 \ln\left(\frac{1.42}{1.4}\right) = \underline{\underline{0.716V}}$ $\quad$ & $i_D = \underline{\underline{1.42mA}}$

3.30



$V_D = \frac{3}{4} = 0.75V$

$i_D = I_S e^{V_D/nV_T}$

$$\frac{i_{D2}}{i_{D1}} = e^{\frac{V_{D2}-V_{D1}}{nV_T}}$$

$$\therefore\ i_D = i_{D2} = i_{D1} e^{\frac{V_{D2}-V_{D1}}{nV_T}}$$

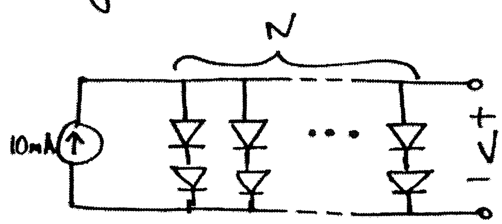
$$= 1 \times e^{\frac{0.78-0.7}{1 \times 0.025}}$$

$$= 7.389\ mA$$

$$\therefore\ R = \frac{10-3}{I_D} = \frac{10-3}{7.389} = \underline{\underline{0.947k\Omega}}$$

3.31

Since $2V_D = 1.4V$ is close to the required 1.25V, use N parallel pairs of diodes to split the current evenly.



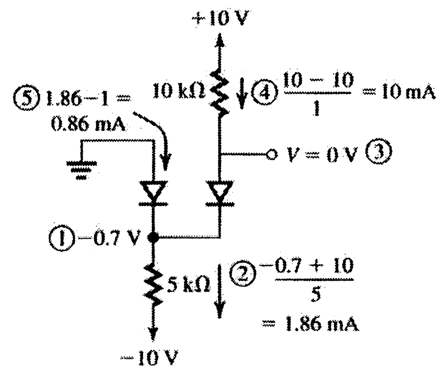
$$\therefore\ V = 2\left[0.7 + 0.1 \log \frac{10/N}{20}\right] = 1.25V$$

$N = 2.8$ $\Rightarrow$ Use $\underline{\underline{3 \text{ sets of diodes}}}$

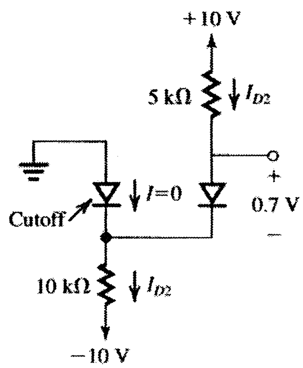
$$V = 2\left(0.7 + 0.1 \log \frac{10/3}{20}\right) = \underline{\underline{1.244V}}$$

3.32 ~ CONSTANT VOLTAGE DROP MODEL

(a)



(b)

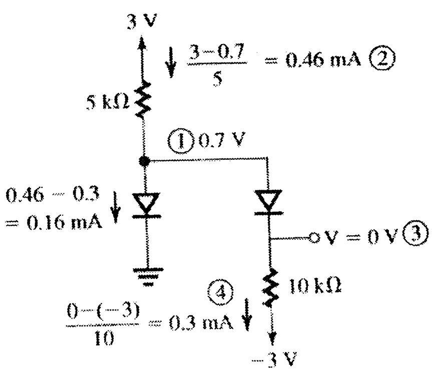


$$I_{D2} = \frac{10 - (-10) - 0.7}{15} = 1.29 \text{ mA}$$

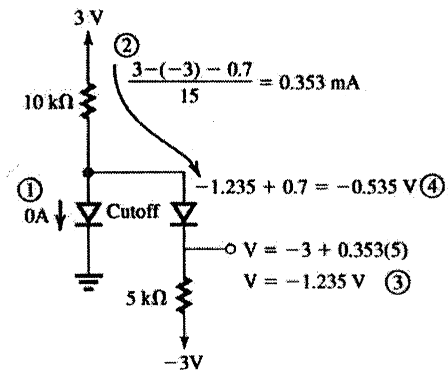
$$v_D = -10 + 1.29(10) + 0.7 = 3.6 \text{ V}$$

3.33

(a)

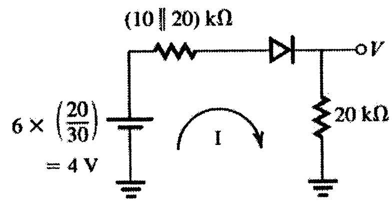


(b)



3.34

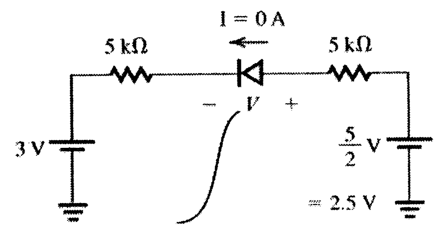
(a)



$$I = \frac{4 - 0.7}{(10 \| 20) + 20} = 0.124 \text{ mA}$$

$$V = 20I = 2.48 \text{ V}$$

(b)

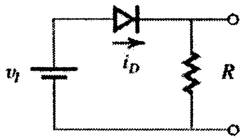


cutoff $\because \frac{5}{2} < \frac{3}{2}$

$\therefore I = 0\text{A}$

$$V = \frac{5}{2} - \frac{3}{2} = -0.5 \text{ V}$$

3.35



$$i_{D,\text{peak}} = \frac{v_{I,\text{peak}} - 0.7}{R} \le 50$$

$$R \ge \frac{120\sqrt{2} - 0.7}{50} = 3.38\ \text{k}\Omega$$

Reverse voltage $= 120\sqrt{2} = 169.7$ V.
The design is essentially the same since the supply voltage >> 0.7 V

3.36

Using the exponential model

$$i_D = I_S e^{\Delta V/nV_T}$$

FOR A +10mV CHANGE

$$\frac{i_{D2}}{i_{D1}} = e^{\Delta V/nV_T} = e^{0.01/n(0.025)}$$

$$= \begin{cases} 1.492 & \sim n=1 \\ 1.221 & \sim n=2 \end{cases}$$

$$\%\ \text{CHANGE} = \frac{i_{D2} - i_{D1}}{i_{D1}} \times 100$$

$$= \begin{cases} (1.492 - 1)\times 100 = +49.2\% & n=1 \\ (1.221-1)\times 100 = 22.1\% & n=2 \end{cases}$$

FOR A −10mV CHANGE

$$\frac{i_{D2}}{i_{D1}} = 10^{-0.01/n(0.025)} = \begin{cases} 0.670 & n=1 \\ 0.819 & n=2 \end{cases}$$

$$\%\ \text{CHANGE} = \begin{cases} (0.670-1)100 = -33\% & n=1 \\ (0.819-1)100 = -18\% & n=2 \end{cases}$$

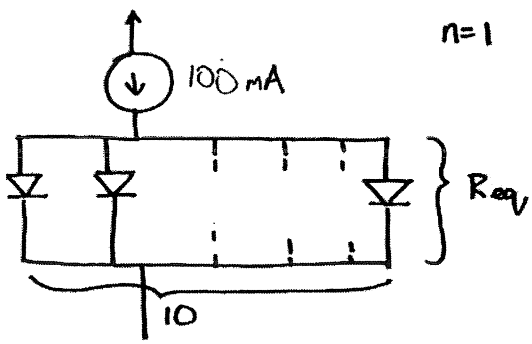
For a current change limited to ±10%

$$\frac{i_{D2}}{i_{D1}} = e^{\Delta V/n \times 0.025} = 0.9 \text{ to } 1.1$$

$$\Delta V = \begin{cases} -2.634\text{mV to } 2.383\text{mV} & n=1 \\ -5.268\text{mV to } 4.766\text{mV} & n=2 \end{cases}$$

3.37

$n=1$



Each diode has the current

$$i_D = \frac{0.1}{10} = 0.01\text{ A}$$

Each diode has a small-signal resistance

$$r_d = \frac{nV_T}{I_D} = \frac{0.025}{0.01} = 2.5\Omega$$

$$R_{eq} = r_d/10 = 0.25\ \Omega$$

(c) $I = 10\mu A$ $\quad I_2 = 990\mu A$

$r_{d1} = \frac{0.025}{10\times10^{-6}} = 2.5k\Omega$ $\qquad r_{d2} = \frac{0.025}{990\times10^{-6}} = 25.25\Omega$

$v_O/v_I = 0.01V/V$

(d) $I = 100\mu A$ $\quad I_2 = 900\mu A$

$r_{d1} = \frac{0.025}{100\times10^{-6}} = 250\Omega$ $\qquad r_{d2} = \frac{0.025}{990\times10^{-6}} = 27.78\Omega$

$\frac{v_O}{v_I} = 0.1\,V/V$

(e) $I = 500\mu A$ $\quad I_2 = 500\mu A$

$r_{d1} = r_{d2} = \frac{0.025}{500\times10^{-6}} = 50\Omega$

$\frac{v_o}{v_I} = \frac{1}{2}\,V/V$

(f) $I = 600\mu A$ $\quad I_2 = 400\mu A$

$r_{d1} = \frac{0.025}{600\times10^{-6}} = 41.67\Omega$ $\qquad r_{d2} = \frac{0.025}{400\times10^{-6}} = 62.5\Omega$

WHEN THE BIAS CURRENT IN EACH DIODE IS $\geq 10\mu A$, THE DIODE RESISTANCE WILL BE $\leq 2.5k\Omega$. To LIMIT THE CURRENT SIGNAL TO A MAXIMUM OF 10% OF BIAS, THE CURRENT SIGNAL MUST BE $\leq 1\mu A$. THUS, THE SIGNAL VOLTAGE ACROSS THE "STARVED" DIODE WILL BE 2.5 mV WHICH IS APPROXIMATELY THE VALUE TO WHICH THE INPUT SIGNAL SWING SHOULD BE LIMITED.

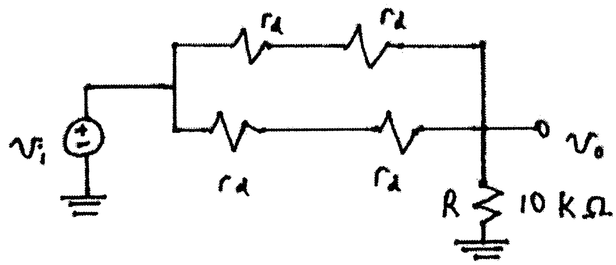
3.41

(a) $\frac{v_o}{v_i} = \frac{R}{R + (2r_d // 2r_d)}$

$= \frac{R}{R + r_d}$

WHERE $r_d = \frac{V_T}{I/2} = \frac{2V_T}{I}$

$= \frac{0.05\,V}{I}$



I (mA)	v_o/v_i (V/V)
0	0
10^{-3}	0.167
0.01	0.667
0.1	0.952
1.0	0.995
10	0.9995

(b) IF THE SIGNAL CURRENT IS TO BE LIMITED TO $\pm 10I$, THE CHANGE IN DIODE VOLTAGE Δv_D CAN BE FOUND FROM

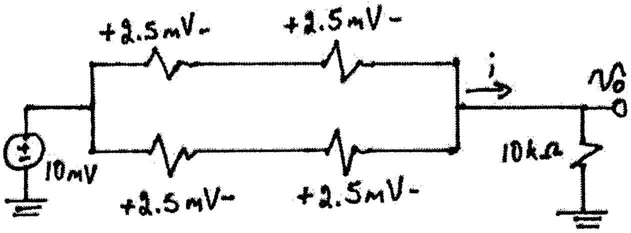
$$\frac{i_D}{I} = e^{\Delta v_D / nV_T} = 0.9 \text{ TO } 1.1$$

THUS, FOR $n = 1$

$\Delta v_D = -2.63\,mV$ TO $+2.38\,mV$

OR APPROXIMATELY $\pm 2.5\,mV$

(b cont.) FOR THE DIODE CURRENT TO REMAIN WITHIN ±10% OF THEIR dc BIAS CURRENTS, THE SIGNAL VOLTAGE ACROSS EACH DIODE MUST BE LIMITED TO 2.5 mV. NOW, IF $v_{i\,PEAK} = 10\text{ mV}$ WE CAN OBTAIN THE FOLLOWING SITUATION



WE SEE THAT $v_o = 5\text{mV}$ AND

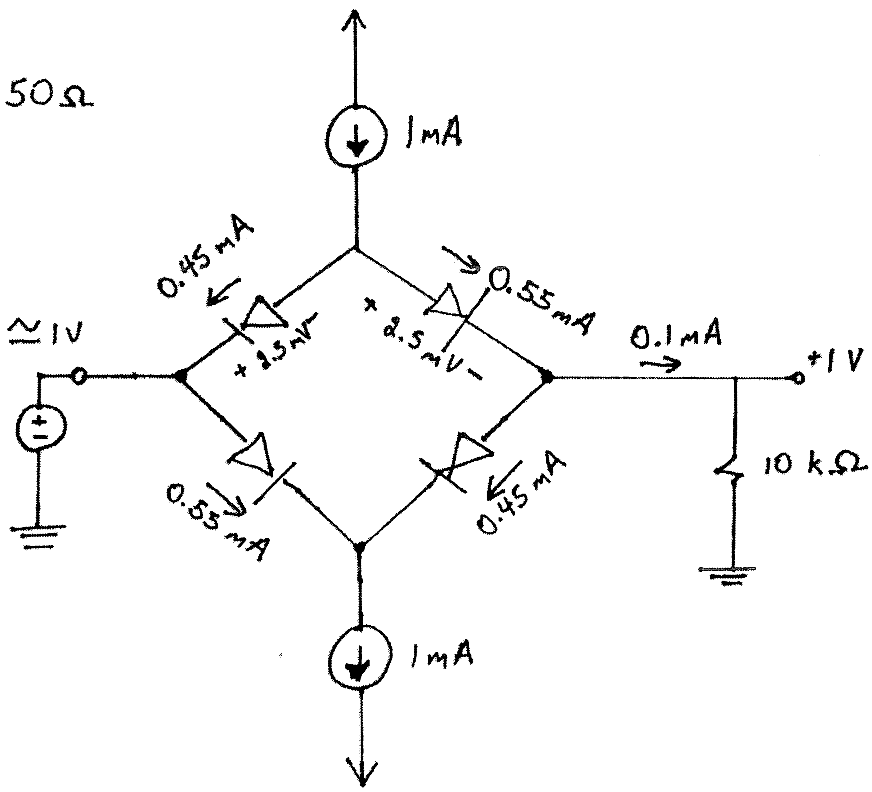
$$i = \frac{5\text{mV}}{10\text{k}\Omega} = 0.5\mu\text{A}.$$

THUS, EACH DIODE IS CARRYING A CURRENT SIGNAL OF 0.25 mA. FOR THIS TO BE AT MOST 10% OF THE dc CURRENT, THE dc CURRENT IN EACH DIODE MUST BE AT LEAST 2.5 μA. IT FOLLOWS THAT THE MINIMUM VALUE OF I MUST BE 5 μA.

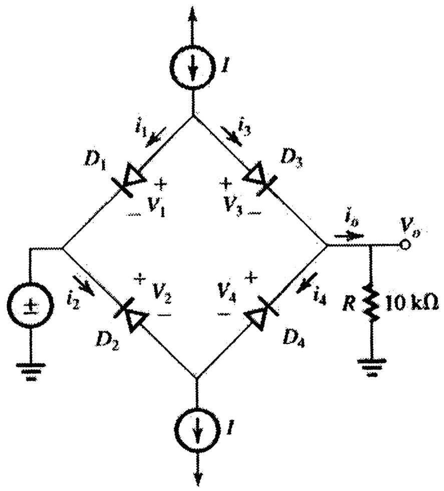
(c) FOR $I = 1\text{mA}$, $I_D = 0.5\text{ mA}$, AND FOR MAXIMUM SIGNAL OF 10%, $I_D = 0.05\text{mA}$. THUS $i_o = 2i_d = 0.1\text{mA}$ AND THE CORRESPONDING MAXIMUM v_o IS $0.1\text{mA} \times 10\text{k}\Omega = 1\text{V}$.
THE CORRESPONDING PEAK INPUT CAN BE FOUND BY DIVIDING v_o BY THE TRANSMISSION FACTOR OF 0.995, THUS

$$v_{i\,MAX} = \frac{1\text{V}}{0.995\text{V}} = 1.005\text{ V}$$

SEE FIGURE.
EACH DIODE HAS $r_d = 50\Omega$



3.42



$I = 1$ mA

Each diode exhibits 0.7 V drop at 1 mA current.
using diode exponential model we have

$$v_2 - v_1 = V_T \ln\left(\frac{i_2}{i_1}\right)$$

and $v_1 = 0.7$ V, $i_1 = 1$ mA

$$\Rightarrow v = 0.7 + V_T \ln\left(\frac{i}{1}\right)$$

$$= 700 + 25\ln(i)$$

Calculation for different values of v_O

$v_O = 0$, $i_O = 0$, the current $I = 1$ mA, divides equally in D_3, D_4 side and D_1, D_2 side.

$$i_1 = i_2 = i_3 = i_4 = \frac{1}{2} = 0.5 \text{ mA}$$

$$v = 700 + 25\ \ln(0.5) \simeq 683 \text{ mV}$$

$$v = v_1 = v_3 = 683 \text{ mV}$$

From circuit

$$v_I = -v_1 + v_3 + v_0 = -683 + 683 + 0 = 0 \text{ V}$$

For $v_O = 1$ V, $i_O = \frac{1}{10\text{ K}} = 0.1$ mA

Because of symmetry of the circuit

$$i_3 = i_2 = \frac{I}{2} + \frac{i_O}{2} = 0.5 + 0.05 = 0.55 \text{ mA}$$

and $i_4 = i_1 = 0.45$

$$v_3 = v_2 = 700 + 25\ln\left(\frac{i_2}{1}\right) = 685 \text{ mV}$$

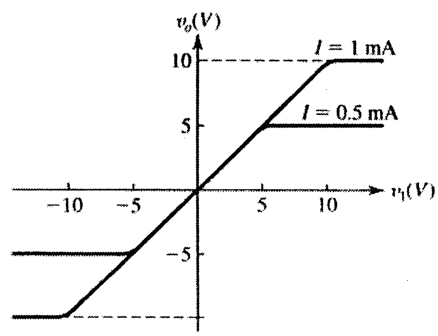
$$v_4 = v_1 = 700 + 25\ln(i_4) = 680 \text{ mV}$$

$v_O(v)$	i_O (mA)	$i_3 = i_2$ (mA)	$i_4 = i_1$ (mA)	$v_3 = v_2$ (mV)	$v_4 = v_1$ (mV)	$v_I = -v_1 + v_3 + v_0 \ln$ V
0	0	0.5	0.5	683	683	0
+1	0.1	0.55	0.45	685	680	1.005
+2	0.2	0.6	0.4	~687	677	2.010
+5	0.5	0.75	0.25	~693	665	5.028
+9	0.9	0.95	0.05	~699	~625	9.074
+9.9	0.99	0.995	0.005	~700	568	10.09
9.99	0.999	0.9995	0.0005	~700	510	10.18
10	1	1	0	700	0	10.7

$$v_I = -v_1 + v_2 + v_0 = -0.680$$

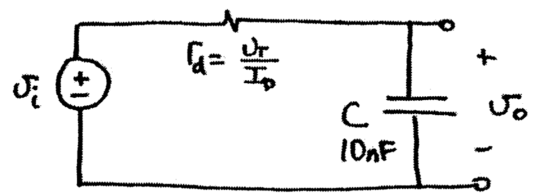
$$+ 0.685 + 1 = 1.005 \text{ V}$$

Similarly other values are calculated in the table for both positive and negative values of v_o
The largest values of v_o on positive and negative side are +10 V and −10 V respectively. This restriction is imposed by the current $I = 1$ mA
A similar table can be generated for the negative values. It is symmetrical.
For $V_I > 10$, v_O will be saturated at 10 V and it is because $I = 1$ mA.
For I = 0.5 mA, will saturate at 0.5 mA × 10 K = 5 V



3.43

Opening the current source we get the following small-signal circuit: $(n=1)$



$$\frac{v_o}{v_i} = \frac{1/sC}{1/sC + r_d} = \frac{1}{1 + sCr_d}$$

$$\text{Phase Shift} = -\tan^{-1}\left(\frac{\omega C r_d}{1}\right)$$

$$= -\tan^{-1}\left(2\pi\, 10^5 \times 10\times10^{-9} \times 0.025/I\right)$$

For a phase shift of -45° we have

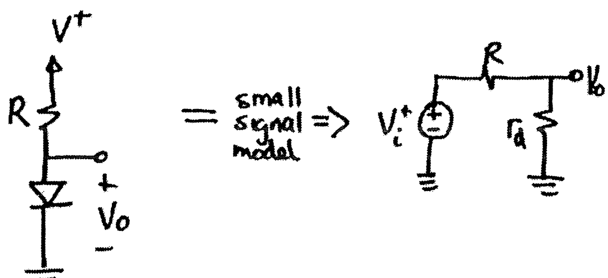
$$2\pi 10^5 \times 10(10^{-9}) \times \frac{0.025}{I} = 1$$

$$I = \underline{\underline{157\,\mu A}}$$

Range of phase shift for $I = 15.7\,\mu A$ to $1570\,\mu A$ is:

$$\underline{\underline{-84.3^\circ \text{ to } -5.71^\circ}}$$

3.44



(a)
$$\frac{\Delta V_o}{\Delta V^+} = \frac{r_d}{r_d + R} = \frac{nV_T/I}{nV_T/I + R}$$

$$= \frac{nV_T}{nV_T + IR} \quad \text{where at no load } I = \frac{V^+ - 0.7}{R}$$

$$= \underline{\underline{\frac{nV_T}{nV_T + V^+ - 0.7}}} \quad \text{Q.E.D.}$$

(b) For m diodes in series use

$$I = \frac{V^+ - m\times 0.7}{R}$$

Thus:

$$\frac{\Delta V_o}{\Delta V^+} = \frac{m r_d}{m r_d + R} = \frac{m(nV_T)}{m(nV_T) + IR}$$

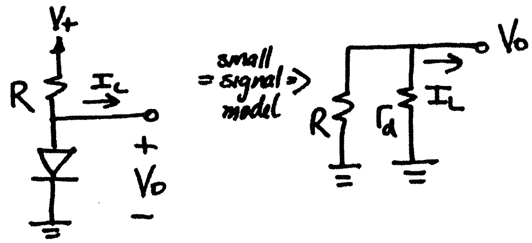
$$= \underline{\underline{\frac{m(nV_T)}{m(nV_T) + V^+ - 0.7m}}}$$

(c) Line Regulation for $V^+ = 10\text{V}$, $n=2$

i) $m=1$ $\quad \frac{\Delta V_o}{\Delta V^+} = \underline{\underline{5.35\,\text{mV/V}}}$

ii) $m=3$ $\quad \frac{\Delta V_o}{\Delta V^+} = \underline{\underline{18.63\,\text{mV/V}}}$

3.45



$$\Delta V_o = -I_L\,(R \parallel r_d)$$

$$\frac{\Delta V_o}{I_L} = -(R \parallel r_d) \qquad \text{Q.E.D.}$$

(b) Given at DC $I_D = \dfrac{V^+ - 0.7}{R}$

Also $r_d = \dfrac{nV_T}{I_D}$

We have:

$$\frac{\Delta V_o}{I_L} = -\frac{1}{\frac{1}{R} + \frac{1}{r_d}}$$

$$= -\frac{1}{\frac{I_D}{V^+ - 0.7} + \frac{I_D}{nV_T}}$$

$$= -\frac{nV_T}{I_D}\,\frac{1}{1 + \frac{nV_T}{V^+ - 0.7}}$$

$$= \frac{-nV_T}{I_D}\,\frac{V^+ - 0.7}{V^+ - 0.7 + nV_T} \qquad \text{Q.E.D.}$$

For $\dfrac{\Delta V_o}{I_L} \leqslant 5\,\dfrac{mV}{mA}$

$$-\frac{2 \times 0.025}{I_D} \times \frac{10 - 0.7}{10 - 0.7 + 0.05} \leqslant \frac{5 \times 10^{-3}}{10^{-3}}$$

$$I_D \geqslant 9.947\,mA \Rightarrow I_D = 10\,mA$$

$$R = \frac{V^+ - 0.7}{I_D} = \frac{10 - 0.7}{10} = 930\,\Omega$$

Thus the diode should be a 10mA diode.

(c) For m diodes

$$I_D = \frac{V^+ - 0.7m}{R} \quad \& \quad r_d = \frac{m(nV_T)}{I_D}$$

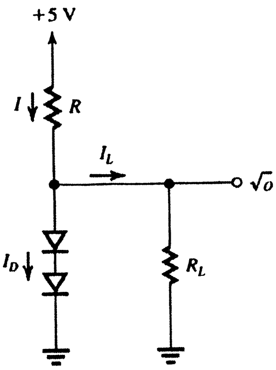
$$\frac{\Delta V_o}{I_L} = \frac{-1}{\frac{1}{R} + \frac{1}{r_d}}$$

$$= \frac{-1}{\frac{I_D}{V^+ - 0.7m} + \frac{I_D}{mnV_T}}$$

$$= -\frac{mnV_T}{I_D}\,\frac{1}{\frac{mnV_T}{V^+ - 0.7m} + 1}$$

$$= \frac{-mnV_T}{I_D}\,\frac{V^+ - 0.7m}{V^+ - 0.7m + mnV_T}$$

3.46



Diode has 0.7 V drop at 10 mA current

$v_o = 1.5$ V when $R_L = 150\ \Omega$

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

$$10 \times 10^{-3} = I_S e^{0.7/0.025}$$

$$\Rightarrow I_S = 6.91 \times 10^{-15}\ \text{A}$$

Voltage drop across each diode $= \frac{1.5}{2} = 0.75$ V

$$\therefore I_D = I_S e^{V/V_T} = 6.91 \times 10^{-15} \times e^{0.75/0.025}$$

$$= 73.9\ \text{mA}$$

$$I_L = 1.5/150 = 10\ \text{mA}$$

$$I = I_D + I_L = 73.9\ \text{mA} + 10\ \text{mA}$$

$$= 83.9\ \text{mA}$$

$$\therefore R = \frac{5 - 1.5}{83.9\ \text{mA}} = 41.7\ \Omega$$

Use small signal model to find voltage v_o when load resistor, R_L, has lower values

$$r_d = \frac{V_T}{I_D} = \frac{0.025}{73.9} = 0.34\ \Omega$$

When load is disconnected all the current I flows through the diode.

$$\therefore I_D = I = 83.9\ \text{mA}$$

$$v_D = V_T \ln\left(\frac{I_D}{I_S}\right) = 0.025 \times \ln\left(\frac{83.9 \times 10^{-3}}{6.91 \times 10^{-15}}\right)$$

$v_D = 0.753$ V

So No load, $v_o = 2\ V_D = 2 \times 0.753 = 1.506$ V.

Increase in voltage $= 1.506 - 1.5 = 0.006$ V

Now load is changed

$R_L = 100\ \Omega$: $I_L = \frac{1.5}{100} = 15$ mA

The diode current reduced by $= 15 - 10 = 5$ mA

$\therefore \Delta V_O = -5\ \text{mA} \times r_d = -1.7$ mV

$R_L = 75\ \Omega$: $I_L = \frac{1.5}{75} = 20$ mA

Diode current reduced by $20 - 10 = 10$ mA

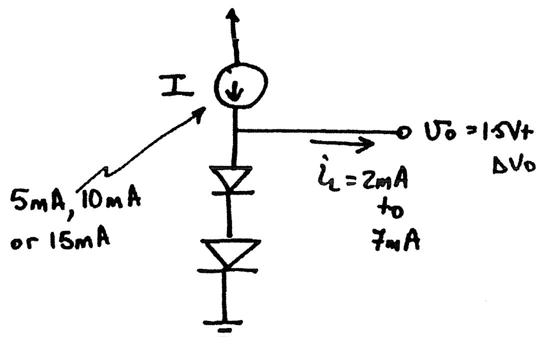
$\therefore \Delta v_O = -10\ r_d = -10 \times 0.34 = -3.4$ mV

$R_L = 50\ \Omega$: $I_L = \frac{1.5}{50} = 30$ mA

Diode current reduced by $30 - 10 = 20$ mA

$\Delta V_O = -20\ r_d = 6.8$ mV

3.47



For a load current of 2 to 7mA, I must be greater than 7 mA. Thus the 5 mA source would not do.

We are left to choose between the 10 and 15 mA sources. The 15 mA source provides lower load regulation because the diodes will have more current flowing through them at all times

This is shown below:

Load Regulation if $I = 10\,mA$

use $\frac{i_{D2}}{i_{D1}} = e^{\Delta V/2 \times nV_T}$ ← 2 diodes

$\therefore e^{\Delta V/0.05 \times 2} = 3/10$ to $8/10$

$\Delta V_o = -120\,mV$ to $-22.3\,mV$

$\therefore$ The peak to peak ripple is

$-120 - (-22.3) \approx -100\,mV$

$$\text{Load Regulation} = \frac{\Delta V_o}{I_L} = \frac{-100}{5}$$

$$= -20\ \frac{mV}{mA}$$

Load Regulation for $I = 15\,mA$.
Here the current through the diodes change from 8 to 13 mA corresponding to

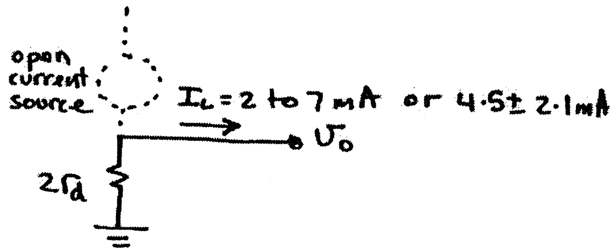
$$\Delta V_o = 0.1 \ln(8/13)$$

$$= -49\,mV$$

$$\text{Load Regulation} = \frac{-49}{5} \approx -10\ \frac{mV}{mA}.$$

The obvious disadvantage of using the 15 mA supply is the requirement of higher current and higher power dissipation.

Alternate solution of Line Regulation using the small signal model



$$\text{Load Regulation} = \frac{\Delta V_o}{I_L} = -2r_d = -\frac{2nV_T}{I_D}$$

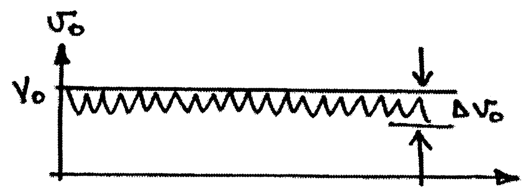
Where the bias current $I_D = 10 - 4.5$ for the 10 mA source.

$$\Rightarrow \frac{\Delta V_o}{I_L} = \frac{-2 \times 2 \times 0.025}{10 - 4.5} = -18.2\ \frac{mV}{mA}$$

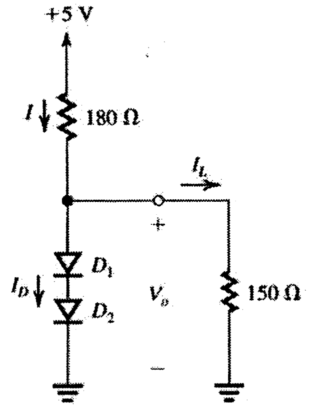
For 15 mA source $I_D = 15 - 4.5$

$$\frac{\Delta V_o}{\Delta I_L} = \frac{-0.1}{15 - 4.5} = -9.5\ \frac{mV}{mA}$$

Sketch of output:-



3.48



Both diodes are 0.7 V, 10 mA diodes
First find V_o with no load, i.e $I_L = 0$ and $I = I_L$.
Use iteration to find V_o and I_D

$$I_D = \frac{5 - 0.7 \times 2}{180\ \Omega} = 20\ \text{mA}$$

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

$$V_2 = 0.7 + 2.3 \times 25 \times 10^{-3} \times \log\left(\frac{20}{10}\right)$$

$= 0.717$ V

$$I_D = \frac{5 - 0.717 \times 2}{180} = 23.79\ \text{mA}$$

$$V_2 = 0.7 + 2.3 V_T \log\left(\frac{23.79}{10}\right)$$

$= 0.7216$ V

$$I_D = \frac{5 - 2 \times 0.7216}{180} = 19.76\ \text{mA}$$

$$V_2 = 0.7 + 2.3 V_T \log\left(\frac{19.76}{10}\right)$$

$= 0.717$ V

$$I_D = \frac{5 - 2 \times 0.717}{180} = 19.81\ \text{mA} \cong I$$

It is almost similar to earlier result, we stop iteration here

$V_D = 0.717$ V and $I_D = 19.81$ mA

So $V_O = 2 \times 0.717 = 1.434$ V

a. Load of 150 Ω is connected

$$I_L = \frac{0.717 \times 2}{150} = 9.56\ \text{mA}$$

$\therefore I_D = I_{\Gamma}\, 9.56 = 19.81 - 9.56 = 10.25$ mA

So now

$$V_O = 2V_D = 2\left[0.7 + 2.3 V_T \log\left(\frac{10.25}{10}\right)\right]$$

$= 1.401$ V

b. As found earlier, with no load $V_o = 1.434$ V

c. With 150 Ω load connected and V_o is lowered by 0.1 V of its nominal value.

$V_O = 1.401 - 0.1 = 1.301$ V

Voltage across each diode $= 1.301/2 = 0.6505$ V

$I_D = 10 \times 10^{-3} e^{\Delta V / V_T}$ where

$$\Delta V = \frac{1.401 - 1.301}{2} = 0.05\ \text{V}$$

$= 7.4$ mA

$$I_L = \frac{1.301\ \text{V}}{150\ \Omega} = 8.7\ \text{mA}$$

$\therefore I = I_D + I_L = 16.1$ mA

$\therefore$ New value of 5V supply $=$

$180\ \Omega \times 16.1\ \text{mA} + V_O \cong 4.2$ V

So the 5 V supply can be lowered to ~ 4.2 V

d. New value of the voltage supply $= 5 + (5-4.2) = 5.8$ V. Now do the problem again as done in the begining and in parts a and b.

$$I_D = \frac{5.8 - 2 \times 0.7}{180} = 24.4\ \text{mA}$$

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

$$= 0.7 + 2.3 V_T \log\left(\frac{24.4}{10}\right)$$

$= 0.722$ V

$$I_D = \frac{5.8 - 2 \times 0.722}{180}$$

$= 24.2$ mA

Doing one more iteration, almost same value is obtained

$\therefore V_D = 0.722$ V, $I_D = 24.2$ mA

Now when 150 Ω load is present

$$I_L = \frac{2 \times 0.722}{150} = 9.6\ \text{mA}$$

So $I_D = 24.2 - 9.6 = 14.6$ mA

$$\therefore V_D = 0.7 + 2.3 \times V_T \log\left(\frac{14.6}{10}\right)$$

$= 0.7095$ V

$V_O = 2\ V_D \cong 1.42$ V

$\therefore$ Loaded output voltage $= 1.42$ V

e. Percentage change in output voltage

$$= \frac{1.42 - 1.301}{5.8 - 4.2} \times 100$$

$\cong 7.4\%$

3.49

(a) $V_Z = V_{Z0} + r_Z I_{ZT}$

$10 = 9.6 + r_Z \times 50 \times 10^{-3}$

$r_Z = \underline{\underline{8\Omega}}$

Power rating:

$V_Z = V_{Z0} + r_Z \times 2I_{ZT}$

$= 9.6 + 8 \times 100 \times 10^{-3}$

$= 10.4V$

$P = 10.4 \times 100 \times 10^{-3} = \underline{\underline{1.04W}}$

(b) $V_Z = V_{Z0} + r_Z I_{ZT}$

$9.1 = V_{Z0} + 30 \times 10 \times 10^{-3}$

$V_{Z0} = \underline{\underline{8.8V}}$

$V_Z = 8.8 + 30 \times 20 \times 10^{-3} = 9.4V$

$P = 9.4 \times 20 \times 10^{-3} = \underline{\underline{188mW}}$

(c) $6.8 = 6.6 + 2 \times I_{ZT}$

$I_{ZT} = \underline{\underline{100mA}}$

$V_Z = 6.6 + 2 \times 200 \times 10^{-3} = 7V$

$P = 7 \times 200 \times 10^{-3} = \underline{\underline{1.4W}}$

(d) $18 = 17.2 + r_Z \times 5 \times 10^{-3}$

$r_Z = \underline{\underline{160\Omega}}$

$V_Z = 17.2 + 160 \times 10 \times 10^{-3} = 18.8V$

$P = 18.8 \times 10 \times 10^{-3} = \underline{\underline{188mW}}$

(e) $7.6 = V_{Z0} + 1.5 \times 200 \times 10^{-3}$

$V_{Z0} = \underline{\underline{7.2V}}$

$V_Z = 7.2 + 1.5 \times 400 \times 10^{-3} = 7.8V$

$P = 7.8 \times 400 \times 10^{-3} = \underline{\underline{3.12W}}$

3.50

(a) Three 6.8 V zeners provide 3 × 6.8 = 20.4 V with 3 × 10 = 30 Ω resistance. Neglecting R, we have

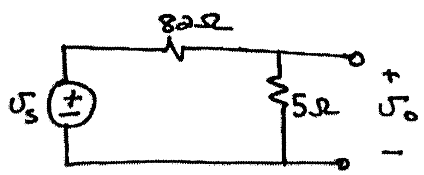
Load Regulation = −30 mv/mA.

(b) For 5.1 V zeners we use 4 diodes to provide 20.4 V with 4 × 30 = 120 Ω resistance.

Load regulation = −120 mV/mA

3.51

Small signal model for line regulation:



$$\frac{\Delta v_o}{\Delta v_s} = \frac{5}{5+82}$$

$$\Delta v_o = \frac{5}{87} \times \Delta v_s$$

$$= \frac{5}{87} \times 1.3$$

$$= \underline{\underline{74.7\ mV}}$$

3.52

$r_z = 30\,\Omega$

$I_{ZK} = 0.5\text{ mA}$

$V_Z = 7.5\text{ V}$

$I_Z = 12\text{ mA}$

$7.5 = V_{Z0} + 12 \times 30 \times 10^{-3}$

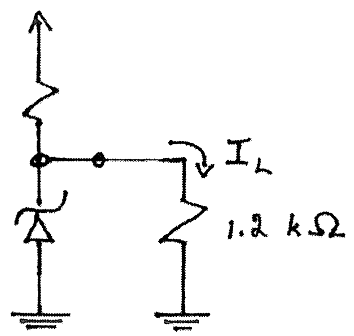
$\Rightarrow V_{Z0} = 7.14\text{ V}$

$I_Z = \frac{7.5}{1.2} = 6.25\text{ mA}$

SELECT $I = 10\text{ mA}$
SO THAT $I_Z = 3.7\text{ mA}$

WHICH IS $> I_{ZK}$

$R = \frac{10 - 7.5}{10} = \underline{\underline{250\,\Omega}}$



FOR $\Delta V^+ = \pm 1\text{V}$

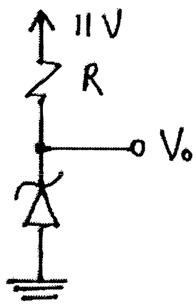
$\Delta V_O = \pm 1 \times \frac{1.2 // 0.03}{0.250 + (1.2 // 0.03)}$

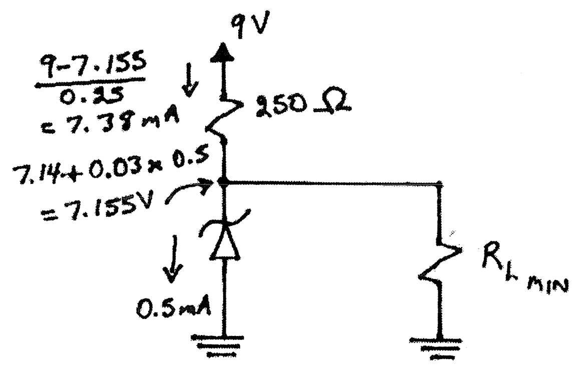
$= \pm 0.1\text{ V}$

THUS $V_O = +7.4\text{ V}$ TO $+7.6\text{ V}$
WITH $V^+ = 11\text{ V}$ AND $I_L = 0$

$V_O = V_{Z0} + \frac{11 - V_O}{0.25} \times 0.03$

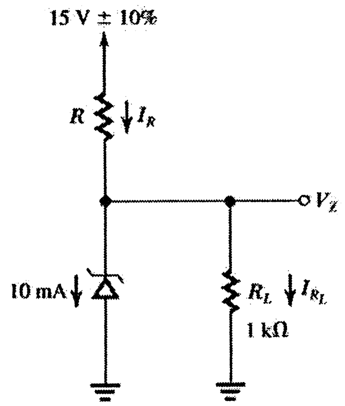
$\Rightarrow V_O = \underline{\underline{7.55\text{ V}}}$





$R_{L_{MIN}} = \frac{7.155}{7.38 - 0.5}$
$= \underline{\underline{1.04\text{ k}\Omega}}$

3.53



$V_z = V_{zo} + r_z I_z$

$9.1 = V_{zo} + 30(0.009)$

$V_{zo} = 8.83\text{V}$

$V_Z = 8.83 + 30(0.01) = 9.13 \text{ V}$

$I_{RL} = 9.13/1 \text{ k}\Omega = 9.13 \text{ mA}$

$I_R = 10 + 9.13 = 19.13 \text{ mA}$

$\therefore R = \dfrac{15 - 9.13}{19.13} = 306.8 \ \Omega$

$\cong 300 \ \Omega$

$$V_Z = 8.83 + 30\left(\frac{15 - V_Z}{300} - \frac{V_Z}{1000}\right)$$

$$= 10.33 - \frac{V_Z}{10} - \frac{3}{100}V_Z$$

$V_Z = 9.14 \text{ V}$

$$V_Z = 8.83 + 30\left(\frac{15 \pm 1.5 - V_Z}{300} - \frac{V_Z}{1000}\right)$$

$$= \frac{1}{1.13}[8.83 + 1.5 \pm 0.15] = 9.14 \pm 0.13 \text{ V}$$

$\therefore \pm 0.13$ V variation in output voltage Halving the load current $\equiv R_L$ doubling

$$V_Z = 8.83 + 30\left(\frac{15 - V_Z}{300} - \frac{V_Z}{2000}\right)$$

$$= \frac{10.33}{1.115} = 9.26 \text{ V}$$

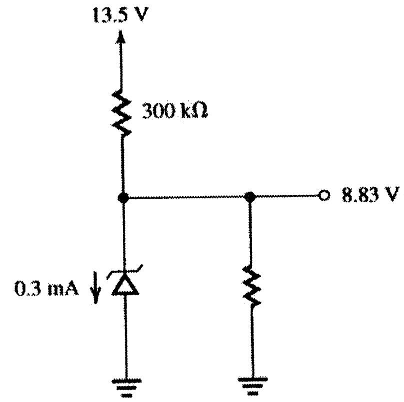
$\therefore 9.26 - 9.14 = 0.12$ V increase in output voltage.

At the edge of the breakdown region

$V_Z \cong V_{ZO} = 8.83 \text{ V} \quad I_{ZK} = 0.3 \text{ mA}$

$$R_L = \frac{8.83}{\dfrac{13.5 - 8.83}{300} - 0.0003}$$

$= 578 \ \Omega$



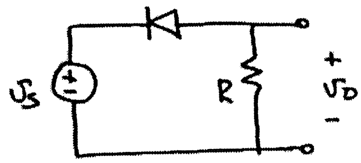
Lowest output voltage = 8.83 V

$$\text{Line Regulation} = \frac{r_Z}{R + r_Z} = \frac{30}{300 + 30}$$

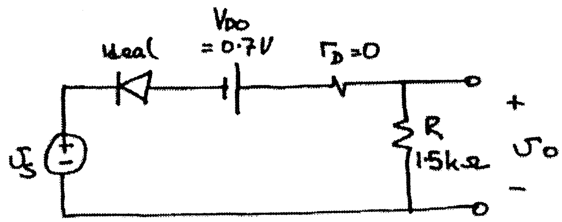
$$= 90 \ \frac{\text{mV}}{\text{V}}$$

$$\text{Load Regulation} = -(r_Z \parallel R) = -29.1 \ \frac{\text{mV}}{\text{mA}}$$

3.54

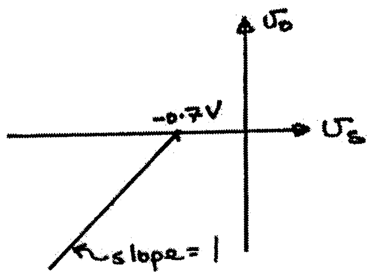


Using the constant voltage drop model:

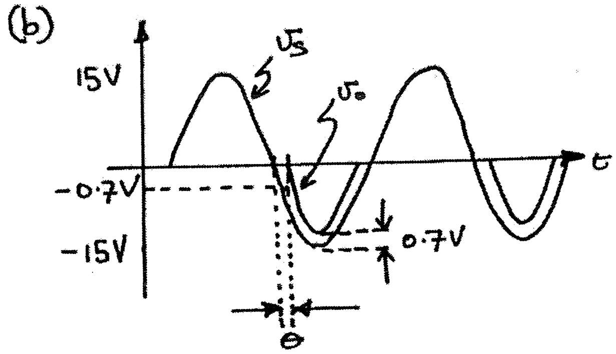


(a) $v_O = v_S + 0.7\text{ V}$, for $v_S \leq -0.7\text{V}$

$v_O = 0$, for $v_S \geq -0.7\text{V}$



(b)



(c) The diode conducts at an angle $\theta = \sin^{-1}\frac{0.7}{15} = 2.67°$ & stops at $\pi - \theta = 177.33°$

Thus the conduction angle is $\pi - 2\theta$ $= 174.66°$ or 3.05 rad.

$$v_{O,avg} = \frac{-1}{2\pi}\int_{\theta}^{\pi-\theta} 15\sin\phi - 0.7\, d\phi$$

$$= \frac{-1}{2\pi}\Big[-15\cos\phi - 0.7\phi\Big]_{\theta}^{\pi-\theta}$$

$$= \frac{-1}{2\pi}\Big[15 \times 2\cos\theta - 0.7(\pi - 2\theta)\Big]$$

$$= \underline{\underline{-4.43\text{V}}}$$

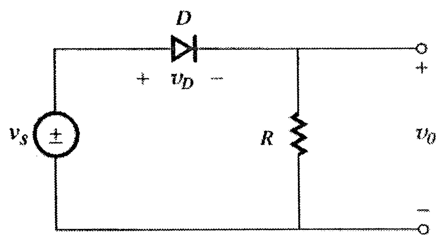
(d) Peak current in diode is:

$$\frac{15 - 0.7}{1.5 \times 10^3} = \underline{\underline{9.5\text{mA}}}$$

(e) PIV occurs when v_S is at its +ve peak and $v_O = 0$.

$\text{PIV} = \underline{\underline{15\text{V}}}$

3.55



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

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

$$v_D - v_D(\text{at 1mA}) = V_T \ln\frac{i_D}{1\text{ mA}}$$

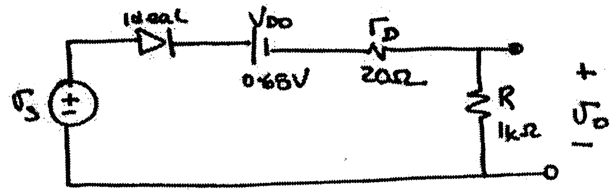
$$v_D = v_D(\text{at 1mA}) + V_T\ln\left[\frac{v_O/R}{10^{-3}}\right]$$

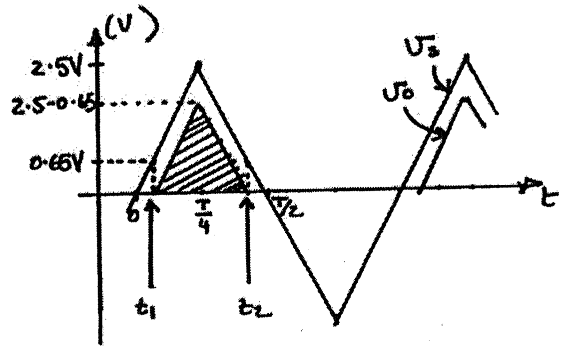
$$v_O = v_S - v_D$$

$$= v_S - v_D(\text{at 1mA}) - V_T\ln\left(\frac{v_O}{R}\right)$$

where R is in kΩ

3.56





find t_1 & t_2 by:

$$\frac{2.5}{T/4} = \frac{0.65}{t_1} \Rightarrow t_1 = 0.065T$$

$$t_2 = T/2 - 0.065T = 0.435T$$

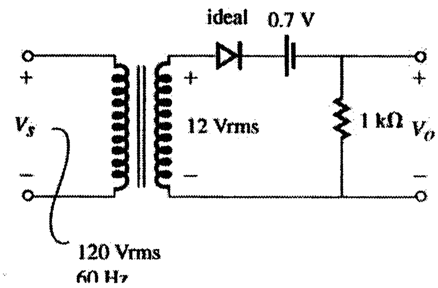
$$v_O\big|_{avg} = \frac{1}{T}\int_T \frac{R}{R+r_D}(v_s - 0.65)\,dt$$

$$= \frac{1}{T}\frac{R}{R+r_D}\left(\text{AREA OF SHADED }\triangle\right)$$

$$= \frac{1}{T}\frac{R}{R+r_D}(2.5-0.65)\left(\frac{T}{4} - 0.065T\right)$$

$$= \frac{1000}{1020}(0.342) = \underline{0.335\text{ V}}$$

3.57



$\hat{V}_O = 12\sqrt{2} - 0.7 = 16.27$ V

Conduction begins at

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

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

$= 0.0412$ rad

Conduction ends at $\pi - \theta$

$\therefore$ Conduction angle $= \pi - 2\theta = 3.06$ rad

The diode conducts for

$\frac{3.06}{2\pi} \times 100 = 48.7\%$ of the cycle

$$V_{O,\text{avg}} = \frac{1}{2\pi}\int_{\theta}^{\pi-\theta}(12\sqrt{2}\sin\phi - 0.7)d\phi$$

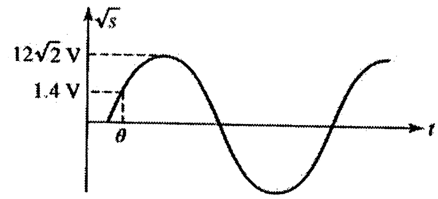
$= 5.06$ V

$i_{D,\text{avg}} = \frac{v_{O,\text{avg}}}{R} = 5.06$ mA

Peak voltage across $R = 12\sqrt{2} - 2V_D$

$= 12\sqrt{2} - 1.4$

$= 15.57$ V



$$\theta = \sin^{-1}\frac{1.4}{12\sqrt{2}} = 0.0826 \text{ rad}$$

Fraction of cycle that D_1 & D_2 conduct is

$$\frac{\pi - 2\theta}{2\pi} \times 100 = 47.4\%$$

Note D_3 & D_4 conduct in the other half cycle so that there is $2(47.4) = 94.8\%$ conduction interval.

$$v_{O,\,avg} = \frac{2}{2\pi}\int_{\theta}^{\pi-\theta}(12\sqrt{2}\sin\phi - 2V_D)d\phi$$

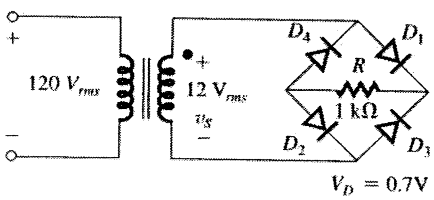
$$= \frac{1}{\pi}[-12\sqrt{2}\cos\phi - 1.4\phi]_{\theta}^{\pi-\theta}$$

$$= \frac{2(12\sqrt{2}\cos\theta)}{\pi} - \frac{1.4(\pi - 2\theta)}{\pi}$$

$$= 9.44 \text{ V}$$

$$i_{R,\,avg}\frac{v_{O,\,avg}}{R} = \frac{9.44}{1} = 9.44 \text{ mA}$$

3.58



3.59

$120\sqrt{2} \pm 10\% : 24\sqrt{2} \pm 10\%$

$\Rightarrow$ turns Ratio = 5:1

$$v_S = \frac{24\sqrt{2}}{2} \pm 10\%$$

$$\text{PIV} = 2V_S|_{max} - V_{DO}$$

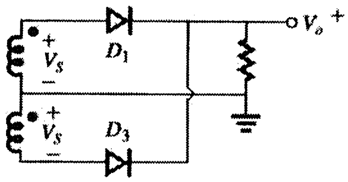
$$= 2 \times \frac{24\sqrt{2}}{2} \times 1.1 - 0.7$$

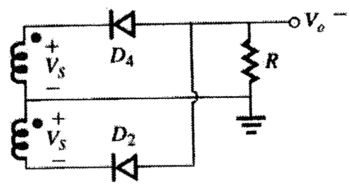
$$= 36.6 \text{ V}$$

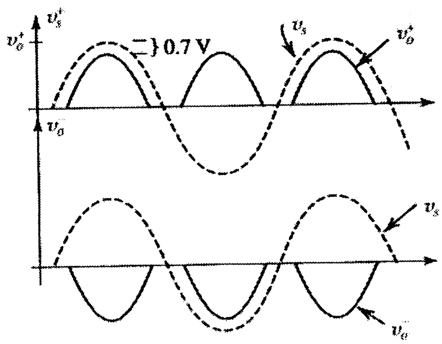
using a factor of 1.5 for safety we select a diode having a PIV rating of 55 V

3.60

The circuit is a full wave rectifier with centre tapped secondary winding. The circuit can be analyzed by looking at v_O^+ and v_O^- seperately.







$$v_{O,\,avg} = \frac{1}{2\pi}\int (V_S \sin\phi - 0.7)d\phi = 15$$

$$= \frac{2V_S}{\pi} - 0.7 = 15$$

assumed $V_S >> 0.7$ V

$$V_S = \frac{15+0.7}{2}\pi = 24.66 \text{ V}$$

Thus voltage across secondary winding

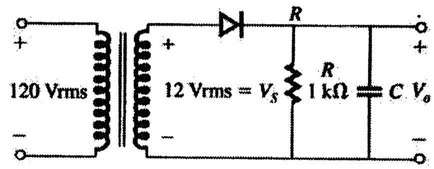
$$= 2V_S = 49.32 \text{ V}$$

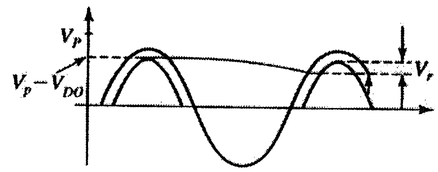
Looking at D_4

$$\text{PIV} = V_S - V_O^-$$
$$= V_S + (V_S - 0.7)$$
$$= 2V_S - 0.7$$
$$= 48.6 \text{ V}$$

If choosing a diode, allow a safety margin of $1.5\text{PIV} = 73$ V

3.61





(i) $v_r \cong (V_P - V_{DO})\frac{T}{CR}$ Eq. (4.28)

$$0.1(V_P - V_{DO}) = (V_P - V_{DO})\frac{T}{CR}$$

$$C = \frac{1}{0.1 \times 60 \times 10^3} = 166.7 \ \mu\text{F}$$

(ii) for

$$v_r = 0.01(V_P - V_{DO}) = \frac{(V_P - V_{DO})T}{CR}$$

(a)

(i) $v_{O,\,avg} = V_P - V_{DO} - \frac{1}{2}V_r$

$$= 12\sqrt{2} - 0.7 - \frac{1}{2}(12\sqrt{2} - 0.7)0.1$$

$$= (12\sqrt{2} - 0.7)\left(1 - \frac{0.1}{2}\right)$$

$$= 15.5 \text{ V}$$

ii) $v_{O,\,avg} = (12\sqrt{2} - 0.7)\left(1 - \frac{0.01}{2}\right)$

$$= 16.19 \text{ V}$$

(b)

i) we have the conduction angle =

$\omega\Delta t \cong \sqrt{2V_r/(V_p - V_{DO})}$

$= \sqrt{\frac{2 \times 0.1(V_P - 0.7)}{(V_P - 0.7)}}$

$= \sqrt{0.2}$

$= 0.447$ rad

∴ Fraction of cycle for

$$\text{conduction} = \frac{0.447}{2\pi} \times 100$$

$$= 7.1\%$$

(ii) $\omega\Delta t \simeq \sqrt{2 \times 0.01 \frac{(V_P - 0.7)}{V_P - 0.7}} = 0.141$ rad

Fraction of cycle $= \frac{0.141}{2\pi} \times 100 = 2.25\%$

(c)(i)

$$i_{D,\text{avg}} = I_L\left(1 + \pi\sqrt{\frac{2(V_P - V_{DO})}{V_r}}\right)$$

$$= \frac{V_{O,\text{avg}}}{R}\left(1 + \pi\sqrt{\frac{2(V_P - V_{DO})}{0.1(V_P - V_{DO})}}\right)$$

$$= \frac{15.5}{10^3}\left(1 + \pi\sqrt{\frac{2}{0.1}}\right)$$

$$= 233 \text{ mA}$$

(ii) $i_{D,\text{avg}} = \frac{16.19}{10^3}(1 + \pi\sqrt{200})$

$$= 735 \text{ mA}$$

NB next user $I_L \cong V_P/R = \frac{V_P - V_{DO}}{R}$

but here are used $i_{D,\text{avg}} = \frac{V_P - V_{DO} - \frac{1}{2}V_r}{R}$

which is more accurate.

(d) (i) $i_{D,\text{peak}} = I_L\left(1 + 2\pi\sqrt{\frac{2(V_P - V_{DO})}{V_r}}\right)$

$$= \frac{15.42}{10^3}\left(1 + 2\pi\sqrt{\frac{2}{0.1}}\right)$$

$$= 449 \text{ mA}$$

(ii) $i_{D,\text{peak}} = \frac{16.19}{10^3}\left(1 + 2\pi\sqrt{\frac{2}{0.01}}\right)$

$$= 1455 \text{ mA}$$

3.62

I) $v_r = 0.1(V_P - V_{DO} \times 2) = \frac{V_P 2 V_{DO}}{2fCR}$

discharge occurs only over $\frac{1}{2}T = \frac{1}{2f}$

$C = \frac{(V_P - 2V_{DO})}{(V_P - 2V_{DO})} \frac{1}{2(0.1)fR} = 83.3\ \mu F$

(ii) $C = \frac{1}{2(0.01)fR} = 833\ \mu F$

(b) (i) Fraction of cycle $= \frac{2\omega\Delta t}{2\pi} \times 100$

$= \sqrt{\frac{2(0.1)}{\pi}} \times 100 = 14.2\%$

(ii) Fraction of cycle

$= \sqrt{\frac{2(0.01)}{\pi}} \times 100 = 4.5\%$

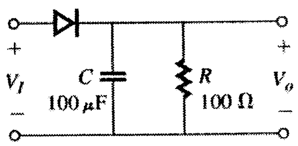
(c) i) $i_{D,avg} = \frac{14.79}{1}\left(1 + \pi\sqrt{\frac{1}{0.2}}\right) = 119\ mA$

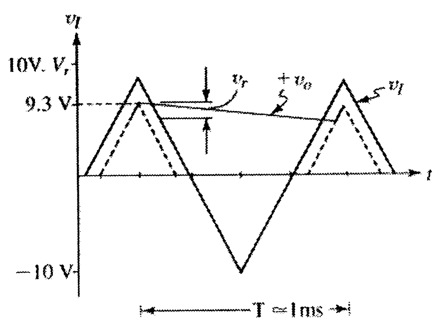
(ii) $i_{D,avg} = \frac{15.49}{1}(1 + \pi/\sqrt{0.02}) = 356\ mA$

(d) (i) $\hat{i}_D = \frac{14.79}{1}\left(1 + 2\pi\sqrt{\frac{1}{0.2}}\right) = 223\ mA$

(ii) $\hat{i}_D = \frac{15.49}{1}\left(1 + 2\pi\sqrt{\frac{1}{0.02}}\right) = 704\ mA$

3.63





During the diode's off interval, the capacitor dia-charges through the resistor R according to :

$v_o = 9.3\ e^{-t/RC} \cong 9.3(1 - T/CR)$

$\therefore v_r = 9.3 - 9.3(1 - T/CR)$

$= \frac{9.3T}{CR}$

$= \frac{9.3}{fCR}$ NB this is Eq(4.38)

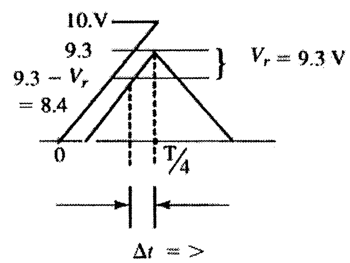
$= 0.93V$

$v_{o,avg} = V_D - V_{DO} - 1/2\ v_r$

$= 9.3 - \frac{1}{2}0.93$

$= 8.84\ V$

(b)



$\Delta t \Rightarrow \frac{10}{T/4} = \frac{0.93}{\Delta t}$

$\Delta t = 0.02325T$

$= 0.02325$ ms

(c) ∴ Charge gained during conduction = Charge lost during discharge

$i_{c,avg}\ \Delta t = C v_r$

$i_{c,avg} = \frac{C v_r}{\Delta t} = \frac{100 \times 10^{-6} \times 0.93}{0.02325 \times 10^{-3}}$

$= 4.0$ A

$i_{D,avg} \cong i_{c,avg} + i_{c,avg}\ \frac{v_{D,avg}}{R}$

$\cong 4.0 + \frac{8.84}{100} = 4.09A$

(d) $i_{c,\max} = C \left.\frac{\partial v_I}{\partial t}\right|_{\text{at onset of conduction}}$

$= C \frac{\partial v_I}{\partial t}$

$= 100 \times 10^{-6} \times 40 \times 10^3$

$= 4A$

$i_{D,\max} = i_{C,\max} + i_{L,\max}$

$= 4 + v_{o,\max} / 100$

$= 4 + 9.3 / 100$

$= 4.09\ A.$

Note that in this case $i_{D,avg} = i_{D,max}$ during to the linear input (i_c is constant and i_L is approximately constant).

3.64 let capacitor C be connected across each of the load resistors R. The two supplies, v_{0^+} and v_{0^-} are identical. Each is a full-wave rectifier similar to that based on the center-tapped-transformer circuit for each supply, the dc output is 15 V and the ripple is 1 V peak-to-peak. Thus $v_o = 15 \pm 1/2$ V. It follows that the peak value of v_s must be $15.5 + 0.7 = 16.2$ V.

∴ Voltage across secondary $= 2(16.2)$

$= 32.4$ V

RMS across secondary $= \frac{32.4}{\sqrt{2}} = 22.9$V rms

Turns Ratio $= \frac{120}{22.9} = 5.24{:}1$

Use Eq.(4.35) to find

$i_{D,\max} = I_L(1 + 2\pi\sqrt{V_P / 2V_r})$

$= 0.2(1 + 2\pi\sqrt{15.5/2})$

$= 3.70\ A$

$v_r = \frac{V_P}{2fCR} = 1$

Eq (4.28)

DISCHARGE OCCURS OVER $T/2 = \frac{1}{2f}$

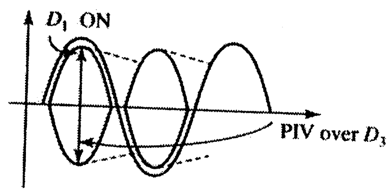
$\Rightarrow C = \frac{15.5}{2 \times 60 \times 75}$

where 200 mA $= \frac{15}{R}$

$R = \frac{15}{0.2} = 75\ \Omega$

$C = 1722\ \mu$F

Consider Ds when looking at PIV



PIV $= \hat{v}_0 + \hat{v}_S$

$= 15.5 + 16.2 = 31.7$ V.

Allowing for 50 % safety margin

PIV $= 1.5 \times 31.7 = 47.6\ V$

use Eq(4.34) to find

$i_{D,avg} = I_L(1 + \pi\sqrt{V_P / 2V_r})$

$= 0.2(1 + \pi\sqrt{15.5/2})$

$= 1.95$ A

3.65

$v_O = v_I(1 + R/R)$

$= 2v_I$ when the diode is conducting.

(a) $v_I = +1V$ $v_O = 2V$ $v_A = 1.7V$ $v_- = v_I = 1V$

b) $v_I = 2V$ $v_O = 4V$ $v_A = 4.7V$ $v_- = 2V$

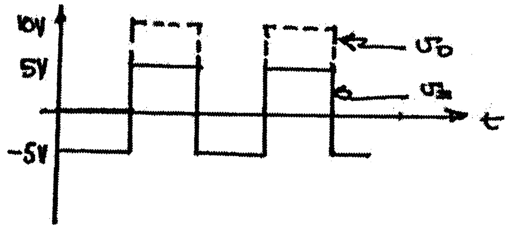
c) $v_I = -1V$ $v_A = -12V$ ~ diode is cut off

$v_O = 0V$

$v_- = 0V$

d)

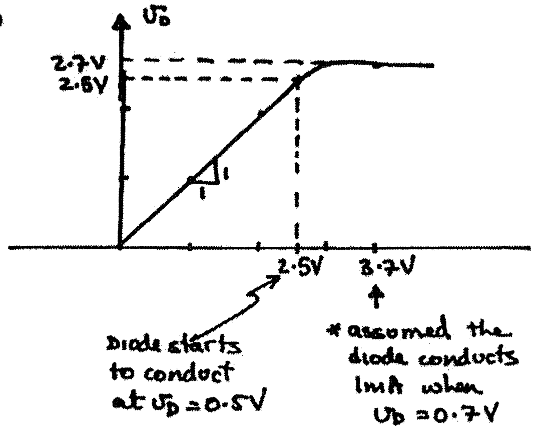
$v_I = -2$ V $v_A = -\underline{12V}$ $v_O = \underline{0V}$ $v_- = \underline{0V}$



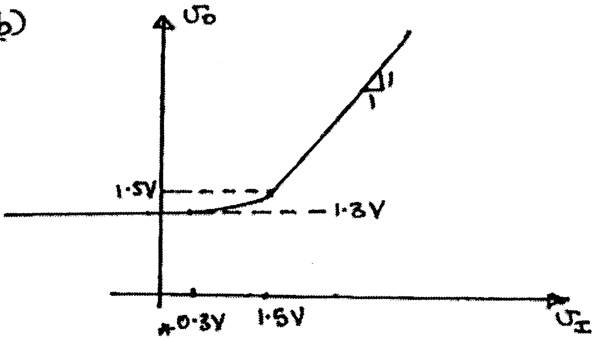
$v_{O,avg} = \underline{5V}$

3.66

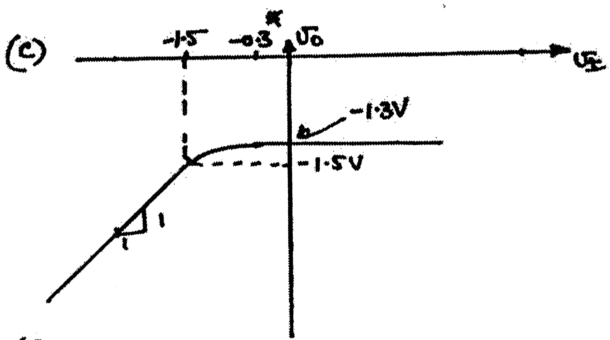
(a)



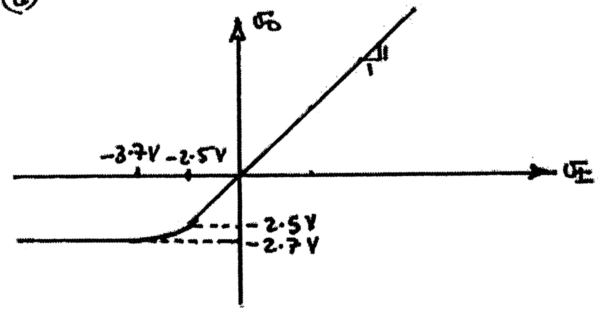
(b)



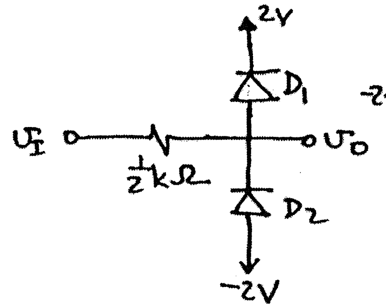
(c)



(d)



3.67



$-2.5 \leq v_I \leq 2.5$ ~ both D_1 & D_2 off

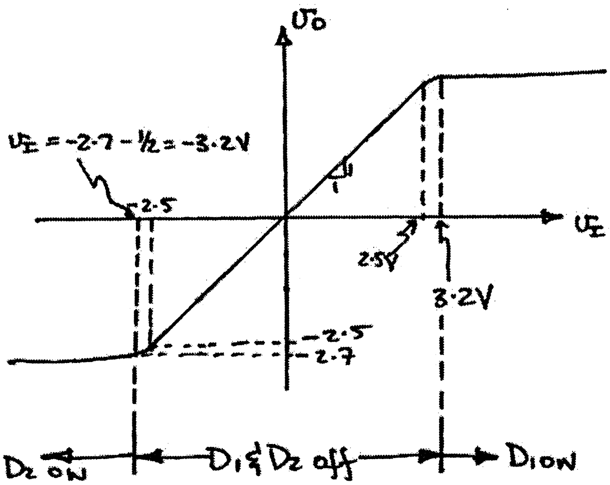
$v_O = v_I$

For $v_I \geq 2.5V$ ~ D_1 on

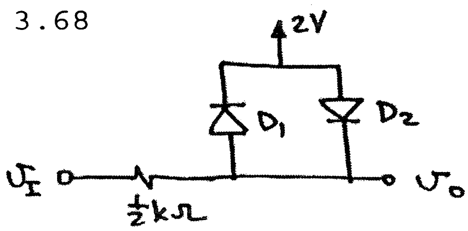
$v_{D1} = 0.7$ at $i_{D1} \geq 1mA$

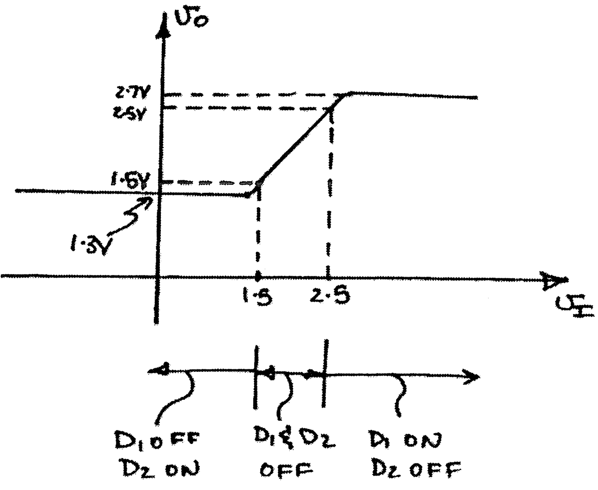
$v_O = 2.7V$ at $v_I = 2.7 + \frac{1}{2} \times 1$

$= \underline{3.2V}$



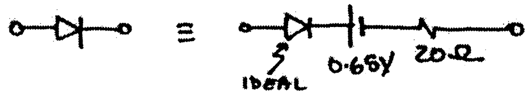
3.68



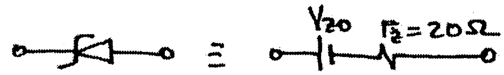


3.69

For each diode



For the zener diode



$$8.2 = V_{Z0} + 10\times10^{-3} \times 20$$

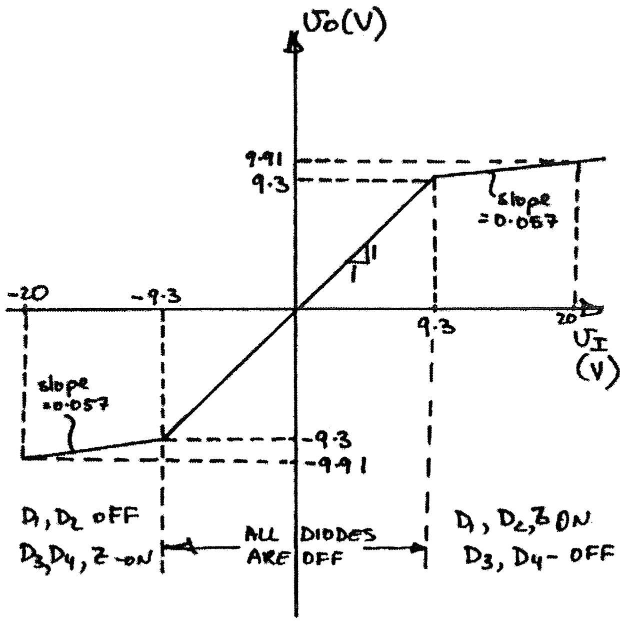
$$V_{Z0} = 8.0\text{V}$$

The limiter thresholds are

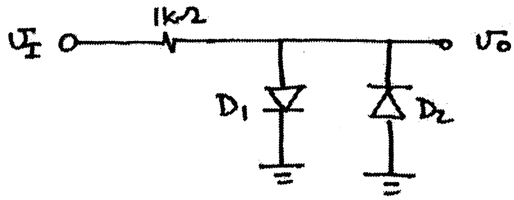
$$\pm(2\times0.65 + 8.0) = \pm 9.3\text{V}$$

For $v_I > 9.3$ (as well as for $v_I < -9.3$)

$$\frac{\partial v_O}{\partial v_I} = \frac{r_{D1} + r_Z + r_{D2}}{1k\Omega + r_{D1} + r_Z + r_{D2}} = \frac{3(20)}{1k\Omega + 3(20)} = 0.057 \frac{V}{V}$$



3.70



For D_1

Given $\frac{i_D}{1mA} = e^{\frac{v_O - 0.7}{nV_T}}$

$(v_O - 0.7) = nV_T \ln(i_D/1mA)$

$= 0.1 \log\left(\frac{i_D}{10^{-3}}\right)$ ← ∴ can find v_O from i_D

$\therefore i_D = 10^{-3} \times 10^{\frac{v_O - 0.7}{0.1}}$

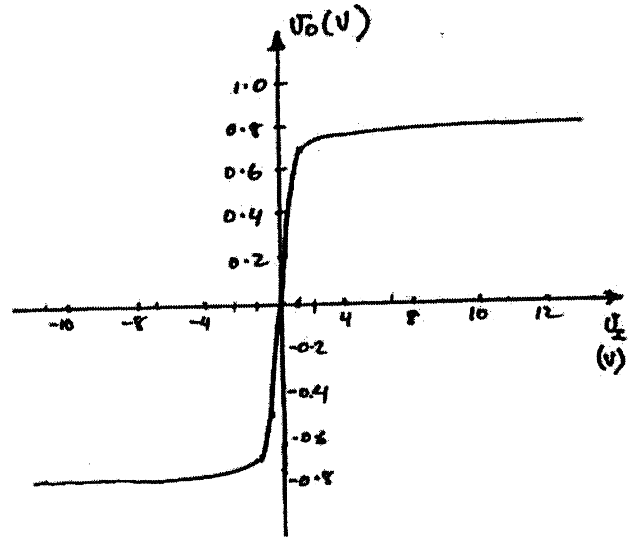
$= 10^{-3} \times 10^{10(v_O - 0.7)}$

& $v_I = v_O + i_D \times 10^3$

$= v_O + 10^{10(v_O - 0.7)}$

for D_2: $v_I = v_O - 10^{-10(v_O - 0.7)}$

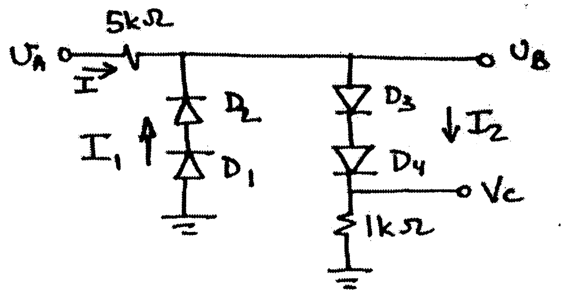
v_O (V)	v_I (V)	
0.5	0.510	D_1 ON
0.6	0.7	D_1 ON
0.7	1.7	D_1 ON
0.8	10.7	D_1 ON
0	0	
−0.5	−0.51	D_2 ON
−0.6	−0.7	D_2 ON
−0.7	−1.7	D_2 ON
−0.8	−10.7	D_2 ON



The limiter is fairly hard with a gain $K \cong 1$

$L_+ \cong 0.8V$, $L_- \cong -0.8V$

3.71



$V_D = 0.7 + 0.1 \log (i_D/0.1)$

(a) For $V_A > 0$ D_1, D_2 off $\Rightarrow I_1 = 0$

$I = I_2 = V_C/1k\Omega$ $V_A = V_B + I_2 5$

(b) For $V_I < 0$ D_3, D_4 off $\Rightarrow V_C = 0$

$I = -I_1$ $V_B = -(V_{D1} + V_{D2})$

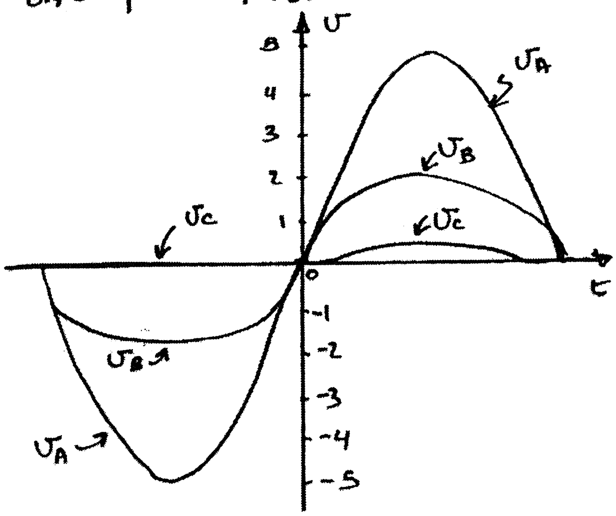
$V_A = -(V_B + 5I_1)$

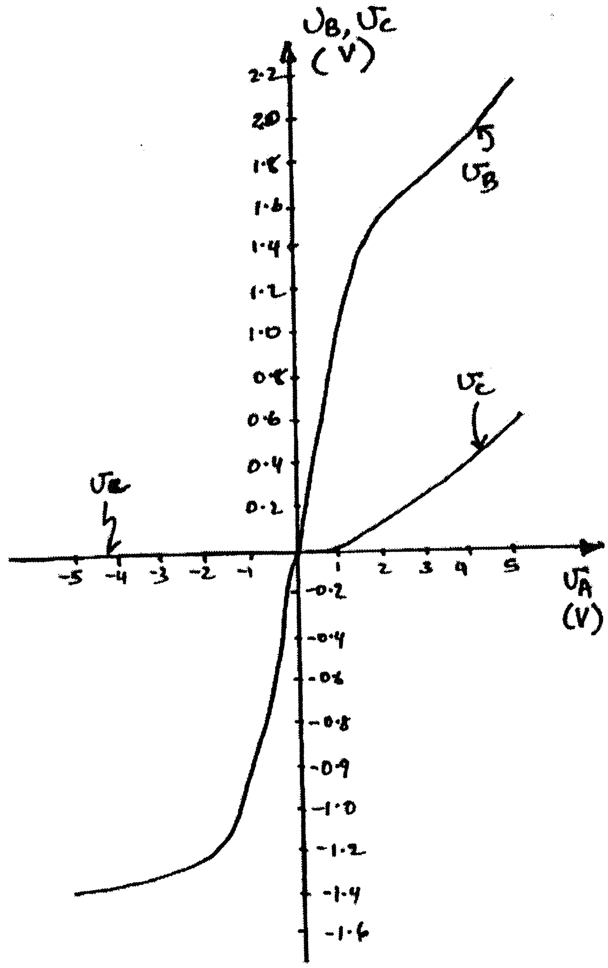
(a) List of points for $V_A > 0$

V_C (V)	I_2 (mA)	V_{D3}, V_{D4} (V)	$V_B = V_C + V_{D3} + V_{D4}$ (V)	V_A (V)
0.0001	0.0001	0.4	0.8	0.8
0.001	0.001	0.5	1.00	1.01
0.01	0.1	0.6	1.21	1.26
0.1	0.1	0.7	1.50	1.90
0.2	0.2	0.73	1.66	2.66
0.3	0.3	0.75	1.80	3.30
0.4	0.4	0.76	1.92	3.92
0.5	0.5	0.77	2.04	4.54
0.6	0.6	0.78	2.16	5.16

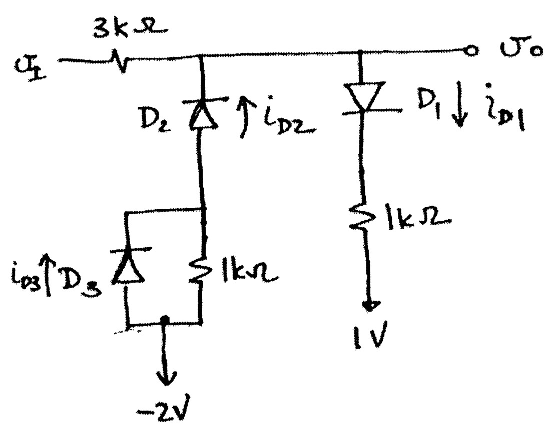
(b) List of Points for $V_A < 0$

I_1 (mA)	v_{D1}, v_{D2} (V)	v_B (V)	v_A (V)
0.0001	0.4	−0.80	−0.80
0.001	0.5	−1.00	−1.01
0.01	0.6	−1.20	−1.25
0.10	0.7	−1.40	−1.90
0.20	0.73	−1.46	−2.46
0.30	0.75	−1.50	−3.00
0.40	0.76	−1.52	−3.52
0.50	0.77	−1.54	−4.04
0.60	0.78	−1.56	−4.56
0.70	0.785	−1.57	−5.07





3.72



At currents $i_{D1} > 1mA$, $v_{D1} \simeq 0.7V$

Let $v_{D1} = 0.71V$ $\quad v_I > 5.7V$

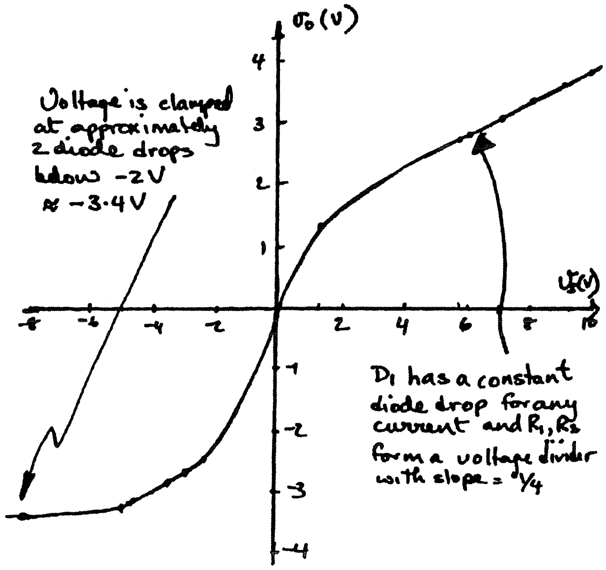
$$v_O = 1.71 + i_{D1} \times 1k\Omega$$

$$= 1.71 + \left(\frac{v_I - 1.71}{4}\right) \times 1$$

$$= \frac{v_I}{4} + 1.2825 \qquad \text{HB slope} = 1/4$$

$\therefore$ for $v_I > 5V$ slope $v_O/v_I \approx 1/4$

v_I (V)	v_O (V)
5.8	2.7325
6.0	2.7825
7.0	3.0325
8.0	3.2825
9.0	3.5325
10.0	3.7825



where points for $-8 \le v_I \le 6$ V are calculated as shown below:

$i_D = 1mA$ at $v_D = 0.7V$ $\quad n = 1$

$$i_D = I_S e^{0.7/0.025} = 10^{-3}$$

$$I_S = 6.914 \times 10^{-16} A.$$

$\therefore$ For Diodes use $\underline{i_D = 6.914 \times 10^{-16} e^{v_D/0.025}}$

D_1 conducting $\quad i_{D2} = 0$

i_{D1} (A)	v_{D1} (V)	v_O (V)	$v_I = (4k)i_{D1} + v_{D1} + 1$ (V)
10^{-10}	0.297	1.297	1.297
10^{-6}	0.527	1.528	1.5313
10^{-5}	0.584	1.595	1.625
10^{-4}	0.64	1.742	2.042
10^{-3}	0.70	2.7	5.7
0.2×10^{-2}	0.74	6.74	12.74
10^{-2}	0.758	11.75	41.75

← even at small i_{D1}, $v_O > 1V$, $v_O \approx v_I$ since $i_{D1} \approx 0$

For the D_2, D_3 arm conducting use the following equations:
Note $v_I < -2.5V$

Starting with a value for V_A ① we have

$$V_{D3} = V_A + 2$$

$$i_{D3} = I_S e^{v_{D3}/0.025} \qquad ②$$

$$i_{D2} = i_{D3} + \frac{V_A + 2}{1} \qquad ③$$

$$v_{D2} = 0.025 \ln\left(\frac{i_{D2}}{6.914 \times 10^{-16}}\right) \qquad ④$$

$$v_O = v_A - v_{D2} \qquad ⑤$$

$$v_I = v_O - i_{D2} \times 3k\Omega \qquad ⑥$$

① v_A (V)	② i_{D3} (A)	③ i_{D2} (A)	④ v_{D2} (V)	⑤ v_O (V)	⑥ v_I (V)
−2.001	7×10^{-16}	10^{-6}	0.527	−2.528	−2.531 Ⓐ
−2.01	10^{-15}	10^{-5}	0.585	−2.595	−2.625
−2.10	3.8×10^{-14}	10^{-4}	0.642	−2.724	−3.024
−2.20	2×10^{-12}	0.2×10^{-3}	0.659	−2.859	−3.459
−2.5	33 μA	0.5×10^{-3}	0.682	−3.128	−4.628 Ⓑ
−2.6	18 μA	0.6×10^{-3}	0.687	−3.287	−5.087
−2.7	1 mA	1.7×10^{-3}	0.713	−3.413	−8.516 Ⓒ
−2.71	1.5 mA	2.2 mA	0.720	−3.43	−10

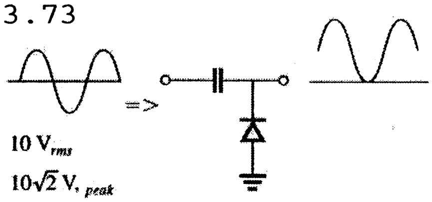
Ⓐ for small i_{D2}, D_3 is off and D_2 is on
$\therefore$ i_2 flows through $1k\Omega$ resistor

CONT.

(B) 0.5 V drop across D_3 causes D_3 to start to conduct

(C) $U_A = -2.7V$
The 0.7 voltage across D_3 clamps the voltage across R_3 so that D_3 control the current i_{D2}

3.73



Average (dc) value of output = $10\sqrt{2}$
$= 14.14\ V$