

Solutions Manual - Microelectronic Circuit Design - 4th Ed

By Richard C. Jaeger, Travis N. Blalock - McGraw-Hill (2010)

NOTE: these answers are for the International Edition (?)

But they're still very similar to the original (sometimes a, b, c, d answers will be switched around, and some numbers may be a little off. As a general rule, subtract 3 from the answer you are looking for and that should be the real one)

Special thanks to Moser from NIU for the main files

February 1, 2012

Go to this website for book updates / corrections by the publisher:

<http://www.jaegerblalock.com/>

1.1

Answering machine
Alarm clock
Automatic door
Automatic lights
ATM
Automobile:
 Engine controller
 Temperature control
 ABS
 Electronic dash
 Navigation system
Automotive tune-up equipment
Baggage scanner
Bar code scanner
Battery charger
Cable/DSL Modems and routers
Calculator
Camcorder
Carbon monoxide detector
Cash register
CD and DVD players
Ceiling fan (remote)
Cellular phones
Coffee maker
Compass
Copy machine
Cordless phone
Depth finder
Digital Camera
Digital watch
Digital voice recorder
Digital scale
Digital thermometer
Electronic dart board
Electric guitar
Electronic door bell
Electronic gas pump
Elevator
Exercise machine
Fax machine
Fish finder
Garage door opener
GPS
Hearing aid
Invisible dog fences
Laser pointer
LCD projector
Light dimmer
Keyboard synthesizer
Keyless entry system
Laboratory instruments
Metal detector
Microwave oven
Model airplanes
MP3 player
Musical greeting cards
Musical tuner
Pagers
Personal computer
Personal planner/organizer (PDA)
Radar detector
Broadcast Radio (AM/FM/Shortwave)
Razor
Satellite radio receiver
Security systems
Sewing machine
Smoke detector
Sprinkler system
Stereo system
 Amplifier
 CD/DVD player
 Receiver
 Tape player
Stud sensor
Talking toys
Telephone
Telescope controller
Thermostats
Toy robots
Traffic light controller
TV receiver & remote control
Variable speed appliances
 Blender
 Drill
 Mixer
 Food processor
 Fan
Vending machines
Video game controllers
Wireless headphones & speakers
Wireless thermometer
Workstations

Electromechanical Appliances*

Air conditioning and heating systems
Clothes washer and dryer
Dish washer
Electrical timer
Iron, vacuum cleaner, toaster
Oven, refrigerator, stove, etc.

*These appliances are historically based only upon on-off (bang-bang) control. However, many of the high end versions of these appliances have now added sophisticated electronic control.

1.2

$$B = 19.97 \times 10^{0.1997(2020-1960)} = 14.5 \times 10^{12} = 14.5 \text{ Tb/chip}$$

1.3

(a)

$$\frac{B_2}{B_1} = \frac{19.97 \times 10^{0.1977(Y_2-1960)}}{19.97 \times 10^{0.1977(Y_1-1960)}} = 10^{0.1977(Y_2-Y_1)} \text{ so } 2 = 10^{0.1977(Y_2-Y_1)}$$

$$Y_2 - Y_1 = \frac{\log 2}{0.1977} = 1.52 \text{ years}$$

(b) $Y_2 - Y_1 = \frac{\log 10}{0.1977} = 5.06 \text{ years}$

1.4

$$N = 1610 \times 10^{0.1548(2020-1970)} = 8.85 \times 10^{10} \text{ transistors}/\mu\text{P}$$

1.5

$$\frac{N_2}{N_1} = \frac{1610 \times 10^{0.1548(Y_2-1970)}}{1610 \times 10^{0.1548(Y_1-1970)}} = 10^{0.1548(Y_2-Y_1)}$$

$$(a) Y_2 - Y_1 = \frac{\log 2}{0.1548} = 1.95 \text{ years}$$

$$(b) Y_2 - Y_1 = \frac{\log 10}{0.1548} = 6.46 \text{ years}$$

1.6 $F = 8.00 \times 10^{-0.05806(2020-1970)} \mu\text{m} = 10 \text{ nm}.$

No, this distance corresponds to the diameter of only a few atoms. Also, the wavelength of the radiation needed to expose such patterns during fabrication is represents a serious problem.

1.7

From Fig. 1.4, there are approximately 600 million transistors on a complex Pentium IV microprocessor in 2004. From Prob. 1.4, the number of transistors/ μP will be 8.85×10^{10} . in 2020. Thus there will be the equivalent of $8.85 \times 10^{10} / 6 \times 10^8 = 148$ Pentium IV processors.

1.8

$$P = (75 \times 10^6 \text{ tubes}) (1.5 \text{ W/tube}) = 113 \text{ MW!} \quad I = \frac{1.13 \times 10^8 \text{ W}}{220 \text{ V}} = 511 \text{ kA!}$$

1.9 D, D, A, A, D, A, A, D, A, D, A**1.10**

$$V_{LSB} = \frac{10.24V}{2^{12} \text{ bits}} = \frac{10.24V}{4096 \text{ bits}} = 2.500 \text{ mV} \quad V_{MSB} = \frac{10.24V}{2} = 5.120V$$

$$100100100110_2 = 2^{11} + 2^8 + 2^5 + 2^2 + 2 = 2342_{10} \quad V_o = 2342(2.500 \text{ mV}) = 5.855 \text{ V}$$

1.11

$$V_{LSB} = \frac{5V}{2^8 \text{ bits}} = \frac{5V}{256 \text{ bits}} = 19.53 \frac{\text{mV}}{\text{bit}} \quad \text{and} \quad \frac{2.77V}{19.53 \frac{\text{mV}}{\text{bit}}} = 142 \text{ LSB}$$

$$142_{10} = (128 + 8 + 4 + 2)_{10} = 10001110_2$$

1.12

$$V_{LSB} = \frac{2.5V}{2^{10} \text{ bits}} = \frac{2.5V}{1024 \text{ bits}} = 2.44 \frac{\text{mV}}{\text{bit}}$$

$$0101101101_2 = (2^8 + 2^6 + 2^5 + 2^3 + 2^2 + 2^0)_{10} = 365_{10} \quad V_o = 365 \left(\frac{2.5V}{1024} \right) = 0.891 \text{ V}$$

1.13

$$V_{LSB} = \frac{10V}{2^{14} \text{ bits}} = 0.6104 \frac{\text{mV}}{\text{bit}} \quad \text{and} \quad \frac{6.83V}{10V} (2^{14} \text{ bits}) = 11191 \text{ bits}$$

$$11191_{10} = (8192 + 2048 + 512 + 256 + 128 + 32 + 16 + 4 + 2 + 1)_{10}$$

$$11191_{10} = 10101110110111_2$$

1.14

A 4 digit readout ranges from 0000 to 9999 and has a resolution of 1 part in 10,000. The number of bits must satisfy $2^B \geq 10,000$ where B is the number of bits. Here B = 14 bits.

1.15

$$V_{LSB} = \frac{5.12V}{2^{12} \text{ bits}} = \frac{5.12V}{4096 \text{ bits}} = 1.25 \frac{\text{mV}}{\text{bit}} \quad \text{and} \quad V_o = (101110111011_2) V_{LSB} \pm \frac{V_{LSB}}{2}$$

$$V_o = (2^{11} + 2^9 + 2^8 + 2^7 + 2^5 + 2^4 + 2^3 + 2 + 1)_{10} 1.25 \text{ mV} \pm 0.0625 \text{ V}$$

$$V_o = 3.754 \pm 0.000625 \quad \text{or} \quad 3.753 \text{ V} \leq V_o \leq 3.755 \text{ V}$$

1.16

$I_B = \text{dc component} = 0.002 \text{ A}$, $i_b = \text{signal component} = 0.002 \cos(1000t) \text{ A}$

1.17

$V_{GS} = 4 \text{ V}$, $v_{gs} = 0.5u(t-1) + 0.2 \cos 2000\pi t \text{ Volts}$

1.18

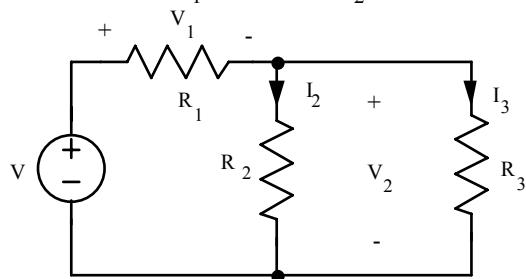
$v_{CE} = [5 + 2 \cos(5000t)] \text{ V}$

1.19

$v_{DS} = [5 + 2 \sin(2500t) + 4 \sin(1000t)] \text{ V}$

1.20

$V = 10 \text{ V}$, $R_1 = 22 \text{ k}\Omega$, $R_2 = 47 \text{ k}\Omega$ and $R_3 = 180 \text{ k}\Omega$.



$$V_1 = 10V \frac{22k\Omega}{22k\Omega + (47k\Omega \parallel 180k\Omega)} = 10V \frac{22k\Omega}{22k\Omega + 37.3k\Omega} = 3.71 \text{ V}$$

$$V_2 = 10V \frac{37.3k\Omega}{22k\Omega + 37.3k\Omega} = 6.29 \text{ V} \quad \text{Checking: } 6.29 + 3.71 = 10.0 \text{ V}$$

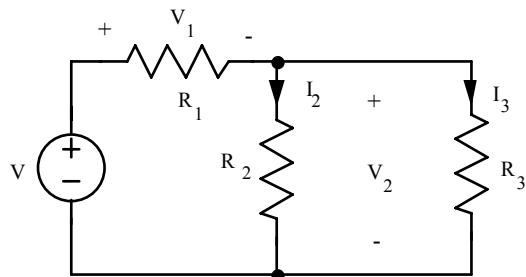
$$I_2 = I_1 \frac{180k\Omega}{47k\Omega + 180k\Omega} = \left(\frac{10V}{22k\Omega + 37.3k\Omega} \right) \frac{180k\Omega}{47k\Omega + 180k\Omega} = 134 \mu\text{A}$$

$$I_3 = I_1 \frac{47k\Omega}{47k\Omega + 180k\Omega} = \left(\frac{10V}{22k\Omega + 37.3k\Omega} \right) \frac{47k\Omega}{47k\Omega + 180k\Omega} = 34.9 \mu\text{A}$$

$$\text{Checking: } I_1 = \frac{10V}{22k\Omega + 37.3k\Omega} = 169 \mu\text{A} \text{ and } I_1 = I_2 + I_3$$

1.21

$V = 18 \text{ V}$, $R_1 = 56 \text{ k}\Omega$, $R_2 = 33 \text{ k}\Omega$ and $R_3 = 11 \text{ k}\Omega$.



$$V_1 = 18V \frac{56k\Omega}{56k\Omega + (33k\Omega \parallel 11k\Omega)} = 15.7 \text{ V} \quad V_2 = 18V \frac{33k\Omega \parallel 11k\Omega}{56k\Omega + (33k\Omega \parallel 11k\Omega)} = 2.31 \text{ V}$$

Checking : $V_1 + V_2 = 15.7 + 2.31 = 18.0 \text{ V}$ which is correct.

$$I_1 = \frac{18V}{56k\Omega + (33k\Omega \parallel 11k\Omega)} = 280 \mu\text{A} \quad I_2 = I_1 \frac{11k\Omega}{33k\Omega + 11k\Omega} = (280 \mu\text{A}) \frac{11k\Omega}{33k\Omega + 11k\Omega} = 70.0 \mu\text{A}$$

$$I_3 = I_1 \frac{33k\Omega}{33k\Omega + 11k\Omega} = (280 \mu\text{A}) \frac{33k\Omega}{33k\Omega + 11k\Omega} = 210 \mu\text{A} \quad \text{Checking : } I_2 + I_3 = 280 \mu\text{A}$$

1.22

$$I_1 = 5mA \frac{(5.6k\Omega + 3.6k\Omega)}{(5.6k\Omega + 3.6k\Omega) + 2.4k\Omega} = 3.97 mA \quad I_2 = 5mA \frac{2.4k\Omega}{9.2k\Omega + 2.4k\Omega} = 1.03 mA$$

$$V_3 = 5mA(2.4k\Omega \parallel 9.2k\Omega) \frac{3.6k\Omega}{5.6k\Omega + 3.6k\Omega} = 3.72V$$

Checking : $I_1 + I_2 = 5.00 \text{ mA}$ and $I_2 R_2 = 1.03mA(3.6k\Omega) = 3.71 \text{ V}$

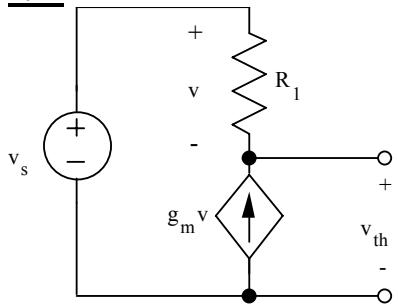
1.23

$$I_2 = 250\mu\text{A} \frac{150k\Omega}{150k\Omega + 150k\Omega} = 125 \mu\text{A} \quad I_3 = 250\mu\text{A} \frac{150k\Omega}{150k\Omega + 150k\Omega} = 125 \mu\text{A}$$

$$V_3 = 250\mu\text{A}(150k\Omega \parallel 150k\Omega) \frac{82k\Omega}{68k\Omega + 82k\Omega} = 10.3V$$

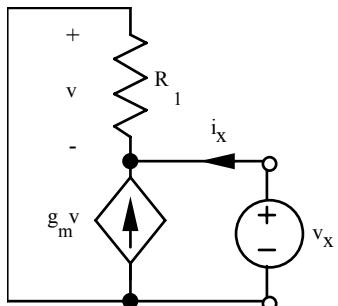
Checking : $I_1 + I_2 = 250 \mu\text{A}$ and $I_2 R_2 = 125\mu\text{A}(82k\Omega) = 10.3 \text{ V}$

1.24



Summing currents at the output node yields:

$$\frac{v}{5 \times 10^4} + .002v = 0 \text{ so } v = 0 \text{ and } v_{th} = v_s - v = v_s$$

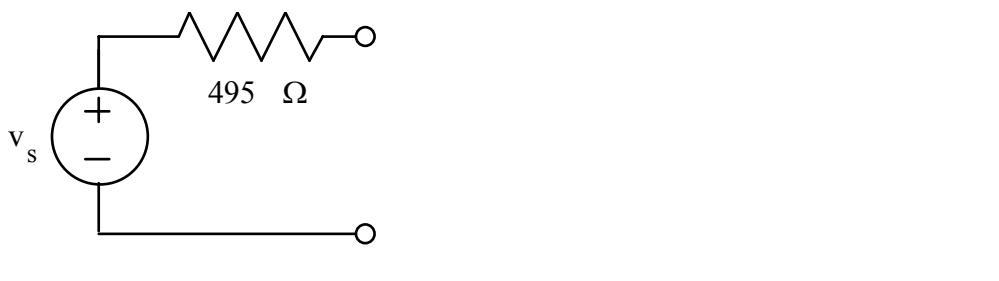


Summing currents at the output node:

$$i_x = -\frac{v}{5 \times 10^4} - 0.002v = 0 \text{ but } v = -v_x$$

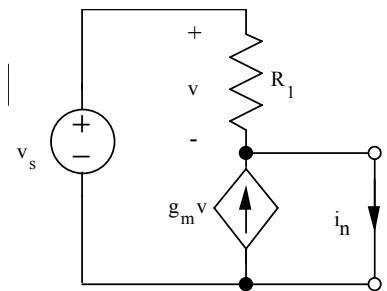
$$i_x = \frac{v_x}{5 \times 10^4} + 0.002v_x = 0 \quad R_h = \frac{v_x}{i_x} = \frac{1}{\frac{1}{R_l} + g_m} = 495 \Omega$$

Thévenin equivalent circuit:



1.25 The Thévenin equivalent resistance is found using the same approach as Problem 1.24, and

$$R_{th} = \left(\frac{1}{4k\Omega} + .025 \right)^{-1} = 39.6 \Omega$$

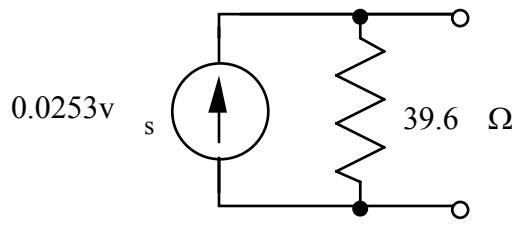


The short circuit current is:

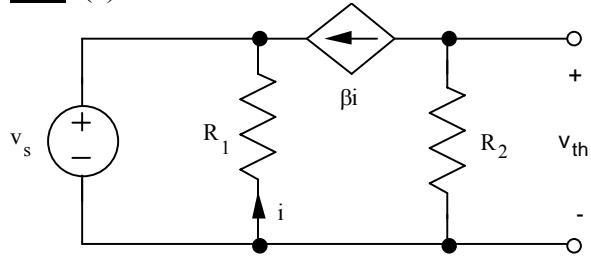
$$i_n = \frac{v}{4k\Omega} + 0.025v \text{ and } v = v_s$$

$$i_n = \frac{v_s}{4k\Omega} + 0.025v_s = 0.0253v_s$$

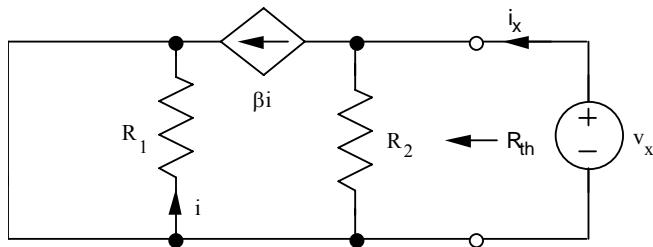
Norton equivalent circuit:



1.26 (a)

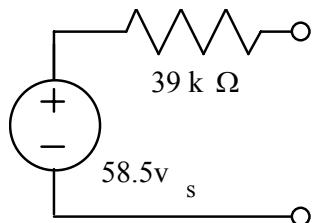


$$V_{th} = V_{oc} = -\beta i R_2 \quad \text{but} \quad i = -\frac{v_s}{R_1} \quad \text{and} \quad V_{th} = \beta v_s \frac{R_2}{R_1} = 120 v_s \frac{39k\Omega}{100k\Omega} = 46.8 v_s$$

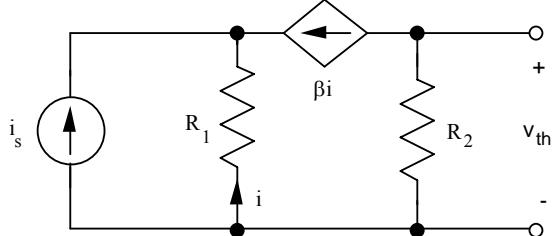


$$R_{th} = \frac{v_x}{i_x} ; \quad i_x = \frac{v_x}{R_2} + \beta i \quad \text{but} \quad i = 0 \quad \text{since} \quad V_{R_1} = 0. \quad R_{th} = R_2 = 39 k\Omega.$$

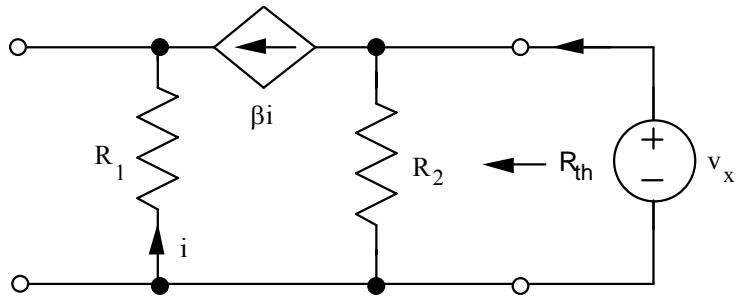
Thévenin equivalent circuit:



(b)

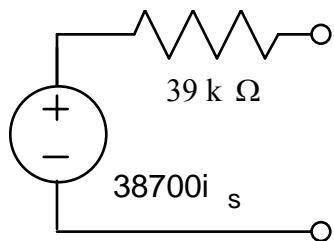


$$V_{th} = V_{oc} = -\beta i R_2 \quad \text{where} \quad i + bi + i_s = 0 \quad \text{and} \quad V_{th} = -\beta \left(-\frac{i_s}{\beta + 1} \right) R_2 = 38700 i_s$$

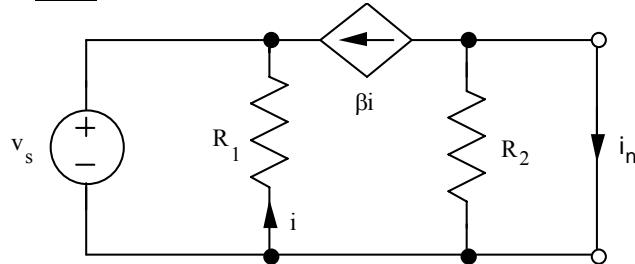


$$R_{th} = \frac{v_x}{i_x} ; \quad i_x = \frac{v_x}{R_2} + \beta i \quad \text{but} \quad i + \beta i = 0 \quad \text{so} \quad i = 0 \quad \text{and} \quad R_{th} = R_2 = 39 \text{ k}\Omega$$

Thévenin equivalent circuit:

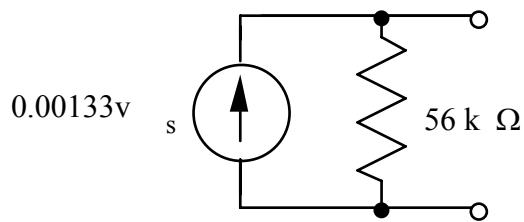


1.27

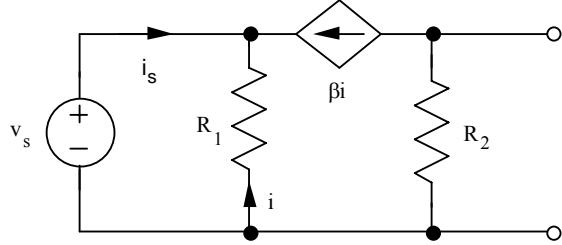


$$i_n = -\beta i \quad \text{but} \quad i = -\frac{v_s}{R_1} \quad \text{and} \quad i_n = \frac{\beta}{R_1} v_s = \frac{100}{75k\Omega} v_s = 1.33 \times 10^{-3} v_s$$

From problem 1.26(a), $R_{th} = R_2 = 56 \text{ k}\Omega$. Norton equivalent circuit:



1.28



$$i_s = \frac{v_s}{R_l} - \beta i = \frac{v_s}{R_l} + \beta \frac{v_s}{R_l} = v_s \frac{\beta + 1}{R_l} \quad R = \frac{v_s}{i_s} = \frac{R_l}{\beta + 1} = \frac{100k\Omega}{81} = 1.24 \Omega$$

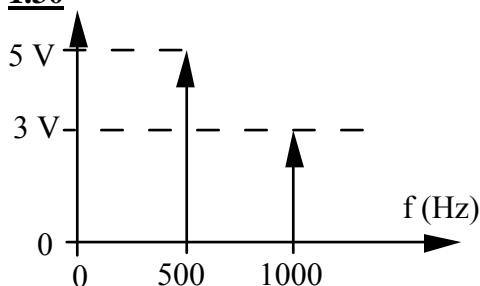
1.29

The open circuit voltage is $v_{th} = -g_m v R_2$ and $v = +i_s R_l$.

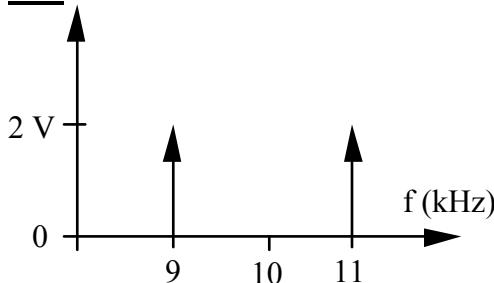
$$v_{th} = -g_m R_l R_2 i_s = -(0.0025)(10^5)(10^6) i_s = 2.5 \times 10^8 i_s$$

For $i_s = 0$, $v = 0$ and $R_{th} = R_2 = 1 M\Omega$

1.30



1.31



$$v = 4 \sin(20000\pi t) \sin(2000\pi t) = \frac{4}{2} [\cos(20000\pi t + 2000\pi t) + \cos(20000\pi t - 2000\pi t)]$$

$$v = 2 \cos(22000\pi t) + 2 \cos(18000\pi t)$$

1.32

$$A = \frac{2 \angle 36^\circ}{10^{-5} \angle 0^\circ} = 2 \times 10^5 \angle 36^\circ \quad |A| = 2 \times 10^5 \quad \angle A = 36^\circ$$

1.33

$$(a) A = \frac{10^{-2} \angle -45^\circ}{2 \times 10^{-3} \angle 0^\circ} = 5 \angle -45^\circ \quad (b) A = \frac{10^{-1} \angle -12^\circ}{10^{-3} \angle 0^\circ} = 100 \angle -12^\circ$$

1.34

$$(a) A_v = -\frac{R_2}{R_1} = -\frac{620k\Omega}{14k\Omega} = -44.3 \quad (b) A_v = -\frac{180k\Omega}{18k\Omega} = -10.0 \quad (c) A_v = -\frac{62k\Omega}{1.6k\Omega} = -38.8$$

1.35

$$v_o(t) = -\frac{R_2}{R_1} v_s(t) = (-90.1 \sin 750\pi t) \text{ mV}$$

$$I_s = \frac{V_s}{R_1} = \frac{0.01V}{910\Omega} = 11.0 \mu A \quad \text{and} \quad i_s = (11.0 \sin 750\pi t) \mu A$$

1.36 Since the voltage across the op amp input terminals must be zero, $v_- = v_+$ and $v_o = v_s$. Therefore $A_v = 1$.

1.37 Since the voltage across the op amp input terminals must be zero, $v_- = v_+ = v_s$. Also, $i_- = 0$.

$$\frac{v_- - v_o}{R_2} + i_- + \frac{v_-}{R_1} = 0 \quad \text{or} \quad \frac{v_s - v_o}{R_2} + \frac{v_s}{R_1} = 0 \quad \text{and} \quad A_v = \frac{v_o}{v_s} = 1 + \frac{R_2}{R_1}$$

1.38 Writing a nodal equation at the inverting input terminal of the op amp gives

$$\frac{v_1 - v_-}{R_1} + \frac{v_2 - v_-}{R_2} = i_- + \frac{v_- - v_o}{R_3} \quad \text{but} \quad v_- = v_+ = 0 \quad \text{and} \quad i_- = 0$$

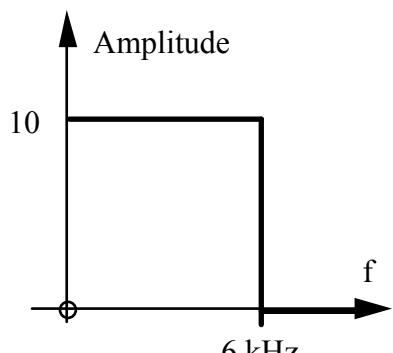
$$v_o = -\frac{R_3}{R_1} v_1 - \frac{R_3}{R_2} v_2 = -0.255 \sin 3770t - 0.255 \sin 10000t \text{ volts}$$

1.39

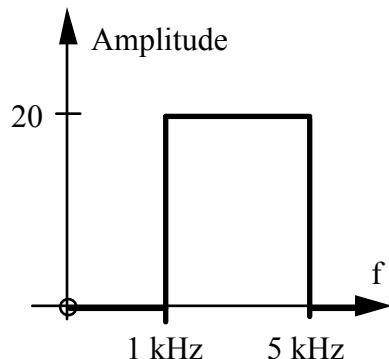
$$v_o = -V_{REF} \left(\frac{b_1}{2} + \frac{b_2}{4} + \frac{b_3}{8} \right)$$

(a) $v_o = -5 \left(\frac{0}{2} + \frac{1}{4} + \frac{1}{8} \right) = -1.875V$ (b) $v_o = -5 \left(\frac{1}{2} + \frac{0}{4} + \frac{0}{8} \right) = -2.500V$

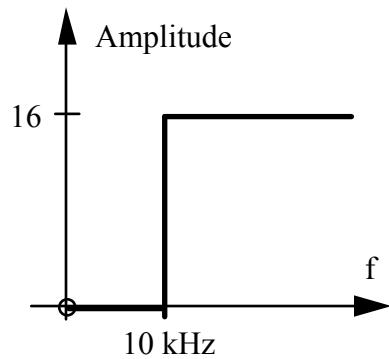
b ₁ b ₂ b ₃	v _O (V)
000	0
001	-0.625
010	-1.250
011	-1.875
100	-2.500
101	-3.125
110	-3.750
111	-4.375

1.40 Low-pass amplifier

1.41 Band-pass amplifier



1.42 High-pass amplifier



1.43

$$v_o(t) = 10 \times 5 \sin(2000\pi t) + 10 \times 3 \cos(8000\pi t) + 0 \times 3 \cos(15000\pi t)$$

$$v_o(t) = [50 \sin(2000\pi t) + 30 \cos(8000\pi t)] \text{ volts}$$

1.44

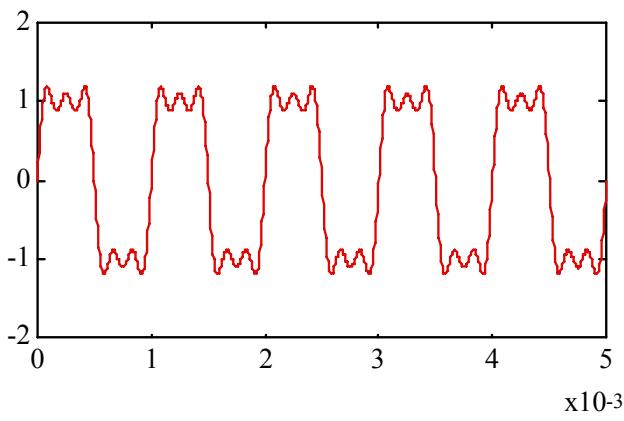
$$v_o(t) = 20 \times 0.5 \sin(2500\pi t) + 20 \times 0.75 \cos(8000\pi t) + 0 \times 0.6 \cos(12000\pi t)$$

$$v_o(t) = [10.0 \sin(2500\pi t) + 15.0 \cos(8000\pi t)] \text{ volts}$$

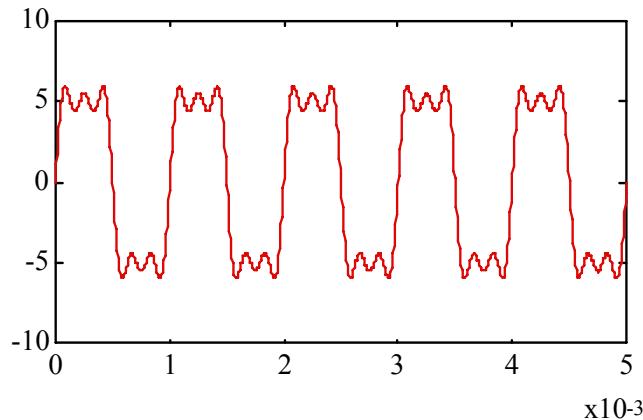
1.45 The gain is zero at each frequency: $v_o(t) = 0$.

1.46

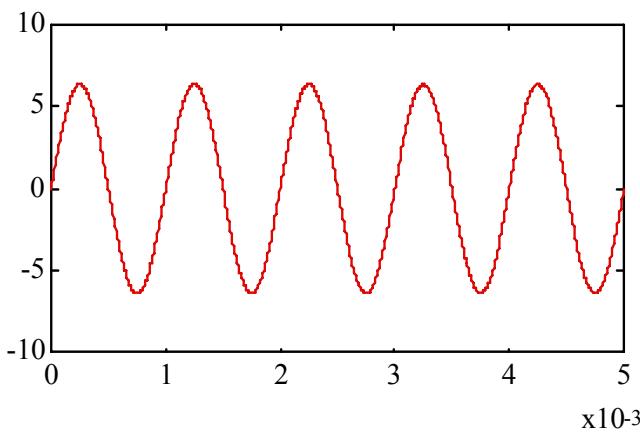
```
t=linspace(0,.005,1000);
w=2*pi*1000;
v=(4/pi)*(sin(w*t)+sin(3*w*t)/3+sin(5*w*t)/5);
v1=5*v;
v2=5*(4/pi)*sin(w*t);
v3=(4/pi)*(5*sin(w*t)+3*sin(3*w*t)/3+sin(5*w*t)/5);
plot(t,v)
plot(t,v1)
plot(t,v2)
plot(t,v3)
```



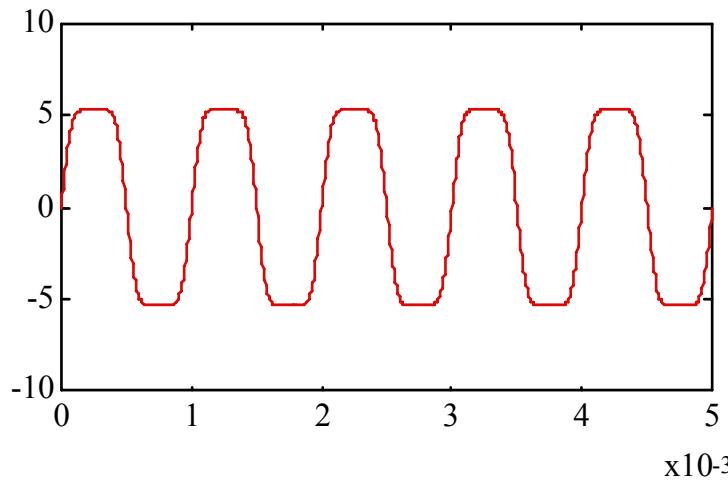
(a)



(b)



(c)



(d)

1.47

- (a) $3000(1-.01) \leq R \leq 3000(1+.01)$ or $2970\Omega \leq R \leq 3030\Omega$
- (b) $3000(1-.05) \leq R \leq 3000(1+.05)$ or $2850\Omega \leq R \leq 3150\Omega$
- (c) $3000(1-.10) \leq R \leq 3000(1+.10)$ or $2700\Omega \leq R \leq 3300\Omega$

1.48

$$V_{nom} = 2.5V \quad |\Delta V| \leq 0.05V \quad T = \frac{0.05}{2.50} = 0.0200 \text{ or } 2.00\%$$

1.49

$$20000\mu F(1-.5) \leq C \leq 20000\mu F(1+.2) \text{ or } 10000\mu F \leq R \leq 24000\mu F$$

1.50

$$8200(1-0.1) \leq R \leq 8200(1+0.1) \text{ or } 7380\Omega \leq R \leq 9020\Omega$$

The resistor is within the allowable range of values.

1.51

(a) $5V(1-.05) \leq V \leq 5V(1+.05)$ or $5.75V \leq V \leq 5.25V$

$V = 5.30$ V exceeds the maximum range, so it is out of the specification limits.

(b) If the meter is reading 1.5% high, then the actual voltage would be

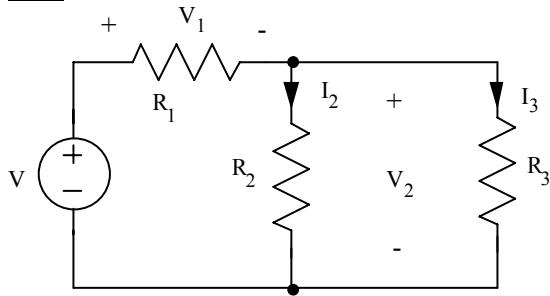
$$V_{meter} = 1.015V_{act} \quad \text{or} \quad V_{act} = \frac{5.30}{1.015} = 5.22V \text{ which is within specifications limits.}$$

1.52

$$TCR = \frac{\Delta R}{\Delta T} = \frac{6562 - 6066}{100 - 0} = 4.96 \frac{\Omega}{^{\circ}C}$$

$$R_{nom} = R|_{0^{\circ}C} + TCR (\Delta T) = 6066 + 4.96(27) = 6200\Omega$$

1.53



$$\text{Let } R_x = R_2 \parallel R_3 \quad \text{then} \quad V_1 = V \frac{R_1}{R_1 + R_x} = \frac{V_1}{1 + \frac{R_x}{R_1}}$$

$$R_x^{\min} = \frac{47k\Omega(0.9)(180k\Omega)(0.9)}{47k\Omega(0.9) + 180k\Omega(0.9)} = 33.5k\Omega \quad R_x^{\max} = \frac{47k\Omega(1.1)(180k\Omega)(1.1)}{47k\Omega(1.1) + 180k\Omega(1.1)} = 41.0k\Omega$$

$$V_1^{\max} = \frac{10(1.05)}{1 + \frac{33.5k\Omega}{22k\Omega(1.1)}} = 4.40V \quad V_1^{\min} = \frac{10(0.95)}{1 + \frac{41.0k\Omega}{22k\Omega(0.9)}} = 3.09V$$

$$I_1 = \frac{V}{R_1 + R_x} \quad \text{and} \quad I_2 = I_1 \frac{R_3}{R_2 + R_3} = \frac{V}{R_1 + R_2 + \frac{R_1 R_2}{R_3}}$$

$$I_2^{\max} = \frac{10(1.05)}{22000(0.9) + 47000(0.9) + \frac{22000(0.9)(47000)(0.9)}{180000(1.1)}} = 158 \mu A$$

$$I_2^{\min} = \frac{10(0.95)}{22000(1.1) + 47000(1.1) + \frac{22000(1.1)(47000)(1.1)}{180000(0.9)}} = 114 \mu A$$

$$I_3 = I_1 \frac{R_2}{R_2 + R_3} = \frac{V}{R_1 + R_3 + \frac{R_1 R_3}{R_2}}$$

$$I_3^{\max} = \frac{10(1.05)}{22000(0.9) + 180000(0.9) + \frac{22000(0.9)(180000)(0.9)}{47000(1.1)}} = 43.1 \mu A$$

$$I_3^{\min} = \frac{10(0.95)}{22000(1.1) + 180000(1.1) + \frac{22000(1.1)(180000)(1.1)}{47000(0.9)}} = 28.3 \mu A$$

1.54

$$I_1 = I \frac{R_2 + R_3}{R_1 + R_2 + R_3} = I \frac{1}{1 + \frac{R_1}{R_2 + R_3}} \quad \text{and similarly} \quad I_2 = I \frac{1}{1 + \frac{R_2 + R_3}{R_1}}$$
$$I_1^{\max} = \frac{5(1.02)}{2400(0.95)} mA = 4.12 mA \quad I_1^{\min} = \frac{5(0.98)}{2400(1.05)} mA = 3.80 mA$$
$$1 + \frac{5600(1.05) + 3600(1.05)}{2400(1.05)}$$
$$1 + \frac{5600(0.95) + 3600(0.95)}{2400(0.95)}$$
$$I_2^{\max} = \frac{5(1.02)}{1 + \frac{5600(0.95) + 3600(0.95)}{2400(1.05)}} mA = 1.14 mA \quad I_2^{\min} = \frac{5(0.98)}{1 + \frac{5600(1.05) + 3600(1.05)}{2400(0.95)}} mA = 0.936 mA$$
$$V_3 = I_2 R_3 = \frac{I}{\frac{1}{R_1} + \frac{1}{R_3} + \frac{R_2}{R_1 R_3}}$$
$$V_3^{\max} = \frac{5(1.02)}{\frac{1}{2400(1.05)} + \frac{1}{3600(1.05)} + \frac{5600(0.95)}{2400(1.05)(3600)(1.05)}} = 4.18 V$$
$$V_3^{\min} = \frac{5(0.98)}{\frac{1}{2400(0.95)} + \frac{1}{3600(0.95)} + \frac{5600(1.05)}{2400(0.95)(3600)(0.95)}} = 3.30 V$$

1.55

From Prob. 1.24 : $R_{th} = \frac{1}{g_m + \frac{1}{R_1}}$

$$R_{th}^{\max} = \frac{1}{0.002(0.8) + \frac{1}{5 \times 10^4(1.2)}} = 619 \Omega \quad R_{th}^{\min} = \frac{1}{0.002(1.2) + \frac{1}{5 \times 10^4(0.8)}} = 412 \Omega$$

1.56 For one set of 200 cases using the equations in Prob. 1.53.

$$V = 10 * (0.95 + 0.1 * \text{RAND}()) \quad R_l = 22000 * (0.9 + 0.2 * \text{RAND}())$$

$$R_l = 4700 * (0.9 + 0.2 * \text{RAND}()) \quad R_3 = 180000 * (0.9 + 0.2 * \text{RAND}())$$

	V ₁	I ₂	I ₃
Min	3.23 V	116 μA	29.9 μA
Max	3.71 V	151 μA	40.9 μA
Average	3.71 V	133 μA	35.1 μA

1.57 For one set of 200 cases using the Equations in Prob. 1.54:

$$I = 0.005 * (0.98 + 0.04 * \text{RAND}()) \quad R_l = 2400 * (0.95 + 0.1 * \text{RAND}())$$

$$R_l = 5600 * (0.95 + 0.1 * \text{RAND}()) \quad R_3 = 3600 * (0.95 + 0.1 * \text{RAND}())$$

	I ₁	I ₂	V ₃
Min	3.82 mA	0.96 mA	3.46 V
Max	4.09 mA	1.12 mA	4.08 V
Average	3.97 mA	1.04 mA	3.73 V

1.58 3.29, 0.995, -6.16; 3.295, 0.9952, -6.155

1.59 (a) (1.763 mA)(20.70 kΩ) = 36.5 V (b) 36 V

(c) (0.1021 □A)(97.80 kΩ) = 9.99 V; 10 V

CHAPTER 2

2.1

Based upon Table 2.1, a resistivity of $2.6 \mu\Omega\text{-cm} < 1 \text{ m}\Omega\text{-cm}$, and aluminum is a conductor.

2.2

Based upon Table 2.1, a resistivity of $10^{15} \Omega\text{-cm} > 10^5 \Omega\text{-cm}$, and silicon dioxide is an insulator.

2.3

$$I_{\max} = \left(10^7 \frac{A}{cm^2}\right) \left(5 \mu m\right) \left(1 \mu m\right) \left(\frac{10^{-8} cm^2}{\mu m^2}\right) = 500 mA$$

2.4

$$n_i = \sqrt{BT^3 \exp\left(-\frac{E_G}{8.62 \times 10^{-5} T}\right)}$$

For silicon, $B = 1.08 \times 10^{31}$ and $E_G = 1.12 \text{ eV}$:

$$n_i = 2.01 \times 10^{-10} /cm^3 \quad 6.73 \times 10^9 /cm^3 \quad 8.36 \times 10^{13} /cm^3 .$$

For germanium, $B = 2.31 \times 10^{30}$ and $E_G = 0.66 \text{ eV}$:

$$n_i = 35.9 /cm^3 \quad 2.27 \times 10^{13} /cm^3 \quad 8.04 \times 10^{15} /cm^3 .$$

2.5

Define an M-File:

```
function f=temp(T)
ni=1E14;
f=ni^2-1.08e31*T^3*exp(-1.12/(8.62e-5*T));
```

$$n_i = 10^{14} /cm^3 \quad \text{for } T = 506 \text{ K} \quad n_i = 10^{16} /cm^3 \quad \text{for } T = 739 \text{ K}$$

2.6

$$n_i = \sqrt{BT^3 \exp\left(-\frac{E_G}{8.62 \times 10^{-5} T}\right)} \quad \text{with} \quad B = 1.27 \times 10^{29} K^{-3} cm^{-6}$$

$$T = 300 \text{ K and } E_G = 1.42 \text{ eV: } n_i = 2.21 \times 10^6 /cm^3$$

$$T = 100 \text{ K: } n_i = 6.03 \times 10^{-19} /cm^3 \quad T = 500 \text{ K: } n_i = 2.79 \times 10^{11} /cm^3$$

2.7

$$v_n = -\mu_n E = \left(-700 \frac{cm^2}{V-s} \right) \left(2500 \frac{V}{cm} \right) = -1.75 \times 10^6 \frac{cm}{s}$$

$$v_p = +\mu_p E = \left(+250 \frac{cm^2}{V-s} \right) \left(2500 \frac{V}{cm} \right) = +6.25 \times 10^5 \frac{cm}{s}$$

$$j_n = -q n v_n = \left(-1.60 \times 10^{-19} C \right) \left(10^{17} \frac{1}{cm^3} \right) \left(-1.75 \times 10^6 \frac{cm}{s} \right) = 2.80 \times 10^4 \frac{A}{cm^2}$$

$$j_p = q n v_p = \left(1.60 \times 10^{-19} C \right) \left(10^3 \frac{1}{cm^3} \right) \left(6.25 \times 10^5 \frac{cm}{s} \right) = 1.00 \times 10^{-10} \frac{A}{cm^2}$$

2.8

$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) \quad B = 1.08 \times 10^{31}$$

$$\left(10^{10}\right)^2 = 1.08 \times 10^{31} T^3 \exp\left(-\frac{1.12}{8.62 \times 10^{-5} T}\right)$$

Using a spreadsheet, solver, or MATLAB yields T = 305.22K

Define an M-File:

```
function f=temp(T)
f=1e20-1.08e31*T^3*exp(-1.12/(8.62e-5*T));
```

Then: fzero('temp',300) | ans = 305.226 K

2.9

$$v = \frac{j}{Q} = \frac{-1000 A / cm^2}{0.01 C / cm^2} = -10^5 \frac{cm}{s}$$

2.10

$$j = Qv = \left(0.4 \frac{C}{cm^3} \right) \left(10^7 \frac{cm}{sec} \right) = 4 \times 10^6 \frac{A}{cm^2} = 4 \frac{MA}{cm^2}$$

2.11

$$v_n = -\mu_n E = \left(-1000 \frac{cm^2}{V-s} \right) \left(-2000 \frac{V}{cm} \right) = +2.00 \times 10^6 \frac{cm}{s}$$

$$v_p = +\mu_p E = \left(+400 \frac{cm^2}{V-s} \right) \left(-2000 \frac{V}{cm} \right) = -8.00 \times 10^5 \frac{cm}{s}$$

$$j_n = -qnv_n = \left(-1.60 \times 10^{-19} C \right) \left(10^3 \frac{1}{cm^3} \right) \left(+2.00 \times 10^6 \frac{cm}{s} \right) = -3.20 \times 10^{-10} \frac{A}{cm^2}$$

$$j_p = qnv_p = \left(1.60 \times 10^{-19} C \right) \left(10^{17} \frac{1}{cm^3} \right) \left(-8.00 \times 10^5 \frac{cm}{s} \right) = -1.28 \times 10^4 \frac{A}{cm^2}$$

2.12

$$(a) \quad E = \frac{5V}{10 \times 10^{-4} cm} = 5000 \frac{V}{cm} \quad (b) \quad V = \left(10^5 \frac{V}{cm} \right) (10 \times 10^{-4} cm) = 100 V$$

2.13

$$j_p = qp v_p = \left(1.60 \times 10^{-19} C \right) \left(\frac{10^{19}}{cm^3} \right) \left(10^7 \frac{cm}{s} \right) = 1.60 \times 10^7 \frac{A}{cm^2}$$

$$i_p = j_p A = \left(1.60 \times 10^7 \frac{A}{cm^2} \right) (1 \times 10^{-4} cm) (25 \times 10^{-4} cm) = 4.00 A$$

2.14

For intrinsic silicon, $\sigma = q(\mu_n n_i + \mu_p n_i) = qn_i(\mu_n + \mu_p)$

$\sigma \geq 1000 (\Omega - cm)^{-1}$ for a conductor

$$n_i \geq \frac{\sigma}{q(\mu_n + \mu_p)} = \frac{1000 (\Omega - cm)^{-1}}{1.602 \times 10^{-19} C (100 + 50) \frac{cm^2}{v - sec}} = \frac{4.16 \times 10^{19}}{cm^3}$$

$$n_i^2 = \frac{1.73 \times 10^{39}}{cm^6} = BT^3 \exp\left(-\frac{E_G}{kT}\right) \text{ with}$$

$$B = 1.08 \times 10^{31} K^{-3} cm^{-6}, \quad k = 8.62 \times 10^{-5} eV/K \text{ and } E_G = 1.12 eV$$

This is a transcendental equation and must be solved numerically by iteration. Using the HP solver routine or a spread sheet yields T = 2701 K. Note that this temperature is far above the melting temperature of silicon.

2.15

For intrinsic silicon, $\sigma = q(\mu_n n_i + \mu_p n_i) = qn_i(\mu_n + \mu_p)$

$\sigma \leq 10^{-5} (\Omega - cm)^{-1}$ for an insulator

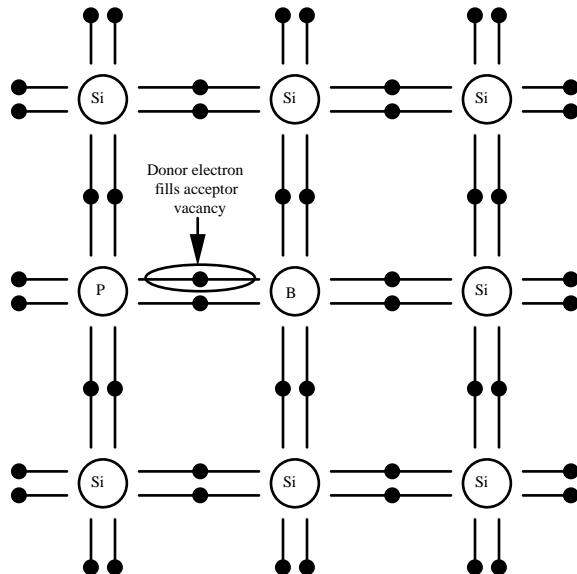
$$n_i \geq \frac{\sigma}{q(\mu_n + \mu_p)} = \frac{10^{-5} (\Omega - cm)^{-1}}{(1.602 \times 10^{-19} C)(2000 + 750) \left(\frac{cm^2}{v - sec} \right)} = \frac{2.270 \times 10^{10}}{cm^3}$$

$$n_i^2 = \frac{5.152 \times 10^{20}}{cm^6} = BT^3 \exp\left(-\frac{E_G}{kT}\right) \text{ with}$$

$$B = 1.08 \times 10^{31} K^{-3} cm^{-6}, k = 8.62 \times 10^{-5} eV/K \text{ and } E_G = 1.12 eV$$

Using MATLAB as in Problem 2.5 yields T = 316.6 K.

2.16



No free electrons or holes (except those corresponding to n_i).

2.17

(a) Gallium is from column 3 and silicon is from column 4. Thus silicon has an extra electron and will act as a donor impurity.

(b) Arsenic is from column 5 and silicon is from column 4. Thus silicon is deficient in one electron and will act as an acceptor impurity.

2.18

Since Ge is from column IV, acceptors come from column III and donors come from column V. (a) Acceptors: B, Al, Ga, In, Tl (b) Donors: N, P, As, Sb, Bi

2.19

(a) Germanium is from column IV and indium is from column III. Thus germanium has one extra electron and will act as a donor impurity.

(b) Germanium is from column IV and phosphorus is from column V. Thus germanium has one less electron and will act as an acceptor impurity.

2.20

$$E = \frac{j}{\sigma} = j\rho = \left(10000 \frac{A}{cm^2}\right) (0.02\Omega - cm) = 200 \frac{V}{cm}, \text{ a small electric field.}$$

2.21

$$\left|j_n^{drift}\right| = \left|qn\mu_n E\right| = \left|qnv_n\right| = \left(1.602 \times 10^{-19}\right) \left(10^{16}\right) \left(\frac{C}{cm^3}\right) \left(10^7 \frac{cm}{s}\right) = 16000 \frac{A}{cm^2}$$

2.22

$$N = \left(\frac{10^{15} \text{ atoms}}{cm^3}\right) (1\mu m) (10\mu m) (0.5\mu m) \left(\frac{10^{-4} cm}{\mu m}\right)^3 = 5,000 \text{ atoms}$$

2.23

$$N_A > N_D: N_A - N_D = 10^{15} - 10^{14} = 9 \times 10^{14} / cm^3$$

If we assume $N_A - N_D \gg 2n_i = 10^{14} / cm^3$:

$$p = N_A - N_D = 9 \times 10^{14} / cm^3 / n = \frac{n_i^2}{p} = \frac{2510^{26}}{9 \times 10^{14}} = 2.78 \times 10^{12} / cm^3$$

$$\text{If we use Eq. 2.12: } p = \frac{9 \times 10^{14} \pm \sqrt{(9 \times 10^{14})^2 + 4(5 \times 10^{13})^2}}{2} = 9.03 \times 10^{14}$$

and $n = 2.77 \times 10^{12} / cm^3$. The answers are essentially the same.

2.24

$$N_A > N_D: N_A - N_D = 5 \times 10^{16} - 10^{16} = 4 \times 10^{16} / cm^3 \gg 2n_i = 2 \times 10^{11} / cm^3$$

$$p = N_A - N_D = 4 \times 10^{14} / cm^3 / n = \frac{n_i^2}{p} = \frac{10^{22}}{4 \times 10^{16}} = 2.50 \times 10^5 / cm^3$$

2.25

$$N_D > N_A: N_D - N_A = 3 \times 10^{17} - 2 \times 10^{17} = 1 \times 10^{17} / cm^3$$

$2n_i = 2 \times 10^{17} / cm^3$; Need to use Eq. (2.11)

$$n = \frac{10^{17} \pm \sqrt{(10^{17})^2 + 4(10^{17})^2}}{2} = 1.62 \times 10^{17} / cm^3$$

$$p = \frac{n_i^2}{n} = \frac{10^{34}}{1.62 \times 10^{17}} = 6.18 \times 10^{16} / cm^3$$

2.26

$$N_D - N_A = -2.5 \times 10^{18} / \text{cm}^3$$

$$\text{Using Eq. 2.11: } n = \frac{-2.5 \times 10^{18} \pm \sqrt{(-2.5 \times 10^{18})^2 + 4(10^{10})^2}}{2}$$

Evaluating this with a calculator yields $n = 0$, and $n = \frac{n_i^2}{p} = \infty$.

No, the result is incorrect because of loss of significant digits within the calculator. It does not have enough digits.

2.27

(a) Since boron is an acceptor, $N_A = 6 \times 10^{18} / \text{cm}^3$. Assume $N_D = 0$, since it is not specified. The material is p-type.

At room temperature, $n_i = 10^{10} / \text{cm}^3$ and $N_A - N_D = 6 \times 10^{18} / \text{cm}^3 \gg 2n_i$

$$\text{So } p = 6 \times 10^{18} / \text{cm}^3 \text{ and } n = \frac{n_i^2}{p} = \frac{10^{20} / \text{cm}^6}{6 \times 10^{18} / \text{cm}^3} = 16.7 / \text{cm}^3$$

(b)

$$\text{At 200K, } n_i^2 = 1.08 \times 10^{31} (200)^3 \exp\left(-\frac{1.12}{8.62 \times 10^{-5} (200)}\right) = 5.28 \times 10^9 / \text{cm}^6$$

$$n_i = 7.27 \times 10^4 / \text{cm}^3 \quad N_A - N_D \gg 2n_i, \text{ so } p = 6 \times 10^{18} / \text{cm}^3 \text{ and } n = \frac{5.28 \times 10^9}{6 \times 10^{18}} = 8.80 \times 10^{-10} / \text{cm}^3$$

2.28

(a) Since arsenic is a donor, $N_D = 3 \times 10^{17} / \text{cm}^3$. Assume $N_A = 0$, since it is not specified. The material is n-type.

At room temperature, $n_i = 10^{10} / \text{cm}^3$ and $N_D - N_A = 3 \times 10^{17} / \text{cm}^3 \gg 2n_i$

$$\text{So } n = 3 \times 10^{17} / \text{cm}^3 \text{ and } p = \frac{n_i^2}{n} = \frac{10^{20} / \text{cm}^6}{3 \times 10^{17} / \text{cm}^3} = 333 / \text{cm}^3$$

$$(b) \text{ At 250K, } n_i^2 = 1.08 \times 10^{31} (250)^3 \exp\left(-\frac{1.12}{8.62 \times 10^{-5} (250)}\right) = 4.53 \times 10^{15} / \text{cm}^6$$

$$n_i = 6.73 \times 10^7 / \text{cm}^3 \quad N_D - N_A \gg 2n_i, \text{ so } n = 3 \times 10^{17} / \text{cm}^3 \text{ and } n = \frac{4.53 \times 10^{15}}{3 \times 10^{17}} = 0.0151 / \text{cm}^3$$

2.29

(a) Arsenic is a donor, and boron is an acceptor. $N_D = 2 \times 10^{18} / \text{cm}^3$, and $N_A = 8 \times 10^{18} / \text{cm}^3$. Since $N_A > N_D$, the material is p-type.

(b) At room temperature, $n_i = 10^{10} / cm^3$ and $N_A - N_D = 6 \times 10^{18} / cm^3 \gg 2n_i$

$$\text{So } p = 6 \times 10^{18} / cm^3 \text{ and } n = \frac{n_i^2}{p} = \frac{10^{20} / cm^6}{6 \times 10^{18} / cm^3} = 16.7 / cm^3$$

2.30

(a) Phosphorus is a donor, and boron is an acceptor. $N_D = 2 \times 10^{17} / cm^3$, and $N_A = 5 \times 10^{17} / cm^3$.

Since $N_A > N_D$, the material is p-type.

(b) At room temperature, $n_i = 10^{10} / cm^3$ and $N_A - N_D = 3 \times 10^{17} / cm^3 \gg 2n_i$

$$\text{So } p = 3 \times 10^{17} / cm^3 \text{ and } n = \frac{n_i^2}{p} = \frac{10^{20} / cm^6}{3 \times 10^{17} / cm^3} = 333 / cm^3$$

2.31

$N_D = 4 \times 10^{16} / cm^3$. Assume $N_A = 0$, since it is not specified.

$N_D > N_A$: material is n - type | $N_D - N_A = 4 \times 10^{16} / cm^3 \gg 2n_i = 2 \times 10^{10} / cm^3$

$$n = 4 \times 10^{16} / cm^3 \quad | \quad p = \frac{n_i^2}{n} = \frac{10^{20}}{4 \times 10^{16}} = 2.5 \times 10^3 / cm^3$$

$$N_D + N_A = 4 \times 10^{16} / cm^3 \quad | \quad \text{Using Fig. 2.13, } \mu_n = 1030 \frac{cm^2}{V-s} \text{ and } \mu_p = 310 \frac{cm^2}{V-s}$$

$$\rho = \frac{1}{q\mu_n n} = \frac{1}{(1.602 \times 10^{-19} C) \left(1030 \frac{cm^2}{V-s} \right) \left(\frac{4 \times 10^{16}}{cm^3} \right)} = 0.152 \Omega \cdot cm$$

2.32

$N_A = 10^{18}/\text{cm}^3$. Assume $N_D = 0$, since it is not specified.

$$N_A > N_D : \text{material is p-type} \quad | \quad N_A - N_D = 10^{18}/\text{cm}^3 >> 2n_i = 2 \times 10^{10}/\text{cm}^3$$

$$p = 10^{18}/\text{cm}^3 \quad | \quad n = \frac{n_i^2}{p} = \frac{10^{20}}{10^{18}} = 100/\text{cm}^3$$

$$N_D + N_A = 10^{18}/\text{cm}^3 \quad | \quad \text{Using Fig. 2.13, } \mu_n = 375 \frac{\text{cm}^2}{V-s} \text{ and } \mu_p = 100 \frac{\text{cm}^2}{V-s}$$

$$\rho = \frac{1}{q\mu_p p} = \frac{1}{1.602 \times 10^{-19} C \left(100 \frac{\text{cm}^2}{V-s} \right) \left(\frac{10^{18}}{\text{cm}^3} \right)} = 0.0624 \Omega-\text{cm}$$

2.33

Indium is from column 3 and is an acceptor. $N_A = 7 \times 10^{19}/\text{cm}^3$. Assume $N_D = 0$, since it is not specified.

$$N_A > N_D : \text{material is p-type} \quad | \quad N_A - N_D = 7 \times 10^{19}/\text{cm}^3 >> 2n_i = 2 \times 10^{10}/\text{cm}^3$$

$$p = 7 \times 10^{19}/\text{cm}^3 \quad / \quad n = \frac{n_i^2}{p} = \frac{10^{20}}{7 \times 10^{19}} = 1.43/\text{cm}^3$$

$$N_D + N_A = 7 \times 10^{19}/\text{cm}^3 \quad | \quad \text{Using Fig. 2.13, } \mu_n = 120 \frac{\text{cm}^2}{V-s} \text{ and } \mu_p = 60 \frac{\text{cm}^2}{V-s}$$

$$\rho = \frac{1}{q\mu_p p} = \frac{1}{1.602 \times 10^{-19} C \left(60 \frac{\text{cm}^2}{V-s} \right) \left(\frac{7 \times 10^{19}}{\text{cm}^3} \right)} = 1.49 \text{ m}\Omega-\text{cm}$$

2.34

Phosphorus is a donor : $N_D = 5.5 \times 10^{16}/\text{cm}^3$ | Boron is an acceptor : $N_A = 4.5 \times 10^{16}/\text{cm}^3$

$$N_D > N_A : \text{material is n-type} \quad | \quad N_D - N_A = 10^{16}/\text{cm}^3 >> 2n_i = 2 \times 10^{10}/\text{cm}^3$$

$$n = 10^{16}/\text{cm}^3 \quad / \quad p = \frac{n_i^2}{p} = \frac{10^{20}}{10^{16}} = 10^4/\text{cm}^3$$

$$N_D + N_A = 10^{17}/\text{cm}^3 \quad | \quad \text{Using Fig. 2.13, } \mu_n = 800 \frac{\text{cm}^2}{V-s} \text{ and } \mu_p = 230 \frac{\text{cm}^2}{V-s}$$

$$\rho = \frac{1}{q\mu_n n} = \frac{1}{1.602 \times 10^{-19} C \left(800 \frac{\text{cm}^2}{V-s} \right) \left(\frac{10^{16}}{\text{cm}^3} \right)} = 0.781 \Omega-\text{cm}$$

2.35

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p = \frac{1}{(1.602 \times 10^{-19} C)(0.054 \Omega - cm)} = \frac{1.16 \times 10^{20}}{V - cm - s}$$

An iterative solution is required. Using the equations in Fig. 2.8:

N _A	μ_p	$\mu_p p$
10^{18}	96.7	9.67×10^{20}
1.1×10^{18}	93.7	1.03×10^{20}
1.2×10^{17}	91.0	1.09×10^{20}
1.3×10^{19}	88.7	1.15×10^{20}

2.36

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p = \frac{1}{(1.602 \times 10^{-19} C)(0.75 \Omega - cm)} = \frac{8.32 \times 10^{18}}{V - cm - s}$$

An iterative solution is required. Using the equations in Fig. 2.8:

N _A	μ_p	$\mu_p p$
10^{16}	406	4.06×10^{18}
2×10^{16}	363	7.26×10^{18}
3×10^{16}	333	1.00×10^{19}
2.4×10^{16}	350	8.40×10^{18}

2.37

Based upon the value of its resistivity, the material is an insulator. However, it is not intrinsic because it contains impurities. Addition of the impurities has increased the resistivity.

2.38

$$\rho = \frac{1}{q\mu_n n} \quad | \quad \mu_n n \approx \mu_n N_D = \frac{1}{(1.602 \times 10^{-19} C)(2 \Omega - cm)} = \frac{3.12 \times 10^{18}}{V - cm - s}$$

An iterative solution is required. Using the equations in Fig. 2.8:

N _D	μ_n	$\mu_n n$
10^{15}	1350	1.35×10^{18}
2×10^{15}	1330	2.67×10^{18}
2.5×10^{15}	1330	3.32×10^{18}

2.3 x 10¹⁵	1330	3.06 x 10¹⁸
------------------------------	-------------	-------------------------------

2.39 (a)

$$\rho = \frac{1}{q\mu_n n} \quad | \quad \mu_n n \approx \mu_n N_D = \frac{1}{(1.602 \times 10^{-19} C)(0.001 \Omega - cm)} = \frac{6.24 \times 10^{21}}{V - cm - s}$$

An iterative solution is required. Using the equations in Fig. 2.8:

N _D	μ_n	$\mu_n n$
10^{19}	116	1.16×10^{21}
7×10^{19}	96.1	6.73×10^{21}
6.5×10^{19}	96.4	6.3×10^{21}

(b)

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p \approx \mu_p N_A = \frac{1}{(1.602 \times 10^{-19} C)(0.001 \Omega - cm)} = \frac{6.24 \times 10^{21}}{V - cm - s}$$

An iterative solution is required using the equations in Fig. 2.8:

N _A	μ_p	$\mu_p p$
1.3×10^{20}	49.3	6.4×10^{21}

2.40

Yes, by adding equal amounts of donor and acceptor impurities the mobilities are reduced, but the hole and electron concentrations remain unchanged. See Problem 2.37 for example. However, it is physically impossible to add exactly equal amounts of the two impurities.

2.41

(a) For the 1 ohm-cm starting material:

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p \approx \mu_p N_A = \frac{1}{(1.602 \times 10^{-19} C)(1 \Omega - cm)} = \frac{6.25 \times 10^{18}}{V - cm - s}$$

An iterative solution is required. Using the equations in Fig. 2.8:

N _A	μ_p	$\mu_p p$
10^{16}	406	4.1×10^{18}
1.5×10^{16}	383	5.7×10^{18}
1.7×10^{16}	374	6.4×10^{19}

To change the resistivity to 0.25 ohm-cm:

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p \approx \mu_p N_A = \frac{1}{(1.602 \times 10^{-19} C)(0.25 \Omega - cm)} = \frac{2.5 \times 10^{19}}{V - cm - s}$$

N_A	μ_p	$\mu_p p$
6×10^{16}	276	1.7×10^{19}
8×10^{16}	233	2.3×10^{19}
1.1×10^{17}	225	2.5×10^{19}

$$\text{Additional acceptor concentration} = 1.1 \times 10^{17} - 1.7 \times 10^{16} = 9.3 \times 10^{16} / \text{cm}^3$$

(b) If donors are added:

N_D	$N_D + N_A$	μ_n	$N_D - N_A$	$\mu_n n$
2×10^{16}	3.7×10^{16}	1060	3×10^{15}	3.2×10^{18}
1×10^{17}	1.2×10^{17}	757	8.3×10^{16}	6.3×10^{19}
8×10^{16}	9.7×10^{16}	811	6.3×10^{16}	5.1×10^{19}
4.1×10^{16}	5.8×10^{16}	950	2.4×10^{16}	2.3×10^{19}

So $N_D = 4.1 \times 10^{16} / \text{cm}^3$ must be added to change achieve a resistivity of 0.25 ohm-cm. The silicon is converted to n-type material.

2.42

Phosphorus is a donor: $N_D = 10^{16} / \text{cm}^3$ and $\mu_n = 1250 \text{ cm}^2/\text{V-s}$ from Fig. 2.8.

$$\sigma = q\mu_n n \approx q\mu_n N_D = (1.602 \times 10^{-19} C)(1250)(10^{16}) = \frac{2.00}{\Omega - \text{cm}}$$

Now we add acceptors until $\sigma = 5.0 (\Omega \cdot \text{cm})^{-1}$:

$$\sigma = q\mu_p p \quad | \quad \mu_p p \approx \mu_p (N_A - N_D) = \frac{5(\Omega - \text{cm})^{-1}}{1.602 \times 10^{-19} C} = \frac{3.12 \times 10^{19}}{V - \text{cm} - \text{s}}$$

N_A	$N_D + N_A$	μ_p	$N_A - N_D$	$\mu_p p$
1×10^{17}	1.1×10^{17}	250	9×10^{16}	2.3×10^{19}
2×10^{17}	2.1×10^{17}	176	1.9×10^{17}	3.3×10^{19}
1.8×10^{17}	1.9×10^{17}	183	1.7×10^{16}	3.1×10^{19}

2.43

Boron is an acceptor: $N_A = 10^{16}/\text{cm}^3$ and $\mu_p = 405 \text{ cm}^2/\text{V-s}$ from Fig. 2.8.

$$\sigma = q\mu_p p \approx q\mu_p N_A = (1.602 \times 10^{-19} \text{ C})(405)(10^{16}) = \frac{0.649}{\Omega \cdot \text{cm}}$$

Now we add donors until $\sigma = 5.5 (\Omega \cdot \text{cm})^{-1}$:

$$\sigma = q\mu_n n \quad | \quad \mu_n n \approx \mu_n (N_D - N_A) = \frac{5.5(\Omega \cdot \text{cm})^{-1}}{1.602 \times 10^{-19} \text{ C}} = \frac{3.43 \times 10^{19}}{\text{V} \cdot \text{cm} \cdot \text{s}}$$

N_D	$N_D + N_A$	μ_n	$N_D - N_A$	$\mu_p p$
8×10^{16}	9×10^{16}	832	7×10^{16}	5.8×10^{19}
6×10^{16}	7×10^{16}	901	5×10^{16}	4.5×10^{19}
4.5×10^{16}	5.5×10^{16}	964	3.5×10^{16}	3.4×10^{19}

2.44

$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23} T}{1.602 \times 10^{-19}} = 8.62 \times 10^{-5} T$$

T (K)	50	75	100	150	200	250	300	350	400
V _T (mV)	4.31	6.46	8.61	12.9	17.2	21.5	25.8	30.1	34.5

2.45

$$j = -qD_n \left(-\frac{dn}{dx} \right) = qV_T \mu_n \frac{dn}{dx}$$

$$j = (1.602 \times 10^{-19} \text{ C})(0.025V) \left(350 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \right) \left(\frac{10^{18} - 0}{0 - 10^{-4}} \right) \frac{1}{\text{cm}^4} = -14.0 \frac{\text{kA}}{\text{cm}^2}$$

2.46

$$j = -qD_p \frac{dp}{dx} = (-1.602 \times 10^{-19} \text{ C}) \left(15 \frac{\text{cm}^2}{\text{s}} \right) \left(-\frac{10^{19} / \text{cm}^3}{2 \times 10^{-4} \text{ cm}} \right) \exp \left(-\frac{x}{2 \times 10^{-4} \text{ cm}} \right)$$

$$j = 1.20 \times 10^5 \exp \left(-5000 \frac{x}{\text{cm}} \right) \frac{\text{A}}{\text{cm}^2}$$

$$I(0) = j(0)A = \left(1.20 \times 10^5 \frac{\text{A}}{\text{cm}^2} \right) \left(10 \mu\text{m}^2 \right) \left(\frac{10^{-8} \text{ cm}^2}{\mu\text{m}^2} \right) = 12.0 \text{ mA}$$

2.47

$$j_p = q\mu_p p E - qD_p \frac{dp}{dx} = q\mu_p p \left(E - V_T \frac{1}{p} \frac{dp}{dx} \right) = 0 \rightarrow E = V_T \frac{1}{p} \frac{dp}{dx}$$

$$E \approx V_T \frac{1}{N_A} \frac{dN_A}{dx} = 0.025 \frac{-10^{22} \exp(-10^4 x)}{10^{14} + 10^{18} \exp(-10^4 x)}$$

$$E(0) = -0.025 \frac{10^{22}}{10^{14} + 10^{18}} = -250 \frac{V}{cm}$$

$$E(5 \times 10^{-4} cm) = -0.025 \frac{10^{22} \exp(-5)}{10^{14} + 10^{18} \exp(-5)} = -246 \frac{V}{cm}$$

2.48

$$j_n^{drift} = q\mu_n n E = (1.60 \times 10^{-19} C) \left(350 \frac{cm^2}{V-s} \right) \left(\frac{10^{16}}{cm^3} \right) \left(-20 \frac{V}{cm} \right) = -11.2 \frac{A}{cm^2}$$

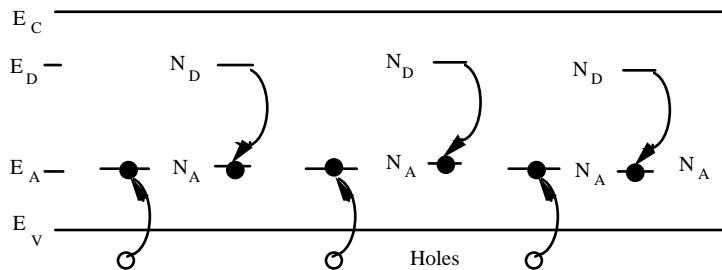
$$j_p^{drift} = q\mu_p p E = (1.60 \times 10^{-19} C) \left(150 \frac{cm^2}{V-s} \right) \left(\frac{1.01 \times 10^{18}}{cm^3} \right) \left(-20 \frac{V}{cm} \right) = -484 \frac{A}{cm^2}$$

$$j_n^{diff} = qD_n \frac{dn}{dx} = (1.60 \times 10^{-19} C) \left(350 \cdot 0.025 \frac{cm^2}{s} \right) \left(\frac{10^4 - 10^{16}}{2 \times 10^{-4} cm^4} \right) = -70.0 \frac{A}{cm^2}$$

$$j_p^{diff} = -qD_p \frac{dp}{dx} = (-1.60 \times 10^{-19} C) \left(150 \cdot 0.025 \frac{cm^2}{s} \right) \left(\frac{10^{18} - 1.01 \times 10^{18}}{2 \times 10^{-4} cm^4} \right) = 30.0 \frac{A}{cm^2}$$

$$j_T = -11.2 - 484 - 70.0 + 30.0 = -535 \frac{A}{cm^2}$$

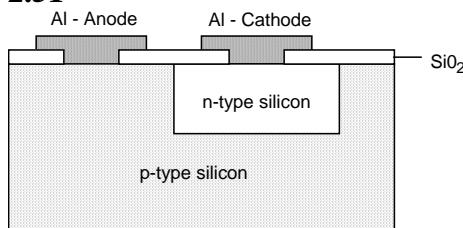
2.49 $N_A = 2N_D$



2.50

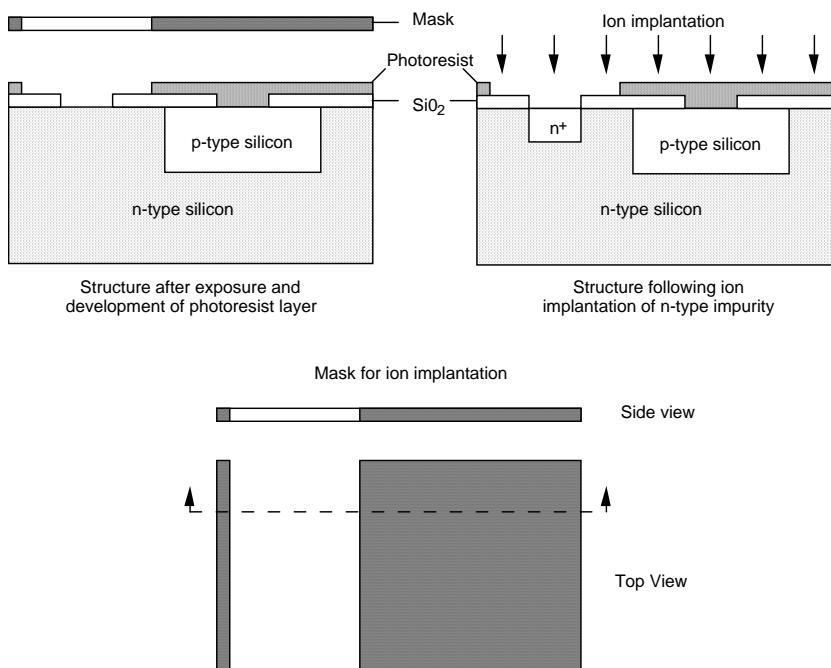
$$\lambda = \frac{hc}{E} = \frac{(6.626 \times 10^{-34} J \cdot s)(3 \times 10^8 m/s)}{(1.12 eV)(1.602 \times 10^{-19} J/eV)} = 1.108 \mu m$$

2.51



2.52

An n-type ion implantation step could be used to form the n^+ region following step (f) in Fig. 2.17. A mask would be used to cover up the opening over the p-type region and leave the opening over the n-type silicon. The masking layer for the implantation could just be photoresist.



2.53

$$(a) N = 8\left(\frac{1}{8}\right) + 6\left(\frac{1}{2}\right) + 4(1) = 8 \text{ atoms}$$

$$(b) V = l^3 = (0.543 \times 10^{-9} \text{ m})^3 = (0.543 \times 10^{-7} \text{ cm})^3 = 1.60 \times 10^{-22} \text{ cm}^3$$

$$(c) D = \frac{8 \text{ atoms}}{1.60 \times 10^{-22} \text{ cm}^3} = 5.00 \times 10^{22} \frac{\text{atoms}}{\text{cm}^3}$$

$$(d) m = \left(2.33 \frac{\text{g}}{\text{cm}^3}\right) 1.60 \times 10^{-22} \text{ cm}^3 = 3.73 \times 10^{-22} \text{ g}$$

(e) From Table 2.2, silicon has a mass of 28.086 protons.

$$m_p = \frac{3.73 \times 10^{-22} \text{ g}}{28.082(8) \text{ protons}} = 1.66 \times 10^{-24} \frac{\text{g}}{\text{proton}}$$

Yes, near the actual proton rest mass.

CHAPTER 3

3.1

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = (0.025V) \ln \frac{(10^{19} \cdot cm^{-3})(10^{18} \cdot cm^{-3})}{10^{20} \cdot cm^{-6}} = 0.979V$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j} = \sqrt{\frac{2(11.7 \cdot 8.854 \times 10^{-14} F \cdot cm^{-1})}{1.602 \times 10^{-19} C} \left(\frac{1}{10^{19} cm^{-3}} + \frac{1}{10^{18} cm^{-3}} \right) (0.979V)}$$

$$w_{do} = 3.73 \times 10^{-6} cm = 0.0373 \mu m$$

$$x_n = \frac{w_{do}}{1 + \frac{N_D}{N_A}} = \frac{0.0373 \mu m}{1 + \frac{10^{18} cm^{-3}}{10^{19} cm^{-3}}} = 0.0339 \mu m \quad | \quad x_p = \frac{w_{do}}{1 + \frac{N_A}{N_D}} = \frac{0.0373 \mu m}{1 + \frac{10^{19} cm^{-3}}{10^{18} cm^{-3}}} = 3.39 \times 10^{-3} \mu m$$

$$E_{MAX} = \frac{q N_A x_p}{\epsilon_s} = \frac{(1.60 \times 10^{-19} C)(10^{19} cm^{-3})(3.39 \times 10^{-3} cm)}{11.7 \cdot 8.854 \times 10^{-14} F/cm} = 5.24 \times 10^5 \frac{V}{cm}$$

3.2

$$p_{po} = N_A = \frac{10^{18}}{cm^3} \quad | \quad n_{po} = \frac{n_i^2}{p_{po}} = \frac{10^{20}}{10^{18}} = \frac{10^2}{cm^3}$$

$$n_{no} = N_D = \frac{10^{15}}{cm^3} \quad | \quad p_{no} = \frac{n_i^2}{n_{no}} = \frac{10^{20}}{10^{15}} = \frac{10^5}{cm^3}$$

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = (0.025V) \ln \frac{(10^{18} cm^{-3})(10^{15} cm^{-3})}{10^{20} cm^{-6}} = 0.748 V$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j} = \sqrt{\frac{2(11.7 \cdot 8.854 \times 10^{-14} F \cdot cm^{-1})}{1.602 \times 10^{-19} C} \left(\frac{1}{10^{18} cm^{-3}} + \frac{1}{10^{15} cm^{-3}} \right) (0.748V)}$$

$$w_{do} = 98.4 \times 10^{-6} cm = 0.984 \mu m$$

3.3

$$p_{po} = N_A = \frac{10^{18}}{cm^3} \quad | \quad n_{po} = \frac{n_i^2}{p_{po}} = \frac{10^{20}}{10^{18}} = \frac{10^2}{cm^3}$$

$$n_{no} = N_D = \frac{10^{18}}{cm^3} \quad | \quad p_{no} = \frac{n_i^2}{n_{no}} = \frac{10^{20}}{10^{18}} = \frac{10^2}{cm^3}$$

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = (0.025V) \ln \frac{(10^{18} \cdot cm^{-3})(10^{18} \cdot cm^{-3})}{10^{20} \cdot cm^{-6}} = 0.921V$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j} = \sqrt{\frac{2(11.7 \cdot 8.854 \times 10^{-14} F \cdot cm^{-1})}{1.602 \times 10^{-19} C} \left(\frac{1}{10^{18} cm^{-3}} + \frac{1}{10^{18} cm^{-3}} \right) (0.921V)}$$

$$w_{do} = 4.881 \times 10^{-6} cm = 0.0488 \mu m$$

3.4

$$p_{po} = N_A = \frac{10^{18}}{cm^3} \quad | \quad n_{po} = \frac{n_i^2}{p_{po}} = \frac{10^{20}}{10^{18}} = \frac{10^2}{cm^3}$$

$$n_{no} = N_D = \frac{10^{18}}{cm^3} \quad | \quad p_{no} = \frac{n_i^2}{n_{no}} = \frac{10^{20}}{10^{18}} = \frac{10^2}{cm^3}$$

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = (0.025V) \ln \frac{(10^{18} \cdot cm^{-3})(10^{20} \cdot cm^{-3})}{10^{20} \cdot cm^{-6}} = 1.04V$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right)} \phi_j = \sqrt{\frac{2(11.7 \cdot 8.854 \times 10^{-14} F \cdot cm^{-1})}{1.602 \times 10^{-19} C} \left(\frac{1}{10^{18} cm^{-3}} + \frac{1}{10^{20} cm^{-3}} \right)} (1.04V)$$

$$w_{do} = 0.0369 \mu m$$

3.5

$$p_{po} = N_A = \frac{10^{16}}{cm^3} \quad | \quad n_{po} = \frac{n_i^2}{p_{po}} = \frac{10^{20}}{10^{16}} = \frac{10^4}{cm^3}$$

$$n_{no} = N_D = \frac{10^{19}}{cm^3} \quad | \quad p_{no} = \frac{n_i^2}{n_{no}} = \frac{10^{20}}{10^{19}} = \frac{10}{cm^3}$$

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = (0.025V) \ln \frac{(10^{19} \cdot cm^{-3})(10^{16} \cdot cm^{-3})}{10^{20} \cdot cm^{-6}} = 0.864V$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right)} \phi_j = \sqrt{\frac{2(11.7 \cdot 8.854 \times 10^{-14} F \cdot cm^{-1})}{1.602 \times 10^{-19} C} \left(\frac{1}{10^{19} cm^{-3}} + \frac{1}{10^{16} cm^{-3}} \right)} (0.864V)$$

$$w_{do} = 0.334 \mu m$$

3.6

$$w_d = w_{do} \sqrt{1 + \frac{V_R}{\phi_j}} \quad | \quad (\text{a}) \quad w_d = 2w_{do} \text{ requires } V_R = 3\phi_j = 2.55 V \quad | \quad w_d = 0.4 \mu m \sqrt{1 + \frac{5}{0.85}} = 1.05 \mu m$$

3.7

$$w_d = w_{do} \sqrt{1 + \frac{V_R}{\phi_j}} \quad | \quad (\text{a}) \quad w_d = 3w_{do} \text{ requires } V_R = 8\phi_j = 4.80 V \quad | \quad w_d = 1 \mu m \sqrt{1 + \frac{10}{0.6}} = 4.20 \mu m$$

3.8

$$j_n = \sigma E, \quad \sigma = \frac{1}{\rho} = \frac{1}{0.5 \Omega \cdot cm} = \frac{2}{\Omega \cdot cm} \quad | \quad E = \frac{j_n}{\sigma} = \frac{1000 A \cdot cm^{-2}}{2(\Omega \cdot cm)^{-1}} = 500 \frac{V}{cm}$$

3.9

$$j_p = \sigma E \quad | \quad E = \frac{j_n}{\sigma} = j_n \rho = (5000 A \cdot cm^{-2}) (2 \Omega \cdot cm) = 10.0 \frac{kV}{cm}$$

3.10

$$j \cong j_n = qnv = (1.60 \times 10^{-19} C) \left(\frac{4 \times 10^{15}}{cm^3} \right) \left(\frac{10^7 cm}{s} \right) = 6400 \frac{A}{cm^2}$$

3.11

$$j \cong j_p = qpv = (1.60 \times 10^{-19} C) \left(\frac{5 \times 10^{17}}{cm^3} \right) \left(\frac{10^7 cm}{s} \right) = 800 \frac{kA}{cm^2}$$

3.12

$$j_p = q\mu_p pE - qD_p \frac{dp}{dx} = 0 \rightarrow E = -\left(\frac{D_p}{\mu_p}\right) \frac{1}{p} \frac{dp}{dx} = -\left(\frac{kT}{q}\right) \frac{1}{p} \frac{dp}{dx}$$

$$p(x) = N_o \exp\left(-\frac{x}{L}\right) \quad | \quad \frac{1}{p} \frac{dp}{dx} = \frac{1}{L} \quad | \quad E = -\frac{V_T}{L} = -\frac{0.025V}{10^{-4} cm} = -250 \frac{V}{cm}$$

The exponential doping results in a constant electric field.

3.13

$$j_p = qD_n \frac{dn}{dx} = q\mu_n V_T \frac{dn}{dx} \quad | \quad \frac{dn}{dx} = \frac{2000 A/cm^2}{(1.60 \times 10^{-19} C) (500 cm^2/V \cdot s) (0.025V)} = \frac{1.00 \times 10^{21}}{cm^4}$$

3.14

$$10 = 10^4 \cdot 10^{-16} [\exp(40V_D) - 1] + V_D \quad \text{and the solver yields } V_D = 0.7464 V$$

3.15

$$f = 10 - 10^4 I_D - 0.025 \ln \frac{I_D + I_S}{I_S} \quad | \quad f' = -10^4 - \frac{0.025}{I_D + I_S} \quad | \quad I'_D = I_D - \frac{f}{f'}$$

Starting the iteration process with $I_D = 100 \mu A$ and $I_S = 10^{-13} A$:

I_D	f	f'
1.000E-04	8.482E+00	-1.025E+04
9.275E-04	1.512E-01	-1.003E+04
9.426E-04	3.268E-06	-1.003E+04
9.426E-04	9.992E-16	-1.003E+04

3.16

- (a) Create the following m-file:

```
function fd=current(id)
fd=10-1e4*id-0.025*log(1+id/1e-13);
```

Then: $fzero('current',1)$ yields ans = 9.4258e-04

(b) Changing I_S to 10^{-15} A:

```
function fd=current(id)
fd=10-1e4*id-0.025*log(1+id/1e-15);
```

Then: $fzero('current',1)$ yields ans = 9.3110e-04

3.17

$$T = \frac{qV_T}{k} = \frac{1.60 \times 10^{-19} C (0.025 V)}{1.38 \times 10^{-23} J/K} = 290 K$$

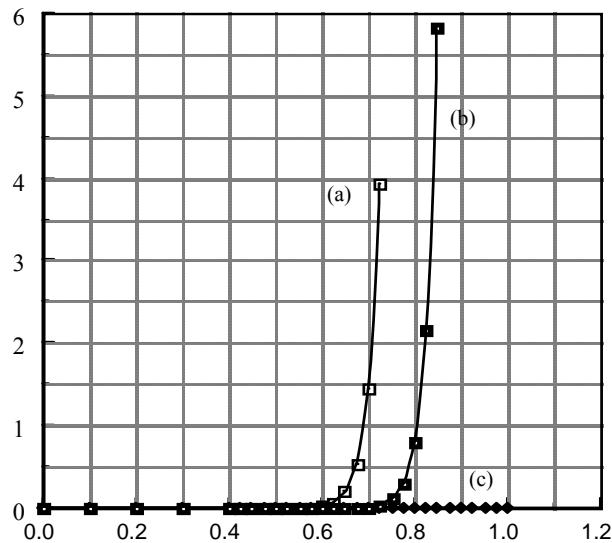
3.18

$$V_T = \frac{kT}{q} = \frac{(1.38 \times 10^{-23} J/K) T}{1.60 \times 10^{-19} C} = 8.63 \times 10^{-5} T$$

For T = 218 K, 273 K and 358 K, V_T = 18.8 mV, 23.6 mV and 30.9 mV

3.19

Graphing $I_D = I_S \left[\exp\left(\frac{40V_D}{n}\right) - 1 \right]$ yields :



3.20

$$nV_T = n \frac{kT}{q} = 1.04 \frac{(1.38 \times 10^{-23} J/K)(300)}{1.60 \times 10^{-19} C} = 26.88 \text{ mV} \quad T = 26.88 \text{ mV} \frac{1.602 \times 10^{-19}}{1.38 \times 10^{-23}} = 312 \text{ K}$$

3.21

$$i_D = I_s \left[\exp\left(\frac{v_D}{nV_T}\right) - 1 \right] \quad \text{or} \quad \frac{v_D}{nV_T} = \ln\left(1 + \frac{i_D}{I_s}\right)$$

$$\text{For } i_D \gg I_s, \quad \frac{v_D}{nV_T} \approx \ln\left(\frac{i_D}{I_s}\right) \quad \text{or} \quad \ln(I_D) = \left(\frac{1}{nV_T}\right)v_D + \ln(I_s)$$

which is the equation of a straight line with slope $1/nV_T$ and x-axis intercept at $-\ln(I_s)$. The values of n and I_s can be found from any two points on the line in the figure: e. g. $i_D = 10^{-4} \text{ A}$ for $v_D = 0.60 \text{ V}$ and $i_D = 10^{-9} \text{ A}$ for $v_D = 0.20 \text{ V}$. Then there are two equations in two unknowns:

$$\ln(10^{-9}) = \left(\frac{40}{n}\right)20 + \ln(I_s) \quad \text{or} \quad 9.21 = \left(\frac{8}{n}\right) + \ln(I_s)$$

$$\ln(10^{-4}) = \left(\frac{40}{n}\right)60 + \ln(I_s) \quad \text{or} \quad 20.72 = \left(\frac{24}{n}\right) + \ln(I_s)$$

Solving for n and I_s yields $n = 1.39$ and $I_s = 3.17 \times 10^{-12} \text{ A} = 3.17 \text{ pA}$.

3.22

$$V_D = nV_T \ln\left(1 + \frac{I_D}{I_s}\right) \quad | \quad I_D = I_s \left[\exp\left(\frac{V_D}{nV_T}\right) - 1 \right]$$

$$(a) V_D = 1.05(0.025V) \ln\left(1 + \frac{7 \times 10^{-5} A}{10^{-18} A}\right) = 0.837V \quad | \quad (b) V_D = 1.05(0.025V) \ln\left(1 + \frac{5 \times 10^{-6} A}{10^{-18} A}\right) = 0.768V$$

$$(c) I_D = 10^{-18} A \left[\exp\left(\frac{0}{1.05 \cdot 0.025V}\right) - 1 \right] = 0 A$$

$$(d) I_D = 10^{-18} A \left[\exp\left(\frac{-0.075V}{1.05 \cdot 0.025V}\right) - 1 \right] = -0.943 \times 10^{-19} A$$

$$(e) I_D = 10^{-18} A \left[\exp\left(\frac{-5V}{1.05 \cdot 0.025V}\right) - 1 \right] = -1.00 \times 10^{-18} A$$

3.23

$$V_D = nV_T \ln\left(1 + \frac{I_D}{I_s}\right) \quad | \quad I_D = I_s \left[\exp\left(\frac{V_D}{nV_T}\right) - 1 \right]$$

$$(a) V_D = 0.025V \ln\left(1 + \frac{10^{-4} A}{10^{-17} A}\right) = 0.748V \quad | \quad (b) V_D = 0.025V \ln\left(1 + \frac{10^{-5} A}{10^{-17} A}\right) = 0.691V$$

$$(c) I_D = 10^{-17} A \left[\exp\left(\frac{0}{0.025V}\right) - 1 \right] = 0 A$$

$$(d) I_D = 10^{-17} A \left[\exp\left(\frac{-0.06V}{0.025V}\right) - 1 \right] = -0.909 \times 10^{-17} A$$

$$(e) I_D = 10^{-17} A \left[\exp\left(\frac{-4V}{0.025V}\right) - 1 \right] = -1.00 \times 10^{-17} A$$

3.24

$$I_D = I_S \left[\exp\left(\frac{V_D}{V_T}\right) - 1 \right] = 10^{-17} A \left[\exp\left(\frac{0.675}{0.025}\right) - 1 \right] = 5.32 \times 10^{-6} A = 5.32 \mu A$$

$$V_D = V_T \ln\left(\frac{I_D}{I_S} + 1\right) = (0.025V) \ln\left(\frac{15.9 \times 10^{-6} A}{10^{-17} A} + 1\right) = 0.703 V$$

3.25

$$V_D = nV_T \ln\left(1 + \frac{I_D}{I_S}\right) = 2(0.025V) \ln\left(1 + \frac{40A}{10^{-10} A}\right) = 1.34 V$$

$$V_D = 2(0.025V) \ln\left(1 + \frac{100A}{10^{-10} A}\right) = 1.38 V$$

3.26

$$(a) I_S = \frac{I_D}{\left[\exp\left(\frac{V_D}{nV_T}\right) - 1 \right]} = \frac{2mA}{\left[\exp\left(\frac{0.82}{0.025}\right) - 1 \right]} = 1.14 \times 10^{-17} A$$

$$(b) I_D = 1.14 \times 10^{-17} A \left[\exp\left(\frac{-5}{0.025}\right) - 1 \right] = -1.14 \times 10^{-17} A$$

3.27

$$(a) I_S = \frac{I_D}{\left[\exp\left(\frac{V_D}{nV_T}\right) - 1 \right]} = \frac{300\mu A}{\left[\exp\left(\frac{0.75}{0.025}\right) - 1 \right]} = 2.81 \times 10^{-17} A$$

$$(b) I_D = 2.81 \times 10^{-17} A \left[\exp\left(\frac{-3}{0.025}\right) - 1 \right] = -2.81 \times 10^{-17} A$$

3.28

$$V_D = nV_T \ln\left(1 + \frac{I_D}{I_S}\right) \quad | \quad 10^{-14} \leq I_S \leq 10^{-12} \quad | \quad V_D = (0.025V) \ln\left(1 + \frac{10^{-3}A}{10^{-12}A}\right) = 0.518 \text{ V}$$

$$V_D = (0.025V) \ln\left(1 + \frac{10^{-3}A}{10^{-14}A}\right) = 0.633 \text{ V} \quad | \quad \text{So, } 0.518 \text{ V} \leq V_D \leq 0.633 \text{ V}$$

3.29

$$V_T = \frac{1.38 \times 10^{-23} (307)}{1.60 \times 10^{-19}} = 0.0264V \quad | \quad I_D = I_S \left[\exp\left(\frac{V_D}{0.0264n}\right) - 1 \right]$$

Varying n and I_S by trial-and-error with a spreadsheet:

n	I _S		
1.039	7.606E-15		
V _D	I _D -Measured	I _D -Calculated	Error Squared
0.500	6.591E-07	6.276E-07	9.9198E-16
0.550	3.647E-06	3.885E-06	5.6422E-14
0.600	2.158E-05	2.404E-05	6.0672E-12
0.650	1.780E-04	1.488E-04	8.518E-10
0.675	3.601E-04	3.702E-04	1.0261E-10
0.700	8.963E-04	9.211E-04	6.1409E-10
0.725	2.335E-03	2.292E-03	1.8902E-09
0.750	6.035E-03	5.701E-03	1.1156E-07
0.775	1.316E-02	1.418E-02	1.0471E-06
	Total Squared Error		1.1622E-06

3.30

$$V_T = \frac{kT}{q} = \frac{(1.38 \times 10^{-23} J / K) T}{1.60 \times 10^{-19} C} = 8.63 \times 10^{-5} T$$

For T = 233 K, 273 K and 323 K, V_T = 20.1 mV, 23.6 mV and 27.9 mV

3.31

$$\frac{kT}{q} = \frac{1.38 \times 10^{-23} (303)}{1.60 \times 10^{-19}} = 26.1 \text{ mV} \quad | \quad V_D = (0.0261V) \ln\left(1 + \frac{10^{-3}}{2.5 \times 10^{-16}}\right) = 0.757 \text{ V}$$

$$\Delta V = (-1.8 \text{ mV} / K)(20K) = -36.0 \text{ mV} \quad | \quad V_D = 0.757 - 0.036 = 0.721 \text{ V}$$

3.32

$$\frac{kT}{q} = \frac{1.38 \times 10^{-23} (298)}{1.602 \times 10^{-19}} = 25.67 \text{ mV} \quad | \quad (a) V_D = (0.02567V) \ln\left(1 + \frac{10^{-4}}{10^{-15}}\right) = 0.650 \text{ V}$$

$$\Delta V = (-2.0 \text{ mV}/K)(25K) = -50.0 \text{ mV}$$

$$(b) V_D = 0.650 - 0.050 = 0.600 \text{ V}$$

3.33

$$\frac{kT}{q} = \frac{1.38 \times 10^{-23} (298)}{1.602 \times 10^{-19}} = 25.67 \text{ mV} \quad | \quad (a) V_D = (0.02567V) \ln\left(1 + \frac{2.5 \times 10^{-4}}{10^{-14}}\right) = 0.615 \text{ V}$$

$$(b) \Delta V = (-1.8 \text{ mV}/K)(60K) = -50.0 \text{ mV} \quad V_D = 0.615 - 0.108 = 0.507 \text{ V}$$

$$(c) \Delta V = (-1.8 \text{ mV}/K)(-80K) = +144 \text{ mV} \quad V_D = 0.615 + 0.144 = 0.758 \text{ V}$$

3.34

$$\frac{dv_D}{dT} = \frac{v_D - V_G - 3V_T}{T} = \frac{0.7 - 1.21 - 3(0.0259)}{300} = -1.96 \frac{\text{mV}}{\text{K}}$$

3.35

$$\frac{I_{S2}}{I_{S1}} = \left(\frac{T_2}{T_1}\right)^3 \exp\left[-\left(\frac{E_G}{k}\right)\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right] = \left(\frac{T_2}{T_1}\right)^3 \exp\left[\left(\frac{E_G}{kT_1}\right)\left(1 - \frac{T_1}{T_2}\right)\right]$$

$$f(x) = \left(x\right)^3 \exp\left[\left(\frac{E_G}{kT_1}\right)\left(1 - \frac{1}{x}\right)\right] \quad x = \frac{T_2}{T_1}$$

Using trial and error with a spreadsheet yields $\Delta T = 4.27$ K, 14.6 K, and 30.7 K to increase the saturation current by 2X, 10X, and 100X respectively.

x	f(x)	Delta T
1.00000	1.00000	0.00000
1.00500	1.27888	1.50000
1.01000	1.63167	3.00000
1.01500	2.07694	4.50000
1.01400	1.97945	4.20000
1.01422	2.00051	4.26600
1.01922	2.54151	5.76600
1.02422	3.22151	7.26600
1.02922	4.07433	8.76600
1.03422	5.14160	10.26600
1.03922	6.47438	11.76600
1.04422	8.13522	13.26600
1.04922	10.20058	14.76600
1.04880	10.00936	14.64000
1.10000	90.67434	30.00000
1.10239	100.0012	30.71610

3.36

$$w_d = w_{do} \sqrt{1 + \frac{V_R}{\phi_j}} \quad | \quad (\text{a}) w_d = 1 \mu m \sqrt{1 + \frac{5}{0.8}} = 2.69 \mu m \quad (\text{b}) w_d = 1 \mu m \sqrt{1 + \frac{10}{0.8}} = 3.67 \mu m$$

3.37

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = (0.025V) \ln \frac{(10^{16} cm^{-3})(10^{15} cm^{-3})}{10^{20} cm^{-6}} = 0.633 V$$

$$w_{do} = \sqrt{\frac{2\varepsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right)} \phi_j = \sqrt{\frac{2(11.7 \cdot 8.854 \times 10^{-14} F \cdot cm^{-1})}{1.602 \times 10^{-19} C} \left(\frac{1}{10^{16} cm^{-3}} + \frac{1}{10^{15} cm^{-3}} \right)} (0.633V)$$

$$w_{do} = 0.949 \mu m \quad | \quad w_d = w_{do} \sqrt{1 + \frac{V_R}{\phi_j}}$$

$$w_d = 0.949 \mu m \sqrt{1 + \frac{10V}{0.633V}} = 3.89 \mu m \quad | \quad w_d = 0.949 \mu m \sqrt{1 + \frac{100V}{0.633V}} = 12.0 \mu m$$

3.38

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = (0.025V) \ln \frac{(10^{18} \text{ cm}^{-3})(10^{20} \text{ cm}^{-3})}{10^{20} \text{ cm}^{-6}} = 1.04 \text{ V}$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j} = \sqrt{\frac{2(11.7 \cdot 8.854 \times 10^{-14} \text{ F} \cdot \text{cm}^{-1})}{1.602 \times 10^{-19} \text{ C}} \left(\frac{1}{10^{18} \text{ cm}^{-3}} + \frac{1}{10^{20} \text{ cm}^{-3}} \right) (1.04 \text{ V})}$$

$$w_{do} = 0.0368 \text{ } \mu\text{m} \quad | \quad w_d = w_{do} \sqrt{1 + \frac{V_R}{\phi_j}}$$

$$w_d = 0.0368 \mu\text{m} \sqrt{1 + \frac{5}{1.04}} = 0.0887 \text{ } \mu\text{m} \quad | \quad w_d = 0.0368 \mu\text{m} \sqrt{1 + \frac{25}{1.04}} = 0.184 \text{ } \mu\text{m}$$

3.39

$$E_{\max} = \frac{2(\phi_j + V_R)}{w_d} = \frac{2(\phi_j + V_R)}{w_{do} \sqrt{1 + \frac{V_R}{\phi_j}}} = \frac{2\phi_j}{w_{do}} \sqrt{1 + \frac{V_R}{\phi_j}}$$

$$3 \times 10^5 \frac{V}{\text{cm}} = \frac{2(0.6V)}{10^{-4} \text{ cm}} \sqrt{1 + \frac{V_R}{0.6}} \rightarrow V_R = 374 \text{ V}$$

3.40

$$E = \frac{2\phi_j}{w_{do}} = \frac{2(0.748V)}{0.984 \times 10^{-4} \text{ cm}} = 15.2 \frac{kV}{\text{cm}} \quad | \quad \sqrt{\phi_j + V_R} = \frac{E_{\max}}{2} \frac{w_{do}}{\sqrt{\phi_j}} = \frac{3 \times 10^5 \frac{V}{\text{cm}} (0.984 \times 10^{-4} \text{ cm})}{2 \sqrt{0.748V}}$$

$$V_R = 291.3 - 0.748 = 291 \text{ V}$$

3.41

$V_Z = 4 \text{ V}$; $R_Z = 0 \Omega$ since the reverse breakdown slope is infinite.

3.42

Since $N_A \gg N_D$, the depletion layer is all on the lightly-doped side of the junction. Also, $V_R \gg \phi_j$, so ϕ_j can be neglected.

$$E_{\max} = \frac{qN_A x_p}{\epsilon_s} = \frac{qN_A w_d}{\epsilon_s} = \frac{qN_A}{\epsilon_s} \sqrt{\frac{2\epsilon_s}{q} \frac{V_R}{N_A}}$$

$$N_A = \frac{E_{\max}^2 \epsilon_s}{2qV_R} = \frac{(3 \times 10^5)^2 (11.7)(8.854 \times 10^{-14})}{2(1.602 \times 10^{-19}) 1000} = 2.91 \times 10^{14} / \text{cm}^3$$

3.43

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = 0.025 \ln \frac{10^{15} 10^{20}}{10^{20}} = 0.864V$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j} = \sqrt{\frac{2(11.7)(8.854 \times 10^{-14})}{1.602 \times 10^{-19}} \left(\frac{1}{10^{15}} + \frac{1}{10^{20}} \right) 0.864} = 1.057 \times 10^{-4} cm$$

$$C_{jo}'' = \frac{\epsilon_s}{w_{do}} = \frac{11.7(8.854 \times 10^{-14})}{1.057 \times 10^{-4}} = 9.80 \times 10^{-9} F/cm^2 \quad | \quad C_j = \frac{C_{jo}'' A}{\sqrt{1 + \frac{V_R}{\phi_j}}} = \frac{9.80 \times 10^{-9} (0.05)}{\sqrt{1 + \frac{5}{0.864}}} = 188 pF$$

3.44

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = 0.025 \ln \frac{10^{18} 10^{15}}{10^{20}} = 0.748V$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j} = \sqrt{\frac{2(11.7)(8.854 \times 10^{-14})}{1.602 \times 10^{-19}} \left(\frac{1}{10^{18}} + \frac{1}{10^{15}} \right) 0.748} = 0.984 \times 10^{-4} cm$$

$$C_{jo}'' = \frac{\epsilon_s}{w_{do}} = \frac{11.7(8.854 \times 10^{-14})}{0.984 \times 10^{-4}} = 10.5 \times 10^{-9} F/cm^2 \quad | \quad C_j = \frac{C_{jo}'' A}{\sqrt{1 + \frac{V_R}{\phi_j}}} = \frac{10.5 \times 10^{-9} (0.02)}{\sqrt{1 + \frac{10}{0.748}}} = 55.4 pF$$

3.45

$$(a) C_D = \frac{I_D \tau_T}{V_T} = \frac{10^{-4} A (10^{-10} s)}{0.025 V} = 400 fF \quad (b) Q = I_D \tau_T = 10^{-4} A (10^{-10} s) = 10 fC$$

$$(c) C_D = \frac{25 \times 10^{-3} A (10^{-10} s)}{0.025 V} = 100 pF \quad | \quad Q = I_D \tau_T = 5 \times 10^{-3} A (10^{-10} s) = 0.50 pC$$

3.46

$$(a) C_D = \frac{I_D \tau_T}{V_T} = \frac{1 A (10^{-8} s)}{0.025 V} = 0.400 \mu F \quad (b) Q = I_D \tau_T = 1 A (10^{-8} s) = 10.0 nC$$

$$(c) C_D = \frac{100 mA (10^{-8} s)}{0.025 V} = 0.04 \mu F \quad | \quad Q = I_D \tau_T = 100 mA (10^{-8} s) = 1.00 nC$$

3.47

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = 0.025 \ln \frac{10^{19} 10^{17}}{10^{20}} = 0.921 V$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j} = \sqrt{\frac{2(11.7)(8.854 \times 10^{-14})}{1.602 \times 10^{-19}} \left(\frac{1}{10^{19}} + \frac{1}{10^{17}} \right) 0.921} = 0.110 \mu m$$

$$C_{jo} = \frac{\epsilon_s A}{w_{do}} = \frac{11.7(8.854 \times 10^{-14})(10^{-4})}{0.110 \times 10^{-4}} = 9.42 pF/cm^2 \quad | \quad C_j = \frac{C_{jo}}{\sqrt{1 + \frac{V_R}{\phi_j}}} = \frac{9.42 pF}{\sqrt{1 + \frac{5}{0.921}}} = 3.72 pF$$

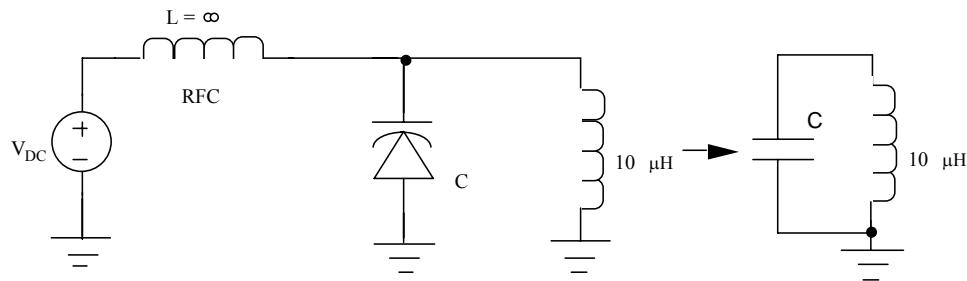
3.48

$$\phi_j = V_T \ln \frac{N_A N_D}{n_i^2} = 0.025 \ln \frac{10^{19} 10^{16}}{10^{20}} = 0.864 V$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j} = \sqrt{\frac{2(11.7)(8.854 \times 10^{-14})}{1.602 \times 10^{-19}} \left(\frac{1}{10^{19}} + \frac{1}{10^{16}} \right) 0.864} = 0.334 \mu m$$

$$C_{jo} = \frac{\epsilon_s A}{w_{do}} = \frac{11.7(8.854 \times 10^{-14})(0.25 cm^2)}{0.334 \times 10^{-4}} = 7750 pF \quad | \quad C_j = \frac{C_{jo}}{\sqrt{1 + \frac{V_R}{\phi_j}}} = \frac{7750 pF}{\sqrt{1 + \frac{3}{0.864}}} = 3670 pF$$

3.49



$$C = \frac{C_{jo}}{\sqrt{1 + \frac{V_R}{\phi_j}}} \quad (a) \quad C = \frac{39 pF}{\sqrt{1 + \frac{1V}{0.75V}}} = 25.5 pF \quad | \quad f_o = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(10^{-5} H)(25.5 pF)}} = 9.97 MHz$$

$$(b) \quad C = \frac{39 pF}{\sqrt{1 + \frac{10V}{0.75V}}} = 10.3 pF \quad | \quad f_o = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(10^{-5} H)(0.3 pF)}} = 15.7 MHz$$

3.50

$$(a) \quad V_D = (0.025V) \ln \left(1 + \frac{50A}{10^{-7} A} \right) = 0.501 V \quad | \quad (b) \quad V_D = (0.025V) \ln \left(1 + \frac{50A}{10^{-15} A} \right) = 0.961 V$$

3.51

$$(a) V_D = (0.025V) \ln\left(1 + \frac{4 \times 10^{-3} A}{10^{-11} A}\right) = 0.495 V \quad | \quad (b) V_D = (0.025V) \ln\left(1 + \frac{4 \times 10^{-3} A}{10^{-14} A}\right) = 0.668 V$$

3.52

$$R_s = R_p + R_n \quad R_p = \rho_p \frac{L_p}{A_p} = (1\Omega - cm) \frac{0.025cm}{0.01cm^2} = 2.5\Omega$$

$$R_n = \rho_n \frac{L_n}{A_n} = (0.01\Omega - cm) \frac{0.025cm}{0.01cm^2} = 0.025\Omega \quad R_s = 2.53 \Omega$$

3.53

$$(a) V'_D = V_T \ln\left(1 + \frac{I_D}{I_S}\right) = (0.025V) \ln\left(1 + \frac{10^{-3}}{5 \times 10^{-16}}\right) = 0.708V$$

$$V_D = V'_D + I_D R_s = 0.708V + 10^{-3} A (10\Omega) = 0.718 V$$

$$(b) V_D = V'_D + I_D R_s = 0.708V + 10^{-3} A (100\Omega) = 0.808 V$$

3.54

$$\rho_c = 10\Omega - \mu m^2 \quad A_c = 1\mu m^2 \quad R_C = \frac{\rho_c}{A_c} = \frac{10\Omega - \mu m^2}{1\mu m^2} = 10\Omega / contact$$

5 anode contacts and 14 cathode contacts

$$\text{Resistance of anode contacts} = \frac{10\Omega}{5} = 2\Omega$$

$$\text{Resistance of cathode contacts} = \frac{10\Omega}{14} = 0.71\Omega$$

3.55

(a) From Fig. 3.21a, the diode is approximately 10.5 μm long x 8 μm wide. Area = 84 μm^2 .

$$(b) \text{Area} = (10.5 \times 0.13 \mu m) \times (8 \times 0.13 \mu m) = 1.42 \mu m^2.$$

3.56

(a) $5 = 10^4 I_D + V_D \quad | \quad V_D = 0 \quad I_D = 0.500mA \quad | \quad I_D = 0 \quad V_D = 5V$

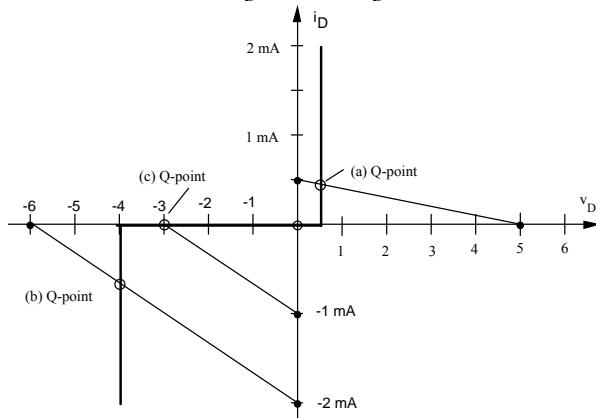
Forward biased - $V_D = 0.5 V \quad I_D = \frac{4.5V}{10^4\Omega} = 0.450 mA$

(b) $-6 = 3000I_D + V_D \quad | \quad V_D = 0 \quad I_D = -2.00mA \quad | \quad I_D = 0 \quad V_D = -6V$

In reverse breakdown - $V_D = -4 V \quad I_D = \frac{-2V}{3k\Omega} = -0.667 mA$

(c) $-3 = -3000I_D + V_D \quad | \quad V_D = 0 \quad I_D = -1.00mA \quad | \quad I_D = 0 \quad V_D = -3V$

Reverse biased - $V_D = -3 V \quad I_D = 0$



3.57

(a) $10 = 5000I_D + V_D \quad | \quad V_D = 0 \quad I_D = 2.00 mA \quad | \quad V_D = 5 V \quad I_D = 1.00 mA$

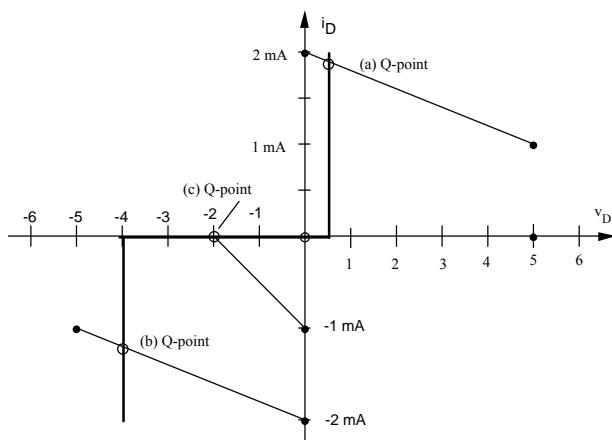
Forward biased - $V_D = 0.5V \quad I_D = \frac{9.5V}{5k\Omega} = 1.90 mA$

(b) $-10 = 5000I_D + V_D \quad | \quad V_D = 0 \quad I_D = -2.00 mA \quad | \quad V_D = -5 V \quad I_D = -1.00 mA$

In reverse breakdown - $V_D = -4V \quad I_D = \frac{-6V}{5k\Omega} = -1.20 mA$

(c) $-2 = 2000I_D + V_D \quad | \quad V_D = 0 \quad I_D = -1.00 mA \quad | \quad I_D = 0 \quad V_D = -2 V$

Reverse biased - $V_D = -2 V \quad I_D = 0$



3.58

*Problem 3.58 - Diode Circuit SPICE Results

V 1 0 DC 5
 R 1 2 10K
 D1 2 0 DIODE1
 .OP
 .MODEL DIODE1 D IS=1E-15
 .END

3.59

$$(a) -10 = 10^4 I_D + V_D \quad | \quad V_D = 0 \quad I_D = -1.00 \text{ mA} \quad | \quad V_D = -5 \text{ V} \quad I_D = -0.500 \text{ mA}$$

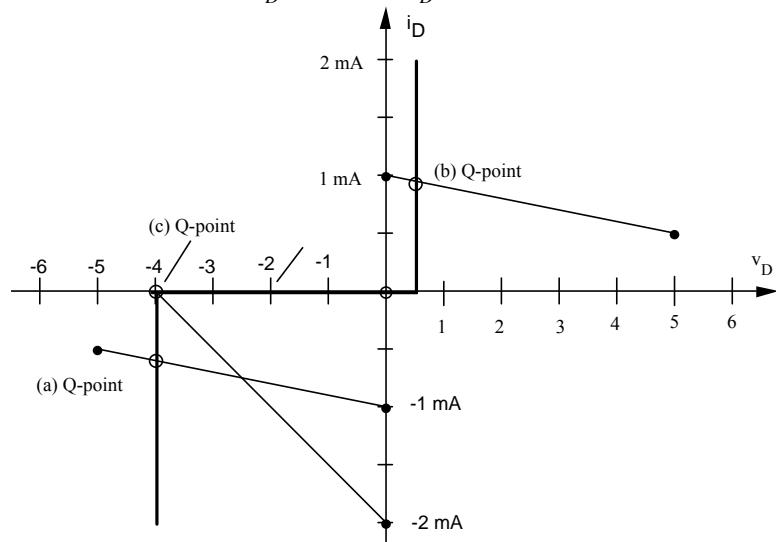
$$\text{In reverse breakdown} - V_D = -4 \text{ V} \quad I_D = \frac{-10 - (-4)V}{10k\Omega} = -0.600 \text{ mA}$$

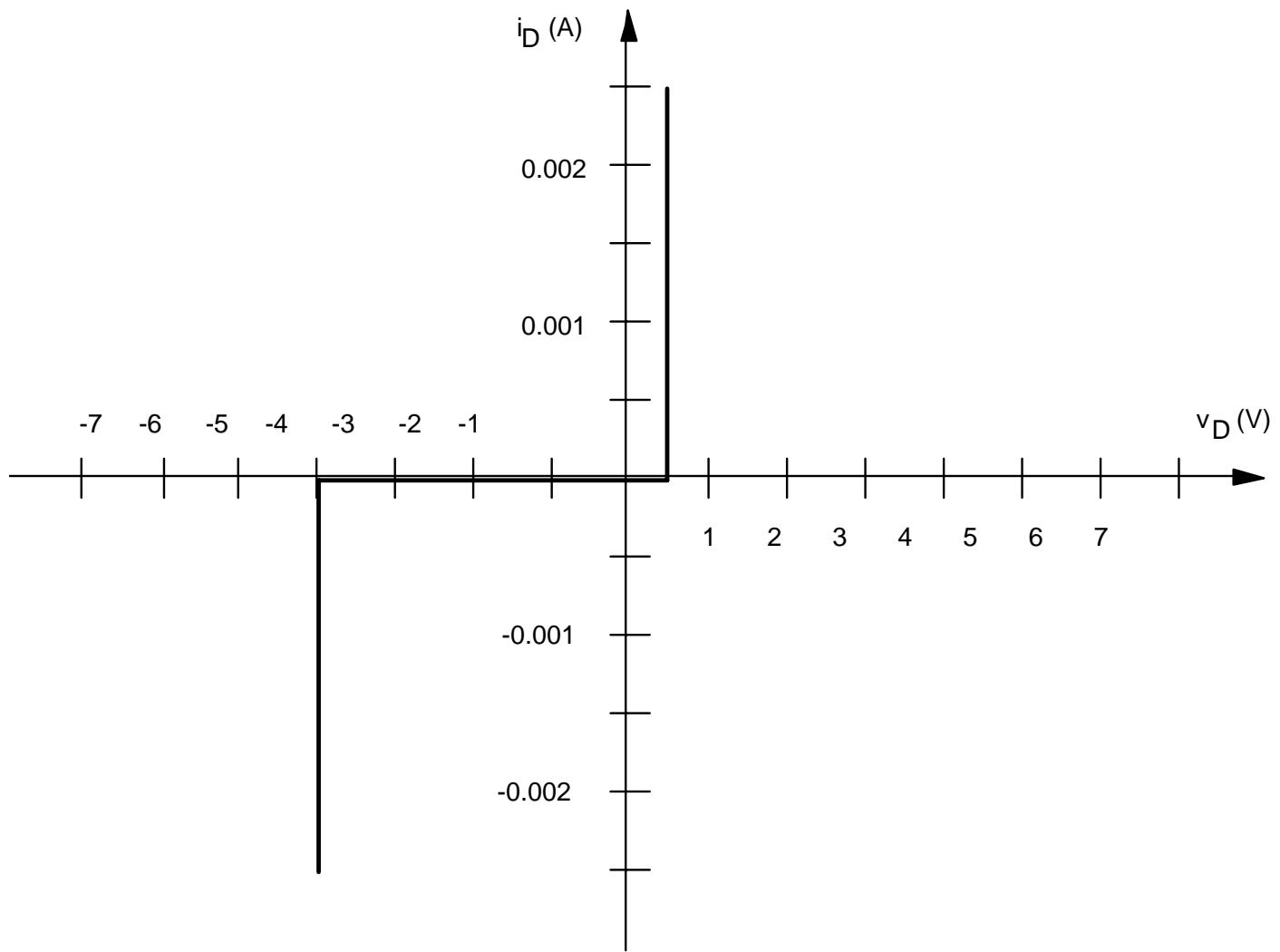
$$(b) 10 = 10^4 I_D + V_D \quad | \quad V_D = 0 \quad I_D = 1.00 \text{ mA} \quad | \quad V_D = 5 \text{ V} \quad I_D = 0.500 \text{ mA}$$

$$\text{Forward biased} - V_D = 0.5 \text{ V} \quad I_D = \frac{10 - 0.5V}{10k\Omega} = 0.950 \text{ mA}$$

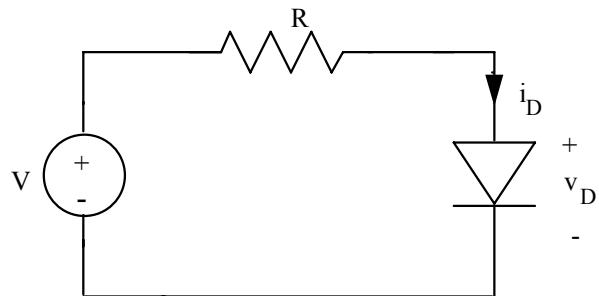
$$(c) -4 = 2000I_D + V_D \quad | \quad V_D = 0 \quad I_D = -2.00 \text{ mA} \quad | \quad I_D = 0 \quad V_D = -4 \text{ V}$$

Reverse biased - $V_D = -4 \text{ V}$ $I_D = 0$





3.60



The load line equation: $V = i_D R + v_D$ We need two points to plot the load line.

(a) $V = 6 \text{ V}$ and $R = 4\text{k}\Omega$: For $v_D = 0$, $i_D = 6\text{V}/4 \text{ k}\Omega = 1.5 \text{ mA}$ and for $i_D = 0$, $v_D = 6\text{V}$.

Plotting this line on the graph yields the Q-pt: (0.5 V, 1.4 mA).

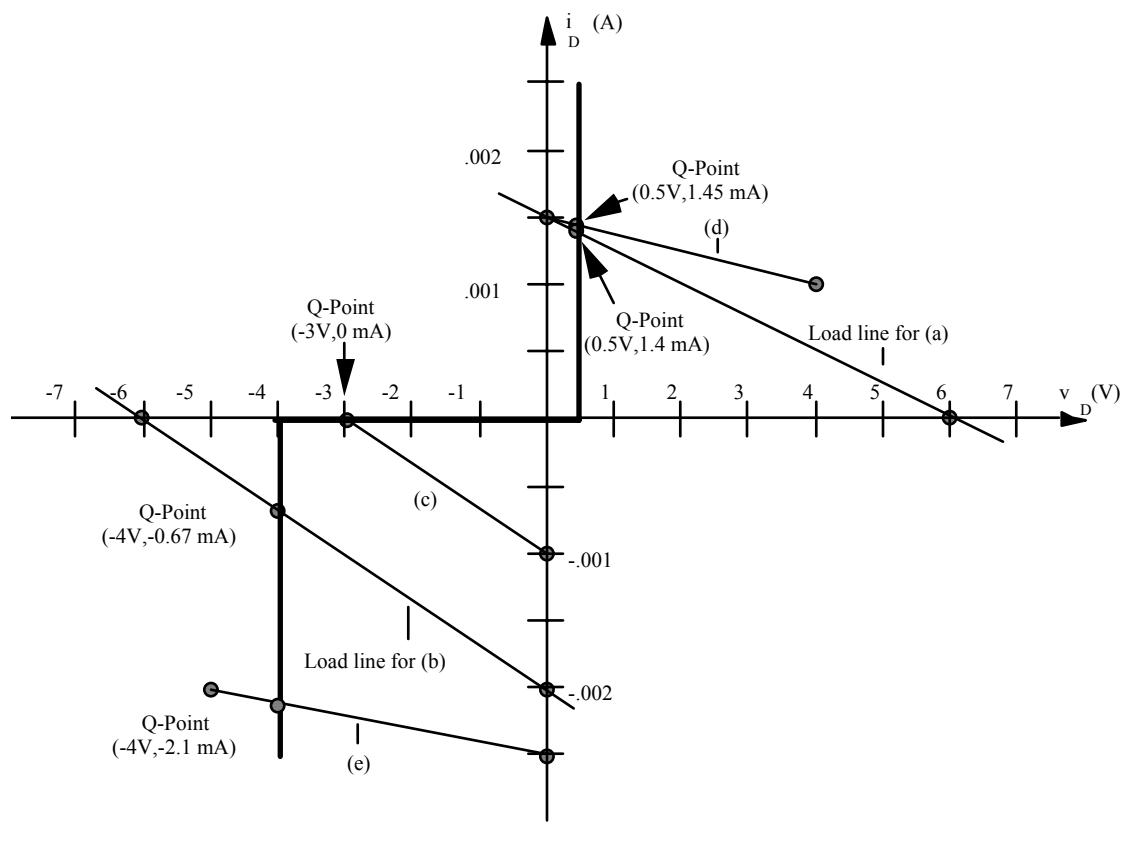
(b) $V = -6 \text{ V}$ and $R = 3\text{k}\Omega$: For $v_D = 0$, $i_D = -6\text{V}/3 \text{ k}\Omega = -2 \text{ mA}$ and for $i_D = 0$, $v_D = -6\text{V}$.

Plotting this line on the graph yields the Q-pt: (-4 V, -0.67 mA).

(c) $V = -3 \text{ V}$ and $R = 3\text{k}\Omega$: Two points: (0V, -1mA), (-3V, 0mA); Q-pt: (-3 V, 0 mA)

(d) $V = +12 \text{ V}$ and $R = 8\text{k}\Omega$: Two points: (0V, 1.5mA), (4V, 1mA); Q-pt: (0.5 V, 1.4 mA)

(e) $V = -25 \text{ V}$ and $R = 10\text{k}\Omega$: Two points: (0V, -2.5mA), (-5V, -2mA); Q-pt: (-4 V, -2.1 mA)



3.61

Using the equations from Table 3.1, ($f = 10 - 10^{-9} \exp \dots$, etc.)
 $V_D = 0.7$ V requires 12 iterations, $V_D = 0.5$ V requires 22 iterations,
 $V_D = 0.2$ V requires 384 iterations - very poor convergence because the second iteration ($V_D = 9.9988$ V) is very bad.

3.62

Using Eqn. (3.28),

$$V = i_D R + V_T \ln\left(\frac{i_D}{I_S}\right) \quad \text{or} \quad 10 = 10^4 i_D + 0.025 \ln(10^{13} i_D)$$

We want to find the zero of the function $f = 10 - 10^4 i_D - 0.025 \ln(10^{13} i_D)$

i_D	f
.001	-0.576
.0001	8.48
.0009	0.427
.00094	0.0259 - converged

3.63

$$f = 10 - 10^4 I_D - 0.025 \ln\left(1 + \frac{I_D}{I_S}\right) \quad | \quad f' = -10^4 - \frac{0.025}{I_D + I_S}$$

x	$f(x)$	$f'(x)$
1.0000E+00	-9.991E+03	-1.000E+04
9.2766E-04	1.496E-01	-1.003E+04
9.4258E-04	3.199E-06	-1.003E+04
9.4258E-04	9.992E-16	-1.003E+04
9.4258E-04	9.992E-16	-1.003E+04

3.64

Create the following m-file:

```
function fd=current(id)
    fd=10-1e4*id-0.025*log(1+id/1e-13);
```

Then: fzero('current',1) yields ans = 9.4258e-04 + 1.0216e-21i

3.65

The one-volt source will forward bias the diode. Load line:

$$1 = 10^4 I_D + V_D \quad | \quad I_D = 0 \quad V_D = 1V \quad | \quad V_D = 0 \quad I_D = 0.1mA \rightarrow (50 \mu A, 0.5 V)$$

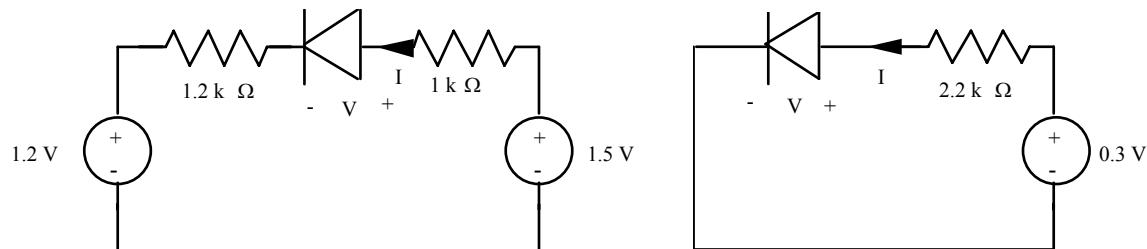
$$\text{Mathematical model: } f = 1 - 10^{-9} [\exp(40V_D) - 1] + V_D \rightarrow (49.9 \mu A, 0.501 V)$$

$$\text{Ideal diode model: } I_D = 1V/10k\Omega = 100\mu A; (100\mu A, 0 V)$$

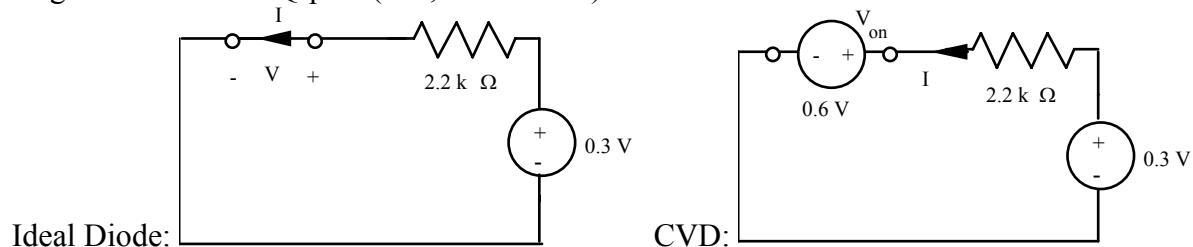
$$\text{Constant voltage drop model: } I_D = (1-0.6)V/10k\Omega = 40.0\mu A; (40.0\mu A, 0.6 V)$$

3.66

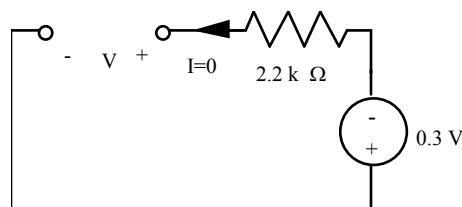
Using Thévenin equivalent circuits yields and then combining the sources



(a) Ideal diode model: The 0.3 V source appears to be forward biasing the diode, so we will assume it is "on". Substituting the ideal diode model for the forward region yields $I = \frac{0.3V}{2.2k\Omega} = 0.136 mA$. This current is greater than zero, which is consistent with the diode being "on". Thus the Q-pt is (0 V, +0.136 mA).



(b) CVD model: The 0.3 V source appears to be forward biasing the diode so we will assume it is "on". Substituting the CVD model with $V_{on} = 0.6 V$ yields $I = \frac{0.3V - 0.6V}{2.2k\Omega} = -136 \mu A$. This current is negative which is not consistent with the assumption that the diode is "on". Thus the diode must be off. The resulting Q-pt is: (0 mA, -0.3 V).



(c) The second estimate is more realistic. 0.3 V is not sufficient to forward bias the diode into significant conduction. For example, let us assume that $I_S = 10^{-15}$ A, and assume that the full 0.3 V appears across the diode. Then

$$i_D = 10^{-15} A \left[\exp\left(\frac{0.3V}{0.025V}\right) - 1 \right] = 163 \text{ pA}, \text{ a very small current.}$$

3.67

The nominal values are:

$$V_A = 3V \left(\frac{R_2}{R_1 + R_2} \right) = 3V \left(\frac{2k\Omega}{2k\Omega + 3k\Omega} \right) = 1.20V \quad \text{and} \quad R_{THA} = \frac{R_1 R_2}{R_1 + R_2} = \frac{2k\Omega(3k\Omega)}{2k\Omega + 3k\Omega} = 1.20k\Omega$$

$$V_C = 3V \left(\frac{R_4}{R_3 + R_4} \right) = 3V \left(\frac{2k\Omega}{2k\Omega + 2k\Omega} \right) = 1.50V \quad \text{and} \quad R_{THC} = \frac{R_3 R_4}{R_3 + R_4} = \frac{2k\Omega(2k\Omega)}{2k\Omega + 2k\Omega} = 1.00k\Omega$$

$$I_D^{nom} = \left(\frac{1.50 - 1.20}{1.20 + 1.00} \right) \frac{V}{k\Omega} = 136 \mu A$$

For maximum current, we make the Thévenin equivalent voltage at the diode anode as large as possible and that at the cathode as small as possible.

$$V_A = \frac{3V}{1 + \frac{R_1}{R_2}} = \frac{3V}{1 + \frac{2k\Omega(0.9)}{2k\Omega(1.1)}} = 1.65V \quad \text{and} \quad R_{THA} = \frac{R_1 R_2}{R_1 + R_2} = \frac{2k\Omega(0.9)2k\Omega(1.1)}{2k\Omega(0.9) + 2k\Omega(1.1)} = 0.990k\Omega$$

$$V_C = \frac{3V}{1 + \frac{R_3}{R_4}} = \frac{3V}{1 + \frac{3k\Omega(1.1)}{2k\Omega(0.9)}} = 1.06V \quad \text{and} \quad R_{THC} = \frac{R_3 R_4}{R_3 + R_4} = \frac{3k\Omega(1.1)2k\Omega(0.9)}{3k\Omega(1.1) + 2k\Omega(0.9)} = 1.17k\Omega$$

$$I_D^{\max} = \left(\frac{1.65 - 1.06}{0.990 + 1.17} \right) \frac{V}{k\Omega} = 274 \mu A$$

For minimum current, we make the Thévenin equivalent voltage at the diode anode as small as possible and that at the cathode as large as possible.

$$V_A = \frac{3V}{1 + \frac{R_1}{R_2}} = \frac{3V}{1 + \frac{2k\Omega(1.1)}{2k\Omega(0.9)}} = 1.350V \quad \text{and} \quad R_{THA} = \frac{R_1 R_2}{R_1 + R_2} = \frac{2k\Omega(1.1)2k\Omega(0.9)}{2k\Omega(1.1) + 2k\Omega(0.9)} = 0.990k\Omega$$

$$V_C = \frac{3V}{1 + \frac{R_3}{R_4}} = \frac{3V}{1 + \frac{3k\Omega(0.9)}{2k\Omega(1.1)}} = 1.347V \quad \text{and} \quad R_{THC} = \frac{R_3 R_4}{R_3 + R_4} = \frac{3k\Omega(0.9)2k\Omega(1.1)}{3k\Omega(0.9) + 2k\Omega(1.1)} = 1.21k\Omega$$

$$I_D^{\min} = \left(\frac{1.350 - 1.347}{0.990 + 1.21} \right) \frac{V}{k\Omega} = 1.39 \mu A \cong 0$$

3.68**SPICE Input**

```
*Problem 3.68
V1 1 0 DC 4
R1 1 2 2K
R2 2 0 2K
R3 1 3 3K
R4 3 0 2K
D1 2 3 DIODE
.MODEL DIODE D IS=1E-15 RS=0
.OP
.END
```

Results

NAME	D1
MODEL	DIODE
ID	1.09E-10
VD	3.00E-01

The diode is essentially off - $V_D = 0.3$ V and $I_D = 0.109$ nA. This result agrees with the CVD model results.

3.69 (a)

$$(a) \text{ Diode is forward biased : } V = 3 - 0 = 3 \text{ V} \mid I = \frac{3 - (-7)}{16k\Omega} = 0.625 \text{ mA}$$

$$(b) \text{ Diode is forward biased : } V = -5 + 0 = -5 \text{ V} \mid I = \frac{5 - (-5)}{16k\Omega} = 0.625 \text{ mA}$$

$$(c) \text{ Diode is reverse biased : } I = 0 \mid V = -5 + 16k\Omega(I) = -5 \text{ V} \mid V_D = -10 \text{ V}$$

$$(d) \text{ Diode is reverse biased : } I = 0 \mid V = 7 - 16k\Omega(I) = 7 \text{ V} \mid V_D = -10 \text{ V}$$

(b)

$$(a) \text{ Diode is forward biased : } V = 3 - 0.7 = 2.3 \text{ V} \mid I = \frac{2.3 - (-7)}{16k\Omega} = 0.581 \text{ mA}$$

$$(b) \text{ Diode is forward biased : } V = -5 + 0.7 = -4.3 \text{ V} \mid I = \frac{5 - (-4.3)}{16k\Omega} = 0.581 \text{ mA}$$

$$(c) \text{ Diode is reverse biased : } I = 0 \mid V = -5 + 16k\Omega(I) = -5 \text{ V} \mid V_D = -10 \text{ V}$$

$$(d) \text{ Diode is reverse biased : } I = 0 \mid V = 7 - 16k\Omega(I) = 7 \text{ V} \mid V_D = -10 \text{ V}$$

3.70 (a)

$$(a) \text{ Diode is forward biased : } V = 3 - 0 = 3 \text{ V} \mid I = \frac{3 - (-7)}{100k\Omega} = 100 \mu A$$

$$(b) \text{ Diode is forward biased : } V = -5 + 0 = -5 \text{ V} \mid I = \frac{5 - (-5)}{100k\Omega} = 100 \mu A$$

$$(c) \text{ Diode is reverse biased : } I = 0 \text{ A} \mid V = -5 + 100k\Omega(I) = -5 \text{ V} \mid V_D = -10 \text{ V}$$

$$(d) \text{ Diode is reverse biased : } I = 0 \text{ A} \mid V = 7 - 100k\Omega(I) = 7 \text{ V} \mid V_D = -10 \text{ V}$$

(b)

(a) Diode is forward biased : $V = 3 - 0.6 = 2.4 \text{ V}$ | $I = \frac{2.4 - (-7)}{100k\Omega} = 94.0 \mu\text{A}$

(b) Diode is forward biased : $V = -5 + 0.6 = -4.4 \text{ V}$ | $I = \frac{5 - (-4.4)}{100k\Omega} = 94.0 \mu\text{A}$

(c) Diode is reverse biased : $I = 0$ | $V = -5 + 100k\Omega(I) = -5 \text{ V}$ | $V_D = -10 \text{ V}$

(d) Diode is reverse biased : $I = 0$ | $V = 7 - 100k\Omega(I) = 7 \text{ V}$ | $V_D = -10 \text{ V}$

3.71 (a)

(a) D_1 on, D_2 on : $I_{D2} = \frac{0 - (-9)}{22k\Omega} = 409 \mu\text{A}$ | $I_{D1} = 409 \mu\text{A} - \frac{6 - 0}{43k\Omega} = 270 \mu\text{A}$

$$D_1 : (409 \mu\text{A}, 0 \text{ V}) \quad D_2 : (270 \mu\text{A}, 0 \text{ V})$$

(b) D_1 on, D_2 off : $I_{D2} = 0$ | $I_{D1} = \frac{6 - 0}{43k\Omega} = 140 \mu\text{A}$ | $V_{D2} = -9 - 0 = -9 \text{ V}$

$$D_1 : (140 \mu\text{A}, 0 \text{ V}) \quad D_2 : (0 \text{ A}, -9 \text{ V})$$

(c) D_1 off, D_2 on : $I_{D1} = 0$ | $I_{D2} = \frac{6 - (-9)}{65k\Omega} = 230 \mu\text{A}$ | $V_{D1} = 6 - 43 \times 10^3 I_{D2} = -3.92 \text{ V}$

$$D_1 : (0 \text{ A}, -3.92 \text{ V}) \quad D_2 : (230 \mu\text{A}, 0 \text{ V})$$

(d) D_1 on, D_2 on : $I_{D2} = \frac{0 - (-6)}{43k\Omega} = 140 \mu\text{A}$ | $I_{D1} = \frac{9 - 0}{22k\Omega} - 140 \mu\text{A} = 270 \mu\text{A}$

$$D_1 : (140 \mu\text{A}, 0 \text{ V}) \quad D_2 : (270 \mu\text{A}, 0 \text{ V})$$

(b)

(a) D_1 on, D_2 on :

$$I_{D2} = \frac{-0.75 - 0.75 - (-9)}{22k\Omega} = 341 \mu\text{A} \quad I_{D1} = 341 \mu\text{A} - \frac{6 - (-0.75)}{43k\Omega} = 184 \mu\text{A}$$

$$D_1 : (184 \mu\text{A}, 0.75 \text{ V}) \quad D_2 : (341 \mu\text{A}, 0.75 \text{ V})$$

(b) D_1 on, D_2 off :

$$I_{D2} = 0 \quad I_{D1} = \frac{6 - 0.75}{43k\Omega} = 122 \mu\text{A} \quad V_{D2} = -9 - 0.75 = -9.75 \text{ V}$$

$$D_1 : (122 \mu\text{A}, 0.75 \text{ V}) \quad D_2 : (0 \text{ A}, -9.75 \text{ V})$$

(c) D₁ off, D₂ on :

$$I_{D1} = 0 \quad | \quad I_{D2} = \frac{6 - 0.75 - (-9)}{65k\Omega} = 219\mu A \quad | \quad V_{D1} = 6 - 43 \times 10^3 I_{D2} = -3.43V$$

$$D_1 : (0 \text{ A}, -3.43 \text{ V}) \quad D_2 : (219 \text{ } \mu A, 0.75 \text{ V})$$

(d) D₁ on, D₂ on :

$$I_{D2} = \frac{0.75 - 0.75 - (-6)}{43k\Omega} = 140\mu A \quad | \quad I_{D1} = \frac{9 - 0.75}{22k\Omega} - 400\mu A = 235\mu A$$

$$D_1 : (235 \text{ } \mu A, 0.75 \text{ V}) \quad D_2 : (140 \text{ } \mu A, 0.75 \text{ V})$$

3.72 (a)

(a) D₁ and D₂ forward biased

$$I_{D2} = \frac{0 - (-9)}{15} \frac{V}{k\Omega} = 600\mu A \quad I_{D1} = I_{D2} - \frac{6 - (0)}{15} \frac{V}{k\Omega} = 200\mu A$$

$$D_1 : (0 \text{ V}, 200 \text{ } \mu A) \quad D_2 : (0 \text{ V}, 600 \text{ } \mu A)$$

(b) D₁ forward biased, D₂ reverse biased

$$I_{D1} = \frac{6 - 0}{15} \frac{V}{k\Omega} = 400\mu A \quad V_{D2} = -9 - 0 = -9 \text{ V}$$

$$D_1 : (0 \text{ V}, 400 \text{ } \mu A) \quad D_2 : (-9 \text{ V}, 0 \text{ A})$$

(c) D₁ reverse biased, D₂ forward biased

$$I_{D2} = \frac{6V - (-9V)}{30k\Omega} = 500\mu A \quad V_{D1} = 6 - 15000 I_{D2} = -1.50V$$

$$D_1 : (-1.50 \text{ V}, 0 \text{ A}) \quad D_2 : (0 \text{ V}, 500 \text{ } \mu A)$$

(d) D₁ and D₂ forward biased

$$I_{D2} = \frac{0 - (-6)}{15} \frac{V}{k\Omega} = 400\mu A \quad I_{D1} = \frac{9 - (0)}{15} \frac{V}{k\Omega} - I_{D2} = 200\mu A$$

$$D_1 : (0 \text{ V}, 200 \text{ } \mu A) \quad D_2 : (0 \text{ V}, 400 \text{ } \mu A)$$

(b)

(a) D₁ on, D₂ on :

$$I_{D2} = \frac{-0.75 - 0.75 - (-9)}{15k\Omega} = 500\mu A \quad | \quad I_{D1} = 500\mu A - \frac{6 - (-0.75)}{15k\Omega} = 50.0\mu A$$

$$D_1 : (50.0 \text{ } \mu A, 0.75 \text{ V}) \quad D_2 : (500 \text{ } \mu A, 0.75 \text{ V})$$

(b) D₁ on, D₂ off :

$$I_{D2} = 0 \quad | \quad I_{D1} = \frac{6 - 0.75}{15k\Omega} = 350\mu A \quad | \quad V_{D2} = -9 - 0.75 = -9.75V$$

$$D_1 : (350 \mu A, 0.75 V) \quad D_2 : (0 A, -9.75 V)$$

(c) D₁ off, D₂ on :

$$I_{D1} = 0 \quad | \quad I_{D2} = \frac{6 - 0.75 - (-9)}{30k\Omega} = 475\mu A \quad | \quad V_{D1} = 6 - 15 \times 10^3 I_{D2} = -1.13V$$

$$D_1 : (0 A, -1.13 V) \quad D_2 : (475 \mu A, 0.75 V)$$

(d) D₁ on, D₂ on :

$$I_{D2} = \frac{0.75 - 0.75 - (-6)}{15k\Omega} = 400\mu A \quad | \quad I_{D1} = \frac{9 - 0.75}{15k\Omega} - 400\mu A = 150\mu A$$

$$D_1 : (150 \mu A, 0.75 V) \quad D_2 : (400 \mu A, 0.75 V)$$

3.73 Diodes are labeled from left to right

$$(a) \text{ D}_1 \text{ on, D}_2 \text{ off, D}_3 \text{ on} : I_{D2} = 0 \quad | \quad I_{D1} = \frac{10 - 0}{3.3k\Omega + 6.8k\Omega} = 0.990mA$$

$$I_{D3} + 0.990mA = \frac{0 - (-5)}{2.4k\Omega} \rightarrow I_{D3} = 1.09mA \quad | \quad V_{D2} = 5 - (10 - 3300I_{D1}) = -1.73V$$

$$D_1 : (0.990 mA, 0 V) \quad D_2 : (0 mA, -1.73 V) \quad D_3 : (1.09 mA, 0 V)$$

(b) D₁ on, D₂ off, D₃ on : I_{D2} = 0 | I_{D3} = 0

$$I_{D1} = \frac{(10 - 0)V}{8.2k\Omega + 12k\Omega} = 0.495mA \quad | \quad V_{D2} = 5 - (10 - 8200I_{D1}) = -0.941V$$

$$I_{D3} = \frac{0 - (-5V)}{10k\Omega} - I_{D1} = 0.005mA$$

$$D_1 : (0.495 mA, 0 V) \quad D_2 : (0 A, -0.941 V) \quad D_3 : (0.005 mA, 0 V)$$

(c) D₁ on, D₂ on, D₃ on

$$I_{D1} = \frac{0 - (-10)}{8.2k\Omega} V = 1.22mA > 0 \quad | \quad I_{12K} = \frac{0 - (2)}{12k\Omega} V = -0.167mA \quad | \quad I_{D2} = I_{D1} + I_{12K} = 1.05mA > 0$$

$$I_{10K} = \frac{2 - (-5)}{10k\Omega} V = 0.700mA \quad | \quad I_{D3} = I_{10K} - I_{12K} = 0.533mA > 0$$

D₁ : (1.22 mA, 0 V) D₂ : (1.05 mA, 0 V) D₃ : (0.533 mA, 0 V)

(d) D₁ off, D₂ off, D₃ on : $I_{D1} = 0$, $I_{D2} = 0$

$$I_{D3} = \frac{12 - (-5)}{4.7 + 4.7 + 4.7} \frac{V}{k\Omega} = 1.21mA > 0 \quad | \quad V_{D1} = 0 - (-5 + 4700I_{D3}) = -0.667V < 0$$

$$V_{D2} = 5 - (12 - 4700I_{D3}) = -1.33V < 0$$

D₁ : (0 A, -0.667 V) D₂ : (0 A, -1.33 V) D₃ : (1.21 mA, 0 V)

3.74 Diodes are labeled from left to right

$$(a) D_1 \text{ on, } D_2 \text{ off, } D_3 \text{ on} : I_{D2} = 0 \quad | \quad I_{D1} = \frac{10 - 0.6 - (-0.6)}{3.3k\Omega + 6.8k\Omega} = 0.990mA$$

$$I_{D3} + 0.990mA = \frac{-0.6 - (-5)}{2.4k\Omega} \rightarrow I_{D3} = 0.843mA \quad | \quad V_{D2} = 5 - (10 - 0.6 - 3300I_{D1}) = -1.13V$$

D₁ : (0.990 mA, 0.600 V) D₂ : (0 A, -1.13 V) D₃ : (0.843 mA, 0.600V)

(b) D₁ on, D₂ off, D₃ off : $I_{D2} = 0$ | $I_{D3} = 0$

$$I_{D1} = \frac{10 - 0.6 - (-5)}{8.2k\Omega + 12k\Omega + 10k\Omega} V = 0.477mA \quad | \quad V_{D2} = 5 - (10 - 0.6 - 8200I_{D1}) = -0.490V$$

$$V_{D3} = 0 - (-5 + 10000I_{D1}) = +0.230V < 0.6V \text{ so the diode is off}$$

D₁ : (0.477 mA, 0.600 V) D₂ : (0 A, -0.490 V) D₃ : (0 A, 0.230 V)

(c) D₁ on, D₂ on, D₃ on

$$I_{D1} = \frac{-0.6 - (-9.4)}{8.2} \frac{V}{k\Omega} = 1.07mA > 0 \quad | \quad I_{12K} = \frac{-0.6 - (1.4)}{12} \frac{V}{k\Omega} = -0.167mA$$

$$I_{D2} = I_{D1} + I_{12K} = 0.906mA > 0 \quad | \quad I_{10K} = \frac{1.4 - (-5)}{10} \frac{V}{k\Omega} = 0.640mA \quad | \quad I_{D3} = I_{10K} - I_{12K} = 0.807mA > 0$$

D₁ : (1.07 mA, 0.600 V) D₂ : (0.906 mA, 0.600 V) D₃ : (0.807 mA, 0.600 V)

(d) D₁ off, D₂ off, D₃ on : $I_{D1} = 0$, $I_{D2} = 0$

$$I_{D3} = \frac{11.4 - (-5)}{4.7 + 4.7 + 4.7} \frac{V}{k\Omega} = 1.16mA > 0 \quad | \quad V_{D1} = 0 - (-5 + 4700I_{D3}) = -0.452V < 0$$

$$V_{D2} = 5 - (11.4 - 4700I_{D3}) = -0.948V < 0$$

$$D_1 : (0 A, -0.452 V) \quad D_2 : (0 A, -0.948 V) \quad D_3 : (1.16 mA, 0.600 V)$$

3.75

*Problem 3.75(a) (Similar circuits are used for the other three cases.)

V1 1 0 DC 10

V2 4 0 DC 5

V3 6 0 DC -5

R1 2 3 3.3K

R2 3 5 6.8K

R3 5 6 2.4K

D1 1 2 DIODE

D2 4 3 DIODE

D3 0 5 DIODE

.MODEL DIODE D IS=1E-15 RS=0

.OP

.END

NAME	D1	D2	D3
MODEL	DIODE	DIODE	DIODE
ID	9.90E-04	-1.92E-12	7.98E-04
VD	7.14E-01	-1.02E+00	7.09E-01

NAME	D1	D2	D3
MODEL	DIODE	DIODE	DIODE
ID	4.74E-04	-4.22E-13	2.67E-11
VD	6.95E-01	-4.21E-01	2.63E-01

NAME	D1	D2	D3
MODEL	DIODE	DIODE	DIODE
ID	8.79E-03	1.05E-03	7.96E-04
VD	7.11E-01	7.16E-01	7.09E-01

NAME	D1	D2	D3
MODEL	DIODE	DIODE	DIODE
ID	-4.28E-13	-8.55E-13	1.15E-03
VD	-4.27E-01	-8.54E-01	7.18E-01

For all cases, the results are very similar to the hand analysis.

3.76

$$I_{D1} = \frac{10 - (-20)}{10k\Omega + 10k\Omega} = 1.50mA \quad | \quad I_{D2} = 0$$

$$I_{D3} = \frac{0 - (-10)}{10k\Omega} = 1.00mA \quad | \quad V_{D2} = 10 - 10^4 I_{D1} - 0 = -5.00V$$

D₁ : (1.50 mA, 0 V) D₂ : (0 A, -5.00 V) D₃ : (1.00 mA, 0 V)

3.77

*Problem 3.77

V1 1 0 DC -20

V2 4 0 DC 10

V3 6 0 DC -10

R1 1 2 10K

R2 4 3 10K

R3 5 6 10K

D1 3 2 DIODE

D2 3 5 DIODE

D3 0 5 DIODE

.MODEL DIODE D IS=1E-14 RS=0

.OP

.END

NAME	D1	D2	D3
MODEL	DIODE	DIODE	DIODE
ID	1.47E-03	-4.02E-12	9.35E-04
VD	6.65E-01	-4.01E+00	6.53E-01

The simulation results are very close to those given in Ex. 3.8.

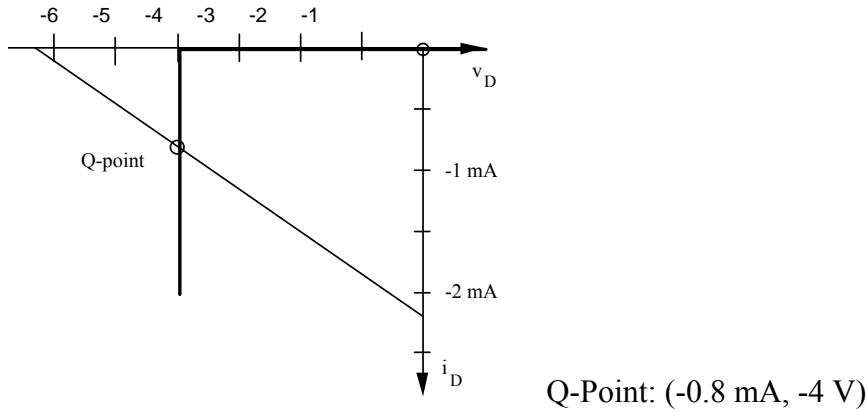
3.78

$$V_{TH} = 24V \frac{3.9k\Omega}{3.9k\Omega + 11k\Omega} = 6.28V \quad | \quad R_{TH} = 11k\Omega \parallel 3.9k\Omega = 2.88k\Omega$$

$$I_Z = \frac{6.28 - 4}{2.88k\Omega} = 0.792mA > 0 \quad | \quad (I_Z, V_Z) = (0.792 mA, 4 V)$$

3.79

$$-6.28 = 2880I_D + V_D \quad | \quad I_D = 0, V_D = -6.28V \quad | \quad V_D = 0, I_D = \frac{-6.28}{2880} = -2.18mA$$



3.80

$$I_S = \frac{27-9}{15k\Omega} = 1.20mA \rightarrow I_L < 1.20\text{ mA} \quad | \quad R_L > \frac{9V}{1.2mA} = 7.50\text{ k}\Omega$$

3.81

$$I_S = \frac{27-9}{15k\Omega} = 1.20mA \quad | \quad P = (9V)(1.20mA) = 10.8\text{ mW}$$

3.82

$$I_Z = \frac{V_S - V_Z}{R_S} - \frac{V_Z}{R_L} = \frac{V_S}{R_S} - V_Z \left(\frac{1}{R_S} + \frac{1}{R_L} \right) \quad | \quad P_Z = V_Z I_Z$$

$$I_Z^{nom} = \frac{30V}{15k\Omega} - 9V \left(\frac{1}{15k\Omega} + \frac{1}{10k\Omega} \right) = 0.500\text{ mA} \quad | \quad P_Z^{nom} = 9V(0.500mA) = 4.5\text{ mW}$$

$$I_Z^{\max} = \frac{30V(1.05)}{15k\Omega(0.95)} - 9V(0.95) \left(\frac{1}{15k\Omega(0.95)} + \frac{1}{10k\Omega(1.05)} \right) = 0.796\text{ mA}$$

$$P_Z^{\max} = 9V(95)(0.796mA) = 6.81\text{ mW}$$

$$I_Z^{\min} = \frac{30V(0.95)}{15k\Omega(1.05)} - 9V(1.05) \left(\frac{1}{15k\Omega(1.05)} + \frac{1}{10k\Omega(0.95)} \right) = 0.215\text{ mA}$$

$$P_Z^{\min} = 9V(1.05)(0.215mA) = 2.03\text{ mW}$$

3.83

$$(a) V_{TH} = 60V \frac{100\Omega}{150\Omega + 100\Omega} = 24.0V \quad | \quad R_{TH} = 150\Omega \parallel 100\Omega = 60\Omega \quad | \quad I_Z = \frac{24-15}{60} = 150\text{ mA}$$

$$P = 15I_Z = 2.25\text{ W} \quad | \quad (b) I_Z = \frac{60-15}{150} = 300\text{ mA} \quad | \quad P = 15I_Z = 4.50\text{ W}$$

3.84

$$I_Z = \frac{V_S - V_Z}{R_S} - \frac{V_Z}{R_L} = \frac{V_S}{R_S} - V_Z \left(\frac{1}{R_S} + \frac{1}{R_L} \right) \quad | \quad P_Z = V_Z I_Z$$

$$I_Z^{nom} = \frac{(60-15)V}{150\Omega} - \frac{15V}{100\Omega} = 150 \text{ mA} \quad | \quad P_Z^{nom} = 15V(150mA) = 2.25 \text{ W}$$

$$I_Z^{\max} = \frac{60V(1.1)}{150\Omega(0.90)} - 15V(0.90) \left(\frac{1}{150\Omega(0.90)} + \frac{1}{100\Omega(1.1)} \right) = 266 \text{ mA}$$

$$P_Z^{\max} = 15V(0.90)(266mA) = 3.59 \text{ W}$$

$$I_Z^{\min} = \frac{60V(0.90)}{150\Omega(1.1)} - 15V(1.1) \left(\frac{1}{150\Omega(1.1)} + \frac{1}{100\Omega(0.9)} \right) = 43.9 \text{ mA}$$

$$P_Z^{\min} = 15V(1.1)(43.9mA) = 0.724 \text{ W}$$

3.85

Using MATLAB, create the following m-file with $f = 60$ Hz:

```
function f=ctime(t)
f=5*exp(-10*t)-6*cos(2*pi*60*t)+1;
```

Then: `fzero('ctime',1/60)` yields `ans = 0.01536129698461`
and $\square T = (1/60)-0.0153613 = 1.305 \text{ ms.}$

$$\Delta T = \frac{1}{120\pi} \sqrt{\frac{2V_r}{V_p}} \quad | \quad V_r = \frac{IT}{C} = \frac{5}{0.1(60)} = 0.8333V$$

$$\Delta T = \frac{1}{120\pi} \sqrt{\frac{2(0.8333)}{6}} = 1.40 \text{ ms}$$

3.86

$$V_D = nV_T \ln \left(1 + \frac{I_D}{I_S} \right) = 2(0.025V) \ln \left(1 + \frac{48.6A}{10^{-9}A} \right) = 1.230 \text{ V}$$

3.87

$$V_{on} = nV_T \ln\left(1 + \frac{I_D}{I_S}\right) \quad | \quad V_D = V_{on} + I_D R_S$$

$$V_D = 1.6(0.025V) \ln\left(1 + \frac{100A}{10^{-8}A}\right) + 100A(0.01\Omega) = 1.92 \text{ V}$$

$$P_{junction} \cong V_{on} I_{DC} = V_{on} \frac{I_P \Delta T}{2T} = 0.92V \left(\frac{100A}{2}\right) \left(\frac{1ms}{16.7ms}\right) = 2.75 \text{ W}$$

$$P_R \cong \frac{4}{3} \left(\frac{T}{\Delta T}\right) I_{DC}^2 R_S = \frac{4}{3} \left(\frac{16.7ms}{1ms}\right) (3A)^2 0.01\Omega = 2.00 \text{ W}$$

$$P_{total} = 4.76 \text{ W}$$

3.88

$$V_{DC} = \frac{1}{T} \int_0^T v(t) dt = \frac{1}{T} \left[(V_p - V_{on})T - \frac{TV_r}{2} \right] = \left[(V_p - V_{on}) - \frac{0.05(V_p - V_{on})}{2} \right] = 0.975(V_p - V_{on})$$

$$V_{DC} = 0.975(18V) = 17.6 \text{ V}$$

3.89

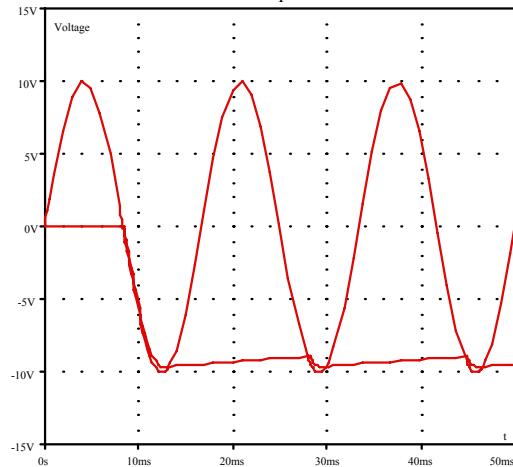
$$P_D = \frac{1}{T} \int_0^T i_D^2(t) R_S dt = \frac{1}{T} \int_0^{\Delta T} I_P^2 \left(1 - \frac{t}{\Delta T}\right)^2 R_S dt$$

$$P_D = \frac{I_P^2 R_S}{T} \int_0^{\Delta T} \left(1 - \frac{2t}{\Delta T} + \frac{t^2}{\Delta T^2}\right)^2 dt = \frac{I_P^2 R_S}{T} \left(t - \frac{t^2}{\Delta T} + \frac{t^3}{3\Delta T^2}\right) \Big|_0^{\Delta T}$$

$$P_D = \frac{I_P^2 R_S}{T} \left(\Delta T - \frac{\Delta T}{3}\right) = \frac{1}{3} I_P^2 R_S \left(\frac{\Delta T}{T}\right)$$

3.90

Using SPICE with $V_p = 10 \text{ V}$.



3.91

$$(a) V_{dc} = -(V_p - V_{on}) = -(6.3\sqrt{2} - 1) = -7.91V \quad (b) C = \frac{IT}{V_r} = \frac{7.91}{0.55} \frac{1}{0.5} \frac{1}{60} = 1.05F$$

$$(c) PIV \geq 2V_p = 2 \cdot 6.3\sqrt{2} = 17.8V \quad (d) I_{surge} = \omega CV_p = 2\pi(60)(1.05)(6.3\sqrt{2}) = 3530A$$

$$(e) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{\frac{2(25)}{6.3\sqrt{2}}} = 0.628ms \quad | \quad I_p = I_{dc} \frac{2T}{\Delta T} = \frac{7.91}{.5} \frac{2}{60} \frac{1}{0.628ms} = 841A$$

3.92

$$V_O^{nom} = -(V_p - V_{on}) = -(6.3\sqrt{2} - 1) = -7.91V$$

$$V_O^{\max} = -(V_p^{\max} - V_{on}) = -[6.3(1.1)\sqrt{2} - 1] = -8.80V$$

$$V_O^{\min} = -(V_p^{\min} - V_{on}) = -[6.3(0.9)\sqrt{2} - 1] = -7.02V$$

3.93

*Problem 3.93

VS 1 0 DC 0 AC 0 SIN(0 10 60)

D1 2 1 DIODE

R 2 0 0.25

C 2 0 0.5

.MODEL DIODE D IS=1E-10 RS=0

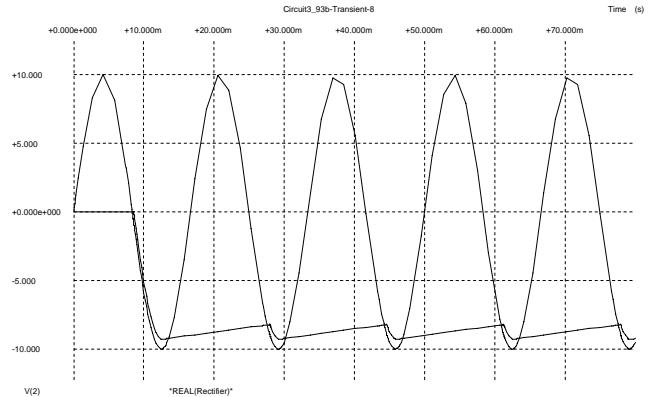
.OPTIONS RELTOL=1E-6

.TRAN 1US 80MS

.PRINT TRAN V(1) V(2) I(VS)

.PROBE V(1) V(2) I(VS)

.END

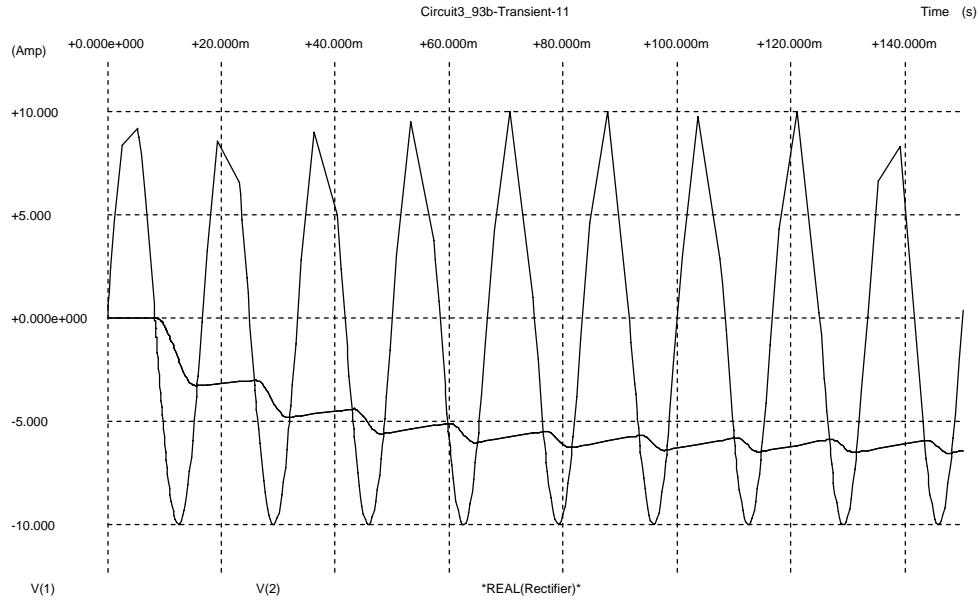


SPICE Graph Results: $V_{DC} = 9.29V$, $V_r = 1.05V$, $I_p = 811A$, $I_{SC} = 1860A$

$$V_{dc} = -(V_p - V_{on}) = -(10 - 1) = -9.00V \quad | \quad V_r = \frac{IT}{C} = \frac{9.00V}{0.25\Omega} \frac{1}{60s} \frac{1}{0.5F} = 1.20V$$

$$I_{SC} = \omega CV_p = 2\pi(60)(0.5)(10) = 1890A \quad | \quad \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{\frac{2(1.2)}{10}} = 1.30ms$$

$$I_p = I_{dc} \frac{2T}{\Delta T} = \frac{9}{0.25} \frac{2}{60} \frac{1}{1.3ms} = 923A$$



SPICE Graph Results: $V_{DC} = -6.55$ V, $V_r = 0.58$ V, $I_p = 150$ A, $I_{SC} = 370$ A
 Note that a significant difference is caused by the diode series resistance.

3.94

$$(a) V_{dc} = -(V_p - V_{on}) = -(6.3\sqrt{2} - 1) = -7.91V \quad (b) C = \frac{IT}{V_r} = \frac{7.91}{0.25} \frac{1}{0.5} \frac{1}{400} = 0.158F$$

$$(c) PIV \geq 2V_p = 2 \cdot 6.3\sqrt{2} = 17.8V \quad (d) I_{surge} = \omega CV_p = 2\pi(400)(0.158)(6.3\sqrt{2}) = 3540A$$

$$(e) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(400)} \sqrt{\frac{2(25)}{6.3\sqrt{2}}} = 94.3\mu s \quad | \quad I_p = I_{dc} \frac{2T}{\Delta T} = \frac{7.91}{.5} \frac{2}{400} \frac{1}{94.3\mu s} = 839A$$

3.95

$$(a) V_{dc} = -(V_p - V_{on}) = -(6.3\sqrt{2} - 1) = -7.91V \quad (b) C = \frac{IT}{V_r} = \frac{7.91}{0.25} \frac{1}{0.5} \frac{1}{10^5} = 633\mu F$$

$$(c) PIV \geq 2V_p = 2 \cdot 6.3\sqrt{2} = 17.8V \quad (d) I_{surge} = \omega CV_p = 2\pi(10^5)(633\mu F)(6.3\sqrt{2}) = 3540A$$

$$(e) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(10^5)} \sqrt{\frac{2(25)}{6.3\sqrt{2}}} = 0.377\mu s \quad | \quad I_p = I_{dc} \frac{2T}{\Delta T} = \frac{7.91}{.5} \frac{2}{10^5} \frac{1}{0.377\mu s} = 839A$$

3.96

$$(a) C = \frac{IT}{V_r} = \frac{1}{3000(0.01)} \frac{1}{60} = 556 \mu F \quad (b) PIV \geq 2V_p = 2 \cdot 3000 = 6000V$$

$$(c) V_{rms} = \frac{3000}{\sqrt{2}} = 2120 V \quad (d) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{2(0.01)} = 0.375ms$$

$$I_p = I_{dc} \frac{2T}{\Delta T} = 1 \left(\frac{2}{60} \right) \left(\frac{1}{0.375ms} \right) = 88.9A \quad (e) I_{surge} = \omega CV_p = 2\pi(60)(556\mu F)(3000) = 629A$$

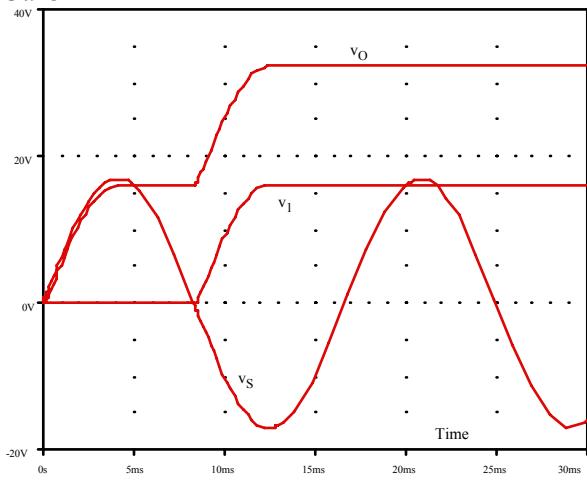
3.97 Assuming $V_{on} = 1 V$:

$$C = \frac{V_p - V_{on}}{V_r} T \frac{1}{R} = \frac{1}{0.025} \left(\frac{1}{60} \right) \left(\frac{30}{3.3} \right) = 6.06 F \mid PIV = 2V_p = 2(3.3 + 1)V = 8.6 V \mid V_{rms} = \frac{3.3 + 1}{\sqrt{2}} = 3.04 V$$

$$\Delta T = \frac{1}{\omega} \sqrt{\frac{2T}{RC}} \frac{V_p - V_{on}}{V_p} = \frac{1}{2\pi(60)} \sqrt{\frac{2}{0.110\Omega(6.06F)}} \left(\frac{1}{60}s \right) \left(\frac{3.3V}{4.3V} \right) = 0.520 ms$$

$$I_p = I_{dc} \frac{2T}{\Delta T} = 30 \left(\frac{2}{60}s \right) \left(\frac{1}{0.520ms} \right) = 1920 A \mid I_{surge} = \omega CV_p = 2\pi(60/s)(6.06F)(4.3V) = 9820 A$$

3.98



$$V_{DC} = 2(V_p - V_{on}) = 2(17 - 1) = 32 V.$$

3.99

*Problem 3.99

VS 2 1 DC 0 AC 0 SIN(0 1500 60)

D1 2 3 DIODE

D2 0 2 DIODE

C1 1 0 500U

C2 3 1 500U

RL 3 0 3K

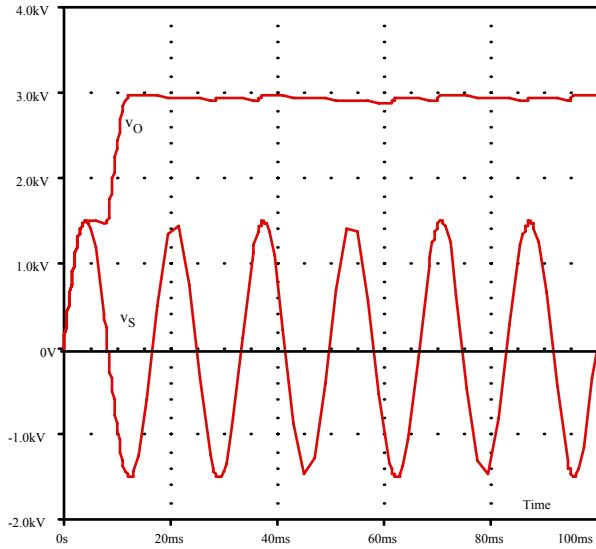
.MODEL DIODE D IS=1E-15 RS=0

.OPTIONS RELTOL=1E-6

.TRAN 0.1MS 100MS

.PRINT TRAN V(2,1) V(3) I(VS)

.PROBE V(3) V(2,1) I(VS)
.END



Simulation Results: $V_{DC} = 2981$ V, $V_r = 63$ V

The doubler circuit is effectively two half-wave rectifiers connected in series. Each capacitor is discharged by $I = 3000V/3000\Omega = 1$ A for 1/60 second. The ripple voltage on each capacitor is 33.3 V. With two capacitors in series, the output ripple should be 66.6 V, which is close to the simulation result.

3.100

$$(a) V_{dc} = -(V_p - V_{on}) = -(15\sqrt{2} - 1) = -20.2 \text{ V} \quad (b) C = \frac{I}{V_r} \left(\frac{T}{2} \right) = \frac{20.2V}{0.5\Omega} \left(\frac{1}{0.25V} \right) \left(\frac{1}{120s} \right) = 1.35 \text{ F}$$

$$(c) PIV \geq 2V_p = 2 \cdot 15\sqrt{2} = 42.4 \text{ V} \quad (d) I_{surge} = \omega CV_p = 2\pi(60)(1.35)(15\sqrt{2}) = 10800 \text{ A}$$

$$(e) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{\frac{2(25)}{15\sqrt{2}}} = 0.407 \text{ ms} \quad | \quad I_p = I_{dc} \frac{T}{\Delta T} = \frac{20.2V}{0.5\Omega} \left(\frac{1}{60} s \right) \frac{1}{0.407ms} = 1650 \text{ A}$$

3.101

$$(a) V_{dc} = -(V_p - V_{on}) = -(9\sqrt{2} - 1) = -11.7 \text{ V} \quad (b) C = \frac{I}{V_r} \left(\frac{T}{2} \right) = \frac{11.7V}{0.5\Omega} \left(\frac{1}{0.25V} \right) \left(\frac{1}{120s} \right) = 0.780 \text{ F}$$

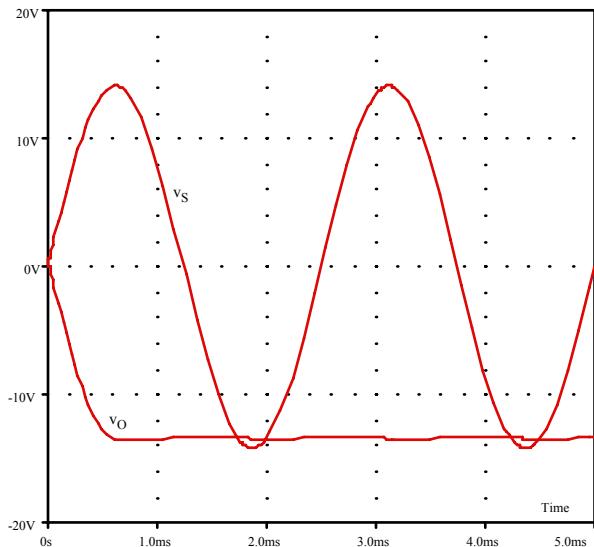
$$(c) PIV \geq 2V_p = 2 \cdot 9\sqrt{2} = 25.5 \text{ V} \quad (d) I_{surge} = \omega CV_p = 2\pi(60)(0.780)(9\sqrt{2}) = 3740 \text{ A}$$

$$(e) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{\frac{2(25)}{9\sqrt{2}}} = 0.526 \text{ ms} \quad | \quad I_p = I_{dc} \frac{T}{\Delta T} = \frac{11.7V}{0.5\Omega} \left(\frac{1}{60} s \right) \frac{1}{0.407ms} = 958 \text{ A}$$

3.102

*Problem 3.102

```
VS1 1 0 DC 0 AC 0 SIN(0 14.14 400)
VS2 0 2 DC 0 AC 0 SIN(0 14.14 400)
D1 3 1 DIODE
D2 3 2 DIODE
C 3 0 22000U
R 3 0 3
.MODEL DIODE D IS=1E-10 RS=0
.OPTIONS RELTOL=1E-6
.TRAN 1US 5MS
.PRINT TRAN V(1) V(2) V(3) I(VS1)
.PROBE V(1) V(2) V(3) I(VS1)
.END
```



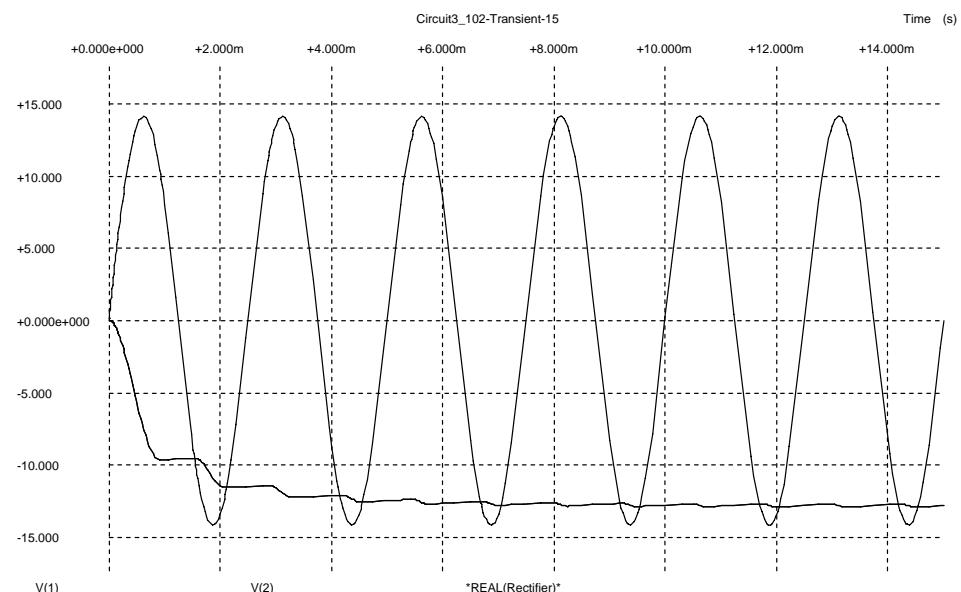
Simulation Results: $V_{DC} = -13.4$ V, $V_r = 0.23$ V, $I_p = 108$ A

$$V_{DC} = V_p - V_{on} = 10\sqrt{2} - 0.7 = 13.4 \text{ V} \quad | \quad V_r = \frac{13.4}{3} \cdot \frac{1}{800} \cdot \frac{1}{22000 \mu F} = 0.254 \text{ V}$$

$$\Delta T = \frac{1}{120\pi} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{120\pi} \sqrt{\frac{2(0.254)}{14.1}} = 0.504 \text{ ms}$$

$$I_p = I_{dc} \frac{T}{\Delta T} = \frac{13.4V}{3\Omega} \frac{1}{60} \text{ s} \frac{1}{0.504 \text{ ms}} = 150 \text{ A}$$

Simulation with $RS = 0.02 \Omega$.



Simulation Results: $V_{DC} = -12.9$ V, $V_r = 0.20$ V, $I_p = 33.3$ A, $I_{SC} = 362$ A. RS results in a significant reduction in the values of I_p and I_{SC} .

3.103

$$(a) C = \frac{V_p - V_{on}}{V_r} T \frac{1}{R} = \frac{1}{0.025} \left(\frac{1s}{120} \right) \left(\frac{30A}{3.3V} \right) = 3.03 F \quad (b) PIV = 2V_p = 2(3.3 + 1)V = 8.6 V$$

$$(c) V_{rms} = \frac{3.3 + 1}{\sqrt{2}} = 3.04 V \quad (d) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{\frac{2(0.025)(3.3)}{4.3}} = 0.520 ms$$

$$(e) I_p = I_{dc} \frac{T}{\Delta T} = 30A \left(\frac{1}{60} s \right) \left(\frac{1}{0.520ms} \right) = 962 A \quad | \quad I_{surge} = \omega CV_p = 2\pi(60/s)(3.03F)(4.3V) = 4910 A$$

3.104

$$(a) C = \frac{I}{V_r} \frac{T}{2} = \frac{1}{3000(0.01)} \frac{1}{2 \cdot 120} = 139 \mu F \quad (b) PIV \geq 2V_p = 6000 V$$

$$(c) V_s = \frac{3000}{\sqrt{2}} = 2120 V \quad (d) \Delta T = \frac{1}{\omega} \sqrt{2 \frac{V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{2(0.01)} = 0.375 ms$$

$$I_p = I_{dc} \frac{T}{\Delta T} = 1 \left(\frac{1}{60} s \right) \left(\frac{1}{0.375ms} \right) = 44.4 A \quad (e) I_{surge} = \omega CV_p = 2\pi(60/s)(139\mu F)(3000V) = 157 A$$

3.105

The circuit is behaving like a half-wave rectifier. The capacitor should charge during the first 1/2 cycle, but it is not. Therefore, diode D₁ is not functioning properly. It behaves as an open circuit.

3.106

$$(a) V_{dc} = -(V_p - 2V_{on}) = -(15\sqrt{2} - 2) = -19.2 V \quad (b) C = \frac{I}{V_r} \left(\frac{T}{2} \right) = \frac{19.2V}{0.5\Omega} \left(\frac{1}{0.25V} \right) \left(\frac{1}{120} s \right) = 1.28 F$$

$$(c) PIV \geq V_p = 15\sqrt{2} = 21.2 V \quad (d) I_{surge} = \omega CV_p = 2\pi(60/s)(1.28F)(15\sqrt{2}) = 10200 A$$

$$(e) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{\frac{2(25)}{15\sqrt{2}}} = 0.407 ms \quad | \quad I_p = I_{dc} \frac{T}{\Delta T} = \frac{19.2V}{0.5\Omega} \left(\frac{1s}{60} \right) \left(\frac{1}{0.407ms} \right) = 1570 A$$

3.107

$$(a) C = \frac{I}{V_r} \left(\frac{T}{2} \right) = \frac{1A}{3000V(0.01)} \left(\frac{1}{120} s \right) = 278 \mu F \quad (b) PIV \geq V_p = 3000 V$$

$$(c) V_s = \frac{3000}{\sqrt{2}} = 2120 V \quad (d) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{2(0.01)} = 0.375 ms$$

$$I_p = I_{dc} \frac{T}{\Delta T} = 1A \left(\frac{1}{60} s \right) \left(\frac{1}{0.375ms} \right) = 44.4 A \quad (e) I_{surge} = \omega CV_p = 2\pi(60)(278\mu F)(3000) = 314 A$$

3.108

$$(a) C = \frac{I}{V_r} \left(\frac{T}{2} \right) = \frac{30A}{(0.025)(3.3V)} \left(\frac{1}{120}s \right) = 3.03 F \quad (b) PIV \geq V_{dc} + 2V_{on} = (3.3 + 2) = 5.3 V$$

$$(c) V_{rms} = \frac{5.3}{\sqrt{2}} = 3.75 V \quad (d) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{2 \left[\frac{0.025(3.3)}{5.3} \right]} = 0.468 ms$$

$$I_p = I_{dc} \frac{T}{\Delta T} = 30A \left(\frac{1}{60}s \right) \frac{1}{0.468ms} = 1070 A \quad (e) I_{surge} = \omega C V_p = 2\pi(60/s)(3.03F)(3.3V) = 3770 A$$

3.109

$$V_1 = V_p - V_{on} = 49.3 V \quad \text{and} \quad V_2 = -(V_p - V_{on}) = -49.3 V.$$

3.110

*Problem 3.110

VS1 1 0 DC 0 AC 0 SIN(0 35 60)

VS2 0 2 DC 0 AC 0 SIN(0 35 60)

D1 1 3 DIODE

D4 2 3 DIODE

D2 4 1 DIODE

D3 4 2 DIODE

C1 3 0 0.1

C2 4 0 0.1

R1 3 0 500

R2 4 0 500

.MODEL DIODE D IS=1E-10 RS=0

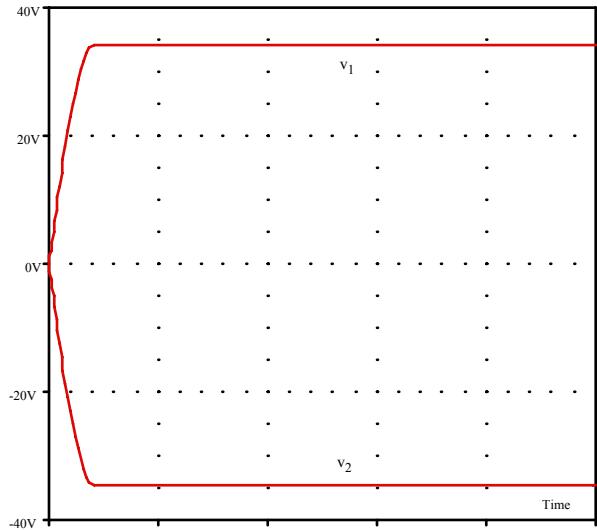
.OPTIONS RELTOL=1E-6

.TRAN 10US 50MS

.PRINT TRAN V(3) V(4)

.PROBE V(3) V(4)

.END



3.111

$$(a) V_{dc} = -(V_p - 2V_{on}) = -(15\sqrt{2} - 2) = -19.2 V \quad (b) C = \frac{I}{V_r} \left(\frac{T}{2} \right) = \frac{19.2V}{0.5\Omega} \left(\frac{1}{0.25} \right) \left(\frac{1}{120} \right) = 1.28 F$$

$$(c) PIV \geq V_p = 15\sqrt{2} = 21.2 V \quad (d) I_{surge} = \omega C V_p = 2\pi(60/s)(1.28F)(15V\sqrt{2}) = 10200 A$$

$$(e) \Delta T = \frac{1}{\omega} \sqrt{\frac{2V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{\frac{2(25)}{15\sqrt{2}}} = 0.407 ms \quad | \quad I_p = I_{dc} \frac{T}{\Delta T} = \frac{19.2V}{0.5\Omega} \left(\frac{1}{60}s \right) \left(\frac{1}{0.407ms} \right) = 1570 A$$

3.112

3.3-V, 15-A power supply with $V_r \leq 10$ mV. Assume $V_{on} = 1$ V.

Rectifier Type	Half Wave	Full Wave	Full Wave Bridge
Peak Current	533 A	266 A	266 A
PIV	8.6 V	8.6 V	5.3 V
Filter Capacitor	25 F	12.5 F	12.5 F

- (i) The large value of C suggests we avoid the half-wave rectifier. This will reduce the cost and size of the circuit.
 - (ii) The PIV ratings are all low and do not indicate a preference for one circuit over another.
 - (iii) The peak current values are lower for the full-wave and full-wave bridge rectifiers and also indicate an advantage for these circuits.
 - (iv) We must choose between use of a center-tapped transformer (full-wave) or two extra diodes (bridge). At a current of 15 A, the diodes are not expensive and a four-diode bridge should be easily found. The final choice would be made based upon cost of available components.
-

3.113

200-V, 3-A power supply with $V_r \leq 4$ V. Assume $V_{on} = 1$ V.

Rectifier Type	Half Wave	Full Wave	Full Wave Bridge
Peak Current	189 A	94.3 A	94.3 A
PIV	402 V	402 V	202 V
Filter Capacitor	12,500 μ F	6250 μ F	6250 μ F

- (i) The the half-wave rectifier requires a larger value of C which may lead to more cost.
 - (ii) The PIV ratings are all low enough that they do not indicate a preference for one circuit over another.
 - (iii) The peak current values are lower for the full-wave and full-wave bridge rectifiers and also indicate an advantage for these circuits.
 - (iv) We must choose between use of a center-tapped transformer (full-wave) or two extra diodes (bridge). At a current of 3 A, the diodes are not expensive and a four-diode bridge should be easily found. The final choice would be made based upon cost of available components.
-

3.114

3000-V, 1-A power supply with $V_r \leq 120$ V. Assume $V_{on} = 1$ V.

Rectifier Type	Half Wave	Full Wave	Full Wave Bridge
Peak Current	133 A	66.6 A	66.6 A
PIV	6000 V	6000 V	3000 V
Filter Capacitor	41.7 μ F	20.8 μ F	20.8 μ F

- (i) A series string of multiple capacitors will normally be required to achieve the voltage rating.
- (ii) The PIV ratings are high, and the bridge circuit offers an advantage here.
- (iii) The peak current values are lower for the full-wave and full-wave bridge rectifiers but neither is prohibitively large.
- (iv) We must choose between use of a center-tapped transformer (full wave) or extra diodes (bridge). With a PIV of 3000 or 6000 volts, multiple diodes may be required to achieve the require PIV rating.

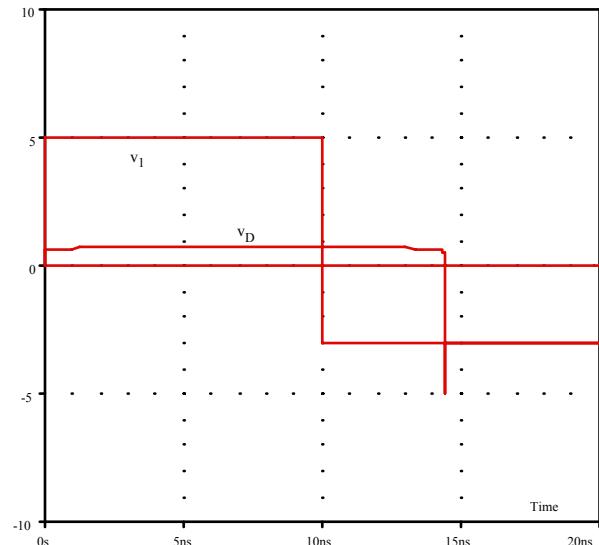
3.115

$$i_D(0^+) = \frac{5V}{1k\Omega} = 5 \text{ mA} \quad | \quad I_F = \frac{5 - V_D}{1k\Omega} = \frac{5 - 0.6}{1k\Omega} = 4.4 \text{ mA}$$

$$I_r = \frac{-3 - 0.6}{1k\Omega} = -3.6 \text{ mA} \quad | \quad \tau_s = (7 \text{ ns}) \ln\left(1 - \frac{4.4 \text{ mA}}{-3.6 \text{ mA}}\right) = 5.59 \text{ ns}$$

3.116

```
*Problem 3.143 - Diode Switching Delay
V1 1 0 PWL(0 0 0.01N 5 10N 5 10.02N -3
20N -3)
R1 1 2 1K
D1 2 0 DIODE
.TRAN .01NS 20NS
.MODEL DIODE D TT=7NS IS=1E-15
.PROBE V(1) V(2) I(V1)
.OPTIONS RELTOL=1E-6
.OP
.END
```



Simulation results give $\Delta S = 4.4$ ns.

3.117

$$i_D(0^+) = \frac{5V}{5\Omega} = 1A \quad | \quad I_F = \frac{5 - V_{on}}{5\Omega} = \frac{5 - 0.6}{1\Omega} = 0.880 A$$

$$I_R = \frac{-3 - 0.6}{5\Omega} = -0.720 A \quad | \quad \tau_s = (250ns) \ln\left(1 - \frac{0.880A}{-0.720A}\right) = 200 ns$$

3.118

*Problem 3.145(a) - Diode Switching Delay

V1 1 0 DC 1.5 PWL(0 0 .01N 1.5 7.5N 1.5

7.52N -1.5 15N -1.5)

R1 1 2 0.75K

D1 2 0 DIODE

.TRAN .02NS 100NS

.MODEL DIODE D TT=50NS IS=1E-15

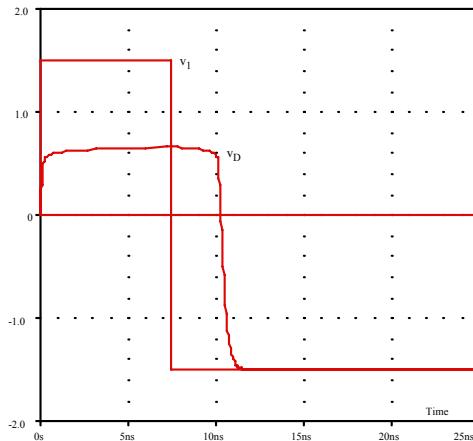
CJO=0.5PF

.PROBE V(1) V(2) I(V1)

.OPTIONS RELTOL=1E-6

.OP

.END



For this case, simulation yields $\square S = 3$ ns.

*Problem 3.145(b) - Diode Switching Delay

V1 1 0 DC 1.5 PWL(0 1.5 7.5N 1.5 7.52N -1.5 15N -1.5)

R1 1 2 0.75K

D1 2 0 DIODE

.TRAN .02NS 100NS

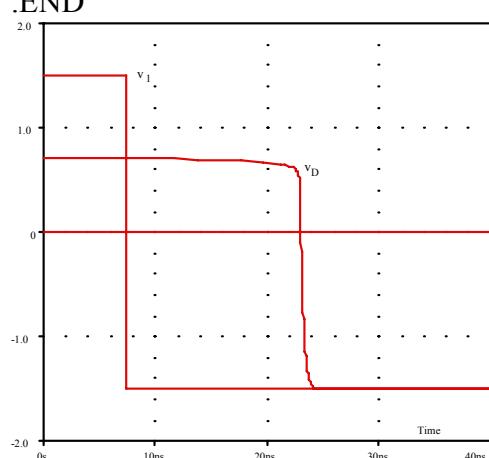
.MODEL DIODE D TT=50NS IS=1E-15 CJO=0.5PF

.PROBE V(1) V(2) I(V1)

.OPTIONS RELTOL=1E-6

.OP

.END



For this case, simulation yields $\square S = 15.5$ ns.

In case (a), the charge in the diode does not have time to reach the steady-state value given by $Q = (1\text{mA})(50\text{ns}) = 50 \text{ pC}$. At most, only $1\text{mA}(7.5\text{ns}) = 7.5 \text{ pC}$ can be stored in the diode. Thus it turns off more rapidly than predicted by the storage time formula. It should turn off in approximately $t = 7.5\text{pC}/3\text{mA} = 2.5 \text{ ns}$ which agrees with the simulation results. In (b), the diode charge has had time to reach its steady-state value. Eq. (3.103) gives: $(50 \text{ ns}) \ln(1 - 1\text{mA}/(-3\text{mA})) = 14.4 \text{ ns}$ which is close to the simulation result.

3.119

$$I_C = 1 - 10^{-15} [\exp(40V_C) - 1] A \quad | \text{ For } V_C = 0, I_{SC} = 1A$$

$$V_{OC} = \frac{1}{40} \ln\left(1 + \frac{1}{10^{-15}}\right) = 0.864 \text{ V}$$

$$P = V_C I_C = V_C [1 - 10^{-15} [\exp(40V_C) - 1]]$$

$$\frac{dP}{dV_C} = 1 - 10^{-15} [\exp(40V_C) - 1] - 40 \times 10^{-15} V_C \exp(40V_C) = 0$$

Using the computer to find V_C yields $V_C = 0.7768 \text{ V}$, $I_C = 0.9688 \text{ A}$, and $P_{max} = 7.53 \text{ Watts}$

3.120

(a) For V_{OC} , each of the three diode terminal currents must be zero, and

$$V_{OC} = V_{C1} + V_{C2} + V_{C3} = \frac{1}{40} V [\ln(1.05 \times 10^{15}) + \ln(1.00 \times 10^{15}) + \ln(0.95 \times 10^{15})] = 2.59 \text{ V}$$

(b) For I_{SC} , the external currents cannot exceed the smallest of the short circuit current of the individual diodes. Thus, $I_{SC} = \min[1.05A, 1.00A, 0.95A] = 0.95 \text{ A}$

Note that diode three will be reverse biased in part (b).

Using the computer to find V_C yields $V_C = 0.7768 \text{ V}$, $I_C = 0.9688 \text{ A}$, and $P_{max} = 7.53 \text{ Watts}$

3.121

$$\lambda = \frac{hc}{E}$$

$$(a) \lambda = \frac{6.625 \times 10^{-34} J \cdot s (3 \times 10^8 \text{ m/s})}{1.12eV (1.602 \times 10^{-19} \text{ J/eV})} = 1.11 \mu\text{m} \text{ - far infrared}$$

$$(b) \lambda = \frac{6.625 \times 10^{-34} J \cdot s (3 \times 10^8 \text{ m/s})}{1.42eV (1.602 \times 10^{-19} \text{ J/eV})} = 0.875 \mu\text{m} \text{ - near infrared}$$

CHAPTER 4

4.1

- (a) $V_G > V_{TN}$ corresponds to the inversion region (b) $V_G \ll V_{TN}$ corresponds to the accumulation region (c) $V_G < V_{TN}$ corresponds to the depletion region
-

4.2 (a)

$$C''_{ox} = \frac{\epsilon_{ox}}{T_{ox}} = \frac{3.9\epsilon_o}{T_{ox}} = \frac{3.9(8.854 \times 10^{-14} F/cm)}{50 \times 10^{-9} m (100 cm/m)} = 6.91 \times 10^{-8} \frac{F}{cm^2} = 69.1 \frac{nF}{cm^2}$$

(b), (c) & (d): Scaling the result from part (a) yields

$$C''_{ox} = 69.1 \frac{nF}{cm^2} \frac{50nm}{20nm} = 173 \frac{nF}{cm^2} \quad | \quad C''_{ox} = 69.1 \frac{nF}{cm^2} \frac{50nm}{10nm} = 346 \frac{nF}{cm^2} \quad | \quad C''_{ox} = 69.1 \frac{nF}{cm^2} \frac{50nm}{20nm} = 691 \frac{nF}{cm^2}$$

4.3

$$C_d = \frac{\epsilon_s}{\sqrt{\frac{2\epsilon_s}{qN_B}(0.75V)}} = \frac{11.7(8.854 \times 10^{-14} F/cm)}{\sqrt{\frac{2(11.7)(8.854 \times 10^{-14} F/cm)}{1.602 \times 10^{-19} (10^{15} / cm^3)}(0.75V)}} = 10.5 \times 10^{-9} F/cm^2$$

4.4 (a)

$$K' = \mu_n C''_{ox} = \mu_n \frac{\epsilon_{ox}}{T_{ox}} = \mu_n \frac{3.9\epsilon_o}{T_{ox}} = \left(500 \frac{cm^2}{V - sec} \right) \frac{3.9(8.854 \times 10^{-14} F/cm)}{50 \times 10^{-9} m (100 cm/m)}$$

$$K' = 34.5 \times 10^{-6} \frac{F}{V - sec} = 34.5 \times 10^{-6} \frac{A}{V^2} = 34.5 \frac{\mu A}{V^2}$$

(b) & (c) Scaling the result from part (a) yields

$$K' = 34.5 \frac{\mu A}{V^2} \frac{50nm}{20nm} = 86.3 \frac{\mu A}{V^2} \quad | \quad K' = 34.5 \frac{\mu A}{V^2} \frac{50nm}{10nm} = 173 \frac{\mu A}{V^2} \quad | \quad K' = 34.5 \frac{\mu A}{V^2} \frac{50nm}{5nm} = 345 \frac{\mu A}{V^2}$$

4.5

$$(a) Q'' = C''_{ox} (V_{GS} - V_{TN}) = \frac{\epsilon_{ox}}{T_{ox}} (V_{GS} - V_{TN}) = \frac{3.9(8.854 \times 10^{-14} F/cm)}{25 \times 10^{-9} m (100 cm/m)} (1V) = 1.38 \times 10^{-7} \frac{C}{cm^2}$$

$$(b) Q'' = C''_{ox} (V_{GS} - V_{TN}) = \frac{\epsilon_{ox}}{T_{ox}} (V_{GS} - V_{TN}) = \frac{3.9(8.854 \times 10^{-14} F/cm)}{10 \times 10^{-9} m (100 cm/m)} (2V) = 6.91 \times 10^{-7} \frac{C}{cm^2}$$

4.6

$$(a) v_n = -\mu_n E = - \left(500 \frac{cm^2}{V-s} \right) \left(2000 \frac{V}{cm} \right) = -1.00 \times 10^6 \frac{cm}{s}$$

$$(a) v_n = -\mu_n E = - \left(400 \frac{cm^2}{V-s} \right) \left(4000 \frac{V}{cm} \right) = -1.60 \times 10^6 \frac{cm}{s}$$

4.7

The carrier velocity must increase as the carriers travel down the channel to compensate for the decrease in carrier density

4.8

$$(a) 0 < 0.8V \rightarrow I_D = 0$$

$$(b) V_{GS} - V_{TN} = 0.2V, V_{DS} = 0.25V \rightarrow \text{Saturation region}$$

$$I_D = K_n \frac{W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = \left(200 \frac{\mu A}{V^2} \right) \left(\frac{5\mu m}{0.5\mu m} \right) (1 - 0.8)^2 = 40.0 \mu A$$

$$(c) V_{GS} - V_{TN} = 1.2V, V_{DS} = 0.25V \rightarrow \text{triode region}$$

$$I_D = K_n \frac{W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = \left(200 \frac{\mu A}{V^2} \right) \left(\frac{5\mu m}{0.5\mu m} \right) \left(2 - 0.8 - \frac{0.25}{2} \right) (0.25) = 538 \mu A$$

$$(d) V_{GS} - V_{TN} = 2.2V, V_{DS} = 0.25V \rightarrow \text{triode region}$$

$$I_D = K_n \frac{W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = \left(200 \frac{\mu A}{V^2} \right) \left(\frac{5\mu m}{0.5\mu m} \right) \left(3 - 0.8 - \frac{0.25}{2} \right) (0.25) = 1.04 mA$$

$$(e) K_n = K_n \frac{W}{L} = \left(200 \frac{\mu A}{V^2} \right) \left(\frac{5\mu m}{0.5\mu m} \right) = 2.00 \frac{mA}{V^2}$$

4.9

$$(a) K_n = K_n \frac{W}{L} = 200 \frac{\mu A}{V^2} \left(\frac{60\mu m}{3\mu m} \right) = 4.00 \frac{mA}{V^2}$$

$$(b) K_n = 200 \frac{\mu A}{V^2} \left(\frac{3\mu m}{0.15\mu m} \right) = 4.00 \frac{mA}{V^2} \quad | \quad (c) K_n = 200 \frac{\mu A}{V^2} \left(\frac{10\mu m}{0.25\mu m} \right) = 8.00 \frac{mA}{V^2}$$

4.10

$$(a) 0 < 1V \rightarrow \text{cutoff region}, I_D = 0 \quad (b) 1V = 1V \rightarrow \text{cutoff region}, I_D = 0$$

$$(c) V_{GS} - V_{TN} = 1V, V_{DS} = 0.1V \rightarrow \text{triode region}$$

$$I_D = K_n \frac{W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = \left(250 \frac{\mu A}{V^2} \right) \left(\frac{10\mu m}{1\mu m} \right) \left(2 - 1 - \frac{0.1}{2} \right) (0.1) = +231 \mu A$$

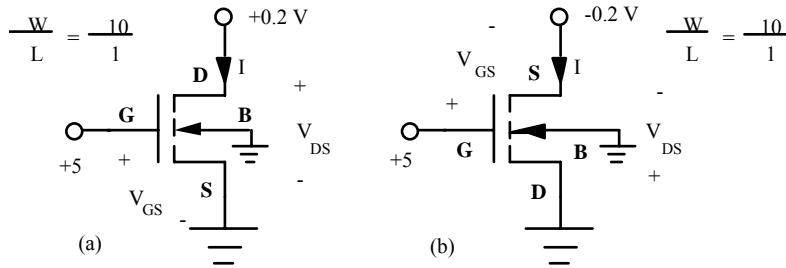
(d) $V_{GS} - V_{TN} = 2V$, $V_{DS} = 0.1V \rightarrow$ triode region

$$I_D = K_n \frac{W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = \left(250 \frac{\mu A}{V^2} \right) \left(\frac{10 \mu m}{1 \mu m} \right) \left(3 - 1 - \frac{0.1}{2} \right) (0.1) = +488 \mu A$$

$$(e) K_n = K_n \frac{W}{L} = \left(250 \frac{\mu A}{V^2} \right) \left(\frac{10 \mu m}{1 \mu m} \right) = 2.50 \frac{mA}{V^2}$$

4.11

Identify the source, drain, gate and bulk terminals and find the current I in the transistors in Fig. P-4.3.



(a)

$$V_{GS} = V_G - V_S = 5V \quad V_{DS} = V_D - V_S = 0.2V \rightarrow \text{Triode region operation}$$

$$I = I_D = K_n \frac{W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = \left(100 \frac{\mu A}{V^2} \right) \left(\frac{10}{1} \right) \left(5 - 0.70 - \frac{0.2}{2} \right) 0.2 = +840 \mu A$$

(b)

$$V_{GS} = V_G - V_S = 5 - (-0.2) = 5.2V \quad V_{DS} = V_D - V_S = 0 - (-0.2) = 0.2V$$

$$I = -I_S = - \left(100 \frac{\mu A}{V^2} \right) \left(\frac{10}{1} \right) \left(5.2 - 0.70 - \frac{0.2}{2} \right) 0.2 = -880 \mu A$$

4.12

$$(a) I = \left(100 \frac{\mu A}{V^2} \right) \left(\frac{10}{1} \right) \left(5 - 0.75 - \frac{0.5}{2} \right) 0.5 = 2.00 mA$$

$$(b) I = \left(100 \frac{\mu A}{V^2} \right) \left(\frac{10}{1} \right) \left(3 - 0.75 - \frac{0.2}{2} \right) 0.2 = 430 \mu A$$

4.13

$$(a) V_{GS} = V_G - V_S = 5 - (-0.5) = 5.5 V \quad V_{DS} = V_D - V_S = 0 - (-0.5) = 0.5 V$$

$$I = -I_S = - \left(100 \frac{\mu A}{V^2} \right) \left(\frac{10}{1} \right) \left(5.5 - 0.75 - \frac{0.5}{2} \right) 0.5 = -2.25 mA$$

$$(b) V_{GS} = V_G - V_S = 3 - (-1) = 4 V \quad V_{DS} = V_D - V_S = 0 - (-1) = 1 V$$

$$I = -I_S = - \left(100 \frac{\mu A}{V^2} \right) \left(\frac{10}{1} \right) \left(4 - 0.75 - \frac{1}{2} \right) 1 = -2.75 mA$$

4.14

$$K_n = K' \frac{W}{L} \quad (a) W = \frac{K_n}{K'} L = \frac{4mA/V^2}{100\mu A/V^2} (0.5\mu m) = 20 \mu m \quad (b) W = \frac{800\mu A/V^2}{100\mu A/V^2} (0.5\mu m) = 4 \mu m$$

4.15

$$(a) R_{on} = \frac{1}{K' \frac{W}{L} (V_{GS} - V_{TN})} = \frac{1}{100 \times 10^{-6} \left(\frac{100}{1} \right) (5 - 0.65)} = 23.0 \Omega$$

$$(b) R_{on} = \frac{1}{100 \times 10^{-6} \left(\frac{100}{1} \right) (3.3 - 0.50)} = 35.7 \Omega$$

4.16

$$R_{on} = \frac{1}{K' \frac{W}{L} (V_{GS} - V_{TN})} \quad \text{or} \quad \frac{W}{L} = \frac{1}{K' (V_{GS} - V_{TN}) R_{on}}$$

$$(a) \frac{W}{L} = \frac{1}{100 \times 10^{-6} (5 - 0.75) (500)} = \frac{4.71}{1} \quad | \quad (b) \frac{W}{L} = \frac{1}{100 \times 10^{-6} (3.3 - 0.75) (500)} = \frac{7.84}{1}$$

4.17

$$R_{on} \leq \frac{0.1V}{5A} = 0.020 \Omega = 20m\Omega \quad | \quad K_n = \frac{I_D}{(V_{GS} - V_{TN} - 0.5V_{DS})V_{DS}} = \frac{5}{(5 - 2 - 0.5(0.1))(0.1)} = 17.0 \frac{A}{V^2}$$

$$\text{Note that this will require } \frac{W}{L} = \frac{K_n}{K'} = \frac{17.0}{0.1} = \frac{170}{1}$$

4.18

Picking two values in saturation :

$$395\mu A = \frac{K_n}{2} (4 - V_{TN})^2 \quad \text{and} \quad 140\mu A = \frac{K_n}{2} (3 - V_{TN})^2$$

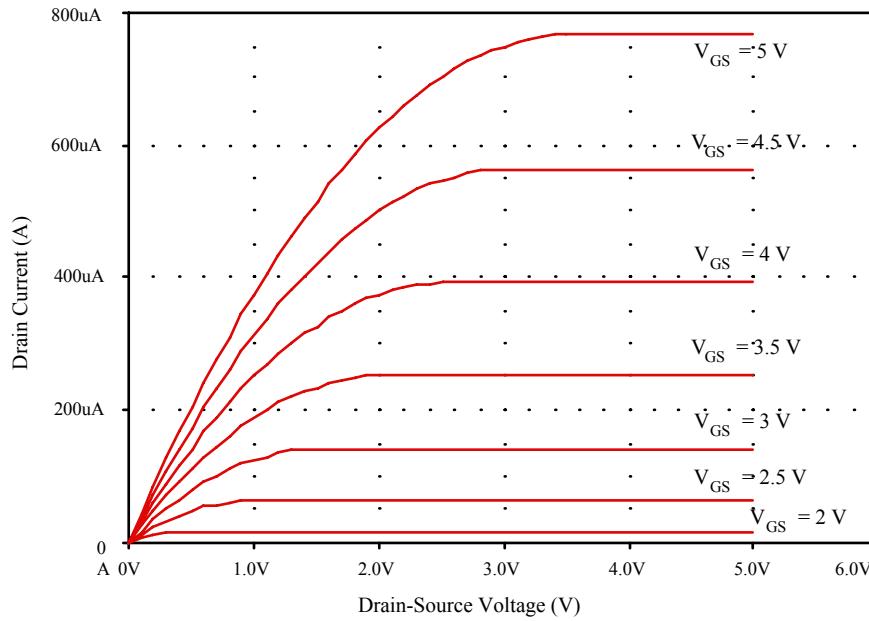
Taking the ratio of these two equations :

$$\frac{395}{140} = \frac{(4 - V_{TN})^2}{(3 - V_{TN})^2} \rightarrow V_{TN} = 1.5 V \rightarrow K_n = 125 \frac{\mu A}{V^2} \quad \frac{W}{L} = \frac{125 \frac{\mu A}{V^2}}{100 \frac{\mu A}{V^2}} = \frac{1.25}{1}$$

From the graph, V_{TN} is somewhat less than 2 V. $V_{TN} > 0 \rightarrow$ enhancement - mode transistor

4.19

Using the parameter values from problem 4.22:



4.20

- (a) For $V_{GS} = 0$, $V_{GS} \leq V_{TN}$ and $I_D = 0$
- (b) For $V_{GS} = 1$ V, $V_{GS} = V_{TN}$ and $I_D = 0$
- (c) $V_{GS} - V_{TN} = 2 - 1 = 1$ V and $V_{DS} = 3.3$ | $V_{DS} > (V_{GS} - V_{TN})$ so the saturation region is correct

$$I_D = \frac{375}{2} \frac{\mu A}{V^2} \left(\frac{5 \mu m}{0.5 \mu m} \right) (2-1)^2 V^2 = 1.88 \text{ mA} \quad | \quad K_n = K'_n \frac{W}{L} = 375 \frac{\mu A}{V^2} \left(\frac{5 \mu m}{0.5 \mu m} \right) = 3.75 \frac{mA}{V^2}$$

- (d) $V_{GS} - V_{TN} = 3 - 1 = 2$ V and $V_{DS} = 3.3$ | $V_{DS} > (V_{GS} - V_{TN})$ so the saturation region is correct

$$I_D = \frac{375}{2} \frac{\mu A}{V^2} \left(\frac{5 \mu m}{0.5 \mu m} \right) (3-1)^2 V^2 = 7.50 \text{ mA}$$

4.21

- (a) For $V_{GS} = 0$, $V_{GS} < V_{TN}$ and $I_D = 0$
- (b) For $V_{GS} = 1$ V, $V_{GS} < V_{TN}$ and $I_D = 0$
- (c) $V_{GS} - V_{TN} = 2 - 1.5 = 0.5$ V and $V_{DS} = 4$ | $V_{DS} > (V_{GS} - V_{TN})$ so the saturation region is correct

$$I_D = \frac{200}{2} \frac{\mu A}{V^2} \left(\frac{10 \mu m}{1 \mu m} \right) (2-1.5)^2 V^2 = 250 \mu A \quad | \quad K_n = K'_n \frac{W}{L} = 200 \frac{\mu A}{V^2} \left(\frac{10 \mu m}{1 \mu m} \right) = 2.00 \frac{mA}{V^2}$$

- (d) $V_{GS} - V_{TN} = 3 - 1.5 = 1.5$ V and $V_{DS} = 4$ | $V_{DS} > (V_{GS} - V_{TN})$ so the saturation region is correct

$$I_D = \frac{200}{2} \frac{\mu A}{V^2} \left(\frac{10 \mu m}{1 \mu m} \right) (3-1.5)^2 V^2 = 2.25 \text{ mA}$$

4.22

(a) $V_{GS} - V_{TN} = 2 - 0.75 = 1.25 \text{ V}$ and $V_{DS} = 0.2 \text{ V}$.

$V_{DS} < V_{GS} - V_{TN}$ so the transistor is operating in the triode region.

$$I_D = K_n' \frac{W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = \left(200 \frac{\mu A}{V^2} \right) \left(\frac{10}{1} \right) \left(2 - 0.75 - \frac{0.2}{2} \right) 0.2 = 460 \mu A$$

(b) $V_{GS} - V_{TN} = 2 - 0.75 = 1.25 \text{ V}$ and $V_{DS} = 2.5 \text{ V}$.

$V_{DS} > V_{GS} - V_{TN}$ so the transistor is operating in the saturation region.

$$I_D = \frac{K_n'}{2} \frac{W}{L} (V_{GS} - V_{TN})^2 = \left(\frac{200 \mu A}{2} \right) \left(\frac{10}{1} \right) (2 - 0.75)^2 = 1.56 \text{ mA}$$

(c) $V_{GS} < V_{TN}$ so the transistor is cutoff with $I_D = 0$.

(d) $I_D \propto K_n'$ so (a) $I_D = \left(\frac{300}{200} \right) 460 \mu A = 690 \mu A$ (b) $I_D = 2.34 \text{ mA}$ (c) $I_D = 0$

4.23

(a) $V_{GS} - V_{TN} = 4 \text{ V}$, $V_{DS} = 6 \text{ V}$. $V_{DS} > V_{GS} - V_{TN}$ --> Saturation region

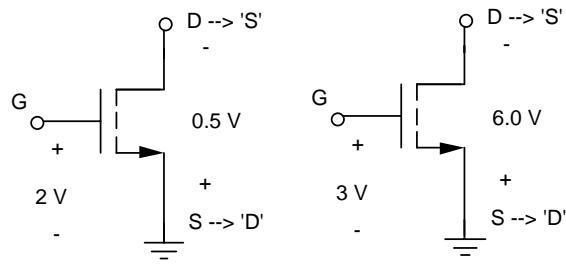
(b) $V_{GS} < V_{TN}$ --> Cutoff region

(c) $V_{GS} - V_{TN} = 1 \text{ V}$, $V_{DS} = 2 \text{ V}$. $V_{DS} > V_{GS} - V_{TN}$ --> Saturation region

(d) $V_{GS} - V_{TN} = 0.5 \text{ V}$, $V_{DS} = 0.5 \text{ V}$. $V_{DS} = V_{GS} - V_{TN}$ --> Boundary between triode and saturation regions

(e) The source and drain of the transistor are now reversed because of the sign change in V_{DS} . Assuming the voltages are defined relative to the original S and D terminals as in Fig. P4.11(b), $V_{GS} = 2 - (-0.5) = 2.5 \text{ V}$, $V_{GS} - V_{TN} = 2.5 - 1 = 1.5 \text{ V}$, and $V_{DS} = 0.5 \text{ V}$ --> triode region

(f) The source and drain of the transistor are again reversed because of the sign change in V_{DS} . Assuming the voltages are defined relative to the original S and D terminals as in Fig. P4.11(b), $V_{GS} = 3 - (-6) = 9 \text{ V}$, $V_{GS} - V_{TN} = 9 - 1 = 8.0 \text{ V}$, and $V_{DS} = 6 \text{ V}$ --> triode region

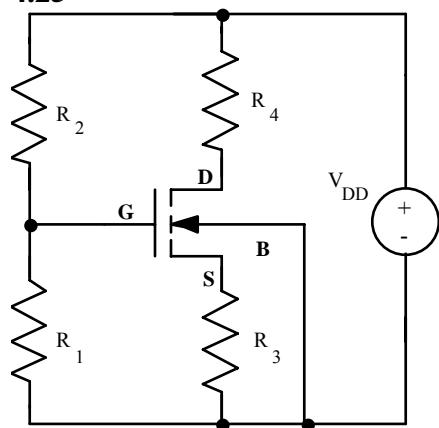
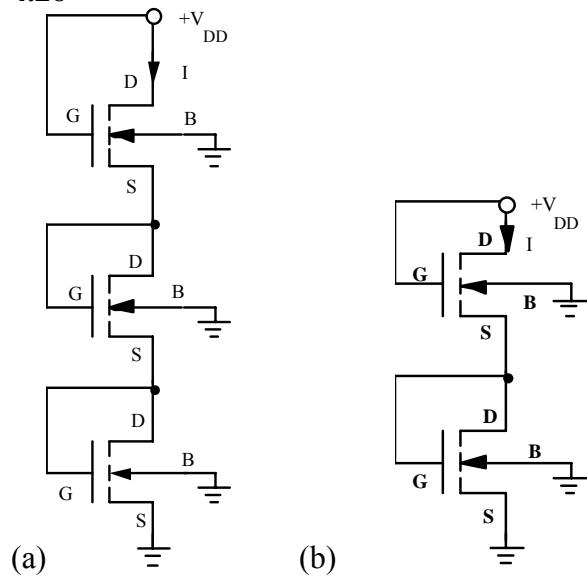


(e) $V_{GS'} = +2.5 \text{ V}$
 $V_{DS'} = +0.5 \text{ V}$

(f) $V_{GS'} = +9.0 \text{ V}$
 $V_{DS'} = +6.0 \text{ V}$

4.24

- (a) $V_{GS} - V_{TN} = 2.6 \text{ V}$, $V_{DS} = 3.3 \text{ V}$. $V_{DS} > V_{GS} - V_{TN}$ \rightarrow Saturation region
- (b) $V_{GS} < V_{TN}$ \rightarrow Cutoff region
- (c) $V_{GS} - V_{TN} = 1.3 \text{ V}$, $V_{DS} = 2 \text{ V}$. $V_{DS} > V_{GS} - V_{TN}$ \rightarrow Saturation region
- (d) $V_{GS} - V_{TN} = 0.8 \text{ V}$, $V_{DS} = 0.5 \text{ V}$. $V_{DS} < V_{GS} - V_{TN}$ \rightarrow triode region
- (e) The source and drain of the transistor are now reversed because of the sign change in V_{DS} . Assuming the voltages are defined relative to the original S and D terminals as in Fig. 4.54(b), $V_{GS} = 2 - (-0.5) = 2.5 \text{ V}$, $V_{GS} - V_{TN} = 2.5 - 0.7 = 1.8 \text{ V}$, and $V_{DS} = 0.5 \text{ V}$ \rightarrow triode region
- (f) The source and drain of the transistor are again reversed because of the sign change in V_{DS} . Assuming the voltages are defined relative to the original S and D terminals as in Fig. 4.54(b), $V_{GS} = 3 - (-3) = 6 \text{ V}$, $V_{GS} - V_{TN} = 6 - 0.7 = 5.3 \text{ V}$, and $V_{DS} = 3 \text{ V}$ \rightarrow triode region

4.25**4.26****4.27**

$V_{DS} = 3.3V$, $V_{GS} - V_{TN} = 1.3$ V; $V_{DS} > V_{GS} - V_{TN}$ so the transistor is saturated.

$$(a) g_m = K_n(V_{GS} - V_{TN}) = 250 \frac{\mu A}{V^2} \left(\frac{20\mu m}{1\mu m} \right) (2 - 0.7) = 6.50 \text{ mS}$$

$$(b) g_m = K_n(V_{GS} - V_{TN}) = 250 \frac{\mu A}{V^2} \left(\frac{20\mu m}{1\mu m} \right) (3.3 - 0.7) = 13.0 \text{ mS}$$

4.28

$$(a) g_m = \frac{\Delta i_D}{\Delta v_{GS}} = \frac{760 - 140}{5 - 3} \frac{\mu A}{V} = 310 \text{ } \mu S \quad | \text{ As a check, we can use the results from Problem 4.22.}$$

$$g_m = K_n(V_{GS} - V_{TN}) = 125 \frac{\mu A}{V^2} (4 - 1.5)V = 313 \text{ } \mu S$$

$$(b) g_m = \frac{\Delta i_D}{\Delta v_{GS}} = \frac{390 - 15}{4 - 2} \frac{\mu A}{V} = 188 \text{ } \mu S \quad | \text{ Checking: } g_m = 125 \frac{\mu A}{V^2} (3 - 1.5)V = 188 \text{ } \mu S$$

4.29

$V_{DS} > V_{GS} - V_{TN}$ so the transistor is saturated.

$$(a) I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS}) = \frac{250}{2} \frac{\mu A}{V^2} (5 - 0.75)^2 (1 + 0.025(6)) = 2.60 \text{ mA}$$

$$(b) I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 = \frac{250}{2} \frac{\mu A}{V^2} (5 - 0.75)^2 = 2.26 \text{ mA}$$

4.30

$V_{DS} > V_{GS} - V_{TN}$ so the transistor is saturated.

$$(a) I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS}) = \frac{500}{2} \frac{\mu A}{V^2} (4 - 1)^2 (1 + 0.02(5)) = 2.48 \text{ mA}$$

$$(b) I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 = \frac{500}{2} \frac{\mu A}{V^2} (4 - 1)^2 = 2.25 \text{ mA}$$

4.31

(a) The transistor is saturated by connection.

$$I_D = \frac{12V - V_{GS}}{10^5 \Omega} = \frac{100 \times 10^{-6}}{2} \left(\frac{10}{1} \right) \frac{A}{V^2} (V_{GS} - 0.75V)^2$$

$$12.5V_{GS}^2 - 17.8V_{GS} - 4.97 = 0$$

$$V_{GS} = 0.266V, 1.214V \Rightarrow V_{GS} = 1.214 \text{ V since it must exceed } 0.75V$$

$$I_D = \frac{12 - 1.214}{10^5} = 108 \text{ } \mu A \quad \text{Checking: } \frac{100 \times 10^{-6}}{2} \left(\frac{10}{1} \right) \frac{A}{V^2} (1.214 - 0.75V)^2 = 108 \text{ } \mu A$$

$$(b) I_D = \frac{12V - V_{GS}}{10^5 \Omega} = \frac{1000 \times 10^{-6}}{2} \frac{A}{V^2} (V_{GS} - 0.75V)^2 (1 + 0.025V_{GS})$$

Starting with the solution from part (a) and solving iteratively yields $V_{GS} = 1.20772$ V and $I_D = 108 \mu A$, essentially no change.

(c)

$$I_D = \frac{12V - V_{GS}}{10^5 \Omega} = \frac{100 \times 10^{-6}}{2} \left(\frac{25}{1} \right) \frac{A}{V^2} (V_{GS} - 0.75V)^2$$

$$62.5V_{GS}^2 - 91.75V_{GS} + 11.16 = 0$$

$V_{GS} = 0.446V, 1.046V \Rightarrow V_{GS} = 1.046$ V since V_{GS} must exceed the threshold voltage.

$$I_D = \frac{12 - 1.046}{10^5} = 110 \mu A \quad \text{Checking: } I_D = \frac{100 \times 10^{-6}}{2} \left(\frac{25}{1} \right) \frac{A}{V^2} (1.046 - 0.75V)^2 = 110 \mu A$$

4.32

(a) The transistor is saturated by connection.

$$I_D = \frac{12V - V_{GS}}{5 \times 10^4 \Omega} = \frac{100 \times 10^{-6}}{2} \left(\frac{10}{1} \right) \frac{A}{V^2} (V_{GS} - 0.75V)^2$$

$$31.25V_{GS}^2 - 45.88V_{GS} + 5.58 = 0$$

$V_{GS} = 0.0588V, 1.401V \Rightarrow V_{GS} = 1.401$ V since V_{GS} must exceed the threshold voltage.

$$I_D = \frac{12 - 1.401}{5 \times 10^4} = 212 \mu A \quad \text{Checking: } I_D = \frac{100 \times 10^{-6}}{2} \left(\frac{10}{1} \right) \frac{A}{V^2} (1.401 - 0.75V)^2 = 212 \mu A$$

$$(b) I_D = \frac{12V - V_{GS}}{5 \times 10^4 \Omega} = \frac{1000 \times 10^{-6}}{2} \frac{A}{V^2} (V_{GS} - 0.75V)^2 (1 + 0.02V_{GS})$$

Starting with the solution from part (a) and solving iteratively yields $V_{GS} = 1.3925$ V and $I_{DS} = 212 \mu A$, essentially no change

4.33

(a) Since $V_{DS} = V_{GS}$ and $V_{TN} > 0$ for both transistors, both devices are saturated.

$$\text{Therefore } I_{D1} = \frac{K_n'}{2} \frac{W}{L} (V_{GS1} - V_{TN})^2 \quad \text{and} \quad I_{D2} = \frac{K_n'}{2} \frac{W}{L} (V_{GS2} - V_{TN})^2.$$

From the circuit, however, I_{D2} must equal I_{D1} since $I_G = 0$ for the MOSFET:

$$I = I_{D1} = I_{D2} \quad \text{or} \quad \frac{K_n'}{2} \frac{W}{L} (V_{GS1} - V_{TN})^2 = \frac{K_n'}{2} \frac{W}{L} (V_{GS2} - V_{TN})^2$$

which requires $V_{GS1} = V_{GS2}$. Using KVL:

$$V_{DD} = V_{DS1} + V_{DS2} = V_{GS1} + V_{GS2} = 2V_{GS2}$$

$$V_{GS1} = V_{GS2} = \frac{V_{DD}}{2} = 5V$$

$$I = \frac{K_n'}{2} \frac{W}{L} (V_{GS1} - V_{TN})^2 = \frac{100}{2} \frac{\mu A}{V^2} \frac{10}{1} (5 - 0.75)^2 V^2 = 9.03 mA$$

(b) The current simply scales by a factor of two (see last equation above), and $I_D = 18.1$ mA.

(c) For this case,

$$I_{D1} = \frac{K_n'}{2} \frac{W}{L} (V_{GS1} - V_{TN})^2 (1 + \lambda V_{DS1}) \text{ and } I_{D2} = \frac{K_n'}{2} \frac{W}{L} (V_{GS2} - V_{TN})^2 (1 + \lambda V_{DS2}).$$

Since $V_{GS} = V_{DS}$ for both transistors

$$I_{D1} = \frac{K_n'}{2} \frac{W}{L} (V_{GS1} - V_{TN})^2 (1 + \lambda V_{GS1}) \text{ and } I_{D2} = \frac{K_n'}{2} \frac{W}{L} (V_{GS2} - V_{TN})^2 (1 + \lambda V_{GS2})$$

and $I_{D1} = I_{D2} = I$

$$\frac{K_n'}{2} \frac{W}{L} (V_{GS1} - V_{TN})^2 (1 + \lambda V_{GS1}) = \frac{K_n'}{2} \frac{W}{L} (V_{GS2} - V_{TN})^2 (1 + \lambda V_{GS2})$$

which again requires $V_{GS1} = V_{GS2} = V_{DD}/2 = 5V$.

$$I = \frac{K_n'}{2} \frac{W}{L} (V_{GS1} - V_{TN})^2 (1 + \lambda V_{DS}) = \frac{100}{2} \frac{\mu A}{V^2} \frac{10}{1} (5 - 0.75)^2 V^2 (1 + (.04)5) = 10.8 mA$$

4.34

(a) Since $V_{DS} = V_{GS}$ and $V_{TN} > 0$ for both transistors, both devices are saturated ("by connection").

$$\text{Therefore } I_{D1} = \frac{K_n'}{2} \left(\frac{W}{L} \right)_1 (V_{GS1} - V_{TN})^2 \text{ and } I_{D2} = \frac{K_n'}{2} \left(\frac{W}{L} \right)_2 (V_{GS2} - V_{TN})^2.$$

From the circuit, however, I_{D2} must equal I_{D1} since $I_G = 0$ for the MOSFET:

$$I = I_{D1} = I_{D2} \text{ or } \frac{K_n'}{2} \left(\frac{10}{1} \right) (V_{GS1} - V_{TN})^2 = \frac{K_n'}{2} \left(\frac{40}{1} \right) (V_{GS2} - V_{TN})^2$$

which requires $V_{GS1} = 2V_{GS2} - V_{TN}$. Using KVL:

$$V_{DD} = V_{DS1} + V_{DS2} = V_{GS2} + V_{GS1} = 3V_{GS2} - V_{TN}$$

$$V_{GS2} = \frac{V_{DD} + V_{TN}}{3} = \frac{10 + 0.75}{3} = 3.583V \quad V_{GS1} = 6.417$$

$$I = \frac{K_n'}{2} \frac{W}{L} (V_{GS1} - V_{TN})^2 = \frac{100}{2} \frac{\mu A}{V^2} \frac{10}{1} (6.417 - 0.75)^2 V^2 = 16.1 mA$$

Checking: $I = \frac{100}{2} \frac{\mu A}{V^2} \frac{40}{1} (3.583 - 0.75)^2 V^2 = 16.1 mA$ which agrees.

(b) For this case with $V_{GS} = V_{DS}$ for both transistors and $I_{D1} = I_{D2}$,

$$I_{D1} = \frac{K_n'}{2} \left(\frac{W}{L} \right)_1 (V_{GS1} - V_{TN})^2 (1 + \lambda V_{GS1}) \text{ and } I_{D2} = \frac{K_n'}{2} \left(\frac{W}{L} \right)_2 (V_{GS2} - V_{TN})^2 (1 + \lambda V_{GS2})$$

where $V_{GS2} = V_{DD} - V_{GS1}$. Therefore,

$$\frac{K_n'}{2} \left(\frac{10}{1} \right) (V_{GS1} - V_{TN})^2 (1 + \lambda V_{GS1}) = \frac{K_n'}{2} \left(\frac{40}{1} \right) (10 - V_{GS1} - V_{TN})^2 (1 + \lambda (10 - V_{GS1}))$$

$V_{GS1} = 6.3163$, $V_{GS2} = 3.6837$, $I_{D1} = 20.4$ mA, Checking: $I_{D2} = 20.4$ mA which agrees.

4.35

(a) Since $V_{DS} = V_{GS}$ and $V_{TN} > 0$ for both transistors, both devices are saturated (“by connection”).

$$\text{Therefore } I_{D1} = \frac{K_n'}{2} \left(\frac{W}{L} \right)_1 (V_{GS1} - V_{TN})^2 \quad \text{and} \quad I_{D2} = \frac{K_n'}{2} \left(\frac{W}{L} \right)_2 (V_{GS2} - V_{TN})^2.$$

From the circuit, however, I_{D2} must equal I_{D1} since $I_G = 0$ for the MOSFET:

$$I = I_{D1} = I_{D2} \quad \text{or} \quad \frac{K_n'}{2} \left(\frac{25}{1} \right) (V_{GS1} - V_{TN})^2 = \frac{K_n'}{2} \left(\frac{12.5}{1} \right) (V_{GS2} - V_{TN})^2$$

$$\text{Solving for } V_{GS2} \text{ yields: } V_{GS2} = \sqrt{2}V_{GS1} - (\sqrt{2}-1)V_{TN}$$

$$\text{Also, } V_{DD} = V_{DS1} + V_{DS2} \quad \text{or} \quad V_{GS1} = 10 - V_{GS2}$$

$$V_{GS1} = \frac{10 + (\sqrt{2}-1)V_{TN}}{1+\sqrt{2}} = 4.271V \quad V_{GS2} = 5.729V$$

$$I = \frac{K_n'}{2} \frac{W}{L} (V_{GS1} - V_{TN})^2 = \frac{100 \mu A}{2} \left(\frac{25}{1} \right) (4.271 - 0.75)^2 V^2 = 15.5 mA$$

$$\text{Checking: } I = \frac{100 \mu A}{2} \left(\frac{12.5}{1} \right) (5.729 - 0.75)^2 V^2 = 15.5 mA - \text{agrees.}$$

(b) For this case with $V_{GS} = V_{DS}$ for both transistors and $I_{D1} = I_{D2}$,

$$I_{D1} = \frac{K_n'}{2} \left(\frac{W}{L} \right)_1 (V_{GS1} - V_{TN})^2 (1 + \lambda V_{GS1}) \quad \text{and} \quad I_{D2} = \frac{K_n'}{2} \left(\frac{W}{L} \right)_2 (V_{GS2} - V_{TN})^2 (1 + \lambda V_{GS2})$$

where $V_{GS2} = V_{DD} - V_{GS1}$. Therefore,

$$\frac{K_n'}{2} \left(\frac{10}{1} \right) (V_{GS1} - V_{TN})^2 (1 + \lambda V_{GS1}) = \frac{K_n'}{2} \left(\frac{40}{1} \right) (10 - V_{GS1} - V_{TN})^2 (1 + \lambda (10 - V_{GS1}))$$

$$V_{GS1} = 4.3265 V, \quad V_{GS2} = 5.6735 V, \quad I_{D1} = 19.4 mA, \quad \text{Checking: } I_{D2} = 19.4 mA - \text{both agree}$$

4.36

$V_{GS} - V_{TN} = 5 - (-2) = 7 V > V_{DS} = 6 V$ so the transistor is operating in the triode region.

$$(a) I_D = 250 \times 10^{-6} \left(5 - (-2) - \frac{6}{2} \right) 6 = 6.00 mA$$

(b) Our triode region model is independent of λ , so $I_D = 6.00 mA$.

4.37

Since $V_{DS} = V_{GS}$, and $V_{TN} < 0$ for an NMOS depletion mode device, $V_{GS} - V_{TN}$ will be greater than V_{DS} and the transistor will be operating in the triode region.

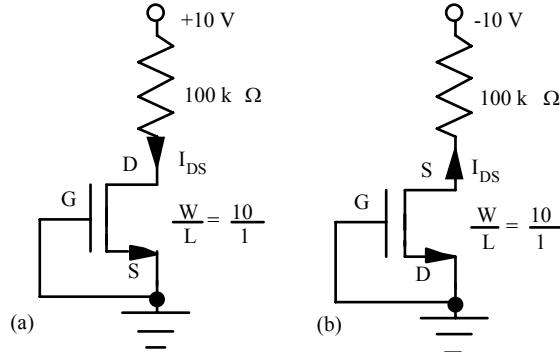
4.38

(a) $V_{DS} = 6V$ | $V_{GS} - V_{TN} = 0 - (-3) = 3V$ so the transistor is saturated

$$I_D = \frac{K_n}{2} (V_{GS1} - V_{TN})^2 = \frac{250 \mu A}{2} \left[0 - (-3V) \right]^2 = 1.13 mA$$

$$(b) I_D = \frac{250 \mu A}{2} \left[0 - (-3V) \right]^2 (1 + 0.025(6)) = 1.29 mA$$

4.39



(a) If the transistor were saturated, then

$$I_D = \frac{100 \times 10^{-6}}{2} \left(\frac{10}{1} \right) (-2)^2 = 2.00 mA$$

but this would require a power supply of greater than 200 V ($2 \text{ mA} \times 100 \text{ k}\Omega$). Thus the transistor must be operating in the triode region.

$$\frac{10V - V_{DS}}{10^5 \Omega} = 10^{-3} \left(0 - (-2) - \frac{V_{DS}}{2} \right) V_{DS}$$

$10 - V_{DS} = 50V_{DS}(4 - V_{DS})$ and $V_{DS} = 0.0504V$ using the quadratic equation.

$$I_D = 10^{-3} \left(2 - \frac{0.0504}{2} \right) 0.0504 = 99.5 \mu A \quad \text{Checking: } \frac{10V - V_{DS}}{10^5 \Omega} = 99.5 \mu A$$

(b) For $R = 50 \text{ k}\Omega$ and $W/L = 20/1$,

$$\frac{10V - V_{DS}}{5 \times 10^4 \Omega} = 2 \times 10^{-3} \left(0 - (-2) - \frac{V_{DS}}{2} \right) V_{DS}$$

$10 - V_{DS} = 50V_{DS}(4 - V_{DS})$, the same as part (a).

$$I_D = 2 \times 10^{-3} \left(2 - \frac{0.0504}{2} \right) 0.0504 = 199 \mu A \quad \text{Checking: } \frac{10V - V_{DS}}{5 \times 10^4 \Omega} = 199 \mu A$$

(c) In this circuit, the drain and source terminals of the transistor are reversed because of the power supply voltage, and the current direction is also reversed. However, now $V_{DS} = V_{GS}$ and since the transistor is a depletion-mode device, it is still operating in the triode region.

$$\frac{10V - V_{DS}}{10^5 \Omega} = 1000 \times 10^{-6} \left(V_{DS} - (-2) - \frac{V_{DS}}{2} \right) V_{DS}$$

$10 - V_{DS} = 50V_{DS}(4 + V_{DS})$ and $V_{DS} = 0.04915V$ using the quadratic equation.

$$I_D = 10^{-3} \left(0.04915 - (-2) - \frac{0.04915}{2} \right) 0.04915 = 99.5 \mu A \quad \text{Checking: } \frac{10V - V_{DS}}{10^5 \Omega} = 99.5 \mu A$$

(d) In this circuit, the drain and source terminals of the transistor are reversed because of the power supply voltage, and the current direction is also reversed. However, now $V_{DS} = V_{GS}$ and since the transistor is a depletion-mode device, it is still operating in the triode region.

$$\frac{10V - V_{DS}}{5 \times 10^4 \Omega} = 2000 \times 10^{-6} \left(V_{DS} - (-2) - \frac{V_{DS}}{2} \right) V_{DS}$$

$10 - V_{DS} = 50V_{DS}(4 + V_{DS})$ Same as part (c). $V_{DS} = 0.04915V$ using the quadratic equation.

$$I_D = 10^{-3} \left(0.04915 - (-2) - \frac{0.04915}{2} \right) 0.04915 = 99.5 \mu A \quad \text{Checking: } \frac{10V - V_{DS}}{10^5 \Omega} = 99.5 \mu A$$

4.40 See figures in previous problem but use W/L = 20/1.

(a) If the transistor were saturated, then $I_D = \frac{25 \times 10^{-6}}{2} \left(\frac{20}{1} \right) (-1)^2 = 250 \mu A$ but this would require a power supply of greater than 25 V. Thus the transistor must be operating in the triode region.

$$\frac{10V - V_{DS}}{10^5 \Omega} = 100 \times 10^{-6} \left(\frac{20}{1} \right) \left(0 - (-1) - \frac{V_{DS}}{2} \right) V_{DS}$$

$10 - V_{DS} = 100V_{DS}(2 - V_{DS})$ and $V_{DS} = 0.05105V$ using the quadratic equation.

$$I_D = 2.00 \times 10^{-3} \left(1 - \frac{0.05105}{2} \right) 0.05105 = 99.5 \mu A \quad \text{Checking: } \frac{10 - 0.05105}{10^5 \Omega} V = 99.5 \mu A$$

(b) In this circuit, the drain and source terminals of the transistor are reversed because of the power supply voltage, and the current direction is also reversed. However, now $V_{DS} = V_{GS}$ and since the transistor is a depletion-mode device, it is still operating in the triode region.

$$V_{DS} = 10 - (10^5) \left(100 \times 10^{-6} \right) \left(\frac{20}{1} \right) \left(V_{DS} - (-1) - \frac{V_{DS}}{2} \right) V_{DS}$$

$$V_{DS} = 10 - 200V_{DS} \left(1 + \frac{V_{DS}}{2} \right) \text{ and } V_{DS} = 0.04858V \text{ using the quadratic equation.}$$

$$I_D = 2000 \times 10^{-6} \left(1 + \frac{0.04858}{2} \right) 0.04858 = 99.5 \mu A \quad \text{Checking: } \frac{10 - 0.04858}{10^5 \Omega} V = 99.5 \mu A$$

4.41

$$(a) V_{TN} = 0.75 + 0.75(\sqrt{1.5 + 0.6} - \sqrt{0.6}) = 1.26V$$

$V_{GS} - V_{TN} = 2 - 1.26 = 0.74V > V_{DS} = 0.2V \Rightarrow$ Triode region

$$I_D = 200 \times 10^{-6} \left(\frac{10}{1} \right) \left(2 - 1.26 - \frac{0.2}{2} \right) 0.2 = 256 \mu A \quad (\text{compared to } 460 \mu A)$$

(b) $V_{GS} - V_{TN} = 2 - 1.26 = 0.74V < V_{DS} = 2.5V \Rightarrow$ Saturation region

$$I_D = \frac{200 \times 10^{-6}}{2} \left(\frac{10}{1} \right) (2 - 1.26)^2 = 548 \mu A \quad (\text{compared to } 1.56 mA)$$

(c) $V_{GS} < V_{TN}$ so the transistor is cut off, and $I_D = 0$.

$$(d) I_D \propto K'_n \text{ so } (a) I_D = \left(\frac{300}{200} \right) 256 \mu A = 384 \mu A \quad (b) I_D = 822 \mu A \quad (c) I_D = 0$$

4.42

$$(a) V_{TN} = 1.5 + 0.5(\sqrt{4 + 0.75} - \sqrt{0.75}) = 2.16V \quad | \quad V_{GS} < V_{TN} \Rightarrow \text{Cutoff} \quad \& \quad I_D = 0$$

(b) $I_D = 0$. The result is independent of V_{DS} .

4.43

$$(a) V_{TN} = 1 + 0.7(\sqrt{3 + 0.6} - \sqrt{0.6}) = 1.79V$$

$V_{GS} - V_{TN} = 2.5 - 1.79 = 0.71V < V_{DS} = 5V \Rightarrow$ Saturation region

$$I_D = \frac{100 \times 10^{-6}}{2} \left(\frac{8}{1} \right) (0.71)^2 = 202 \mu A$$

(b) $0.5 < 0.71 \Rightarrow$ Triode region

$$I_D = 100 \times 10^{-6} \left(\frac{8}{1} \right) \left(0.71 - \frac{0.5}{2} \right) 0.5 = 184 \mu A$$

4.44

$$0.85 = -1.5 + 1.5(\sqrt{V_{SB} + 0.75} - \sqrt{0.75}) \quad | \quad \text{Solving for } V_{SB} \text{ yields } V_{SB} = 5.17 V$$

$$\text{Checking: } V_{TN} = -1.5 + 1.5(\sqrt{5.17 + 0.75} - \sqrt{0.75}) = 0.85 V$$

4.45

Using trial and error with a spreadsheet yielded:

$$V_{TO} = 0.74V \quad \gamma = 0.84\sqrt{V} \quad 2\phi_F = 0.87V \quad \text{RMS Error} = 51.9 \text{ mV}$$

4.46

$$(a) K' = \mu_p C''_{ox} = \mu_p \frac{\epsilon_{ox}}{T_{ox}} = \mu_p \frac{3.9\epsilon_0}{T_{ox}} = \left(200 \frac{cm^2}{V \cdot sec}\right) \frac{3.9(8.854 \times 10^{-14} F/cm)}{50 \times 10^{-9} m (100 cm/m)}$$

$$K' = 13.8 \times 10^{-6} \frac{F}{V \cdot sec} = 13.8 \frac{\mu A}{V^2}$$

$$(b) \text{ Scaling the result from Part (a) yields: } K_n' = 13.8 \frac{\mu A}{V^2} \frac{50 nm}{20 nm} = 34.5 \frac{\mu A}{V^2}$$

$$(c) K_n' = 13.8 \frac{\mu A}{V^2} \frac{50 nm}{10 nm} = 69.0 \frac{\mu A}{V^2}$$

$$(d) K_n' = 13.8 \frac{\mu A}{V^2} \frac{50 nm}{5 nm} = 138 \frac{\mu A}{V^2}$$

4.47

The pinchoff points and threshold voltage can be estimated directly from the graph: e. g. $V_{GS} = -3$ V curve gives $V_{TP} = 2.5 - 3 = -0.5$ V or from the $V_{GS} = -5$ V curve gives $V_{TP} = 4.5 - 5 = -0.5$ V.

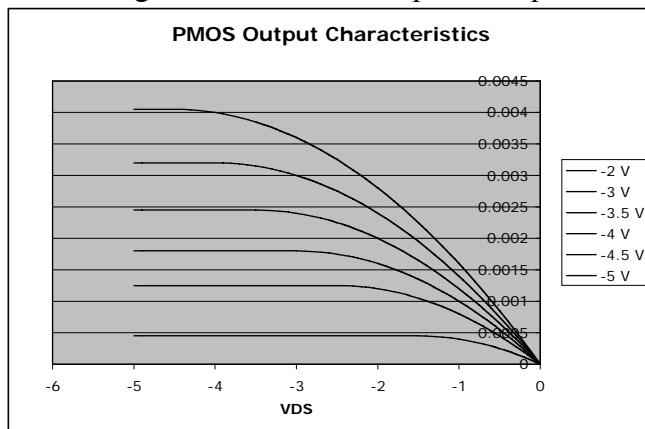
Alternately, choosing two points in saturation, say $I_D = 1.25$ mA for $V_{GS} = -3$ V and $I_D = 4.05$ mA for $V_{GS} = -5$ V:

$$\sqrt{\frac{I_{D1}}{I_{D2}}} = \sqrt{\frac{(V_{GS1} - V_{TP})}{(V_{GS2} - V_{TP})}} \quad \text{or} \quad \sqrt{\frac{1.25}{4.05}} = \sqrt{\frac{(-3 - V_{TP})}{(-5 - V_{TP})}}$$

Solving for V_{TP} yields: $0.8V_{TP} = -0.4V$ and $V_{TP} = -0.500V$.

$$\text{Solving for } K_p: K_p = \frac{2I_D}{(V_{GS} - V_{TP})^2} = \frac{2(1.25 \text{ mA})}{(-3 + 0.5)^2} = 0.400 \frac{\text{mA}}{V^2} \quad | \quad \frac{W}{L} = \frac{K_p}{K'} = \frac{400 \frac{\mu A}{V^2}}{40 \frac{\mu A}{V^2}} = \frac{10}{1}$$

4.48 Using the values from the previous problem



(I_{DSAT}, V_{DSAT}) : (0.45 mA, -1.5 V) (1.25 mA, -2.5 V) (1.8 mA, -3 V) (2.45 mA, -3.5 V) (3.7 mA, -4 V) (4.05 mA, -4 V)

4.49

(a) $V_{GS} - V_{TP} = -1.1 + 0.75 = -0.35V$ | $V_{DS} = -0.2V \rightarrow$ Triode region

$$I_D = \frac{40\mu A}{V^2} \left(\frac{20}{1} \right) \left[-1.1 - (-0.75) - \frac{(-0.2)}{2} \right] (-0.2) = 40.0 \mu A$$

(b) $V_{GS} - V_{TP} = -1.3 + 0.75 = -0.55V$ | $V_{DS} = -0.2V \rightarrow$ Triode region

$$I_D = \frac{40\mu A}{V^2} \left(\frac{20}{1} \right) \left[-1.3 - (-0.75) - \frac{(-0.2)}{2} \right] (-0.2) = 72.0 \mu A$$

(c) $V_{TP} = -[0.75 + .5(\sqrt{1+.6} - \sqrt{-6})] = -0.995V$

$V_{GS} - V_{TP} = -1.1 - (-0.995) = -0.105V$ | $V_{DS} = -0.2V \rightarrow$ saturation region

$$I_D = \frac{1}{2} \left(\frac{40\mu A}{V^2} \right) \left(\frac{20}{1} \right) (-1.1 + 0.995)^2 = 4.41 \mu A$$

(d) $V_{GS} - V_{TP} = -1.3 + 0.995 = -0.305V$ | $V_{DS} = -0.2V \rightarrow$ triode region

$$I_D = \frac{10\mu A}{V^2} \left(\frac{10}{1} \right) \left[-1.3 - (-0.995) - \frac{(-0.2)}{2} \right] (-0.2) = 32.8 \mu A$$

4.50

For PMOS: $R_{on} = \frac{1}{K_p \frac{W}{L} |V_{GS} - V_{TP}|}$ or $\frac{W}{L} = \frac{1}{K_p |V_{GS} - V_{TN}| R_{on}}$

(a) $\frac{W}{L} = \frac{1}{40 \times 10^{-6} |-5 + 0.70|(1)} = \frac{5810}{1}$ | (b) $\frac{W}{L} = \frac{1}{100 \times 10^{-6} (5 - 0.70)(1)} = \frac{2330}{1}$

4.51

For PMOS: $R_{on} = \frac{1}{K_p \frac{W}{L} |V_{GS} - V_{TP}|}$ or $\frac{W}{L} = \frac{1}{K_p |V_{GS} - V_{TN}| R_{on}}$

(a) $\frac{W}{L} = \frac{1}{40 \times 10^{-6} |-5 + 0.70|(2000)} = \frac{2.91}{1}$ | (b) $\frac{W}{L} = \frac{1}{100 \times 10^{-6} (5 - 0.70)(2000)} = \frac{1.16}{1}$

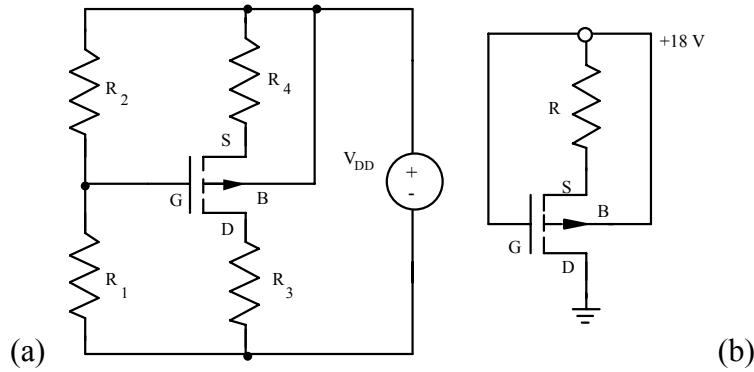
4.52

For PMOS: $R_{on} = \frac{1}{K_p \frac{W}{L} |V_{GS} - V_{TP}|}$ (a) $R_{on} = \frac{1}{40 \times 10^{-6} \left(\frac{200}{1} \right) |5 - (-0.75)|} = 29.4 \Omega$

(b) $R_{on} = \frac{1}{100 \times 10^{-6} \left(\frac{200}{1} \right) (5 - 0.75)} = 11.8 \Omega$ (c) $\frac{W}{L} = \frac{1}{40 \times 10^{-6} |5 - (-0.75)| (11.8)} = \frac{499}{1}$

Checking: $\left(\frac{W}{L} \right)_p = \frac{K_n'}{K_p'} \left(\frac{W}{L} \right)_n = 2.5 (200) = \frac{500}{1}$

4.53



4.54

(a) For $V_{IN} = 0$, the NMOS device is on with $V_{GS} = 5$ and $V_{SB} = 0$, and the PMOS transistor is off with $V_{GS} = 0$, $V_O = 0$, and $V_{SB} = 0$.

$$R_{on} = \frac{1}{(100 \times 10^{-6})(10)(5 - 0.75)} = 235 \Omega$$

(b) For $V_{IN} = 5V$, the NMOS device is off with $V_{GS} = 0$, and the PMOS transistor is on with $V_{GS} = -5V$, $V_O = 5V$, and $V_{SB} = 0$.

$$R_{on} = \frac{1}{(40 \times 10^{-6})(25)(-5 + 0.75)} = 235 \Omega$$

4.55

$$R_{on} \leq \frac{0.1V}{0.5A} = 0.2 \Omega \quad K_p = \frac{I_D}{(V_{GS} - V_{TP} - 0.5V_{DS})V_{DS}} = \frac{0.5A}{[-10V - (-2V) - 0.5(-0.1V)][-0.1V]} = 0.629 \frac{A}{V^2}$$

4.56

$$V_{TP} = -0.75 - 0.5(\sqrt{4 + 0.6} - \sqrt{0.6}) = -1.44V$$

$$V_{GS} - V_{TP} = -1.5 - (-1.44) = -0.065 \quad | \quad V_{DS} = -4V \Rightarrow \text{Saturation region}$$

$$I_D = \frac{40 \times 10^{-6}}{2} \frac{A}{V^2} \left(\frac{25}{1} \right) [-1.5 - (-1.44)]^2 = 1.80 \mu A$$

4.57

$$V_{GS} - V_{TP} = -1.5 - (-0.75) = -0.75V \quad | \quad V_{DS} = -0.5V$$

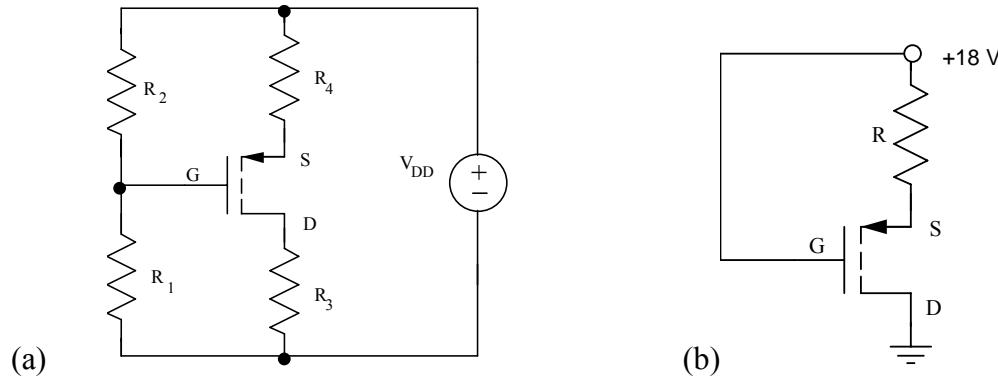
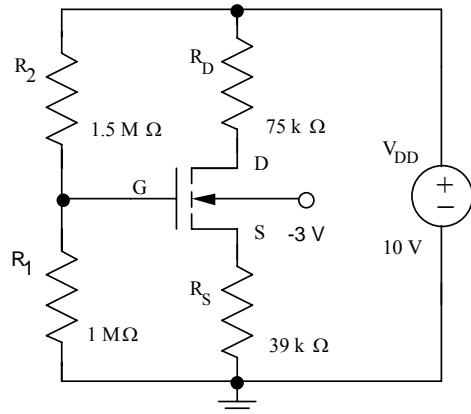
$$V_{GS} - V_{TN} < V_{DS} \Rightarrow \text{Triode region} \quad | \quad I_D = 40 \times 10^{-6} \frac{A}{V^2} \left(\frac{40}{1} \right) \left[-1.5 - (-0.75) - \frac{(-0.5)}{2} \right] (-0.5) = 400 \mu A$$

4.58

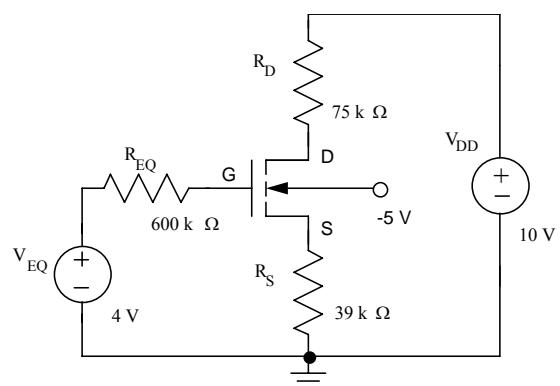
The PMOS transistor could be either an enhancement-mode or a depletion-mode device depending upon the specific values of R_1 , R_2 and R_4 . Thus an enhancement device with $V_{TP} < 0$ is correct and the symbol is correct.

4.59

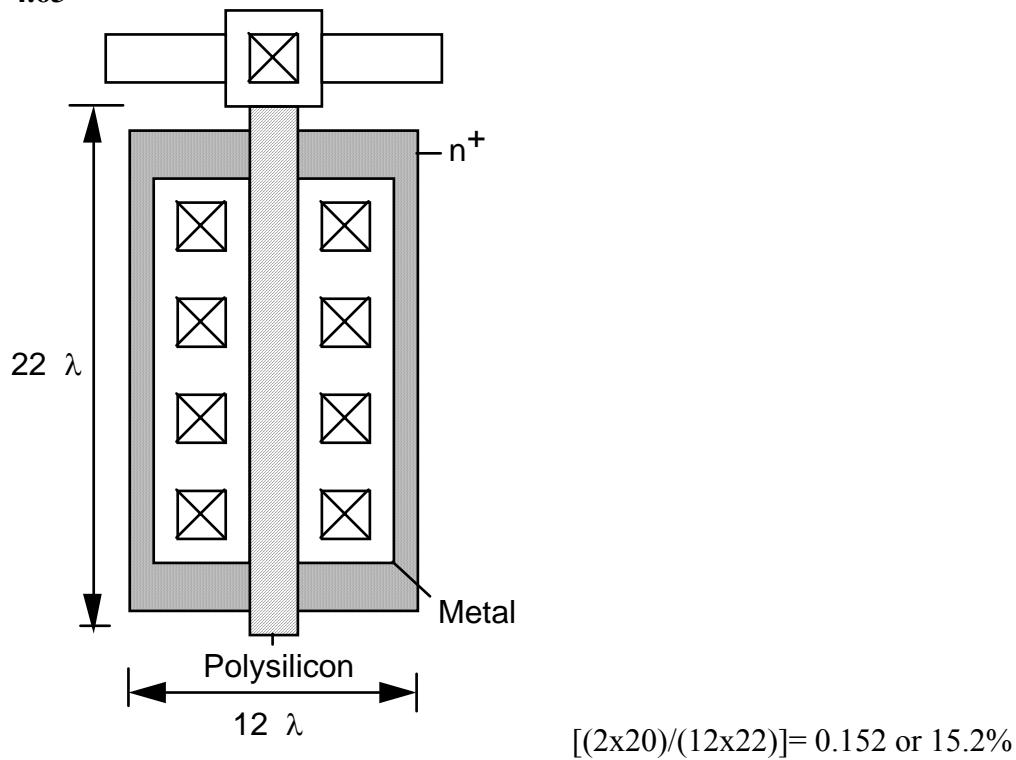
If this PMOS transistor is conducting, then its threshold voltage must be greater than zero and it is a depletion-mode device. The symbol is that of an enhancement-mode device and is incorrect.

4.60**4.61**

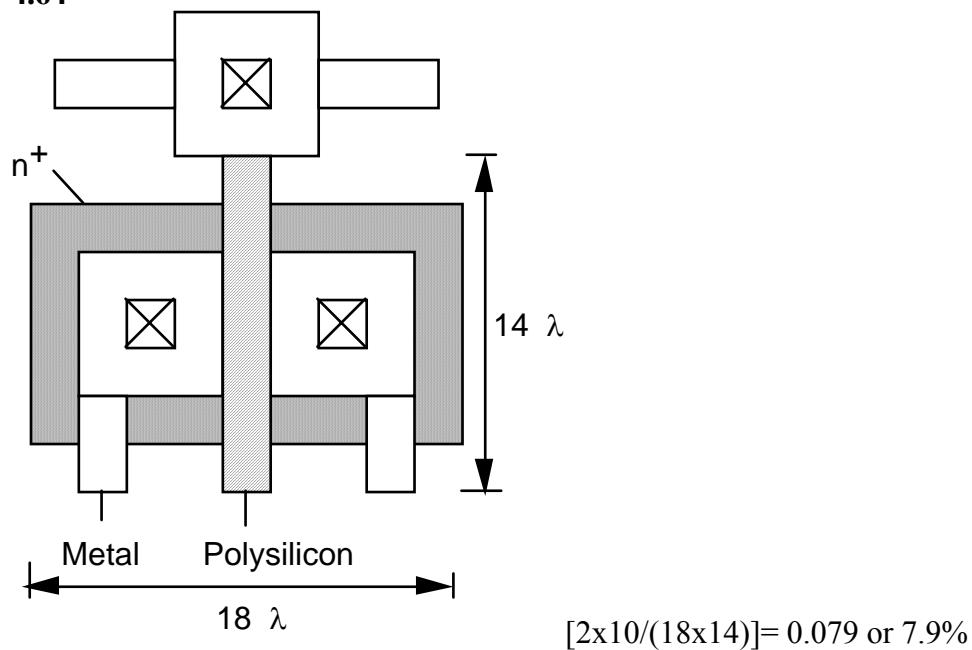
4.62



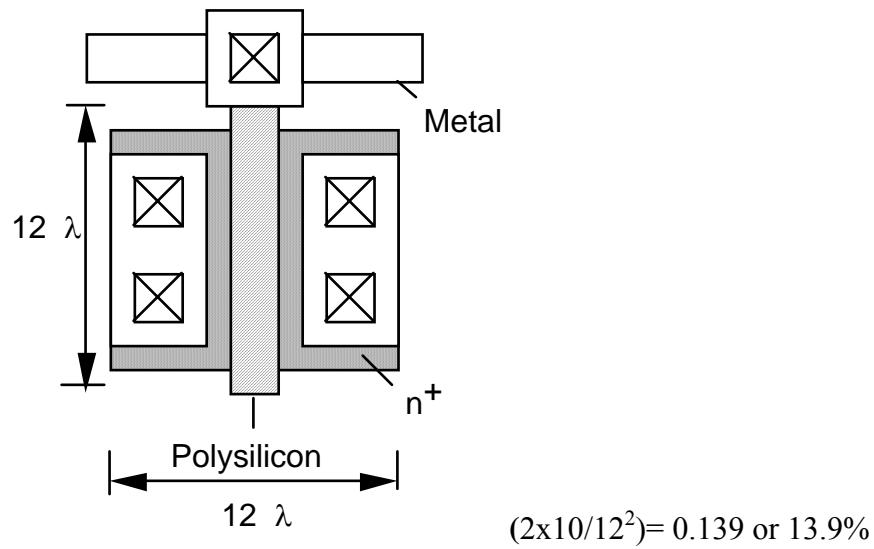
4.63



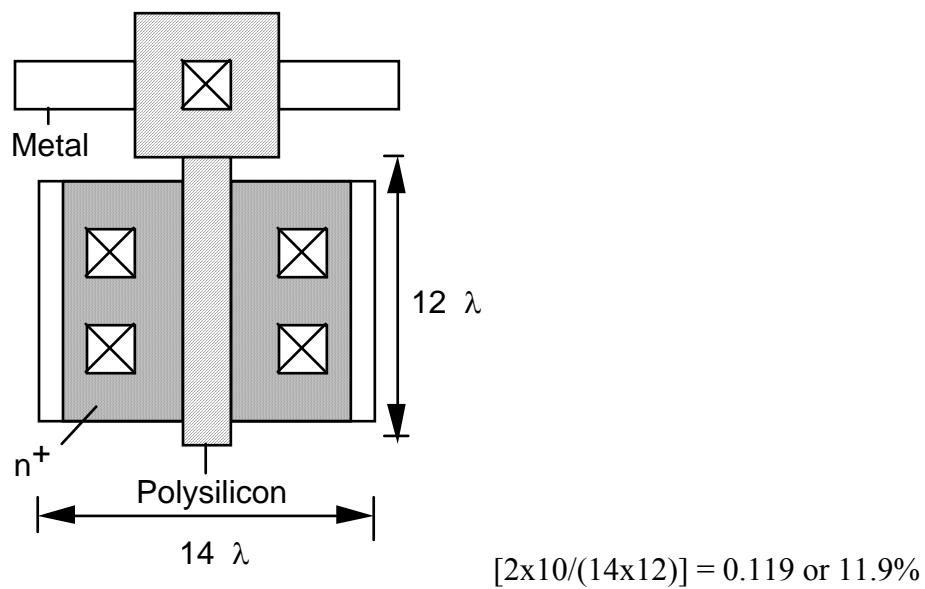
4.64



4.65



4.66



4.67

$$(a) C_{ox}'' = \frac{\varepsilon_{ox}}{T_{ox}} = \frac{(3.9) \left(8.854 \times 10^{-14} \frac{F}{cm} \right)}{5 \times 10^{-6} cm} = 6.906 \times 10^{-8} \frac{F}{cm^2}$$

$$C_{GC} = C_{ox}'' WL = \left(6.906 \times 10^{-8} \frac{F}{cm^2} \right) (20 \times 10^{-4} cm) (2 \times 10^{-4} cm) = 27.6 fF$$

$$(b) C_{ox}'' = 1.73 \times 10^{-7} \frac{F}{cm^2} \quad | \quad C_{GC} = 69.1 fF$$

$$(c) C_{ox}'' = 3.45 \times 10^{-7} \frac{F}{cm^2} \quad | \quad C_{GC} = 138 fF$$

$$(d) C_{ox}'' = 7.90 \times 10^{-7} \frac{F}{cm^2} \quad | \quad C_{GC} = 276 fF$$

4.68

$$C_{ox}'' = \frac{\varepsilon_{ox}}{T_{ox}} = \frac{(3.9) \left(8.854 \times 10^{-14} \frac{F}{cm} \right)}{1 \times 10^{-6} cm} = 3.46 \times 10^{-7} \frac{F}{cm^2}$$

$$C_{GC} = C_{ox}'' WL = \left(3.46 \times 10^{-7} \frac{F}{cm^2} \right) (5 \times 10^{-4} cm) (5 \times 10^{-5} cm) = 8.64 fF$$

4.69

$$C_{OL}' = \frac{\varepsilon_{ox}}{T_{ox}} L = \frac{(3.9) \left(8.854 \times 10^{-14} \frac{F}{cm} \right)}{10 \times 10^{-9} m \left(10^2 \frac{cm}{m} \right)} (0.5 \times 10^{-4} cm) = 17.3 \frac{pF}{cm}$$

4.70

$$(a) C_{GS} = C_{GD} = \frac{C_{ox}'' WL}{2} + C_{OL}' W = \frac{\left(1.4 \times 10^{-15} \frac{F}{\mu m^2} \right) (10 \mu m) (1 \mu m)}{2} + \left(4 \times 10^{-15} \frac{F}{\mu m} \right) (10 \mu m) = 47 fF$$

$$(b) C_{GS} = \frac{2}{3} C_{ox}'' WL + C_{OL}' W = \frac{2}{3} 14 fF + 40 fF = 49 fF$$

$$C_{GD} = C_{OL}' W = \left(4 \times 10^{-15} \frac{F}{\mu m} \right) (10 \mu m) = 40 fF$$

$$(c) C_{GS} = C_{GD} = C_{OL}' W = \left(4 \times 10^{-15} \frac{F}{\mu m} \right) (10 \mu m) = 40 fF$$

4.71

$$C_{ox}'' = \frac{\epsilon_{ox}}{T_{ox}} = \frac{(3.9) \left(8.854 \times 10^{-14} \frac{F}{cm} \right)}{100 \times 10^{-9} m \left(10^2 \frac{cm}{m} \right)} = 3.453 \times 10^{-8} \frac{F}{cm^2}$$

$$C_{GC} = C_{ox}'' WL = \left(3.453 \times 10^{-8} \frac{F}{cm^2} \right) \left(50 \times 10^6 \mu m^2 \right) \left(10^{-4} \frac{cm}{\mu m} \right)^2 = 17.3 nF$$

4.72

$$L = 2\Lambda = 1\mu m \quad | \quad W = 10L = 5\mu m \quad | \quad C_{ox}'' = \frac{\epsilon_{ox}}{T_{ox}} = \frac{3.9(8.854 \times 10^{-14} F/cm)}{150 \times 10^{-7} cm} = 0.23 fF/\mu m^2$$

Triode region :

$$C_{GS} = C_{GD} = \frac{C_{ox}'' WL}{2} + C_{GSO}W = \frac{(0.23 fF/\mu m^2)(5\mu m^2)}{2} + (0.02 fF/\mu m)(5\mu m) = 0.675 fF$$

$$\text{Saturation region : } C_{GS} = \frac{2}{3} C_{ox}'' WL + C_{GSO}W = 0.867 fF \quad | \quad C_{GS} = C_{GSO}W = 0.10 fF$$

$$Cutoff : C_{GS} = C_{GD} = C_{GSO}W = 0.10 fF$$

4.73

$$(a) C_{ox}'' = \frac{\epsilon_{ox}}{T_{ox}} = \frac{(3.9) \left(8.854 \times 10^{-14} \frac{F}{cm} \right)}{100 \times 10^{-9} m \left(10^2 \frac{cm}{m} \right)} = 3.453 \times 10^{-8} \frac{F}{cm^2}$$

$$C_{GC} = C_{ox}'' WL = \left(3.453 \times 10^{-8} \frac{F}{cm^2} \right) \left(10 \times 10^{-4} cm \right) \left(1 \times 10^{-4} cm \right) = 3.45 fF$$

$$(b) C_{GC} = C_{ox}'' WL = \left(3.453 \times 10^{-8} \frac{F}{cm^2} \right) \left(100 \times 10^{-4} cm \right) \left(1 \times 10^{-4} cm \right) = 34.5 fF$$

4.74

$$C_{SB} = C_j A_S + C_{jsw} P_S \quad | \quad C_{DB} = C_j A_D + C_{jsw} P_D \quad | \quad A_S = 50 \Lambda^2 = 12.5 \mu m^2 \quad | \quad P_S = 30 \Lambda = 15 \mu m$$

$$C_j = \frac{\varepsilon_s}{w_{do}} \quad | \quad w_{do} = \sqrt{\frac{2\varepsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_A} \right) \phi_j} \quad | \quad \phi_j = V_T \ln \left(\frac{N_A N_D}{n_i^2} \right) = 0.025 \ln \left(\frac{10^{20} 10^{16}}{10^{20}} \right) = 0.921 V$$

$$w_{do} = \sqrt{\frac{2(11.7)(8.854 \times 10^{-14})}{1.602 \times 10^{-19}} \left(\frac{1}{10^{20}} + \frac{1}{10^{16}} \right) 0.921} = 3.45 \times 10^{-5} cm$$

$$C_j = \frac{(11.7)(8.854 \times 10^{-14} F/cm)}{3.45 \times 10^{-5} cm} = 3.00 \times 10^{-8} F/cm^2$$

$$C_{SB} = (3.00 \times 10^{-8} F/cm^2)(12.5 \times 10^{-8} cm^2) + 5 \times 10^{-4} cm (3.00 \times 10^{-8} F/cm^2)(15 \times 10^{-4} cm) = 26.3 fF$$

$$C_{DB} = C_{SB} = 26.3 fF$$

4.75

$$KP = K_n' = K_n \frac{L}{W} = 175 \frac{\mu A}{V^2} \left(\frac{0.25 \mu m}{5 \mu m} \right) = 8.75 U \quad | \quad VTO = V_{TN} = 0.7$$

$$\text{PHI} = 2\phi_F = 0.8V \quad | \quad L = 0.25U \quad | \quad W = 5U \quad | \quad \text{LAMBDA} = 0.02$$

4.76

$$(a) VTO = 0.7 \quad | \quad \text{PHI} = 2\phi_F = 0.6 \quad | \quad \text{GAMMA} = 0.75$$

$$(b) VTO = 0.74 \quad | \quad \text{PHI} = 0.87 \quad | \quad \text{GAMMA} = 0.84$$

4.77

$$KP = K_n' = 50U \quad VTO = V_{TN} = 1V \quad L = 0.5U \quad W = 2.5U \quad \text{LAMBDA} = 0$$

4.78

$$KP = K_n' = 10U \quad VTO = V_{TN} = 1V \quad L = 0.6U \quad W = 1.5U \quad \text{LAMBDA} = 0$$

4.79

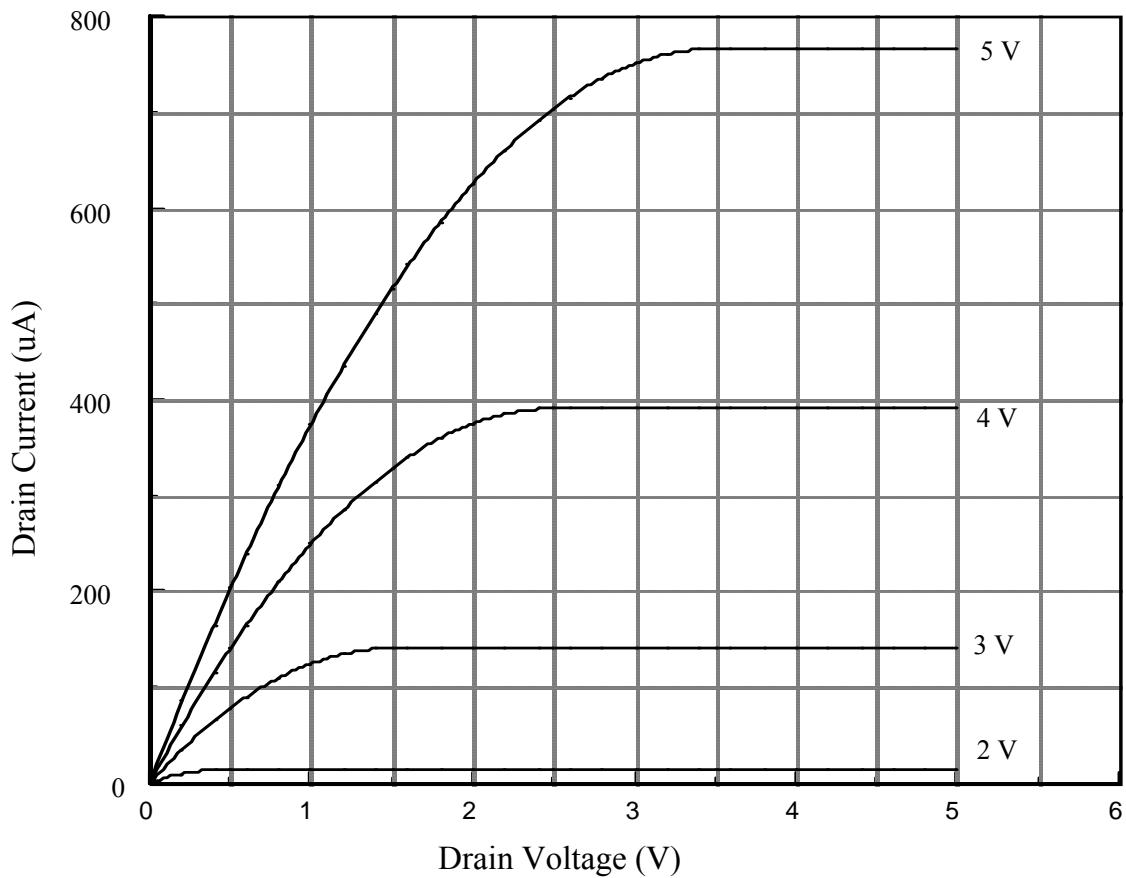
$$KP = K_p' = 10U \quad VTO = V_{TP} = -1V \quad L = 0.5U$$

$$\text{Using the } -3\text{-V curve, } K_p = 2 \frac{50 \mu A}{[-3 - (-1)]^2} = 25 \frac{\mu A}{V^2} \quad W = 1.25U \quad \text{LAMBDA} = 0$$

4.80

$$KP = K_n' = 25U \quad VTO = V_{TN} = 1V \quad L = 0.6U \quad W = 0.6U \quad \text{LAMBDA} = 0$$

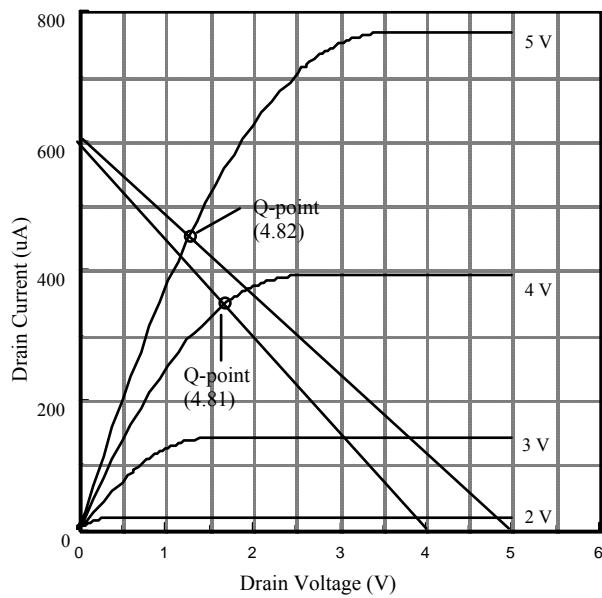
NMOS i-v Characteristics for Load-Line Problems



4.81

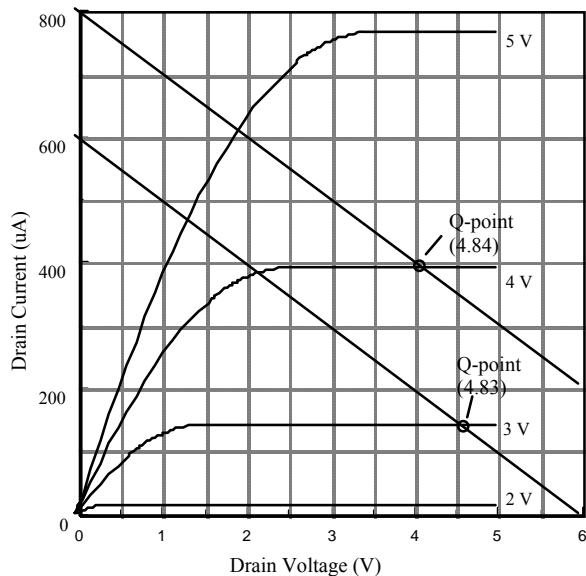
For $V_{DS} = 0$, $I_D = \frac{4V}{6.8k\Omega} = 0.588mA$. For $I_D = 0$, $V_{DS} = 4V$.

Also, $V_{GS} = 4V$. From the graph, the transistor is operating below pinchoff in the triode region and the Q-point is Q-point: (350 μA , 1.7V)

**4.82**

For $V_{DS} = 0$, $I_D = \frac{5V}{8.3k\Omega} = 0.602mA$. For $I_D = 0$, $V_{DS} = 5V$.

For $V_{GS} = 5V$, the Q-point is (450 μA , 1.25 V). From the graph in Prob. 4.81, the transistor is operating below pinchoff in the triode region.

4.83

$$V_{GS} = \frac{V_{DD}}{2} = 3V \quad | \quad 6 = 10^4 I_D + V_{DS} \quad | \quad V_{DS} = 0, I_D = 0.6mA \quad | \quad I_D = 0, V_{DS} = 6V$$

From the graph, Q-pt: (140 μA, 4.6V) in the saturation region.

4.84

$$V_{GS} = \frac{V_{DD}}{2} = 4V \quad | \quad 8 = 10^4 I_D + V_{DS} \quad | \quad V_{DS} = 6, I_D = 0.2mA \quad | \quad V_{DS} = 0, I_D = 0.8mA$$

See graph for Problem 4.83: Q-pt: (390 μA, 4.1 V) in saturation region.

4.85

$$(a) V_{GG} = \frac{100k\Omega}{100k\Omega + 220k\Omega} 12V = 3.75V \quad | \quad \text{Assume saturation}$$

$$3.75 = V_{GS} + 24 \times 10^3 I_D = V_{GS} + 24 \times 10^3 \left(\frac{100 \times 10^{-6}}{2} \right) \left(\frac{5}{1} \right) (V_{GS} - 1)^2$$

$$6V_{GS}^2 - 11V_{GS} + 2.25 = 0 \rightarrow V_{GS} = 1.599V \text{ and } I_D = 89.7\mu A$$

$$V_{DS} = 12 - 36 \times 10^3 I_D = 8.77V \quad | \quad V_{DS} > V_{GS} - V_{TN} \text{ Saturation is correct.}$$

$$\text{Checking: } V_{GG} = 24 \times 10^3 I_D + V_{GS} = 3.75V \text{ which is correct.}$$

$$Q\text{-point: } (89.7 \mu A, 8.77 V)$$

(b) Assume saturation

$$3.75 = V_{GS} + 24 \times 10^3 I_D = V_{GS} + 24 \times 10^3 \left(\frac{100 \times 10^{-6}}{2} \right) \left(\frac{10}{1} \right) (V_{GS} - 1)^2$$

$$12V_{GS}^2 - 23V_{GS} + 8.25 = 0 \rightarrow V_{GS} = 1.439V \text{ and } I_D = 96.4\mu A$$

$$V_{DS} = 12 - 36 \times 10^3 I_D = 8.53V \quad | \quad V_{DS} > V_{GS} - V_{TN} \text{ Saturation is correct.}$$

$$\text{Checking: } V_{GG} = 24 \times 10^3 I_D + V_{GS} = 3.75V \text{ which is correct.}$$

$$Q\text{-point: } (96.4 \mu A, 8.53 V)$$

4.86

$$V_{GG} = \frac{10k\Omega}{10k\Omega + 22k\Omega} 12V = 3.75V \quad | \quad \text{Assume saturation}$$

$$3.75 = V_{GS} + 2.4 \times 10^3 I_D = V_{GS} + 24 \times 10^3 \left(\frac{100 \times 10^{-6}}{2} \right) \left(\frac{20}{1} \right) (V_{GS} - 1)^2$$

$$2.4V_{GS}^2 - 3.8V_{GS} + 1.35 = 0 \rightarrow V_{GS} = 1.882V \text{ and } I_D = 778\mu A$$

$$V_{DS} = 12 - 3.6 \times 10^3 I_D = 9.20V \quad | \quad V_{DS} > V_{GS} - V_{TN} \text{ Saturation is correct.}$$

$$\text{Checking: } V_{GG} = 2.4 \times 10^3 I_D + V_{GS} = 3.75V \text{ which is correct.}$$

$$Q\text{-point: } (778 \mu A, 9.20 V)$$

4.87

$$V_{GG} = \frac{1M\Omega}{1M\Omega + 2.2M\Omega} 12V = 3.75V \quad | \text{ Assume saturation}$$

$$3.75 = V_{GS} + 2.4 \times 10^3 I_D = V_{GS} + 2.4 \times 10^3 \left(\frac{100 \times 10^{-6}}{2} \right) \left(\frac{5}{1} \right) (V_{GS} - 1)^2$$

$$60V_{GS}^2 - 119V_{GS} + 56.25 = 0 \rightarrow V_{GS} = 1.206V \text{ and } I_D = 10.6\mu A$$

$$V_{DS} = 12 - 3.6 \times 10^5 I_D = 8.18V \quad | \quad V_{DS} > V_{GS} - V_{TN} \text{ Saturation is correct.}$$

Checking: $V_{GG} = 2.4 \times 10^3 I_D + V_{GS} = 3.75V$ which is correct.

Q-point: (10.6 μA , 8.18 V)

4.88

$$(a) V_{GG} = \frac{100k\Omega}{100k\Omega + 220k\Omega} 15V = 4.69V \quad | \text{ Assume Saturation}$$

$$4.69 = V_{GS} + 24 \times 10^3 I_D = V_{GS} + 24 \times 10^3 \left(\frac{100 \times 10^{-6}}{2} \right) \left(\frac{5}{1} \right) (V_{GS} - 1)^2$$

$$6V_{GS}^2 - 11V_{GS} + 1.31 = 0 \rightarrow V_{GS} = 1.705V \text{ and } I_D = 124 \mu A$$

$$V_{DS} = 15 - 36 \times 10^3 I_D = 10.5 V \quad | \quad V_{DS} > V_{GS} - V_{TN} \text{ Saturation is correct.}$$

Checking: $V_{GG} = 24 \times 10^3 I_D + V_{GS} = 4.68V$ which is correct.

Q-point: (124 μA , 10.5 V)

$$(b) V_{GG} = 4.69V \quad | \text{ Assume Saturation}$$

$$4.69 = V_{GS} + 24 \times 10^3 I_D = V_{GS} + 24 \times 10^3 \left(\frac{100 \times 10^{-6}}{2} \right) \left(\frac{10}{1} \right) (V_{GS} - 1)^2$$

$$12V_{GS}^2 - 23V_{GS} + 7.31 = 0 \rightarrow V_{GS} = 1.514V \text{ and } I_D = 132 \mu A$$

$$V_{DS} = 15 - 36 \times 10^3 I_D = 10.3 V \quad | \quad V_{DS} > V_{GS} - V_{TN} \text{ Saturation is correct.}$$

Checking: $V_{GG} = 24 \times 10^3 I_D + V_{GS} = 4.68V$ which is correct.

Q-point: (132 μA , 10.3 V)

4.89

$$(a) V_{GG} = \frac{200k\Omega}{200k\Omega + 430k\Omega} 12V = 3.81V \quad | \text{ Assume Saturation}$$

$$3.81 = V_{GS} + 47 \times 10^3 I_D = V_{GS} + 47 \times 10^3 \left(\frac{100 \times 10^{-6}}{2} \right) \left(\frac{5}{1} \right) (V_{GS} - 1)^2$$

$$23.5V_{GS}^2 - 45V_{GS} + 15.88 = 0 \rightarrow V_{GS} = 1.448V \text{ and } I_D = 50.3 \mu A$$

$$V_{DS} = 12 - 71 \times 10^3 I_D = 8.43 V \quad | \quad V_{DS} > V_{GS} - V_{TN} \text{ Saturation is correct.}$$

Checking: $V_{GG} = 47 \times 10^3 I_D + V_{GS} = 3.81V$ which is correct.

Q-point: (50.3 μA , 8.43 V)

(b) $V_{GS} = 3.81V$ | Assume Saturation

$$3.81 = V_{GS} + 47 \times 10^3 I_D = V_{GS} + 47 \times 10^3 \left(\frac{100 \times 10^{-6}}{2} \right) \left(\frac{15}{1} \right) (V_{GS} - 1)^2$$

$$70.5V_{GS}^2 - 139V_{GS} + 62.88 = 0 \rightarrow V_{GS} = 1.269V \text{ and } I_D = 54.3 \mu A$$

$$V_{DS} = 12 - 71 \times 10^3 I_D = 8.15 V \mid V_{DS} > V_{GS} - V_{TN} \text{ Saturation is correct.}$$

Checking: $V_{GS} = 47 \times 10^3 I_D + V_{GS} = 3.82V$ which is correct.

Q-point: (54.3 μA , 8.15 V)

4.90

(a) Setting KP = 500U, VTO = 1, and GAMMA = 0 yields $I_D = 89.6 \mu A$, $V_{GS} = 1.60 V$ and $V_{DS} = 8.77 V$

(a) Setting KP = 1000U, VTO = 1, and GAMMA = 0 yields $I_D = 96.3 \mu A$, $V_{GS} = 1.44 V$ and $V_{DS} = 8.53 V$

4.91

(a) Setting KP = 500U, VTO = 1, and GAMMA = 0 yields $I_D = 124 \mu A$, $V_{GS} = 1.71 V$ and $V_{DS} = 10.5 V$

(a) Setting KP = 1000U, VTO = 1, and GAMMA = 0 yields $I_D = 132 \mu A$, $V_{GS} = 1.51 V$ and $V_{DS} = 10.2 V$

4.92

(a) Setting KP = 500U, VTO = 1, and GAMMA = 0 yields $I_D = 50.2 \mu A$, $V_{GS} = 1.45 V$ and $V_{DS} = 8.43 V$

(a) Setting KP = 1000U, VTO = 1, and GAMMA = 0 yields $I_D = 54.1 \mu A$, $V_{GS} = 1.27 V$ and $V_{DS} = 8.16 V$

4.93

(300 $k\Omega$, 700 $k\Omega$) or (1.2 $M\Omega$, 2.8 $M\Omega$). We normally desire the current in the gate bias network to be much less than I_D . We also usually like the parallel combination of R_1 and R_2 to be as large as possible.

4.94

(a) $I_D = \frac{35 \times 10^{-6}}{2} (4 - 1 - 1700I_D)^2$ and using the quadratic equation,

$$I_D = 134 \mu A. \quad V_{DS} = 10 - 134 \times 10^{-6} (1700 + 38300) = 4.64V$$

(b) $I_D = \frac{25 \times 10^{-6}}{2} (4 - 0.75 - 1700I_D)^2$ and using the quadratic equation,

$$I_D = 116 \mu A. \quad V_{DS} = 10 - 116 \times 10^{-6} (1700 + 38300) = 5.36V$$

4.95

(a) Example 4.3

Setting KP = 25U and VTO = 1 yields $I_D = 34.4 \mu A$, $V_{GS} = 2.66 V$ and $V_{DS} = 6.08 V$ \checkmark
Results agree with hand calculations

(b) Example 4.4

Setting KP = 25U and VTO = 1 yields $I_D = 99.2 \mu A$, $V_{GS} = 3.82 V$ and $V_{DS} = 6.03 V$ \checkmark
Results are almost identical to hand calculations

4.96

$$K_n' = 100 \mu A/V^2 \quad | \quad V_{TN} = 0.75V \quad | \quad \text{Choose } V_{DS} = V_{R_D} = V_{R_S} = 4V \text{ and } V_{GS} - V_{TN} = 1V$$

$$R_S = \frac{4}{100 \mu A} = 40 k\Omega \Rightarrow 39 k\Omega \text{ and } V_{R_S} = 3.9V \quad | \quad R_D = \frac{4.1}{100 \mu A} = 41 k\Omega \Rightarrow 43 k\Omega$$

$$V_{GS} - V_{TN} = \sqrt{\frac{2I_D}{K_n}} = 1V \quad \text{and} \quad K_n = \frac{2I_D}{1V^2} = 200 \mu A/V^2 \Rightarrow \frac{W}{L} = \frac{2}{1} \quad |$$

$$V_G = V_S + V_{GS} = 3.9 + 1 + 0.75 = 5.65V$$

$$5.65V = \frac{R_1}{R_1 + R_2} 12V \quad | \quad 5.65V = \frac{R_1 R_2}{R_1 + R_2} \left(\frac{12V}{R_2} \right) \quad | \quad R_2 = 250 k\Omega \left(\frac{12V}{5.65V} \right) = 530 k\Omega \Rightarrow 560 k\Omega$$

$$5.65V = \frac{R_1}{R_1 + 560 k\Omega} 12V \Rightarrow R_1 = 500 k\Omega \Rightarrow 510 k\Omega$$

$$R_1 = 510 k\Omega, R_2 = 560 k\Omega, R_S = 39 k\Omega, R_D = 43 k\Omega, \frac{W}{L} = \frac{2}{1}$$

4.97

$$K_n' = 100 \mu A/V^2 \quad | \quad V_{TN} = 0.75V \quad | \quad \text{Choose } V_{DS} = V_{R_D} = V_{R_S} = 3V \text{ and } V_{GS} - V_{TN} = 1V$$

$$R_S = \frac{3}{0.25mA} = 12 k\Omega \quad | \quad R_D = \frac{3}{0.25mA} = 12 k\Omega$$

$$V_{GS} - V_{TN} = \sqrt{\frac{2I_D}{K_n}} = 1V \quad \text{and} \quad K_n = \frac{2I_D}{1V^2} = 500 \mu A/V^2 \Rightarrow \frac{W}{L} = \frac{5}{1}$$

$$V_G = V_S + V_{GS} = 3 + 1 + 0.75 = 4.75V$$

$$4.75V = \frac{R_1}{R_1 + R_2} 9V \quad | \quad 4.75V = \frac{R_1 R_2}{R_1 + R_2} \left(\frac{9V}{R_2} \right) \quad | \quad R_2 = 250 k\Omega \left(\frac{9V}{4.75V} \right) = 473 k\Omega \Rightarrow 470 k\Omega$$

$$4.75V = \frac{R_1}{R_1 + 470 k\Omega} 9V \Rightarrow R_1 = 525 k\Omega \Rightarrow 510 k\Omega$$

$$R_1 = 510 k\Omega, R_2 = 470 k\Omega, R_S = 12 k\Omega, R_D = 12 k\Omega, \frac{W}{L} = \frac{5}{1}$$

4.98

$K_n = 100 \mu A/V^2$ | $V_{TN} = 0.75V$ | Choose $V_{DS} = V_{R_D} = V_{R_S} = 5V$ and $V_{GS} - V_{TN} = 1V$

$$R_S = \frac{5}{0.5mA} = 10k\Omega \quad | \quad R_D = \frac{5}{0.5mA} = 10k\Omega$$

$$V_{GS} - V_{TN} = \sqrt{\frac{2I_D}{K_n}} = 1V \quad \text{and} \quad K_n = \frac{2I_D}{1V^2} = 1mA/V^2 \Rightarrow \frac{W}{L} = \frac{10}{1}$$

$$V_G = V_S + V_{GS} = 5 + 1 + 0.75 = 6.75V$$

$$6.75V = \frac{R_1}{R_1 + R_2} 15V \quad | \quad 6.75V = \frac{R_1 R_2}{R_1 + R_2} \left(\frac{15V}{R_2} \right) \quad | \quad R_2 = 600k\Omega \left(\frac{15V}{6.75V} \right) = 1.33M\Omega \Rightarrow 1.5M\Omega$$

$$6.75V = \frac{R_1}{R_1 + 1.5M\Omega} 15V \Rightarrow R_1 = 1.23M\Omega \Rightarrow 1.2M\Omega$$

$$R_1 = 1.2M\Omega, R_2 = 1.5M\Omega, R_S = 10k\Omega, R_D = 10k\Omega, \frac{W}{L} = \frac{10}{1}$$

4.99

Assume Saturation. For $I_G = 0$, $V_{GS} = -10^4 I_D = -10^4 \left(\frac{10^{-3}}{2} \right) (V_{GS} + 5)^2$

$$5V_{GS}^2 + 51V_{GS} + 125 = 0 \Rightarrow V_{GS} = -4.10V \text{ and } I_D = 410 \mu A$$

$$V_{DS} = 15 - 15000I_D = 8.85V \quad | \quad V_{DS} > V_{GS} - V_{TN} \text{ so saturation is ok.}$$

Q - Point : (410 μA , 8.85V)

4.100

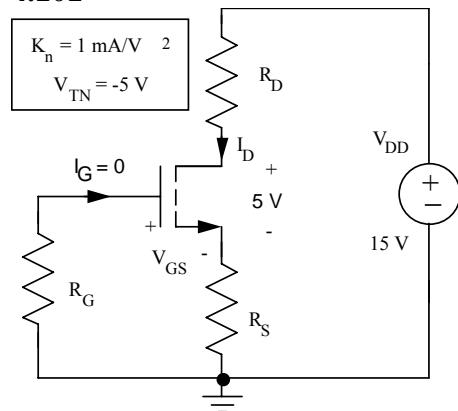
Assume Saturation. For $I_G = 0$, $V_{GS} = -27 \times 10^3 I_D = -27 \times 10^4 \left(\frac{6 \times 10^{-4}}{2} \right) (V_{GS} + 4)^2$

$$8.1V_{GS}^2 + 65.8V_{GS} + 129.6 = 0 \Rightarrow V_{GS} = -3.36V \text{ and } I_D = 124 \mu A$$

$$V_{DS} = 12 - 78000I_D = 2.36V \quad | \quad V_{DS} > V_{GS} - V_{TN} \text{ so saturation is ok.}$$

Q - Point : (124 μA , 2.36V)

4.101



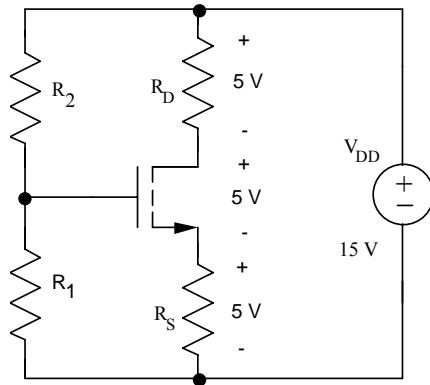
Assume Saturation. $I_G = 0$. $250\mu A = \left(\frac{1mA/V^2}{2}\right)(V_{GS} + 5)^2$

$$V_{GS} = -5 + \sqrt{\frac{0.25mA}{0.5mA}} = -4.29V \quad | \quad R_s = \frac{4.29V}{0.25mA} = 17.2k\Omega \Rightarrow 18k\Omega$$

$$V_{DS} = 15 - I_D(R_D + R_s) \Rightarrow R_D = \frac{15 - 5 - 4.29}{0.25} \frac{V}{mA} = 22.88k\Omega \Rightarrow 24k\Omega$$

R_G is arbitrary but normally fairly large. Choose $R_G = 510 k\Omega$.

4.102



Assume Saturation. $I_G = 0$. Assume power supply is split in thirds: $V_{DS} = V_{R_D} = V_{R_S} = 5V$

Note that although, this is a depletion-mode device, I_D exceeds $\frac{K_n}{2} V_{TN}^2$ and this will require $V_{GS} > 0$.

$$R_s = \frac{5V}{2mA} = 2.5k\Omega \Rightarrow 2.4k\Omega \text{ and } V_{R_s} \text{ will be } 4.8V \quad | \quad 2mA = \left(\frac{0.25mA/V^2}{2}\right)(V_{GS} + 2)^2$$

$$V_{GS} = -2 + \sqrt{\frac{2mA}{0.125mA}} = +2.00V \quad | \quad V_G = V_S + V_{GS} = 4.8 + 2 = 6.8V$$

$$6.8 = 15 \frac{R_1}{R_1 + R_2} \Rightarrow R_1 = 680 k\Omega \text{ and } R_2 = 820 k\Omega \text{ is one convenient possibility.}$$

Another is $R_1 = 68 k\Omega$ and $R_2 = 82 k\Omega$. Both choices have $I_{R_2} \ll I_D$.

$$R_D = \frac{(15 - 5 - 4.8)V}{2mA} = 2.60k\Omega \Rightarrow 2.70 k\Omega$$

4.103

(a) The transistor is saturated by connection.

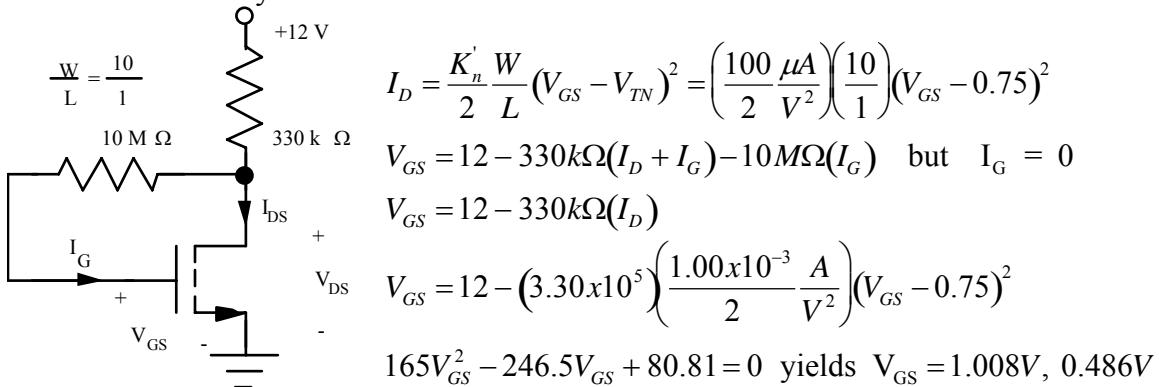
$$V_{GS} = 12 - 10^5 I_D \quad \text{and} \quad I_D = \frac{100 \times 10^{-6}}{2} \left(\frac{10}{1} \right) \left(\frac{A}{V^2} \right) (V_{GS} - 0.75V)^2$$

$50V_{GS}^2 - 74V_{GS} + 16.13 = 0 \Rightarrow V_{GS} = 1.214V, -0.266V \Rightarrow V_{GS} = 1.214V$ since V_{GS} must

exceed the threshold voltage. | $I_D = \frac{100 \times 10^{-6}}{2} \left(\frac{10}{1} \right) \left(\frac{A}{V^2} \right) (1.214 - 0.75V)^2$

$$I_D = 104 \mu A \quad | \quad \text{Checking: } I_D = \frac{12 - 1.21}{10^5} = 108 \mu A \quad | \quad \text{Q-Point: } (108 \mu A, 1.21 V)$$

(b) Using KVL, $V_{DS} = 10^7 I_G + V_{GS}$. But, since $I_G = 0$, $V_{GS} = V_{DS}$. Also $V_{TN} = 0.75 V > 0$, so the transistor is saturated by connection.



V_{GS} must be 1.008 V since 0.486 V is below threshold.

$$I_D = \left(\frac{100 \mu A}{2} \right) \frac{10}{1} (1.008 - 0.75)^2 = 33.3 \mu A \quad \text{and} \quad V_{DS} = V_{GS}$$

Q-Point: (33.3 μA, 1.01 V) Checking: $I_D = (12 - 1.01)V/330k\Omega = 33.3 \mu A$. \checkmark

4.104

(a) The transistor is saturated by connection.

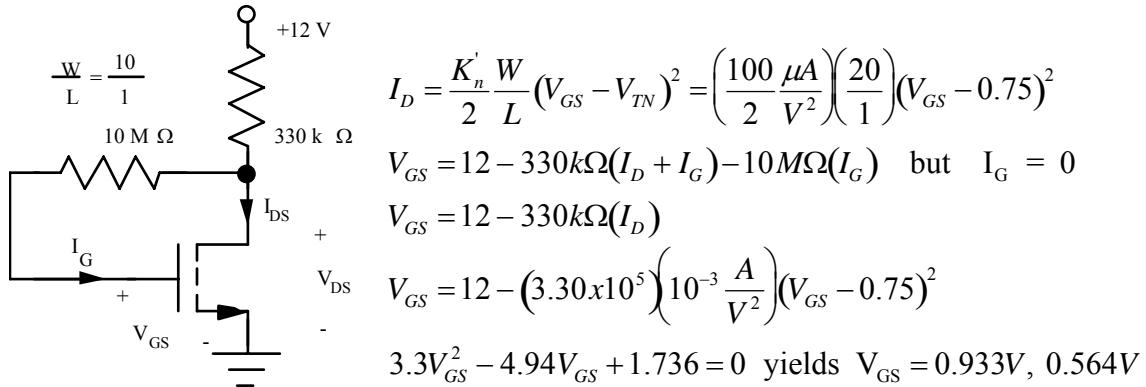
$$V_{GS} = 12 - 10^5 I_D \quad \text{and} \quad I_D = \frac{100 \times 10^{-6}}{2} \left(\frac{20}{1} \right) \left(\frac{A}{V^2} \right) (V_{GS} - 0.75V)^2$$

$100V_{GS}^2 - 149V_{GS} + 44.25 = 0 \Rightarrow V_{GS} = 1.08V, 0.410V \Rightarrow V_{GS} = 1.08V$ since V_{GS} must

exceed the threshold voltage. $I_D = \frac{100 \times 10^{-6}}{2} \left(\frac{20}{1} \right) \left(\frac{A}{V^2} \right) (1.08 - 0.75V)^2 = 109 \mu A$

$$\text{Checking: } I_D = \frac{12 - 1.08}{10^5} = 109 \mu A \quad | \quad \text{Q-Point: } (109 \mu A, 1.08 V)$$

(b) Using KVL, $V_{DS} = 10^7 I_G + V_{GS}$. But, since $I_G = 0$, $V_{GS} = V_{DS}$. Also $V_{TN} = 0.75 V > 0$, so the transistor is saturated by connection.



V_{GS} must be 0.933 V since 0.564 V is below threshold.

$$I_D = \left(\frac{100 \mu A}{2 V^2}\right) \left(\frac{20}{1}\right) (0.933 - 0.75)^2 = 33.5 \mu A \quad \text{Checking: } \frac{12 - 0.933}{330k\Omega} V = 33.5 \mu A$$

and $V_{DS} = V_{GS}$: Q-Point: (33.5 μA, 0.933 V)

4.105

$$(a) \text{ Assume saturation: } I_D = \frac{K_n' W}{2 L} (V_{GS} - V_{TN})^2 = \left(\frac{100 \mu A}{2 V^2}\right) \left(\frac{10}{1}\right) (V_{GS} - 0.75)^2$$

$$V_{GS} = 15 - 330k\Omega(I_D + I_G) - 10M\Omega(I_G) \quad \text{but } I_G = 0$$

$V_{GS} = 15 - 330k\Omega(I_D)$ and $V_{GS} = V_{DS}$ so saturation region operation is correct

$$V_{GS} = 15 - (3.30 \times 10^5) \left(\frac{10^{-3}}{2} \frac{A}{V^2}\right) (V_{GS} - 0.75)^2$$

$$3.30V_{GS}^2 - 4.93V_{GS} + 1.556 = 0 \quad \text{yields } V_{GS} = 1.041V, 0.453V$$

$$I_D = \left(\frac{100 \mu A}{2 V^2}\right) \left(\frac{10}{1}\right) (1.041 - 0.75)^2 = 42.3 \mu A \quad \text{Checking: } I_D = \frac{15 - 1.041}{330k\Omega} V = 42.3 \mu A$$

Q-Point: (42.3 μA, 1.04 V)

(b) Assume saturation

$$I_D = \frac{K_n' W}{2 L} (V_{GS} - V_{TN})^2 = \left(\frac{100 \mu A}{2 V^2}\right) \left(\frac{25}{1}\right) (V_{GS} - 0.75)^2$$

$$V_{GS} = 15 - 330k\Omega(I_D + I_G) - 10M\Omega(I_G) \quad \text{but } I_G = 0$$

$V_{GS} = 15 - 330k\Omega(I_D)$ and $V_{GS} = V_{DS}$ so saturation region operation is correct.

$$V_{GS} = 15 - (3.30 \times 10^5) \left(\frac{2.50 \times 10^{-3}}{2} \frac{A}{V^2}\right) (V_{GS} - 0.75)^2$$

$$8.25V_{GS}^2 - 12.355V_{GS} + 4.341 = 0 \quad \text{yields } V_{GS} = 0.9345V, 0.563V$$

$$I_D = \left(\frac{100 \mu A}{2 V^2}\right) \left(\frac{25}{1}\right) (0.9345 - 0.75)^2 = 42.6 \mu A \quad \text{Checking: } I_D = \frac{15 - 0.9345}{330k\Omega} V = 42.6 \mu A$$

Q-Point: (42.6 μA, 0.935 V)

4.106

(a) Assume saturation $I_D = \frac{K_n}{2} \frac{W}{L} (V_{GS} - V_{TN})^2 = \left(\frac{100 \mu A}{2 V^2}\right) \left(\frac{10}{1}\right) (V_{GS} - 0.75)^2$

$$V_{GS} = 12 - 470k\Omega(I_D + I_G) - 10M\Omega(I_G) \quad \text{but } I_G = 0$$

$V_{GS} = 12 - 470k\Omega(I_D)$ and $V_{GS} = V_{DS}$ so saturation region operation is correct.

$$V_{GS} = 12 - \left(4.70 \times 10^5\right) \left(\frac{10^{-3}}{2} \frac{A}{V^2}\right) (V_{GS} - 0.75)^2$$

$$4.70V_{GS}^2 - 7.03V_{GS} + 2.404 = 0 \quad \text{yields } V_{GS} = 0.9666V, 0.529V$$

$$I_D = \left(\frac{100 \mu A}{2 V^2}\right) \left(\frac{10}{1}\right) (0.9666 - 0.75)^2 = 23.5 \mu A \quad | \quad \text{Checking: } I_D = \frac{12 - 0.967}{470k\Omega} = 23.5 \mu A$$

Q - Point : (23.5 μA , 0.967 V)

(b) Since the current in R_G is zero, the drain current is independent of R_G .

4.107

(a) Create an M-file:

```
function f=bias(id)
vtn=1+0.5*(sqrt(22e3*id)-sqrt(0.6));
f=id-(25e-6/2)*(6-22e3*id-vtn)^2;
fzero('bias',1e-4) yields ans = 8.8043e-05
```

(b) Modify the M-file:

```
function f=bias(id)
vtn=1+0.75*(sqrt(22e3*id)-sqrt(0.6));
f=id-(25e-6/2)*(6-22e3*id-vtn)^2;
fzero('bias',1e-4) yields ans = 8.3233e-05
```

4.108

Using a spreadsheet similar to Table 4.2 yields: (a) 88.04 μA , (b) 83.23 μA .

4.109

$$V_{GG} = \frac{100k\Omega}{100k\Omega + 220k\Omega} 12V = 3.75V \quad | \quad \text{Assume saturation}$$

$$V_{TN} = 1 + 0.6 \left(\sqrt{24 \times 10^3 I_D + 0.6} - \sqrt{0.6} \right) \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{5 \times 10^{-4}}}$$

$$I_D = \frac{3.75 - V_{GS}}{24k\Omega} \quad | \quad \text{Solving iteratively yields } I_D = 73.1 \mu A \text{ with } V_{TN} = 1.460V$$

$V = 12V - I_D(24k\Omega + 12k\Omega) = 9.37 V$ Transistor is saturated. Q - Point : (73.1 μA , 9.37 V)

4.110

$$V_{GG} = \frac{100k\Omega}{100k\Omega + 220k\Omega} 12V = 3.75V \quad | \text{ Assume saturation}$$

$$(a) V_{TN} = 1 + 0.75 \left(\sqrt{24 \times 10^3 I_D + 0.6} - \sqrt{0.6} \right) \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{5 \times 10^{-4}}}$$

$$I_D = \frac{3.75 - V_{GS}}{24k\Omega} \quad | \quad \text{Solving iteratively yields } I_D = 69.7 \mu A \text{ with } V_{TN} = 1.550V$$

$V_{DS} = 12V - I_D(24k\Omega + 12k\Omega) = 9.49 V$ The transistor is saturated. Q-Point : (69.7 μA , 9.49 V)

$$(b) V_{TN} = 1 + 0.6 \left(\sqrt{24 \times 10^3 I_D + 0.6} - \sqrt{0.6} \right) \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{5 \times 10^{-4}}}$$

$$I_D = \frac{3.75 - V_{GS}}{24k\Omega} \quad | \quad \text{Solving iteratively yields } I_D = 73.1 \mu A \text{ with } V_{TN} = 1.460V$$

$V = 12V - I_D(24k\Omega + 24k\Omega) = 8.49 V$ The transistor is saturated. Q-Point : (73.1 μA , 8.49 V)

4.111

(a) $\gamma = 0.6 \quad V_{TN} = 1.46 V \quad I_D = 73.1 \mu A \quad V_{DS} = 9.37 V$

(b) $\gamma = 0.75 \quad V_{TN} = 1.55 V \quad I_D = 69.7 \mu A \quad V_{DS} = 9.49 V$

(c) $\gamma = 0.6 \quad V_{TN} = 1.46 V \quad I_D = 73.1 \mu A \quad V_{DS} = 8.49 V$

These results all agree with the hand calculations.

(They should - they are all solving the same sets of equations.)

4.112

(a) $\gamma = 0 \quad V_{TN} = 1.00 V \quad I_D = 50.2 \mu A \quad V_{DS} = 8.43 V$

$\gamma = 0.5 \quad V_{TN} = 1.42 V \quad I_D = 42.2 \mu A \quad V_{DS} = 9.01 V$

(b) $\gamma = 0 \quad V_{TN} = 1.00 V \quad I_D = 54.1 \mu A \quad V_{DS} = 8.16 V$

$\gamma = 0.5 \quad V_{TN} = 1.44 V \quad I_D = 45.2 \mu A \quad V_{DS} = 8.79 V$

The $\gamma = 0$ values agree with the hand calculations in the original problem. Including body effect in the simulations reduces the Q-point current by approximately 15%. Although this may sound large, it is within the error that will be introduced by the use of 5% resistors and typical device tolerances. So, we normally omit γ in our hand calculations, and then refine the results using SPICE.

4.113

(a) $\gamma = 0 \quad V_{TN} = 1.00 V \quad I_D = 89.6 \mu A \quad V_{DS} = 8.77 V$

$\gamma = 0.5 \quad V_{TN} = 1.39 V \quad I_D = 75.5 \mu A \quad V_{DS} = 9.28 V$

(b) $\gamma = 0 \quad V_{TN} = 1.00 V \quad I_D = 96.3 \mu A \quad V_{DS} = 8.53 V$

$\gamma = 0.5 \quad V_{TN} = 1.41 V \quad I_D = 80.8 \mu A \quad V_{DS} = 9.09 V$

The $\gamma = 0$ values agree with the hand calculations in the original problem. Including body effect in the simulations reduces the Q-point current by approximately 15%. Although this may sound

large, it is within the error that will be introduced by the use of 5% resistors and typical device tolerances. So, we normally omit γ in our hand calculations, and then refine the results using SPICE.

4.114

$$\gamma=0 \quad V_{TN} = 1.00 \text{ V} \quad I_D = 778 \text{ } \mu\text{A} \quad V_{DS} = 9.20 \text{ V}$$

$$\gamma=0.5 \quad V_{TN} = 1.35 \text{ V} \quad I_D = 661 \text{ } \mu\text{A} \quad V_{DS} = 9.62 \text{ V}$$

The $\gamma = 0$ values agree with the hand calculations in the original problem. Including body effect in the simulations reduces the Q-point current by approximately 15%. Although this may sound large, it is within the error that will be introduced by the use of 5% resistors and typical device tolerances. So, we normally omit γ in our hand calculations, and then refine the results using SPICE.

4.115

$$\gamma=0 \quad V_{TN} = 1.00 \text{ V} \quad I_D = 10.5 \text{ } \mu\text{A} \quad V_{DS} = 8.03 \text{ V}$$

$$\gamma=0.5 \quad V_{TN} = 1.45 \text{ V} \quad I_D = 9.18 \text{ } \mu\text{A} \quad V_{DS} = 8.69 \text{ V}$$

The $\gamma = 0$ values agree with the hand calculations in the original problem. Including body effect in the simulations reduces the Q-point current by approximately 15%. Although this may sound large, it is within the error that will be introduced by the use of 5% resistors and typical device tolerances. So, we normally omit γ in our hand calculations, and then refine the results using SPICE.

4.116

(a) Both transistors are saturated by connection and the two drain currents must be equal.

$$I_{D1} = \frac{K_{n1}}{2} (V_{GS1} - V_{TN1})^2 \quad \text{and} \quad I_{D2} = \frac{K_{n2}}{2} (V_{GS2} - V_{TN2})^2$$

But since the transistors are identical, $I_{D1} = I_{D2}$ requires $V_{GS1} = V_{GS2} = V_{DD}/2 = 2.5\text{V}$.

$$I_{D1} = I_{D2} = \frac{100 \times 10^{-6}}{2} \left(\frac{20}{1} \right) (2.5 - 1)^2 = 2.25 \text{ mA}$$

(b) For this case, the same arguments hold, and $V_{GS1} = V_{GS2} = V_{DD}/2 = 5\text{V}$.

$$I_{D1} = I_{D2} = \frac{100 \times 10^{-6}}{2} \left(\frac{20}{1} \right) (5 - 1)^2 = 16.0 \text{ mA}$$

(c) For this case, the threshold voltages will be different due to the body-effect in the upper transistor. The drain currents must be the same, but the gate-source voltages will be different:

$$V_{GS1} = V_{TN1} + \sqrt{\frac{2I_D}{K_n}} ; \quad V_{GS2} = V_{TN2} + \sqrt{\frac{2I_D}{K_n}} ; \quad V_{GS1} + V_{GS2} = 5\text{V}.$$

$$V_{TN1} = 1\text{V} \quad V_{TN2} = 1 + 0.5 \left(\sqrt{V_{GS1} + 0.6} - \sqrt{0.6} \right)$$

Combining these equations yields

$$5 - 2V_{GS1} - 0.5(\sqrt{V_{GS1} + 0.6} - \sqrt{0.6}) = 0 \Rightarrow V_{GS1} = 2.27V; V_{GS2} = 5 - V_{GS1} = 2.73V$$

$$I_{D2} = I_{D1} = \frac{100 \times 10^{-6}}{2} \left(\frac{20}{1} \right) (2.27 - 1)^2 = 1.61 \text{ mA.}$$

$$\text{Checking: } V_{TN2} = 1 + 0.5(\sqrt{2.27 + 0.6} - \sqrt{0.6}) = 1.46V$$

$$I_{D2} = \frac{100 \times 10^{-6}}{2} \left(\frac{20}{1} \right) (2.73 - 1.46)^2 = 1.61 \text{ mA.}$$

4.117

If we assume saturation, we find $I_D = 234 \mu\text{A}$ and $V_{DS} = 0.65 \text{ V}$, and the transistor is not saturated. Assuming triode region operation,

$$V_{GS} = 10 - 2 \times 10^4 I_D \quad | \quad V_{DS} = 10 - 4 \times 10^4 I_D$$

$$I_D = 100 \frac{\mu\text{A}}{V^2} \left(\frac{2}{1} \right) \left(10 - 2 \times 10^4 I_D - 1 - \frac{10 - 4 \times 10^4 I_D}{2} \right) (10 - 4 \times 10^4 I_D)$$

$$\text{Collecting terms: } 16.5 \times 10^4 I_D = 40 \rightarrow I_D = 242 \mu\text{A}$$

$$V_{DS} = 10 - 4 \times 10^4 (2.42 \times 10^{-4}) = 0.320V \quad | \quad \text{Q-Pt: } (242 \mu\text{A}, 0.320V)$$

$$\text{Checking the operating region: } V_{GS} - V_{TN} = 4.16V > V_{DS}$$

$$\text{and the triode region assumption is correct. Checking: } I_D = \frac{10 - 0.32}{40k\Omega} V = 242 \mu\text{A}$$

4.118

If we assume saturation, we find an inconsistent answer. Assuming triode region operation,

$$V_{GS} = 10 - 2 \times 10^4 I_D \quad | \quad V_{DS} = 10 - 3 \times 10^4 I_D$$

$$I_D = 100 \frac{\mu\text{A}}{V^2} \left(\frac{4}{1} \right) \left(10 - 2 \times 10^4 I_D - 1 - \frac{10 - 3 \times 10^4 I_D}{2} \right) (10 - 3 \times 10^4 I_D)$$

$$\text{Collecting terms: } 1.5 \times 10^8 I_D^2 - 1.725 \times 10^5 I_D + 40 = 0 \rightarrow I_D = 322 \mu\text{A}$$

$$V_{DS} = 10 - 3 \times 10^4 (3.22 \times 10^{-4}) = 0.340V \quad | \quad \text{Q-Pt: } (322 \mu\text{A}, 0.340V)$$

$$\text{Checking the operating region: } V_{GS} - V_{TN} = 2.56V > V_{DS}$$

$$\text{and the triode region assumption is correct. Checking: } I_D = \frac{10 - 0.34}{30k\Omega} V = 322 \mu\text{A}$$

4.119

For (a) and (b), $\gamma = 0$. The transistor parameters are identical so $3V_{GS} = 15V$ or $V_{GS} = 5V$.

$$(a) I_D = \frac{1}{2} \left(100 \times 10^{-6} \right) \left(\frac{20}{1} \right) (5 - 0.75)^2 = 18.1 \text{ mA}$$

$$(b) I_D = \frac{1}{2} \left(100 \times 10^{-6} \right) \left(\frac{50}{1} \right) (5 - 0.75)^2 = 45.2 \text{ mA}$$

(c) Now we have three different threshold voltages and need an iterative solution. Using MATLAB:

```
function f=Prob112(id)
gamma=0.5;
vgs1=.75+sqrt(2*id/2e-3);
vtn2=0.75+gamma*(sqrt(vgs1+0.6)-sqrt(0.6));
vgs2=vtn2+sqrt(2*id/2e-3);
vtn3=0.75+gamma*(sqrt(vgs1+vgs2+0.6)-sqrt(0.6));
vgs3=vtn3+sqrt(2*id/2e-3);
f=15-vgs1-vgs2-vgs3;
fzero('Prob112',1e-4) --> ans = 0.0130      ID = 13.0 mA
```

4.120

$$(a) \gamma = 0 \quad \frac{W}{L} = \frac{20}{1} \quad V_{TN} = 0.75 \text{ V} \quad I_D = 18.1 \text{ mA} \quad V_{DS} = 5.00 \text{ V}$$

$$(b) \gamma = 0 \quad \frac{W}{L} = \frac{50}{1} \quad V_{TN} = 0.75 \text{ V} \quad I_D = 45.2 \text{ mA} \quad V_{DS} = 5.00 \text{ V}$$

$$(b) \gamma = 0.5 \quad \frac{W}{L} = \frac{20}{1} \quad V_{TN3} = 1.95 \text{ V} \quad I_{D3} = 13.0 \text{ mA} \quad V_{DS3} = 5.56 \text{ V}$$

$$V_{TN2} = 1.48 \text{ V} \quad I_{D2} = 13.0 \text{ mA} \quad V_{DS2} = 5.09 \text{ V} \quad V_{TN1} = 0.75 \text{ V} \quad I_{D1} = 13.0 \text{ mA} \quad V_{DS1} = 4.36 \text{ V}$$

Results are identical to calculations in Prob. 4.119

4.121

For $V_{GS} = 5 \text{ V}$ and $V_{DS} = 0.5 \text{ V}$, the transistor will be in the triode region.

$$I_D = \frac{(5 - 0.5)V}{82k\Omega} = 54.88\mu A \quad | \quad 54.88 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{W}{L} \right) \left(5 - 0.75 - \frac{0.5}{2} \right) 0.5 \quad | \quad \frac{W}{L} = \frac{0.274}{1} = \frac{1}{3.64}$$

4.122

For $V_{GS} = 3.3 \text{ V}$ and $V_{DS} = 0.25 \text{ V}$, the transistor will be in the triode region.

$$I_D = \frac{(3.3 - 0.25)V}{180k\Omega} = 16.94\mu A \quad | \quad 16.94 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{W}{L} \right) \left(3.3 - 0.75 - \frac{0.25}{2} \right) 0.25 \quad | \quad \frac{W}{L} = \frac{0.280}{1} = \frac{1}{3.57}$$

4.123

(a) The transistor is saturated by connection. For this circuit,

$$V_{GS} = V_{DD} + I_D R = -15 + 75000 I_D$$

$$I_D = \frac{4 \times 10^{-5}}{2} \left(\frac{1}{1} \right) (-15 + 75000 I_D + 0.75)^2 \Rightarrow 153 \mu A$$

$$V_{GS} = -15 + 75000 I_D = -3.525 V$$

$$V_{DS} = V_{GS} = -3.525 V \quad | \quad Q\text{-point: } (153 \mu A, -3.53 V)$$

(b) Here the transistor has $V_{GS} = -15 V$, a large value, so the transistor is most likely operating in the triode region.

$$I_D = \frac{V_{DS} - (-15)}{75000} = 4 \times 10^{-5} \left(-15 - (-0.75) - \frac{V_{DS}}{2} \right) V_{DS} \Rightarrow V_{DS} = -0.347 V \text{ and } I_D = 195 \mu A.$$

$$\text{Checking: } I_D = \frac{15 - 0.347}{785 k\Omega} V = 195 \mu A \quad | \quad Q\text{-point: } (195 \mu A, -0.347 V)$$

$$\text{Checking the region of operation: } V_{DS} = -0.347 V > V_{GS} - V_{TP} = -15 + 0.75 = -14.25 V$$

Triode region is correct

4.124

Set W=1U L=1U KP=40U VTO=-0.75 GAMMA=0

Results are almost identical to hand calculations for both parts.

4.125

(a) $I_{DP} = I_{DN}$, and both transistors are saturated by connection. $10 = -V_{GSP} + V_{GSN}$

$$\frac{1}{2} \left(\frac{40 \mu A}{V^2} \right) \left(\frac{20}{1} \right) (-10 + V_{GSN} + 0.75)^2 = \frac{1}{2} \left(\frac{100 \mu A}{V^2} \right) \left(\frac{20}{1} \right) (V_{GSN} - 0.75)^2$$

$$(9.25 - V_{GSN}) = \sqrt{2.5} (V_{GSN} - 0.75) \rightarrow V_{GSN} = 4.04 V \quad | \quad V_{GSP} = -5.96 V$$

$$I_{DP} = I_{DN} = 10.8 mA \quad | \quad V_o = V_{GSN} = 4.04 V$$

(b) Everything is the same except the currents scale by 80/20:

$$I_{DP} = I_{DN} = 43.2 mA$$

4.126

For (a) and (b), $\gamma = 0$. The transistor parameters are identical so $-3V_{GS} = 15V$ or $V_{GS} = -5V$.

$$(a) I_D = \frac{1}{2} \left(40 \times 10^{-6} \right) \frac{40}{1} (-5 + 0.75)^2 = 14.4 mA$$

$$(b) I_D = \frac{1}{2} \left(40 \times 10^{-6} \right) \frac{75}{1} (-5 + 0.75)^2 = 27.1 mA$$

(c) Now we have three different threshold voltages and need an iterative solution. Using MATLAB:

```
function f=PMOSStack(id)
gamma=0.5;
```

```

vsg1=.75+sqrt(2*id/1.6e-3);
vtp2=-0.75-gamma*(sqrt(vsg1+0.6)-sqrt(0.6));
vsg2=-vtp2+sqrt(2*id/1.6e-3);
vtp3=-0.75-gamma*(sqrt(vsg1+vsg2+0.6)-sqrt(0.6));
vsg3=-vtp3+sqrt(2*id/1.6e-3);
f=15-vsg1-vsg2-vsg3;
fzero('PMOSStack',1e-1) --> ans = 0.0104   ID = 10.4 mA.

```

4.127

- (a) W=40U L=1U KP=40U VTO=-0.75 GAMMA=0
- (b) W=75U L=1U KP=40U VTO=-0.75 GAMMA=0
- (c) W=75U L=1U KP=40U VTO=-0.75 GAMMA=0.5

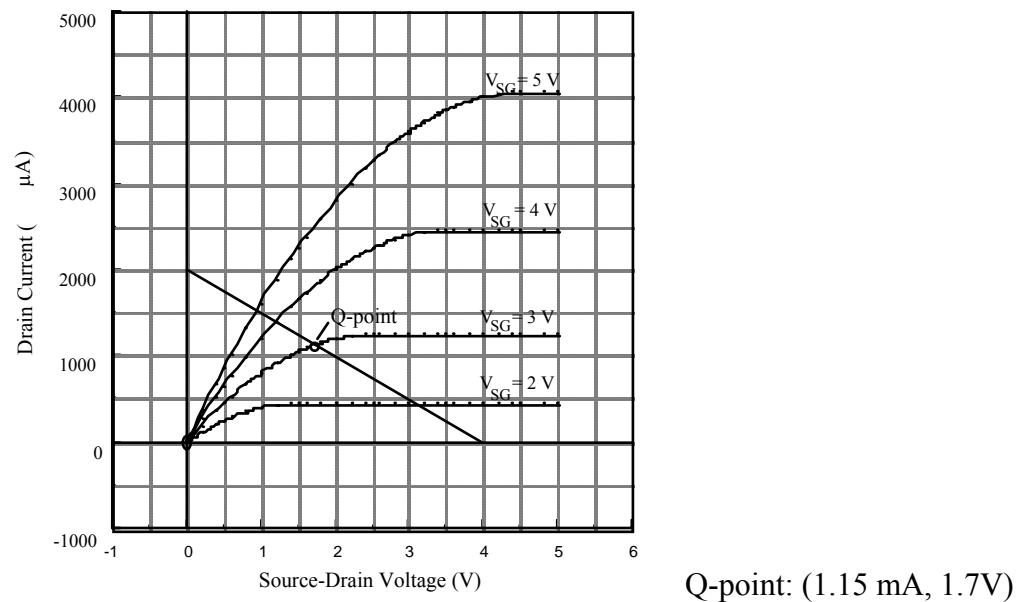
Results agree with hand calculations.

4.128

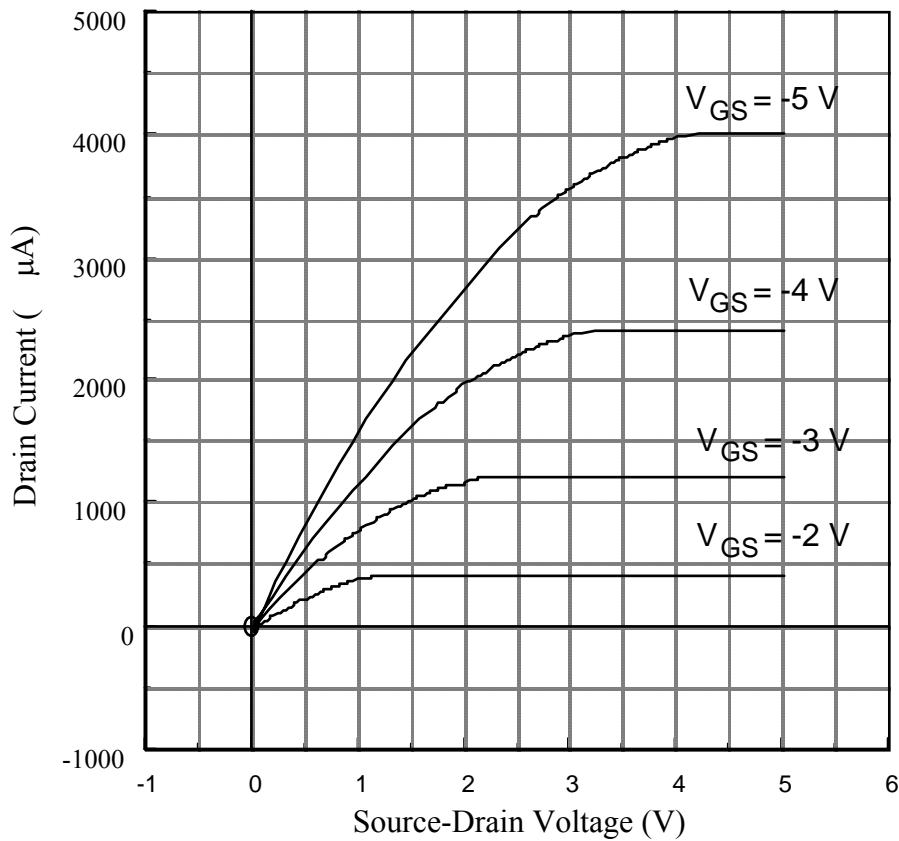
For $V_{DS} = 0$, $I_D = \frac{4V}{2k\Omega} = 2mA$. For $I_D = 0$, $V_{DS} = -4V$. ($V_{SD} = +4V$)

$$V_{GS} = V_{EQ} = -4V \frac{300k\Omega}{300k\Omega + 100k\Omega} = -3V \quad (V_{SG} = +3V)$$

From the graph, the transistor is operating below pinchoff in the linear region.



PMOS Transistor Output Characteristics



4.129

$$(a) V_{GS} = \frac{15V}{2} = 7.5V \mid 7.5 = 10^5 I_D - V_{GS} \mid 7.5 = 10^5 \left(\frac{4 \times 10^{-5}}{2} \right) \frac{20}{1} (V_{GS} + 0.75)^2 - V_{GS}$$

$$4V_{GS}^2 + 5.9V_{GS} - 1.5 = 0 \rightarrow V_{GS} = -1.148V \text{ and } I_D = 63.5\mu A$$

$$V_{DS} = -(15 - (100k\Omega + 50k\Omega)I_D) = -5.47V \mid Q\text{-point: } (59.78 \mu A, -5.47 V)$$

(b) For saturation, $V_{DS} \leq V_{GS} - V_{TP}$ or $V_{SD} \geq V_{SG} + V_{TP}$

$$15 - (100k\Omega + R)I_D \geq 7.5 - 100k\Omega I_D - 0.75 \rightarrow R \leq 130 k\Omega$$

4.130

Setting W=20U, L=1U, LEVEL=1, KP=40U, VTO=-0.75 yields results identical to the previous problem.

4.131

(a) Using MATLAB:

```
function f=bias4(id)
gamma=0.5;
vbs=1e5*id;
vgs=-7.5+vbs;
vtp=-0.75-gamma*(sqrt(vbs+0.6)-sqrt(0.6));
f=id-(8e-4/2)*(vgs-vtp)^2;
fzero('bias4',4e-5) --> ans = 5.5278e-05 --> ID = 55.3 μA
```

$$V_{DS} = -15 + (100k\Omega + R) I_D$$

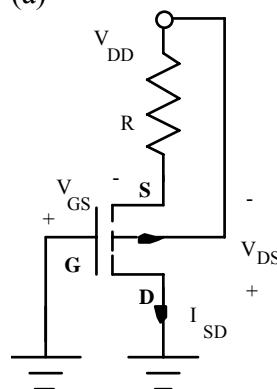
$$(b) V_{DS} \leq V_{GS} - V_{TP} \mid -15 + (100k\Omega + R)I_D \leq -1.972 + 1.600 \mid R \leq 164 k\Omega$$

4.132

Setting W=20U, L=1U, LEVEL=1, KP=40U, VTO=-0.75 GAMMA=0.5 yields results identical to the previous problem.

4.133

(a)



The arrow identifies the transistor as a PMOS device. Since $\gamma = 0$, we do not need to worry about body effect: $V_{TP} = V_{TO}$. Since $V_{DS} = V_{GS}$, and $V_{TP} < 0$, the transistor is saturated.

$$I_D = \frac{K_p}{2} \frac{W}{L} (V_{GS} - V_{TP})^2 \quad \text{and} \quad -V_{GS} = 12 - 10^5 I_D$$

$$-V_{GS} = 12 - 10^5 \left(\frac{4 \times 10^{-5}}{2} \right) \left(\frac{10}{1} \right) (V_{GS} - (-0.75))^2$$

$$20V_{GS}^2 + 29V_{GS} - 0.75 = 0 \quad \text{yields} \quad V_{GS} = -1.475V, +0.0255V$$

We require $V_{GS} < V_{TP} = -0.75$ V for the transistor to be conducting so

$$V_{GS} = -1.475V \quad \text{and} \quad I_D = \frac{4 \times 10^{-5}}{2} \left(\frac{10}{1} \right) \frac{A}{V^2} (-1.475 - (-0.75))^2 = 105 \mu A$$

Since $V_{DS} = V_{GS}$, the Q-point is given by: Q-Point = (105 μA , -1.475 V).

(b) Using MATLAB for the second part (Set gamma = 0 for part (a)):

```
function f=bias2(id)
gamma=1.0;
vgs=-12+1e5*id;
vsb=-vgs;
vtp=-0.75-gamma*(sqrt(vsb+0.6)-sqrt(0.6));
f=id-5e-5*(vgs-vtp)^2;
```

fzero('bias2',1e-4) --> ans = 9.5996e-05 and Q-Point = (96.0 μA , 2.40 V).

4.134

$$V_{GG} = \frac{15V}{2} = 7.5V \quad | \quad 7.5 = 5 \times 10^4 I_D - V_{GS} \quad | \quad 7.5 = 5 \times 10^4 \left(\frac{4 \times 10^{-5}}{2} \right) \frac{40}{1} (V_{GS} + 0.75)^2 - V_{GS}$$

$$890V_{GS}^2 + 119V_{GS} - 30 = 0 \rightarrow V_{GS} = -1.166V \text{ and } I_D = 138 \mu A$$

$$V_{DS} = -(15 - (R + 50k\Omega)I_D) = -5V \rightarrow R = 22.3 k\Omega \quad I_D = 138 \mu A$$

4.135

$$V_{GG} = \frac{15V}{2} = 7.5V \quad | \quad 7.5 = 15 - 5 \times 10^4 I_D + V_{GS} \quad | \quad 7.5 = 5 \times 10^4 \left(\frac{4 \times 10^{-5}}{2} \right) \frac{40}{1} (V_{GS} - V_{TP})^2 - V_{GS}$$

$$V_{TP} = -0.75 - 0.5 \left(\sqrt{5 \times 10^4 I_D + 0.6} - \sqrt{0.6} \right)$$

Solving iteratively yields $I_D = 111 \mu A$ with $V_{TP} = -1.60V$

$$V_{DS} = -(15 - (R + 50k\Omega)I_D) = -5V \rightarrow R = 40.1 k\Omega$$

4.136

$$(a) V_{GG} = 15V \frac{510k\Omega}{510k\Omega + 270k\Omega} = 9.81V \mid 9.81 = 15 - 10^5 I_D + V_{GS}$$

$$5.19 = 10^5 \left(\frac{4 \times 10^{-5}}{2} \right) \frac{20}{1} (V_{GS} + 0.75)^2 - V_{GS}$$

$$40V_{GS}^2 + 59V_{GS} + 17.31 = 0 \rightarrow V_{GS} = -1.071 \text{ V and } I_D = 41.2 \mu\text{A}$$

(b) For saturation, $V_{DS} \leq V_{GS} - V_{TP}$

$$-15 + (100k\Omega + R)I_D \leq -1.071 + 0.75 \rightarrow R \leq 256 \text{ k}\Omega$$

4.137

$$(a) V_{GG} = 15V \frac{510k\Omega}{510k\Omega + 270k\Omega} = 9.81V \mid 9.81 = 15 - 10^5 I_D + V_{GS}$$

$$5.19 = 10^5 \left(\frac{4 \times 10^{-5}}{2} \right) \frac{20}{1} (V_{GS} - V_{TP})^2 - V_{GS} \mid V_{TP} = -0.75 - 0.5(\sqrt{10^5 I_D + 0.6} - \sqrt{0.6})$$

Solving iteratively yields $I_D = 35.2 \mu\text{A}$ with $V_{TP} = -1.38 \text{ V}$ and $V_{GS} = -1.67 \text{ V}$

(b) For saturation, $V_{DS} \leq V_{GS} - V_{TP}$

$$-15 + (100k\Omega + R)I_D \leq -1.67 + 1.38 \rightarrow R \leq 318 \text{ k}\Omega$$

4.138

(a) Assume an equal voltage (5V) split between R_D , R_S and V_{DS} . We need $V_{DS} \leq V_{GS} - V_{TP}$

$$\text{or } -5 \leq V_{GS} - V_{TP}. \text{ Choose } V_{GS} - V_{TP} = -2V. K_n = \frac{2I_D}{(V_{GS} - V_{TP})^2} = \frac{2mA}{4} \rightarrow \frac{W}{L} = \frac{12.5}{1}.$$

$$V_{GS} = -2 - 0.75 = -2.75V. V_{EQ} = 5 - V_{GS} = 7.75V.$$

$$7.75 = 15 \frac{R_1}{R_1 + R_2} = \frac{15}{R_2} \frac{R_1 R_2}{R_1 + R_2} = \frac{15}{R_2} 100k\Omega. R_2 = 193.5k\Omega \rightarrow 200k\Omega.$$

$$7.75 = 15 \frac{R_1}{R_1 + R_2} \rightarrow R_1 = 214k\Omega \rightarrow 220k\Omega. V_{EQ} = 15 \frac{220k\Omega}{220k\Omega + 200k\Omega} = 7.86V$$

$$R_S = \frac{7.86V - 2.75V}{1mA} = 5.11k\Omega \rightarrow 5.1k\Omega \mid R_D = \frac{15 - 5 - 5.1}{1mA} = 4.9k\Omega \rightarrow 4.7k\Omega$$

Note that R_1 is connected between the gate and +15 V, and R_2 is connected between the gate and ground.

(b) For the NMOS case, choose $W/L = 5/1$. The resistors now have the same values except R_2 is now connected between the gate and +15 V, R_1 is connected between the gate and ground, and $R_D = \frac{15 - 6 - 5.1}{1mA} = 3.9k\Omega$

4.139

(a) Assume an equal voltage (3V) split between R_D , R_S and V_{DS} . We need $V_{DS} \leq V_{GS} - V_{TP}$

$$\text{or } -3 \leq V_{GS} - V_{TP}. \text{ Choose } V_{GS} - V_{TP} = -1V. K_n = \frac{2I_D}{(V_{GS} - V_{TP})^2} = \frac{1mA}{1} \rightarrow \frac{W}{L} = \frac{25}{1}.$$

$$V_{GS} = -1 - 0.75 = -1.75V. V_{EQ} = 3 - V_{GS} = 4.75V.$$

$$4.75 = 9 \frac{R_1}{R_1 + R_2} = 9 \frac{R_1 R_2}{R_2 (R_1 + R_2)} = 9 \frac{R_1 R_2}{R_2} 1M\Omega. R_2 = 1.7M\Omega \rightarrow 1.8M\Omega.$$

$$4.75 = 9 \frac{R_1}{R_1 + R_2} \rightarrow R_1 = 2.01M\Omega \rightarrow 2M\Omega \quad | \quad V_{EQ} = 9 \frac{2M\Omega}{1.8M\Omega + 2M\Omega} = 4.74V$$

$$R_S = \frac{4.74V - 1.75V}{0.5mA} = 5.97k\Omega \rightarrow 6.2k\Omega \quad | \quad R_D = \frac{9 - 3 - 3}{0.5mA} = 6.0k\Omega \rightarrow 6.2k\Omega$$

Note that R_1 is connected between the gate and +9 V, and R_2 is connected between the gate and ground. $R_1 = 2M\Omega$, $R_2 = 1.8M\Omega$, $R_S = R_D = 6.2k\Omega$, $W/L = 25/1$

(b) For the NMOS case, choose $W/L = 40/1$. The resistors now have the same values except R_2 is now connected between the gate and +9 V, and R_1 is connected between the gate and ground.

4.140

$$V_{GS} = 10^4 I_D \quad | \quad \text{Assume saturation: } I_D = \left(\frac{40 \mu A}{2 V^2} \right) \left(\frac{10}{1} \right) (10^4 I_D - 4)^2$$

$$\text{Collecting terms: } 10^8 I_D^2 - 8.5 \times 10^4 I_D + 16 = 0 \rightarrow I_D = 281 \mu A$$

$$V_{DS} = -(15 - 10^4 I_D) = -12.2V \quad | \quad Q\text{-Pt: } (281 \mu A, -12.2 V)$$

Checking: $V_{GS} - V_{TP} = 2 - 4 = -1.19 V \quad | \quad V_{DS} = -12.2 \quad | \quad \text{Saturation is correct.}$

4.141

$$V_{GS} = 10^4 I_D \quad | \quad V_{TP} = 4 - 0.25(\sqrt{V_{GS} + 0.6} - \sqrt{0.6}) \quad | \quad I_D = \frac{4 \times 10^{-4}}{2} (V_{GS} - V_{TP})^2$$

Solving these equations iteratively yields $I_D = 260 \mu A$

$$V_{DS} = -(15 - 10^4 I_D) = -12.4V \quad | \quad Q\text{-Pt: } (260 \mu A, -12.4 V)$$

4.142

Note: The answers are very sensitive to round-off error and are best solved iteratively using MATLAB, a spreadsheet, HP solver, etc. Hand calculations using the quadratic equation will generally yield poor results.

Saturated by connection with $V_{TP} = -1$

$$I_D = \frac{4x10^{-5}}{2} \left(\frac{10}{1} \right) \left[3.3x10^5 I_D - 12 - (-1) \right]^2 \rightarrow 121 - 7.265x10^6 I_D + 1.089x10^{11} I_D^2 = 0$$

$$I_D = 34.6\mu A, 32.1\mu A \mid V_{DS} = 3.3x10^5 I_D - 12 = -0.582V, -1.407V \mid Q\text{-point: } (32.1\mu A, -1.41 V)$$

since the transistor would not be conducting for $V_{GS} = -0.582V$.

4.143

Note: The answers are very sensitive to round-off error and are best solved iteratively using MATLAB, a spreadsheet, HP solver, etc. Hand calculations using the quadratic equation will generally yield poor results.

Saturated by connection with $V_{TP} = -3$

$$I_D = \frac{4x10^{-5}}{2} \left(\frac{30}{1} \right) \left[3.3x10^5 I_D - 12 - (-3) \right]^2 \rightarrow 81 - 5.941x10^6 I_D + 1.089x10^{11} I_D^2 = 0$$

$$I_D = 27.07\mu A \mid V_{DS} = 3.3x10^5 I_D - 12 = -3.067V \mid Q\text{-point: } (27.1\mu A, -3.07 V)$$

4.144

Note: The answers are very sensitive to round-off error and are best solved iteratively using MATLAB, a spreadsheet, HP solver, etc. Hand calculations using the quadratic equation will generally yield poor results.

(a) Large V_{GS} – Assume triode region.

$$V_{DS} = 12 - 3.3x10^5 I_D \mid I_D = 40x10^{-6} \left(\frac{10}{1} \right) \left(12 - 0.75 - \frac{V_{DS}}{2} \right) V_{DS}$$

Q -point: $(36.1\mu A, 80.6 \text{ mV}) \mid V_{DS} < V_{GS} - V_{TN}$ so triode region is correct.

$$(b) \text{ Saturated by connection: } I_D = \frac{10x10^{-6}}{2} \left(\frac{25}{1} \right) \left(3.3x10^5 I_D - 12 + 0.75 \right)^2$$

Q -point: $(32.4\mu A, -1.32V)$

$$(c) V_{TP} = -0.75 - 0.5 \left(\sqrt{3.3x10^5 I_D + 0.6} - \sqrt{0.6} \right)$$

$$I_D = \frac{40x10^{-6}}{2} \left(\frac{25}{1} \right) \left(3.3x10^5 I_D - 12 - V_{TP} \right)^2 \mid V_{DS} = -(12 - 3.3x10^5 I_D)$$

Q -point: $(28.8\mu A, -2.49 V)$

4.145

$$(a) K_n = \mu_n \frac{\varepsilon_{ox}}{T_{ox}} \frac{W}{L} = 500 \frac{cm^2}{V-s} \left[\frac{3.9(8.854 \times 10^{-14} F/cm)}{40 \times 10^{-7} cm} \right] \left[\frac{20 \mu m}{2 \mu m} \right] = 432 \frac{\mu A}{V^2}$$

$$I_D = \frac{432 \mu A}{2} (4-1)^2 = 1.94 mA$$

$$(b) K'_n = 2K_n \quad | \quad V' = \frac{V}{2} \quad | \quad I'_D = \frac{864 \mu A}{2} \left(\frac{4}{2} - \frac{1}{2} \right)^2 = 0.972 mA$$

4.146

$$(a) C_{GC} = C''_{ox} WL = \left[\frac{3.9(8.854 \times 10^{-14} F/cm)}{20 \times 10^{-7} cm} \right] (20 \times 10^{-4} cm) (10^{-4} cm) = 34.5 fF$$

$$(b) \alpha = 2 \quad | \quad C'_{GC} = \frac{C_{GC}}{\alpha} = 17.3 fF$$

4.147

$$f_T = \frac{1}{2\pi} \frac{g_m}{C_{GC}} \quad | \quad g_m = \frac{\partial I_D}{\partial V_{GS}} = K_P (V_{GS} - V_{TP}) = \mu_p C''_{ox} \frac{W}{L} \quad | \quad C_{GC} = C''_{ox} WL$$

$$f_T = \frac{1}{2\pi} \frac{\mu_p}{L^2} (V_{GS} - V_{TP}), \text{ but } (V_{GS} - V_{TP}) < 0 \text{ for PMOS transistor.}$$

Since f_T should be positive, $f_T = \frac{1}{2\pi} \frac{\mu_p}{L^2} |(V_{GS} - V_{TP})|$

4.148

$$(a) f_T = \frac{1}{2\pi} \left(\frac{\mu}{L^2} \right) (V_{GS} - V_{TN})$$

$$f_{TN} = \frac{1}{2\pi} \left[\frac{400 cm^2/V-s}{(10^{-4} cm)^2} \right] (1V) = 6.37 GHz \quad | \quad f_{TP} = 0.4 f_{TN} = 2.55 GHz$$

$$(b) f_{TN} = \frac{1}{2\pi} \left[\frac{400 cm^2/V-s}{(10^{-5} cm)^2} \right] (1V) = 637 GHz \quad | \quad f_{TP} = 0.4 f_{TN} = 255 GHz$$

4.149

$$(a) K_n = \mu_n \frac{\varepsilon_{ox}}{T_{ox}} \frac{W}{L} = 400 \frac{cm^2}{V-s} \left[\frac{3.9(8.854 \times 10^{-14} F/cm)}{80 \times 10^{-7} cm} \right] \left[\frac{2 \mu m}{0.1 \mu m} \right] = 345 \frac{\mu A}{V^2}$$

$$I_D = \frac{345 \mu A}{2} (2)^2 = 690 \mu A$$

$$(b) I_D = C''_ox \frac{W}{2} (V_{GS} - V_{TN}) v_{sat} = \frac{3.9(8.854 \times 10^{-14} F/cm)}{80 \times 10^{-7} cm} \left[\frac{2 \times 10^{-4} cm}{2} \right] (2V) (10^7 cm/s) = 86.3 \mu A$$

4.150

For $V_{GS} = 0$, $I_D = 10^{-22} A$. For $V_{TN} = 0.5 V$ and $V_{GS} = 0$, $I_D = 10^{-15} A$.

CHAPTER 5

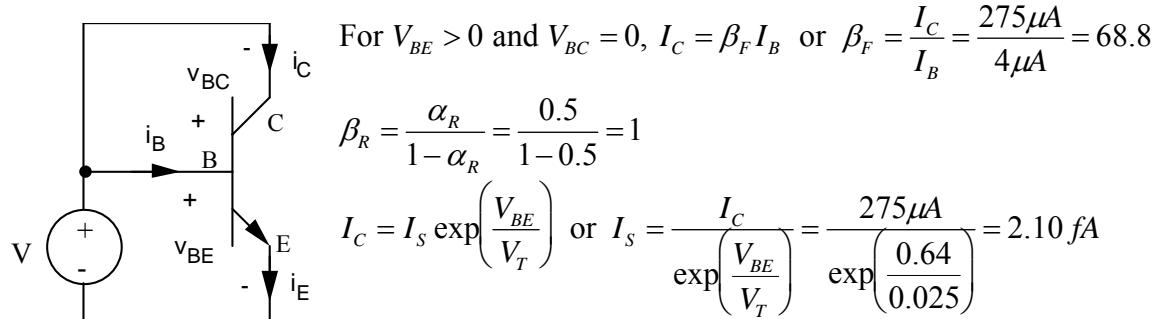
5.1

Base Contact = B
n-type Emitter = D

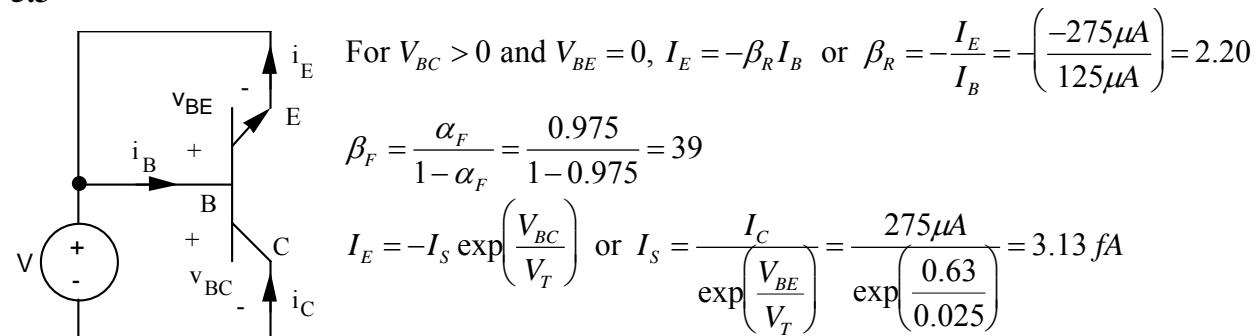
Collector Contact = A
n-type Collector = F

Emitter Contact = C
Active Region = E

5.2



5.3



5.4

Using $\beta = \frac{\alpha}{1-\alpha}$ and $\alpha = \frac{\beta}{\beta+1}$:

Table 5.P1	
□	□
0.167	0.200
0.400	0.667
0.750	3.00
0.909	10.0
0.980	49.0
0.995	200
0.999	1000
0.9998	5000

5.5

(a) For this circuit, $V_{BE} = 0$ V, $V_{BC} = -5$ V and $I = I_C$. Substituting these values into the collector current expression in Eq. (5.13):

$$I_C = I_s \left[\exp(0) - \exp\left(\frac{-5}{0.025}\right) \right] - \frac{I_s}{\beta_R} \left[\exp\left(\frac{-5}{0.025}\right) - 1 \right]$$

$$I = I_C = I_s \left(1 + \frac{1}{\beta_R} \right) = 10^{-15} A \left(1 + \frac{1}{1} \right) = 2 fA.$$

(b) For this circuit, the constraints are $V_{BC} = -5$ V and $I_E = 0$. Substituting these values into the emitter current expression in Eq. (5.13):

$$I_E = I_s \left[\exp\left(\frac{V_{BE}}{V_T}\right) - \exp\left(\frac{V_{BC}}{V_T}\right) \right] + \frac{I_s}{\beta_F} \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right] = 0 \quad \text{which gives}$$

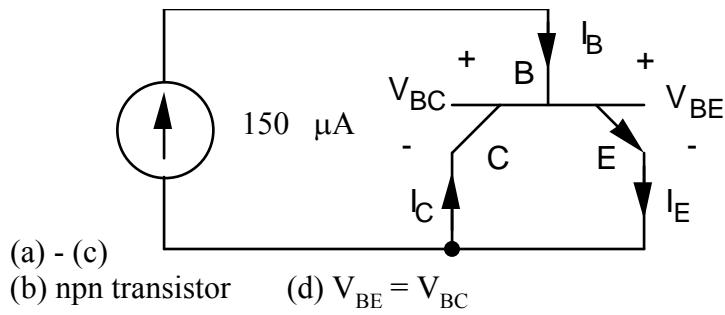
$$\exp\left(\frac{V_{BE}}{V_T}\right) = \frac{1}{1 + \beta_F} + \frac{\beta_F}{1 + \beta_F} \exp\left(\frac{V_{BC}}{V_T}\right). \quad \text{Substituting this result into } I_C :$$

$$I_{CBO} = \frac{I_s}{1 + \beta_F} \left[1 - \exp\left(\frac{V_{BC}}{V_T}\right) \right] - \frac{I_s}{\beta_R} \left[\exp\left(\frac{V_{BC}}{V_T}\right) - 1 \right].$$

$$\text{For } V_{BC} = -5V, I_{CBO} = I_s \left[\frac{1}{1 + \beta_F} + \frac{1}{\beta_R} \right] = 10^{-15} A \left[\frac{1}{101} + \frac{1}{1} \right] = 1.01 fA, \text{ and}$$

$$V_{BE} = V_T \ln\left(\frac{1}{1 + \beta_F}\right) = 0.025V \ln\left(\frac{1}{101}\right) = -0.115 V \neq 0!$$

5.6



$$(e) I_C = -\frac{I_S}{\beta_R} \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right]$$

$$I_E = +\frac{I_S}{\beta_F} \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right]$$

$$I_B = I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right) \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right]$$

$$\frac{I_E}{I_B} = \frac{1}{1 + \frac{\beta_F}{\beta_R}} \quad \text{and} \quad \frac{I_E}{I_C} = -\frac{\beta_R}{\beta_F}$$

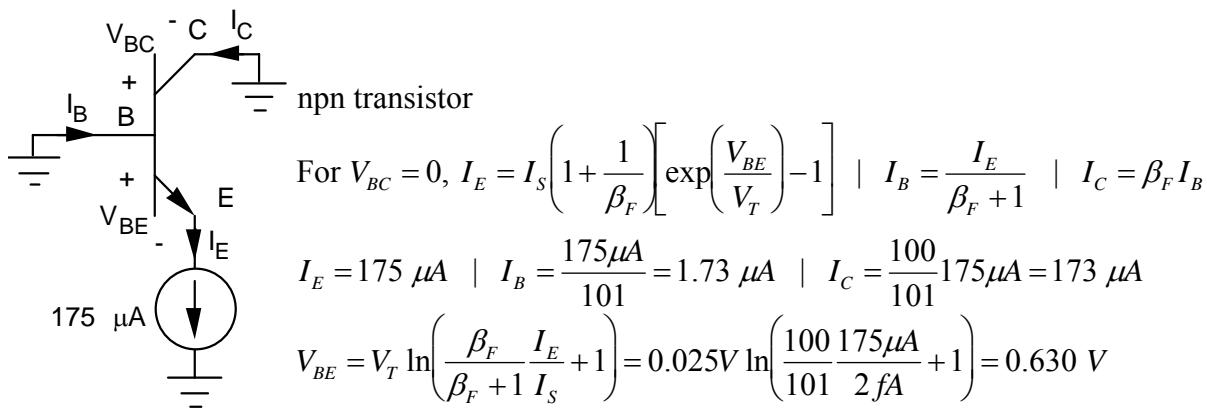
$$(f) \text{ Using } I_C = -\frac{\beta_F}{\beta_R} I_E = -400 I_E \quad \text{and} \quad I_B = I_E - I_C = 401 I_E$$

For the circuit $I_B = 150 \mu A$

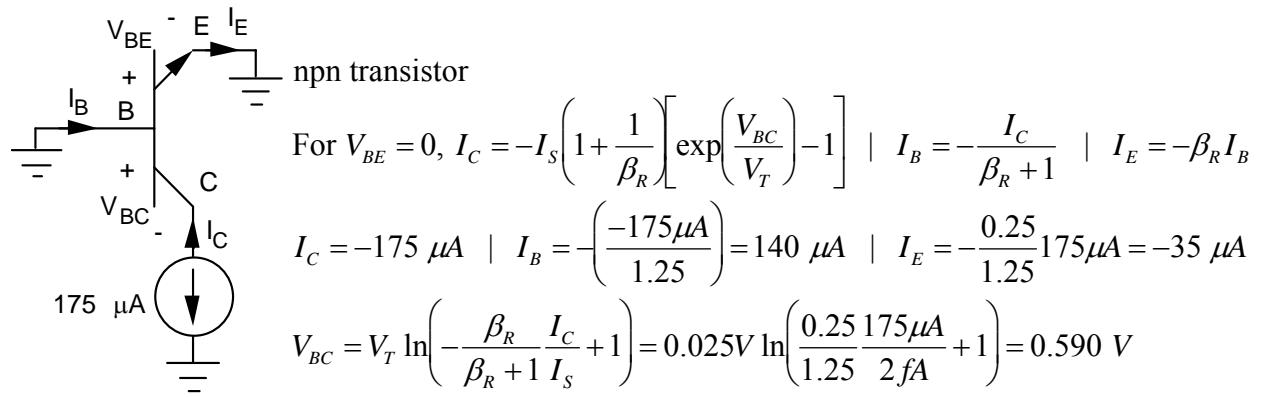
$$\text{Therefore } I_E = \frac{150 \mu A}{401} = 0.374 \mu A, \text{ and } I_C = -149.6 \mu A.$$

$$V_{BC} = V_{BE} = V_T \ln \left(\frac{I_B}{I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right)} \right) = (0.025V) \ln \left(\frac{150 \mu A}{2fA \left(\frac{1}{100} + \frac{1}{0.25} \right)} \right) = 0.591 V$$

5.7



5.8



5.9

Using $v_{BC} = 0$ in Eq. 5.13 and recognizing that $i = i_C + i_B = i_E$:

$$i = i_E = I_s \left(1 + \frac{1}{\beta_F} \right) \exp \left(\frac{v_{BE}}{V_T} \right) - 1 \right], \text{ and the reverse saturation current}$$

of the diode connected transistor is $I'_s = I_s \left(1 + \frac{1}{\beta_F} \right) = (2 fA) \left(1 + \frac{1}{100} \right) = 2.02 fA$

5.10

Using $v_{BE} = 0$ in Eq. 5.13 and recognizing that $i = -i_C$:

$$i = -i_C = -I_s \left(1 + \frac{1}{\beta_R} \right) \exp \left(\frac{v_{BC}}{V_T} \right) - 1 \right], \text{ and the reverse saturation current}$$

of the diode connected transistor is $I'_s = I_s \left(1 + \frac{1}{\beta_R} \right) = (5 fA) \left(1 + \frac{1}{3} \right) = 6.67 fA$

5.11

$$(a) i_T = I_s \left[\exp \left(\frac{v_{BE}}{V_T} \right) - \exp \left(\frac{v_{BC}}{V_T} \right) \right] = 5 \times 10^{-16} A \left[\exp \left(\frac{0.75}{0.025} \right) - \exp \left(\frac{-3}{0.025} \right) \right] = 5.34 mA$$

(b) The current is symmetric: For $V_{BC} = 0.75$ V and $V_{BE} = -3$ V, $i_T = -5.34$ mA.

5.12

$$(a) i_T = I_s \left[\exp \left(\frac{v_{BE}}{V_T} \right) - \exp \left(\frac{v_{BC}}{V_T} \right) \right] = 10^{-15} A \left[\exp \left(\frac{0.70}{0.025} \right) - \exp \left(\frac{-3}{0.025} \right) \right] = 1.45 mA$$

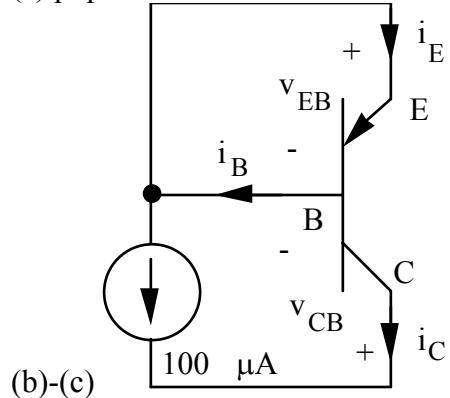
(b) The current is symmetric: For $V_{BC} = 0.70$ V and $V_{BE} = -3$ V, $i_T = -1.45$ mA.

5.13

Base Contact = F	Collector Contact = G	Emitter Contact = E
p-type Emitter = D	p-type Collector = A	Active Region = C

5.14

(a) pnp transistor



(b)-(c)

(d) Using Eq. (5.17) with $v_{EB} = 0$ and dropping the "-1" terms:

$$i_C = -I_s \left(1 + \frac{1}{\beta_R}\right) \exp\left(\frac{v_{CB}}{V_T}\right) \quad i_E = -I_s \exp\left(\frac{v_{CB}}{V_T}\right) \quad i_B = \frac{I_s}{\beta_R} \exp\left(\frac{v_{CB}}{V_T}\right)$$

$$\frac{I_E}{I_C} = \frac{1}{1 + \frac{1}{\beta_R}} = \frac{\beta_R}{\beta_R + 1} = \alpha_R \quad \frac{I_E}{I_B} = -\beta_R$$

$$I_C = -100 \mu A, \quad I_E = \alpha_R I_C = 0.25 I_C = -25.0 \mu A$$

$$I_B = -\frac{I_E}{\beta_R} \quad \beta_R = \frac{\alpha_R}{1 - \alpha_R} = \frac{0.25}{1 - 0.25} = \frac{1}{3} \quad I_B = +75 \mu A$$

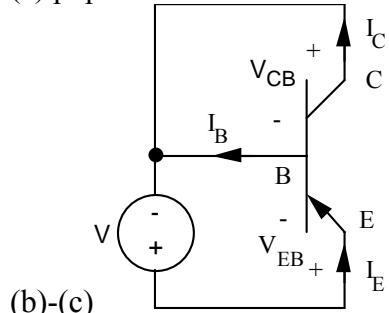
$$\beta_F = \frac{\alpha_F}{1 - \alpha_F} = \frac{0.985}{1 - 0.985} = 65.7$$

$$V_{EB} = 0 \quad \text{and} \quad I_E = -I_s \exp\left(\frac{V_{CB}}{V_T}\right) \quad V_{CB} = V_T \ln\left(-\frac{I_E}{I_s}\right)$$

$$V_{CB} = 0.025V \ln\left(-\frac{-25 \times 10^{-6} A}{10^{-15} A}\right) = 0.599 V$$

5.15

(a) pnp



(b)-(c)

(d) Using Eq. (5.17) with $V_{CB} = 0$ and dropping the "-1" terms:

$$i_E = I_S \left(1 + \frac{1}{\beta_F} \right) \exp\left(\frac{V_{EB}}{V_T}\right) \quad i_C = -I_S \exp\left(\frac{V_{EB}}{V_T}\right) \quad i_B = \frac{I_S}{\beta_F} \exp\left(\frac{V_{EB}}{V_T}\right)$$

$$I_S = \frac{I_C}{\exp\left(\frac{V_{EB}}{V_T}\right)} = \frac{300 \mu A}{\exp\left(\frac{0.640}{0.025V}\right)} = 2.29 fA$$

$$\beta_F = \frac{I_C}{I_B} = \frac{300 \mu A}{4 \mu A} = 75 \quad | \quad \beta_R = \frac{\alpha_R}{1 - \alpha_R} = \frac{0.2}{1 - 0.2} = 0.25$$

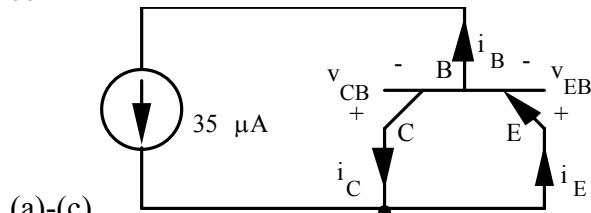
5.16

Using $V_{CB} = 0$ in Eq. 5.17 and recognizing that $i = i_E$:

$$i = i_E = I_S \left(1 + \frac{1}{\beta_F} \right) \left[\exp\left(\frac{V_{EB}}{V_T}\right) - 1 \right], \text{ and the reverse saturation current}$$

$$\text{of the diode connected transistor is } I_S' = I_S \left(1 + \frac{1}{\beta_F} \right) = (2 fA) \left(1 + \frac{1}{100} \right) = 2.02 fA$$

5.17



(a)-(c)

(b) pnp transistor(d)

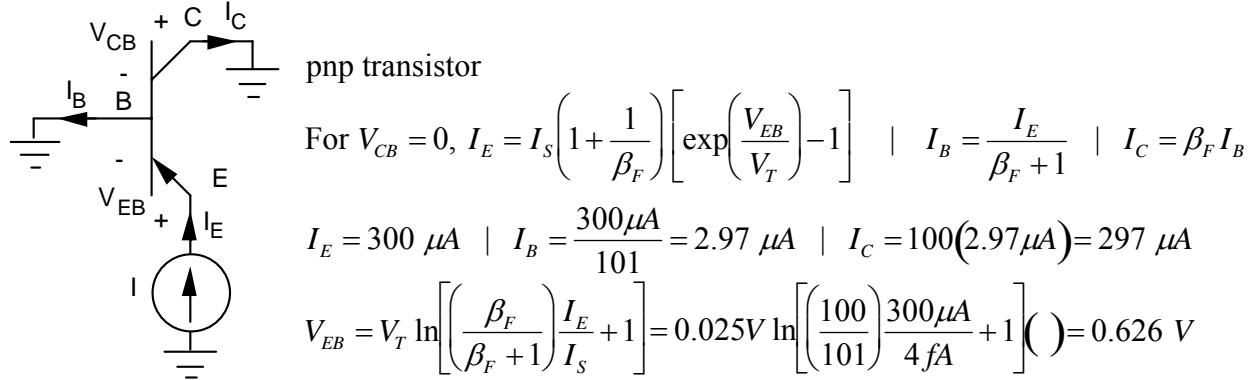
$$v_{EB} = v_{CB} \quad i_C = -\frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] \quad i_E = +\frac{I_S}{\beta_F} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] \quad i_B = +I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right) \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right]$$

$$\frac{I_E}{I_B} = \frac{\frac{1}{\beta_F}}{\frac{1}{\beta_F} + \frac{1}{\beta_R}} = \frac{\beta_R}{\beta_F + \beta_R} = \frac{4}{79} = 0.0506 \quad | \quad \frac{I_E}{I_B} = -\frac{\beta_R}{\beta_F} = -\frac{4}{75} = -0.0533$$

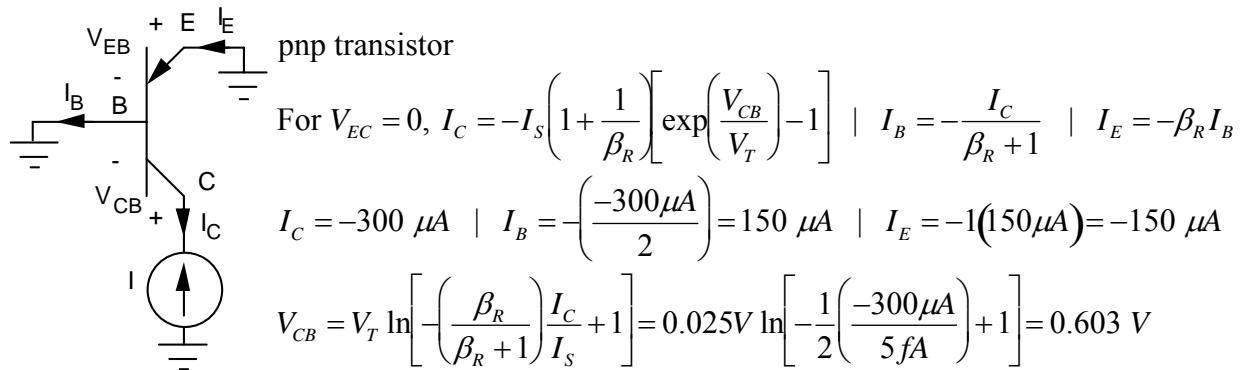
$$I_B = 35 \mu A \quad I_E = \frac{4}{79} I_B = 1.77 \mu A \quad I_C = -\frac{75}{4} I_E = -33.2 \mu A$$

$$V_{EB} = V_T \ln \left(1 - \frac{\beta_R I_C}{I_s} \right) \quad V_{CB} = V_{EB} = 0.025V \ln \left(1 - \frac{4(-33.2 \times 10^{-6} A)}{2 \times 10^{-15} A} \right) = 0.623 V$$

5.18



5.19



5.20

$$(a) i_T = I_S \left[\exp \left(\frac{V_{EB}}{V_T} \right) - \exp \left(\frac{V_{CB}}{V_T} \right) \right] = 5 \times 10^{-16} A \left[\exp \left(\frac{0.70}{0.025} \right) - \exp \left(\frac{-3}{0.025} \right) \right] = 723 \mu A$$

(b) The current is symmetric: For $V_{CB} = 0.75 V$ and $V_{EB} = -3 V$, $i_T = -723 \mu A$.

5.21

$$\begin{aligned}
 (a) i_F &= I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] = 4 \times 10^{-15} A \left[\exp\left(\frac{0.73V}{0.025V}\right) - 1 \right] = 19.2 \text{ mA} \\
 i_R &= I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] = 4 \times 10^{-15} A \left[\exp\left(\frac{-3V}{0.025V}\right) - 1 \right] = -4.00 \text{ fA} \\
 i_T &= i_F - i_R = 19.2 \text{ mA} \quad | \quad \frac{i_F}{\beta_F} = \frac{19.2 \text{ mA}}{80} = 240 \text{ } \mu\text{A} \quad | \quad \frac{i_R}{\beta_R} = \frac{-4.00 \text{ fA}}{2} = -2.00 \text{ } \mu\text{A} \\
 (b) i_F &= I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] = 4 \times 10^{-15} A \left[\exp\left(\frac{-3V}{0.025V}\right) - 1 \right] = -4.00 \text{ fA} \\
 i_R &= I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] = 4 \times 10^{-15} A \left[\exp\left(\frac{0.73V}{0.025V}\right) - 1 \right] = 19.2 \text{ mA} \\
 i_T &= i_F - i_R = -19.2 \text{ mA} \quad | \quad \frac{i_F}{\beta_F} = \frac{-4.00 \text{ fA}}{80} = -0.05 \text{ } \mu\text{A} \quad | \quad \frac{i_R}{\beta_R} = \frac{19.2 \text{ mA}}{2} = 9.60 \text{ mA}
 \end{aligned}$$

5.22

$$\begin{aligned}
 (a) i_F &= I_S \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] = 6 \times 10^{-15} A \left[\exp\left(\frac{0.68V}{0.025V}\right) - 1 \right] = 3.90 \text{ mA} \\
 i_R &= I_S \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right] = 6 \times 10^{-15} A \left[\exp\left(\frac{-3V}{0.025V}\right) - 1 \right] = -6.00 \text{ fA} \\
 i_T &= i_F - i_R = 3.90 \text{ mA} \quad | \quad \frac{i_F}{\beta_F} = \frac{3.90 \text{ mA}}{60} = 65.0 \text{ } \mu\text{A} \quad | \quad \frac{i_R}{\beta_R} = \frac{-6.00 \text{ fA}}{3} = -2.00 \text{ } \mu\text{A} \\
 (b) i_F &= I_S \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] = 6 \times 10^{-15} A \left[\exp\left(\frac{-3V}{0.025V}\right) - 1 \right] = -6.00 \text{ fA} \\
 i_R &= I_S \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right] = 6 \times 10^{-15} A \left[\exp\left(\frac{0.68V}{0.025V}\right) - 1 \right] = 3.90 \text{ mA} \\
 i_T &= i_F - i_R = -3.90 \text{ mA} \quad | \quad \frac{i_F}{\beta_F} = \frac{-6.00 \text{ fA}}{60} = -0.100 \text{ fA} \quad | \quad \frac{i_R}{\beta_R} = \frac{3.90 \text{ mA}}{3} = 1.30 \text{ mA}
 \end{aligned}$$

5.23

$$\begin{aligned}
i_E &= I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right) \right] + \frac{I_S}{\beta_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 - \exp\left(\frac{v_{BC}}{V_T}\right) + 1 \right] + \frac{I_S}{\beta_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] \\
i_E &= I_S \left[1 + \frac{1}{\beta_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 - \exp\left(\frac{v_{BC}}{V_T}\right) + 1 \right] - I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] \right] = \frac{I_S}{\alpha_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] - I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] \\
i_C &= I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right) \right] - \frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 - \exp\left(\frac{v_{BC}}{V_T}\right) + 1 \right] - \frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] \\
i_C &= I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] - I_S \left[1 + \frac{1}{\beta_R} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] \right] = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] - \frac{I_S}{\alpha_R} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]
\end{aligned}$$

Defining $I_{ES} = \frac{I_S}{\alpha_F}$ and $I_{CS} = \frac{I_S}{\alpha_R}$, then we see $I_S = \alpha_F I_{ES} = \alpha_R I_{CS}$ and

$$\begin{aligned}
i_E &= I_{ES} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] - \alpha_R I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] \\
i_C &= \alpha_F I_{ES} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] - I_{CS} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] \\
i_B &= i_E - i_C = (1 - \alpha_F) I_{ES} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] + (1 - \alpha_R) I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]
\end{aligned}$$

5.24

$$\alpha_F = \frac{\beta_F}{\beta_F + 1} = \frac{100}{101} = 0.990 \quad | \quad \alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{0.5}{1.5} = 0.333 \quad | \quad I_{ES} = \frac{I_S}{\alpha_F} = \frac{2fA}{0.990} = 2.02 fA$$

$$I_{CS} = \frac{I_S}{\alpha_R} = \frac{2fA}{0.333} = 6.00 fA \quad | \quad \alpha_F I_{ES} = \alpha_R I_{CS} = I_S$$

5.25

$$\begin{aligned}
i_E &= I_S \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 - \exp\left(\frac{v_{CB}}{V_T}\right) + 1 \right] + \frac{I_S}{\beta_F} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] = I_S \left(1 + \frac{1}{\beta_F} \right) \exp\left(\frac{v_{EB}}{V_T}\right) - 1 - I_S \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right] \\
i_C &= I_S \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 - \exp\left(\frac{v_{CB}}{V_T}\right) + 1 \right] - \frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right] = I_S \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] - I_S \left(1 + \frac{1}{\beta_R} \right) \exp\left(\frac{v_{CB}}{V_T}\right) - 1 \\
i_E &= I_{ES} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] - \alpha_R I_{CS} \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right] \\
i_C &= \alpha_F I_{ES} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] - I_{CS} \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right] \\
i_B &= i_E - i_C = (1 - \alpha_F) I_{ES} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] + (1 - \alpha_R) I_{CS} \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right]
\end{aligned}$$

5.26

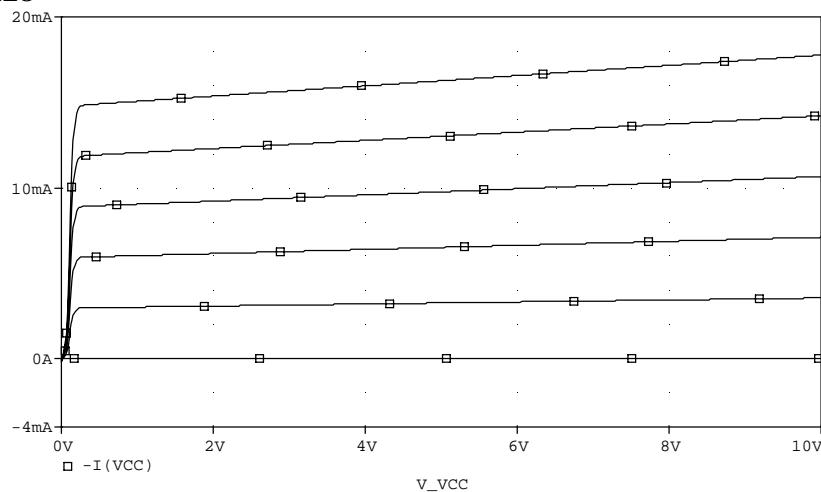
At $I_C = 5 \text{ mA}$ and $V_{CE} = 5 \text{ V}$, $I_B = 60 \mu\text{A}$: $\beta_F = \frac{I_C}{I_B} = \frac{5 \text{ mA}}{60 \mu\text{A}} = 83.3$

At $I_C = 7 \text{ mA}$ and $V_{CE} = 7.5 \text{ V}$, $I_B = 80 \mu\text{A}$: $\beta_F = \frac{I_C}{I_B} = \frac{7 \text{ mA}}{80 \mu\text{A}} = 87.5$

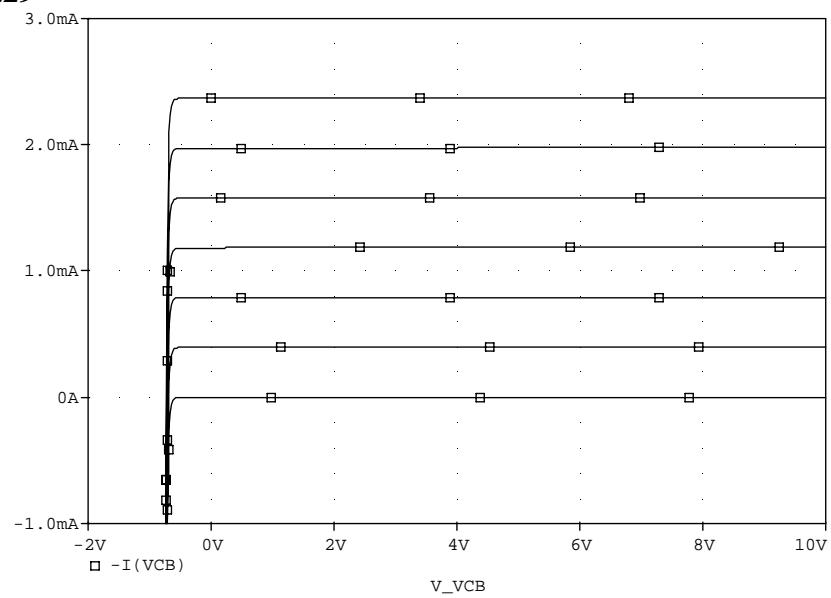
At $I_C = 10 \text{ mA}$ and $V_{CE} = 14 \text{ V}$, $I_B = 100 \mu\text{A}$: $\beta_F = \frac{I_C}{I_B} = \frac{10 \text{ mA}}{100 \mu\text{A}} = 100$

5.27

See Problem 5.28

5.28

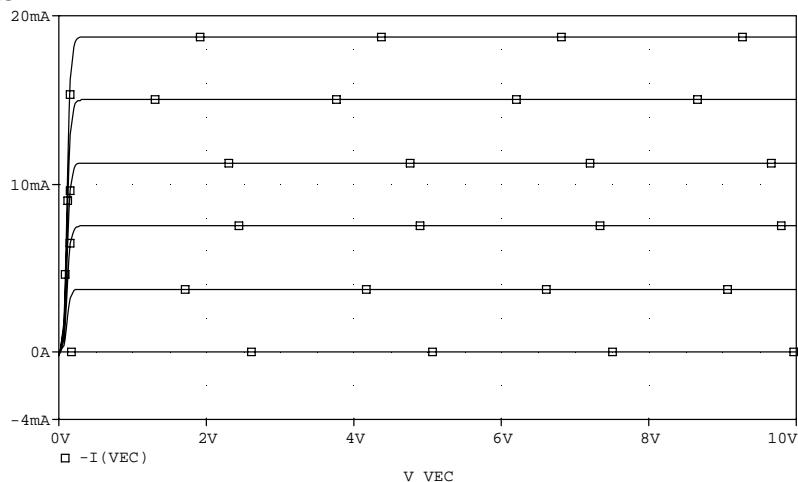
5.29



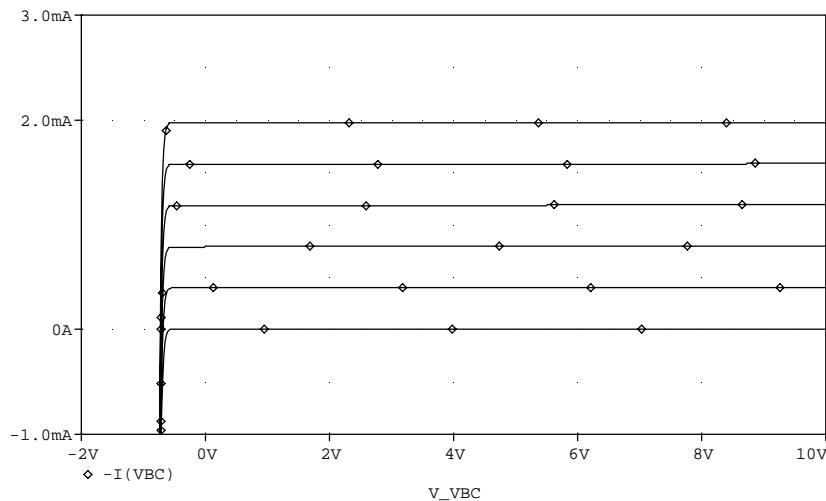
5.30

See Problem 5.31

5.31



5.32



5.33

The change in v_{BE} for a decade change in i_C is $\Delta V_{BE} = V_T \ln(10) = 2.30V_T$.

$$\text{The reciprocal of the slope is } 2.30V_T = 2.30 \frac{kT}{q} = 2.30 \left(\frac{1.38 \times 10^{-23}}{1.60 \times 10^{-19}} \right) T \text{ (V/dec)}$$

- (a) 39.6 mV/dec (b) 49.5 mV/dec (c) 59.4 mV/dec (d) 69.3 mV/dec

5.34

- (a) The break down voltage is equal to that of the emitter-base junction: $V_Z = 6$ V. (b) The break down voltage is determined by the base-collector junction: $V_Z = 50$ V. (c) The break down voltage is set by the emitter-base junction: $V_Z = 6$ V.

5.35

- (a) The base-emitter junction breaks down with $V_{EB} = 6.3$ V.

$$I_R = \frac{5 - 6.3 - (-5)}{1600} \frac{V}{\Omega} = 2.31 \text{ mA}$$

- (b) The base-emitter junction is forward biased; $V_{BE} = 0.7$ V

$$I_R = \frac{5 - 0.7 - (-5)}{24000} \frac{V}{\Omega} = 388 \mu\text{A}$$

- (c) $V_{BE} = 0$, and the collector-base junction is reversed biased with $V_{BC} \approx -10$ V which is less than the breakdown voltage of 75 V. The transistor is operating in cutoff.

$$\text{Using Eq. (5.13), } I_R = I_C = I_S(1 - 0) - \frac{I_S}{\beta_R}(0 - 1) = I_S \left(1 + \frac{1}{\beta_R} \right) \approx 0$$

5.36

$$V_{CE} = V_{CB} + V_{BE} = V_{CB} + 0.7 \leq 65.7 \text{ V}$$

5.37

(a) I_B is forced to be negative by the current source, and the largest negative base current according to the Transport model is

$$I_B = -I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right) = -10^{-15} A \left(\frac{1}{50} + \frac{1}{0.5} \right) = -2.02 fA$$

(b) I_B is forced to be -1 mA by the current source. One or both of the junctions must enter the breakdown region in order to supply this current. For the case of a normal BJT, the base-emitter junction will break down and supply the current since it has the lower reverse breakdown voltage.

5.38

Base-Emitter Voltage	Base-Collector Voltage	
	0.7 V	-5.0 V
-5.0 V	Reverse Active	Cutoff
0.7 V	Saturation	Forward Active

5.39

(a) $v_{BE} > 0, v_{BC} = 0$, forward-active region; $v_{BE} = 0, v_{BC} > 0$, reverse-active region; $v_{BE} > 0, v_{BC} = 0$, forward-active region

(b) $v_{EB} < 0, v_{CB} < 0$, cutoff region

(c) $v_{EB} > 0, v_{CB} < 0$, forward-active region

(d) $v_{BE} > 0, v_{BC} < 0$, forward-active region; $v_{BE} > 0, v_{BC} > 0$, saturation region

5.40

(a) $v_{BE} = 0, v_{BC} < 0$ cutoff region

(b) $v_{BC} < 0, I_E = 0$, cutoff region

5.41

(a) $v_{BE} > 0, v_{BC} > 0$ saturation region

(b) $v_{BE} > 0, v_{BC} = 0$, forward-active region

(c) $v_{BE} = 0, v_{BC} > 0$, reverse-active region

5.42

Emitter-Base Voltage	Collector-Base Voltage	
	0.7 V	-0.65 V
0.7 V	Saturation	Forward Active
-0.65 V	Reverse Active	Cutoff

5.43

- (a) $v_{BE} > 0, v_{BC} = 0$, forward-active region
- (b) $v_{BE} = 0, v_{BC} > 0$, reverse-active region

5.44

- (a) $v_{EB} = 0, v_{CB} > 0$, reverse-active region
- (b) $v_{EB} > 0, v_{CB} = 0$, forward-active region

5.45

- (a) $v_{EB} > 0, v_{CB} > 0$, saturation region
- (b) $v_{EB} > 0, v_{CB} = 0$, forward-active region
- (c) $v_{EB} = 0, v_{CB} > 0$, reverse-active region

5.46

(a) pnp transistor with $V_{EB} = -3V$ and $V_{CB} = -3V \rightarrow Cutoff$ | Using Eq. (5.17) :

$$I_C = +\frac{I_S}{\beta_R} = \frac{10^{-15} A}{2} = 0.5 \times 10^{-15} = 0.5 \text{ fA} \quad | \quad I_E = -\frac{I_S}{\beta_F} = \frac{10^{-15} A}{75} = 13.3 \times 10^{-18} = 13.3 \text{ aA}$$

$$I_B = -I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right) = 10^{-15} A \left(\frac{1}{75} + \frac{1}{4} \right) = 0.263 \times 10^{-15} = 0.263 \text{ fA}$$

(b) npn transistor with $V_{BE} = -5V$ and $V_{BC} = -5V \rightarrow Cutoff$ | The currents are the same as in part (a).

5.47

$$i_C = 10^{-16} \left[\exp\left(\frac{0.3}{0.025}\right) - \exp\left(\frac{-5}{0.025}\right) \right] - \frac{10^{-16}}{1} \left[\exp\left(\frac{-5}{0.025}\right) - 1 \right] = 16.3 \text{ pA}$$

$$i_E = 10^{-16} \left[\exp\left(\frac{0.3}{0.025}\right) - \exp\left(\frac{-5}{0.025}\right) \right] + \frac{10^{-16}}{19} \left[\exp\left(\frac{0.3}{0.025}\right) - 1 \right] = 17.1 \text{ pA}$$

$$i_B = \frac{10^{-16}}{19} \left[\exp\left(\frac{0.3}{0.025}\right) - 1 \right] + \frac{10^{-16}}{1} \left[\exp\left(\frac{-5}{0.025}\right) - 1 \right] = 0.857 \text{ pA}$$

These currents are all very small - for most practical purposes it still appears to be cutoff. Since $V_{BE} > 0$ and $V_{BC} < 0$, the transistor is actually operating in the forward-active region. Note that $I_C = \beta_F I_B$.

5.48

An npn transistor with $V_{BE} = 0.7V$ and $V_{BC} = -0.7V \rightarrow$ Forward - active region

$$\text{Using Eq. (5.45): } I_E = (\beta_F + 1)I_B \quad | \quad \beta_F = \frac{I_E}{I_B} - 1 = \frac{10mA}{0.15mA} - 1 = 65.7$$

$$I_E = I_S \left(1 + \frac{1}{\beta_F} \right) \exp \left(\frac{V_{BE}}{V_T} \right) \quad | \quad I_S = \frac{0.01A}{\left(1 + \frac{1}{65.7} \right) \exp \left(\frac{0.7}{0.025} \right)} = 6.81 \times 10^{-15} A = 6.81 fA$$

5.49

A pnp transistor with $V_{EB} = 0.7V$ and $V_{CB} = -0.7V \Rightarrow$ Forward - active region

$$\text{Using Eq. (5.44): } \beta_F = \frac{I_C}{I_B} = \frac{2.5mA}{0.04mA} = 62.5 \quad | \quad I_C = I_S \exp \left(\frac{V_{EB}}{V_T} \right) \quad | \quad I_S = \frac{2.5mA}{\exp \left(\frac{0.7V}{0.025V} \right)} = 1.73 fA$$

5.50

$$I_E = \frac{-0.7V - (-3.3V)}{47k\Omega} = 55.3\mu A \quad | \quad I_B = \frac{I_E}{\beta_F + 1} = \frac{55.3\mu A}{81} = 0.683\mu A$$

$$I_C = \beta_F I_B = 80(0.683\mu A) = 54.6\mu A \quad | \quad \text{Check: } I_B + I_C = I_E \text{ is ok}$$

5.51

$$(a) f_\beta = \frac{f_T}{\beta_F} = \frac{500 MHz}{759} = 6.67 MHz$$

$$(b) \text{ The graph represents the Bode magnitude plot. Thus } \beta(s) = \frac{\beta_F}{1 + \frac{s}{\omega_\beta}} = \frac{\beta_F \omega_\beta}{s + \omega_\beta} = \frac{\omega_T}{s + \omega_\beta}$$

$$\alpha(s) = \frac{\beta(s)}{\beta(s) + 1} = \frac{\frac{\omega_T}{s + \omega_\beta}}{\frac{\omega_T}{s + \omega_\beta} + 1} = \frac{\omega_T}{s + \omega_T + \omega_\beta} = \frac{\beta_F \omega_\beta}{s + (\beta_F + 1)\omega_\beta} = \frac{\frac{\beta_F}{\beta_F + 1}}{1 + \frac{s}{(\beta_F + 1)\omega_\beta}} \approx \frac{\alpha_F}{1 + \frac{s}{\omega_T}}$$

$$|\alpha(j\omega)| = \sqrt{1 + \left(\frac{\omega}{\omega_T} \right)^2}$$

5.52

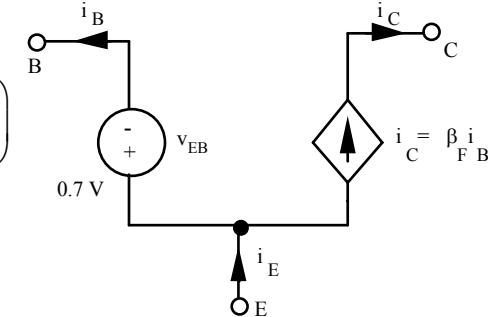
$$v_{EB} > 0 \quad v_{CB} < -4V_T$$

$$i_C = I_S \exp\left(\frac{V_{EB}}{V_T}\right) + \frac{I_S}{\beta_R} \approx I_S \exp\left(\frac{V_{EB}}{V_T}\right)$$

$$i_E = I_S \exp\left(\frac{V_{EB}}{V_T}\right) + \frac{I_S}{\beta_F} \exp\left(\frac{V_{EB}}{V_T}\right) = \frac{I_S}{\alpha_F} \exp\left(\frac{V_{EB}}{V_T}\right)$$

$$i_B = \frac{I_S}{\beta_F} \exp\left(\frac{V_{EB}}{V_T}\right) - \frac{I_S}{\beta_R} \approx \frac{I_S}{\beta_F} \exp\left(\frac{V_{EB}}{V_T}\right)$$

$$i_C = \beta_F i_B \quad | \quad i_C = \alpha_F i_E$$



5.53

An npn transistor with $V_{BE} = -0.7V$ and $V_{BC} = +0.7V \rightarrow$ Reverse - active region

$$\text{Using Eq. (5.51): } I_C = -(\beta_R + 1)I_B \quad | \quad \beta_R = -\frac{I_C}{I_B} - 1 = -\frac{-75\mu A}{40\mu A} - 1 = 0.875$$

$$I_E = -I_S \exp\left(\frac{V_{BC}}{V_T}\right) \quad | \quad I_E = -35\mu A \quad | \quad I_S = -\frac{-35\mu A}{\exp\left(\frac{0.7}{0.025}\right)} = 2.42 \times 10^{-17} A = 0.0242 fA = 24.2 aA$$

5.54

A pnp transistor with $V_{EB} = -0.7 V$ and $V_{CB} = +0.7 V \rightarrow$ Reverse – active region

$$i_C = -I_S \exp\left(\frac{V_{CB}}{V_T}\right) - \frac{I_S}{\beta_R} \exp\left(\frac{V_{CB}}{V_T}\right) = -\frac{I_S}{\alpha_R} \exp\left(\frac{V_{CB}}{V_T}\right)$$

$$i_E = -I_S \exp\left(\frac{V_{CB}}{V_T}\right) - \frac{I_S}{\beta_F} \approx -I_S \exp\left(\frac{V_{CB}}{V_T}\right)$$

$$i_B = -\frac{I_S}{\beta_F} + \frac{I_S}{\beta_R} \exp\left(\frac{V_{CB}}{V_T}\right) \approx \frac{I_S}{\beta_R} \exp\left(\frac{V_{CB}}{V_T}\right)$$

$$\beta_R = -\frac{i_E}{i_B} = -\frac{(-0.1mA)}{0.15mA} = 0.667 \quad | \quad I_S = -\frac{i_E}{\exp\left(\frac{V_{CB}}{V_T}\right)} = -\frac{-10^{-4} A}{\exp\left(\frac{0.7}{0.025}\right)} = 6.91 \times 10^{-17} A$$

5.55

$$I_C = -\frac{-0.7V - (-3.3V)}{56k\Omega} = -46.4 \mu A \quad | \quad I_B = -\frac{I_C}{\beta_R + 1} = -\frac{-46.4\mu A}{1.75} = 26.5 \mu A$$

$$I_E = I_C + I_B = -46.4\mu A + 26.5\mu A = -19.9 \mu A$$

5.56

$$\beta_{FOR} = \frac{I_C}{I_B} = \frac{1mA}{1mA} = 1 \quad | \quad V_{CESAT} = V_T \ln \left[\left(\frac{1}{\alpha_R} \right) \frac{1 + \frac{\beta_{FOR}}{(\beta_R + 1)}}{1 - \left(\frac{\beta_{FOR}}{\beta_F} \right)} \right] \quad | \quad \alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{2}{3}$$

$$V_{CESAT} = 0.025 \ln \left[\left(\frac{3}{2} \right) \frac{1 + \frac{1}{(2+1)}}{1 - \left(\frac{1}{50} \right)} \right] = 17.8 \text{ mV}$$

$$V_{BE} = V_T \ln \left[\frac{I_B + (1 - \alpha_R) I_C}{I_S \left(\frac{1}{\beta_F} + 1 - \alpha_R \right)} \right] = (0.025V) \ln \left[\frac{1mA + (1 - 0.667)1mA}{10^{-15} A (0.02 + 1 - 0.667)} \right] = 0.724 \text{ V}$$

5.57

$$i_C = I_S \exp \left(\frac{v_{EB}}{V_T} \right) - \frac{I_S}{\alpha_R} \exp \left(\frac{v_{CB}}{V_T} \right) \quad | \quad i_B = \frac{I_S}{\beta_F} \exp \left(\frac{v_{EB}}{V_T} \right) + \frac{I_S}{\beta_R} \exp \left(\frac{v_{CB}}{V_T} \right) \quad | \quad \text{Simultaneous}$$

solution yields: $v_{EB} = V_T \ln \frac{i_B + (1 - \alpha_R) i_C}{I_S \left[\frac{1}{\beta_F} + (1 - \alpha_R) \right]}$ | $v_{CB} = V_T \ln \frac{i_B - \frac{i_C}{\beta_F}}{I_S \left[\frac{1}{\alpha_R} \right] \frac{1}{\beta_F} + (1 - \alpha_R)}$

$$v_{ECSAT} = v_{EB} - v_{CB} = V_T \ln \left[\left(\frac{1}{\alpha_R} \right) \frac{1 + \frac{i_C}{(\beta_R + 1) i_B}}{1 - \frac{i_C}{\beta_F i_B}} \right] \text{ for } i_B > \frac{i_C}{\beta_F}$$

5.58

(a) Substituting $i_C = 0$ in Eq. 5.30 gives

$$V_{CESAT} = V_T \ln \left(\frac{1}{\alpha_R} \right) = (0.025V) \ln \left(\frac{1}{0.5} \right) = 0.0173 \text{ V} = 17.3 \text{ mV}$$

(b) By symmetry

$$V_{ECSAT} = V_T \ln \left(\frac{1}{\alpha_F} \right)$$

or by using $i_E = 0$ and $i_C = -i_B$,

$$V_{CESAT} = V_T \ln\left(\frac{1}{\alpha_R}\right) \frac{1 - \frac{\beta_R}{\beta_R + 1}}{1 + \frac{1}{\beta_F}} = V_T \ln\left(\frac{1}{\alpha_R}\right) \frac{\beta_R}{\beta_F + 1} = V_T \ln\left(\frac{1}{\alpha_R}\right) \frac{\alpha_R}{\alpha_F}$$

$$V_{CESAT} = V_T \ln(\alpha_F) \text{ and } V_{ECSAT} = V_T \ln\left(\frac{1}{\alpha_F}\right)$$

$$V_{ECSAT} = V_T \ln\left(\frac{1}{\alpha_F}\right) = (0.025V) \ln\left(\frac{1}{0.99}\right) = 0.000251 \text{ V} = 0.251 \text{ mV}$$

5.59

(a) Substituting $i_C = 0$ in Eq. 5.30 gives

$$V_{CESAT} = V_T \ln\left(\frac{1}{\alpha_R}\right) = (0.025V) \ln\left(\frac{1}{0.33}\right) = 27.7 \text{ mV}$$

(b) By symmetry

$$V_{ECSAT} = V_T \ln\left(\frac{1}{\alpha_F}\right) = (0.025V) \ln\left(\frac{1}{0.95}\right) = 1.28 \text{ mV}$$

5.60

$$(a) V_{CESAT} = V_T \ln\left(\frac{1}{\alpha_R}\right) \frac{1 + \frac{\beta_{FOR}}{(\beta_R + 1)}}{1 - \left(\frac{\beta_{FOR}}{\beta_F}\right)} \mid \alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{0.9}{0.9 + 1} = 0.4737$$

$$0.1 = 0.025 \ln\left(\frac{1}{0.4737}\right) \frac{1 + \frac{\beta_{FOR}}{(0.9 + 1)}}{1 - \left(\frac{\beta_{FOR}}{15}\right)} \rightarrow \beta_{FOR} = 11.05$$

$$0.4737 \exp(4) = \frac{1 + \frac{\beta_{FOR}}{(0.9 + 1)}}{1 - \left(\frac{\beta_{FOR}}{15}\right)} \rightarrow \beta_{FOR} = 11.05 \mid I_B = \frac{I_C}{\beta_{FOR}} = \frac{20A}{11.05} = 1.81A$$

$$(b) 0.04 = 0.025 \ln\left(\frac{1}{0.4737}\right) \frac{1 + \frac{\beta_{FOR}}{(0.9 + 1)}}{1 - \left(\frac{\beta_{FOR}}{15}\right)} \rightarrow \beta_{FOR} = 1.97 \mid I_B = \frac{I_C}{\beta_{FOR}} = \frac{20A}{1.97} = 10.1A$$

5.61

With $V_{BE} = 0.7$ and $V_{BC} = 0.5$, the transistor is technically in the saturation region, but calculating the currents using the transport model in Eq. (5.13) yields

$$i_C = 10^{-16} \left[\exp\left(\frac{0.7}{0.025}\right) - \exp\left(\frac{0.5}{0.025}\right) \right] - \frac{10^{-16}}{1} \left[\exp\left(\frac{0.5}{0.025}\right) - 1 \right] = 144.5 \mu A$$

$$i_E = 10^{-16} \left[\exp\left(\frac{0.7}{0.025}\right) - \exp\left(\frac{0.5}{0.025}\right) \right] + \frac{10^{-16}}{39} \left[\exp\left(\frac{0.7}{0.025}\right) - 1 \right] = 148.3 \mu A$$

$$i_B = \frac{10^{-16}}{39} \left[\exp\left(\frac{0.7}{0.025}\right) - 1 \right] + \frac{10^{-16}}{1} \left[\exp\left(\frac{0.5}{0.025}\right) - 1 \right] = 3.757 \mu A$$

At 0.5 V, the collector-base junction is not heavily forward biased compared to the base-emitter junction, and $I_C = 38.5I_B \approx \beta_F I_B$. The transistor still acts as if it is operating in the forward-active region.

5.62

(a) The current source will forward bias the base - emitter junction ($V_{BE} \approx 0.7V$) and the collector - base junction will then be reverse biased ($V_{BC} \approx -2.3V$). Therefore, the npn transistor is in the forward - active region.

$$I_C = \beta_F I_B = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \quad | \quad V_{BE} = 0.025 \ln\left(\frac{50(175 \times 10^{-6} A)}{10^{-16} A}\right) = 0.803 V$$

(b) Since $I_B = 175 \mu A$ and $I_C = 0$, $I_C < \beta_F I_B$, and the transistor is saturated.

$$\text{Using Eq. (5.53): } V_{BE} = 0.025 \ln \frac{175 \times 10^{-6} + 0}{10^{-16} \left[\frac{1}{50} + \left(1 - \frac{.5}{1.5} \right) \right]} = 0.714 V \quad | \quad \text{Using Eq. (5.54) with } i_C = 0,$$

$$V_{CESAT} = 0.025 \ln\left(\frac{1}{\alpha_R}\right) = 0.025 \ln\left(\frac{\beta_R + 1}{\beta_R}\right) = 0.025 \ln\left(\frac{1.5}{0.5}\right) = 27.5 \text{ mV}$$

5.63

$$i_C = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right) \right] + \frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]$$

$$i_E = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right) \right] + \frac{I_S}{\beta_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right]$$

$$v_{BE} > 4V_T \text{ and } v_{BC} < -4V_T$$

$$i_C \cong I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) \right] \text{ and } i_E = I_S \left(1 + \frac{1}{\beta_F} \right) \left[\exp\left(\frac{v_{BE}}{V_T}\right) \right] = \frac{I_S}{\alpha_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) \right] \rightarrow i_C \cong \alpha_F i_E$$

$$v_{BE} \cong V_T \ln\left(\frac{i_C}{I_S}\right) = V_T \ln\left(\frac{\alpha_F i_E}{I_S}\right)$$

5.64

$$I_{SD} = \frac{I_S}{\alpha_F} = \frac{1fA}{0.98} = 1.02 \text{ fA}$$

5.65

Both transistors are in the forward - active region. For simplicity, assume $V_A = \infty$.

$I = I_{C1} + I_{B1} + I_{B2}$ | Since the transistors are identical and have the same V_{BE} ,

$$I_{C2} = I_{C1} \text{ and } I_{B1} = I_{B2} \quad | \quad I = I_{C1} + 2I_{B1} = (\beta_F + 2)I_{B1} \quad | \quad I_{C2} = \beta_F I_{B2} = \beta_F I_{B1}$$

$$I_{C2} = \frac{\beta_F}{\beta_F + 2} I = \frac{25}{25+2} 25\mu A \quad | \quad I_{C2} = 23.2 \mu A \quad | \quad \text{See the Current Mirror in Chapter 15.}$$

5.66

$$C_D = \frac{I_C}{V_T} \tau_F = \frac{50 \times 10^{-12}}{0.025} I_C = 2 \times 10^{-9} I_C \text{ (F)} \quad (\text{a) } 4 \text{ fF} \quad (\text{b) } 0.4 \text{ pF} \quad (\text{c) } 40 \text{ pF}$$

5.67

Using Fig. 2.8 with $N = \frac{10^{18}}{\text{cm}^3}$, $\mu_n = 260 \frac{\text{cm}^2}{\text{V} \cdot \text{s}}$ and $\mu_p = 100 \frac{\text{cm}^2}{\text{V} \cdot \text{s}}$

$$(a) npn : \tau_F = \frac{W_B^2}{2D_n} = \frac{W_B^2}{2V_T \mu_n} = \frac{(1 \times 10^{-4} \text{ cm})^2}{2(0.025 \text{ V}) \left(260 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \right)} = 0.769 \text{ ns}$$

$$(b) pnp : \tau_F = \frac{W_B^2}{2D_p} = \frac{W_B^2}{2V_T \mu_p} = \frac{(1 \times 10^{-4} \text{ cm})^2}{2(0.025 \text{ V}) \left(100 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \right)} = 2.00 \text{ ns}$$

5.68

$$\text{For } f \gg f_\beta, f_T = \beta \cdot f = 10(75 \text{ MHz}) = 750 \text{ MHz} \quad | \quad f_\beta = \frac{f_T}{\beta_F} = \frac{750 \text{ MHz}}{200} = 3.75 \text{ MHz}$$

5.69

$$\beta_F = \frac{f_T}{f_\beta} = \frac{900 \text{ MHz}}{5 \text{ MHz}} = 180 \quad | \quad \text{For } f \gg 5 \text{ MHz}, \beta(f) = \frac{f_T}{f} = \frac{900 \text{ MHz}}{50 \text{ MHz}} = 18$$

5.70

$$N_A = \frac{6 \times 10^{18}}{\text{cm}^3} \rightarrow \mu_n = 130 \frac{\text{cm}^2}{\nu - s} \text{ using Fig. 2.8. } D_n = \mu_n V_T = 130 \frac{\text{cm}^2}{\nu - s} (0.025V) = 3.25 \frac{\text{cm}^2}{\text{s}}$$

$$I_s = \frac{qAD_n n_i^2}{N_A W_B} = \frac{1.60 \times 10^{-19} C (25 \times 10^{-8} \text{ cm}^2) \left(3.25 \frac{\text{cm}^2}{\text{s}} \right) \left(\frac{10^{20}}{\text{cm}^6} \right)}{\frac{6 \times 10^{18}}{\text{cm}^3} (0.4 \times 10^{-4} \text{ cm})} = 5.42 \times 10^{-20} \text{ A}$$

5.71

$$W_B = \sqrt{2D_n \tau_F} \quad | \quad \tau_F \leq \frac{1}{2\pi f} = \frac{1}{2\pi (5 \times 10^9)} = 31.8 \text{ ps}$$

$$N_A = \frac{5 \times 10^{18}}{\text{cm}^3} \rightarrow \mu_n = 135 \frac{\text{cm}^2}{\nu - s} \text{ using Fig. 2.8.}$$

$$D_n = \mu_n V_T = 135 \frac{\text{cm}^2}{\nu - s} (0.025V) = 3.38 \frac{\text{cm}^2}{\text{s}}$$

$$W_B \leq \sqrt{2 \left(3.38 \frac{\text{cm}^2}{\text{s}} \right) 31.8 \times 10^{-12} \text{ s}} = 0.147 \text{ } \mu\text{m}$$

5.72

$$I_C = \beta_F I_B = \beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) I_B \quad | \quad \beta_{FO} \left(1 + \frac{5}{V_A} \right) = \frac{240 \mu\text{A}}{3 \mu\text{A}} \text{ and } \beta_{FO} \left(1 + \frac{10}{V_A} \right) = \frac{265 \mu\text{A}}{3 \mu\text{A}}$$

$$\frac{\left(1 + \frac{10}{V_A} \right)}{\left(1 + \frac{5}{V_A} \right)} = \frac{265 \mu\text{A}}{240 \mu\text{A}} \Rightarrow V_A = 43.1 \text{ V} \quad | \quad \beta_{FO} = \frac{80}{\left(1 + \frac{5}{43.1} \right)} = 71.7$$

5.73

$$(a) I_C = I_s \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right] \left[1 + \frac{V_{CE}}{V_A} \right] = 10^{-16} A \left[\exp\left(\frac{0.72V}{0.025V}\right) - 1 \right] \left[1 + \frac{10V}{65V} \right] = 371 \mu A$$

$$(b) I_C = I_s \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right] = 10^{-16} A \left[\exp\left(\frac{0.72V}{0.025V}\right) - 1 \right] = 322 \mu A$$

(c) 1.15 : 1 (a) is 15% larger than (b) due to the Early effect.

5.74

$$I_C = \beta_F I_B = \beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) I_B \quad | \quad \text{We need two Q - points from the output characteristics.}$$

For example : (10 mA, 14 V) and (5 mA, 5 V)

$$10mA = \beta_{FO} \left(1 + \frac{14}{V_A} \right) 0.1mA \quad \text{and} \quad 5mA = \beta_{FO} \left(1 + \frac{5}{V_A} \right) 0.06mA \quad \text{yields}$$

$$100 = \beta_{FO} \left(1 + \frac{14}{V_A} \right) \quad \text{and} \quad 83.3 = \beta_{FO} \left(1 + \frac{5}{V_A} \right). \quad \text{Solving these two equations yields}$$

$$\beta_{FO} = 72.9 \quad \text{and} \quad V_A = 37.6 V.$$

5.75

$$\text{Fig. 5.16(a)}: I_E = I_C + I_B = \left[\beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) + 1 \right] I_B \cong \left[\beta_{FO} \left(1 + \frac{V_{CB} + V_{BE}}{V_A} \right) + 1 \right] \frac{I_s}{\beta_{FO}} \exp\left(\frac{V_{BE}}{V_T}\right) \\ \left[1 + \frac{5 + V_{BE}}{50} + \frac{1}{19} \right] \left(5 \times 10^{-15} \right) \exp\left(\frac{V_{BE}}{0.025}\right) = 100 \mu A \rightarrow V_{BE} = 0.589V \text{ by iteration}$$

$$I_B = \frac{100 \mu A}{\left[19 \left(1 + \frac{5.589}{50} \right) + 1 \right]} = 4.52 \mu A \quad | \quad I_C = 19 \left(1 + \frac{5.589}{50} \right) I_B = 95.48 \mu A$$

$$\text{For } V_A = \infty, I_E = I_s \exp\left(\frac{V_{BE}}{V_T}\right) \quad | \quad V_{BE} = 0.025 \ln \frac{100 \mu A}{5 fA} = 0.593 V$$

$$\text{Fig. 5.16(b)}: I_B = \frac{I_s}{\beta_{FO}} \exp\left(\frac{V_{BE}}{V_T}\right) \rightarrow V_{BE} = 0.025 \ln \frac{19(100 \mu A)}{5 fA} = 0.667 V$$

$$I_C = \beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) I_B = 19 \left(1 + \frac{5}{50} \right) 100 \mu A = 2.09 mA \quad | \quad I_E = I_C + I_B = 2.19 mA$$

V_{BE} is independent of V_A in the equation above.

5.76

$$I_C = \beta_F I_B \quad | \quad I_E = (\beta_F + 1) I_B \quad | \quad \beta_F = \beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) = 50 \left(1 + \frac{9 + 0.7}{50} \right) = 59.7$$

$$I_E = \frac{(9 - 0.7)V}{8200\Omega} = 1.01 \text{ mA} \quad | \quad I_B = \frac{I_E}{\beta_F + 1} = \frac{1.01 \text{ mA}}{60.7} = 16.7 \text{ } \mu\text{A} \quad | \quad I_C = 59.7 I_B = 0.996 \text{ mA}$$

5.77

$$g_m = \frac{I_C}{V_T} \quad | \quad V_T = \frac{kT}{q} = \frac{(1.38 \times 10^{-23} \text{ J/K})(300 \text{ K})}{1.60 \times 10^{-19} \text{ C}} = 25.9 \text{ mV}$$

$$(a) g_m = \frac{10^{-5} \text{ A}}{V_T} = 0.387 \text{ mS} \quad (b) g_m = \frac{10^{-4} \text{ A}}{V_T} = 3.87 \text{ mS}$$

$$(c) g_m = \frac{10^{-3} \text{ A}}{V_T} = 38.7 \text{ mS} \quad (d) g_m = \frac{10^{-2} \text{ A}}{V_T} = 0.387 \text{ S}$$

(e) The values of g_m are the same for the pnp.

5.78

$$C_D = \frac{I_C}{V_T} \tau_F = \frac{10 \times 10^{-12}}{0.0258} I_C = 3.88 \times 10^{-10} I_C \text{ (F)} \quad (a) \text{ 0.388 fF} \quad (b) \text{ 0.388 pF} \quad (c) \text{ 3.88 pF}$$

5.79

The following are from the Cadence website and the file psrefman.pdf:

IS = 10fA, BF = 100, BR = 1, VAF = ∞ , VAR = ∞ , TF = 0, TR = 0,

NF = 1, NE = 1.5, RB = 0, RC = 0, RE = 0, ISE = 0, ISC = 0, ISS = 0,

IKF = ∞ , IKR = ∞ , CJF = 0, CJC = 0.

These default values apply to both npn and pnp transistors.

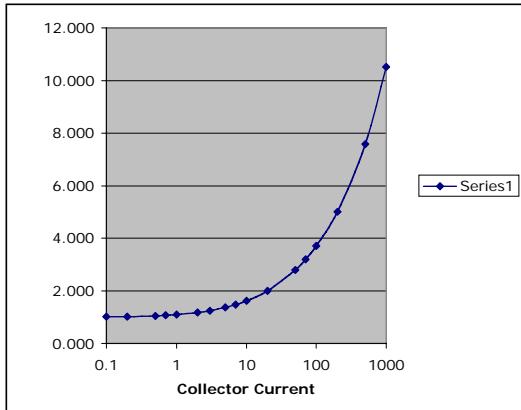
5.80

$$(a) KBQ = \frac{1 + \left[1 + 4 \left(\frac{i_F}{IKF} \right) \right]^{NK}}{2} = \frac{1 + \sqrt{1 + 4 \left(\frac{1 \text{ mA}}{10 \text{ mA}} \right)}}{2} = 1.09 \rightarrow 8.3\% \text{ reduction}$$

$$(a) KBQ = \frac{1 + \sqrt{1 + 4 \left(\frac{10 \text{ mA}}{10 \text{ mA}} \right)}}{2} = 1.62 \quad | \quad i_C = \frac{i_F}{1.62} = 0.62i_F \rightarrow 38\% \text{ reduction}$$

$$(a) KBQ = \frac{1 + \sqrt{1 + 4 \left(\frac{50 \text{ mA}}{10 \text{ mA}} \right)}}{2} = 2.79 \quad | \quad i_C = \frac{i_F}{2.79} = 0.36i_F \rightarrow 64\% \text{ reduction}$$

5.81



5.82

$$(a) V_{EQ} = \frac{36k\Omega}{36k\Omega + 68k\Omega} 10V = 3.462V \quad | \quad R_{EQ} = 36k\Omega \parallel 68k\Omega = 23.54k\Omega$$

$$I_B = \frac{3.462 - 0.7}{23.54 + (50+1)\beta_3} \frac{V}{k\Omega} = 1.618\mu A \quad | \quad I_C = 50I_B = 80.9 \mu A \quad | \quad I_E = 51I_B = 82.5 \mu A$$

$$V_{CE} = 10 - 43000I_C - 33000I_E = 3.797V \quad | \quad \text{Q-point: } (80.9 \mu A, 3.80 V)$$

$$(b) V_{EQ} = \frac{7.2k\Omega}{7.2k\Omega + 13.6k\Omega} 10V = 3.462V \quad | \quad R_{EQ} = 7.2k\Omega \parallel 13.6k\Omega = 4.708k\Omega$$

$$I_B = \frac{3.462 - 0.7}{4.708 + (50+1)\beta_3} \frac{V}{k\Omega} = 8.092\mu A \quad | \quad I_C = 50I_B = 404.6\mu A \quad | \quad I_E = 51I_B = 412.7 \mu A$$

$$V_{CE} = 10 - 8600I_C - 6600I_E = 3.7976V \quad | \quad \text{Q-point: } (405 \mu A, 3.80 V)$$

$$(c) V_{EQ} = \frac{68k\Omega}{36k\Omega + 68k\Omega} 10V = 6.538V \quad | \quad R_{EQ} = 36k\Omega \parallel 68k\Omega = 23.54k\Omega$$

$$I_B = \frac{10 - 0.7 - 6.538}{23.54 + (50+1)\beta_3} \frac{V}{k\Omega} = 1.618\mu A \quad | \quad I_C = 50I_B = 80.9 \mu A \quad | \quad I_E = 51I_B = 82.5 \mu A$$

$$V_{CE} = 10 - 33000I_C - 43000I_E = 3.797V \quad | \quad \text{Q-point: } (80.9 \mu A, 3.80 V)$$

$$(b) V_{EQ} = \frac{13.6k\Omega}{7.2k\Omega + 13.6k\Omega} 10V = 6.538V \quad | \quad R_{EQ} = 7.2k\Omega \parallel 13.6k\Omega = 4.708k\Omega$$

$$I_B = \frac{10 - 0.7 - 6.538}{4.708 + (50+1)\beta_3} \frac{V}{k\Omega} = 8.092\mu A \quad | \quad I_C = 50I_B = 404.6\mu A \quad | \quad I_E = 51I_B = 412.7 \mu A$$

$$V_{CE} = 10 - 6600I_C - 8600I_E = 3.7976V \quad | \quad \text{Q-point: } (405 \mu A, 3.80 V)$$

5.83

$$(a) V_{EQ} = \frac{36k\Omega}{36k\Omega + 68k\Omega} 10V = 3.462V \quad | \quad R_{EQ} = 36k\Omega \parallel 68k\Omega = 23.54k\Omega$$

$$I_B = \frac{3.462 - 0.7}{23.54 + (75+1)\parallel 2} \frac{V}{k\Omega} = 1.629\mu A \quad | \quad I_C = 75I_B = 122.2\mu A \quad | \quad I_E = 76I_B = 123.8\mu A$$

$$V_{CE} = 10 - 43000I_C - 22000I_E = 2.022V \quad | \quad \text{Q-point: } (122\mu A, 2.02V)$$

$$(b) V_{EQ} = \frac{68k\Omega}{36k\Omega + 68k\Omega} 10V = 6.538V \quad | \quad R_{EQ} = 36k\Omega \parallel 68k\Omega = 23.54k\Omega$$

$$I_B = \frac{10 - 0.7 - 6.538}{23.54 + (75+1)\parallel 2} \frac{V}{k\Omega} = 1.629\mu A \quad | \quad I_C = 75I_B = 122.2\mu A \quad | \quad I_E = 76I_B = 123.8\mu A$$

$$V_{EC} = 10 - 22000I_C - 43000I_E = 2.022V \quad | \quad \text{Q-point: } (122\mu A, 2.02V)$$

5.84

*Problem 5.83(a)
VCC 1 0 10
R1 3 0 36K
R2 1 3 68K
RC 1 2 43K
RE 4 0 33K
Q1 2 3 4 NPN
.MODEL NPN NPN IS=1E-16 BF=50 BR=0.25
.OP
.END

*Problem 5.83(b)
VCC 1 0 10
R1 3 0 36K
R2 1 3 68K
RC 1 2 43K
RE 4 0 33K
Q1 2 3 4 NPN
.MODEL NPN NPN IS=1E-16 BF=50 BR=0.25 VAF=60
.OP
.END

*Problem 5.83(c)
VCC 1 0 10
R1 1 3 36K
R2 3 0 68K
RC 4 0 43K
RE 1 2 33K
Q1 4 3 2 PNP
.MODEL PNP PNP IS=1E-16 BF=50 BR=0.25
.OP
.END

*Problem 5.83(d)
VCC 1 0 10

R1 1 3 36K
 R2 3 0 68K
 RC 4 0 43K
 RE 1 2 33K
 Q1 4 3 2 PNP
 .MODEL PNP PNP IS=1E-16 BF=50 BR=0.25 VAF=60
 .OP
 .END

5.85

$$V_{EQ} = 10 \frac{6.2k\Omega}{6.2k\Omega + 12k\Omega} = 3.41V \text{ and } R_{EQ} = 6.2k\Omega \parallel 12k\Omega = 4.09k\Omega$$

$$I_C = \beta_F I_B = 100 \frac{3.41 - 0.7}{4090 + 101(7500)} = 0.356mA.$$

$$V_{CE} = 10 - 0.356mA(5.1k\Omega) - \frac{101}{100}0.356mA(7.5k\Omega) = 5.49V$$

Q-point : (0.356 mA, 5.49 V)

5.86

$$V_{EQ} = 15 \frac{120k\Omega}{120k\Omega + 240k\Omega} = 5.00V \text{ and } R_{EQ} = 120k\Omega \parallel 240k\Omega = 80k\Omega$$

$$I_C = \beta_F I_B = 100 \frac{5.00 - 0.700}{80000 + 101(100000)} = 42.2\mu A.$$

$$V_{CE} = 15 - 42.2 \times 10^{-6} A(10^5 \Omega) - \frac{101}{100}42.2 \times 10^{-6} A(1.5 \times 10^5 \Omega) = 4.39V$$

Q-point : (42.2 μA, 4.39 V)

5.87

$$(a) I_E = \frac{I_C}{\alpha_F} = \left(\frac{101}{100} \right) 1mA = 1.01mA \quad | \quad R_E = \frac{2V}{1.01mA} = 1.98k\Omega \rightarrow 2.0 k\Omega$$

$$R_C = \frac{(12 - 5 - 2)V}{1.00mA} = 5k\Omega \rightarrow 5.1 k\Omega \quad | \quad V_B = 2 + 0.7 = 2.7V$$

$$\text{Set } R_1 = \frac{V_B}{10I_B} = \frac{2.7V}{10(0.01mA)} = 27k\Omega \rightarrow 27 k\Omega$$

$$R_2 = \frac{(12 - 2.7)V}{11I_B} = \frac{9.3V}{11(0.01mA)} = 84.55k\Omega \rightarrow 82 k\Omega$$

$$(b) V_{EQ} = \frac{27k\Omega}{27k\Omega + 82k\Omega} 12V = 2.972V \quad | \quad R_{EQ} = 27k\Omega \parallel 82k\Omega = 20.31k\Omega$$

$$I_B = \frac{2.972 - 0.7}{20.31 + (100+1)} \frac{V}{k\Omega} = 10.22\mu A \quad | \quad I_C = 100I_B = 1.022mA \quad | \quad I_E = 101I_B = 1.033mA$$

$$V_{CE} = 12 - 5100I_C - 2000I_E = 4.723V \quad | \quad Q\text{-point: } (1.02mA, 4.72V)$$

5.88

$$(a) I_E = \frac{I_C}{\alpha_F} = \left(\frac{76}{75} \right) 10\mu A = 10.13\mu A \quad | \quad \text{Let } V_{R_C} = V_{R_E} = V_{CE} = 6V$$

$$R_E = \frac{6V}{10.13\mu A} = 592k\Omega \rightarrow 620k\Omega$$

$$R_C = \frac{6V}{10\mu A} = 600k\Omega \rightarrow 620k\Omega \quad | \quad V_B = 6 + 0.7 = 6.7V$$

$$\text{Set } R_1 = \frac{V_B}{10I_B} = \frac{6.7V}{10 \left(\frac{10\mu A}{75} \right)} = 5.03M\Omega \rightarrow 5.1M\Omega$$

$$R_2 = \frac{(18 - 6.7)V}{11I_B} = \frac{11.3V}{11 \left(\frac{10\mu A}{75} \right)} = 7.71M\Omega \rightarrow 7.5M\Omega$$

$$(b) V_{EQ} = \frac{5.1M\Omega}{5.1M\Omega + 7.5M\Omega} 18V = 7.286V \quad | \quad R_{EQ} = 5.1M\Omega \parallel 7.5M\Omega = 3.036M\Omega$$

$$I_B = \frac{7.286 - 0.7}{3036 + (75+1)} \frac{V}{k\Omega} = 0.1313\mu A \quad | \quad I_C = 75I_B = 9.848\mu A \quad | \quad I_E = 76I_B = 9.980\mu A$$

$$V_{CE} = 18 - 620000I_C - 620000I_E = 5.707V \quad | \quad Q\text{-point: } (9.85\mu A, 5.71V)$$

5.89

$$(a) I_E = \frac{I_C}{\alpha_F} = \left(\frac{61}{60} \right) 850\mu A = 864.2\mu A \quad | \quad R_E = \frac{1V}{864.2\mu A} = 1.16k\Omega \rightarrow 1.2k\Omega$$

$$R_C = \frac{(5 - 2 - 1)V}{850\mu A} = 2.35k\Omega \rightarrow 2.4k\Omega \quad | \quad V_B = 5 - 1 - 0.7 = 3.3V$$

$$\text{Set } R_1 = \frac{V_{R_1}}{10I_B} = \frac{5 - 3.3V}{10 \left(\frac{850\mu A}{60} \right)} = 12.0k\Omega \rightarrow 12k\Omega$$

$$R_2 = \frac{V_{R_2}}{11I_B} = \frac{3.3V}{11 \left(\frac{850\mu A}{60} \right)} = 21.2k\Omega \rightarrow 22k\Omega$$

$$(b) V_{EQ} = \frac{22k\Omega}{12k\Omega + 22k\Omega} 5V = 3.24V \quad | \quad R_{EQ} = 12k\Omega \parallel 22k\Omega = 7.77k\Omega$$

$$I_B = \frac{5 - 0.7 - 3.24}{7.77 + (60+1) \cdot 1.2} \frac{V}{k\Omega} = 13.1\mu A \quad | \quad I_C = 60I_B = 786\mu A \quad | \quad I_E = 61I_B = 799\mu A$$

$$V_{CE} = 5 - 1200I_E - 2400I_C = 2.14V \quad | \quad \text{Q-point: } (786 \mu A, 2.14 V)$$

5.90

$$(a) V_{R_E} = 1V, V_{R_C} = 9V \quad | \quad I_B = \frac{11mA}{50} = 0.220mA$$

$$I_E = \frac{I_C}{\alpha_F} = \left(\frac{51}{50} \right) 11mA = 11.22mA \quad | \quad R_E = \frac{1V}{11.22mA} = 89.1\Omega \rightarrow 91\Omega$$

$$R_C = \frac{9V}{11.0mA} = 818\Omega \rightarrow 820\Omega \quad | \quad V_B = -15 + 1 + 0.7 = -13.3V$$

$$\text{Set } R_I = \frac{V_{R_I}}{10I_B} = \frac{-13.3V - (-15V)}{10(0.220mA)} = 772\Omega \rightarrow 750\Omega$$

$$R_2 = \frac{0 - (13.3V)}{11I_B} = \frac{13.3V}{11(0.220mA)} = 5.50k\Omega \rightarrow 5.6k\Omega$$

$$(b) V_{EQ} = \frac{5.6k\Omega}{0.75k\Omega + 5.6k\Omega} (-15V) = -13.2V \quad | \quad R_{EQ} = 0.75k\Omega \parallel 5.6k\Omega = 0.661k\Omega$$

$$I_B = \frac{-13.2 - 0.7 - (-15)V}{661 + (50+1)(91)} \frac{V}{\Omega} = 0.207mA \quad | \quad I_C = 50I_B = 10.3mA \quad | \quad I_E = 51I_B = 10.6mA$$

$$V_{CE} = 0 - 820I_C - 91I_E - (-15V) = 5.59V \quad | \quad \text{Q-point: } (10.2 mA, 5.59 V)$$

5.91 Problem numbers on graph

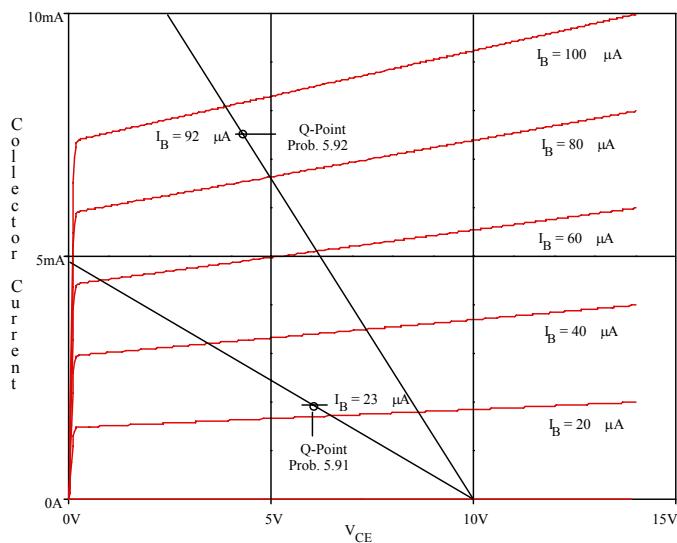
$$V_{EQ} = \frac{3.3k\Omega}{3.3k\Omega + 7.5k\Omega} 10V = 3.056V \quad | \quad R_{EQ} = 7.5k\Omega \parallel 3.3k\Omega = 2.292k\Omega$$

$$V_{CE} = 10 - 820I_C - 1200I_E \quad | \quad \text{From characteristics at } V_{CE} = 5V : \beta_F \approx \frac{5mA}{60\mu A} = 83$$

$$V_{CE} = 10 - 820I_C - 1200 \frac{84}{83} I_C = 10 - 2034I_C$$

Load line points: $I_C = 0, V_{CE} = 10V$ and $V_{CE} = 0, I_C = 4.9mA$

$$I_B = \frac{3.056 - 0.7}{2292 + (83+1)1200} = 23\mu A \quad | \quad \text{From Graph: Q-point: } (1.9 mA, 6.0 V)$$



5.92

$$V_{EQ} = \frac{6.8k\Omega}{6.8k\Omega + 3.6k\Omega}(10) = 6.538V \quad | \quad R_{EQ} = 6.8k\Omega \parallel 3.6k\Omega = 2.354k\Omega$$

$$V_{EC} = 10 - 420I_C - 330I_E \quad | \quad \text{From characteristics at } V_{EC} = 5V : \beta_F \cong \frac{5mA}{60\mu A} = 83$$

$$V_{EC} = 10 - 420I_C - 3300 \frac{84}{83} I_C = 10 - 754I_C$$

Load line points: $I_C = 0, V_{EC} = 10V$ and $V_{EC} = 0, I_C = 13.3mA$ – off the graph

$$V_{EC} = 5V, I_C = 6.63mA \quad | \quad I_B = \frac{10 - 0.7 - 6.538}{2354 + (83+1)\beta 30} = 92\mu A$$

From Graph: Q-point: $(7.5 mA, 4.3 V)$

5.93

Writing a loop equation starting at the 9 V supply gives: $9 = 1500(I_C + I_B) + 10000I_B + V_{BE}$
 Assuming forward-active region operation, $V_{BE} = 0.7$ V and $I_C = \beta_F I_B$.

$$9 = 1500(\beta_F I_B + I_B) + 10000I_B + 0.7$$

$$I_B = \frac{9 - 0.7}{1500(\beta_F + 1) + 1000} \quad \text{and} \quad I_C = \beta_F I_B = \frac{\beta_F(9 - 0.7)}{1500(\beta_F + 1) + 1000}$$

$$(a) I_C = \frac{30(9 - 0.7)V}{1.5kW(30 + 1) + 10kW} = 4.41 \text{ mA} \quad | \quad V_{CE} = 9 - 1500I_E = 2.17V \quad | \quad \text{Q-pt: } (4.41\text{mA}, 2.17\text{V})$$

$$(b) I_C = \frac{100(9 - 0.7)V}{1.5k\Omega(100 + 1) + 10k\Omega} = 5.14 \text{ mA} \quad | \quad V_{CE} = 9 - 1500I_E = 1.21V \quad | \quad \text{Q-pt: } (5.14\text{mA}, 1.21\text{V})$$

$$(c) I_C = \frac{250(9 - 0.7)V}{1.5k\Omega(250 + 1) + 10k\Omega} = 5.37 \text{ mA} \quad | \quad V_{CE} = 9 - 1500I_E = 0.913V \quad | \quad \text{Q-pt: } (5.37\text{mA}, 0.913\text{V})$$

$$(d) I_C = \frac{(9 - 0.7)V}{1500\Omega} = 5.53 \text{ mA} \quad | \quad V_{CE} = 9 - 1500I_E = 0.705V \quad | \quad \text{Q-pt: } (5.53\text{mA}, 0.705\text{V})$$

5.94

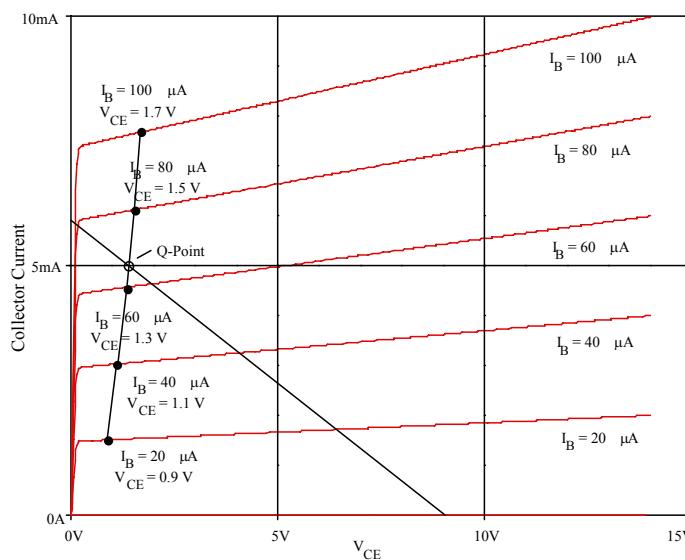
$$V_{CE} = 9 - (I_C + I_B)1500 \quad | \quad V_{CE} = 9 - \left(I_C + \frac{I_C}{\beta_F}\right)1500 \quad | \quad I_B = \frac{V_{CE} - 0.7}{10^4}$$

$$\text{From Fig. P5.26 at } 5V: \beta_F = \frac{5\text{mA}}{60\mu\text{A}} = 83.3 \quad | \quad V_{CE} = 9 - 1518I_C$$

$$I_C = 0, V_{CE} = 9V \quad | \quad V_{CE} = 0, I_C = 5.93mA$$

$$V_{CE} = 0.9V, I_B = 20\mu\text{A} \quad | \quad V_{CE} = 1.3V, I_B = 60\mu\text{A} \quad | \quad V_{CE} = 1.7V, I_B = 100\mu\text{A}$$

From graph: Q-point = (5.0 mA, 1.3 V)



5.95

$$(a) V_{EC} = 10 - (I_C + I_B)R_C = 10 - I_E R_C \quad | \quad I_E = \frac{I_C}{\alpha_F} = \frac{\beta_F + 1}{\beta_F} I_C = \frac{61}{60} 10mA = 10.17mA$$

$$R_C = \frac{(10 - 3)V}{10.17mA} = 689\Omega \rightarrow 680 \Omega \quad | \quad R_B = \frac{V_{EC} - V_{EB}}{I_B} = \frac{(3 - 0.7)V}{0.1667mA} = 13.8k\Omega \rightarrow 14 k\Omega$$

$$(b) 5 - 0.7 - 14000I_B - 680(I_C + I_B) - (-5) = 0$$

$$I_B = \frac{10 - 0.7}{14000 + 41(680)} \frac{V}{\Omega} = 222.1\mu A \quad | \quad I_C = \beta_F I_B = 8.88 mA$$

$$V_{EC} = 10V - (8.88mA)680\Omega = 3.96 V \quad | \quad Q\text{-point: } (8.88 mA, 3.96 V)$$

5.96

$$V_{CE} = 1.5 - (I_C + I_B)R_C \rightarrow R_C = \frac{1.5 - 0.9}{20\mu A + \frac{20\mu A}{50}} = 29.4k\Omega \rightarrow 30 k\Omega$$

$$R_B = \frac{V_{CE} - V_{BE}}{I_B} = \frac{0.9 - 0.65}{\frac{20\mu A}{50}} = 625k\Omega \rightarrow 620 k\Omega$$

$$\text{For } R_C = 30k\Omega: V_{CE} = 1.5 - 30k\Omega(I_C + I_B)R_C = 1.5 - 30k\Omega(126)I_B \quad | \quad I_B = \frac{V_{CE} - 0.65}{620k\Omega}$$

$$V_{CE} = 1.5 - 30k\Omega(126) \frac{V_{CE} - 0.65}{620k\Omega} \rightarrow V_{CE} = 0.770V$$

$$I_C = 125I_B = 125 \frac{0.770 - 0.65}{620k\Omega} = 24.2\mu A \quad | \quad Q\text{-point: } (24.2 \mu A, 0.770 V)$$

5.97

$$12 = R_C(I_C + I_B) + V_Z + V_{BE} = 500(I_E) + 7.7 \quad | \quad I_E = \frac{12 - 7.7}{500} = 8.60mA$$

$$I_B = \frac{I_E}{\beta_F + 1} = \frac{8.60mA}{101} = 85.2\mu A \quad | \quad I_C = \beta_F I_B = 8.52mA \quad | \quad V_{CE} = 7.70V$$

$$\text{Q-point} = (8.52 \text{ mA}, 7.70 \text{ V})$$

5.95

$$V_{EQ} = 6 + 100 \frac{15 - 6}{7800 + 100} = 6.114V \quad | \quad R_{EQ} = 100\Omega \parallel 7800\Omega = 98.73\Omega$$

$$I_B = \frac{20mA}{51} + \frac{V_o}{51(4700\Omega)} = \frac{20mA}{51} + \frac{6.14 - 98.7I_B - V_{BE}}{51(4700\Omega)} \rightarrow I_C = 50I_B = 50 \frac{101.1 - V_{BE}}{2.398 \times 10^5}$$

$$V_{BE} = 0.025 \ln \frac{I_C}{10^{-16}}$$

Using MATLAB: fzero('IC107',.02) ---> ans =0.0207

```
function f=IC107(ic)
vbe=0.025*log(ic/1e-16);
f=ic-50*(101.1-vbe)/2.398e5;
```

$$V_o = 6.14 - 98.7 \frac{20.7mA}{51} - .025 \ln \frac{20.7mA}{10^{-16}} = 5.276 V$$

5.99

*Problem 5.98

VCC 1 0 DC 15

R1 1 2 7.8K

RZ 2 4 100

VZ 4 0 DC 6

Q1 1 2 3 NPN

RE 3 0 4.7K

IL 3 0 20MA

.MODEL NPN NPN IS=1E-16 BF=50 BR=0.25

.OP

.END

Output voltages will differ slightly due to different value of V_T .

5.100

$$v_o = 7 - 100i_B - v_{BE} = 7 - 100i_B - V_T \ln \frac{i_C}{I_S} = 7 - 100i_B - V_T \ln \frac{\alpha_F i_L}{I_S}$$

$$v_o = 7 - 100i_B - V_T \ln i_L - V_T \ln \frac{\alpha_F}{I_S}$$

$$R_o = -\frac{dv_o}{di_L} = -\left(-100\Omega \frac{di_B}{di_L} - \frac{V_T}{i_L} \right) = \frac{100\Omega}{51} + \frac{0.025V}{0.02A} = 3.21\Omega$$

5.101

Since the voltage across the op - amp input must be zero, $v_o = V_Z = 10 V$.

Since the input current to the op amp is zero, $I_E = \frac{V_o}{100} = 100 mA$

$$I_{+15} = I_Z + I_C = I_Z + \alpha_F I_E = \frac{15V - 10V}{47k\Omega} + \frac{60}{61} 100mA = 98.5 mA$$

5.102

Since the voltage across the op - amp input must be zero, $v_o \frac{47\Omega}{47\Omega + 47\Omega} = V_z$

and $v_o = 10 \text{ V}$. Since the input current to the op amp is zero,

$$I_E = \frac{I_C}{\alpha_F} = \frac{10V}{94\Omega} \left(\frac{41}{40} \right) = 109 \text{ mA} \quad I_{+15} = I_Z + I_E = \frac{15V - 5V}{82k\Omega} + 109mA = 109 \text{ mA}$$

5.103

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} \quad | \quad \text{For } I_C^{\min} : V_{CC} = 0.95(15) = 14.25 \text{ V}$$

$$R_1 = 0.95(82k\Omega) = 77.9k\Omega \quad | \quad R_2 = 1.05(120k\Omega) = 126k\Omega \quad | \quad R_E = 1.05(6.8k\Omega) = 7.14k\Omega$$

$$V_{EQ} = \frac{77.9}{77.9 + 126} 14.25V = 5.44V \quad | \quad R_{EQ} = 77.9k\Omega \parallel 126k\Omega = 48.1k\Omega$$

$$I_C^{\min} = 100 \frac{5.44V - 0.7V}{48.1k\Omega + (101)7.14k\Omega} = 616 \mu A$$

$$V_{CE}^{\max} = 14.25 - I_C^{\min} [0.95(6.8k\Omega)] - I_E^{\min} 7.14k\Omega$$

$$V_{CE}^{\max} = 14.25 - 3.98 - 4.44 = 5.83V \quad | \quad Q\text{-point} : (616 \mu A, 5.83 V)$$

$$\text{For } I_C^{\max} : V_{CC} = 1.05(15) = 15.75 \text{ V}$$

$$R_1 = 1.05(82k\Omega) = 86.1k\Omega \quad | \quad R_2 = 0.95(120k\Omega) = 114k\Omega \quad | \quad R_E = 0.95(6.8k\Omega) = 6.46k\Omega$$

$$V_{EQ} = \frac{86.1}{86.1 + 114} 15.75V = 6.78V \quad | \quad R_{EQ} = 86.1k\Omega \parallel 114k\Omega = 49.0k\Omega$$

$$I_C^{\max} = 100 \frac{6.78V - 0.7V}{49.0k\Omega + (101)6.46k\Omega} = 867 \mu A$$

$$V_{CE}^{\min} = 15.75 - I_C^{\max} [1.05(6.8k\Omega)] - I_E^{\max} 6.46k\Omega$$

$$V_{CE}^{\min} = 15.75 - 6.19 - 5.66V = 3.90V \quad | \quad Q\text{-point} : (867 \mu A, 3.90 V)$$

5.104

Using the Spreadsheet approach in Fig. 5.40, Eq. set (5.66) becomes:

1. $V_{CC} = 15(1 + 0.1(RAND() - 0.5))$
2. $R_i = 82000(1 + 0.1(RAND() - 0.5))$
3. $R_2 = 120000(1 + 0.1(RAND() - 0.5))$
4. $R_E = 6800(1 + 0.1(RAND() - 0.5))$
5. $R_C = 6800(1 + 0.1(RAND() - 0.5))$
6. $\beta_F = 100$

500 Cases	I_C (A)	V_{CE} (V)
Average	7.69E-04	4.51
Std. Dev.	4.02E-05	0.40
Min	6.62E-04	3.31
Max	8.93E-04	5.55

5.105

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} \quad | \quad \text{For } I_C^{\min} : V_{CC} = 0.95(12) = 11.4 \text{ V}$$

$$R_i = 0.95(18k\Omega) = 17.1k\Omega \quad | \quad R_2 = 1.05(36k\Omega) = 37.8k\Omega \quad | \quad R_E = 1.05(16k\Omega) = 16.8k\Omega$$

$$V_{EQ} = \frac{17.1}{17.1 + 37.8} 11.4V = 3.55V \quad | \quad R_{EQ} = 17.1k\Omega \parallel 37.8k\Omega = 11.8k\Omega$$

$$I_C^{\min} = 50 \frac{3.55V - 0.7V}{11.8k\Omega + (51)16.8k\Omega} = 164 \mu A$$

$$V_{CE}^{\max} = 11.4 - I_C^{\min} [0.95(22k\Omega)] - I_E^{\min} 16.8k\Omega$$

$$V_{CE}^{\max} = 11.4 - 3.43 - 2.81 = 5.16V \quad | \quad Q\text{-po int: } (164 \mu A, 5.16 V)$$

$$\text{For } I_C^{\max} : V_{CC} = 1.05(12) = 12.6 \text{ V}$$

$$R_i = 1.05(18k\Omega) = 18.9k\Omega \quad | \quad R_2 = 0.95(36k\Omega) = 34.2k\Omega \quad | \quad R_E = 0.95(16k\Omega) = 15.2k\Omega$$

$$V_{EQ} = \frac{18.9}{18.9 + 34.2} 12.6V = 4.49V \quad | \quad R_{EQ} = 18.9k\Omega \parallel 34.2k\Omega = 12.2k\Omega$$

$$I_C^{\max} = 150 \frac{4.49V - 0.7V}{12.2k\Omega + (151)15.2k\Omega} = 246 \mu A$$

$$V_{CE}^{\min} = 12.6 - I_C^{\max} [1.05(22k\Omega)] - I_E^{\max} 15.2k\Omega$$

$$V_{CE}^{\min} = 12.6 - 5.68 - 3.77V = 3.15V \quad | \quad Q\text{-po int: } (246 \mu A, 3.15 V)$$

500 Cases	I_C (A)	V_{CE} (V)
Average	2.02E-04	4.26
Std. Dev.	1.14E-05	0.32
Min	1.71E-04	3.43
Max	2.35E-04	5.21

The averages are close to the hand calculations that go with Fig. 5.35. The minimum and maximum values fall within the worst-case analysis as we expect.

5.106

Using the Spreadsheet approach with zero tolerance on the current gain, Eq. set (5.66) becomes:

1. $V_{CC} = 12 \left(1 + 0.0 \left(RAND() - 0.5\right)\right)$
2. $R_i = 18000 \left(1 + 0.1 \left(RAND() - 0.5\right)\right)$
3. $R_2 = 36000 \left(1 + 0.1 \left(RAND() - 0.5\right)\right)$
4. $R_E = 16000 \left(1 + 0.1 \left(RAND() - 0.5\right)\right)$
5. $R_C = 22000 \left(1 + 0.1 \left(RAND() - 0.5\right)\right)$
6. $\beta_F = 100 \left(1 + 0.0 \left(RAND() - 0.5\right)\right)$

500 Cases	IC (A)	VCE (V)
Average	2.03E-04	4.29
Std. Dev.	1.10E-05	0.32
Min	1.74E-04	3.46
Max	2.36E-04	5.27

Note that the current gain tolerance has little effect on the results.

5.107

- (a) Approximately 22 cases fall outside the interval $[170\mu A, 250\mu A]$: $100\% \frac{22}{500} = 4.4\% \text{ fail}$
 - (b) Approximately 125 cases fall inside the interval $[3.2V, 4.8V]$: $100\% \frac{125}{500} = 25\% \text{ fail}$
-

5.108

Using the Spreadsheet approach with 50% tolerance on the current gain, a tolerance TP on V_{CC} , and a tolerance TR on resistor values, Eq. set (5.66) becomes:

1. $V_{CC} = 12 * \left(1 + 2 * TP * \left(RAND() - 0.5\right)\right)$
2. $R_i = 18000 * \left(1 + 2 * TR * \left(RAND() - 0.5\right)\right)$
3. $R_2 = 36000 * \left(1 + 2 * TR * \left(RAND() - 0.5\right)\right)$
4. $R_E = 16000 * \left(1 + 2 * TR * \left(RAND() - 0.5\right)\right)$
5. $R_C = 22000 * \left(1 + 2 * TR * \left(RAND() - 0.5\right)\right)$
6. $\beta_F = 100 * \left(1 + 1 * \left(RAND() - 0.5\right)\right)$

10,000 case Monte Carlo runs indicate that the specifications cannot be achieved even with ideal resistors. For TP = 5% and TR = 0%, 18 % of the circuits fail. With TP = 2% and TR = 0%, 1.5% percent fail. The specifications can be met with TP = 1% and TR = 1%.

5.109

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} \quad | \quad \text{For } I_C^{\min} : V_{CC} = 0.95(12) = 11.4 \text{ V}$$

$$R_1 = 0.8(18k\Omega) = 14.4k\Omega \quad | \quad R_2 = 1.2(36k\Omega) = 43.2k\Omega \quad | \quad R_E = 1.2(16k\Omega) = 19.2k\Omega$$

$$V_{EQ} = \frac{14.4}{14.4 + 43.2} 11.4V = 2.85V \quad | \quad R_{EQ} = 14.4k\Omega \parallel 43.2k\Omega = 10.8k\Omega$$

$$I_C^{\min} = 50 \frac{2.85V - 0.7V}{10.8k\Omega + (51)19.2k\Omega} = 109 \mu A$$

$$V_{CE}^{\max} = 11.4 - I_C^{\min} [0.8(22k\Omega)] - I_E^{\min} 19.2k\Omega$$

$$V_{CE}^{\max} = 11.4 - 1.91 - 2.13 = 7.36V \quad | \quad \text{Q-point: } (109 \text{ mA}, 7.36 \text{ V})$$

$$\text{For } I_C^{\max} : V_{CC} = 1.05(12) = 12.6 \text{ V}$$

$$R_1 = 1.2(18k\Omega) = 21.6k\Omega \quad | \quad R_2 = 0.8(36k\Omega) = 28.8k\Omega \quad | \quad R_E = 0.8(16k\Omega) = 12.8k\Omega$$

$$V_{EQ} = \frac{21.6}{21.6 + 28.8} 12.6V = 5.40V \quad | \quad R_{EQ} = 21.6k\Omega \parallel 28.8k\Omega = 12.3k\Omega$$

$$I_C^{\max} = 150 \frac{5.4V - 0.7V}{12.3k\Omega + (151)12.8k\Omega} = 362 \mu A$$

$$V_{CE}^{\min} = 12.6 - I_C^{\max} [1.2(22k\Omega)] - I_E^{\max} 12.8k\Omega$$

$$V_{CE}^{\min} = 12.6 - 9.57 - 4.67V = -1.64V! \quad \text{Saturated!}$$

The forward-active region assumption is violated. See the next problem.

Based upon a Monte Carlo analysis, only about 1% of the circuits actually have this problem, although V_{CE} will be relatively small in many circuits.

5.110

Using the Spreadsheet approach:

1. $V_{CC} = 12 * (1 + .1 * (RAND() - 0.5))$
2. $R_i = 18000 * (1 + 0.4 * (RAND() - 0.5))$
3. $R_2 = 36000 * (1 + 0.4 * (RAND() - 0.5))$
4. $R_E = 16000 * (1 + 0.4 * (RAND() - 0.5))$
5. $R_C = 22000 * (1 + 0.4 * (RAND() - 0.5))$
6. $\beta_F = 100 * (1 + 1 * (RAND() - 0.5))$
7. $V_A = 75 * (1 + 0.66 * (RAND() - 0.5))$

In order to avoid an iterative solution at each step, assume that V_{CE} does not influence the base current. Then,

$$I_B = \frac{V_{EQ} - 0.7}{R_{EQ} + (\beta_{FO} + 1)R_E} \quad \text{and} \quad V_{CE} = \frac{V_{CC} - \beta_{FO} I_B \left(R_C + \frac{R_E}{\alpha_F} \right)}{1 + \frac{\beta_{FO}}{V_A} I_B \left(R_C + \frac{R_E}{\alpha_F} \right)} \quad | \quad I_C = \beta_{FO} I_B \left(1 + \frac{V_{CE}}{V_A} \right)$$

500 Cases	V_{CE} (V)	I_C (A)
Average	3.81E+00	2.049E-04
Std. Dev.	1.26E+00	3.785E-05
Min**	-2.07E-01	1.264E-04
Max	6.94E+00	3.229E-04

**Note: In this particular simulation, there were 4 cases in which the transistor was saturated.

CHAPTER 6

6.1

$$(a) P_{avg} = \frac{1W}{10^5 \text{ gates}} = 10 \mu W / \text{gate} \quad (b) I = \frac{10^{-5}W / \text{gate}}{2.5V} = 4 \mu A / \text{gate}$$

6.2

$$(a) P_{avg} = \frac{100}{2 \times 10^7 \text{ gates}} = 5 \mu W / \text{gate} \quad (b) I = \frac{5 \times 10^{-6}W / \text{gate}}{2.5V} = 2 \mu A / \text{gate}$$

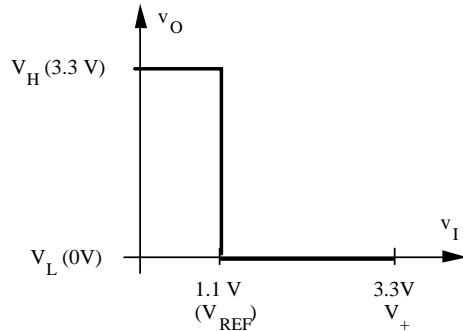
$$(c) I_{total} = 2 \frac{\mu A}{\text{gate}} (2 \times 10^7 \text{ gates}) = 40 A$$

6.3

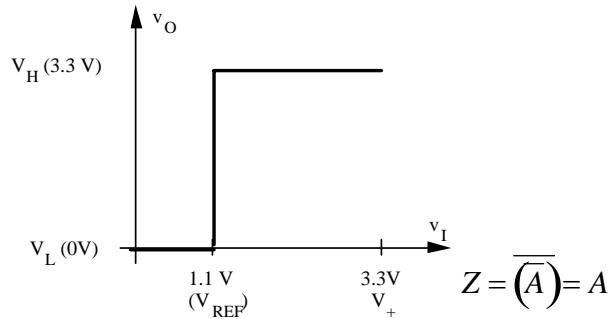
$$(a) V_H = 2.5V \mid V_L = 0V \mid P_{V_H} = I^2R = 0 mW \mid P_{V_L} = \left(\frac{2.5 - 0}{10^5} \right)^2 10^5 = 62.5 \mu W$$

$$(b) V_H = 3.3V \mid V_L = 0V \mid P_{V_H} = I^2R = 0 mW \mid P_{V_L} = \left(\frac{3.3 - 0}{10^5} \right)^2 10^5 = 109 \mu W$$

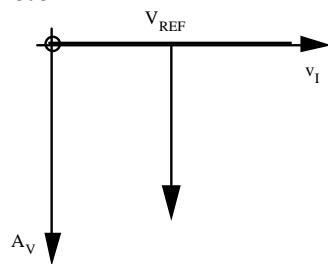
6.4



6.5



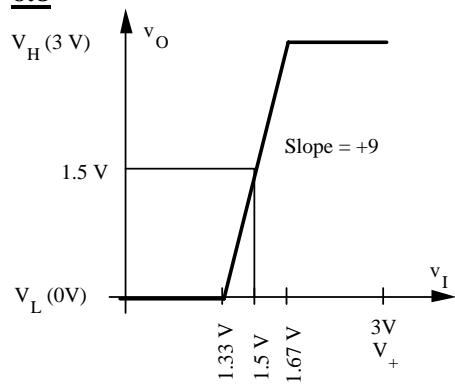
6.6



6.7

$$V_H = 3 \text{ V} \quad | \quad V_L = 0 \text{ V} \quad | \quad V_{IH} = 2 \text{ V} \quad | \quad V_{IL} = 1 \text{ V} \quad | \quad A_V = \frac{dv_o}{dv_I} = \frac{-3V}{1V} = -3$$

6.8



6.9

$$V_{OH} = 5 \text{ V} \quad V_{IH} = V_{REF} = 2 \text{ V}$$

$$NM_H = 5 - 2 = 3 \text{ V}$$

$$V_{OL} = 0 \text{ V} \quad V_{IL} = V_{REF} = 2 \text{ V}$$

$$NM_L = 2 - 0 = 2 \text{ V}$$

6.10

We would like to achieve the highest possible noise margins for both states and have them be symmetrical. Therefore $V_{REF} = 3.3/2=1.65 \text{ V}$.

6.11

$$V_H = 3.3 \text{ V} \quad | \quad V_L = 0 \text{ V} \quad | \quad V_{IH} = 1.8 \text{ V} \quad | \quad V_{OL} \cong 0.25 \text{ V} \quad | \quad V_{IL} = 1.5 \text{ V} \quad | \quad V_{IH} \cong 3.0 \text{ V}$$

$$NM_H = 3.0 - 1.8 = 1.2 \text{ V} \quad | \quad NM_L = 1.5 - 0.25 = 1.25 \text{ V}$$

6.12

$$V_H = 2.5 \text{ V} \quad | \quad V_L = 0.20 \text{ V}$$

6.13

$$V_H = -0.80 \text{ V} \quad | \quad V_L = -1.35 \text{ V}$$

6.14

$$V_{IH} = V_{OH} - NM_H = -0.8 - 0.5 = -1.3 \text{ V} \quad | \quad V_{IL} = NM_L + V_{OL} = 0.5 + (-2) = -1.5 \text{ V}$$

6.15

$$\tau_P = PDP/P = 10^{-13} \text{ J}/10^{-4} \text{ W} = 10^{-9} \text{ s} = 1 \text{ ns}$$

6.16

$$(a) P_{avg} = \frac{1W}{2.5 \times 10^5 \text{ gates}} = 4 \mu\text{W/gate} \quad (b) I = \frac{4 \times 10^{-6} \text{ W/gate}}{2.5 \text{ V}} = 1.60 \mu\text{A/gate}$$

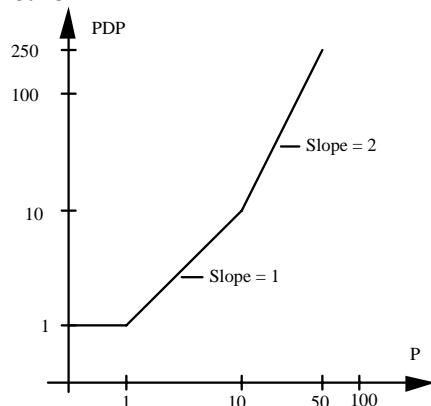
$$(c) PDP = 2 \text{ ns} (4 \mu\text{W}) = 8 \text{ fJ}$$

6.17

$$(a) P_{avg} = \frac{100 \text{ W}}{10^8 \text{ gates}} = 1 \mu\text{W/gate} \quad (b) I = \frac{1 \mu\text{W/gate}}{2.5 \text{ V}} = 0.4 \mu\text{A/gate}$$

$$(c) PDP = 1 \text{ ns} (1 \mu\text{W}) = 1 \text{ fJ}$$

6.18



6.19

$$(a) v(t) = i(t)R + v_c(t) \mid i(t) = C \frac{dv_c(t)}{dt} \mid v(t) = RC \frac{dv_c(t)}{dt} + v_c(t) \mid v(t) = 1 \text{ for } t \geq 0$$

$$v(t) = 1 - \exp\left(-\frac{t}{RC}\right) \mid 0.9 = 1 - \exp\left(-\frac{t_{90\%}}{RC}\right) \rightarrow t_{90\%} = -RC \ln(0.1)$$

$$0.1 = 1 - \exp\left(-\frac{t_{10\%}}{RC}\right) \rightarrow t_{10\%} = -RC \ln(0.9) \mid t_r = t_{90\%} - t_{10\%} = RC \ln(9) = 2.20RC$$

$$(b) v(t) = 0 \quad v_c(0) = 1 \quad v(t) = \exp\left(-\frac{t}{RC}\right) \mid 0.9 = \exp\left(-\frac{t_{90\%}}{RC}\right) \rightarrow t_{90\%} = -RC \ln(0.9)$$

$$0.1 = \exp\left(-\frac{t_{10\%}}{RC}\right) \rightarrow t_{10\%} = -RC \ln(0.1) \mid t_f = t_{10\%} - t_{90\%} = RC \ln(9) = 2.20RC$$

6.20

$$(a) V_H = 2.5V \mid V_L = 0.20V$$

$$(b) V_{10\%} = V_L + 0.1\Delta V = 0.20 + 0.23 = 0.43V \rightarrow t_{10\%} \cong 23 \text{ ns for } v_o$$

$$V_{90\%} = V_L + 0.9\Delta V = 0.20 + 2.07 = 2.27V \rightarrow t_{90\%} \cong 33 \text{ ns for } v_o \rightarrow t_r = 33 - 23 = 10 \text{ ns}$$

For fall time: $t_{10\%} \cong 2.5 \text{ ns for } v_o \quad t_{90\%} \cong 0.8 \text{ ns for } v_o \rightarrow t_f = 1.7 \text{ ns}$

For v_I , $t_{10\%} \cong 0 \text{ ns} \quad t_{90\%} \cong 1 \text{ ns} \quad t_r = 1 \text{ ns} \mid t_f \cong 1 \text{ ns}$

$$(c) \tau_{PHL} \cong 1.5ns - 0.5ns = 1ns \mid \tau_{PLH} \cong 26ns - 21ns = 5ns \quad (d) \tau_p = \frac{1+5}{2}ns = 3ns$$

6.21

$$(a) V_H = -0.78V \mid V_L = -1.36V$$

$$(b) V_{10\%} = V_L + 0.1\Delta V = -1.36 + 0.1(0.58) = -1.30V \rightarrow t_{10\%} \cong 32.5 \text{ ns for } v_o$$

$$V_{90\%} = V_L + 0.9\Delta V = -1.36 + 0.9(0.58) = -0.84V \rightarrow t_{90\%} \cong 42 \text{ ns for } v_o$$

$$t_r = 42 - 32.5 = 9.5 \text{ ns}$$

For fall time: $t_{10\%} \cong 11.5 \text{ ns for } v_o \quad t_{90\%} \cong 2 \text{ ns for } v_o \rightarrow t_f = 9.5 \text{ ns}$

For v_I , $t_{10\%} \cong 0 \text{ ns} \quad t_{90\%} \cong 1 \text{ ns} \quad t_r = 1 \text{ ns} \mid t_f \cong 1 \text{ ns}$

$$(c) V_{50\%} = \frac{-0.78 - 1.36}{2} = -1.07V \mid \tau_{PHL} \cong 4 \text{ ns} \mid \tau_{PLH} \cong 4 \text{ ns} \quad (d) \tau_p = \frac{4+4}{2} \text{ ns} = 4 \text{ ns}$$

6.22

$$(A + B)(A + C)$$

$$AA + AC + BA + BC$$

$$A + AC + BA + BC$$

$$A(1+C) + AB + BC$$

$$A + AB + BC$$

$$A(1+B) + BC$$

$$A + BC$$

6.23

$$Z = AB\bar{C} + ABC + \bar{A}BC$$

$$Z = AB\bar{C} + +ABC + ABC + \bar{A}BC$$

$$Z = AB(\bar{C} + C) + (A + \bar{A})BC$$

$$Z = AB(1) + (1)BC$$

$$Z = AB + BC$$

6.24

$$\begin{array}{cccc} A & B & C & Z \end{array}$$

$$\begin{array}{cccc} 0 & 0 & 0 & 0 \end{array}$$

$$\begin{array}{cccc} 0 & 0 & 1 & 0 \end{array}$$

$$\begin{array}{cccc} 0 & 1 & 0 & 0 \end{array}$$

$$\begin{array}{cccc} 0 & 1 & 1 & 1 \end{array}$$

$$\begin{array}{cccc} 1 & 0 & 0 & 0 \end{array}$$

$$\begin{array}{cccc} 1 & 0 & 1 & 0 \end{array}$$

$$\begin{array}{cccc} 1 & 1 & 0 & 1 \end{array}$$

$$\begin{array}{cccc} 1 & 1 & 1 & 1 \end{array}$$

$$Z = AB + BC$$

6.25

$$Z = \overline{A}\overline{B}C + ABC + \overline{A}BC + A\overline{B}C$$

$$Z = C(\overline{A}\overline{B} + AB + \overline{A}B + A\overline{B})$$

$$Z = C(\overline{A}\overline{B} + \overline{A}B + AB + A\overline{B})$$

$$Z = C(\overline{A}(\overline{B} + B) + A(B + \overline{B}))$$

$$Z = C(\overline{A}(1) + A(1))$$

$$Z = C(1)$$

$$Z = C$$

6.26

$$\begin{array}{cccc} A & B & C & Z \end{array}$$

$$\begin{array}{cccc} 0 & 0 & 0 & 0 \end{array}$$

$$\begin{array}{cccc} 0 & 0 & 1 & 1 \end{array}$$

$$\begin{array}{cccc} 0 & 1 & 0 & 0 \end{array}$$

$$\begin{array}{cccc} 0 & 1 & 1 & 1 \end{array}$$

$$\begin{array}{cccc} 1 & 0 & 0 & 0 \end{array}$$

$$\begin{array}{cccc} 1 & 0 & 1 & 1 \end{array}$$

$$\begin{array}{cccc} 1 & 1 & 0 & 0 \end{array}$$

$$\begin{array}{cccc} 1 & 1 & 1 & 1 \end{array}$$

$$Z = C$$

6.27

<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>Z</i>
0	0	0	0	0
0	0	0	1	0
0	0	1	0	0
0	0	1	1	0
0	1	0	0	0
0	1	0	1	0
0	1	1	0	0
0	1	1	1	0
1	0	0	0	0
1	0	0	1	0
1	0	1	0	0
1	0	1	1	0
1	1	0	0	0
1	1	0	1	0
1	1	1	0	0
1	1	1	1	1

6.28

<i>A</i>	<i>B</i>	<i>C</i>	<i>Z</i> ₁	<i>Z</i> ₂
0	0	0	0	1
0	0	1	0	1
0	1	0	0	0
0	1	1	0	1
1	0	0	0	0
1	0	1	0	1
1	1	0	1	1
1	1	1	1	1

$$Z = \overline{\overline{AB} + \overline{CD}}$$

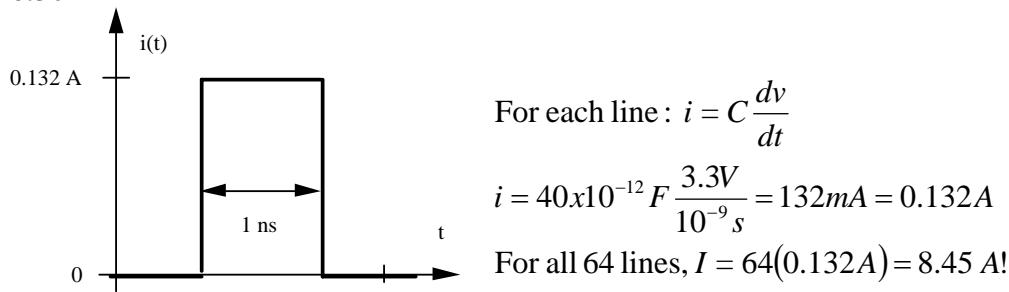
$$Z = (\overline{\overline{AB}})(\overline{\overline{CD}})$$

$$Z = ABCD$$

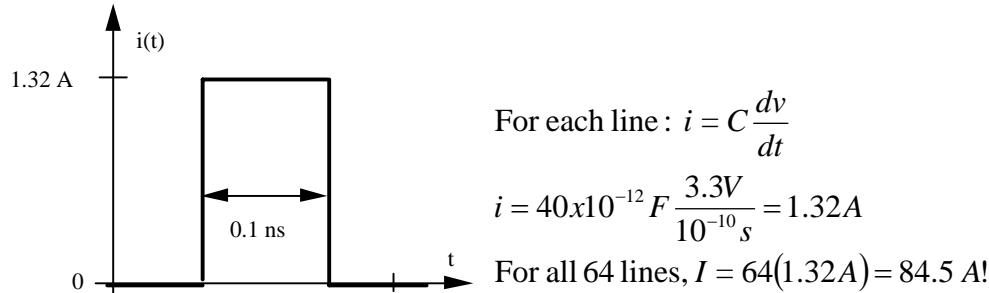
6.29

(a) Fanout = 2 (b) Fanout = 1

6.30



6.31



6.32

$$C = 3 \left(\frac{\epsilon_{ox} A}{t_{ox}} \right) = 3 \frac{3.9 \epsilon_o L W}{t_{ox}} = 3 \frac{3.9 \left(8.854 \times 10^{-14} \frac{F}{cm} \right) \left(\frac{7.5mm}{2} \frac{0.1cm}{mm} \right) (1.5\mu m)}{1\mu m} = 0.583 pF$$

6.33

$$\Delta T = \frac{C \Delta V}{I} = \frac{K C''_{ox} W L \Delta V}{\frac{1}{2} \mu_n C''_{ox} \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2} \mid \text{Let } W^* = \alpha W \text{ and } L^* = \alpha L$$

$$\Delta T^* = \frac{C^* \Delta V^*}{I^*} = \frac{K (\alpha W) (\alpha L) (\alpha \Delta V)}{\frac{1}{2} \mu_n \left(\frac{\alpha W}{\alpha L} \right) (\alpha V_{GS} - \alpha V_{TN})^2} = \alpha \Delta T$$

$$P = VI = \frac{V}{2} \mu_n C''_{ox} \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2 = \frac{V}{2} \mu_n \frac{\epsilon_{ox}}{T_{ox}} \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2$$

$$P^* = \frac{\alpha V}{2} \mu_n \frac{\epsilon_{ox}}{\alpha T_{ox}} \left(\frac{\alpha W}{\alpha L} \right) (\alpha V_{GS} - \alpha V_{TN})^2 = \alpha^2 P$$

$$P D P^* = P^* \Delta T^* = (\alpha \Delta T) \alpha^2 P = \alpha^3 P \Delta T = \alpha^3 P D P$$

$$\text{Power density} = \frac{P}{A} = \frac{P}{WL} \mid \frac{P^*}{A^*} = \frac{\alpha^2 P}{\alpha W (\alpha L)} = \frac{P}{A}$$

6.34

$$(a) I_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2 = \frac{1}{2} \mu_n \frac{\epsilon_{ox}}{T_{ox}} \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2$$

$$I_D^* = \frac{1}{2} \mu_n \frac{\epsilon_{ox}}{T_{ox}} \left(\frac{\frac{W}{2}}{\frac{L}{2}} \right) (V_{GS} - V_{TN})^2 = 2I_D$$

(b) $P^* = V(2I) = 2VI = 2P$ - The power has increased by a factor of two.

$$(c) C_G = C_{ox}' WL = \frac{\epsilon_{ox}}{T_{ox}} WL \mid C_G^* = \frac{\epsilon_{ox}}{T_{ox}} \frac{W}{2} \frac{L}{2} = \frac{C_G}{2}$$

The capacitance has decreased by a factor of two.

$$(d) \Delta T^* = \frac{C^* \Delta V^*}{I^*} = \frac{K \left(\frac{W}{2} \right) \left(\frac{L}{2} \right) (\Delta V)}{\frac{1}{2} \mu_n \left(\frac{\frac{W}{2}}{\frac{L}{2}} \right) (V_{GS} - V_{TN})^2} = \frac{\Delta T}{4}$$

6.35

$$(a) P_{avg} = \frac{1W}{0.5(2 \times 10^6 \text{ gates})} = 1 \mu W/\text{gate} \quad (b) I = \frac{1 \mu W/\text{gate}}{1.8V} = 0.556 \mu A/\text{gate}$$

6.36

$$(a) P_{avg} = \frac{20W}{\left(\frac{2}{3}\right) 20 \times 10^6 \text{ gates}} = 1.5 \mu W/\text{gate} \quad (b) I = \frac{1.5 \mu W/\text{gate}}{1.8V} = 0.833 \mu A/\text{gate}$$

6.37

$$I_{DD} = \frac{50 \mu W}{2.5V} = 20 \mu A \mid \text{Let } V_L = \frac{V_{TN}}{3} = 0.2V \mid R = \frac{2.5 - 0.2}{2 \times 10^{-5}} = 115 \text{ k}\Omega$$

$$\text{M}_S \text{ is in the triode region : } 20 \times 10^{-6} = 60 \times 10^{-6} \left(\frac{W}{L} \right)_S \left(2.5 - 0.6 - \frac{0.2}{2} \right) 0.2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{0.926}{1} = \frac{1}{1.08}$$

6.38

(a) For M_S off, $I_D = 0$ and $V_H = 2.5V$.

$$\text{For } V_L, I_D = \frac{2.5 - V_L}{200k\Omega} = K_n \left(V_H - V_{TN} - \frac{V_L}{2} \right) V_L \quad | \quad K_n = \left(\frac{3}{1} \right) \left(60 \frac{\mu A}{V^2} \right) = 180 \frac{\mu A}{V^2}$$

$$2.5 - V_L = \left(2 \times 10^5 \right) \left(180 \frac{\mu A}{V^2} \right) \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow 36V_L^2 - 138.8V_L + 5 = 0$$

$$V_L = 0.0364 \text{ V} \quad | \quad I_D = \frac{2.5 - 0.0364}{200k\Omega} = 12.3 \text{ } \mu A \quad | \quad P = 2.5V(12.3 \text{ } \mu A) = 30.8 \text{ } \mu W$$

$$\text{Checking: } I_D = 180 \frac{\mu A}{V^2} \left(2.5 - 0.6 - \frac{0.0364}{2} \right) 0.0364 = 12.3 \text{ } \mu A$$

(b) For M_S off, $I_D = 0$ and $V_H = 2.5V$.

$$\text{For } V_L, I_D = \frac{2.5 - V_L}{400k\Omega} = K_n \left(V_H - V_{TN} - \frac{V_L}{2} \right) V_L \quad | \quad K_n = \left(\frac{6}{1} \right) \left(60 \frac{\mu A}{V^2} \right) = 360 \frac{\mu A}{V^2}$$

$$2.5 - V_L = \left(4 \times 10^5 \right) \left(360 \frac{\mu A}{V^2} \right) \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow 144V_L^2 - 549.2V_L + 5 = 0$$

$$V_L = 9.13 \text{ mV} \quad | \quad I_D = \frac{2.5 - 0.00913}{400k\Omega} = 6.23 \text{ } \mu A \quad | \quad P = 2.5V(6.23 \text{ } \mu A) = 15.6 \text{ } \mu W$$

$$\text{Checking: } I_D = 360 \frac{\mu A}{V^2} \left(2.5 - 0.6 - \frac{0.00913}{2} \right) 0.00913 = 6.21 \text{ } \mu A$$

6.39

(a) For M_S off, $I_D = 0$ and $V_H = 2.5V$.

$$\text{For } V_L, I_D = \frac{2.5 - V_L}{200k\Omega} = K_n \left(V_H - V_{TN} - \frac{V_L}{2} \right) V_L \quad | \quad K_n = \left(\frac{3}{1} \right) \left(60 \frac{\mu A}{V^2} \right) = 180 \frac{\mu A}{V^2}$$

$$2.5 - V_L = \left(2 \times 10^5 \right) \left(180 \frac{\mu A}{V^2} \right) \left(2.5 - 0.8 - \frac{V_L}{2} \right) V_L \rightarrow 36V_L^2 - 124.4V_L + 5 = 0$$

$$V_L = 0.0407 \text{ V} \quad | \quad I_D = \frac{2.5 - 0.0407}{200k\Omega} = 12.3 \text{ } \mu A \quad | \quad P = 2.5V(12.3 \text{ } \mu A) = 30.7 \text{ } \mu W$$

$$\text{Checking: } I_D = 180 \frac{\mu A}{V^2} \left(2.5 - 0.8 - \frac{0.0407}{2} \right) 0.0407 = 12.3 \text{ } \mu A$$

$$(b) 2.5 - V_L = \left(2 \times 10^5 \right) \left(180 \frac{\mu A}{V^2} \right) \left(2.5 - 0.4 - \frac{V_L}{2} \right) V_L \rightarrow 36V_L^2 - 153.2V_L + 5 = 0$$

$$V_L = 0.0329 \text{ V} \quad | \quad I_D = \frac{2.5 - 0.0329}{200k\Omega} = 12.3 \text{ } \mu A \quad | \quad P = 2.5V(12.3 \text{ } \mu A) = 30.8 \text{ } \mu W$$

$$\text{Checking: } I_D = 180 \frac{\mu A}{V^2} \left(2.5 - 0.4 - \frac{0.0329}{2} \right) 0.0329 = 12.3 \text{ } \mu A$$

6.40

$$(a) V_{IL} = V_{TN} + \frac{1}{K_n R} = 0.6V + \frac{1}{3 \left(\frac{60 \mu A}{V^2} \right) (200k\Omega)} = 0.6 + \frac{1}{36} = 0.627 \text{ V}$$

$$V_{OH} = V_{DD} - \frac{1}{2K_n R} = 2.5 - \frac{1}{72} = 2.49V \quad | \quad V_{OL} = \sqrt{\frac{2V_{DD}}{3K_n R}} = \sqrt{\frac{5}{108}} = 0.215V$$

$$V_{IH} = V_{TN} - \frac{1}{K_n R} + 1.63 \sqrt{\frac{V_{DD}}{K_n R}} = 0.6 - \frac{1}{36} + 1.63 \sqrt{\frac{2.5}{36}} = 1.00V$$

$$NM_L = 0.627 - 0.215 = 0.412 \text{ V} \quad | \quad NM_H = 2.49 - 1.00 = 1.49 \text{ V}$$

$$(b) V_{IL} = V_{TN} + \frac{1}{K_n R} = 0.6V + \frac{1}{\frac{6}{1} \left(\frac{60 \mu A}{V^2} \right) (400k\Omega)} = 0.6 + \frac{1}{144} = 0.607 \text{ V}$$

$$V_{OH} = V_{DD} - \frac{1}{2K_n R} = 2.5 - \frac{1}{288} = 2.50V \quad | \quad V_{OL} = \sqrt{\frac{2V_{DD}}{3K_n R}} = \sqrt{\frac{5}{432}} = 0.108V$$

$$V_{IH} = V_{TN} - \frac{1}{K_n R} + 1.63 \sqrt{\frac{V_{DD}}{K_n R}} = 0.6 - \frac{1}{144} + 1.63 \sqrt{\frac{2.5}{144}} = 0.807V$$

$$NM_L = 0.607 - 0.108 = 0.499 \text{ V} \quad | \quad NM_H = 2.50 - 0.807 = 1.69 \text{ V}$$

6.41

(a) For M_S off, I_D = 0 and V_H = 2.5V.

$$\text{For } V_L, I_D = \frac{2.5 - V_L}{400k\Omega} = K_n \left(V_H - V_{TN} - \frac{V_L}{2} \right) V_L \quad | \quad K_n = \left(\frac{6}{1} \right) \left(\frac{60 \mu A}{V^2} \right) = 360 \frac{\mu A}{V^2}$$

$$2.5 - V_L = \left(4 \times 10^5 \right) \left(360 \frac{\mu A}{V^2} \right) \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow 144V_L^2 - 549.2V_L + 5 = 0$$

$$V_L = 9.13 \text{ mV} \quad | \quad I_D = \frac{2.5 - 0.00913}{400k\Omega} = 6.23 \mu A \quad | \quad P = 2.5V (6.23 \mu A) = 15.6 \mu W$$

$$\text{Checking: } I_D = 360 \frac{\mu A}{V^2} \left(2.5 - 0.6 - \frac{0.00913}{2} \right) 0.00913 = 6.23 \mu A$$

$$(b) 2.5 - V_L = 144 \left(2.5 - 0.5 - \frac{V_L}{2} \right) V_L \rightarrow 144V_L^2 - 578V_L + 5 = 0$$

$$V_L = 8.67 \text{ mV} \quad | \quad I_D = \frac{2.5 - 0.00867}{400k\Omega} = 6.33 \mu A \quad | \quad P = 2.5V (6.33 \mu A) = 15.8 \mu W$$

$$\text{Checking: } I_D = 360 \frac{\mu A}{V^2} \left(2.5 - 0.5 - \frac{0.00867}{2} \right) 0.00867 = 6.23 \mu A$$

$$(c) 2.5 - V_L = 144 \left(2.5 - 0.7 - \frac{V_L}{2} \right) V_L \rightarrow 144V_L^2 - 520.4V_L + 5 = 0$$

$$V_L = 9.63 \text{ mV} \quad | \quad I_D = \frac{2.5 - 0.00963}{400k\Omega} = 6.23 \mu A \quad | \quad P = 2.5V(6.23 \mu A) = 15.6 \mu W$$

$$\text{Checking: } I_D = 360 \frac{\mu A}{V^2} \left(2.5 - 0.7 - \frac{0.00963}{2} \right) 0.00963 = 6.22 \mu A$$

In this design, we see that V_L is not sensitive to V_{TN} .

6.42

$$(a) V_{IL} = V_{TN} + \frac{1}{K_n R} = 0.6V + \frac{1}{\frac{6}{1} \left(60 \frac{\mu A}{V^2} \right) (400k\Omega)} = 0.6 + \frac{1}{144} = 0.607V$$

$$V_{OH} = V_{DD} - \frac{1}{2K_n R} = 2.5 - \frac{1}{288} = 2.50V \quad | \quad V_{OL} = \sqrt{\frac{2V_{DD}}{3K_n R}} = \sqrt{\frac{5}{432}} = 0.108V$$

$$V_{IH} = V_{TN} - \frac{1}{K_n R} + 1.63 \sqrt{\frac{V_{DD}}{K_n R}} = 0.6 - \frac{1}{144} + 1.63 \sqrt{\frac{2.5}{144}} = 0.807V$$

$$NM_L = 0.607 - 0.108 = 0.499 \text{ V} \quad | \quad NM_H = 2.50 - 0.807 = 1.69 \text{ V}$$

$$(b) V_{IL} = 0.6 + \frac{1}{K_n R} \quad | \quad V_{OL} = \sqrt{\frac{5}{3K_n R}} \quad | \quad NM_L = V_{IL} - V_{OL} = 0$$

Solving for $K_n R$ yields no solution. Zero noise margin will not occur.

6.43

$$(a) I_D = \frac{P}{V_{DD}} = \frac{0.25mW}{2.5V} = 100\mu A \quad | \quad R = \frac{V_{DD} - V_L}{I_D} = \frac{2.5 - 0.5}{1 \times 10^{-4}} = 20.0 k\Omega$$

Using the values corresponding to Fig. 6.12, $K_p' = 100\mu A/V^2$

$$100\mu A = \left(100 \times 10^{-6} \right) \left(\frac{W}{L} \right)_S \left(2.5 - 0.6 - \frac{0.5}{2} \right) 0.5 \rightarrow \left(\frac{W}{L} \right)_S = \frac{1.21}{1}$$

$$(b) V_{IL} = V_{TN} + \frac{1}{K_n R} = 0.6V + \frac{1}{\left(1.21 \times 100 \frac{\mu A}{V^2} \right) (20k\Omega)} = 0.6 + \frac{1}{2.42} = 1.01 \text{ V}$$

$$V_{OH} = V_{DD} - \frac{1}{2K_n R} = 2.5 - \frac{1}{4.84} = 2.29V \quad | \quad V_{OL} = \sqrt{\frac{2V_{DD}}{3K_n R}} = \sqrt{\frac{5}{7.26}} = 0.830V$$

$$V_{IH} = V_{TN} - \frac{1}{K_n R} + 1.63 \sqrt{\frac{V_{DD}}{K_n R}} = 0.6 - \frac{1}{2.42} + 1.63 \sqrt{\frac{2.5}{2.42}} = 1.84V$$

$$NM_L = 1.01 - 0.83 = 0.18 \text{ V} \quad | \quad NM_H = 2.29 - 1.84 = 0.450 \text{ V}$$

6.44

$$(a) I_D = \frac{P}{V_{DD}} = \frac{0.25mW}{3.3V} = 75.76\mu A \quad | \quad R = \frac{V_{DD} - V_L}{I_D} = \frac{3.3 - 0.2}{75.76 \times 10^{-6}} = 40.9 k\Omega$$

$$75.76 \times 10^{-6} = (100 \times 10^{-6}) \left(\frac{W}{L} \right)_S \left(3.3 - 0.7 - \frac{0.2}{2} \right) 0.2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{1.52}{1}$$

$$(b) V_{IL} = V_{TN} + \frac{1}{K_n R} = 0.7V + \frac{1}{(1.52)(100 \frac{\mu A}{V^2})(40.9 k\Omega)} = 0.7 + \frac{1}{6.22} = 0.861 V$$

$$V_{OH} = V_{DD} - \frac{1}{2K_n R} = 3.3 - \frac{1}{12.4} = 3.22 \quad | \quad V_{OL} = \sqrt{\frac{2V_{DD}}{3K_n R}} = \sqrt{\frac{6.6}{18.7}} = 0.594V$$

$$V_{IH} = V_{TN} - \frac{1}{K_n R} + 1.63 \sqrt{\frac{V_{DD}}{K_n R}} = 0.7 - \frac{1}{6.22} + 1.63 \sqrt{\frac{3.3}{6.22}} = 1.73V$$

$$NM_L = 0.861 - 0.594 = 0.267 V \quad | \quad NM_H = 3.22 - 1.73 = 1.49 V$$

6.45

$$(a) R = \frac{V_{DD} - V_L}{I_D} = \frac{3 - 0.25}{33 \times 10^{-6}} = 83.3 k\Omega$$

$$33 \times 10^{-6} = (60 \times 10^{-6}) \left(\frac{W}{L} \right)_S \left(3 - 0.75 - \frac{0.25}{2} \right) 0.25 \rightarrow \left(\frac{W}{L} \right)_S = \frac{1.04}{1}$$

(b) SPICE yields $V_L = 0.249 V$ with $I_D = 33.0 \mu A$.

6.46

$$(a) R = \frac{V_{DD} - V_L}{I_D} = \frac{2 - 0.15}{10 \times 10^{-6}} = 185 k\Omega$$

$$10^{-5} = (75 \times 10^{-6}) \left(\frac{W}{L} \right)_S \left(2 - 0.6 - \frac{0.15}{2} \right) 0.15 \rightarrow \left(\frac{W}{L} \right)_S = \frac{1}{1.49}$$

(b) SPICE yields $V_L = 0.15 V$ with $I_D = 10 \mu A$.

6.47

$$(a) R_{on} = \frac{1}{K_n \frac{W}{L} (V_{GS} - V_{TN})} = \frac{1}{60 \times 10^{-6} \left(\frac{10}{1}\right) (5-1)} = 417 \Omega$$

$$(b) R_{on} = \frac{1}{K_p \frac{W}{L} (V_{SG} + V_{TP})} = \frac{1}{25 \times 10^{-6} \left(\frac{10}{1}\right) (5-1)} = 1000 \Omega$$

(c) A resistive connection exists between the source and drain.

$$(d) \frac{W}{L} = \frac{1}{K_n (V_{GS} - V_{TN}) R_{on}} = \frac{1}{60 \times 10^{-6} (3-1) (417)} = \frac{20}{1}$$

$$\frac{W}{L} = \frac{1}{K_p (V_{SG} + V_{TP}) R_{on}} = \frac{1}{25 \times 10^{-6} (3-1) (1000)} = \frac{20}{1}$$

6.48

$$V_H = V_{DD} - \left(V_{TO} + \gamma \left(\sqrt{V_{SB} + 2\phi_F} - \sqrt{2\phi_F} \right) \right) \rightarrow V_H = 3.3 - \left(0.75 + 0.75 \left(\sqrt{V_H + 0.7} - \sqrt{0.7} \right) \right)$$

$$(V_H - 4.88)^2 = 0.5625(V_H + 0.7) \rightarrow V_H^2 - 6.918V_H + 9.706 = 0$$

$$V_H = 4.962V, 1.956V \rightarrow V_H = 1.96 V$$

$$\text{Checking: } V_{TN} = 0.75 + 0.75 \left(\sqrt{1.956 + 0.75} - \sqrt{0.75} \right) = 1.345V \quad | \quad V_H = 3.3 - 1.345 = 1.96V$$

6.49

$$V_H = V_{DD} - \left(V_{TO} + \gamma \left(\sqrt{V_{SB} + 2\phi_F} - \sqrt{2\phi_F} \right) \right) \rightarrow V_H = 3.3 - \left(0.6 + 0.6 \left(\sqrt{V_H + 0.6} - \sqrt{0.6} \right) \right)$$

$$(V_H - 3.165)^2 = 0.36(V_H + 0.6) \rightarrow V_H^2 - 6.69V_H + 9.80 = 0$$

$$V_H = 2.166V, 4.524V \rightarrow V_H = 2.17 V$$

$$\text{Checking: } V_{TN} = 0.5 + 0.6 \left(\sqrt{2.166 + 0.6} - \sqrt{0.6} \right) = 1.133V \quad | \quad V_H = 3.3 - 1.133 = 2.167V$$

6.50

$$V_H = V_{DD} - \left(V_{TO} + \gamma \left(\sqrt{V_{SB} + 2\phi_F} - \sqrt{2\phi_F} \right) \right) \rightarrow V_H = 2.5 - \left(0.5 + 0.85 \left(\sqrt{V_H + 0.6} - \sqrt{0.6} \right) \right)$$

$$(V_H - 2.659)^2 = 0.7225(V_H + 0.6) \rightarrow V_H^2 - 6.04V_H + 6.634 = 0$$

$$V_H = 1.444V, 4.596V \rightarrow V_H = 1.44 V$$

$$\text{Checking: } V_{TN} = 0.5 + 0.85 \left(\sqrt{1.444 + 0.6} - \sqrt{0.6} \right) = 1.057V \quad | \quad V_H = 2.5 - 1.057 = 1.443V$$

6.51

For $\gamma = 0$, $V_H = V_{DD} - V_{TN} = 3.3 - 0.6 = 2.7V$ | For $V_L : I_{DL} = I_{DS}$

$$\frac{K_n}{2} \left(\frac{1}{2} \right) \left(3.3 - V_L - 0.6 \right)^2 = K_n \left(\frac{4}{1} \right) \left(2.7 - 0.6 + -\frac{V_L}{2} \right) V_L \rightarrow 9V_L^2 - 39V_L + 7.29 = 0$$

$$V_L = 0.1958V \quad | \quad I_{DD} = \frac{60 \times 10^{-6}}{2} \left(\frac{1}{2} \right) \left(3.3 - 0.1958 - 0.6 \right)^2 = 94.1\mu A$$

$$P = (3.3V)(94.08\mu A) = 0.311 mW$$

$$\text{Checking: } I_{DD} = 60 \times 10^{-6} \left(\frac{4}{1} \right) \left(2.7 - 0.6 - \frac{0.1958}{2} \right) 0.1958 = 94.1\mu A$$

6.52

(a) For $\gamma = 0$, $V_H = V_{DD} - V_{TN} = 3.3 - 0.8 = 2.5V$ | For $V_L : I_{DL} = I_{DS}$

$$\frac{K_n}{2} \frac{1}{2} \left(3.3 - V_L - 0.8 \right)^2 = K_n \left(\frac{4}{1} \right) \left(2.5 - 0.8 - \frac{V_L}{2} \right) V_L \rightarrow 9V_L^2 - 32.2V_L + 6.25 = 0 \quad | \quad V_L = 0.206V$$

$$I_{DD} = \frac{60 \times 10^{-6}}{2} \frac{1}{2} \left(3.3 - 0.206 - 0.8 \right)^2 = 78.9\mu A \quad | \quad P = 3.3V(78.9\mu A) = 0.260 mW$$

$$\text{Checking: } I_{DD} = 60 \times 10^{-6} \left(\frac{4}{1} \right) \left(2.5 - 0.8 - \frac{0.206}{2} \right) 0.206 = 79.0\mu A$$

(b) For $\gamma = 0$, $V_H = V_{DD} - V_{TN} = 3.3 - 0.4 = 2.9V$ | For $V_L : I_{DL} = I_{DS}$

$$\frac{K_n}{2} \frac{1}{2} \left(3.3 - V_L - 0.4 \right)^2 = K_n \left(\frac{4}{1} \right) \left(2.9 - 0.4 - \frac{V_L}{2} \right) V_L \rightarrow 9V_L^2 - 45.8V_L + 8.41 = 0 \quad | \quad V_L = 0.191 V$$

$$I_{DD} = \frac{60 \times 10^{-6}}{2} \frac{1}{2} \left(3.3 - 0.191 - 0.4 \right)^2 = 110\mu A \quad | \quad P = 3.3V(110\mu A) = 0.363 mW$$

$$\text{Checking: } I_{DD} = 60 \times 10^{-6} \left(\frac{4}{1} \right) \left(2.9 - 0.4 - \frac{0.191}{2} \right) 0.191 = 110\mu A$$

6.53

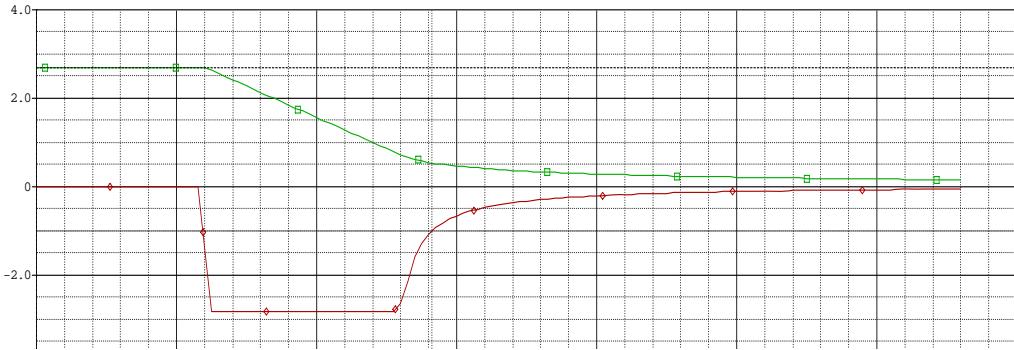
$V_{IL} = V_{TNS} = 0.6 V$ | $V_{OH} = V_H = V_{DD} - V_{TNL} = 3.3 - 0.6 = 2.7V$

$$\text{At } V_{IH} \text{ (See Eq. 6.29 Second Edition)} \quad V_{OL} = \frac{V_{DD} - V_{TNL}}{\sqrt{1+3K_R}} \frac{3.3 - 0.6}{\sqrt{1+3\frac{4}{0.5}}} = 0.540V$$

$$V_{IH} = V_{TNS} + \frac{V_{OL}}{2} + \frac{(V_{DD} - V_{OL} - V_{TNL})^2}{2K_R V_{OL}} = 0.6 + \frac{0.54}{2} + \frac{0.5}{2(4)} \frac{1}{0.54} (3.3 - 0.54 - 0.6)^2 = 1.41V$$

$$NM_H = 2.7 - 1.41 = 1.29 V \quad | \quad NM_L = 0.60 - 0.54 = 0.06 V$$

These values are readily confirmed with SPICE.



6.54

(a) For $\gamma = 0$, $V_H = V_{DD} - V_{TN} = 3.3 - 0.6 = 2.7V$ | For V_L : $I_{DL} = I_{DS}$

$$\frac{K_n}{2} \frac{1}{1} (3.3 - V_L - 0.6)^2 = K_n \left(\frac{8}{1} \right) \left(2.7 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow 9V_L^2 - 39V_L + 7.29 = 0$$

$$V_L = 0.1958V \quad | \quad I_{DD} = \frac{60 \times 10^{-6}}{2} \left(\frac{1}{1} \right) (3.3 - 0.1958 - 0.6)^2 = 188\mu A$$

$$P = (3.3V)(188\mu A) = 0.621 mW$$

$$\text{Checking: } I_{DD} = 60 \times 10^{-6} \left(\frac{8}{1} \right) \left(2.7 - 0.6 - \frac{0.1958}{2} \right) 0.1958 = 188\mu A \text{ - check is ok}$$

(b) $V_{IL} = V_{TNS} = 0.6 V$ | $V_{OH} = V_H = V_{DD} - V_{TNL} = 3.3 - 0.6 = 2.7V$

$$\text{At } V_{IH} \text{ (See Eq. 6.29 Second Edition)} \quad V_{OL} = \frac{V_{DD} - V_{TNL}}{\sqrt{1+3K_R}} \frac{3.3 - 0.6}{\sqrt{1+3\frac{4}{0.5}}} = 0.540V$$

$$V_{IH} = V_{TNS} + \frac{V_{OL}}{2} + \frac{(V_{DD} - V_{OL} - V_{TNL})^2}{2K_R V_{OL}} = 0.6 + \frac{0.54}{2} + \frac{0.5}{2(4)} \frac{1}{0.54} (3.3 - 0.54 - 0.6)^2 = 1.41V$$

$$NM_H = 2.7 - 1.41 = 1.29 V \quad | \quad NM_L = 0.60 - 0.54 = 0.06 V$$

These values are easily checked with SPICE. See Prob. 6.53,

(c) For $\gamma = 0$, $V_H = V_{DD} - V_{TN} = 3.3 - 0.7 = 2.6V$ | For V_L : $I_{DL} = I_{DS}$

$$\frac{K_n}{2} \frac{1}{1} (3.3 - V_L - 0.7)^2 = K_n \left(\frac{8}{1} \right) \left(2.6 - 0.7 - \frac{V_L}{2} \right) V_L \rightarrow 9V_L^2 - 32.2V_L + 6.25 = 0$$

$$V_L = 0.200V \quad | \quad I_{DD} = \frac{60 \times 10^{-6}}{2} \frac{1}{1} (3.3 - 0.200 - 0.7)^2 = 173\mu A$$

$$P = (3.3V)(173\mu A) = 570 \mu W$$

$$\text{Checking: } I_{DD} = 60 \times 10^{-6} \left(\frac{8}{1} \right) \left(2.6 - 0.7 - \frac{0.200}{2} \right) 0.200 = 173\mu A \text{ - check is ok}$$

6.55

$$(a) V_H = V_{DD} - \left(V_{TO} + \gamma \left(\sqrt{V_{SB} + 2\phi_F} - \sqrt{2\phi_F} \right) \right) \rightarrow V_H = 3.3 - \left(0.7 + 0.5 \left(\sqrt{V_H + 0.6} - \sqrt{0.6} \right) \right)$$

$$\left(V_H - 2.987 \right)^2 = 0.25 \left(V_H + 0.6 \right) \rightarrow V_H^2 - 6.225V_H + 8.772 = 0 \rightarrow V_H = 2.156 \text{ V}$$

$$V_L = 0.20V \quad | \quad I_D = \frac{0.25mW}{3.3V} = 75.76\mu A \quad | \quad 75.76 = 100 \left(\frac{W}{L} \right)_S \left(2.156 - 0.7 - \frac{0.20}{2} \right) 0.20$$

$$\left(\frac{W}{L} \right)_S = \frac{2.79}{1} \quad | \quad V_{TNL} = 0.7 + 0.5 \left(\sqrt{0.2 + 0.6} - \sqrt{0.6} \right) = 0.760V$$

$$75.76 = \frac{100}{2} \left(\frac{W}{L} \right)_L \left(3.3 - 0.20 - 0.760 \right)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{3.61}$$

$$(b) V_{IL} = V_{TNS} = 0.70V \quad | \quad V_{OH} = V_H = 2.16V$$

Finding V_{IH} (See Eq 6.29 in 2nd Ed.): $V_{OL} = \frac{V_{DD} - V_{TNL}}{\sqrt{1 + 3 \left(\frac{W/L}{L} \right)_S \left(\frac{W/L}{L} \right)_L}} = \frac{3.3 - V_{TNL}}{\sqrt{1 + 3(2.79)(3.61)}} = \frac{3.3 - V_{TNL}}{5.587}$

$$V_{TNL} = 0.7 + 0.5 \left(\sqrt{V_{OL} + 0.6} - \sqrt{0.6} \right) \quad | \quad 5.587V_{OL} = 3.3 - \left(0.7 + 0.5 \left(\sqrt{V_{OL} + 0.6} - \sqrt{0.6} \right) \right)$$

Using the quadratic equation: $V_{OL} = 0.4432V \rightarrow V_{TNL} = 0.8234V$

$$V_{IH} = V_{TNS} + \frac{V_{OL}}{2} + \frac{(W/L)_L}{(W/L)_S} \frac{1}{2V_{OL}} (V_{DD} - V_{OL} - V_{TNL})^2$$

$$V_{IH} = 0.7 + \frac{0.443}{2} + \frac{1}{10.07} \left(\frac{1}{2} \right) \frac{1}{0.443} (3.3 - 0.443 - 0.823)^2 \quad | \quad V_{IH} = 1.39V$$

$$NM_H = 2.16 - 1.39 = 0.77 \text{ V} \quad | \quad NM_L = 0.7 - 0.443 = 0.26 \text{ V}$$



6.56

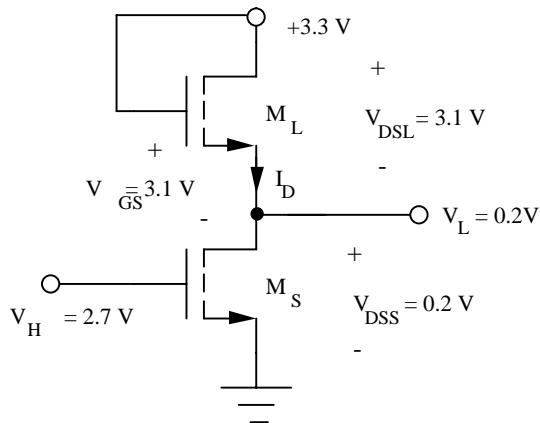
$$I_{DD} = \frac{0.4mW}{2.5V} = 160\mu A \quad | \quad V_{TNL} = 0.6 + 0.5(\sqrt{0.3+0.6} - \sqrt{0.6}) = 0.687V$$

$$160 \times 10^{-6} = \frac{100 \times 10^{-6}}{2} \left(\frac{W}{L} \right)_L (2.5 - 0.3 - 0.687)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1.40}{1}$$

$$160 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{W}{L} \right)_S \left(1.55 - 0.6 - \frac{0.3}{2} \right) 0.3 \rightarrow \left(\frac{W}{L} \right)_S = \frac{6.67}{1}$$

6.57

$$(a) V_{DD} = 3.3 \text{ V} \quad V_{TN} = 1 \text{ V} \quad I_D = 75 \mu A \quad V_L = 0.2 \text{ V} \quad V_H = V_{DD} - V_{TN} = 3.3 \text{ V} - 0.6 \text{ V} = 2.7 \text{ V}$$



$$I_{DS} = I_{DL} = 75\mu A$$

$$I_{DS} = K_n \left(\frac{W}{L} \right)_S \left(V_{GSS} - V_{THS} - \frac{V_{DSS}}{2} \right) V_{DSS} \quad 75\mu A = 100 \frac{\mu A}{V^2} \left(\frac{W}{L} \right)_S \left(2.7 - 0.6 - \frac{0.2}{2} \right) 0.2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{1.88}{1}$$

$$I_{DL} = \frac{K_n}{2} \left(\frac{W}{L} \right)_L \left(V_{GSL} - V_{TNL} \right)^2 \quad 75\mu A = \frac{100 \frac{\mu A}{V^2}}{2} \left(\frac{W}{L} \right)_L \left(3.3 - 0.2 - 0.6 \right)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{4.17}$$

$$(b) V_H = V_{DD} - \left(V_{TO} + \gamma \left(\sqrt{V_{SB} + 2\phi_F} - \sqrt{2\phi_F} \right) \right) \rightarrow V_H = 3.3 - \left(0.6 + 0.5 \left(\sqrt{V_H + 0.6} - \sqrt{0.6} \right) \right)$$

$$\left(V_H - 3.087 \right)^2 = 0.25 \left(V_H + 0.6 \right) \rightarrow V_H^2 - 6.424 V_H + 9.381 = 0 \rightarrow V_H = 2.245$$

$$75\mu A = 100 \frac{\mu A}{V^2} \left(\frac{W}{L} \right)_S \left(2.245 - 0.6 - \frac{0.2}{2} \right) 0.2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{2.43}{1}$$

$$I_{DL} = \frac{K_n}{2} \left(\frac{W}{L} \right)_L \left(V_{GSL} - V_{TNL} \right)^2 \quad | \quad V_{TNL} = 0.6 + 0.5 \left(\sqrt{0.2 + 0.6} - \sqrt{0.6} \right) = 0.660V$$

$$75\mu A = \frac{100 \frac{\mu A}{V^2}}{2} \left(\frac{W}{L} \right)_L \left(3.3 - 0.2 - 0.66 \right)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{3.97}$$

6.58

(a) For $\gamma = 0$, $V_H = V_{DD} - V_{TO} = 2 - 0.6 = 1.4V$

$$I_{DS} = K_n \left(\frac{W}{L} \right)_S \left(V_H - V_{TNS} - \frac{V_L}{2} \right) V_L + 25 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{W}{L} \right)_S \left(1.4 - 0.6 - \frac{0.15}{2} \right) 0.15 \rightarrow \left(\frac{W}{L} \right)_S = \frac{2.30}{1}$$

$$I_{DL} = \frac{K_n}{2} \left(\frac{W}{L} \right)_L \left(V_{GSL} - V_{TNL} \right)^2 + 25 \times 10^{-6} = \frac{100 \times 10^{-6}}{2} \left(\frac{W}{L} \right)_L \left(2 - 0.15 - 0.6 \right)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{3.13}$$

(b) For $\gamma = 0.6$, $V_H = V_{DD} - V_{TNL} = 2 - [0.6 + 0.6(\sqrt{V_H + 0.6} - \sqrt{0.6})] \rightarrow V_H = 1.09V$

$$I_{DS} = K_n \left(\frac{W}{L} \right)_S \left(V_H - V_{TNS} - \frac{V_L}{2} \right) V_L + 25 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{W}{L} \right)_S \left(1.09 - 0.6 - \frac{0.15}{2} \right) 0.15 \rightarrow \left(\frac{W}{L} \right)_S = \frac{4.02}{1}$$

For $V_O = V_L = 0.15V$, $V_{TN} = 0.6 + 0.6(\sqrt{0.15 + 0.6} - \sqrt{0.6}) = 0.655V$

$$I_{DL} = \frac{K_n}{2} \left(\frac{W}{L} \right)_L \left(V_{GSL} - V_{TNL} \right)^2 + 25 \times 10^{-6} = \frac{100 \times 10^{-6}}{2} \left(\frac{W}{L} \right)_L \left(2 - 0.15 - 0.655 \right)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{2.86}$$

(c) Using LEVEL=1 KP=100U VTO=0.6 GAMMA=0, the values of I_D and V_L agree with our hand calculations. The results also agree for GAMMA=0.6.

6.59

$$I_{DS} = I_{DL} + K_n \left(\frac{W}{L} \right)_S \left(V_{GSS} - V_{TNS} - \frac{V_{DSL}}{2} \right) V_{DSL} = \frac{K_n}{2} \left(\frac{W}{L} \right)_L \left(V_{GSL} - V_{TNL} \right)^2$$

$$K_n \left(\frac{4.71}{1} \right) \left(2.5 - 0.6 - \frac{V_o}{2} \right) V_o = \frac{K_n}{2} \left(\frac{1}{1.68} \right) \left(2.5 - V_o - V_{TNL} \right)^2$$

$V_{TNL} = 0.6 + 0.5(\sqrt{V_o + 0.6} - \sqrt{0.6})$ An iterative solution yields $V_o = 0.1061 V$

6.60

$$I_{DS} = I_{DL} + K_n \left(\frac{W}{L} \right)_S \left(V_H - V_{TNS} - \frac{V_L}{2} \right) V_L = \frac{K_n}{2} \left(\frac{W}{L} \right)_L \left(2.5 - V_L - V_{TNL} \right)^2$$

which is independent of K_n . Ratioed logic maintains V_L and V_H independent of K_n . So $V_H = 1.55V$ and $V_L = 0.20V$. However, $I_{DS} = I_{DL} \propto K_n$:

$$\text{So, } I_D = 80 \mu A \frac{80 \mu A / V^2}{100 \mu A / V^2} = 64.0 \mu A \quad P = 2.5V(64 \mu A) = 0.160 mW$$

$$\text{Checking: } I_{DS} = 80 \frac{\mu A}{V^2} \left(\frac{4.71}{1} \right) \left(1.55 - 0.6 - \frac{0.2}{2} \right) 0.2 = 64.1 \mu A$$

6.61

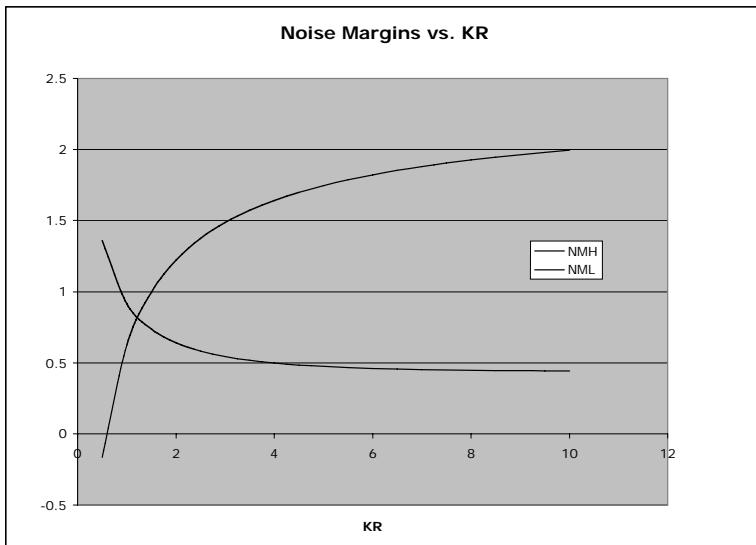
$$I_{DS} = I_{DL} + K_n \left(\frac{W}{L} \right)_S \left(V_H - V_{TNS} - \frac{V_L}{2} \right) V_L = \frac{K_n}{2} \left(\frac{W}{L} \right)_L \left(2.5 - V_L - V_{TNL} \right)^2$$

which is independent of K_n . Ratioed logic maintains V_L and V_H independent of K_n . So $V_H = 1.55V$ and $V_L = 0.20V$. However, $I_{DS} = I_{DL} \propto K_n$:

$$\text{So, } I_D = 80\mu A \frac{120\mu A/V^2}{100\mu A/V^2} = 96.0 \mu A \quad P = 2.5V(96\mu A) = 0.240 \text{ mW}$$

$$\text{Checking: } I_{DS} = 120 \frac{\mu A}{V^2} \left(\frac{4.71}{1} \right) \left(1.55 - 0.6 - \frac{0.2}{2} \right) 0.2 = 96.1\mu A$$

6.62



6.63

- (a) $V_H = V_{DD} - V_{TNL}$ does not depend upon λ . However, V_L is dependent upon λ .
- (b) SPICE yields $V_L = 0.20 \text{ V}, 0.207 \text{ V}, 0.217 \text{ V}, \text{ and } 0.232 \text{ V}$ for $\lambda = 0, 0.02/\text{V}, 0.05/\text{V}, \text{ and } 0.1/\text{V}$ respectively. The current also increases: $I_{DD} = 80.1, 82.8, 86.9 \text{ and } 93.3 \mu A$, respectively.

6.64

$$V_{TNL} = 0.6 + 0.5 \left(\sqrt{0.20 + 0.6} - \sqrt{0.6} \right) = 0.660V$$

$$V_{GSL} - V_{TNL} = 4 - 0.2 - 0.66 = 3.14V \quad | \quad V_{DSL} = 2.5 - 0.2 = 2.30V \rightarrow \text{Triode region}$$

$$80\mu A = 100 \frac{\mu A}{V^2} \left(\frac{W}{L} \right)_L \left(4 - 0.2 - 0.66 - \frac{2.3}{2} \right) 2.3 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{5.72}$$

$$80\mu A = 100 \frac{\mu A}{V^2} \left(\frac{W}{L} \right)_S \left(2.5 - 0.6 - \frac{0.2}{2} \right) 0.2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{2.22}{1}$$

6.65

For linear operation at $v_o = V_L$: $V_{TNL} = 0.8 + 0.5(\sqrt{0.2+0.6} - \sqrt{0.6}) = 0.860V$

$$V_{GSL} - V_{TNL} \geq V_{DSL} : V_{GG} - 0.20 - 0.860 \geq 2.5 - 0.2 \rightarrow V_{GG} \geq 3.36V$$

We also require: $V_{GG} \geq 2.5 + V_{TNL} = 2.5 + 0.8 + 0.5(\sqrt{2.5+0.6} - \sqrt{0.6}) = 3.79V$ so $V_{GG} \geq 3.79V$

6.66

If $V_H = 3.3V$, $V_{TNL} = 0.6 + 0.5(\sqrt{3.3+0.6} - \sqrt{0.6}) = 1.2V$

$5 - 1.2 = 3.8V > 3.3V$ so $V_H = 3.3V$ is correct.

$$I_{DS} = I_{DL} + K_n \left(\frac{5}{1} \right) \left(3.3 - 0.6 - \frac{V_L}{2} \right) V_L = \frac{K_n}{2} \left(\frac{1}{2} \right) (3.3 - V_L - V_{TNL})^2$$

$V_{TNL} = 0.6 + 0.5(\sqrt{V_L + 0.6} - \sqrt{0.6})$ An interative solution gives $V_L = 0.1222V$, $V_{TNL} = 0.6376V$

$$I_{DS} = \frac{100\mu A}{2} \left(\frac{1}{2} \right) (3.3 - 0.1222 - 0.6376)^2 = 161\mu A \quad | \quad P = 3.3V(161\mu A) = 0.532mW$$

6.67

We require $V_{GG} \geq V_{DD} + V_{TNL}$ so $V_H = V_{DD}$

$$V_{TNL} = V_{TO} + \gamma(\sqrt{V_{SB} + 0.6} - \sqrt{0.6}) = 0.6 + 0.6(\sqrt{3.3+0.6} - \sqrt{0.6}) = 1.32V$$

$$V_{GG} \geq 3.3 + 1.32 = 4.62V$$

6.68

We require $V_{GG} \geq V_{DD} + V_{TNL}$ so $V_H = V_{DD}$

$$V_{TNL} = V_{TO} + \gamma(\sqrt{V_{SB} + 0.6} - \sqrt{0.6}) = 0.6 + 0.6(\sqrt{3.3+0.6} - \sqrt{0.6}) = 1.32V$$

$$V_{GG} \geq 3.3 + 1.32 = 4.62V \quad | \quad \text{Design decision - Choose } V_{GG} = 5V$$

$$I_{DD} = \frac{300\mu W}{3.3V} = 90.9\mu A$$

$$\text{For M}_S : 90.9\mu A = 100\mu A \left(\frac{W}{L} \right)_S \left(3.3 - 0.6 - \frac{0.2}{2} \right) 0.2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{1.75}{1}$$

$$\text{For M}_L : V_{TNL} = 0.6 + 0.6(\sqrt{0.2+0.6} - \sqrt{0.6}) = 0.672V$$

$$90.9\mu A = 100\mu A \left(\frac{W}{L} \right)_L \left(5 - .2 - 0.672 - \frac{3.3 - 0.2}{2} \right) (3.3 - 0.2) \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{8.79}$$

6.69

We require $V_{TNL} \leq 0$: $-1 + \gamma(\sqrt{2.5+0.6} - \sqrt{0.6}) \leq 0 \rightarrow \gamma \leq 1.014$

6.70

$$(a) V_H = V_{DD} \quad | \quad I_{DS} = I_{DL} \quad | \quad K_n' \left(\frac{W}{L} \right)_S \left(V_{DD} - V_{TNS} - \frac{V_L}{2} \right) V_L = \frac{K_n'}{2} \left(\frac{W}{L} \right)_L \left(V_{TNL} \right)^2$$

For ratioed logic, both V_H and V_L are independent of K_n' . $V_H = 2.5 \text{ V}$ | $V_L = 0.2 \text{ V}$

$$\text{However, } I_D \propto K_n' \quad | \quad I_{DS} = 80 \mu A \left(\frac{80}{100} \right) = 64 \mu A \quad | \quad P = 2.5V(64 \mu A) = 0.160 \text{ mW}$$

$$(b) V_H = 2.5 \text{ V} \quad V_L = 0.2 \text{ V} \quad I_{DS} = 80 \mu A \left(\frac{120}{100} \right) = 96 \mu A \quad | \quad P = 2.5V(96 \mu A) = 0.240 \text{ mW}$$

6.71

$$I_{DD} = \frac{0.20 \text{ mW}}{3.3 \text{ V}} = 60.1 \mu A \quad V_{TNL} = -1 + 0.5 \left(\sqrt{3.3 + 0.6} - \sqrt{0.6} \right) = -0.400 \text{ V} \rightarrow V_H = 3.3 \text{ V}$$

$$60.1 \mu A = 100 \mu A \left(\frac{W}{L} \right)_S \left(3.3 - 0.6 - \frac{0.20}{2} \right) 0.20 \rightarrow \left(\frac{W}{L} \right)_S = \frac{1.16}{1} \quad | \quad \text{For } V_o = V_L = 0.2 \text{ V},$$

$$V_{TNL} = -1 + 0.5 \left(\sqrt{0.20 + 0.6} - \sqrt{0.6} \right) = -0.940 \text{ V} \quad | \quad 60.1 \mu A = \frac{100 \mu A}{2} \left(\frac{W}{L} \right)_L (-0.940)^2 \quad | \quad \left(\frac{W}{L} \right)_L = \frac{1.36}{1}$$

6.72

$$\text{Assume } V_H = V_{DD} = 3.3 \text{ V} \quad | \quad \text{Checking: } V_{TNL} = -2 + 0.5 \left(\sqrt{3.3 + 0.6} - \sqrt{0.6} \right) = -1.40$$

$$V_{TNL} < 0, \text{ so our assumption is correct.} \quad | \quad I_{DD} = \frac{P}{V_{DD}} = \frac{250 \mu W}{3.3 \text{ V}} = 75.8 \mu A$$

$$\text{For } M_S \text{ in the triode region, } 75.8 \mu A = 100 \mu A \left(\frac{W}{L} \right)_S \left(3.3 - 0.6 - \frac{0.2}{2} \right) 0.2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{1.46}{1}$$

$$\text{For } M_L \text{ in the saturation region, } V_{TNL} = -2 + 0.5 \left(\sqrt{0.2 + 0.6} - \sqrt{0.6} \right) = -1.94 \text{ V and}$$

$$75.8 \mu A = \frac{100 \mu A}{2} \left(\frac{W}{L} \right)_L (0 - V_{TNL})^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{2.48}$$

6.73

(a) No, V_H does not depend upon λ .

(b) As λ increases, I_{DD} increases in M_L , and V_L increases.

λ	I_{DD}	V_L
0	78.2 μA	195 mV
0.02/V	81.4 μA	203 mV
0.05/V	86.0 μA	214 mV
0.1/v	93.6 μA	231 mV

6.74

(a) The PMOS load is still saturated, so I_{DD} remains the same : $I_{DD} = 80\mu A$.

$$\text{Also, } V_H = 2.5 \text{ V. } 80 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{W}{L} \right)_n \left(2.5 - 0.6 - \frac{0.25}{2} \right) 0.25 \rightarrow \left(\frac{W}{L} \right)_n = \frac{1.80}{1}$$

$$(\text{b}) V_{IL} = V_{TNS} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_S}{K_L} = \frac{1.80(100)}{1.11(40)} = 4.05 \quad V_{IL} = 0.6 + \frac{2.5 - 0.6}{\sqrt{4.05^2 + 4.05}} = 1.02 \text{ V}$$

$$V_{OH} = V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 2.5 - (2.5 - 0.6) \left(1 - \sqrt{\frac{4.05}{5.05}} \right) = 2.30 \text{ V}$$

$$V_{OL} = \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{2.5 - 0.6}{\sqrt{3(4.05)}} = 0.545 \text{ V} \quad V_{IH} = V_{TNS} + 2V_{OL} = 0.6 + 2(0.545) = 1.69 \text{ V}$$

$$NM_H = V_{OH} - V_{IH} = 2.30 - 1.69 = 0.610 \text{ V} \quad NM_L = V_{IL} - V_{OL} = 1.02 - 0.545 = 0.475 \text{ V}$$

6.75

(a) The PMOS load is still saturated, so I_{DD} remains the same : $I_{DD} = 80\mu A$.

$$\text{Also, } V_H = 2.5 \text{ V. } 80 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{2.22}{1} \right)_n \left(2.5 - 0.5 - \frac{V_L}{2} \right) V_L \rightarrow V_L = 0.189 \text{ V}$$

$$(\text{b}) V_{IL} = V_{TNS} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_S}{K_L} = \frac{2.22}{1.11} \left(\frac{100}{40} \right) = 5.00 \quad V_{IL} = 0.5 + \frac{2.5 - 0.6}{\sqrt{5^2 + 5}} = 0.847 \text{ V}$$

$$V_{OH} = V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 2.5 - (2.5 - 0.6) \left(1 - \sqrt{\frac{5}{5+1}} \right) = 2.33 \text{ V}$$

$$V_{OL} = \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{2.5 - 0.6}{\sqrt{3(5)}} = 0.491 \text{ V} \quad V_{IH} = V_{TNS} + 2V_{OL} = 0.5 + 2(0.491) = 1.48 \text{ V}$$

$$NM_H = V_{OH} - V_{IH} = 2.33 - 1.48 = 0.849 \text{ V} \quad NM_L = V_{IL} - V_{OL} = 0.847 - 0.491 = 0.356 \text{ V}$$

(c) The PMOS load is still saturated, so I_{DD} remains the same : $I_{DD} = 80\mu A$.

$$\text{Also, } V_H = 2.5 \text{ V. } 80 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{2.22}{1} \right)_n \left(2.5 - 0.7 - \frac{V_L}{2} \right) V_L \rightarrow V_L = 0.213 \text{ V}$$

$$(\text{d}) V_{IL} = V_{TNS} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_S}{K_L} = \frac{2.22}{1.11} \left(\frac{100}{40} \right) = 5.00 \quad V_{IL} = 0.7 + \frac{2.5 - 0.6}{\sqrt{5^2 + 5}} = 1.05 \text{ V}$$

$$V_{OH} = V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 2.5 - (2.5 - 0.6) \left(1 - \sqrt{\frac{5}{5+1}} \right) = 2.33 \text{ V}$$

$$V_{OL} = \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{2.5 - 0.6}{\sqrt{3(5)}} = 0.490 \text{ V} \quad V_{IH} = V_{TNS} + 2V_{OL} = 0.7 + 2(0.490) = 1.68 \text{ V}$$

$$NM_H = V_{OH} - V_{IH} = 2.33 - 1.68 = 0.650 \text{ V} \quad NM_L = V_{IL} - V_{OL} = 1.05 - 0.490 = 0.560 \text{ V}$$

6.76

(a) The PMOS load is still saturated, so I_{DD} remains the same : $I_{DD} = 80\mu A$.

$$\text{Also, } V_H = 2.5 \text{ V. } 80 \times 10^{-6} = 120 \times 10^{-6} \left(\frac{2.22}{1} \right)_n \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow V_L = 0.165 \text{ V}$$

$$(\text{b}) V_{IL} = V_{TN} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_s}{K_L} = \frac{2.22}{1.11} \left(\frac{120}{40} \right) = 6 \quad V_{IL} = 0.6 + \frac{2.5 - 0.6}{\sqrt{6^2 + 6}} = 0.893V$$

$$V_{OH} = V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 2.5 - (2.5 - 0.6) \left(1 - \sqrt{\frac{6}{6+1}} \right) = 2.36V$$

$$V_{OL} = \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{2.5 - 0.6}{\sqrt{3(6)}} = 0.448V \quad V_{IH} = V_{TN} + 2V_{OL} = 0.6 + 2(0.448) = 1.50V$$

$$NM_H = V_{OH} - V_{IH} = 2.36 - 1.50 = 0.860 \text{ V} \quad NM_L = V_{IL} - V_{OL} = 0.893 - 0.448 = 0.445 \text{ V}$$

(c) The PMOS load is still saturated, so I_{DD} remains the same : $I_{DD} = 80\mu A$.

$$\text{Also, } V_H = 2.5 \text{ V. } 80 \times 10^{-6} = 80 \times 10^{-6} \left(\frac{2.22}{1} \right)_n \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow V_L = 0.254 \text{ V}$$

$$(\text{d}) V_{IL} = V_{TN} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_s}{K_L} = \frac{2.22}{1.11} \left(\frac{80}{40} \right) = 4 \quad V_{IL} = 0.6 + \frac{2.5 - 0.6}{\sqrt{4^2 + 4}} = 1.03V$$

$$V_{OH} = V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 2.5 - (2.5 - 0.6) \left(1 - \sqrt{\frac{4}{4+1}} \right) = 2.30V$$

$$V_{OL} = \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{2.5 - 0.6}{\sqrt{3(4)}} = 0.549V \quad V_{IH} = V_{TN} + 2V_{OL} = 0.6 + 2(0.549) = 1.70V$$

$$NM_H = V_{OH} - V_{IH} = 2.30 - 1.70 = 0.600 \text{ V} \quad NM_L = V_{IL} - V_{OL} = 1.03 - 0.549 = 0.481 \text{ V}$$

6.77

(a) The PMOS load is still saturated, and $V_H = 2.5 V$.

$$I_{DD} = \frac{40 \times 10^{-6}}{2} \left(\frac{1.11}{1} \right)_n (2.5 - 0.5)^2 \rightarrow I_{DD} = 88.8 \mu A$$

$$\text{For } M_S : 88.8 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{2.22}{1} \right)_n \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow V_L = 0.224 V$$

$$(b) V_{IL} = V_{TN} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_S}{K_L} = \frac{2.22}{1.11} \left(\frac{100}{40} \right) = 5 \quad V_{IL} = 0.6 + \frac{2.5 - 0.5}{\sqrt{5^2 + 5}} = 0.965 V$$

$$V_{OH} = V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 2.5 - (2.5 - 0.5) \left(1 - \sqrt{\frac{5}{5+1}} \right) = 2.33 V$$

$$V_{OL} = \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{2.5 - 0.5}{\sqrt{3(5)}} = 0.516 V \quad V_{IH} = V_{TN} + 2V_{OL} = 0.6 + 2(0.516) = 1.63 V$$

$$NM_H = V_{OH} - V_{IH} = 2.33 - 1.63 = 0.700 V \quad NM_L = V_{IL} - V_{OL} = 0.965 - 0.516 = 0.449 V$$

(c) The PMOS load is still saturated, and $V_H = 2.5 V$.

$$I_{DD} = \frac{40 \times 10^{-6}}{2} \left(\frac{1.11}{1} \right)_n (2.5 - 0.7)^2 \rightarrow I_{DD} = 71.9 \mu A$$

$$\text{For the NMOS device : } 71.9 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{2.22}{1} \right)_n \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow V_L = 0.179 V$$

$$(d) V_{IL} = V_{TN} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_S}{K_L} = \frac{2.22}{1.11} \left(\frac{100}{40} \right) = 5 \quad V_{IL} = 0.6 + \frac{2.5 - 0.7}{\sqrt{5^2 + 5}} = 0.929 V$$

$$V_{OH} = V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 2.5 - (2.5 - 0.7) \left(1 - \sqrt{\frac{5}{5+1}} \right) = 2.34 V$$

$$V_{OL} = \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{2.5 - 0.7}{\sqrt{3(5)}} = 0.465 V \quad V_{IH} = V_{TN} + 2V_{OL} = 0.6 + 2(0.465) = 1.53 V$$

$$NM_H = V_{OH} - V_{IH} = 2.34 - 1.53 = 0.810 V \quad NM_L = V_{IL} - V_{OL} = 0.929 - 0.465 = 0.464 V$$

6.78

(a) The PMOS load is still saturated, and $V_H = 2.5 V$.

$$I_{DD} = \frac{50 \times 10^{-6}}{2} \left(\frac{1.11}{1} \right)_n \left(2.5 - 0.6 \right)^2 \rightarrow I_{DD} = 100 \mu A$$

$$\text{For } M_S : 100 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{2.22}{1} \right)_n \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow V_L = 0.254 V$$

$$(b) V_{IL} = V_{TN} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_S}{K_L} = \frac{2.22}{1.11} \left(\frac{100}{50} \right) = 4 \quad V_{IL} = 0.6 + \frac{2.5 - 0.6}{\sqrt{4^2 + 4}} = 1.03 V$$

$$V_{OH} = V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 2.5 - (2.5 - 0.6) \left(1 - \sqrt{\frac{4}{4+1}} \right) = 2.30 V$$

$$V_{OL} = \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{2.5 - 0.6}{\sqrt{3(4)}} = 0.549 V \quad V_{IH} = V_{TN} + 2V_{OL} = 0.6 + 2(0.549) = 1.70 V$$

$$NM_H = V_{OH} - V_{IH} = 2.30 - 1.70 = 0.600 V \quad NM_L = V_{IL} - V_{OL} = 1.03 - 0.549 = 0.481 V$$

(c) The PMOS load is still saturated, and $V_H = 2.5 V$.

$$I_{DD} = \frac{30 \times 10^{-6}}{2} \left(\frac{1.11}{1} \right)_n \left(2.5 - 0.6 \right)^2 \rightarrow I_{DD} = 60.0 \mu A$$

$$\text{For the NMOS device : } 60 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{2.22}{1} \right)_n \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow V_L = 0.148 V$$

$$(d) V_{IL} = V_{TN} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_S}{K_L} = \frac{2.22}{1.11} \left(\frac{100}{30} \right) = 6.67 \quad V_{IL} = 0.6 + \frac{2.5 - 0.6}{\sqrt{6.67^2 + 6.67}} = 0.866 V$$

$$V_{OH} = V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 2.5 - (2.5 - 0.6) \left(1 - \sqrt{\frac{6.67}{6.67+1}} \right) = 2.37 V$$

$$V_{OL} = \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{2.5 - 0.6}{\sqrt{3(6.67)}} = 0.425 V \quad V_{IH} = V_{TN} + 2V_{OL} = 0.6 + 2(0.425) = 1.45 V$$

$$NM_H = V_{OH} - V_{IH} = 2.37 - 1.45 = 0.920 V \quad NM_L = V_{IL} - V_{OL} = 0.866 - 0.425 = 0.441 V$$

6.79

$$(a) I_{DD} = \frac{P}{V_{DD}} = \frac{100 \mu W}{1.8 V} = 55.6 \mu A$$

$$\text{For the saturated PMOS load : } 55.6 \times 10^{-6} = \frac{25 \times 10^{-6}}{2} \left(\frac{W}{L} \right)_p \left(1.8 - 0.5 \right)^2 \rightarrow \left(\frac{W}{L} \right)_p = \frac{2.63}{1}$$

$$\text{For the linear NMOS switch : } 55.6 \times 10^{-6} = 60 \times 10^{-6} \left(\frac{W}{L} \right)_n \left(1.8 - 0.5 - \frac{0.2}{2} \right) 0.2 \rightarrow \left(\frac{W}{L} \right)_n = \frac{3.86}{1}$$

$$\begin{aligned}
(b) V_{IL} &= V_{TN} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_S}{K_L} = \frac{3.86}{2.63} \left(\frac{60}{25} \right) = 3.52 \quad V_{IL} = 0.5 + \frac{1.8 - 0.5}{\sqrt{3.52^2 + 3.52}} = 0.826V \\
V_{OH} &= V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 1.8 - (1.8 - 0.5) \left(1 - \sqrt{\frac{3.52}{3.52 + 1}} \right) = 1.65V \\
V_{OL} &= \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{1.8 - 0.5}{\sqrt{3(3.52)}} = 0.400V \quad V_{IH} = V_{TN} + 2V_{OL} = 0.5 + 2(0.400) = 1.30V \\
NM_H &= V_{OH} - V_{IH} = 1.65 - 1.30 = 0.300 V \quad NM_L = V_{IL} - V_{OL} = 0.826 - 0.400 = 0.426 V
\end{aligned}$$

6.80

$$(a) I_D = \frac{P}{V_{DD}} = \frac{200\mu W}{3V} = 66.7\mu A$$

For the saturated PMOS load: $66.7 \times 10^{-6} = \frac{25 \times 10^{-6}}{2} \left(\frac{W}{L} \right)_p (3 - 0.6)^2 \rightarrow \left(\frac{W}{L} \right)_p = \frac{0.926}{1} = \frac{1}{1.08}$

For the linear NMOS switch: $66.7 \times 10^{-6} = 60 \times 10^{-6} \left(\frac{W}{L} \right)_n \left(3 - 0.6 - \frac{0.3}{2} \right) 0.3 \rightarrow \left(\frac{W}{L} \right)_n = \frac{1.65}{1}$

$$(b) V_{IL} = V_{TN} + \frac{V_{DD} + V_{TP}}{\sqrt{K_R^2 + K_R}} \quad K_R = \frac{K_S}{K_L} = 1.65 \left(1.08 \right) \left(\frac{60}{25} \right) = 4.28 \quad V_{IL} = 0.6 + \frac{3 - 0.6}{\sqrt{4.28^2 + 4.28}} = 1.11V$$

$$V_{OH} = V_{DD} - (V_{DD} + V_{TP}) \left(1 - \sqrt{\frac{K_R}{K_R + 1}} \right) = 3 - (3 - 0.6) \left(1 - \sqrt{\frac{4.28}{4.28 + 1}} \right) = 2.76V$$

$$V_{OL} = \frac{V_{DD} + V_{TP}}{\sqrt{3K_R}} = \frac{3 - 0.6}{\sqrt{3(4.28)}} = 0.670V \quad V_{IH} = V_{TN} + 2V_{OL} = 0.6 + 2(0.670) = 1.94V$$

$$NM_H = V_{OH} - V_{IH} = 2.76 - 1.94 = 0.821 V \quad NM_L = V_{IL} - V_{OL} = 1.11 - 0.670 = 0.440 V$$

6.81

With A = 1 = B, the circuit is equivalent to a single 4.44/1 switching device.

$$100\mu A \left(\frac{4.44}{1} \right) \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L = \frac{100\mu A}{2} \left(\frac{1.81}{1} \right) (V_{TNL})^2 \quad | \quad V_{TNL} = -1 + 0.5 \left(\sqrt{V_L + 0.6} - \sqrt{0.6} \right)$$

$$\text{Solving iteratively} \rightarrow V_L = 0.1033V \quad | \quad V_{TNL} = -0.968V \quad (b) I_{DD} = \frac{100\mu A}{2} \left(\frac{1.81}{1} \right) (0.968)^2 = 84.8 \mu A$$

6.82

$$80\mu A = 100\mu A \left(\frac{W}{L} \right)_A \left(2.5 - 0.6 - \frac{0.1}{2} \right) 0.1 \rightarrow \left(\frac{W}{L} \right)_A = \frac{4.32}{1}$$

$$V_{TNB} = 0.6 + 0.5 \left(\sqrt{0.1 + 0.6} - \sqrt{0.6} \right) = 0.631$$

$$80\mu A = 100\mu A \left(\frac{W}{L} \right)_B \left(2.5 - 0.1 - 0.631 - \frac{0.1}{2} \right) 0.1 \rightarrow \left(\frac{W}{L} \right)_A = \frac{4.65}{1}$$

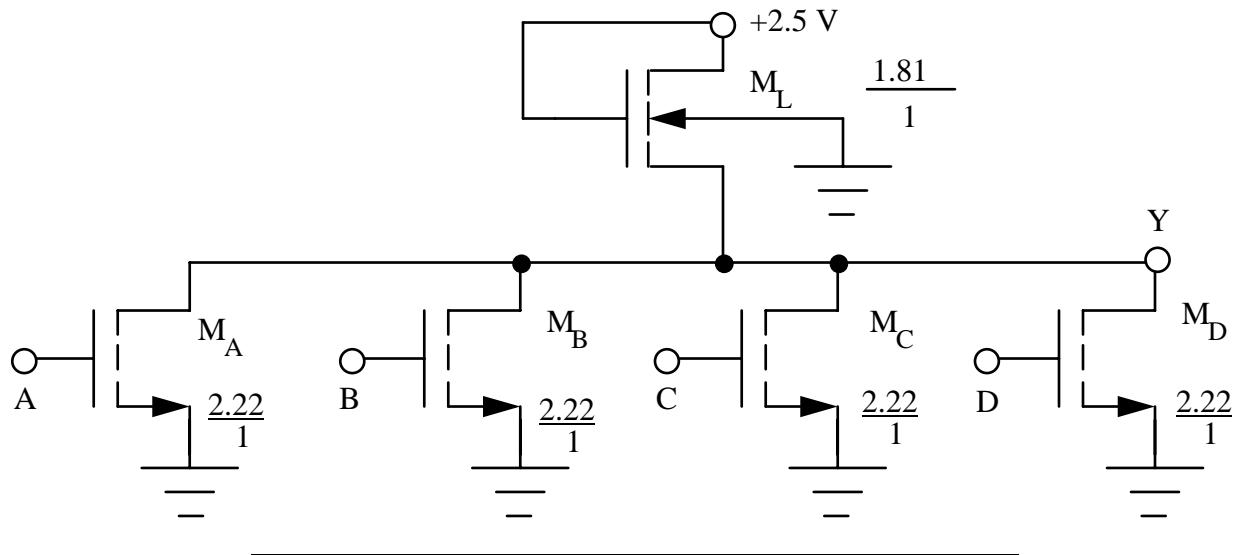
6.83

We require $\left(\frac{R_{on}}{W} \right)_A + \left(\frac{R_{on}}{W} \right)_B = \frac{R_{on}}{K}$ and the total area $A_T \propto (WL)_A + (WL)_B$

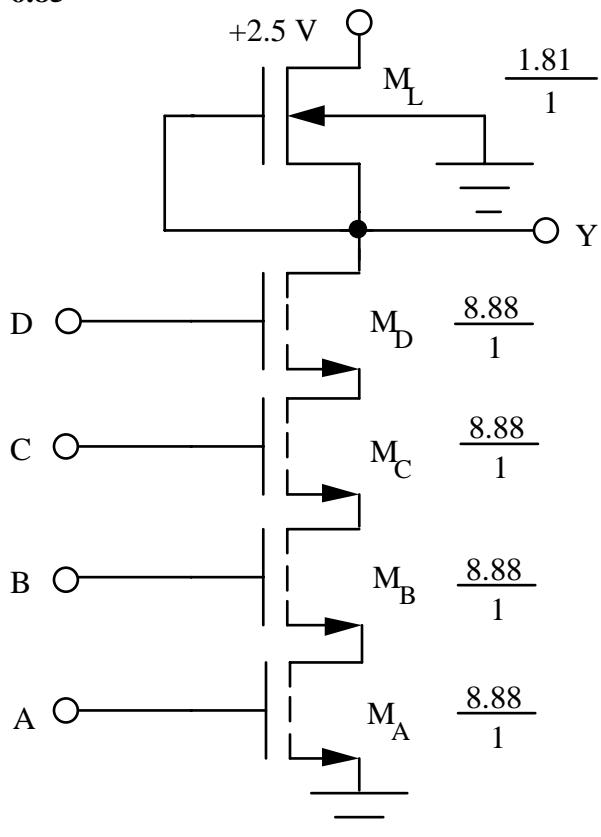
$$\text{Setting } L = 1, \frac{1}{W_A} + \frac{1}{W_B} = \frac{1}{K} \rightarrow W_A = \frac{KW_B}{W_B - K} \rightarrow A_T \propto \frac{KW_B}{W_B - K} + W_B = \frac{W_B^2}{W_B - K}$$

$$\text{Finding the minimum: } \frac{d}{dW_B} \left(\frac{W_B^2}{W_B - K} \right) = \frac{W_B^2 - 2KW_B}{(W_B - K)^2} = 0 \rightarrow W_B = 2K \quad \& \quad W_A = 2K.$$

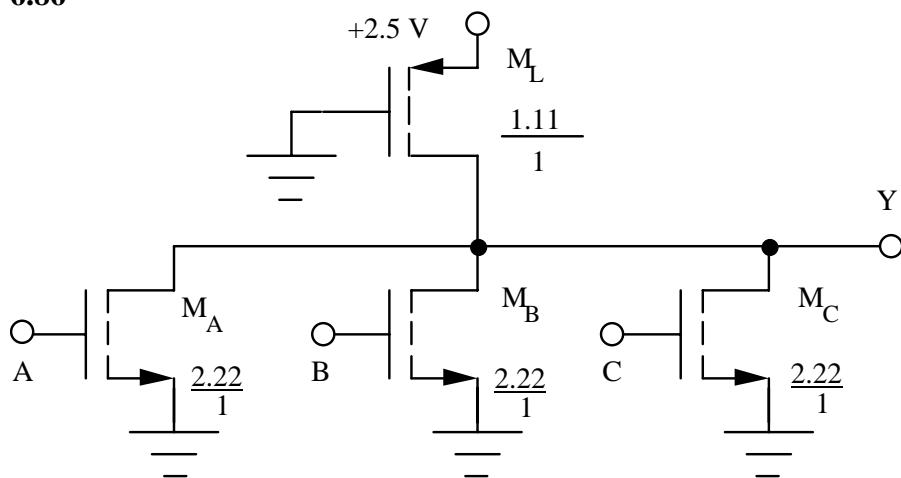
6.84



6.85



6.86

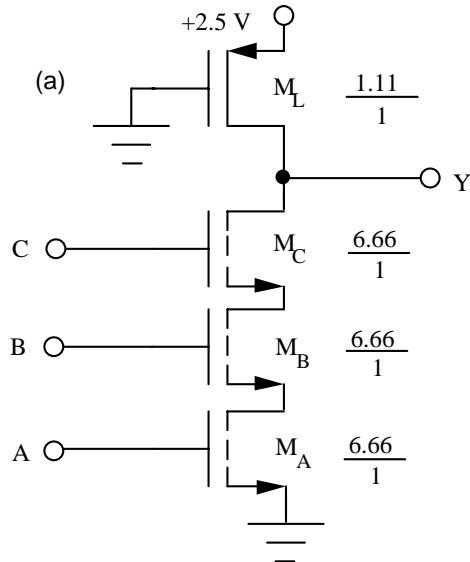


(a) With $A = B = C = 1$, the circuit is equivalent to a single 6.66/1 switching device.

$$100\mu A \left(\frac{6.66}{1} \right) \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L = \frac{40\mu A}{2} \left(\frac{1.81}{1} \right) (0.6)^2 \rightarrow V_L = 0.1033V$$

$$(b) I_{DD} = \frac{40\mu A}{2} \left(\frac{1.81}{1} \right) (0.6)^2 = 13.0 \mu A$$

6.87



(b) The PMOS device remains saturated with $I_{DD} = 80\mu A$.

$$\text{For } M_A : 80\mu A = 100\mu A \left(\frac{6.66}{1} \right) \left(2.5 - 0.6 - \frac{V_{DSA}}{2} \right) V_{DSA} \rightarrow V_{DSA} = 0.0643V$$

$$\text{For } M_B : V_{T_{NB}} = 0.6 + 0.5 \left(\sqrt{0.0643 + 0.6} - \sqrt{0.6} \right) = 0.620$$

$$80\mu A = 100\mu A \left(\frac{6.66}{1} \right) \left(2.5 - 0.0643 - 0.620 - \frac{V_{DSB}}{2} \right) V_{DSB} \rightarrow V_{DSB} = 0.0674V$$

$$\text{For } M_C : V_{T_{NC}} = 0.6 + 0.5 \left(\sqrt{0.0643 + 0.674 + 0.6} - \sqrt{0.6} \right) = 0.640$$

$$80\mu A = 100\mu A \left(\frac{6.66}{1} \right) \left(2.5 - 0.0674 - 0.0643 - 0.640 - \frac{V_{DSC}}{2} \right) V_{DSC} \rightarrow V_{DSC} = 0.0709V$$

$$V_L = V_{DSA} + V_{DSB} + V_{DSC} = 0.203 V$$

$$(c) \text{ Assume equal values of } V_{DS} = \frac{0.2}{3} = 0.0667V$$

$$\text{For } M_A : 80\mu A = 100\mu A \left(\frac{W}{L} \right)_A \left(2.5 - 0.6 - \frac{0.0667}{2} \right) 0.0667 \rightarrow \left(\frac{W}{L} \right)_A = \frac{6.43}{1}$$

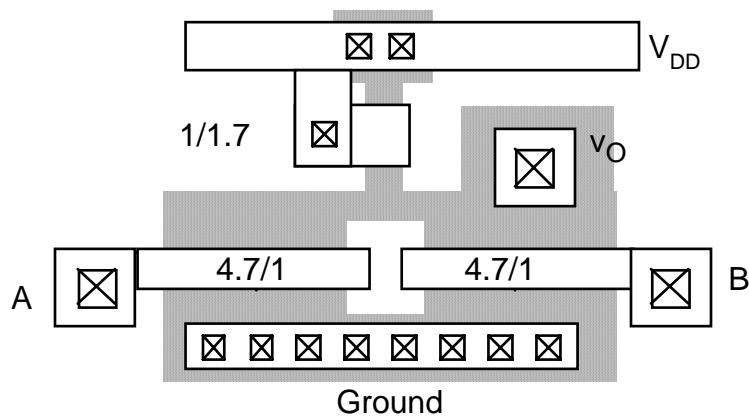
$$\text{For } M_B : V_{T_{NB}} = 0.6 + 0.5 \left(\sqrt{0.0667 + 0.6} - \sqrt{0.6} \right) = 0.621$$

$$80\mu A = 100\mu A \left(\frac{W}{L} \right)_B \left(2.5 - 0.0667 - 0.621 - \frac{0.0667}{2} \right) 0.0667 \rightarrow \left(\frac{W}{L} \right)_B = \frac{6.74}{1}$$

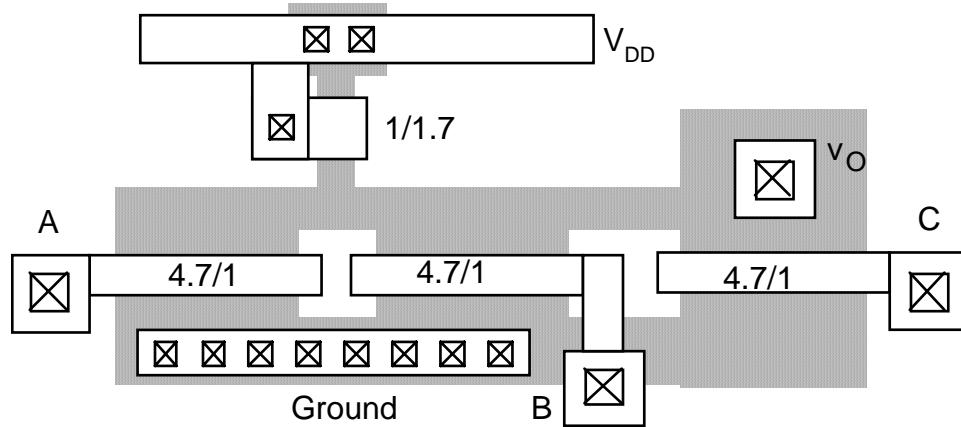
$$\text{For } M_C : V_{T_{NC}} = 0.6 + 0.5 \left(\sqrt{0.1334 + 0.6} - \sqrt{0.6} \right) = 0.641$$

$$80\mu A = 100\mu A \left(\frac{W}{L} \right)_B \left(2.5 - 0.1334 - 0.641 - \frac{0.0667}{2} \right) 0.0667 \rightarrow \left(\frac{W}{L} \right)_B = \frac{7.09}{1}$$

6.88



6.89



6.90

$$Y = \overline{(A+B)(C+D)(E+F)} + \left(\frac{W}{L}\right)_L = \frac{1.81}{1} + \left(\frac{W}{L}\right)_{A-F} = 3\left(\frac{2.22}{1}\right) = \frac{6.66}{1}$$

6.91

(a) The only change to the schematic is to connect the gate of load transistor M_L to its drain instead of its source.

(b) There is no change to the logic function $Y = \overline{(A+B)(C+D)(E+F)}$

$$(c) \left(\frac{W}{L}\right)_L = \frac{1}{1.68} + \left(\frac{W}{L}\right)_{ABCDEF} = 3\left(\frac{4.71}{1}\right) = \frac{14.1}{1}$$

6.92

$$Y = \overline{(A+B)(C+D)E} + \left(\frac{W}{L}\right)_L = \frac{1.11}{1} + \left(\frac{W}{L}\right)_{A-E} = 3\left(\frac{2.22}{1}\right) = \frac{6.66}{1}$$

6.93

(a) In the new circuit schematic, the PMOS transistor is replaced with a saturated NMOS load device as in Fig. 6.29(b).

(b) The logic function is unchanged: $Y = \overline{(A+B)(C+D)E}$

$$(c) \left(\frac{W}{L}\right)_L = \frac{1}{1.68} + \left(\frac{W}{L}\right)_{ABCDE} = 3\left(\frac{4.71}{1}\right) = \frac{14.1}{1}$$

6.94

$$(a) Y = \overline{ACE + ACDF + BF + BDE} \quad (b) \left(\frac{W}{L}\right)_L = 3\frac{1.11}{1} = \frac{3.33}{1} \quad | \quad \text{ACDF path contains 4 devices}$$

$$\left(\frac{W}{L}\right)_{A,C,D,F} = 3\left[4\left(\frac{2.22}{1}\right)\right] = \frac{26.6}{1} + \left(\frac{1}{\frac{W}{L}}\right)_B + \left(\frac{1}{\frac{W}{L}}\right)_{ACDF} + \left(\frac{1}{\frac{W}{L}}\right)_E = \frac{1}{3\frac{2.22}{1}} \rightarrow \left(\frac{W}{L}\right)_{B,E} = \frac{17.8}{1}$$

6.95

(a) In the new circuit schematic, the PMOS transistor is replaced with a saturated NMOS load device as in Fig. 6.29(b).

(b) There is no change to the logic function $Y = \overline{ACDF + ACE + BDE + BF}$

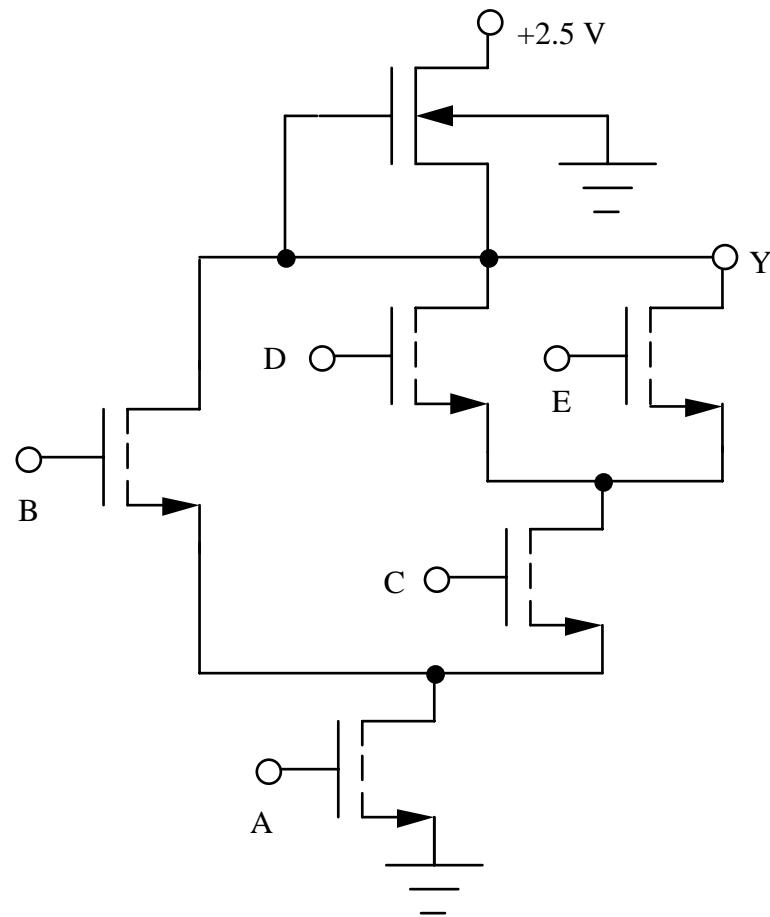
$$(c) \left(\frac{W}{L}\right)_L = \frac{1}{1.68} + \left(\frac{W}{L}\right)_{ACDF} = 4\left(\frac{4.71}{1}\right) = \frac{18.8}{1}$$

$R_{oB} + R_{onD} + R_{onE}$ setting $R_{oB} = R_{onE}$:

$$\left(\frac{1}{\frac{W}{L}}\right)_B + \frac{1}{18.8} + \left(\frac{1}{\frac{W}{L}}\right)_E = \left(\frac{2}{\frac{W}{L}}\right)_B + \frac{1}{18.8} = \frac{1}{4.71} \rightarrow \left(\frac{W}{L}\right)_B = \frac{12.6}{1}$$

Checking: $R_{oB} + R_{onF} = \frac{1}{18.8} + \frac{1}{12.6} = \frac{1}{7.42} \leq \frac{1}{4.71}$ so path BF is ok.

6.96



$$\left(\frac{W}{L}\right)_L = \frac{1.81}{1}$$

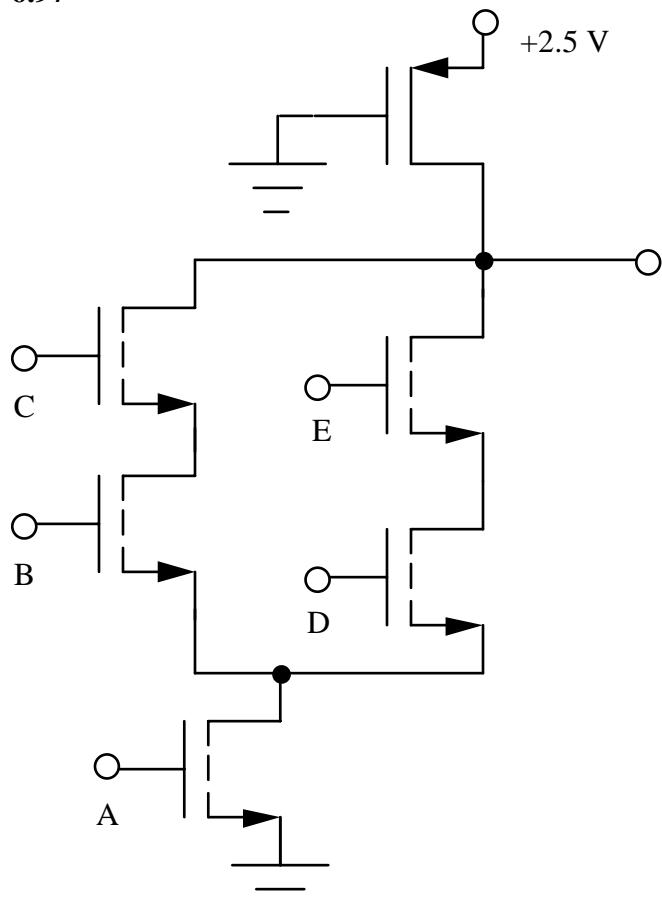
DCA and ECA paths contain three devices

$$\left(\frac{W}{L}\right)_{A,C,D,E} = 3 \left(\frac{2.22}{1}\right) = \frac{6.66}{1}$$

$$\frac{1}{\left(\frac{W}{L}\right)_A} + \frac{1}{\left(\frac{W}{L}\right)_B} = \frac{1}{\left(\frac{2.22}{1}\right)}$$

$$\frac{1}{\left(\frac{6.66}{1}\right)_A} + \frac{1}{\left(\frac{W}{1}\right)_B} = \frac{1}{\left(\frac{2.22}{1}\right)} \rightarrow \left(\frac{W}{L}\right)_B = \frac{3.33}{1}$$

6.97

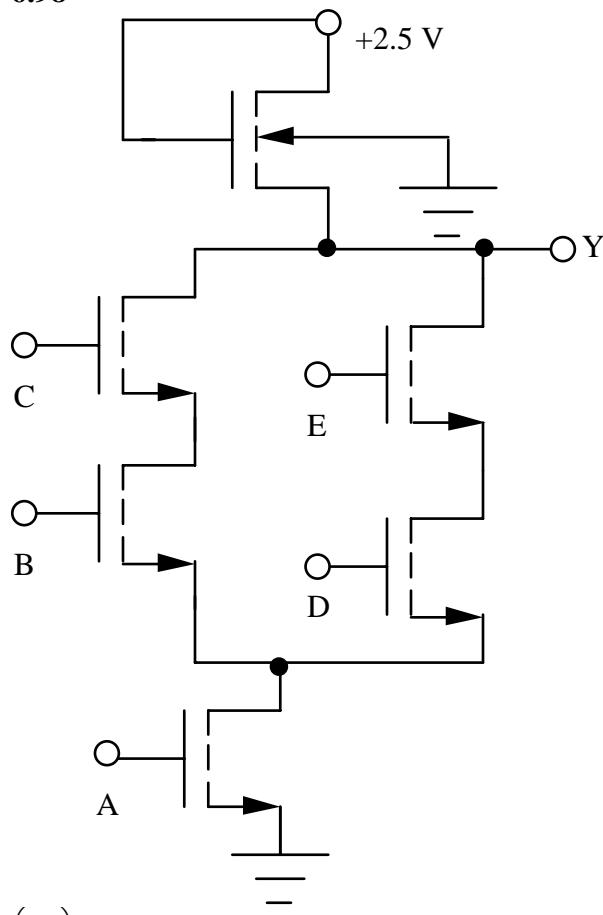


$$\left(\frac{W}{L}\right)_L = \frac{1}{2} \left(\frac{1.11}{1} \right) = \frac{1}{1.80}$$

CBA and EDA paths contain three devices

$$\left(\frac{W}{L}\right)_{A-E} = \frac{1}{2} (3) \left(\frac{2.22}{1} \right) = \frac{3.33}{1}$$

6.98

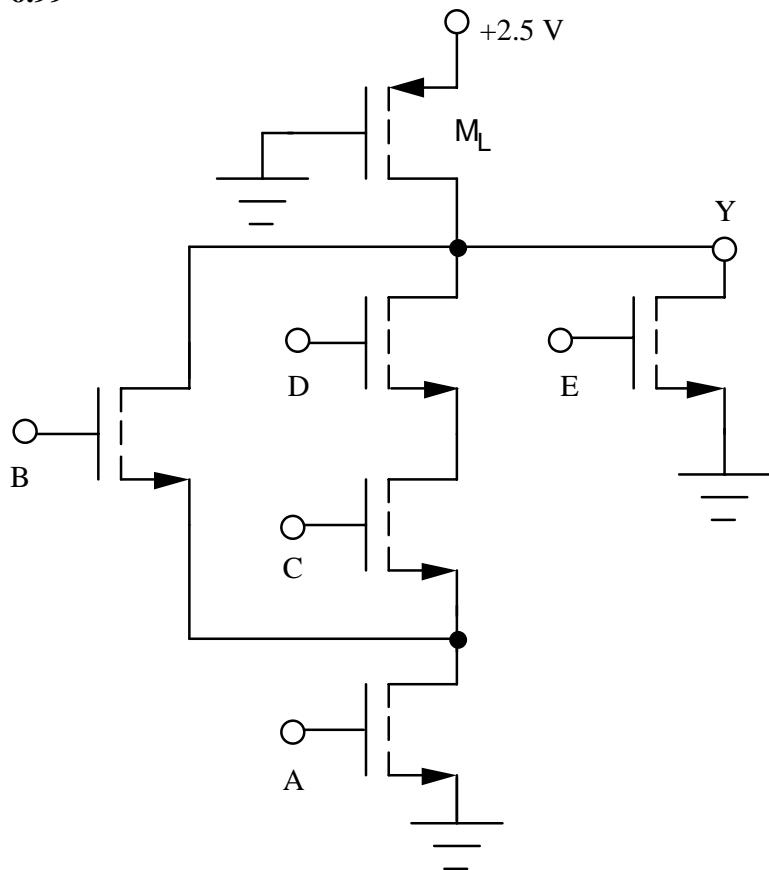


$$\left(\frac{W}{L}\right)_L = \frac{1}{1.68}$$

CBA and EDA paths contain three devices

$$\left(\frac{W}{L}\right)_{A-E} = 3 \left(\frac{4.71}{1}\right) = \frac{14.1}{1}$$

6.99



$$\left(\frac{W}{L}\right)_L = \frac{1.11}{1} \quad \left(\frac{W}{L}\right)_E = \frac{2.22}{1}$$

DCA path contains three devices

$$\left(\frac{W}{L}\right)_{A,C,D} = 3 \left(\frac{2.22}{1}\right) = \frac{6.66}{1}$$

$$\frac{1}{\left(\frac{6.66}{1}\right)_A} + \frac{1}{\left(\frac{W}{L}\right)_B} = \frac{1}{\left(\frac{2.22}{1}\right)} \rightarrow \left(\frac{W}{L}\right)_B = \frac{3.33}{1}$$

6.100

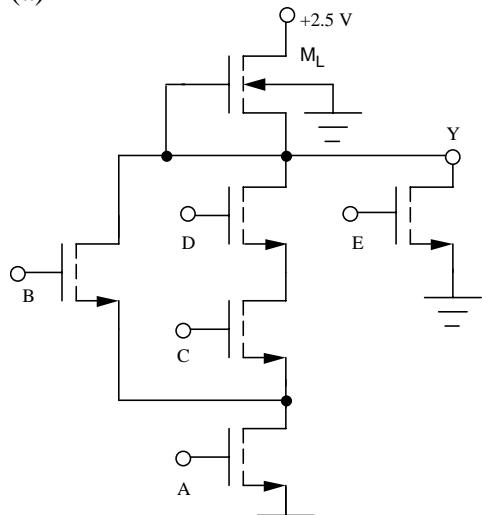
$$Y = \overline{A(B+D)(C+E) + (C+E)G + F} = \overline{(C+E)[A(B+D) + G] + F}$$

$$\left(\frac{W}{L}\right)_L = 2 \frac{1.81}{1} = \frac{3.62}{1} \quad | \quad \left(\frac{W}{L}\right)_{A-E} = 2 \left[3 \left(\frac{2.22}{1} \right) \right] = \frac{13.3}{1}$$

$$\left(\frac{W}{L}\right)_F = 2 \left(\frac{2.22}{1} \right) = \frac{4.44}{1} \quad | \quad \frac{1}{\left(\frac{W}{L}\right)_G} + \frac{1}{\left(\frac{13.3}{1}\right)} = \frac{1}{2 \cdot 2.22} \rightarrow \left(\frac{W}{L}\right)_G = \frac{6.67}{1}$$

6.101

(a)



$$\left(\frac{W}{L}\right)_L = \frac{1.81}{1} \quad \left(\frac{W}{L}\right)_E = \frac{2.22}{1}$$

DCA path contains three devices

$$\begin{aligned} \left(\frac{W}{L}\right)_{A,C,D} &= 3 \left(\frac{2.22}{1}\right) = \frac{6.66}{1} \\ \left(\frac{1}{\left(\frac{W}{L}\right)_A}\right) + \left(\frac{1}{\left(\frac{W}{L}\right)_B}\right) &= \left(\frac{1}{\left(\frac{2.22}{1}\right)}\right) \rightarrow \left(\frac{W}{L}\right)_B = \frac{3.33}{1} \end{aligned}$$

(b) Device E remains the same.

$$A, C, D: V_{DS} = \frac{V_L}{3} = \frac{0.20}{3} = 0.0667V \quad | \quad B: V_{DS} = 2 \frac{V_L}{3} = 2 \frac{0.20}{3} = 0.133V$$

$$100\mu A \left(\frac{W}{L}\right)_A \left(2.5 - .6 - \frac{0.0667}{2}\right) 0.0667 = 80\mu A \rightarrow \left(\frac{W}{L}\right)_A = \frac{6.43}{1}$$

$$V_{TNB} = V_{TNC} = 0.6 + 0.5 \left(\sqrt{0.0667 + 0.6} - \sqrt{0.6} \right) = 0.621V$$

$$100\mu A \left(\frac{W}{L}\right)_B \left(2.5 - 0.0667 - 0.621 - \frac{0.133}{2}\right) 0.133 = 80\mu A \rightarrow \left(\frac{W}{L}\right)_B = \frac{3.45}{1}$$

$$100\mu A \left(\frac{W}{L}\right)_C \left(2.5 - 0.0667 - 0.621 - \frac{0.0667}{2}\right) 0.0667 = 80\mu A \rightarrow \left(\frac{W}{L}\right)_C = \frac{6.74}{1}$$

$$V_{TND} = 0.6 + 0.5 \left(\sqrt{0.133 + 0.6} - \sqrt{0.6} \right) = 0.641V$$

$$100\mu A \left(\frac{W}{L}\right)_D \left(2.5 - 0.133 - 0.641 - \frac{0.0667}{2}\right) 0.0667 = 80\mu A \rightarrow \left(\frac{W}{L}\right)_D = \frac{7.09}{1}$$

6.102

Device A remains the same. $\left(\frac{W}{L}\right)_A = \frac{2.22}{1}$

$$B, C, D: V_{DS} = \frac{V_L}{2} = \frac{0.20}{2} = 0.100V$$

$$100\mu A \left(\frac{W}{L}\right)_{C,D} \left(2.5 - 0.6 - \frac{0.100}{2}\right) 0.100 = 80\mu A \rightarrow \left(\frac{W}{L}\right)_{C,D} = \frac{4.32}{1}$$

$$V_{T_{NB}} = 0.6 + 0.5 \left(\sqrt{0.100 + 0.6} - \sqrt{0.6} \right) = 0.631V$$

$$100\mu A \left(\frac{W}{L}\right)_B \left(2.5 - 0.100 - 0.631 - \frac{0.100}{2}\right) 0.100 = 80\mu A \rightarrow \left(\frac{W}{L}\right)_B = \frac{4.65}{1}$$

6.103

The load device remains the same.

$$B, C, D: V_{DS} = \frac{V_L}{3} = \frac{0.20}{3} = 0.0667V \quad | \quad A: V_{DS} = 2 \frac{V_L}{3} = 2 \frac{0.20}{3} = 0.133V$$

$$100\mu A \left(\frac{W}{L}\right)_B \left(2.5 - 0.6 - \frac{0.0667}{2}\right) 0.0667 = 80\mu A \rightarrow \left(\frac{W}{L}\right)_B = \frac{6.43}{1}$$

$$V_{T_{NA}} = V_{T_{ND}} = 0.6 + 0.5 \left(\sqrt{0.0667 + 0.6} - \sqrt{0.6} \right) = 0.621V$$

$$100\mu A \left(\frac{W}{L}\right)_A \left(2.5 - 0.0667 - 0.621 - \frac{0.133}{2}\right) 0.133 = 80\mu A \rightarrow \left(\frac{W}{L}\right)_A = \frac{3.45}{1}$$

$$100\mu A \left(\frac{W}{L}\right)_D \left(2.5 - 0.0667 - 0.621 - \frac{0.0667}{2}\right) 0.0667 = 80\mu A \rightarrow \left(\frac{W}{L}\right)_D = \frac{6.74}{1}$$

$$V_{T_{NC}} = 0.6 + 0.5 \left(\sqrt{0.133 + 0.6} - \sqrt{0.6} \right) = 0.641V$$

$$100\mu A \left(\frac{W}{L}\right)_C \left(2.5 - 0.133 - 0.641 - \frac{0.0667}{2}\right) 0.0667 = 80\mu A \rightarrow \left(\frac{W}{L}\right)_C = \frac{7.09}{1}$$

6.104

The load device remains the same.

$$A, B : V_{DS} = \frac{V_L}{2} = \frac{0.20}{2} = 0.10V \quad | \quad C, D : V_{DS} = \frac{V_L}{4} = \frac{0.20}{4} = 0.050V$$

$$100\mu A \left(\frac{W}{L} \right)_B \left(2.5 - .6 - \frac{0.10}{2} \right) 0.10 = 80\mu A \rightarrow \left(\frac{W}{L} \right)_B = \frac{4.32}{1}$$

$$V_{TNA} = V_{TND} = 0.6 + 0.5 \left(\sqrt{0.1 + 0.6} - \sqrt{0.6} \right) = 0.631V$$

$$100\mu A \left(\frac{W}{L} \right)_A \left(2.5 - 0.10 - 0.631 - \frac{0.10}{2} \right) 0.10 = 80\mu A \rightarrow \left(\frac{W}{L} \right)_A = \frac{4.65}{1}$$

$$100\mu A \left(\frac{W}{L} \right)_D \left(2.5 - 0.10 - 0.631 - \frac{0.05}{2} \right) 0.05 = 80\mu A \rightarrow \left(\frac{W}{L} \right)_D = \frac{9.17}{1}$$

$$V_{TNC} = 0.6 + 0.5 \left(\sqrt{0.15 + 0.6} - \sqrt{0.6} \right) = 0.646V$$

$$100\mu A \left(\frac{W}{L} \right)_C \left(2.5 - 0.15 - 0.646 - \frac{0.05}{2} \right) 0.05 = 80\mu A \rightarrow \left(\frac{W}{L} \right)_C = \frac{9.53}{1}$$

6.105

Device E and the load device remain the same. In the worst case, for paths BCD or ADE

$$A, B, C, D, E : V_{DS} = \frac{V_L}{3} = \frac{0.20}{3} = 0.0667V$$

$$100\mu A \left(\frac{W}{L} \right)_{B,E} \left(2.5 - .6 - \frac{0.0667}{2} \right) 0.0667 = 80\mu A \rightarrow \left(\frac{W}{L} \right)_{B,E} = \frac{6.43}{1}$$

$$V_{TND} = 0.6 + 0.5 \left(\sqrt{0.0667 + 0.6} - \sqrt{0.6} \right) = 0.621V$$

$$100\mu A \left(\frac{W}{L} \right)_D \left(2.5 - 0.0667 - 0.621 - \frac{0.0667}{2} \right) 0.0667 = 80\mu A \rightarrow \left(\frac{W}{L} \right)_D = \frac{6.74}{1}$$

$$V_{TNA} = V_{TNC} = 0.6 + 0.5 \left(\sqrt{0.133 + 0.6} - \sqrt{0.6} \right) = 0.641V$$

$$100\mu A \left(\frac{W}{L} \right)_{A,C} \left(2.5 - 0.133 - 0.641 - \frac{0.0667}{2} \right) 0.0667 = 80\mu A \rightarrow \left(\frac{W}{L} \right)_{A,C} = \frac{7.09}{1}$$

6.106

A	B	Y
0	0	1
(a) 0	1	0
1	0	0
1	1	1

(b) $Y = \overline{AB} + AB = \overline{A \oplus B}$

(c) Assuming equal voltage drops (0.10V) across M_p and M_s :

M_p must carry one unit of load current with one - half the drain - source

$$\text{voltage } (V_{DS} = 0.10V) \text{ of the switching transistor in Fig.6.29(d).} \rightarrow \left(\frac{W}{L}\right)_p = \frac{4.44}{1}$$

M_s must carry two units of load current with one - half the drain - source

$$\text{voltage } (V_{DS} = 0.10V) \text{ of the switching transistor in Fig.6.29(d).} \rightarrow \left(\frac{W}{L}\right)_s = \frac{8.88}{1}$$

(d) M_s will not change. M_p will need to be somewhat larger.

(e) Coincidence gate (Exclusive NOR)

6.107

Original design 0.20 mW - 1 mW requires 5 times larger current.

$$(a) R = \frac{28.8k\Omega}{5} = 5.76k\Omega \quad \left(\frac{W}{L}\right)_s = 5 \frac{2.22}{1} = \frac{11.1}{1}$$

$$(b) \left(\frac{W}{L}\right)_L = 5 \frac{1}{1.68} = \frac{2.98}{1} \quad \left(\frac{W}{L}\right)_s = 5 \frac{4.71}{1} = \frac{23.6}{1}$$

$$(c) \left(\frac{W}{L}\right)_L = 5 \frac{1}{5.72} = \frac{1}{1.14} \quad \left(\frac{W}{L}\right)_s = 5 \frac{2.22}{1} = \frac{11.1}{1}$$

$$(d) \left(\frac{W}{L}\right)_L = 5 \frac{1.81}{1} = \frac{9.05}{1} \quad \left(\frac{W}{L}\right)_s = 5 \frac{2.22}{1} = \frac{11.1}{1}$$

$$(e) \left(\frac{W}{L}\right)_L = 5 \frac{1.11}{1} = \frac{5.55}{1} \quad \left(\frac{W}{L}\right)_s = 5 \frac{2.22}{1} = \frac{11.1}{1}$$

6.108

$$\left(\frac{W}{L}\right)_L = 4 \frac{1.81}{1} = \frac{7.24}{1} \quad | \quad \left(\frac{W}{L}\right)_{A-E} = 4 \left[3 \left(\frac{2.22}{1} \right) \right] = \frac{26.6}{1}$$

$$\left(\frac{W}{L}\right)_F = 4 \left(\frac{2.22}{1} \right) = \frac{8.88}{1} \quad | \quad \left(\frac{1}{\frac{W}{L}}\right)_G + \left(\frac{1}{\frac{26.6}{1}}\right) = \frac{1}{4 \frac{2.22}{1}} \rightarrow \left(\frac{W}{L}\right)_G = \frac{13.3}{1}$$

6.109

$$\left(\frac{W}{L}\right)_L = \frac{1}{4} \left(\frac{1.81}{1} \right) = \frac{1}{2.21} \quad | \quad \left(\frac{W}{L}\right)_{A-F} = \frac{1}{4} \left[3 \left(\frac{2.22}{1} \right) \right] = \frac{1.67}{1}$$

6.110

$$(a) \left(\frac{W}{L}\right)_L = 3 \left(\frac{1.81}{1} \right) = \frac{5.43}{1} \quad | \quad \left(\frac{W}{L}\right)_{BCD} = 3 \left(\frac{6.66}{1} \right) = \frac{20.0}{1} \quad | \quad \left(\frac{W}{L}\right)_A = 3 \left(\frac{3.33}{1} \right) = \frac{9.99}{1}$$

$$(b) \left(\frac{W}{L}\right)_L = \frac{1}{5} \left(\frac{1.81}{1} \right) = \frac{1}{2.76} \quad | \quad \left(\frac{W}{L}\right)_{BCD} = \frac{1}{5} \left(\frac{6.66}{1} \right) = \frac{1.33}{1} \quad | \quad \left(\frac{W}{L}\right)_A = \frac{1}{5} \left(\frac{3.33}{1} \right) = \frac{1}{1.50}$$

6.111

$$(a) \left(\frac{W}{L}\right)_L = \frac{1}{10} \left(\frac{1.81}{1} \right) = \frac{1}{5.53} \quad | \quad \left(\frac{W}{L}\right)_{AB} = \frac{1}{10} \left(\frac{4.44}{1} \right) = \frac{1}{2.25} \quad | \quad \left(\frac{W}{L}\right)_{CD} = 2 \left(\frac{1}{2.25} \right) = \frac{1}{1.13}$$

$$(b) \left(\frac{W}{L}\right)_L = \frac{2.5}{1} \left(\frac{1.81}{1} \right) = \frac{4.53}{1} \quad | \quad \left(\frac{W}{L}\right)_{AB} = \frac{2.5}{1} \left(\frac{4.44}{1} \right) = \frac{11.1}{1} \quad | \quad \left(\frac{W}{L}\right)_{CD} = 2 \left(\frac{11.1}{1} \right) = \frac{22.2}{1}$$

6.112

$$(a) \left(\frac{W}{L}\right)_L = 4 \left(\frac{1.11}{1} \right) = \frac{4.44}{1} \quad | \quad \left(\frac{W}{L}\right)_{ABCDE} = 4 \left(\frac{6.66}{1} \right) = \frac{26.6}{1}$$

$$(b) \left(\frac{W}{L}\right)_L = \frac{1}{3} \left(\frac{1.11}{1} \right) = \frac{1}{2.70} \quad | \quad \left(\frac{W}{L}\right)_{ABCDE} = \frac{1}{3} \left(\frac{6.66}{1} \right) = \frac{2.22}{1}$$

6.113

$$(a) I_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2 = \frac{1}{2} \mu_n \frac{\varepsilon_{ox}}{T_{ox}} \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2$$

$$I_D^* = \frac{1}{2} \mu_n \frac{\varepsilon_{ox}}{T_{ox}} \left(\frac{\frac{W}{2}}{\frac{L}{2}} \right) (V_{GS} - V_{TN})^2 = 2I_D \quad | \quad \frac{I_D^*}{I_D} = 2$$

(b) $P_D^* = V(2I) = 2VI = 2P_D$ - Power dissipation has increased by a factor of two.

6.114

For each line : $i = C \frac{dv}{dt}$ | Assume the transition occurs in ΔT seconds generating

a current pulse with constant amplitude $I = 10 \times 10^{-12} F \frac{2.5V}{\Delta T}$.

Then $I_{avg} = \frac{2.5 \times 10^{-11}}{\Delta T} \frac{\Delta T}{50ns} = 500 \mu A$ and $P = 64(2.5V)I_{avg} = 64(2.5)(0.50mA) = 80 \text{ mW}$

$$(b) P \propto V^2 \text{ so } P = 80 \text{ mW} \left(\frac{3.3}{2.5} \right)^2 = 139 \text{ mW}$$

6.115

$$\tau_{PHL} \propto \frac{C}{K_S} \text{ and } \tau_{PLH} \propto \frac{C}{K_L} \mid \text{ For either case, } \tau_{PHL} \propto \frac{C}{K_S} = \frac{C'' WL}{\mu_n C'' \frac{W}{L}} = \frac{L^2}{\mu_n}$$

6.116

$$\tau_p = \frac{PDP}{P_D} = \frac{100fJ}{100\mu W} = \frac{10^{-13}J}{10^{-4}W} = 1 \text{ ns}$$

6.117

$$V_H = 2.5V \mid V_L = 0.20V \mid V_{50\%} = \frac{2.5 + 0.20}{2} = 1.35V$$

$$V_{90\%} = 2.5 - 0.23 = 2.27V \mid V_{10\%} = 0.25 + 0.23 = 0.48V$$

$$(a) v_I : t_r = 22.5 - 1.5 = 21 \text{ ns} \mid v_O : t_r = 81 - 58 = 23 \text{ ns}$$

$$v_I : t_f = 62 - 55 = 7 \text{ ns} \mid v_O : t_r = 12.5 - 6 = 6.5 \text{ ns}$$

$$(b) \tau_{PHL} = 2.5 \text{ ns} \mid \tau_{PLH} = 7 \text{ ns} \quad (c) \tau_p = \frac{2.5 + 7}{2} = 4.8 \text{ ns}$$

6.118

$$(a) T = 301(\tau_{PHL} + \tau_{PLH}) = 602 \frac{(\tau_{PHL} + \tau_{PLH})}{2} = 602 \tau_p = 602(0.1ns) = 60.2 \text{ ns}$$

(b) An even number of inverters has a potential steady state and may not oscillate.

6.119

$$t_r = 2.2RC = 2.2(28.8k\Omega)(0.5pF) = 31.7 \text{ ns}$$

$$t_f \cong 3.7R_{onS}C = \frac{3.7C}{K_n(V_{GS} - V_{TN})} = \frac{3.7(0.5pF)}{2.22(10^{-4})(2.5 - 0.6)} = 4.39 \text{ ns}$$

$$\tau_{PLH} = 0.69RC = 0.69(28.8k\Omega)(0.5pF) = 9.94 \text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onS}C = \frac{1.2C}{K_n(V_{GS} - V_{TN})} = \frac{1.2(0.5pF)}{2.22(10^{-4})(2.5 - 0.6)} = 1.78 \text{ ns} \quad \tau_p = \frac{9.94 + 1.78}{2} = 5.86 \text{ ns}$$

6.120

$$t_r = 2.2RC = 2.2(28.8k\Omega)(0.5pF) = 31.7 \text{ ns}$$

$$t_f \cong 3.7R_{onS}C = \frac{3.7C}{K_n(V_{GS} - V_{TN})} = \frac{3.7(0.5pF)}{2.22(10^{-4})(3.3 - 0.6)} = 3.09 \text{ ns}$$

$$\tau_{PLH} = 0.69RC = 0.69(28.8k\Omega)(0.5pF) = 9.94 \text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onS}C = \frac{1.2C}{K_n(V_{GS} - V_{TN})} = \frac{1.2(0.5pF)}{2.22(10^{-4})(3.3 - 0.6)} = 1.00 \text{ ns} \quad \tau_p = \frac{9.94 + 1.00}{2} = 5.47 \text{ ns}$$

6.121

$$\text{Resistive Load: } \tau_p = \frac{\tau_{PLH} + \tau_{PHL}}{2} \quad V_H = 2.5V \quad V_L = 0.20V \quad V_{TNS} = 0.6V$$

$$\tau_{PLH} = 0.69RC \quad \text{and} \quad \tau_{PHL} = 1.2R_{onS}C \quad \text{for} \quad R_{onS} = \frac{C}{K_S(V_H - V_{TNS})} = \frac{C}{K_S(2.5 - 0.6)} = \frac{0.526C}{K_S}$$

$$\frac{2.5 - V_L}{R} = K_S \left(V_{GS} - V_{TN} - \frac{V_L}{2} \right) V_L \rightarrow K_S R = \frac{2.5 - 0.20}{\left(2.5 - 0.6 - \frac{0.20}{2} \right) 0.20} = 6.39$$

$$2.5 \text{ ns} = \frac{1}{2} \left(1 \text{ pF} \left[0.69 \left(\frac{6.39}{K_S} \right) + \frac{0.526}{K_S} \right] \right) \rightarrow K_S = 987 \frac{\mu A}{V^2} \quad | \quad \left(\frac{W}{L} \right)_S = \frac{987}{60} = \frac{16.5}{1} \quad \text{and} \quad R = 6.47 \text{ k}\Omega$$

$$I_{DDL} = \frac{(2.5 - 0.20)V}{6.47k\Omega} = 356\mu A \quad | \quad \bar{P} = \frac{2.5(356\mu A)}{2} = 0.444 \text{ mW}$$

6.122

Resistive load inverter – λ has very little effect on the results:

$$\lambda = 0: t_r = 3.8 \text{ ns} \quad t_f = 1.3 \text{ ns} \quad \tau_{PLH} = 10.0 \text{ ns} \quad \tau_{PHL} = 1.6 \text{ ns}$$

$$\lambda = 0.04/\text{V}: t_r = 31.6 \text{ ns} \quad t_f = 3.6 \text{ ns} \quad \tau_{PLH} = 9.9 \text{ ns} \quad \tau_{PHL} = 1.5 \text{ ns}$$

6.123

Ignore body effect for simplicity. Equate drain currents to find V_L :

$$\frac{1}{2} \frac{K_n}{2} (2.5 - V_L - 0.6)^2 = 4K_n \left(2.5 - 0.6 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow V_L = 0.156V$$

$$R_{onL} = \frac{1}{K_L (V_{GS} - V_{TN})} = \frac{1}{0.5(60 \times 10^{-6})(2.5 - 0.156 - 0.6)} = 19.1k\Omega$$

$$R_{onS} = \frac{1}{K_S (V_{GS} - V_{TN})} = \frac{1}{4(60 \times 10^{-6})(2.5 - 0.6 - 0.6)} = 3.21k\Omega$$

$$t_r \cong 11.9 R_{onL} C = 11.9 (0.5 pF) (19.1 k\Omega) = 114 \text{ ns}$$

$$t_f \cong 3.7 R_{onS} C = 3.7 (0.5 pF) (3.21 k\Omega) = 5.94 \text{ ns}$$

$$\tau_{PLH} \cong 3.0 R_{onL} C = 3.0 (0.5 pF) (19.1 k\Omega) = 28.7 \text{ ns}$$

$$\tau_{PHL} \cong 1.2 R_{onS} C = 1.2 (0.5 pF) (3.21 k\Omega) = 1.93 \text{ ns} \quad \tau_p = \frac{28.7 + 1.93}{2} = 15.3 \text{ ns}$$

6.124

Ignore body effect for simplicity. Equate drain currents to find V_L :

$$V_{TN} = 0.6 \rightarrow V_H = 3.3 - 0.6 = 2.7V$$

$$\frac{4}{1} \frac{(60 \times 10^{-6})}{2} \left(2.7 - 0.6 - \frac{V_L}{2} \right) V_L = \frac{1}{2} \frac{(60 \times 10^{-6})}{2} (3.3 - V_L - 0.6)^2$$

$$9V_L^2 - 39.0V_L + 7.29 = 0 \rightarrow V_L = 0.196V$$

$$R_{onL} = \frac{1}{0.5(60 \times 10^{-6})(3.3 - 0.196 - 0.6)} = 13.3k\Omega$$

$$R_{onS} = \frac{1}{4(60 \times 10^{-6})(2.7 - 0.6)} = 1.98k\Omega$$

$$t_r = 11.9 R_{onL} C = 11.9 (13.3 k\Omega) (0.3 pF) = 47.5 \text{ ns}$$

$$\tau_{PLH} = 3.0 R_{onL} C = 3.0 (13.3 k\Omega) (0.3 pF) = 12.0 \text{ ns}$$

$$t_f = 3.7 R_{onS} C = 3.7 (1.98 k\Omega) (0.3 pF) = 2.20 \text{ ns}$$

$$\tau_{PHL} = 1.2 R_{onS} C = 1.2 (1.98 k\Omega) (0.3 pF) = 0.713 \text{ ns}$$

$$\tau_p = \frac{12.0 + 0.713}{2} = 6.36 \text{ ns}$$

6.125

$$\tau_p = \frac{\tau_{PLH} + \tau_{PHL}}{2} = \frac{3.0R_{onL} + 1.2R_{onS}}{2}C \rightarrow 3.0R_{onL} + 1.2R_{onS} = \frac{2(2 \times 10^{-9}s)}{10^{-12}F} = 4000\Omega$$

$$K_s \left(V_{GSS} - V_{TNS} - \frac{V_L}{2} \right) V_L = \frac{K_L}{2} \left(V_{GSL} - V_{TNL} \right)^2 \quad \text{Ignore body effect for simplicity.}$$

$$K_s \left(2.5 - 0.6 - 0.6 - \frac{0.25}{2} \right) 0.25 = \frac{K_L}{2} \left(2.5 - 0.25 - 0.6 \right)^2 \rightarrow K_s = 4.63K_L$$

$$\frac{3.0}{K_L(2.5 - 0.25 - 0.6)} + \frac{1.2}{4.63K_L(2.5 - 0.6 - 0.6)} = 4000\Omega \rightarrow K_L = 5.04 \times 10^{-4} A/V^2$$

$$\left(\frac{W}{L} \right)_L = \frac{5.04 \times 10^{-4}}{6.0 \times 10^{-5}} = \frac{8.41}{1} \quad \left(\frac{W}{L} \right)_S = 4.63 \frac{8.41}{1} = 38.9$$

6.126

$$V_H = 2.5V \quad V_L = 0.2V \quad V_{TNL} = 0.6 + 0.5(\sqrt{0.2 + 0.6} - \sqrt{0.6}) = 0.66V$$

$$R_{onL} = \frac{1}{K_L(V_{GS} - V_{TN})} = \frac{5.72}{(6 \times 10^{-5})(4 - 0.2 - 0.66)} = 30.4k\Omega$$

$$R_{onS} = \frac{1}{K_S(V_{GS} - V_{TN})} = \frac{1}{2.22(6 \times 10^{-5})(2.5 - 0.6)} = 3.95k\Omega$$

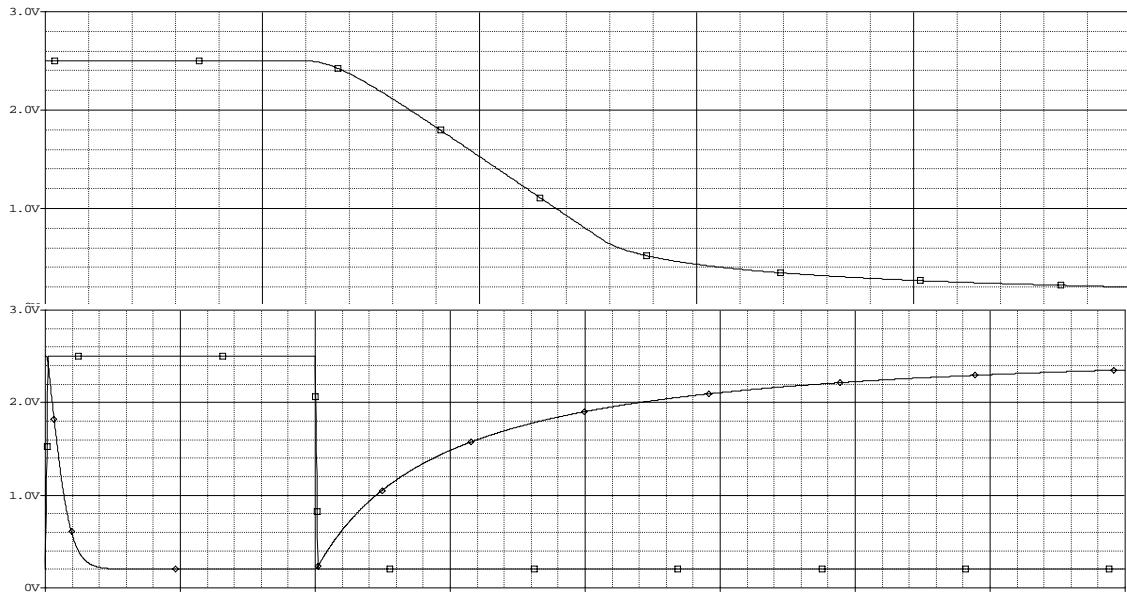
$$t_r \cong 3.7R_{onL}C = 3.7(0.7 \mu F)(30.4k\Omega) = 78.7 \text{ ns}$$

$$t_f \cong 3.7R_{onS}C = 3.7(0.7 \mu F)(3.95k\Omega) = 10.2 \text{ ns}$$

$$\tau_{PLH} \cong 0.69R_{onL}C = 0.69(0.7 \mu F)(30.4k\Omega) = 14.7 \text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onS}C = 1.2(0.7 \mu F)(3.95k\Omega) = 3.32 \text{ ns} \quad \tau_p = \frac{14.7 + 3.32}{2} = 9.00 \text{ ns}$$

6.127



Results: $t_f = 1.0 \text{ ns}$, $t_r = 22.3 \text{ ns}$, $\tau_{PHL} = 0.47 \text{ ns}$, $\tau_{PLH} = 4.0 \text{ ns}$, $\tau_p = 4.2 \text{ ns}$

6.128

$$\tau_p = \frac{\tau_{PLH} + \tau_{PHL}}{2} = \frac{3.6R_{onL} + 1.2R_{onS}}{2}C \rightarrow 3.6R_{onL} + 1.2R_{onS} = \frac{2(3 \times 10^{-9} \text{ s})}{10^{-12} F} = 6000 \Omega$$

$$K_s \left(V_{GSS} - V_{TNS} - \frac{V_L}{2} \right) V_L = \frac{K_L}{2} (-V_{TNL})^2 \quad \text{Ignore body effect for simplicity.}$$

$$K_s \left(3 - 0.6 - \frac{0.25}{2} \right) 0.25 = \frac{K_L}{2} (3)^2 \rightarrow K_s = 7.91 K_L$$

$$\frac{3.6}{K_L(3)} + \frac{1.2}{7.91 K_L(3 - 0.6)} = 6000 \Omega \rightarrow K_L = 2.11 \times 10^{-4} \text{ A/V}^2$$

$$\left(\frac{W}{L} \right)_L = \frac{2.11 \times 10^{-4}}{6.0 \times 10^{-5}} = \frac{3.52}{1} \quad \left(\frac{W}{L} \right)_S = 7.91 \frac{3.52}{1} = 27.8$$

$$t_r = 8.1 R_{onL} C = \frac{8.1(10^{-12})}{3.52(6 \times 10^{-5})(3)} = 12.8 \text{ ns} \quad t_f = 3.7 R_{onS} C = \frac{3.7(10^{-12})}{27.8(6 \times 10^{-5})(3 - 0.6)} = 0.924 \text{ ns}$$

6.129

$$\tau_P = \frac{\tau_{PLH} + \tau_{PHL}}{2} = \frac{3.6R_{onL} + 1.2R_{onS}}{2} C \rightarrow 3.6R_{onL} + 1.2R_{onS} = \frac{2(10^{-9}s)}{0.2 \times 10^{-12} F} = 10.0k\Omega$$

$$K_s \left(V_{GSS} - V_{TNS} - \frac{V_L}{2} \right) V_L = \frac{K_L}{2} (-V_{TNL})^2 \quad \text{Ignore body effect for simplicity.}$$

$$K_s \left(3.3 - 0.75 - \frac{0.20}{2} \right) 0.20 = \frac{K_L}{2} (2)^2 \rightarrow K_s = 4.08 K_L$$

$$\frac{3.6}{K_L(2)} + \frac{1.2}{4.08 K_L(3.3 - 0.75)} = 10k\Omega \rightarrow K_L = 1.92 \times 10^{-4} A/V^2$$

$$\left(\frac{W}{L} \right)_L = \frac{1.92 \times 10^{-4}}{6.0 \times 10^{-5}} = \frac{3.19}{1} \quad \left(\frac{W}{L} \right)_S = 4.08 \frac{3.19}{1} = 13.0$$

$$I_{DD} = \frac{K_L}{2} (-V_{TNL})^2 = \frac{1.92 \times 10^{-4}}{2} (2)^2 = 384 \mu A \quad \bar{P} = \frac{3.3(384 \mu A)}{2} = 0.634 mW$$

6.130

$$(a) V_{TN} = 0.6 + 0.5(\sqrt{0.20 + 0.6} - \sqrt{0.6}) = 0.660V$$

$$80 \times 10^{-6} = \frac{100 \times 10^{-6}}{2} \left(\frac{W}{L} \right)_L (2.5 - 0.20 - 0.66)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{1.68}$$

$$(b) 80 \times 10^{-6} = \frac{100 \times 10^{-6}}{2} \left(\frac{W}{L} \right)_L (2.5 - 0.20 - 0.6)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{1.81}$$

$$(c) 80 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{W}{L} \right)_L \left(4 - 0.20 - 0.66 - \frac{2.3}{2} \right) 2.3 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{5.72}$$

$$(d) 80 \times 10^{-6} = 100 \times 10^{-6} \left(\frac{W}{L} \right)_L \left(4 - 0.20 - 0.6 - \frac{2.3}{2} \right) 2.3 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1}{5.89}$$

$$(e) V_{TN} = -1 + 0.5(\sqrt{0.20 + 0.6} - \sqrt{0.6}) = -0.940V$$

$$80 \times 10^{-6} = \frac{100 \times 10^{-6}}{2} \left(\frac{W}{L} \right)_L (-0.940)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1.81}{1}$$

$$(f) 80 \times 10^{-6} = \frac{100 \times 10^{-6}}{2} \left(\frac{W}{L} \right)_L (-1)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{1.60}{1}$$

6.131

For $V_{DD} = -2.5$ V, we have $V_H = -0.20$ V with a power dissipation of 0.20 mW. Since these gates are all ratioed logic design, the ratio of the W/L ratios of the load and switching transistors does not change. We only need to scale both equally to achieve the power level.

$$(a) R_L = 28.8k\Omega \quad | \quad \left(\frac{W}{L}\right)_s = \frac{100}{40} \frac{2.22}{1} = \frac{5.55}{1}$$

$$(b) \left(\frac{W}{L}\right)_L = \frac{100}{60} \frac{1}{1.68} = \frac{1.49}{1} \quad | \quad \left(\frac{W}{L}\right)_s = \frac{100}{60} \frac{4.71}{1} = \frac{11.8}{1}$$

$$(c) \left(\frac{W}{L}\right)_L = \frac{100}{60} \frac{1}{5.72} = \frac{1}{2.29} \quad | \quad \left(\frac{W}{L}\right)_s = \frac{100}{60} \frac{2.22}{1} = \frac{5.55}{1}$$

$$(d) \left(\frac{W}{L}\right)_L = \frac{100}{60} \frac{1.81}{1} = \frac{4.53}{1} \quad | \quad \left(\frac{W}{L}\right)_s = \frac{100}{60} \frac{2.22}{1} = \frac{5.55}{1}$$

$$(e) \left(\frac{W}{L}\right)_L = \frac{100}{60} \frac{1.11}{1} = \frac{2.78}{1} \quad | \quad \left(\frac{W}{L}\right)_s = \frac{100}{60} \frac{2.22}{1} = \frac{5.55}{1}$$

6.132

$$V_L = -2.5 + 0.6 = -1.9 \text{ V} \quad | \quad \left(\frac{2}{1}\right) \left(25 \times 10^{-6}\right) \left(-1.9 - (-0.6) - \frac{-V_H}{2}\right) (-V_H) = \frac{1}{4} \left(\frac{25 \times 10^{-6}}{2}\right) \left(-2.5 - V_H - (-0.6)\right)^2$$

$$9V_H^2 - 24.6V_H + 3.61 = 0 \rightarrow V_H = -0.156 \text{ V}$$

6.133

Pretend this is an NMOS gate with $V_{DD} = 3.3V$ and $V_L = 0.33V$

$$V_H = 3.3 - \left[0.6 + 0.75 \left(\sqrt{V_H + 0.7} - \sqrt{0.7} \right) \right] \rightarrow V_H = 2.08V$$

$$V_{TNL} = 0.6 + 0.75 \left(\sqrt{0.33 + 0.7} - \sqrt{0.7} \right) = 0.734 \quad | \quad I_{DD} = \frac{0.1mW}{3.3V} = 30.3\mu A$$

$$30.3\mu A = \frac{40\mu A}{2} \left(\frac{W}{L}\right)_L \left(3.3 - 0.33 - 0.734\right)^2 \rightarrow \left(\frac{W}{L}\right)_L = \frac{0.303}{1} = \frac{1}{3.30}$$

$$30.3\mu A = 40\mu A \left(\frac{W}{L}\right)_S \left(2.08 - 0.60 - \frac{0.33}{2}\right) 0.33 \rightarrow \left(\frac{W}{L}\right)_S = \frac{1.75}{1}$$

6.134

$$V_L = -V_{TPL} \quad | \quad V_L = -\left[0.6 - 0.75(\sqrt{2.5 - V_L + 0.7} - \sqrt{0.7})\right] \rightarrow V_L = 1.07V$$

$$K_p \left(\frac{W}{L} \right)_S \left(V_{GS} - V_{TPS} - \frac{V_{DS}}{2} \right) V_{DS} = \frac{K_p}{2} \left(\frac{W}{L} \right)_L \left(V_{GSL} - V_{TPL} \right)^2$$

$$\frac{3}{1} \left(1.07 - 2.5 - (-0.6) - \frac{V_H - 2.5}{2} \right) (V_H - 2.5) = \frac{1}{2} \left(\frac{1}{3} \right) (V_H + V_{TPL})^2$$

$V_{TPL} = -0.6 - 0.75(\sqrt{V_H + 0.7} - \sqrt{0.7})$ Solving the last two equations iteratively : $V_H = 2.30 V$

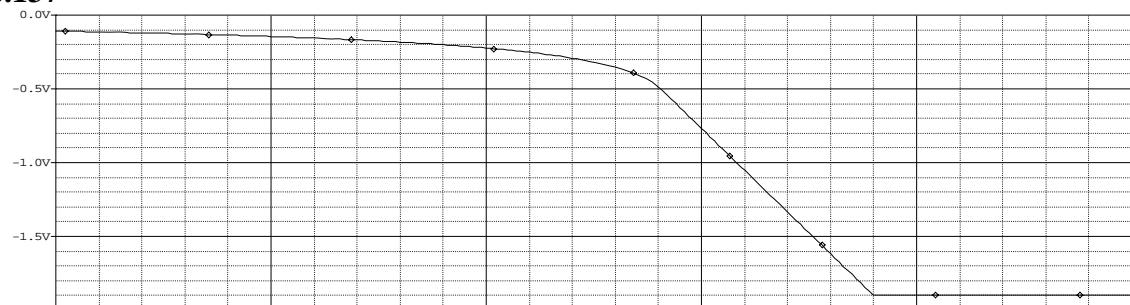
6.135

Y is low only when both A and B are high: $\bar{Y} = AB$ or $Y = \overline{AB}$.

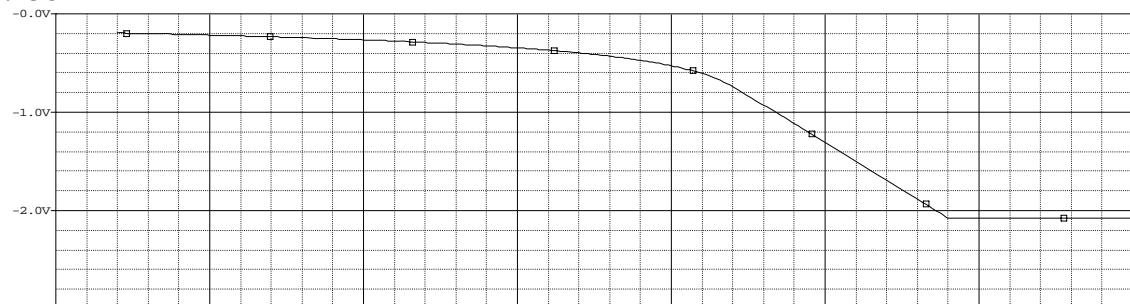
Alternatively, Y is high when either A or B is low : $Y = \overline{A} + \overline{B} = \overline{AB}$

6.136

Y is high only when both A and B are low : $Y = \overline{AB}$ or $Y = \overline{A} + \overline{B}$

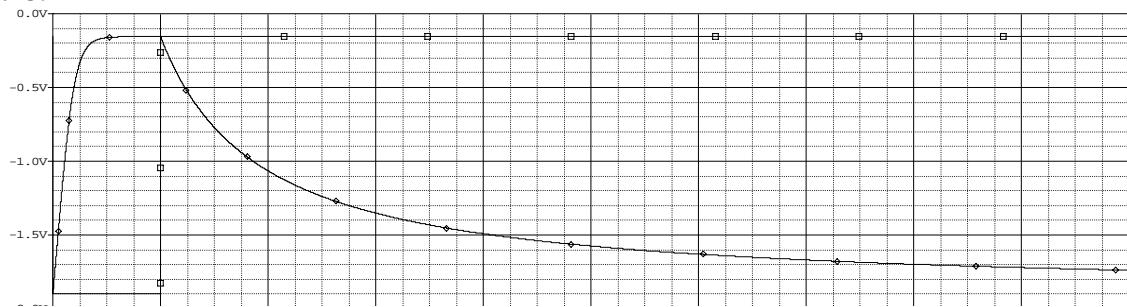
6.137

$V_L = -1.90$ and $V_H = -0.156$ agree with the hand calculations in Prob. 6.132

6.138

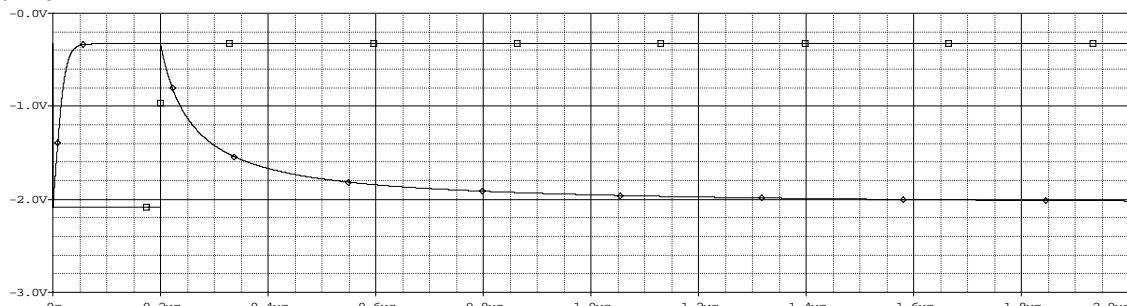
$V_H = -0.33$ and $V_L = -2.08$ agree with the design values in Prob. 6.133.

6.139



$t_r = 16.8 \text{ ns}$, $t_f = 560 \mu\text{s}$, $\tau_{PLH} = 11.7 \text{ ns}$, $\tau_{PHL} = 60 \text{ ns}$, $\tau_p = 35.9 \text{ ns}$

6.140



$t_r = 46 \text{ ns}$, $t_f = 1.1 \text{ s}$, $\tau_{PLH} = 21 \text{ ns}$, $\tau_{PHL} = 122 \text{ ns}$, $\tau_p = 72 \text{ ns}$

CHAPTER 7

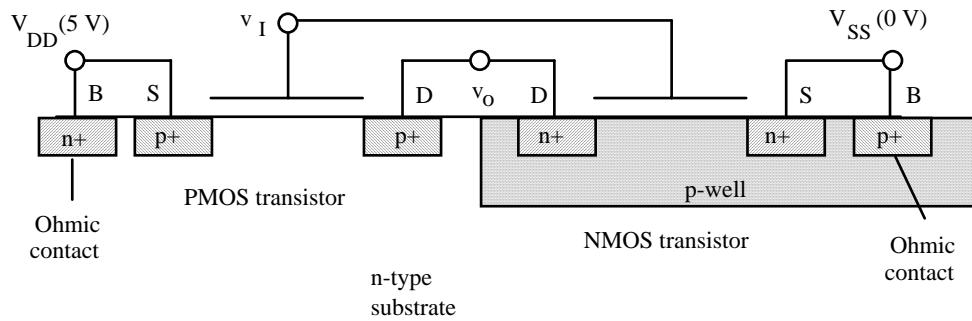
7.1

$$K_n' = \mu_n C_{ox}'' = \mu_n \frac{\epsilon_{ox}}{T_{ox}} = \mu_n \frac{3.9\epsilon_0}{T_{ox}} = \left(500 \frac{cm^2}{V \cdot sec} \right) \frac{(3.9)(8.854 \times 10^{-14} F/cm)}{10 \times 10^{-9} m (100 cm/m)}$$

$$K_n' = 173 \times 10^{-6} \frac{F}{V \cdot sec} = 173 \times 10^{-6} \frac{A}{V^2} = 173 \frac{\mu A}{V^2}$$

$$K_p' = \mu_p C_{ox}'' = \frac{\mu_p}{\mu_n} K_n' = \left(\frac{200}{500} \right) 173 \frac{\mu A}{V^2} = 69.1 \frac{\mu A}{V^2}$$

7.2



7.3

$$(a) I = I_s A = \left(500 \frac{pA}{cm^2} \right) (1cm \times 0.5cm) = 250 pA$$

$$(b) I = I_s A + \left(20 \times 10^6 \right) \left(100 \frac{pA}{cm^2} \right) (2 \times 10^{-4} cm) (5 \times 10^{-4} cm) = 250 + 200 = 450 pA$$

(c) Same as (b)

7.4

$$C = 3 \left(\frac{\epsilon_{ox} A}{t_{ox}} \right) = 3 \frac{3.9 \epsilon_0 L W}{t_{ox}} = 3 \frac{3.9 \left(8.854 \times 10^{-14} \frac{F}{cm} \right) \left(\frac{10mm}{2} \frac{0.1cm}{mm} \right) (1\mu m)}{1\mu m} = 0.518 pF$$

7.5

(a) $V_H = 2.5$ V, $V_L = 0$ V

(b) $V_H = 1.8$ V, $V_L = 0$ V

7.6

- (a) $V_H = 2.5 \text{ V}$, $V_L = 0 \text{ V}$
 (b) Same as (a). V_H and V_L don't depend upon W/L in a CMOS gate.
-

7.7

- (a) $V_H = 3.3 \text{ V}$, $V_L = 0 \text{ V}$
 (b) Same as (a). V_H and V_L don't depend upon W/L in a CMOS gate.
-

7.8

(a) $V_H = 2.5V$ | $V_L = 0V$ | For M_N , $V_{GS} = 0$, so M_N is cut off.

For M_P , $V_{GS} = -2.5$, $V_{DS} = 0V$ and $V_{TP} = -0.60V$. For $|V_{DS}| < |V_{GS} - V_{TP}|$, M_P is in the triode region.

(b) For M_N , $V_{GS} = 2.5$, $V_{DS} = 0V$ and $V_{TN} = 0.60V$. For $V_{DS} < V_{GS} - V_{TN}$, M_N is in the triode region.

For M_P , $V_{GS} = 0$, so M_P is cut off.

(c) For M_N , $V_{GS} = 1.25$, $V_{DS} = 1.25 \text{ V}$ and $V_{TN} = 0.60V$. For $V_{DS} > V_{GS} - V_{TN}$, M_N is saturated.

For M_P , $V_{GS} = -1.25$, $V_{DS} = -1.25V$ and $V_{TP} = -0.75V$. For $|V_{DS}| > |V_{GS} - V_{TP}|$, M_P is saturated.

7.9

(a) $V_H = 3.3V$ | $V_L = 0V$ | For M_N , $V_{GS} = 0$, so M_N is cut off.

For M_P , $V_{GS} = -3.3$, $V_{DS} = 0V$ and $V_{TP} = -0.75V$. For $|V_{DS}| < |V_{GS} - V_{TP}|$, M_P is in the triode region.

(b) For M_N , $V_{GS} = 3.3$, $V_{DS} = 0V$ and $V_{TN} = 0.75V$. For $V_{DS} < V_{GS} - V_{TN}$, M_N is in the triode region.

For M_P , $V_{GS} = 0$, so M_P is cut off.

(c) For M_N , $V_{GS} = 1.65$, $V_{DS} = 1.65 \text{ V}$ and $V_{TN} = 0.75V$. For $V_{DS} > V_{GS} - V_{TN}$, M_N is saturated.

For M_P , $V_{GS} = -1.65$, $V_{DS} = -1.65V$ and $V_{TP} = -0.75V$. For $|V_{DS}| > |V_{GS} - V_{TP}|$, M_P is saturated.

7.10

- (a) $V_H = 0 \text{ V}$, $V_L = -5.2 \text{ V}$
 (b) Same as (a). V_H and V_L don't depend upon W/L in a CMOS gate.
-

7.11

For $v_I = v_O$, both transistors will be saturated since $v_{GS} = v_{DS}$ for each device. Equating the drain currents with $K_n = K_p$ yields:

(a) Both transistors are saturated with $V_{DS} = V_{GS}$

$$\frac{K_n}{2}(v_I - V_{TN})^2 = \frac{K_p}{2}(v_I - V_{DD} - V_{TP})^2 \text{ so } v_I - V_{TN} = V_{DD} - v_I + V_{TP}$$

$$v_O = v_I = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{2.5 + 0.6 - .6}{2} = 1.25V$$

$$(b) I_{DN} = \frac{K_n}{2}(v_I - V_{TN})^2 = \frac{100\mu A}{2} \left(\frac{2}{1}\right)(1.25 - 0.6)^2 = 42.3\mu A$$

$$\text{Checking } I_{DP} = \frac{K_p}{2}(v_I - V_{DD} - V_{TP})^2 = \frac{40\mu A}{2} \left(\frac{5}{1}\right)(1.25 - 2.5 + 0.6)^2 = 42.3\mu A$$

(c) For $K_n = 2.5K_p$,

$$\frac{2.5K_p}{2}(v_I - V_{TN})^2 = \frac{K_p}{2}(v_I - V_{DD} - V_{TP})^2 \text{ or } 1.58(v_I - V_{TN}) = V_{DD} - v_I + V_{TP}$$

$$v_O = v_I = \frac{V_{DD} + 1.58V_{TN} + V_{TP}}{2.58} = \frac{2.5 + 1.58(0.6) + (-0.6)}{2.58} = 1.104V$$

$$(d) I_{DN} = \frac{100\mu A}{2} \left(\frac{2}{1}\right)(1.104 - 0.6)^2 = 25.4\mu A \quad | \text{ Check by finding } I_{DP} :$$

$$I_{DP} = \frac{40\mu A}{2} \left(\frac{5}{1}\right)(1.104 - 2.5 + 0.6)^2 = 25.3\mu A$$

7.12

(a) For $v_I = v_O$, both transistors will be saturated since $v_{GS} = v_{DS}$ for each device. Equating the drain currents with $K_n = K_p$ yields:

(i) $\frac{K_n}{2}(v_I - V_{TN})^2 = \frac{K_p}{2}(v_I - V_{DD} - V_{TP})^2$ and $v_I - V_{TN} = V_{DD} - v_I + V_{TP}$

$$v_O = v_I = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{3.3 + 0.75 - 0.75}{2} = 1.65V$$

$$(ii) I_{DN} = \frac{K_n}{2}(v_I - V_{TN})^2 = \frac{100\mu A}{2} \left(\frac{2}{1}\right)(1.65 - 0.75)^2 = 81\mu A$$

$$\text{Checking: } I_{DP} = \frac{K_p}{2}(v_I - V_{DD} + V_{TP})^2 = \frac{40\mu A}{2} \left(\frac{5}{1}\right)(1.65 - 3.3 + 0.75)^2 = 81\mu A$$

For $K_n = 2.5 K_p$,

$$(iii) \frac{2.5K_p}{2}(v_I - V_{TN})^2 = \frac{K_p}{2}(v_I - V_{DD} - V_{TP})^2 \text{ so } 1.58(v_I - V_{TN}) = V_{DD} - v_I + V_{TP}$$

$$v_o = v_I = \frac{V_{DD} + 1.58V_{TN} + V_{TP}}{2.58} = \frac{3.3 + 1.58(0.75) + (-0.75)}{2.58} = 1.448V$$

$$(iv) I_{DN} = \frac{100\mu A}{2} \left(\frac{2}{1} \right) (1.448 - 0.75)^2 = 48.7\mu A \quad | \text{ Check by finding } I_{DP} :$$

$$I_{DP} = \frac{40\mu A}{2} \left(\frac{2}{1} \right) (1.448 - 3.3 + 0.75)^2 = 48.6\mu A$$

(b) For $v_I = v_O$, both transistors will be saturated since $v_{GS} = v_{DS}$ for each device. Equating the drain currents with $K_n = K_p$ yields:

$$(i) \frac{K_n}{2}(v_I - V_{TN})^2 = \frac{K_p}{2}(v_I - V_{DD} - V_{TP})^2 \text{ and } v_I - V_{TN} = V_{DD} - v_I + V_{TP}$$

$$v_o = v_I = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{2.5 + 0.6 - 0.6}{2} = 1.25V$$

$$(ii) I_{DN} = \frac{K_n}{2}(v_I - V_{TN})^2 = \frac{100\mu A}{2} \left(\frac{2}{1} \right) (1.25 - 0.6)^2 = 42.3\mu A$$

$$\text{Checking: } I_{DP} = \frac{K_p}{2}(v_I - V_{DD} + V_{TP})^2 = \frac{100\mu A}{2} \left(\frac{2}{1} \right) (1.25 - 2.5 + 0.6)^2 = 42.3\mu A$$

For $K_n = 2.5 K_p$,

$$(iii) \frac{2.5K_p}{2}(v_I - V_{TN})^2 = \frac{K_p}{2}(v_I - V_{DD} - V_{TP})^2 \text{ and } 1.58(v_I - V_{TN}) = V_{DD} - v_I + V_{TP}$$

$$v_o = v_I = \frac{V_{DD} + 1.58V_{TN} + V_{TP}}{2.58} = \frac{2.5 + 1.58(0.60) + (-0.60)}{2.58} = 1.104V$$

$$(iv) I_{DN} = \frac{100\mu A}{2} \left(\frac{2}{1} \right) (1.104 - 0.60)^2 = 25.4\mu A \quad | \text{ Check by finding } I_{DP} :$$

$$I_{DP} = \frac{40\mu A}{2} \left(\frac{2}{1} \right) (1.104 - 2.5 + 0.60)^2 = 25.3\mu A$$

7.13

(a) For $v_I = v_O$, both transistors will be saturated since $v_{GS} = v_{DS}$ for each device. Equating the drain currents with $K_n = K_p$ yields:

$$(i) \frac{K_n}{2} (v_I - V_{TN})^2 = \frac{K_p}{2} (v_I - V_{DD} - V_{TP})^2 \text{ and } v_I - V_{TN} = V_{DD} - v_I + V_{TP}$$

$$v_O = v_I = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{1.8 + 0.5 - 0.5}{2} = 0.90V$$

$$(ii) I_{DN} = \frac{K_n}{2} (v_I - V_{TN})^2 = \frac{100\mu A}{2} \left(\frac{2}{1}\right) (0.9 - 0.5)^2 = 16.0\mu A$$

$$\text{Checking: } I_{DP} = \frac{K_p}{2} (v_I - V_{DD} - V_{TP})^2 = \frac{40\mu A}{2} \left(\frac{5}{1}\right) (0.9 - 1.8 + 0.5)^2 = 16.0\mu A$$

For $K_n = 2.5 K_p$,

$$(iii) \frac{2.5K_p}{2} (v_I - V_{TN})^2 = \frac{K_p}{2} (v_I - V_{DD} - V_{TP})^2 \text{ so } 1.58(v_I - V_{TN}) = V_{DD} - v_I + V_{TP}$$

$$v_O = v_I = \frac{V_{DD} + 1.58V_{TN} + V_{TP}}{2.58} = \frac{1.8 + 1.58(0.5) + (-0.5)}{2.58} = 0.810V$$

$$(iv) I_{DN} = \frac{100\mu A}{2} \left(\frac{2}{1}\right) (0.810 - 0.5)^2 = 96.2\mu A \quad | \text{ Check by finding } I_{DP} :$$

$$I_{DP} = \frac{40\mu A}{2} \left(\frac{5}{1}\right) (0.810 - 1.8 + 0.5)^2 = 96.0\mu A$$

(b) For $v_I = v_O$, both transistors will be saturated since $v_{GS} = v_{DS}$ for each device. Equating the drain currents with $K_n = K_p$ yields:

$$(i) \frac{K_n}{2} (v_I - V_{TN})^2 = \frac{K_p}{2} (v_I - V_{DD} - V_{TP})^2 \text{ and } v_I - V_{TN} = V_{DD} - v_I + V_{TP}$$

$$v_O = v_I = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{2.5 + 0.75 - 0.65}{2} = 1.30V$$

$$(ii) I_{DN} = \frac{K_n}{2} (v_I - V_{TN})^2 = \frac{100\mu A}{2} \left(\frac{2}{1}\right) (1.30 - 0.75)^2 = 30.3\mu A$$

$$\text{Checking: } I_{DP} = \frac{K_p}{2} (v_I - V_{DD} + V_{TP})^2 = \frac{40\mu A}{2} \left(\frac{5}{1}\right) (1.30 - 2.5 + 0.65)^2 = 30.3\mu A$$

For $K_n = 2.5 K_p$,

$$(iii) \frac{2.5K_p}{2} (v_I - V_{TN})^2 = \frac{K_p}{2} (v_I - V_{DD} - V_{TP})^2 \text{ and } 1.58(v_I - V_{TN}) = V_{DD} - v_I + V_{TP}$$

$$v_O = v_I = \frac{V_{DD} + 1.58V_{TN} + V_{TP}}{2.58} = \frac{2.5 + 1.58(0.75) + (-0.65)}{2.58} = 1.176V$$

$$(iv) I_{DN} = \frac{100\mu A}{2} \left(\frac{2}{1}\right) (1.176 - 0.75)^2 = 18.2\mu A \quad | \text{ Check by finding } I_{DP} :$$

$$I_{DP} = \frac{40\mu A}{2} \left(\frac{2}{1}\right) (1.176 - 2.5 + 0.65)^2 = 18.2\mu A$$

(c) For $v_I = v_O$, both transistors will be saturated since $v_{GS} = v_{DS}$ for each device. Equating the drain currents with $K_n = K_p$ yields:

$$(i) \frac{K_n}{2} (v_I - V_{TN})^2 = \frac{K_p}{2} (v_I - V_{DD} - V_{TP})^2 \text{ and } v_I - V_{TN} = V_{DD} - v_I + V_{TP}$$

$$v_O = v_I = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{2.5 + 0.65 - 0.75}{2} = 1.20V$$

$$(ii) I_{DN} = \frac{K_n}{2} (v_I - V_{TN})^2 = \frac{100\mu A}{2} \left(\frac{2}{1}\right) (1.20 - 0.65)^2 = 30.3\mu A$$

$$\text{Checking : } I_{DP} = \frac{K_p}{2} (v_I - V_{DD} + V_{TP})^2 = \frac{40\mu A}{2} \left(\frac{5}{1}\right) (1.20 - 2.5 + 0.75)^2 = 30.3\mu A$$

For $K_n = 2.5 K_p$,

$$(iii) \frac{2.5K_p}{2} (v_I - V_{TN})^2 = \frac{K_p}{2} (v_I - V_{DD} - V_{TP})^2 \text{ and } 1.58(v_I - V_{TN}) = V_{DD} - v_I + V_{TP}$$

$$v_O = v_I = \frac{V_{DD} + 1.58V_{TN} + V_{TP}}{2.58} = \frac{2.5 + 1.58(0.65) + (-0.75)}{2.58} = 1.076V$$

$$(iv) I_{DN} = \frac{100\mu A}{2} \left(\frac{2}{1}\right) (1.076 - 0.65)^2 = 18.2\mu A \quad | \text{ Check by finding } I_{DP} :$$

$$I_{DP} = \frac{40\mu A}{2} \left(\frac{2}{1}\right) (1.076 - 2.5 + 0.75)^2 = 18.2\mu A$$

7.14

*PROBLEM 7.14 - CMOS INVERTER TRANSFER CHARACTERISTICS

VIN 1 0 DC 0

VDD 3 0 DC 2.5

M1 2 1 0 0 MOSN W=2U L=1U

M2 2 1 3 3 MOSP W=2U L=1U

.DC VIN 0 2.5 .01

*.DC VIN 2.16 2.17 .0001

.MODEL MOSN NMOS KP=10E-5 VTO=0.6 GAMMA=0

.MODEL MOSP PMOS KP=4E-5 VTO=-0.6 GAMMA=0

.PRINT DC V(2)

.END

Result: $v_I = 1.104 \text{ V}$

$$\frac{2.5K_p}{2}(v_I - V_{TN})^2 = \frac{K_p}{2}(V_{DD} - v_I + V_{TP})^2 \text{ and } 1.58(v_I - V_{TN}) = V_{DD} - v_I + V_{TP}$$

$$v_o = v_I = \frac{V_{DD} + 1.58V_{TN} + V_{TP}}{2.58} = \frac{2.5 + 1.58(0.6) + (-0.6)}{2.58} = 1.10 \text{ V}$$

7.15

(a) $V_H = 3.3 \text{ V}$. For $v_O = V_L$, assume M_p is saturated and M_n is in the triode region.

$$\frac{K_p}{2} \left(\frac{1}{1} \right) (-3.3 + 0.6)^2 = K_n \left(\frac{4}{1} \right) 3.3 - 0.6 + \frac{V_L}{2} V_L$$

$$\frac{4 \times 10^{-5}}{2(10 \times 10^{-5})} \left(\frac{7.29}{4} \right) = \left(2.7 + \frac{V_L}{2} \right) V_L \text{ and rearranging: } V_L^2 + 5.4V_L - 0.729 = 0$$

$V_L = 0.132 \text{ V}$. Checking the assumptions - For M_n , $3.3 - 0.6 > 0.132$. Triode region is correct. For M_p , $V_{GS} - V_{TP} = -3.3 + 0.6 = -2.7 \text{ V}$ and $V_{DS} = 0.132 - 3.3 = -3.17 \text{ V}$. Saturation region operation is correct.

(b) $V_H = 2.5 \text{ V}$. For $v_O = V_L$, assume M_p is saturated and M_n is in the triode region.

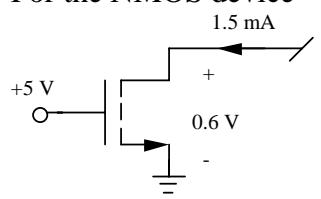
$$\frac{K_p}{2} \left(\frac{1}{1} \right) (-2.5 + 0.6)^2 = K_n \left(\frac{4}{1} \right) 2.5 - 0.6 + \frac{V_L}{2} V_L$$

$$\frac{4 \times 10^{-5}}{2(10 \times 10^{-5})} \left(\frac{3.61}{4} \right) = \left(1.9 + \frac{V_L}{2} \right) V_L \text{ and rearranging: } V_L^2 + 3.8V_L - 0.361 = 0$$

$V_L = 0.0928 \text{ V}$. Checking the assumptions - For M_n , $2.5 - 0.6 > 0.0928$. Triode region is correct. For M_p , $V_{GS} - V_{TP} = -2.5 + 0.6 = -1.9 \text{ V}$ and $V_{DS} = 0.0928 - 2.5 = -2.41 \text{ V}$. Saturation region operation is correct.

7.16

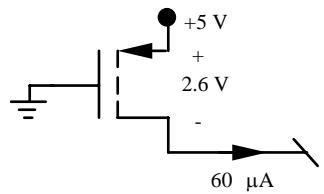
For the NMOS device



$$\left(100 \times 10^{-6}\right) \left(\frac{W}{L}\right)_n \left(5 - 0.6 - \frac{0.6}{2}\right) 0.6 = 1.5 \times 10^{-3}$$

$$\left(\frac{W}{L}\right)_n = \frac{61.0}{1}$$

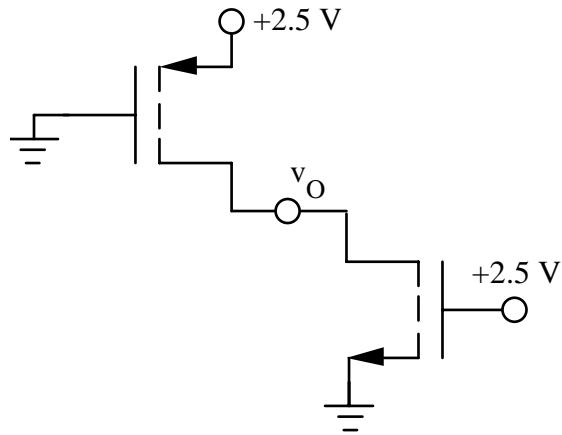
For the PMOS device



$$\left(40 \times 10^{-6}\right) \left(\frac{W}{L}\right)_p \left(5 - 0.6 - \frac{2.6}{2}\right) 2.6 = 6 \times 10^{-5}$$

$$\left(\frac{W}{L}\right)_p = \frac{1}{5.37}$$

7.17



$$K_n = 2000 \frac{\mu A}{V^2} \quad \text{and} \quad K_p = 1600 \frac{\mu A}{V^2}.$$

Therefore the output will be forced below $V_{DD}/2$.

For both transistors, $|V_{GS} - V_{TN}| = 1.9V$. Assume that both devices are in the linear region.

$$\left(\frac{40}{1}\right)\left(4 \times 10^{-5}\right)\left(-2.5 + 0.6 - \frac{V_o - 2.5}{2}\right)(V_o - 2.5) = \left(\frac{20}{1}\right)\left(10 \times 10^{-5}\right)\left(2.5 - 0.6 - \frac{V_o}{2}\right)V_o$$

$$\text{Rearranging: } V_o^2 - 14.2V_o + 13 = 0 \Rightarrow V_o = 0.9836V \quad | \quad V_{DSN} = 0.984V \quad | \quad V_{DSP} = -1.52V$$

and the assumed operating regions are correct.

$$I_{DP} = \left(\frac{40}{1}\right)\left(4 \times 10^{-5}\right)\left(-2.5 + 0.6 - \frac{0.9836 - 2.5}{2}\right)(0.9836 - 2.5) = 2.77 \text{ mA, and checking}$$

$$I_{DN} = \left(\frac{20}{1}\right)\left(10 \times 10^{-5}\right)\left(2.5 - 0.6 - \frac{0.9836}{2}\right)0.9836 = 2.77 \text{ mA.}$$

7.18

$$K_R = \frac{K_n}{K_p} = 2.5 \quad | \quad V_{IH} = \frac{2(2.5)(2.5 - 0.6 - 0.6)}{(2.5 - 1)(\sqrt{1 + 3(2.5)})} - \frac{2.5 - 2.5(0.6) - 0.6}{2.5 - 1} = 1.22V$$

$$V_{OL} = \frac{(2.5 + 1)(1.22) - 2.5 - 2.5(0.6) + 0.6}{2(2.5)} = 0.174V$$

$$V_{IL} = \frac{2(\sqrt{2.5})(2.5 - 0.6 - 0.6)}{(2.5 - 1)(\sqrt{2.5 + 3})} - \frac{2.5 - 2.5(0.6) - 0.6}{2.5 - 1} = 0.902V$$

$$V_{OH} = \frac{(2.5 + 1)(0.902) + 2.5 - 2.5(0.6) + 0.6}{2} = 2.38V$$

$$NM_H = V_{OH} - V_{IH} = 2.38 - 1.22 = 1.16 \text{ V} \quad NM_L = V_{IL} - V_{OL} = 0.902 - 0.174 = 0.728 \text{ V}$$

7.19

$$(a) \text{For } K_R = 1: NM_H = \frac{V_{DD} - V_{TN} - 3V_{TP}}{4} = \frac{3.3 - 0.75 - 3(-0.75)}{4} = 1.20 \text{ V}$$

$$\text{and } NM_L = \frac{V_{DD} + 3V_{TN} + V_{TP}}{4} = \frac{3.3 + 3(0.75) + 0.75}{4} = 1.20 \text{ V}$$

$$(b) K_R = \frac{K_n}{K_p} = 2.5 \quad / \quad V_{IH} = \frac{2(2.5)(3.3 - 0.75 - 0.75)}{(2.5 - 1)(\sqrt{1 + 3(2.5)})} - \frac{3.3 - 2.5(0.75) - 0.75}{2.5 - 1} = 1.61 \text{ V}$$

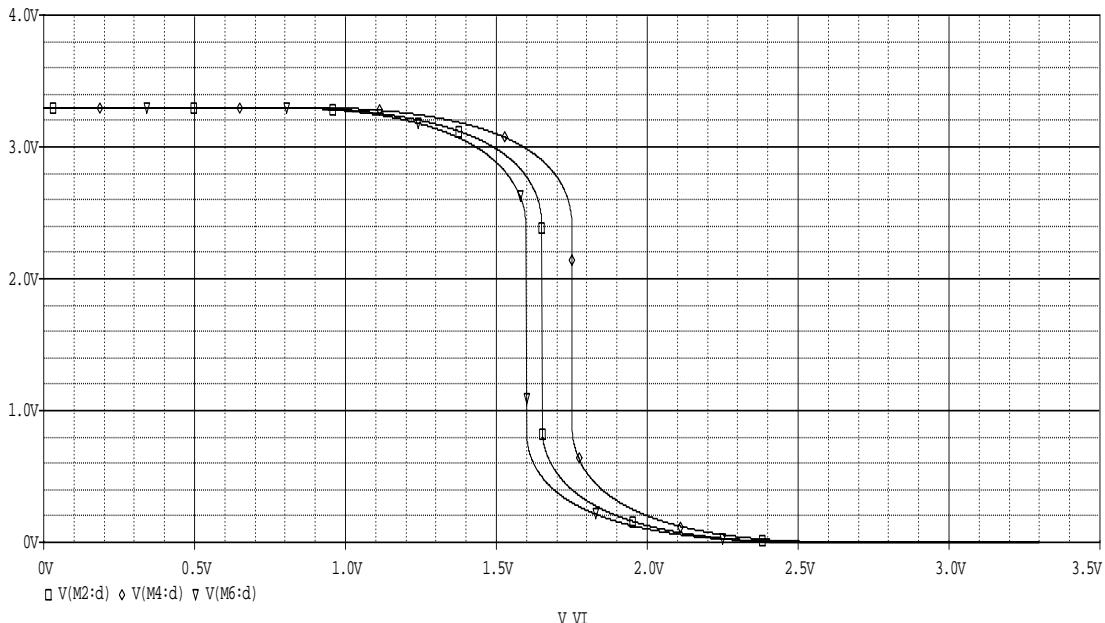
$$V_{OL} = \frac{(2.5 + 1)(1.61) - 3.3 - 2.5(0.75) + 0.75}{2(2.5)} = 0.242 \text{ V}$$

$$V_{IL} = \frac{2(\sqrt{2.5})(3.3 - 0.75 - 0.75)}{(2.5 - 1)(\sqrt{2.5 + 3})} - \frac{3.3 - 2.5(0.75) - 0.75}{2.5 - 1} = 1.17 \text{ V}$$

$$V_{OH} = \frac{(2.5 + 1)(1.17) + 3.3 - 2.5(0.75) + 0.75}{2} = 3.14 \text{ V}$$

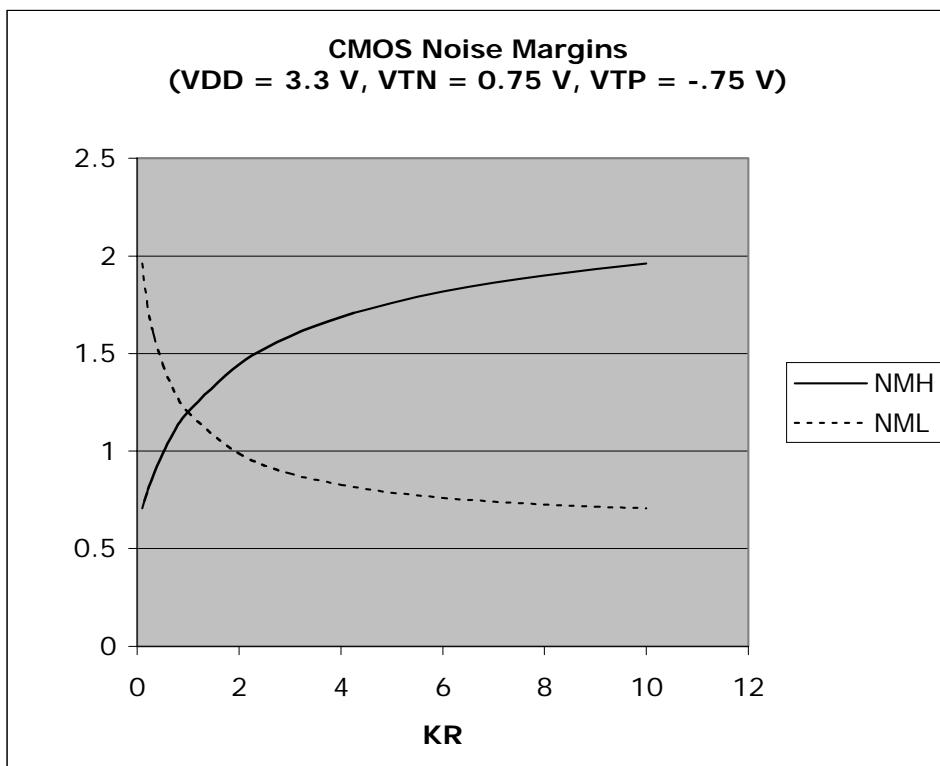
$$NM_H = V_{OH} - V_{IH} = 3.14 - 1.61 = 1.53 \text{ V} \quad NM_L = V_{IL} - V_{OL} = 1.17 - 0.242 = 0.928 \text{ V}$$

7.20

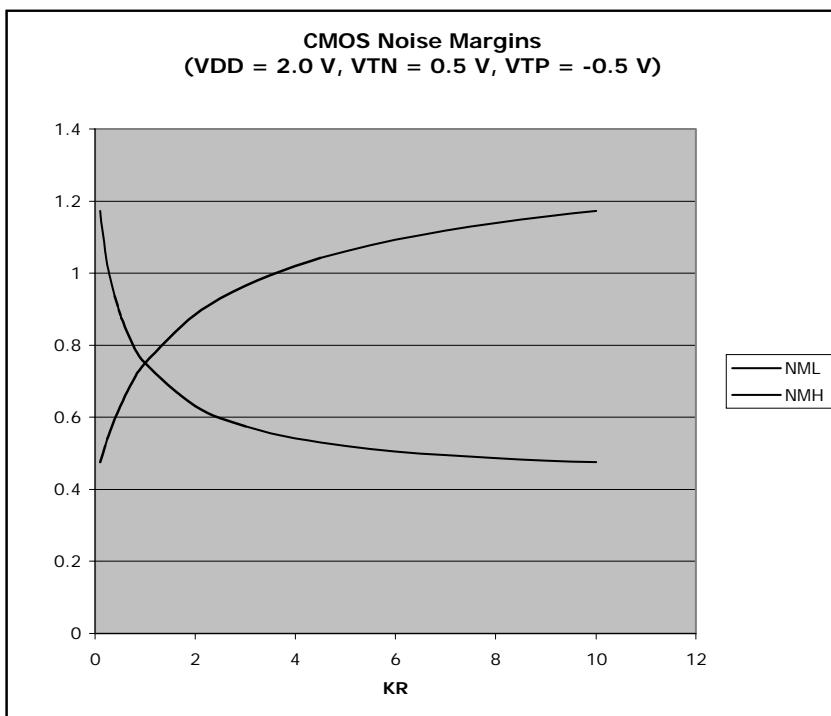


7.21

(a)



(b)



7.22

$$(a) t_r \cong 3.6R_{onP}C = \frac{3.6C}{K_p|V_{GS} - V_{TP}|} = \frac{3.6(0.25\text{pF})}{5(4 \times 10^{-5})(2.5 + 0.6)} = 2.36 \text{ ns}$$

$$t_f \cong 3.6R_{onN}C = \frac{3.6C}{K_n(V_{GS} - V_{TN})} = \frac{3.6(0.25\text{pF})}{2(10^{-4})(2.5 - 0.6)} = 2.36 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onP}C = \frac{t_r}{3} = 0.788 \text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onN}C = \frac{t_f}{3} = 0.788 \text{ ns} \quad \tau_p = \frac{0.788 + 0.788}{2} = 0.788 \text{ ns}$$

$$(b) t_r \cong 3.6R_{onP}C = \frac{3.6C}{K_p|V_{GS} - V_{TP}|} = \frac{3.6(0.25\text{pF})}{5(4 \times 10^{-5})(2.0 + 0.6)} = 3.21 \text{ ns}$$

$$t_f \cong 3.6R_{onN}C = \frac{3.6C}{K_n(V_{GS} - V_{TN})} = \frac{3.6(0.25\text{pF})}{2(10^{-4})(2 - 0.6)} = 3.21 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onP}C = \frac{t_r}{3} = 1.07 \text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onN}C = \frac{t_f}{3} = 1.07 \text{ ns} \quad \tau_p = \frac{1.07 + 1.07}{2} = 1.07 \text{ ns}$$

$$(c) t_r \cong 3.6R_{onP}C = \frac{3.6C}{K_p|V_{GS} - V_{TP}|} = \frac{3.6(0.25\text{pF})}{5(4 \times 10^{-5})(1.8 + 0.6)} = 3.75 \text{ ns}$$

$$t_f \cong 3.6R_{onN}C = \frac{3.6C}{K_n(V_{GS} - V_{TN})} = \frac{3.6(0.25\text{pF})}{2(10^{-4})(1.8 - 0.6)} = 3.75 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onP}C = \frac{t_r}{3} = 1.25 \text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onN}C = \frac{t_f}{3} = 1.25 \text{ ns} \quad \tau_p = \frac{1.25 + 1.25}{2} = 1.25 \text{ ns}$$

7.23

$$t_r \cong 3.6R_{onP}C = \frac{3.6C}{K_p|V_{GS} - V_{TP}|} = \frac{3.6(0.5\text{pF})}{2(4 \times 10^{-5})(2.5 + 0.6)} = 11.9 \text{ ns}$$

$$t_f \cong 3.6R_{onN}C = \frac{3.6C}{K_n(V_{GS} - V_{TN})} = \frac{3.6(0.5\text{pF})}{2(10^{-4})(2.5 - 0.6)} = 4.74 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onP}C = \frac{t_r}{3} = 3.96 \text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onN}C = \frac{t_f}{3} = 1.58 \text{ ns} \quad \tau_p = \frac{3.96 + 1.58}{2} = 2.77 \text{ ns}$$

7.24

$$t_r \cong 3.6R_{onP}C = \frac{3.6C}{K_p|V_{GS} - V_{TP}|} = \frac{3.6(0.15\text{pF})}{5(4 \times 10^{-5})(2.5 + 0.6)} = 1.42 \text{ ns}$$

$$t_f \cong 3.6R_{onN}C = \frac{3.6C}{K_n(V_{GS} - V_{TN})} = \frac{3.6(0.15\text{pF})}{2(10^{-4})(2.5 - 0.6)} = 1.42 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onP}C = \frac{t_r}{3} = 0.474 \text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onN}C = \frac{t_f}{3} = 0.474 \text{ ns} \quad \tau_p = \frac{0.474 + 0.474}{2} = 0.474 \text{ ns}$$

7.25

$$t_r \cong 3.6R_{onP}C = \frac{3.6C}{K_p|V_{GS} - V_{TP}|} = \frac{3.6(0.2\text{pF})}{5(4 \times 10^{-5})(3.3 + 0.75)} = 1.41 \text{ ns}$$

$$t_f \cong 3.6R_{onN}C = \frac{3.6C}{K_n(V_{GS} - V_{TN})} = \frac{3.6(0.2\text{pF})}{2(10^{-4})(3.3 - 0.75)} = 1.41 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onP}C = \frac{t_r}{3} = 0.470 \text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onN}C = \frac{t_f}{3} = 0.470 \text{ ns} \quad \tau_p = \frac{0.470 + 0.470}{2} = 0.470 \text{ ns}$$

7.26

For the symmetrical design, $\tau_{PLH} = \tau_{PHL}$ and $\tau_p = \tau_{PHL}$

$$3\text{ns} = \frac{1.2(1\text{pF})}{\left(\frac{W}{L}\right)_n(100 \times 10^{-6})(2.5 - 0.6)} \rightarrow \left(\frac{W}{L}\right)_n = \frac{2.11}{1} \quad | \quad \left(\frac{W}{L}\right)_p = 2.5 \left(\frac{W}{L}\right)_n = \frac{5.26}{1}$$

$$t_r = t_f = 3\tau_{PHL} = 9.00 \text{ ns}$$

7.27

(a) For the symmetrical design, $\tau_{PLH} = \tau_{PHL}$ and $\tau_p = \tau_{PHL}$

$$1\text{ns} = \frac{1.2(10\text{pF})}{\left(\frac{W}{L}\right)_n (100 \times 10^{-6})(2.5 - 0.6)} \rightarrow \left(\frac{W}{L}\right)_n = \frac{63.2}{1} \quad | \quad \left(\frac{W}{L}\right)_p = 2.5 \left(\frac{W}{L}\right)_n = \frac{158}{1}$$

$$t_r = t_f = 3\tau_{PHL} = 3.00 \text{ ns}$$

$$(b) \quad 1\text{ns} = \frac{1.2(10\text{pF})}{\left(\frac{W}{L}\right)_n (100 \times 10^{-6})(3.3 - 0.7)} \rightarrow \left(\frac{W}{L}\right)_n = \frac{46.2}{1} \quad | \quad \left(\frac{W}{L}\right)_p = 2.5 \left(\frac{W}{L}\right)_n = \frac{115}{1}$$

$$t_r = t_f = 3\tau_{PHL} = 3.00 \text{ ns}$$

7.28

For the symmetrical design, $\tau_{PLH} = \tau_{PHL}$ and $\tau_p = \tau_{PHL}$

$$0.2\text{ns} = \frac{1.2(0.1\text{pF})}{\left(\frac{W}{L}\right)_n (100 \times 10^{-6})(1.5 - 0.5)} \rightarrow \left(\frac{W}{L}\right)_n = \frac{6.00}{1} \quad | \quad \left(\frac{W}{L}\right)_p = 2.5 \left(\frac{W}{L}\right)_n = \frac{15.0}{1}$$

$$t_r = t_f = 3\tau_{PHL} = 0.600 \text{ ns}$$

7.29

For the symmetrical design, $\tau_{PLH} = \tau_{PHL}$ and $\tau_p = \tau_{PHL}$

$$0.4\text{ns} = \frac{1.2(0.1\text{pF})}{\left(\frac{W}{L}\right)_n (100 \times 10^{-6})(2.5 - 0.6)} \rightarrow \left(\frac{W}{L}\right)_n = \frac{1.58}{1} \quad | \quad \left(\frac{W}{L}\right)_p = 2.5 \left(\frac{W}{L}\right)_n = \frac{3.95}{1}$$

$$t_r = t_f = 3\tau_{PHL} = 1.20 \text{ ns}$$

7.30

*PROBLEM 7.30 - CMOS INVERTER DELAY

*SIMULATION USES THE MODELS IN APPENDIX B

VIN 1 0 PULSE (0 2.5 0 0.1N 0.1N 10N 20N)

VDD 3 0 DC 2.5

M1 2 1 0 0 MOSN W=4U L=2U AS=16P AD=16P

M2 2 1 3 3 MOSP W=10U L=2U AS=40P AD=40P

CL 2 0 100FF

.OP

.TRAN 0.1N 20N

.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99

+LAMBDA=.02 TOX=41.5N

+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P

.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5

+LAMBDA=.05 TOX=41.5N

```

+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
.PRINT TRAN V(2)
.PROBE V(1) V(2)
.END

```

Results: $t_r = 1.7$ ns, $t_f = 2.25$ ns, $\tau_{PHL} = 1.1$ ns, $\tau_{PLH} = 0.9$ ns

$$\tau_{PHL} = 1.2R_{onm}C \quad \tau_{PLH} = 1.2R_{onp}C$$

$$C_1 = \frac{\tau_{PHL}}{1.29R_{onm}} = \frac{1.1 \times 10^{-9}}{1.2} \left(\frac{2}{1} \right) (50 \times 10^{-6}) (2.5 - 0.91) = 146 \text{ fF} \quad | \quad \text{Inverter is symmetrical, so}$$

$$C_2 = \frac{\tau_{PLH}}{1.2R_{onp}} = \frac{9 \times 10^{-10}}{1.2} \left(\frac{5}{1} \right) (20 \times 10^{-6}) (2.5 - 0.77) = 130 \text{ fF} \quad | \quad \bar{C} = \frac{146 + 130}{2} \text{ fF} = 138 \text{ fF}$$

7.31

```

*PROBLEM 7.31 - FIVE CASCADED INVERTERS
*SIMULATION USES THE MODELS IN APPENDIX B
VDD 1 0 DC 2.5
VIN 2 0 PULSE (0 2.5 0 0.1N 0.1N 10N 20N)
*
```

```
MN1 3 2 0 0 MOSN W=16U L=2U AS=64P AD=64P
MP1 3 2 1 1 MOSP W=40U L=2U AS=160P AD=160P
```

```
*AS=4UM*W - AD=4UM*W
```

```
CL1 3 0 100FF
```

```
*
```

```
MN2 4 3 0 0 MOSN W=16U L=2U AS=64P AD=64P
MP2 4 3 1 1 MOSP W=40U L=2U AS=160P AD=160P
```

```
CL2 4 0 100FF
```

```
*
```

```
MN3 5 4 0 0 MOSN W=16U L=2U AS=64P AD=64P
MP3 5 4 1 1 MOSP W=40U L=2U AS=160P AD=160P
```

```
CL3 5 0 100FF
```

```
*
```

```
MN4 6 5 0 0 MOSN W=16U L=2U AS=64P AD=64P
MP4 6 5 1 1 MOSP W=40U L=2U AS=160P AD=160P
```

```
CL4 6 0 100FF
```

```
*
```

```
MN5 7 6 0 0 MOSN W=16U L=2U AS=64P AD=64P
MP5 7 6 1 1 MOSP W=40U L=2U AS=160P AD=160P
```

```
CL5 7 0 100FF
```

```
.OP
```

```
.TRAN 0.025N 20N
```

```
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99
```

```
+LAMBDA=.02 TOX=41.5N
```

```
+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
```

```
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5
```

```
+LAMBDA=.05 TOX=41.5N
```

```
+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
```

.PROBE V(2) V(3) V(5) V(6)

.END

First inverter : $t_r = 0.83 \text{ ns}$, $t_f = 1.4 \text{ ns}$, $\tau_{PLH} = 0.35 \text{ ns}$, $\tau_{PHL} = 0.42 \text{ ns}$

Fourth inverter : $t_r = 0.96 \text{ ns}$, $t_f = 1.0 \text{ ns}$, $\tau_{PLH} = 0.64 \text{ ns}$, $\tau_{PHL} = 1.1 \text{ ns}$

$$\tau_{PHL} = 1.2R_{onn}C \quad \tau_{PLH} = 1.2R_{onp}C$$

$$C_1 = \frac{\tau_{PHL}}{1.2R_{onn}} = \frac{0.42 \times 10^{-9}}{1.2} \left(\frac{8}{1} \right) \left(50 \times 10^{-6} \right) (2.5 - 0.91) = 223 \text{ fF} \quad | \text{ The inverter is symmetrical, so}$$

$$C_2 = \frac{\tau_{PLH}}{1.2R_{onp}} = \frac{0.35 \times 10^{-9}}{1.2} \left(\frac{20}{1} \right) \left(20 \times 10^{-6} \right) (2.5 - 0.77) = 202 \text{ fF} \quad | \bar{C} = \frac{223 + 202}{2} \text{ fF} = 212 \text{ fF}$$

The average capacitance of 212 fF that is required to fit the results is consistent with the device capacitances calculated by SPICE. The approximate 3:1 relationship holds between rise/fall times and the propagation delay times in the first inverter. The first inverter response is faster than that of the fourth inverter because of the rapid rise and fall times on the input signal. The first inverter response is closest to our model used for hand calculations. However, the response of inverter four would be more representative of the actual logic situation.

7.32

$$(a) \frac{100W}{100 \times 10^6 \text{ gates}} = 1 \mu W / \text{gate} \quad (b) I = \frac{100W}{1.8V} = 55.6 A$$

7.33

$$(a) \frac{5W}{2 \times 10^6 \text{ gates}} = 2.5 \mu W / \text{gate} \quad P = CV_{DD}^2f ; C = \frac{2.5 \times 10^{-6}}{3.3^2 (5 \times 10^6)} = 45.9 \text{ fF}$$

$$(b) C = \frac{2.5 \times 10^{-6}}{2.5^2 (5 \times 10^6)} = 80.0 \text{ fF}$$

7.34

$$(a) I = I_s A = \left(400 \frac{pA}{cm^2} \right) (0.5cm \times 1cm) = 200 pA$$

$$(b) I = I_s A + \left(75 \times 10^6 \right) \left(150 \frac{pA}{cm^2} \right) \left(2.5 \times 10^{-4} cm \right) \left(1 \times 10^{-4} cm \right) = 200 + 281 = 481 pA$$

(c) Same as (b)

7.35

$$(a) P = 64CV_{DD}^2f = 64 \left(25 \times 10^{-12} \right) \left(2.5^2 \right) \frac{1}{10^{-8}} = 1.00 W \quad (b) P = 64 \left(25 \times 10^{-12} \right) \left(3.3^2 \right) \frac{1}{10^{-8}} = 1.74 W$$

7.36

Peak current occurs for $v_o = v_i$. Assume both transistors are saturated since $v_o = v_i$.

$$\frac{20}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (v_i - V_{TN})^2 = \frac{20}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (v_i - V_{DD} - V_{TP})^2 \rightarrow 1.58(v_i - V_{TN}) = V_{DD} - v_i + V_{TP}$$

$$(a) v_o = v_i = \frac{V_{DD} + 1.58V_{TN} + V_{TP}}{2.58} = \frac{3.3 + 1.58(0.6) + (-0.6)}{2.58} = 1.414 \text{ V}$$

$$i_D = \frac{20}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (1.414 - 0.6)^2 = 663 \mu\text{A}$$

Checking the current: $i_D = \frac{20}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (1.414 - 3.3 + 0.6)^2 = 662 \mu\text{A}$ | Within roundoff error.

$$(b) v_o = v_i = \frac{2.5 + 1.58(0.6) + (-0.6)}{2.58} = 1.104 \text{ V} \quad i_D = \frac{20}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (1.104 - 0.6)^2 = 254 \mu\text{A}$$

Checking the current: $i_D = \frac{20}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (1.104 - 2.5 + 0.6)^2 = 253 \mu\text{A}$ | Within roundoff error.

7.37

For a symmetrical inverter, the peak current occurs for $v_o = v_i = \frac{V_{DD}}{2}$.

Assume both transistors are saturated since $v_o = v_i$.

$$\frac{2}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (v_i - V_{TN})^2 = \frac{5}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (v_i - V_{DD} - V_{TP})^2 \rightarrow (v_i - V_{TN}) = V_{DD} - v_i + V_{TP}$$

$$(a) v_o = v_i = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{3.3 + (0.7) + (-0.7)}{2} = 1.65 \text{ V}$$

$$i_{DN} = \frac{2}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (1.65 - 0.7)^2 = 90.3 \mu\text{A} \quad \text{Checking: } i_{DP} = \frac{5}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (1.65 - 3.3 + 0.7)^2 = 90.3 \mu\text{A}$$

$$(b) v_o = v_i = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{2 + (0.5) + (-0.5)}{2} = 1.00 \text{ V}$$

$$i_{DN} = \frac{2}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (1.00 - 0.5)^2 = 25.0 \mu\text{A} \quad \text{Checking: } i_{DP} = \frac{5}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (1.0 - 2 + 0.5)^2 = 25.0 \mu\text{A}$$

7.38

For a symmetrical inverter, the peak current occurs for $v_o = v_I = \frac{V_{DD}}{2}$.

Assume both transistors are saturated since $v_o = v_I$.

$$\frac{2}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (v_I - V_{TN})^2 = \frac{5}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (v_I - V_{DD} - V_{TP})^2 \rightarrow (v_I - V_{TN}) = V_{DD} - v_I + V_{TP}$$

$$(a) v_o = v_I = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{2.5 + (0.7) + (-0.7)}{2} = 1.25 \text{ V}$$

$$i_{DN} = \frac{2}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (1.25 - 0.7)^2 = 30.3 \mu\text{A} \quad \text{Checking: } i_{DP} = \frac{5}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (1.25 - 2.5 + 0.7)^2 = 30.3 \mu\text{A}$$

$$(b) v_o = v_I = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{2.5 + (0.65) + (-0.55)}{2} = 1.30 \text{ V}$$

$$i_{DN} = \frac{2}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (1.30 - 0.65)^2 = 42.3 \mu\text{A} \quad \text{Checking: } i_{DP} = \frac{5}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (1.3 - 2.5 + 0.55)^2 = 42.3 \mu\text{A}$$

7.39

For the inverter, the peak current occurs for $v_o = v_I$. Assume both transistors are saturated since $v_o = v_I$.

$$\frac{2}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (v_I - V_{TN})^2 = \frac{5}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (v_I - V_{DD} - V_{TP})^2 \rightarrow (v_I - V_{TN}) = V_{DD} - v_I + V_{TP}$$

$$(a) v_o = v_I = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{2 + (0.55) + (-0.45)}{2} = 1.05 \text{ V}$$

$$i_{DN} = \frac{2}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (1.05 - 0.55)^2 = 25.0 \mu\text{A} \quad \text{Checking: } i_{DP} = \frac{5}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (1.05 - 2 + 0.45)^2 = 25.0 \mu\text{A}$$

$$(b) v_o = v_I = \frac{V_{DD} + V_{TN} + V_{TP}}{2} = \frac{2 + (0.45) + (-0.55)}{2} = 0.950 \text{ V}$$

$$i_{DN} = \frac{2}{1} \left(\frac{100 \times 10^{-6}}{2} \right) (0.95 - 0.45)^2 = 25.0 \mu\text{A} \quad \text{Checking: } i_{DP} = \frac{5}{1} \left(\frac{40 \times 10^{-6}}{2} \right) (0.95 - 2 + 0.55)^2 = 25.0 \mu\text{A}$$

7.40

$$(a) PDP \cong \frac{CV_{DD}^2}{5} = \frac{(0.25 \text{ pF})(2.5^2)}{5} = 0.313 \text{ pJ} \quad P = CV_{DD}^2 f = (0.25 \text{ pF})(2.5^2)(10^8) = 156 \mu\text{W}$$

$$(b) PDP \cong \frac{CV_{DD}^2}{5} = \frac{(0.25 \text{ pF})(2^2)}{5} = 0.200 \text{ pJ} \quad P = CV_{DD}^2 f = (0.25 \text{ pF})(2^2)(10^8) = 100 \mu\text{W}$$

$$(c) PDP \cong \frac{CV_{DD}^2}{5} = \frac{(0.25 \text{ pF})(1.8^2)}{5} = 0.163 \text{ pJ} \quad P = CV_{DD}^2 f = (0.25 \text{ pF})(1.8^2)(10^8) = 81.0 \mu\text{W}$$

7.41

$$(a) PDP \cong \frac{CV_{DD}^2}{7.5} = \frac{(0.2\text{ pF})(3.3^2)}{7.5} = 0.290\text{ pJ} \quad (\text{b}) f_{\max} \cong \frac{1}{7.5\tau_p}$$

$$\tau_{PLH} = 1.2R_{onP}C = \frac{1.2C}{K_p|V_{GS} - V_{TP}|} = \frac{1.2(0.2\text{ pF})}{5(4 \times 10^{-5})(3.3 - 0.75)} = 0.471\text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onN}C = \frac{1.2C}{K_n(V_{GS} - V_{TN})} = \frac{1.2(0.2\text{ pF})}{2(10^{-4})(3.3 - 0.75)} = 0.471\text{ ns}$$

$$\tau_p = \frac{0.471 + 0.471}{2} = 0.471\text{ ns} \quad f_{\max} \cong \frac{1}{7.5\tau_p} = \frac{1}{7.5(0.471\text{ ns})} = 283\text{ MHz}$$

$$(c) P = CV_{DD}^2 f = (0.2\text{ pF})(3.3^2)(2.83 \times 10^8) = 616\text{ }\mu\text{W}$$

7.42

$$(a) PDP \cong \frac{CV_{DD}^2}{7.5} = \frac{(0.15\text{ pF})(2.5^2)}{7.5} = 0.125\text{ pJ} \quad (\text{b}) f_{\max} \cong \frac{1}{7.5\tau_p}$$

$$\tau_{PLH} = 1.2R_{onP}C = \frac{1.2C}{K_p|V_{GS} - V_{TP}|} = \frac{1.2(0.15\text{ pF})}{5(4 \times 10^{-5})(2.5 - 0.6)} = 0.474\text{ ns}$$

$$\tau_{PHL} \cong 1.2R_{onN}C = \frac{1.2C}{K_n(V_{GS} - V_{TN})} = \frac{1.2(0.15\text{ pF})}{2(10^{-4})(2.5 - 0.6)} = 0.474\text{ ns}$$

$$\tau_p = \frac{0.474 + 0.474}{2} = 0.474\text{ ns} \quad f_{\max} \cong \frac{1}{7.5\tau_p} = \frac{1}{7.5(0.474\text{ ns})} = 282\text{ MHz}$$

$$(c) P = CV_{DD}^2 f = (0.15\text{ pF})(2.5^2)(2.82 \times 10^8) = 264\text{ }\mu\text{W}$$

7.43

*PROBLEM 7.41 - INVERTER PDP

VDD 1 0 DC 2.5

VIN 2 0 PULSE (0 2.5 0 0.1N 0.1N 15N 30N)

*

MN1 3 2 0 0 MOSN W=4U L=1U AS=8P AD=8P

MP1 3 2 1 1 MOSP W=4U L=1U AS=8P AD=8P

C1 3 0 200fF

*AS=2UM*W - AD=2UM*W

*

MN2 4 2 0 0 MOSN W=8U L=1U AS=16P AD=16P

MP2 4 2 1 1 MOSP W=8U L=2U AS=16P AD=16P

C2 4 0 200fF

*

MN3 5 2 0 0 MOSN W=16U L=1U AS=32P AD=32P

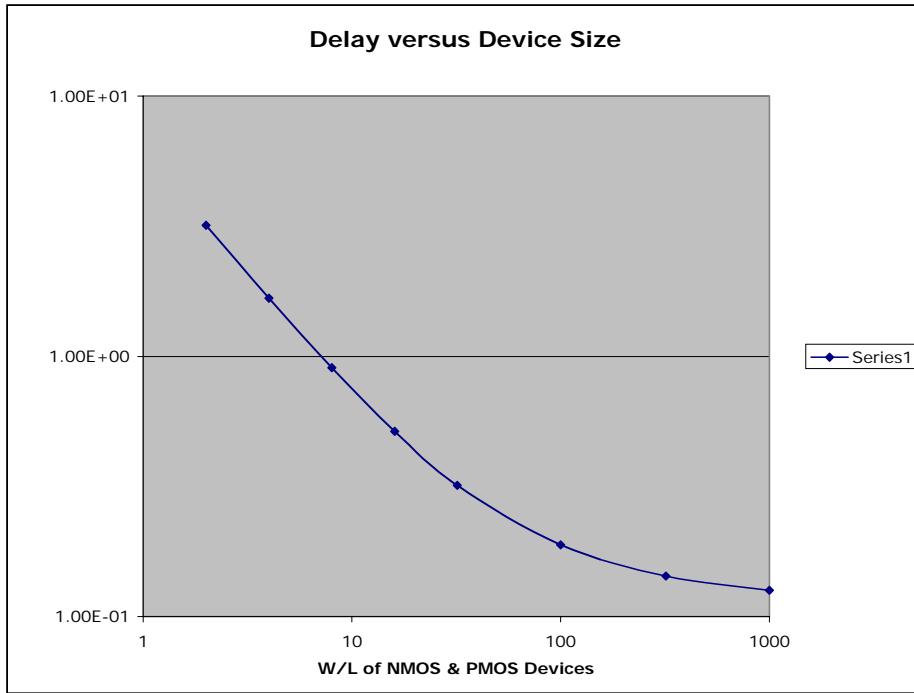
MP3 5 2 1 1 MOSP W=16U L=1U AS=32P AD=32P

```

C3 5 0 200fF
*
MN4 6 2 0 0 MOSN W=32U L=1U AS=64P AD=64P
MP4 6 2 1 1 MOSP W=32U L=1U AS=64P AD=64P
C4 6 0 200fF
*
MN5 7 2 0 0 MOSN W=64U L=1U AS=128P AD=128P
MP5 7 2 1 1 MOSP W=64U L=1U AS=128P AD=128P
C5 7 0 200fF
*
MN6 8 2 0 0 MOSN W=100U L=1U AS=200P AD=200P
MP6 8 2 1 1 MOSP W=100U L=1U AS=200P AD=200P
C6 8 0 200fF
*
MN7 9 2 0 0 MOSN W=320U L=1U AS=640P AD=640P
MP7 9 2 1 1 MOSP W=2320U L=1U AS=640P AD=640P
C7 9 0 200fF
*
MN9 11 2 0 0 MOSN W=1000U L=1U AS=2000P AD=2000P
MP9 11 2 1 1 MOSP W=1000U L=1U AS=2000P AD=2000P
C9 11 0 200fF
*
.OP
.TRAN 0.025N 50N
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99
+LAMBDA=.02 TOX=41.5N
+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5
+LAMBDA=.05 TOX=41.5N
+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
.PROBE V(2) V(3) V(4) V(5) V(6) V(7) V(8) V(9) V(10) V(11)
.END

```

At small device sizes, the power-delay product will be $CV_{DD}^2 = 1.25 \text{ pJ}$.



7.44

$$\Delta T = \frac{C \Delta V}{I} = \frac{K C_{ox}'' W L \Delta V}{\frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2} \quad | \quad \text{Let } W' = \alpha W, L' = \alpha L, T_{ox}' = \alpha T_{ox}, V' = \alpha V$$

$$\Delta T' = \frac{C' \Delta V'}{I'} = \frac{K (\alpha W) (\alpha L) (\alpha \Delta V)}{\frac{1}{2} \mu_n \left(\frac{\alpha W}{\alpha L} \right) (\alpha V_{GS} - \alpha V_{TN})^2} = \alpha \Delta T$$

$$P = VI = \frac{V}{2} \mu_n C_{ox}'' \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2 = \frac{V}{2} \mu_n \frac{\epsilon_{ox}}{T_{ox}} \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2$$

$$P' = \frac{\alpha V}{2} \mu_n \frac{\epsilon_{ox}}{\alpha T_{ox}} \left(\frac{\alpha W}{\alpha L} \right) (\alpha V_{GS} - \alpha V_{TN})^2 = \alpha^2 P$$

$$PDP' = P' \Delta T' = (\alpha \Delta T) \alpha^2 P = \alpha^3 P \Delta T = \alpha^3 PDP$$

7.45

$$\Delta T = \frac{C \Delta V}{I} = \frac{K C_{ox}'' W L \Delta V}{\frac{1}{2} \mu_n C_{ox}' \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2} \quad | \quad \text{Let } W' = \alpha W, L' = \alpha L, T_{ox}' = \alpha T_{ox}$$

$$\Delta T' = \frac{C' \Delta V'}{I'} = \frac{K (\alpha W) (\alpha L) (\Delta V)}{\frac{1}{2} \mu_n \left(\frac{\alpha W}{\alpha L} \right) (V_{GS} - V_{TN})^2} = \alpha^2 \Delta T$$

$$P = VI = \frac{V}{2} \mu_n C_{ox}' \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2 = \frac{V}{2} \mu_n \frac{\varepsilon_{ox}}{T_{ox}} \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2$$

$$P' = \frac{V}{2} \mu_n \frac{\varepsilon_{ox}}{\alpha T_{ox}} \left(\frac{\alpha W}{\alpha L} \right) (V_{GS} - V_{TN})^2 = \frac{P}{\alpha}$$

$$PDP' = P' \Delta T' = (\alpha^2 \Delta T) \frac{P}{\alpha} = \alpha P \Delta T = \alpha PDP$$

7.46

(Note: Simulation time needs to be extended.)

*PROBLEM 7.46 - FIVE CASCADED INVERTERS

VDD 1 0 DC 2.5

VIN 2 0 PULSE (0 2.5 0 0.1N 0.1N 25N 50N)

*

MN1 3 2 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP1 3 2 1 1 MOSP W=5U L=1U AS=40P AD=40P

C1 3 0 0.25P

*AS=8UM*W - AD=8UM*W

*

MN2 4 3 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP2 4 3 1 1 MOSP W=5U L=1U AS=40P AD=40P

C2 4 0 0.25P

*

MN3 5 4 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP3 5 4 1 1 MOSP W=5U L=1U AS=40P AD=40P

C3 5 0 0.25P

*

MN4 6 5 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP4 6 5 1 1 MOSP W=5U L=1U AS=40P AD=40P

C4 6 0 0.25P

*

MN5 7 6 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP5 7 6 1 1 MOSP W=5U L=8U AS=40P AD=40P

C5 7 0 0.25P

.OP

.TRAN 0.025N 50N

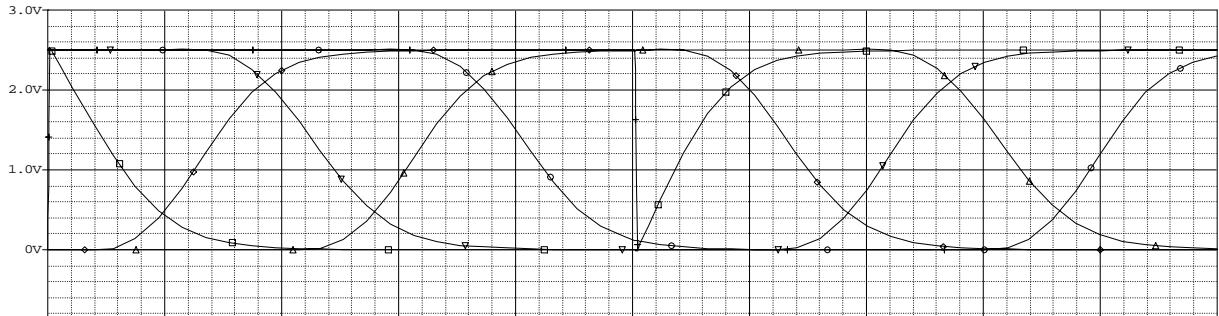
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99

+LAMBDA=.02 TOX=41.5N

```

+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5
+LAMBDA=.05 TOX=41.5N
+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
.PROBE V(2) V(3) V(5) V(6)
.END

```



First inverter : $t_r = 4.6 \text{ ns}$, $t_f = 5.4 \text{ ns}$, $\tau_{PLH} = 2.6 \text{ ns}$, $\tau_{PHL} = 2.1 \text{ ns}$

Fourth inverter : $t_r = 5.8 \text{ ns}$, $t_f = 6.3 \text{ ns}$, $\tau_{PLH} = 4.2 \text{ ns}$, $\tau_{PHL} = 4.7 \text{ ns}$

$$\tau_{PHL} = 1.2R_{onm}C = \frac{0.25 \times 10^{-12}}{\left(\frac{2}{1}\right)\left(50 \times 10^{-6}\right)(2.5 - 0.91)} = 1.58 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onp}C = \frac{0.25 \times 10^{-12}}{\left(\frac{5}{1}\right)\left(20 \times 10^{-6}\right)(2.5 - 0.77)} = 1.45 \text{ ns}$$

The inverters are slower than the equations predict because of the additional capacitances in the transistor models. The effective capacitance appears to be approximately 0.4 pF. The delay of the interior inverter is substantially slower than predicted by the formula because of the slow rise and fall times of the driving signals.

7.47

(Note: Simulation time needs to be extended.)

*PROBLEM 7.47(a) - FIVE CASCADED SYMMETRICAL INVERTERS

VDD 1 0 DC 5

VIN 2 0 PULSE (0 5 0 0.1N 0.1N 75N 150N)

*

MN1 3 2 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP1 3 2 1 1 MOSP W=5U L=1U AS=40P AD=40P

C1 3 0 1P

*AS=8UM*W - AD=8UM*W

*

MN2 4 3 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP2 4 3 1 1 MOSP W=5U L=1U AS=40P AD=40P

C2 4 0 1P

*

MN3 5 4 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP3 5 4 1 1 MOSP W=5U L=1U AS=40P AD=40P

C3 5 0 1P

*

MN4 6 5 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP4 6 5 1 1 MOSP W=5U L=1U AS=40P AD=40P

C4 6 0 1P

*

MN5 7 6 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP5 7 6 1 1 MOSP W=5U L=1U AS=40P AD=40P

C5 7 0 1P

.OP

.TRAN 0.025N 150N

.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99

+LAMBDA=.02 TOX=41.5N CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P

.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5

+LAMBDA=.05 TOX=41.5N CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P

.PROBE V(2) V(3) V(5) V(6)

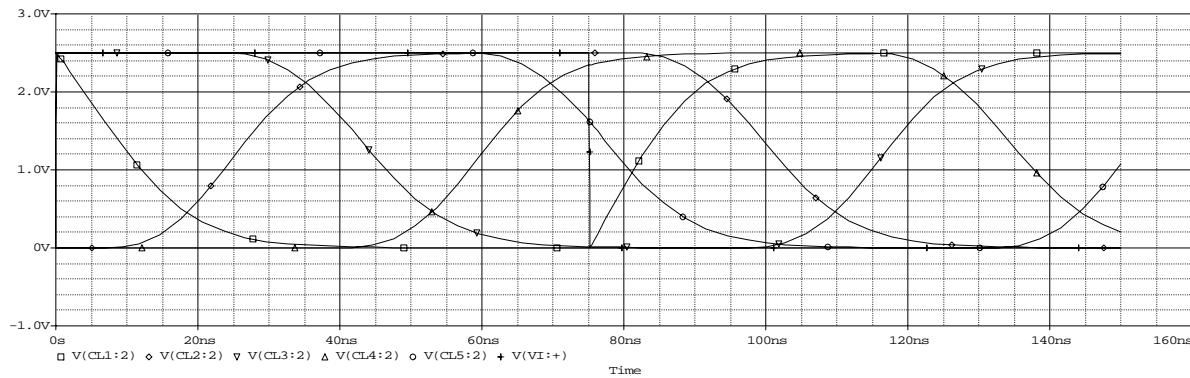
.END

First inverter : $t_r = 17.7 \text{ ns}$, $t_f = 20.7 \text{ ns}$, $\tau_{PLH} = 8.1 \text{ ns}$, $\tau_{PHL} = 9.9 \text{ ns}$

Fourth inverter : $t_r = 22.3 \text{ ns}$, $t_f = 24.2 \text{ ns}$, $\tau_{PLH} = 16.3 \text{ ns}$, $\tau_{PHL} = 18.3 \text{ ns}$

$$\tau_{PHL} = 1.2R_{onm}C = \frac{1.2 \times 10^{-12}}{\left(\frac{2}{1}\right)\left(50 \times 10^{-6}\right)(2.5 - 0.91)} = 7.6 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onp}C = \frac{1.2 \times 10^{-12}}{\left(\frac{5}{1}\right)\left(20 \times 10^{-6}\right)(2.5 - 0.77)} = 6.9 \text{ ns}$$



The inverters are slower than the equations predict because of the additional capacitances in the transistor models. The delay of the interior inverter is substantially slower than predicted by the formula because of the slow rise and fall times of the driving signals.

*PROBLEM 7.47(b) - FIVE CASCADeD MINIMUM SIZE INVERTERS

VDD 1 0 DC 5

VIN 2 0 PULSE (0 5 0 0.1N 0.1N 125N 250N)

*

MN1 3 2 0 0 MOSN W=4U L=2U AS=16P AD=16P

MP1 3 2 1 1 MOSP W=4U L=2U AS=16P AD=16P

C1 3 0 1P

*AS=4UM*W - AD=4UM*W

*

MN2 4 3 0 0 MOSN W=4U L=2U AS=16P AD=16P

MP2 4 3 1 1 MOSP W=4U L=2U AS=16P AD=16P

C2 4 0 1P

*

MN3 5 4 0 0 MOSN W=4U L=2U AS=16P AD=16P

MP3 5 4 1 1 MOSP W=4U L=2U AS=16P AD=16P

C3 5 0 1P

*

MN4 6 5 0 0 MOSN W=4U L=2U AS=16P AD=16P

MP4 6 5 1 1 MOSP W=4U L=2U AS=16P AD=16P

C4 6 0 1P

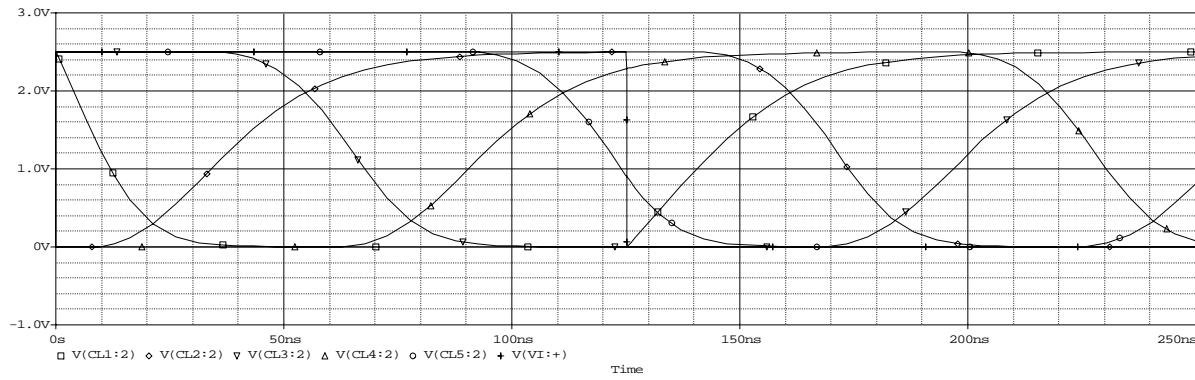
*

MN5 7 6 0 0 MOSN W=4U L=2U AS=16P AD=16P

```

MP5 7 6 1 1 MOSP W=4U L=2U AS=16P AD=16P
C5 7 0 1P
.OP
.TRAN 0.025N 250N
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99
+LAMBDA=.02 TOX=41.5N
+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5
+LAMBDA=.05 TOX=41.5N
+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
.PROBE V(2) V(3) V(5) V(6)
.END

```



First inverter : $t_r = 43.7 \text{ ns}$, $t_f = 20.6 \text{ ns}$, $\tau_{PLH} = 19.7 \text{ ns}$, $\tau_{PHL} = 9.7 \text{ ns}$

Fourth inverter : $t_r = 47.5 \text{ ns}$, $t_f = 31.4 \text{ ns}$, $\tau_{PLH} = 30.4 \text{ ns}$, $\tau_{PHL} = 25.7 \text{ ns}$

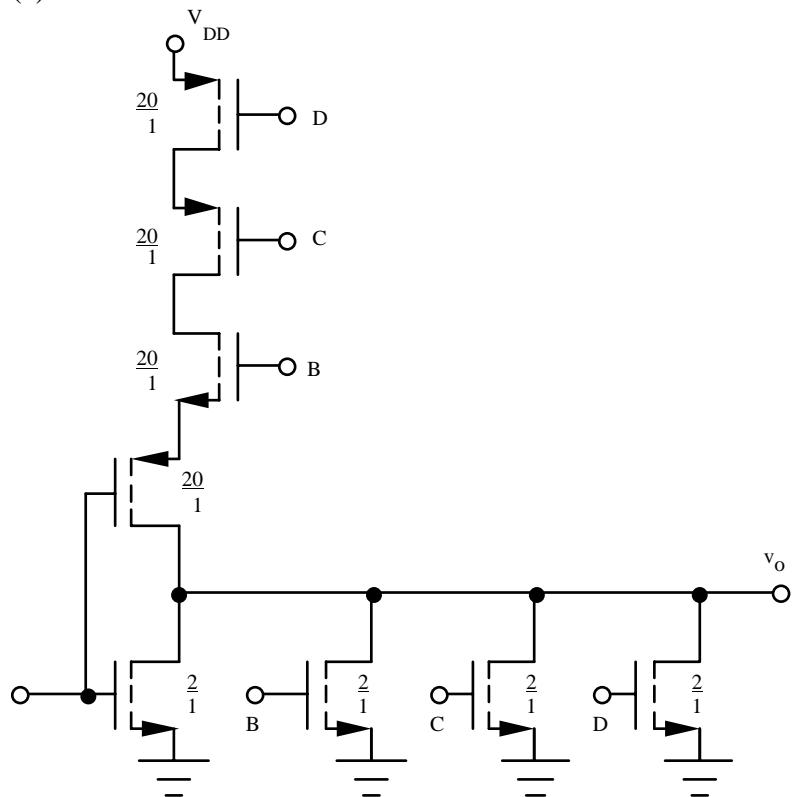
$$\tau_{PHL} = 1.2R_{onp}C = \frac{1.2 \times 10^{-12}}{\left(\frac{2}{1}\right)(50 \times 10^{-6})(2.5 - 0.91)} = 7.5 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onp}C = \frac{1.2 \times 10^{-12}}{\left(\frac{2}{1}\right)(20 \times 10^{-6})(2.5 - 0.77)} = 17.3 \text{ ns}$$

The inverters are slower than the equations predict because of the additional capacitances in the transistor models. The delay of the interior inverter is substantially slower than predicted by the formula because of the slow rise and fall times of the driving signals.

7.48

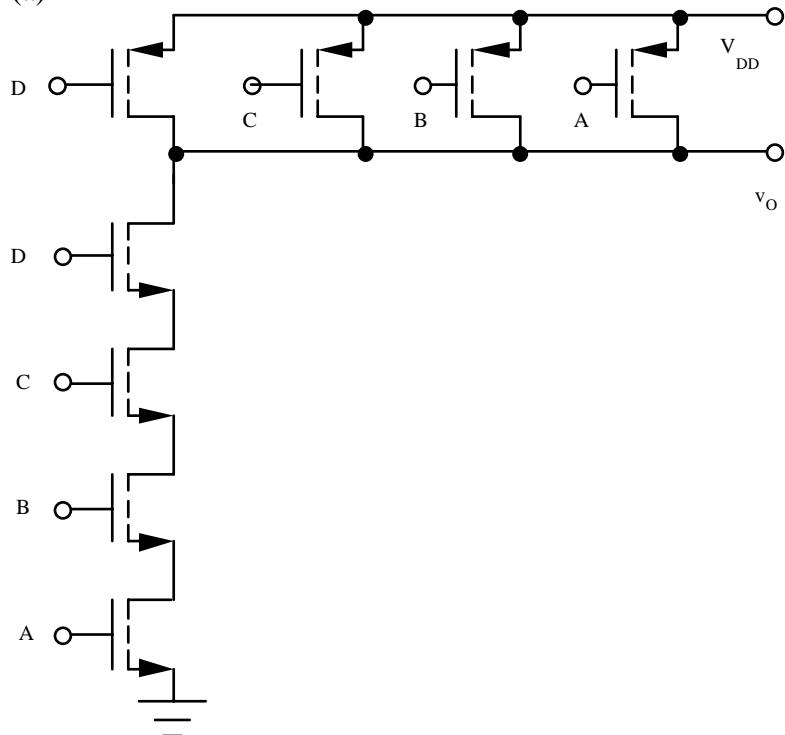
(a)



$$(b) \text{NMOS : } 3\left(\frac{2}{1}\right) = \frac{6}{1} \mid \text{PMOS : } 3\left(\frac{20}{1}\right) = \frac{60}{1}$$

7.49

(a)



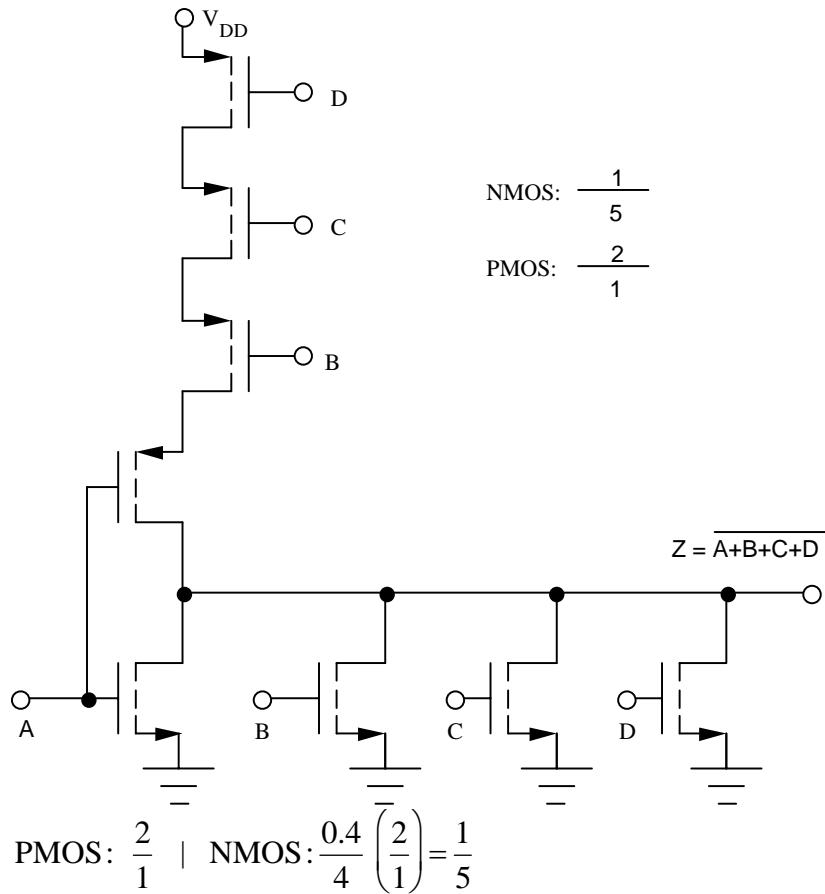
$$(a) \text{ NMOS: } \frac{W}{L} = 4 \left(\frac{2}{1} \right) = \frac{8}{1}$$

$$\text{PMOS: } \frac{W}{L} = \frac{5}{1}$$

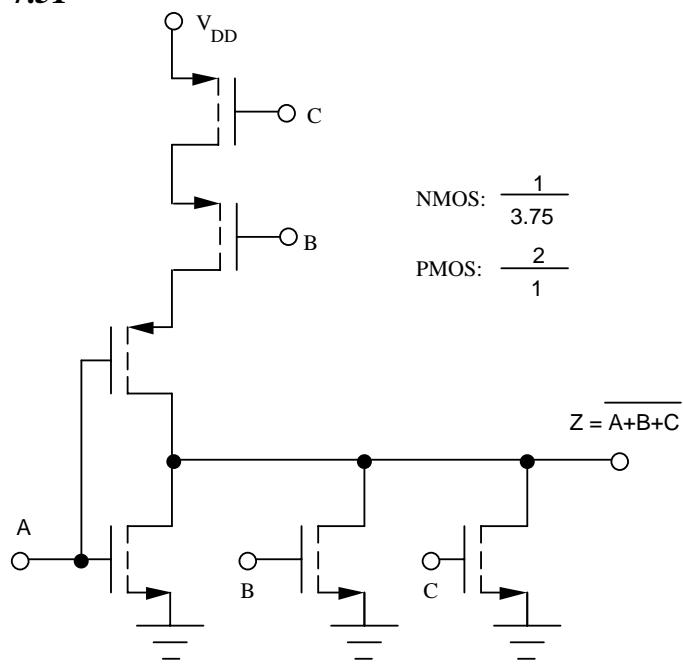
$$(b) \text{ NMOS: } \frac{W}{L} = 2(4) \left(\frac{2}{1} \right) = \frac{16}{1}$$

$$\text{PMOS: } \frac{W}{L} = 2 \left(\frac{5}{1} \right) = \frac{10}{1}$$

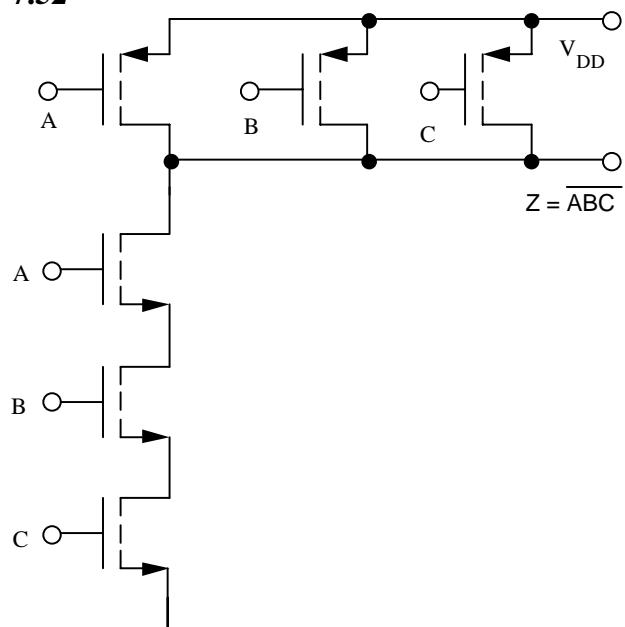
7.50



7.51

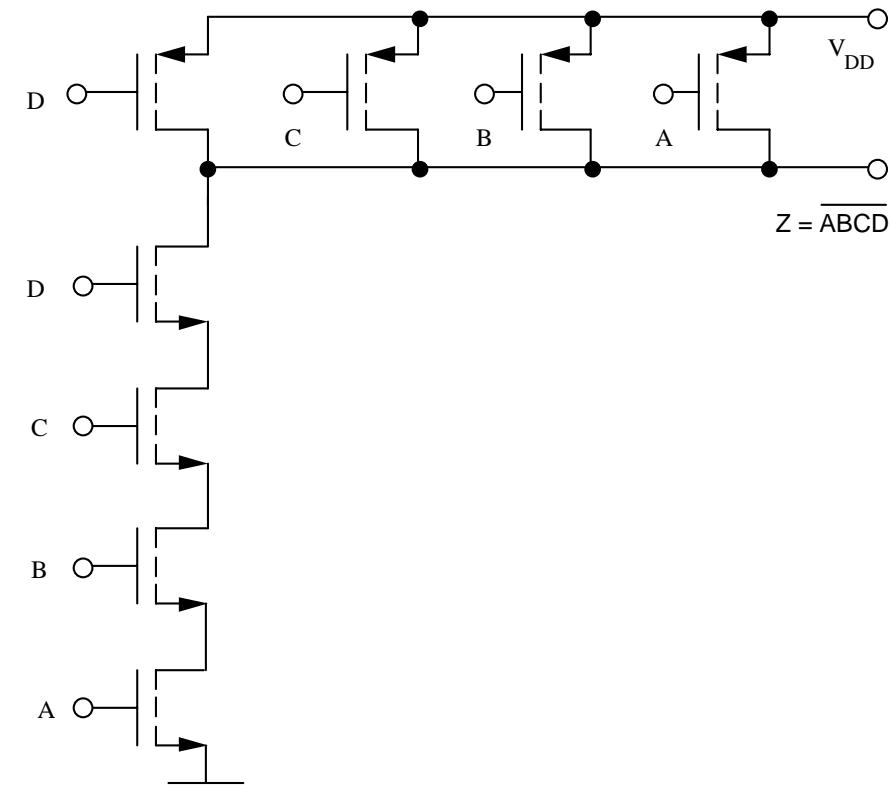


7.52



$$(W/L)_N = 2/1, (W/L)_P = 2.5(2/1)/3, = 1.67/1$$

7.53



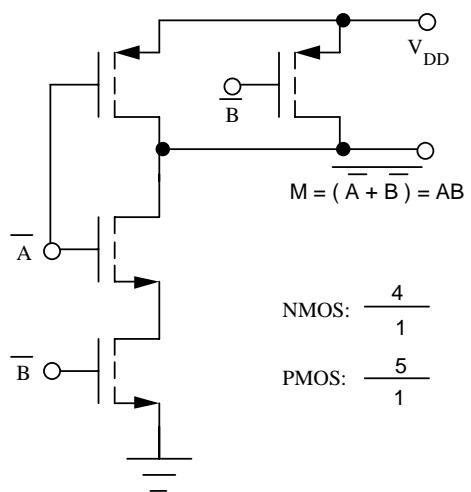
$$(W/L)_N = 2/1, (W/L)_P = 2.5(2/1)/4, = 1.25/1$$

7.54

Output Z is A multiplied by B. From the truth table, $Z = AB$, a two input AND gate.

A	B	Z
0	0	0
0	1	0
1	0	0
1	1	1

Assuming complemented variables are available,



7.55

(The dc input should be 0 V.)

*PROBLEM 7.55 - TWO-INPUT CMOS NOR GATE

VDD 1 0 DC 2.5

VA 2 0 DC 0 PULSE (0 2.5 0 0.1N 0.1N 25N 50N)

VB 5 0 DC 0

*

MNA 4 2 0 0 MOSN W=2U L=1U AS=16P AD=16P

MPA 4 2 3 1 MOSP W=10U L=1U AS=80P AD=80P

MNB 4 5 0 0 MOSN W=2U L=1U AS=16P AD=16P

MPB 3 5 1 1 MOSP W=10U L=1U AS=80P AD=80P

CL 4 0 1PF

*

MNC 6 5 0 0 MOSN W=2U L=1U AS=16P AD=16P

MPC 6 5 7 1 MOSP W=10U L=1U AS=80P AD=80P

MND 6 2 0 0 MOSN W=2U L=1U AS=16P AD=16P

MPD 7 2 1 1 MOSP W=10U L=1U AS=80P AD=80P

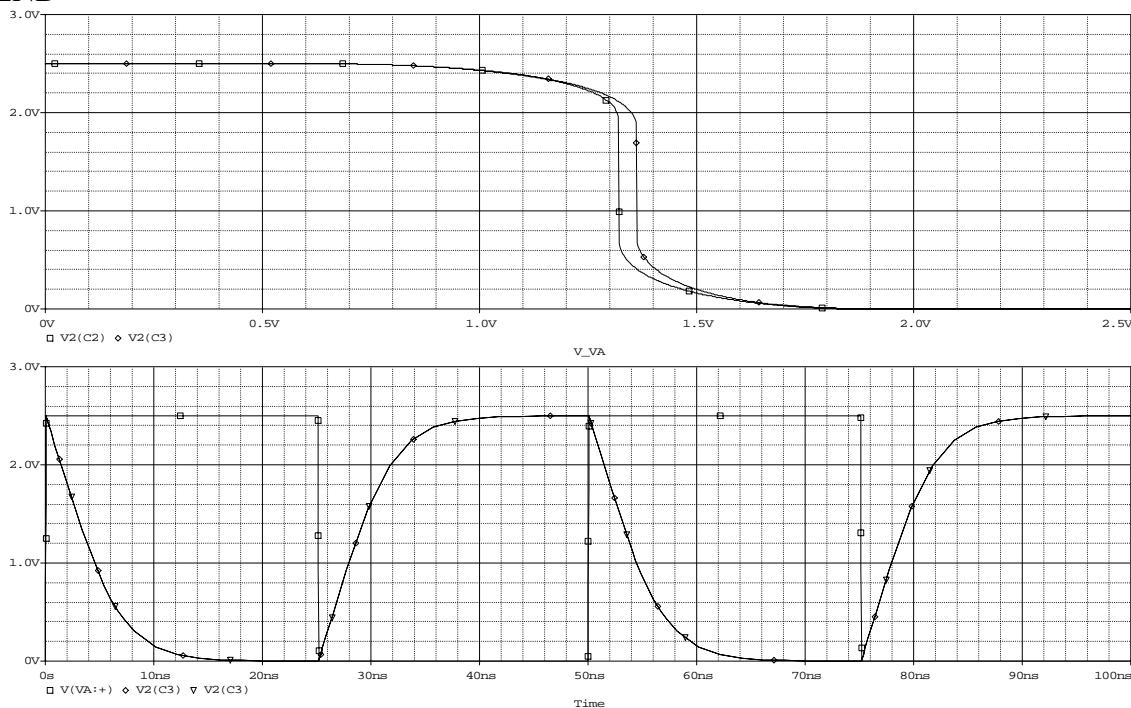
CL 6 0 1PF

*

```

.OP
.DC VDD 0 2.5 0.01
.TRAN 0.1N 50N
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0
+LAMBDA=.02 TOX=41.5N
+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0
+LAMBDA=.05 TOX=41.5N
+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
.PROBE V(2) V(4) V(6)
.END

```



The transitions of the two VTCs are separated by approximately 50 mV. The dynamic characteristics for switching one input with the other constant are essentially identical. The two transitions are virtually identical because of the ideal step inputs: $\tau_{PHL} = 3.6$ ns, $\tau_{PLH} = 3.6$ ns, $t_f = 8.1$ ns, $t_r = 7.9$ ns. With the inputs switched together, τ_{PHL} and t_f are reduced by 50% because the two NMOS devices are working in parallel.

7.56

The simulation results show only slight changes from those of Problem 7.55.

7.57

*PROBLEM 7.54 - TWO-INPUT CMOS NAND GATE

VDD 1 0 DC 2.5

VA 2 0 DC 0 PULSE (0 2.5 0 0.1N 0.1N 25N 50N)

VB 4 0 DC 2.5

*

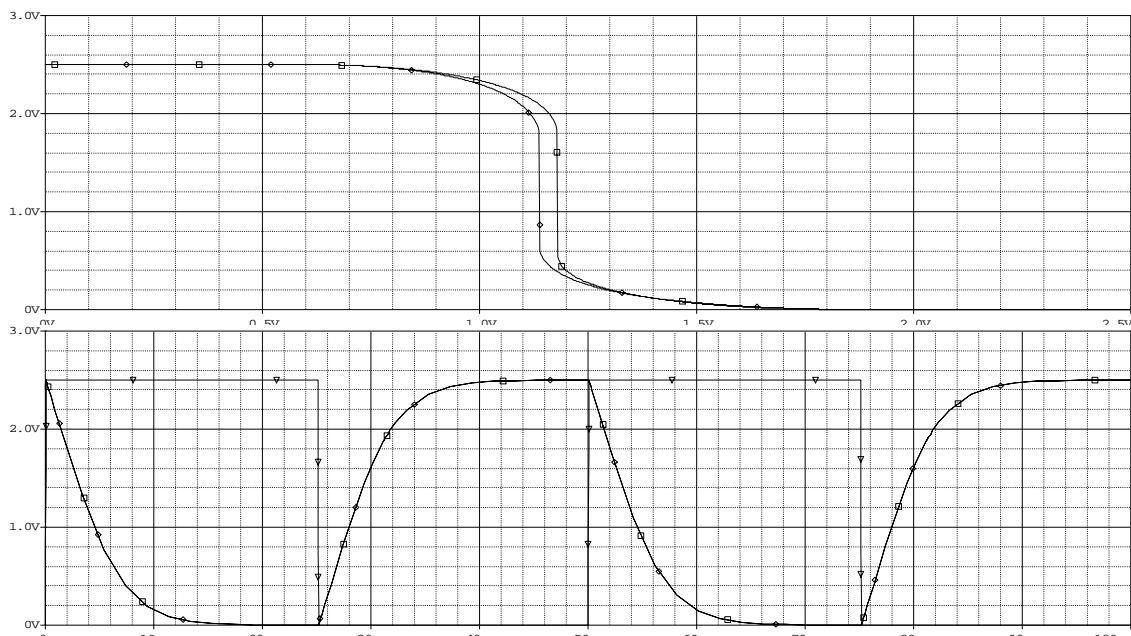
MNA 3 4 0 0 MOSN W=4U L=1U AS=16P AD=16P

MPA 5 4 1 1 MOSP W=5U L=1U AS=80P AD=80P

```

MNB 5 2 3 0 MOSN W=4U L=1U AS=16P AD=16P
MPB 5 2 1 1 MOSP W=5U L=1U AS=80P AD=80P
CL1 5 0 1PF
*
MNC 6 2 0 0 MOSN W=4U L=1U AS=16P AD=16P
MPC 7 2 1 1 MOSP W=5U L=1U AS=80P AD=80P
MND 7 4 6 0 MOSN W=4U L=1U AS=16P AD=16P
MPD 7 4 1 1 MOSP W=5U L=1U AS=80P AD=80P
CL2 7 0 1PF
*
.OP
.DC VA 0 2.5 0.01
.TRAN 0.05N 50N
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0
+LAMBDA=.02 TOX=41.5N CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0 LAMBDA=.05 TOX=41.5N
+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
.PROBE V(2) V(5) V(7)
.END

```



The transitions of the two VTCs are separated by approximately 50 mV. The dynamic characteristics for switching one input with the other constant are essentially identical. The two transitions are virtually identical because of the ideal step inputs: $\tau_{PHL} = 3.6$ ns, $\tau_{PLH} = 3.7$ ns, $t_f = 8.0$ ns, $t_r = 8.1$ ns. With the inputs switched together, τ_{PLH} and t_r are reduced by 50% because the two PMOS devices are working in parallel

7.58

The simulation results show only slight changes.

7.59

Worst-case paths are the same as the symmetrical reference inverter:

$$\text{PMOS tree : } \left(\frac{1}{3} \right) \left(\frac{15}{1} \right) = \left(\frac{5}{1} \right) \quad | \quad \text{NMOS tree : } \left(\frac{1}{2} \right) \left(\frac{4}{1} \right) = \left(\frac{2}{1} \right) \quad | \quad \text{For } V_{DD} = 2.5V,$$

$$\tau_{PLH} = 1.2R_{onP}C = \frac{1.2C}{K_p|V_{GS} - V_{TP}|} = \frac{1.2(1.25\text{ pF})}{5(4 \times 10^{-5})(2.5 + 0.6)} = 3.95\text{ ns}$$

$$\tau_{PHL} \approx 1.2R_{onN}C = \frac{1.2C}{K_n(V_{GS} - V_{TN})} = \frac{1.2(1.25\text{ pF})}{2(10^{-4})(2.5 - 0.6)} = 3.95\text{ ns}$$

Since there is a 2.5:1 ratio in transistor sizes, $\tau_{PLH} = \tau_{PHL}$,

$$\tau_P = \tau_{PHL} = 3.95\text{ ns} \quad \text{and} \quad t_r = t_f = 3\tau_{PHL} = 3\tau_P = 11.8\text{ ns}$$

7.60

(a) A depletion-mode design requires the same number of NMOS transistors in the switching network, but only one load transistor. The depletion-mode design requires 5 transistors total. The CMOS design requires 8 transistors.

(b) For the CMOS design, first find the worst - case delay of the circuit in Fig. 7.30

and then scale the result to achieve the desired delay. For $V_{DD} = 2.5$ V,

$$\tau_{PHL} = \frac{1.2C}{K_n(V_{DD} - V_{TN})} = \frac{1.2(10^{-12})}{\frac{1}{2}\left(\frac{2}{1}\right)(100 \times 10^{-6})(2.5 - 0.6)} = 6.32 \text{ ns}$$

$$\tau_{PLH} = \frac{1.2C}{K_p(V_{DD} + V_{TP})} = \frac{1.2(10^{-12})}{\frac{1}{3}\left(\frac{2}{1}\right)(40 \times 10^{-6})(2.5 + 0.6)} = 23.7 \text{ ns}$$

$$\tau_p = \frac{6.32 + 23.7}{2} \text{ ns} = 15.0 \text{ ns} \rightarrow \left(\frac{W}{L}\right)_{all} = \frac{15.0 \text{ ns}}{10 \text{ ns}} \left(\frac{2}{1}\right) = \left(\frac{3.00}{1}\right)$$

$$\text{Relative Area} = 8(3.00)(1) = 24.0$$

For the depletion - mode design, first assume that τ_p is dominated by τ_{PLH} .

$$\tau_{PLH} \approx 2\tau_p \quad | \quad \tau_{PLH} = 3.6R_{onL}C$$

$$\left(\frac{W}{L}\right)_L = \frac{3.6(10^{-12})}{2(10^{-8})(40 \times 10^{-6})(1)} = \frac{4.50}{1} \quad | \quad \text{Since NMOS is ratioed logic, the } \frac{W}{L} \text{ ratios}$$

$$\text{must maintain the ratio in Fig. 7.29(d): } \left(\frac{W}{L}\right)_S = \frac{(2.22/1)4.50}{(1.81/1)1} = \frac{5.52}{1}$$

$$\text{Using this value, } \tau_{PHL} = \frac{1.2(10^{-12})}{5.52(100 \times 10^{-6})(2.5 - 0.6)} = 1.14 \text{ ns} \text{ and}$$

$$\tau_p = \frac{20 + 1.14}{2} \text{ ns} = 10.6 \text{ ns}$$

Rescaling to achieve $\tau_p = 10 \text{ ns}$:

$$\left(\frac{W}{L}\right)_L = \frac{10.6}{10} \left(\frac{4.50}{1}\right) = \frac{4.77}{1} \quad | \quad \left(\frac{W}{L}\right)_A = \frac{10.6}{10} \left(\frac{5.52}{1}\right) = \frac{5.85}{1} \quad | \quad \left(\frac{W}{L}\right)_{B-D} = 2 \left(\frac{W}{L}\right)_A = \frac{11.7}{1}$$

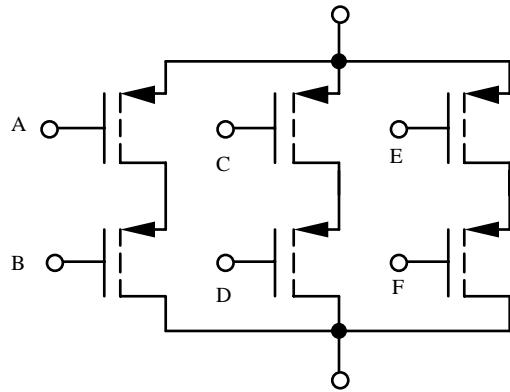
$$\text{Relative area} = (4.50)(1) + 3(11.7)(1) + (5.85)(1) = 45.5$$

The CMOS design uses 47% less area and consumes no static power.

7.61

$$(a) Y = \overline{(A+B)(C+D)(E+F)}$$

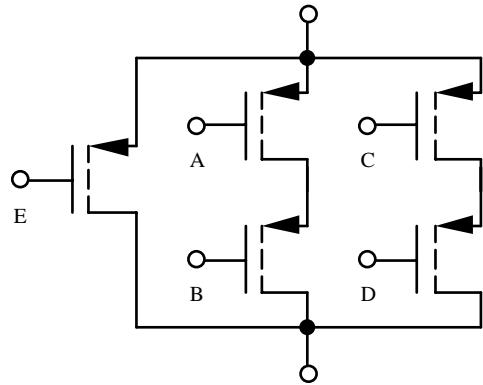
$$(b) \text{ NMOS: } \frac{W}{L} = 3 \left(\frac{2}{1} \right) = \frac{6}{1} \quad \text{PMOS: } \frac{W}{L} = 2 \left(\frac{5}{1} \right) = \frac{10}{1}$$



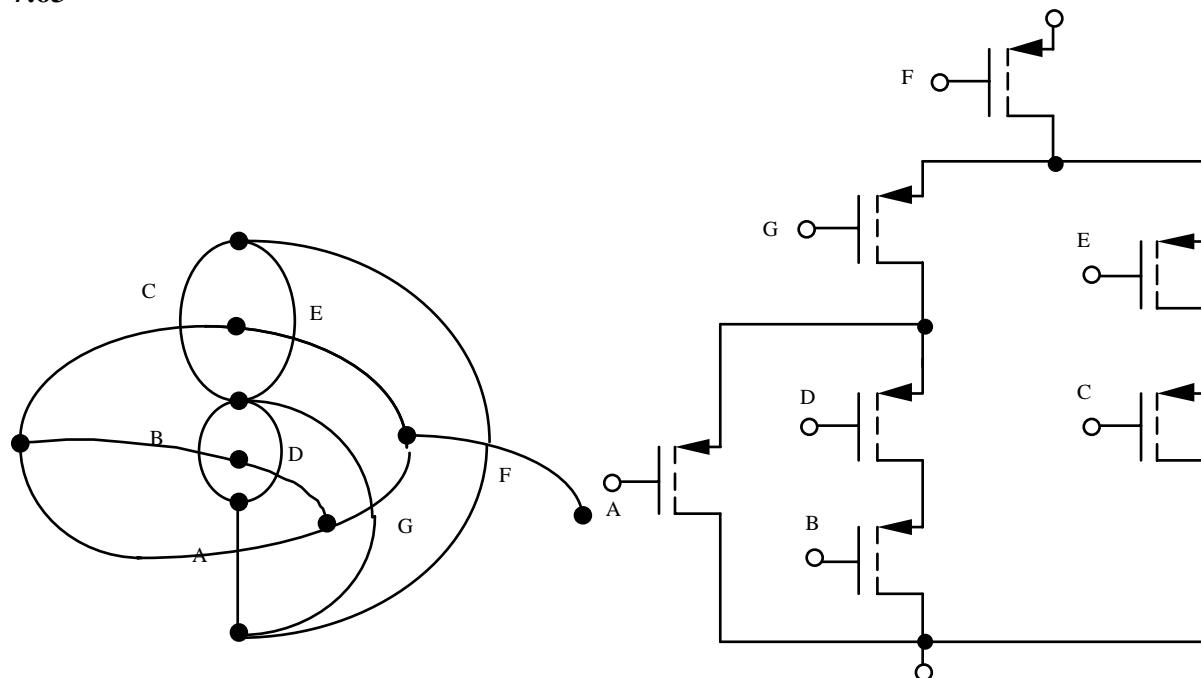
7.62

$$(a) Y = \overline{(A+B)(C+D)E}$$

$$(b) \text{ NMOS: } \frac{W}{L} = 3 \left(3 \left(\frac{2}{1} \right) \right) = \frac{18}{1} \quad \text{PMOS: } \left(\frac{W}{L} \right)_{A-D} = 2 \left(3 \left(\frac{5}{1} \right) \right) = \frac{30}{1} \quad \left(\frac{W}{L} \right)_E = \left(3 \left(\frac{5}{1} \right) \right) = \frac{15}{1}$$



7.63



$$(a) Y = \overline{F + G(C+E) + A(B+D)(C+E)} = \overline{F + (C+E)(G + A(B+D))}$$

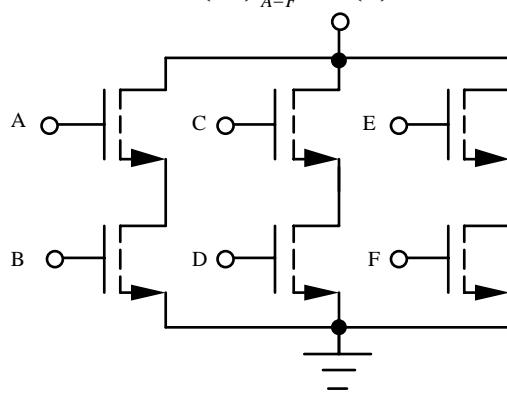
$$(b) \text{NMOS: } \left(\frac{W}{L}\right)_{A-E} = 3\left(2\left(\frac{2}{1}\right)\right) = \frac{12}{1} \quad | \quad \left(\frac{W}{L}\right)_F = \left(2\left(\frac{2}{1}\right)\right) = \frac{4}{1} \quad | \quad \left(\frac{W}{L}\right)_G = \frac{1}{1} - \frac{1}{12} = \frac{6}{12}$$

$$\text{PMOS: } \left(\frac{W}{L}\right)_{F,G,B,D} = 4\left(2\left(\frac{5}{1}\right)\right) = \frac{40}{1} \quad | \quad \left(\frac{W}{L}\right)_A = \frac{1}{1} - \frac{2}{40} = \frac{20}{1} \quad | \quad \left(\frac{W}{L}\right)_{C,E} = 2\frac{1}{1} - \frac{1}{40} = \frac{26.7}{1}$$

7.64

$$(a) Y = (\overline{A} + \overline{B})(\overline{C} + \overline{D})(\overline{E} + \overline{F}) = \overline{AB + CD + EF}$$

$$(b) \text{NMOS: } \left(\frac{W}{L}\right)_{A-F} = 2\left(\frac{2}{1}\right) = \frac{4}{1} \quad \text{PMOS: } \left(\frac{W}{L}\right)_{A-F} = 3\left(\frac{5}{1}\right) = \frac{15}{1}$$

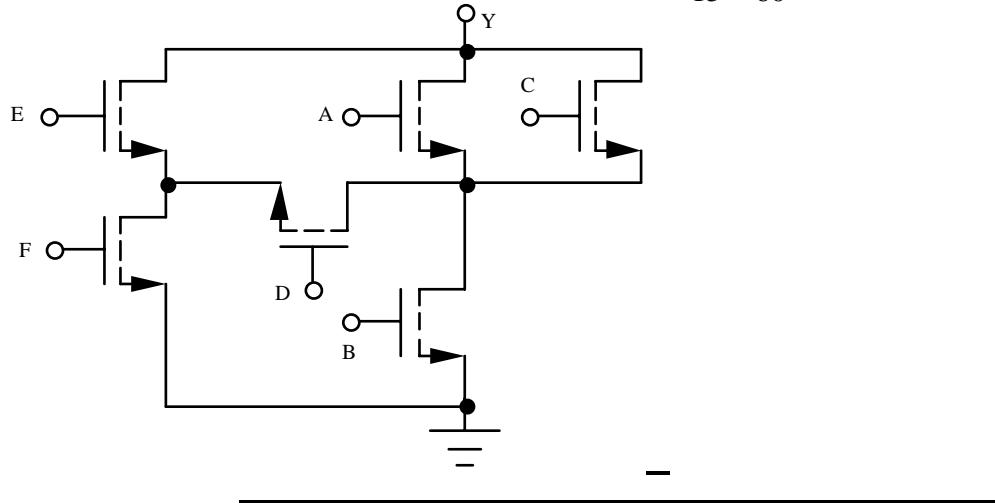


7.65

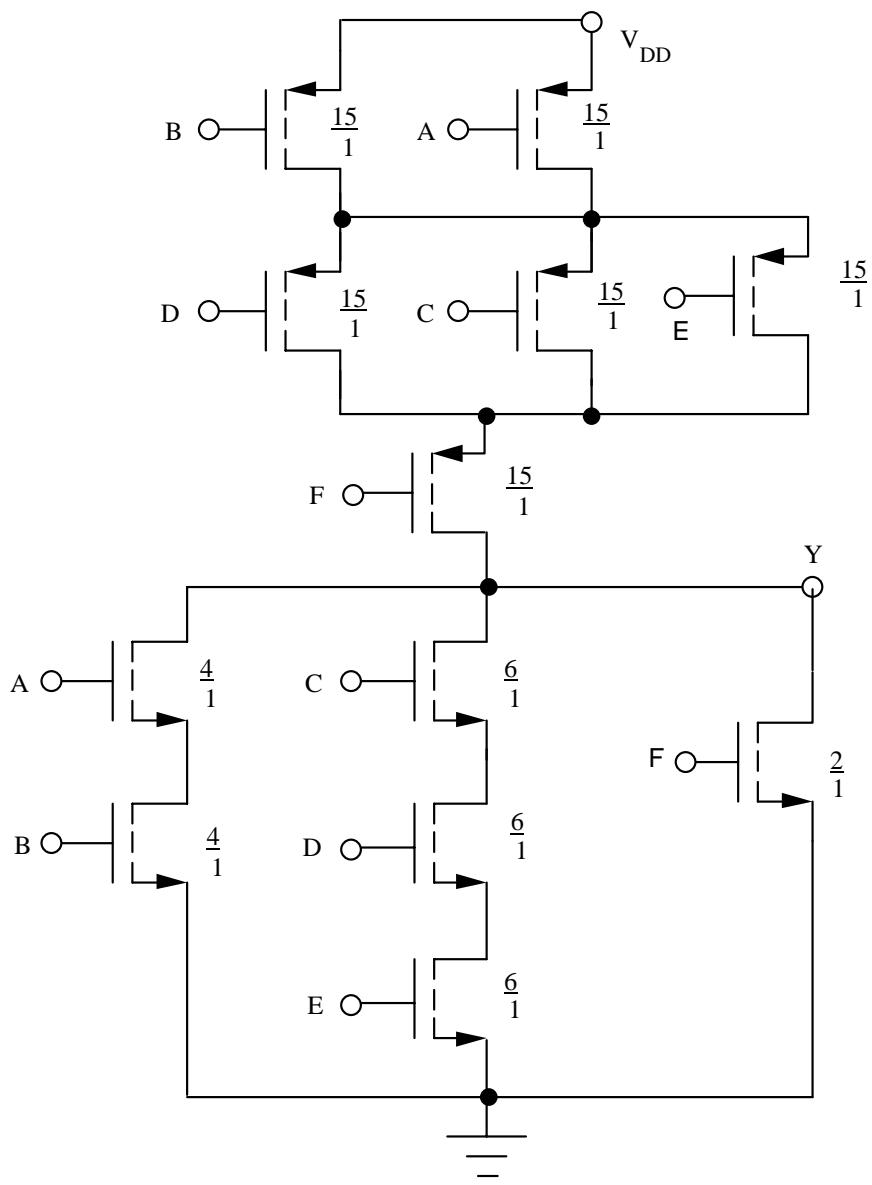
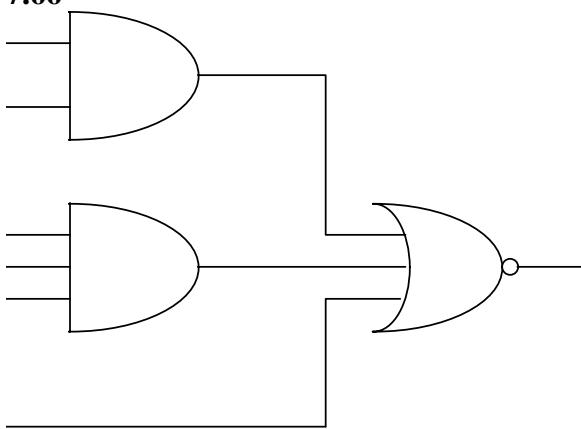
$$(a) Y = \overline{ACE} + \overline{ACDF} + \overline{BDE} + \overline{BF} = \overline{(A+C)(B+DF)} + E(F+DB)$$

$$(b) \text{ NMOS: } \left(\frac{W}{L}\right)_{A-F} = 3(3)\left(\frac{2}{1}\right) = \frac{18}{1}$$

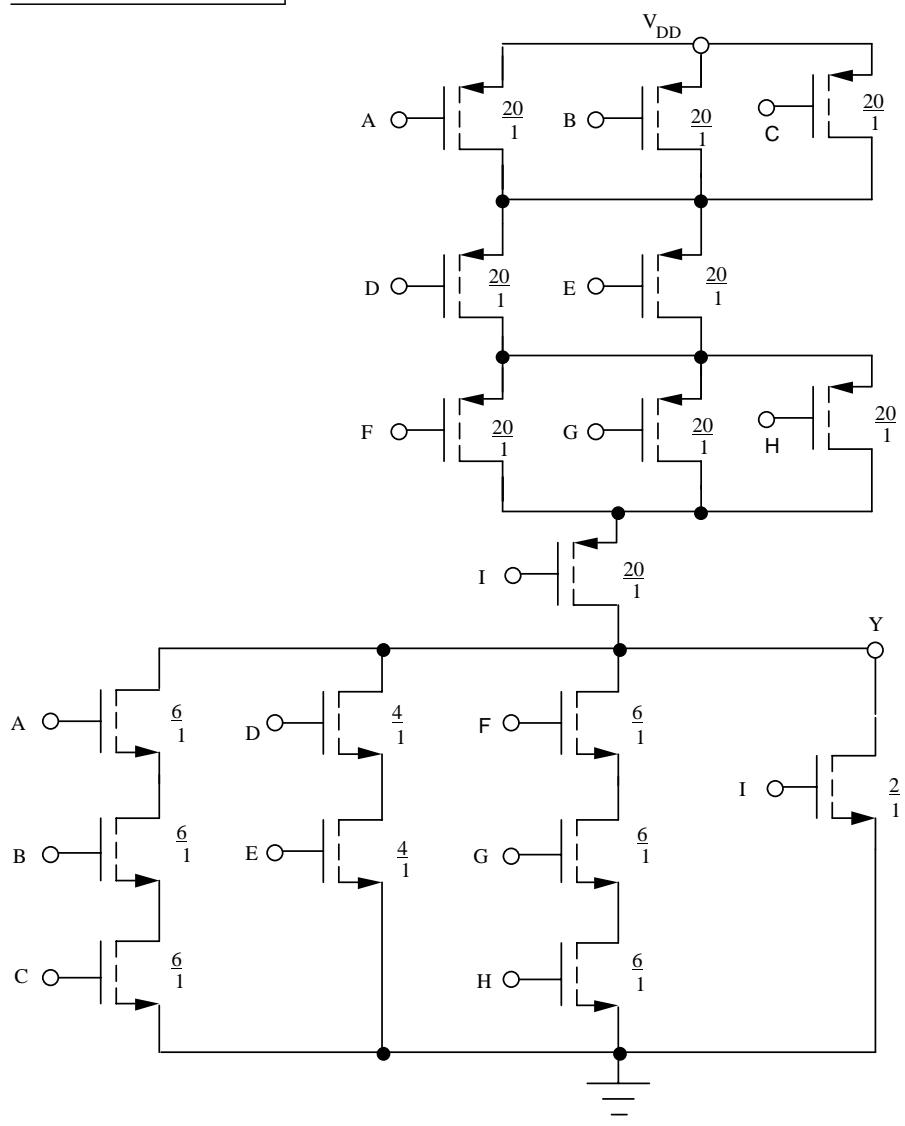
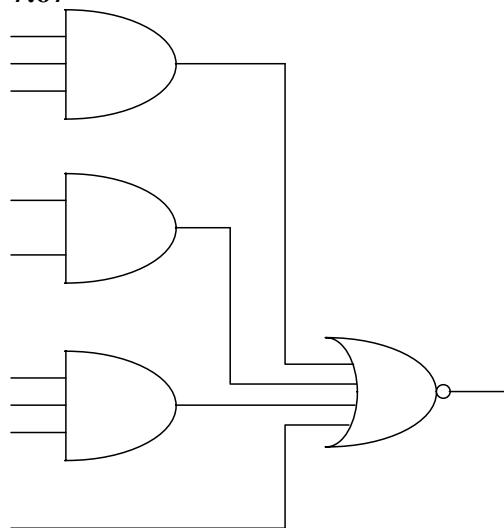
$$\text{PMOS: } \left(\frac{W}{L}\right)_{A,C,D,F} = 4(3)\left(\frac{5}{1}\right) = \frac{60}{1} \quad \left(\frac{W}{L}\right)_{B,E} = 2 \frac{1}{\frac{1}{15} - \frac{1}{60}} = \frac{40}{1}$$



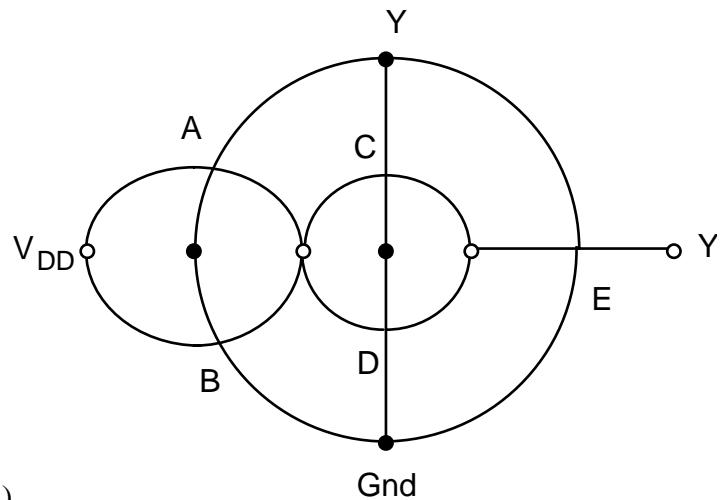
7.66



7.67

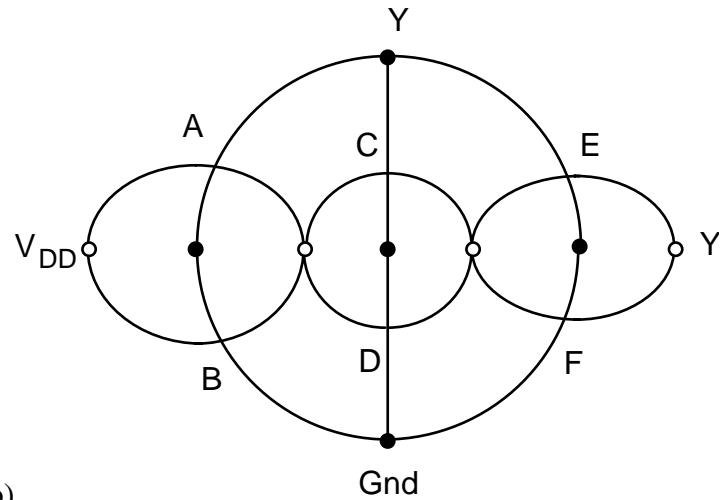


7.68



(a)

An Euler path does not appear to exist.

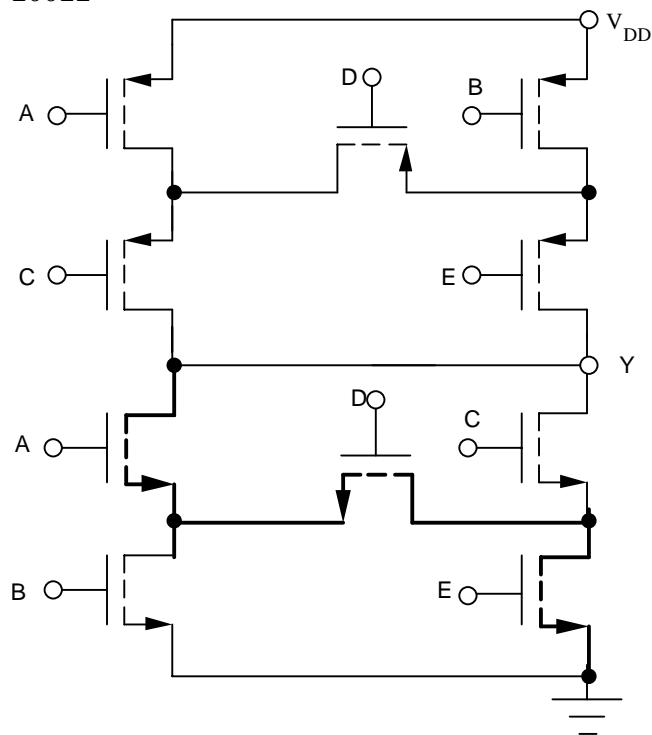


(b)

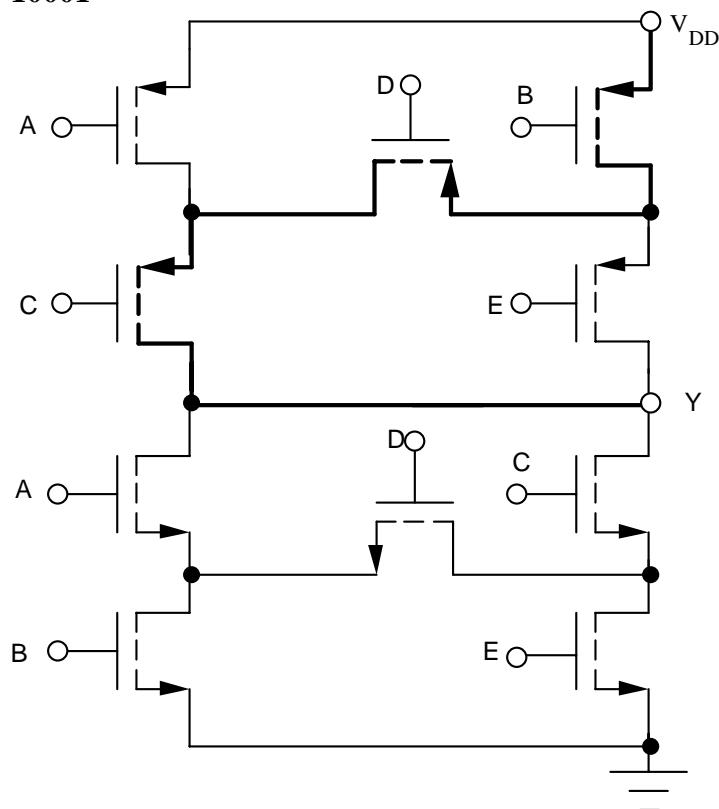
An Euler path does not appear to exist.

7.69

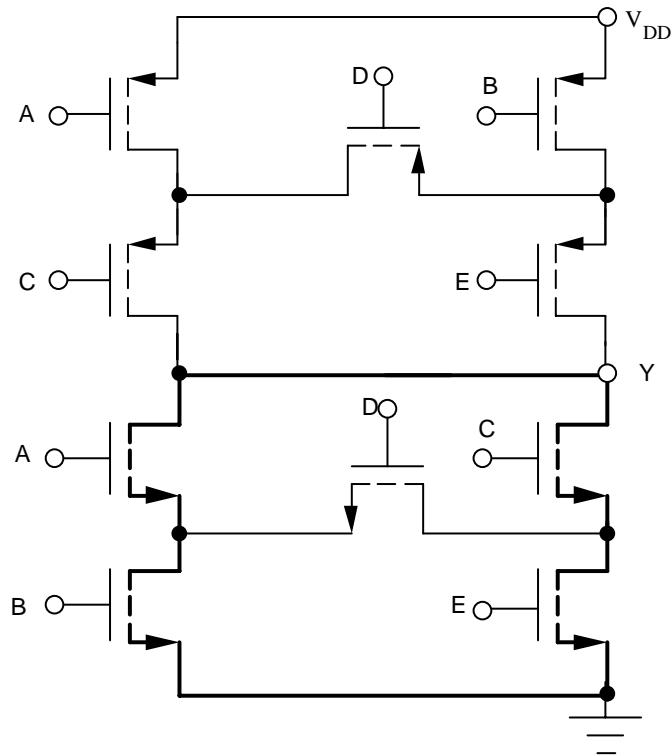
10011



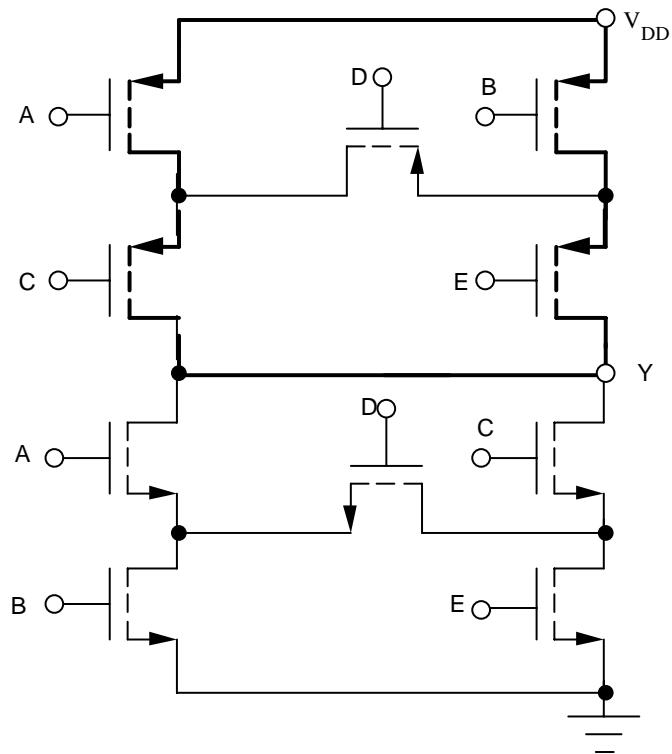
10001



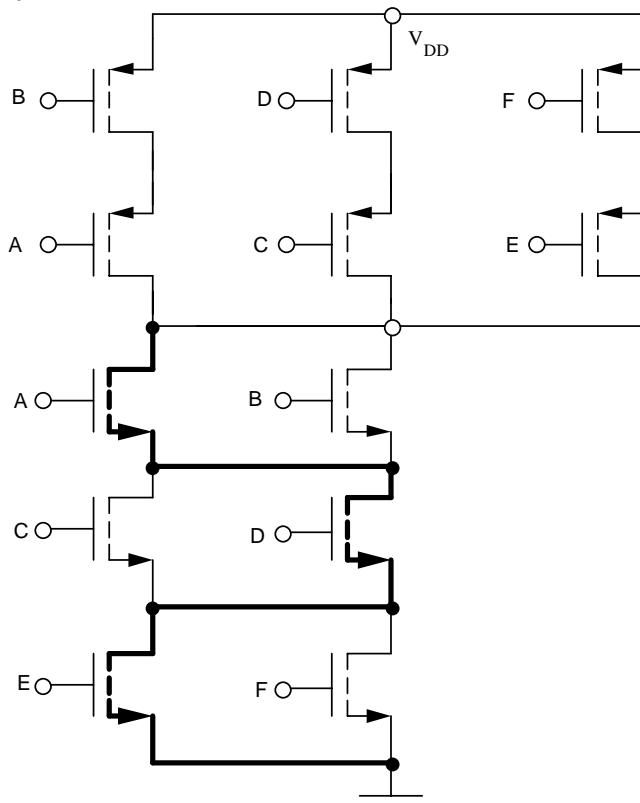
11101



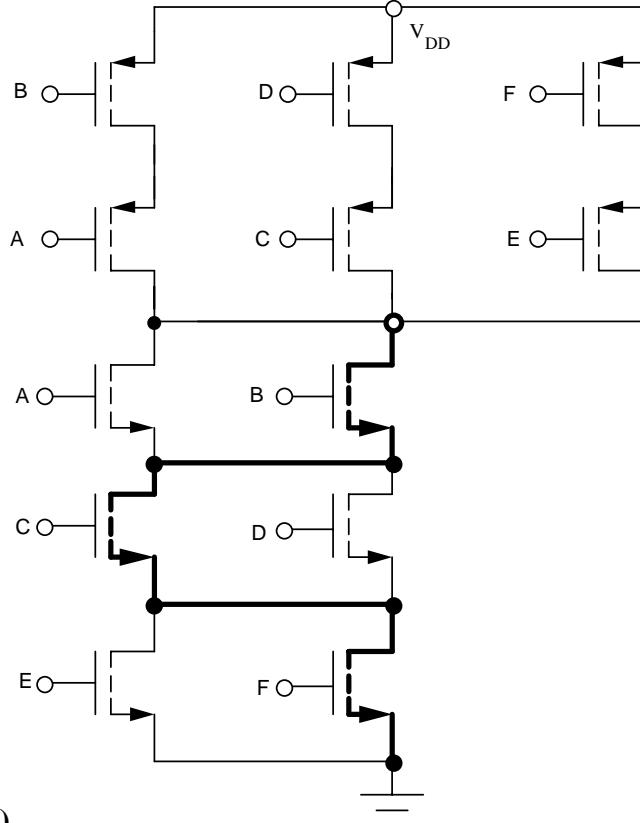
00010



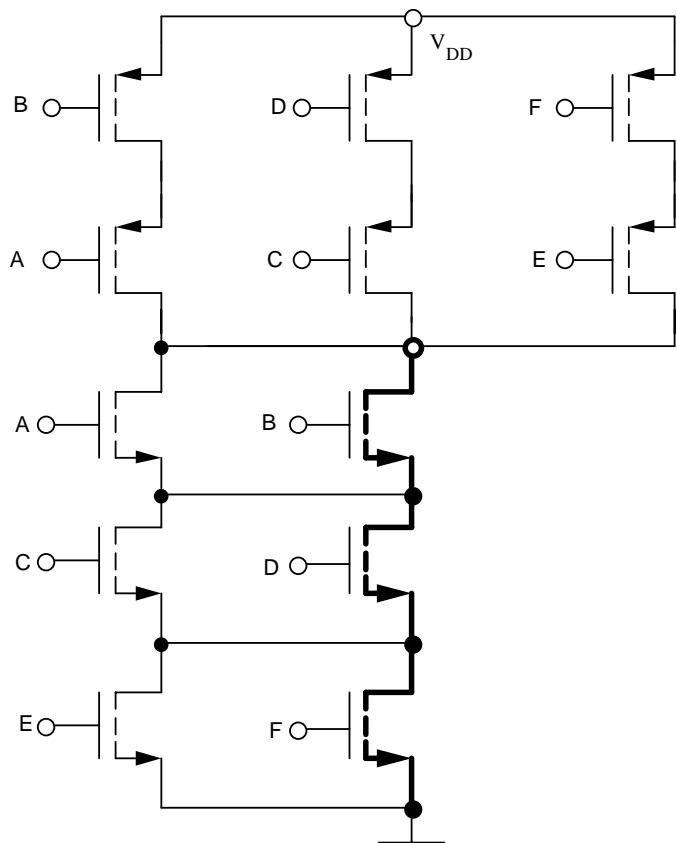
7.70



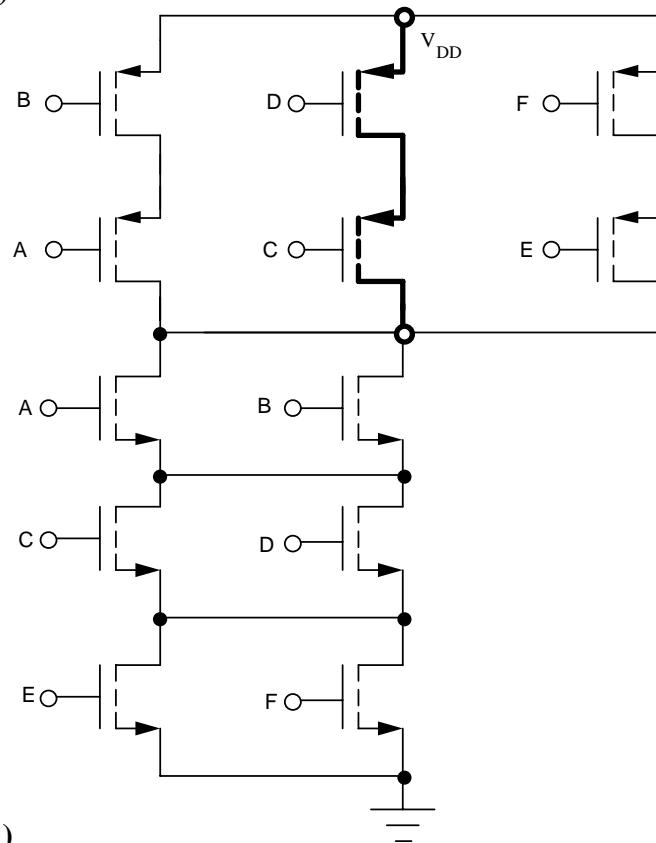
(a)



(b)

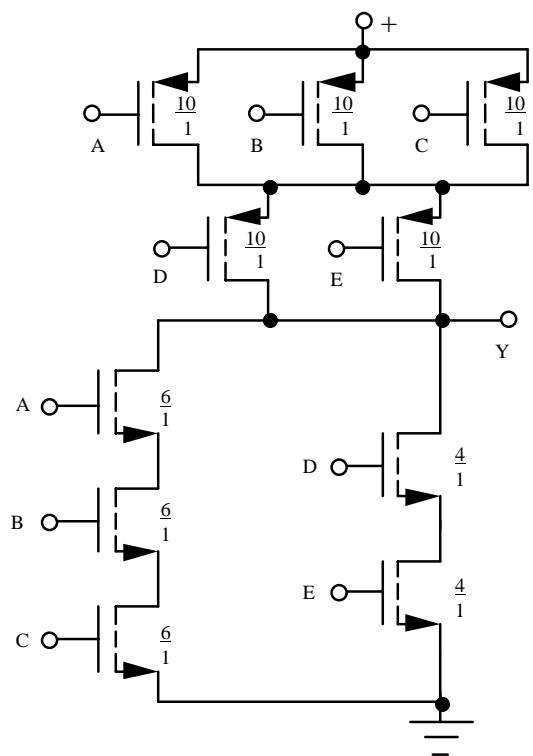


(c)

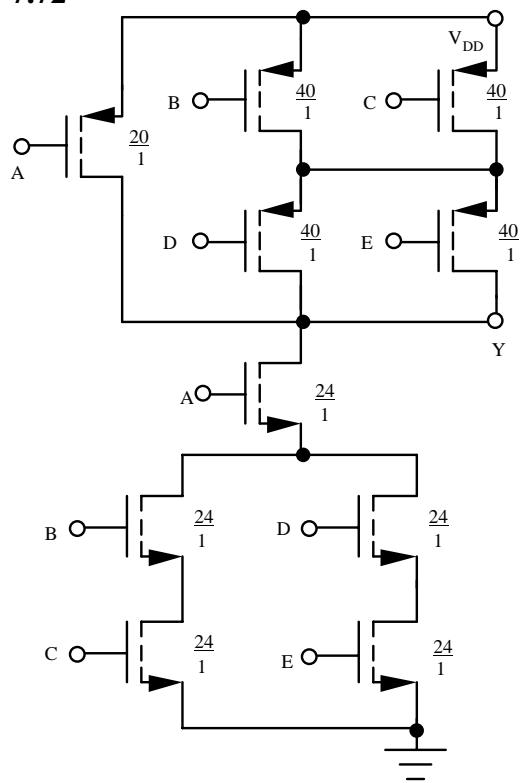


(d)

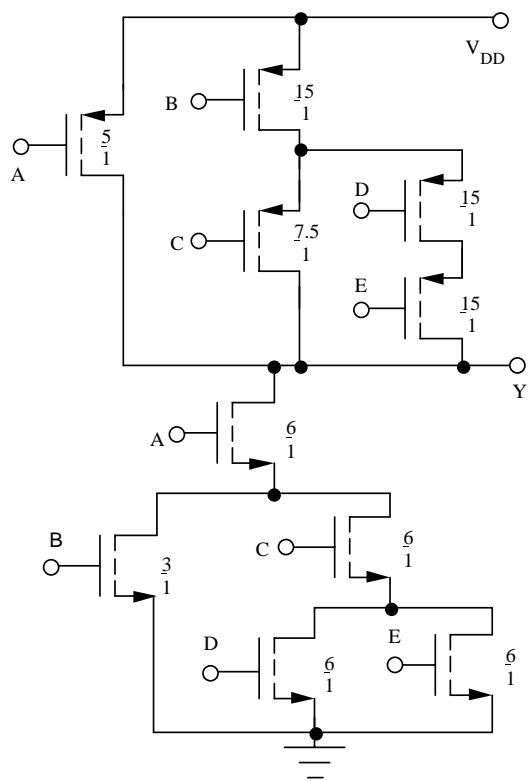
7.71



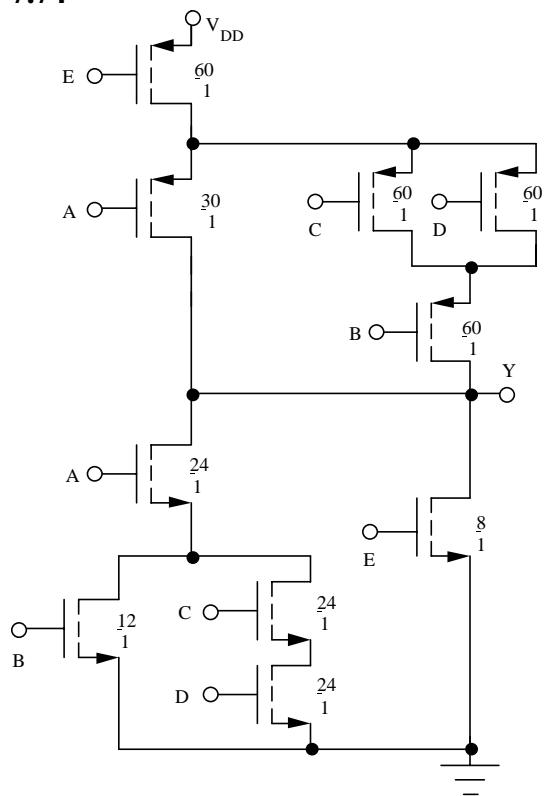
7.72



7.73

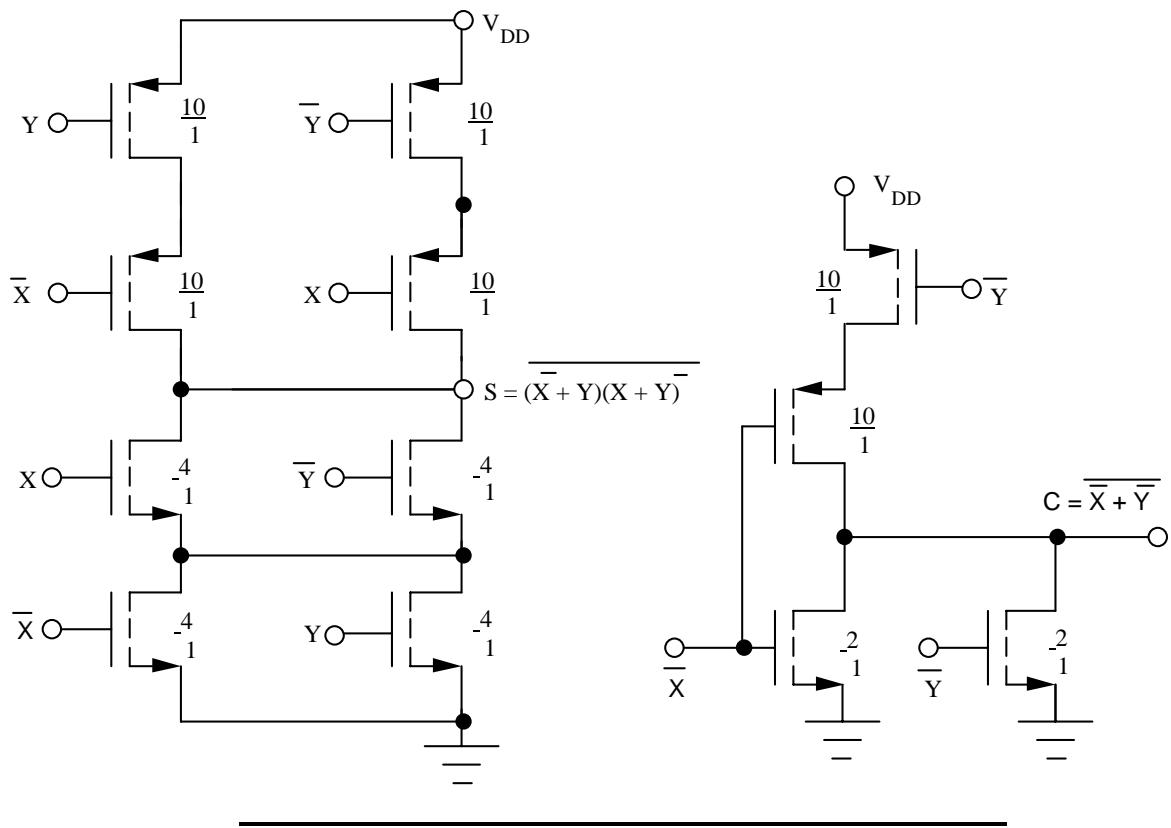


7.74



7.75

$$S = X \oplus Y = X\bar{Y} + \bar{X}Y \quad \text{and} \quad C = XY$$



7.76

X_i	Y_i	C_{i-1}	S_i	C_i
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

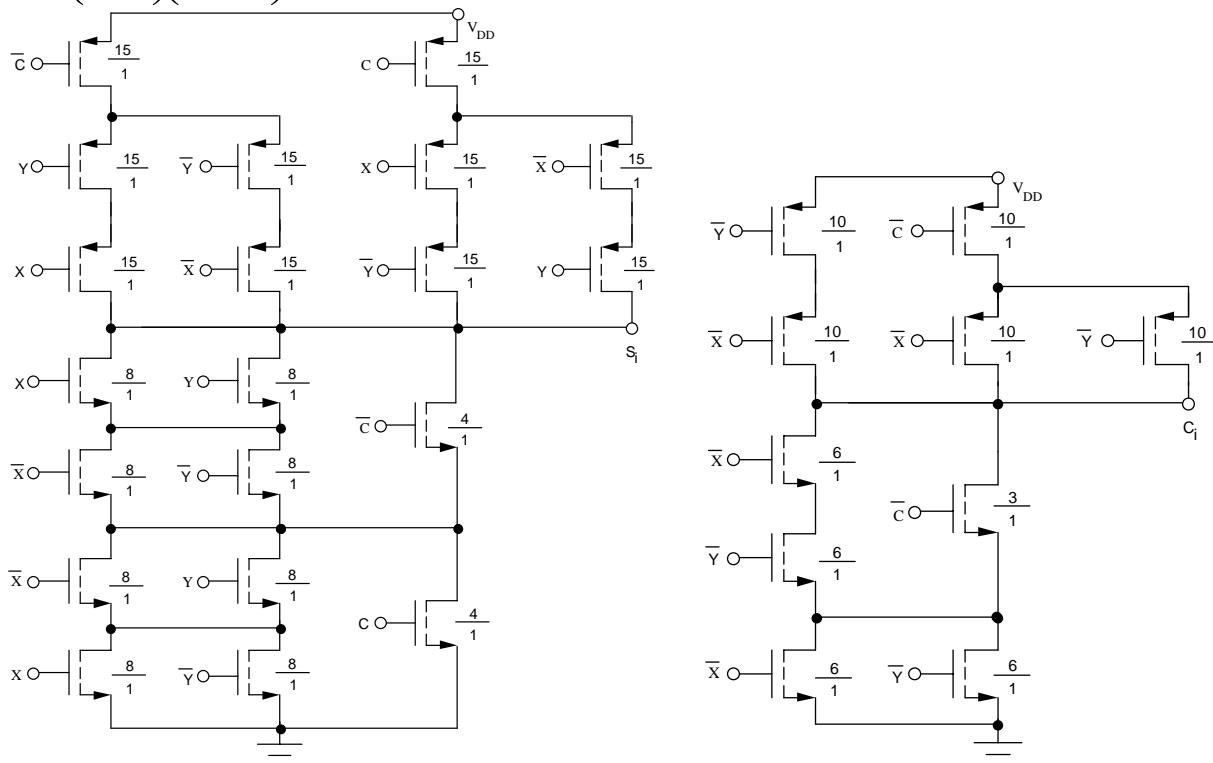
$$\text{Let } X = X_i \quad Y = Y_i \quad C = C_{i-1}$$

$$S_i = \overline{XY}\overline{C} + X\overline{Y}\overline{C} + \overline{X}\overline{Y}C + XYC = \overline{C}(\overline{XY} + X\overline{Y}) + C(XY + \overline{X}\overline{Y})$$

$$S_i = \overline{(\overline{C} + (X + \overline{Y})(\overline{X} + Y))(\overline{C} + (\overline{X} + \overline{Y})(X + Y))}$$

$$C_i = XY + XC + YC = XY + C(X + Y)$$

$$C_i = \overline{(\overline{X} + \overline{Y})(\overline{C} + \overline{X}\overline{Y})}$$



7.77

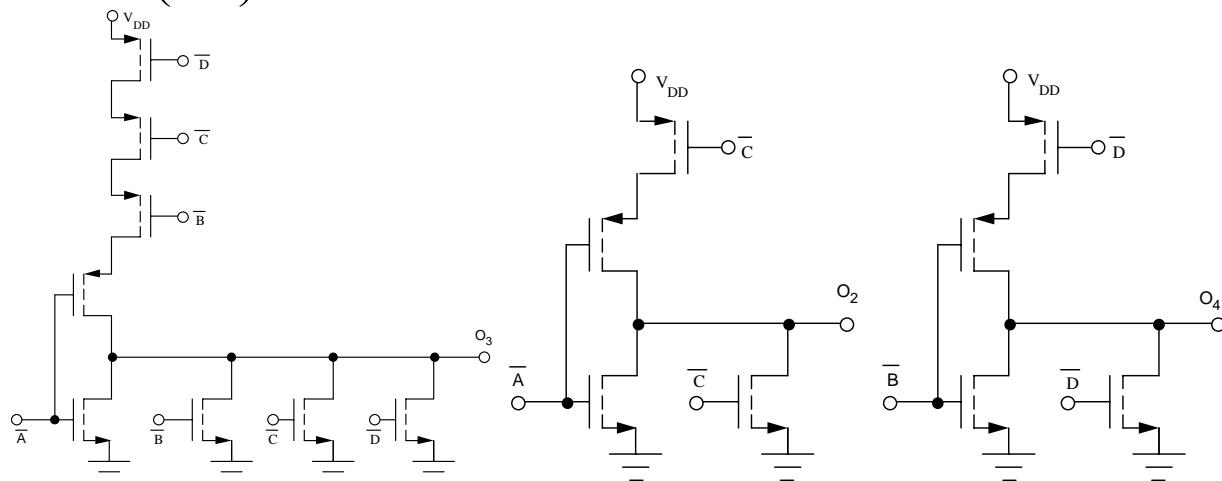
N A B	M C D	Output O ₃ O ₂ O ₁ O ₀	N A B	M C D	Output O ₃ O ₂ O ₁ O ₀
0 0	0 0	0 0 0 0	1 0	0 0	0 0 0 0
0 0	0 1	0 0 0 0	1 0	0 1	0 0 1 0
0 0	1 0	0 0 0 0	1 0	1 0	0 1 0 0
0 0	1 1	0 0 0 0	1 0	1 1	0 1 1 0
0 1	0 0	0 0 0 0	1 1	0 0	0 0 0 0
0 1	0 1	0 0 0 1	1 1	0 1	0 0 1 1
0 1	1 0	0 0 1 0	1 1	1 0	0 1 1 0
0 1	1 1	0 0 1 1	1 1	1 1	1 0 0 1

$$O_3 = ABCD = \overline{(\bar{A} + \bar{B} + \bar{C} + \bar{D})}$$

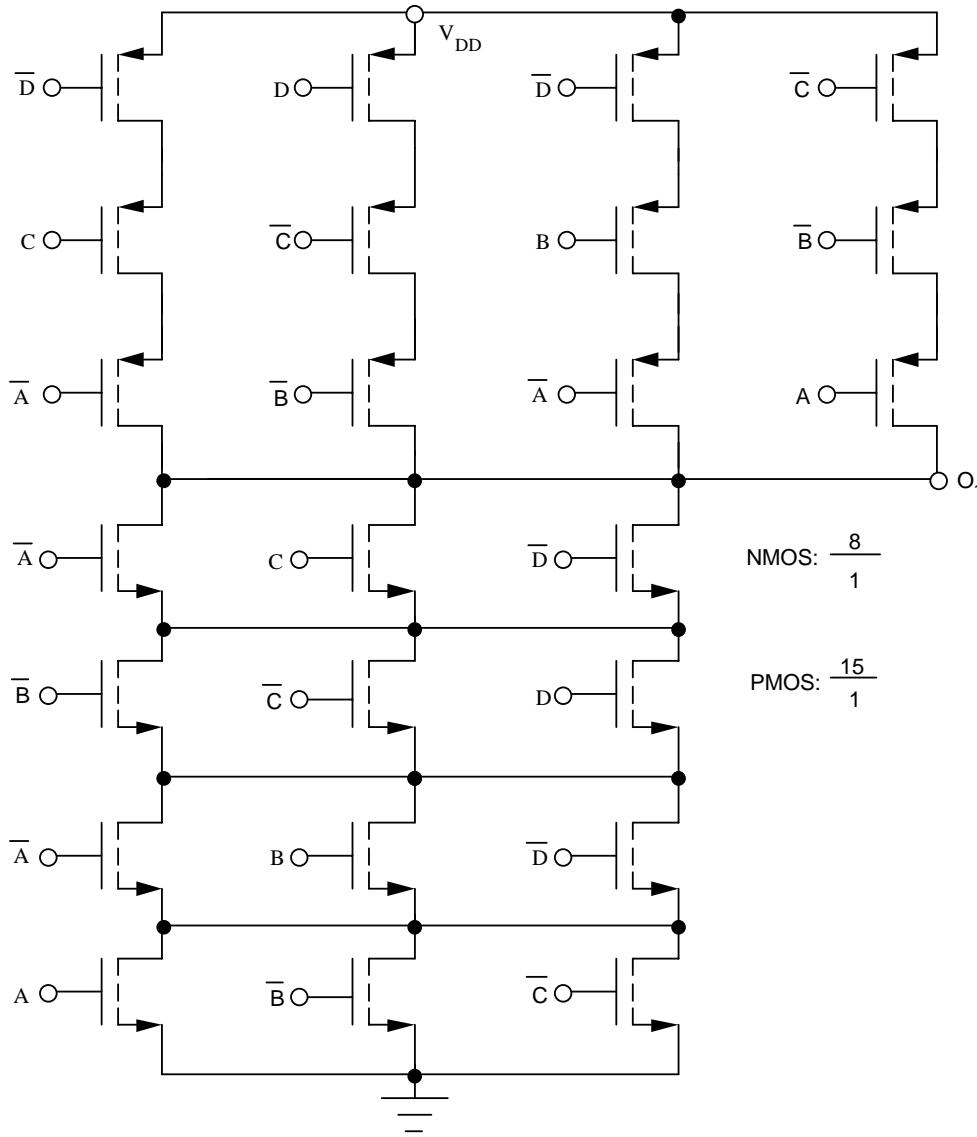
$$O_2 = AC = \overline{(\bar{A} + \bar{C})}$$

$$O_1 = \bar{A}\bar{B}C + A\bar{B}\bar{D} + B\bar{C}\bar{D} + A\bar{C}\bar{D} = (\bar{A} + \bar{B} + \bar{C})(\bar{A} + B + \bar{D})(\bar{B} + \bar{C} + D)(\bar{A} + C + \bar{D})$$

$$O_0 = BD = \overline{(\bar{B} + \bar{D})}$$



$$\left(\frac{W}{L}\right)_N = \frac{2}{1} \quad \left(\frac{W}{L}\right)_P = \frac{20}{1} \quad | \quad \left(\frac{W}{L}\right)_N = \frac{2}{1} \quad \left(\frac{W}{L}\right)_P = \frac{10}{1} \quad | \quad \left(\frac{W}{L}\right)_N = \frac{2}{1} \quad \left(\frac{W}{L}\right)_P = \frac{10}{1}$$



7.78

$$(a) \tau_{PHL} = 1.2R_{on}C = \frac{1.2(0.4 \times 10^{-12})}{(2/1)(100 \times 10^{-6})(2.5 - 0.6)} = 1.26 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onp}C = \frac{1.2(0.4 \times 10^{-12})}{(2/3)(40 \times 10^{-6}) - 2.5 + 0.6} = 9.47 \text{ ns} \quad | \quad \tau_p = \frac{\tau_{PLH} + \tau_{PHL}}{2} = 5.37 \text{ ns}$$

$$(b) \tau_{PHL} = 1.2R_{on}C = \frac{1.2(0.4 \times 10^{-12})}{(2/1)(100 \times 10^{-6})(2.5 - 0.6)} = 1.26 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onp}C = \frac{1.2(0.4 \times 10^{-12})}{(2/1)(40 \times 10^{-6}) - 2.5 + 0.6} = 3.16 \text{ ns} \quad | \quad \tau_p = \frac{\tau_{PLH} + \tau_{PHL}}{2} = 2.21 \text{ ns}$$

7.79

$$(a) \tau_{PHL} = 1.2R_{onn}C = \frac{1.2(0.18 \times 10^{-12})}{(2/5)(100 \times 10^{-6})(2.5 - 0.6)} = 2.84 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onp}C = \frac{1.2(0.18 \times 10^{-12})}{(2/1)(40 \times 10^{-6}) - 2.5 + 0.6} = 1.42 \text{ ns} \quad | \quad \tau_p = \frac{\tau_{PLH} + \tau_{PHL}}{2} = 2.13 \text{ ns}$$

$$(b) \tau_{PHL} = 1.2R_{onn}C = \frac{1.2(0.18 \times 10^{-12})}{(2/1)(100 \times 10^{-6})(2.5 - 0.6)} = 0.568 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onp}C = \frac{1.2(0.4 \times 10^{-12})}{(2/1)(40 \times 10^{-6}) - 2.5 + 0.6} = 3.16 \text{ ns} \quad | \quad \tau_p = \frac{\tau_{PLH} + \tau_{PHL}}{2} = 1.86 \text{ ns}$$

7.80

The worst-case NMOS path contains 2 transistors. The worst-case PMOS path contains 3 transistors.

$$\tau_{PHL} = 1.2R_{onn}C = \frac{1.2(250 \times 10^{-15})}{(2/2)(100 \times 10^{-6})(2.5 - 0.6)} = 1.58 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onp}C = \frac{1.2(250 \times 10^{-15})}{(2/3)(40 \times 10^{-6}) - 2.5 + 0.6} = 5.92 \text{ ns}$$

7.81

The worst-case NMOS path contains 3 transistors. The worst-case PMOS path contains 3 transistors.

$$\tau_{PHL} = 1.2R_{onn}C = \frac{1.2(400 \times 10^{-15})}{(2/3)(100 \times 10^{-6})(2.5 - 0.6)} = 3.79 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onp}C = \frac{1.2(400 \times 10^{-15})}{(2/3)(40 \times 10^{-6}) - 2.5 + 0.6} = 9.47 \text{ ns}$$

7.82

The worst-case NMOS path contains 3 transistors (ABE or CBD). The worst-case PMOS path also contains 3 transistors.

$$\tau_{PHL} = 1.2R_{onn}C = \frac{1.2(10^{-12})}{(2/3)(100 \times 10^{-6})(2.5 - 0.6)} = 9.47 \text{ ns}$$

$$\tau_{PLH} = 1.2R_{onp}C = \frac{1.2(10^{-12})}{(2/3)(40 \times 10^{-6}) - 2.5 + 0.6} = 23.7 \text{ ns} \quad | \quad \tau_p = \frac{\tau_{PLH} + \tau_{PHL}}{2} = 16.6 \text{ ns}$$

7.83

The worst-case NMOS path contains 3 transistors.

$$\tau_{PHL} = 1.2R_{on}C = \frac{1.2(10^{-12})}{(2/3)(100 \times 10^{-6})(2.5 - 0.6)} = 9.47 \text{ ns}$$

7.84

Student PSPICE will only accept 5 inverters.

*PROBLEM 7.84(a) - FIVE CASCDED INVERTERS

VDD 1 0 DC 2.5

VIN 2 0 PULSE (0 2.55 0 0.1N 0.1N 20N 40N)

*

MN1 3 2 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP1 3 2 1 1 MOSP W=2U L=1U AS=16P AD=16P

C1 3 0 200fF

*AS=8UM*W - AD=8UM*W

*

MN2 4 3 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP2 4 3 1 1 MOSP W=2U L=1U AS=16P AD=16P

C2 4 0 200fF

*

MN3 5 4 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP3 5 4 1 1 MOSP W=2U L=1U AS=16P AD=16P

C3 5 0 200fF

*

MN4 6 5 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP4 6 5 1 1 MOSP W=2U L=1U AS=16P AD=16P

C4 6 0 200fF

*

MN5 7 6 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP5 7 6 1 1 MOSP W=2U L=1U AS=16P AD=16P

C5 7 0 200fF

*

.OP

.TRAN 0.025N 40N

.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99

+LAMBDA=.02 TOX=41.5N

+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P

.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5

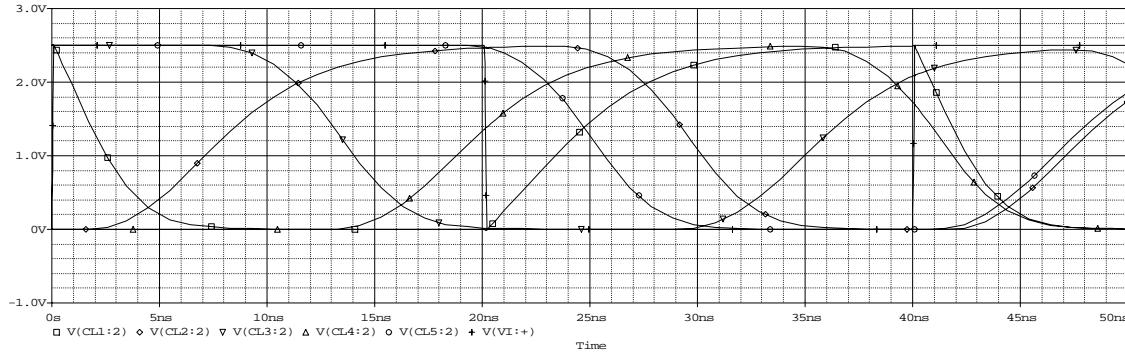
+LAMBDA=.05 TOX=41.5N

+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P

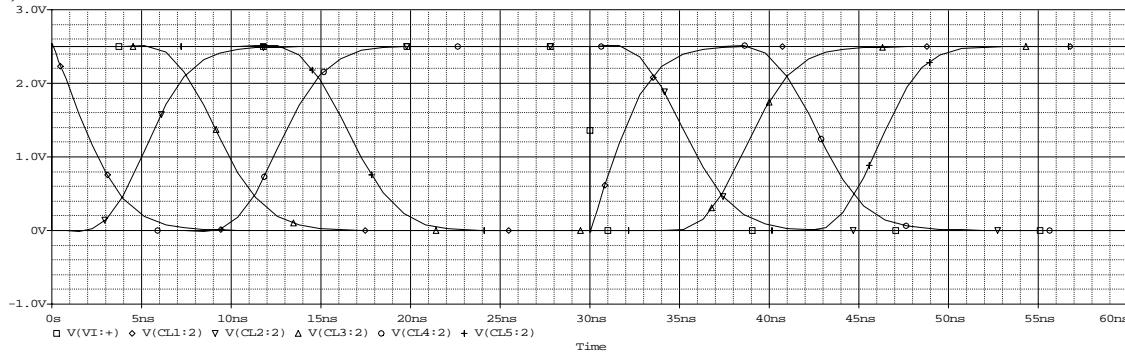
.PROBE V(2) V(3) V(4) V(10) V(11)

.END

(a)



(b)



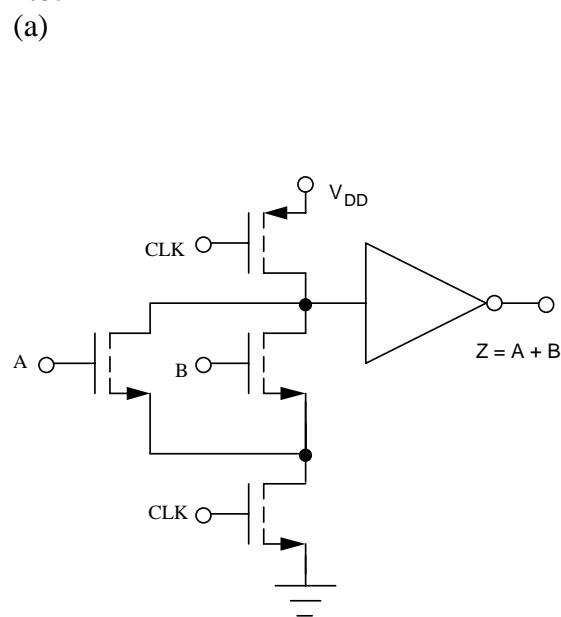
(a) The minimum size inverters yield $\tau_p = 5.8 \text{ ns}$.

(b) The symmetrical inverters yield $\tau_p = 3.7 \text{ ns}$.

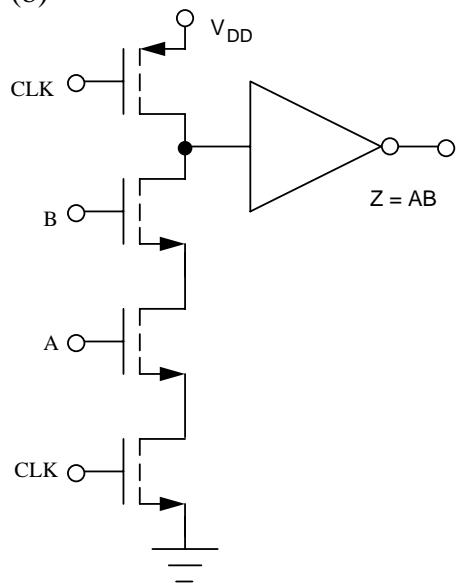
Note that these results are larger than the delay equation estimate because of the slope of the waveforms.

7.85

(a)

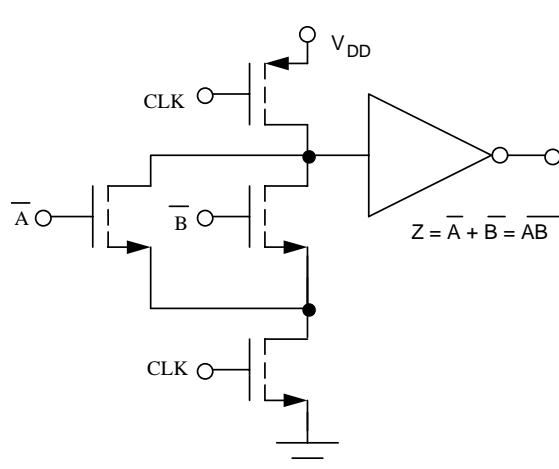


(b)

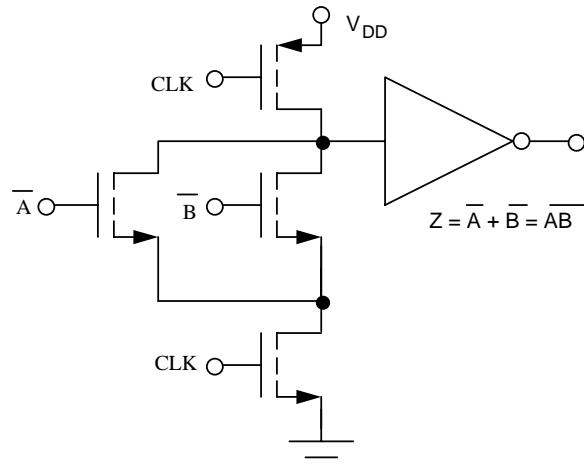


7.86

(a)

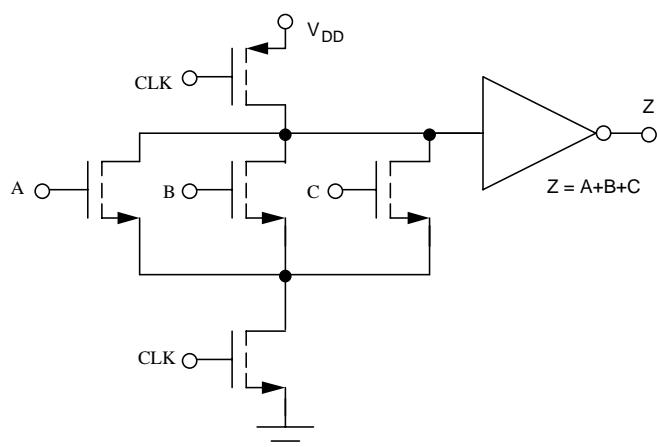


(b)

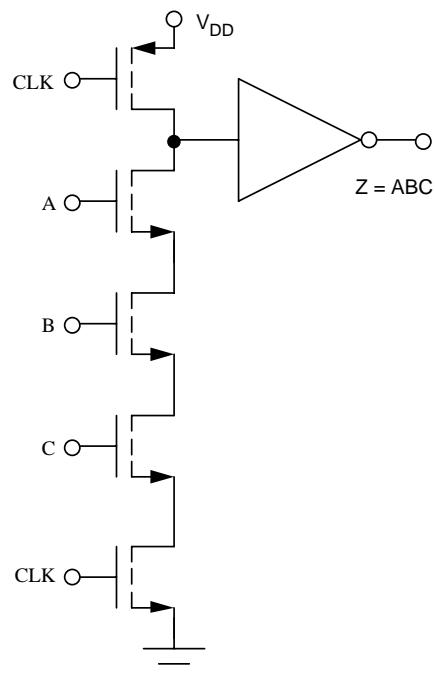


7.87

(a)

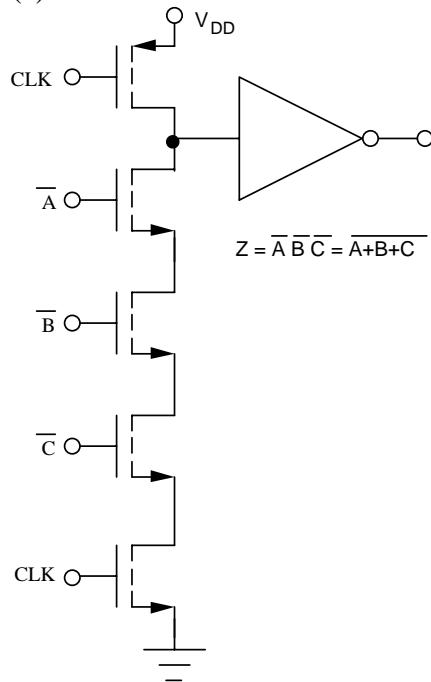


(b)

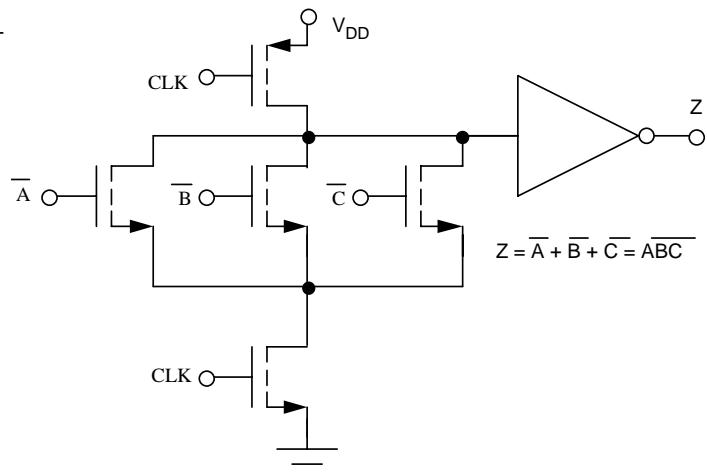


7.88

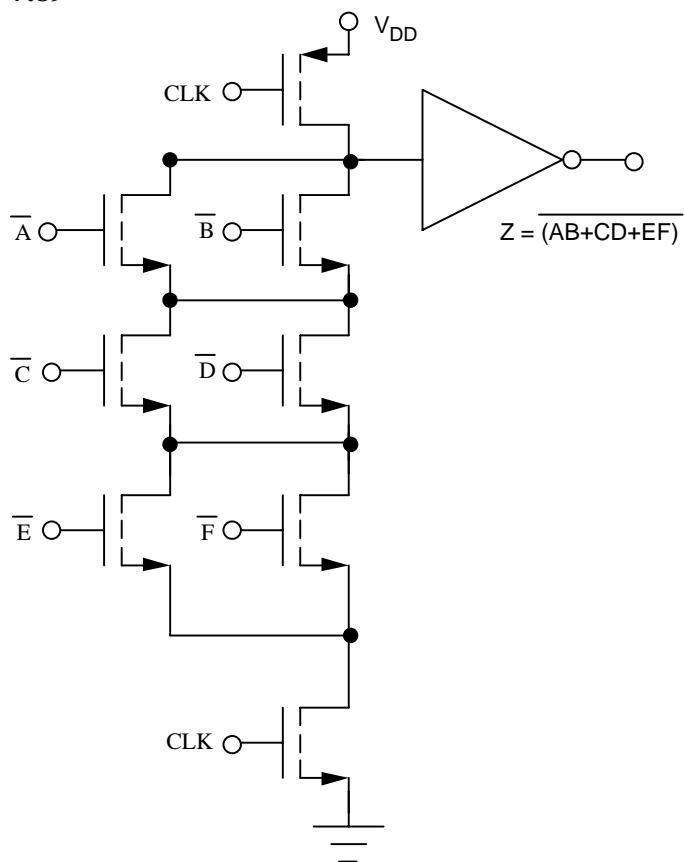
(a)



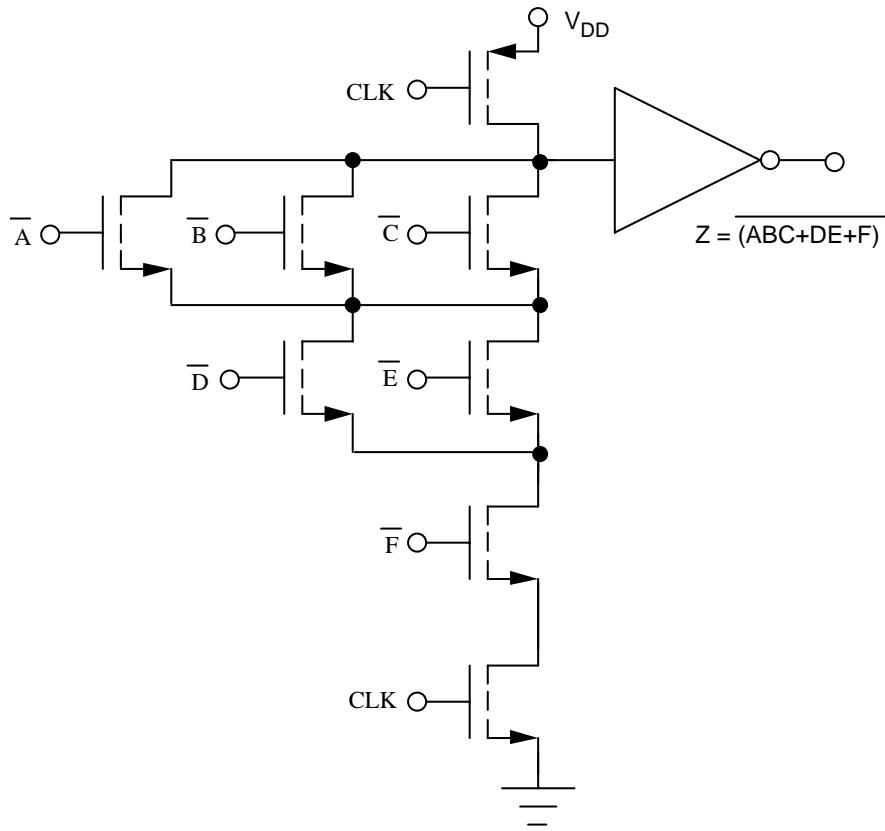
(b)



7.89



7.90



7.91

Charge sharing occurs. Assuming C_2 and C_3 are discharged (the worst case)

$$(a) V_B = \frac{C_1 V_{DD} + C_2(0)}{C_1 + C_2} = \frac{2C_2 V_{DD}}{2C_2 + C_2} = \frac{2}{3} V_{DD} \quad | \quad \text{Node B drops to } \frac{2}{3} V_{DD}.$$

$$(b) V_B = \frac{(C_1 + C_2)\frac{2}{3} V_{DD} + C_3(0)}{C_1 + C_2 + C_3} = \frac{3C_2\left(\frac{2}{3} V_{DD}\right)}{2C_2 + C_2 + C_2} = \frac{V_{DD}}{2} \quad | \quad \text{Node B drops to } \frac{1}{2} V_{DD}.$$

$$(c) V_B = \frac{C_1 V_{DD}}{C_1 + C_2 + C_3} = \frac{R C_2 V_{DD}}{R C_2 + C_2 + C_2} = \frac{R}{R+2} V_{DD} \geq V_{IH} \rightarrow R(V_{DD} - V_{IH}) \geq 2V_{IH}$$

$$R \geq \frac{2V_{IH}}{V_{DD} - V_{IH}} = \frac{2V_{IH}}{NM_H}$$

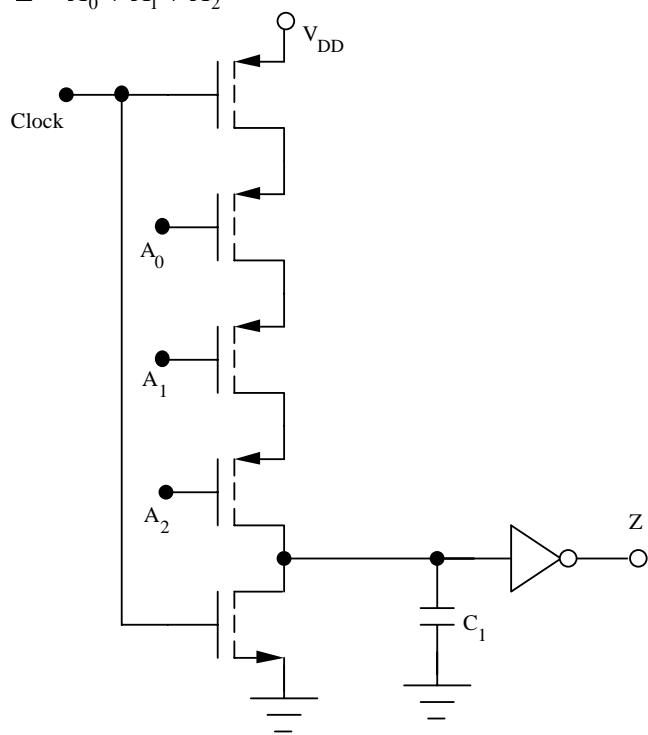
Using $V_{DD} = 2.5V$, $V_{TN} = 0.6V$, $V_{TP} = -0.6V$ in Eq. (8.9):

$$V_{IH} = \frac{5(2.5) + 3(0.6) + 5(-0.6)}{8} = 1.41V \quad | \quad NM_H = \frac{2.5 - 0.6 - 3(-0.6)}{4} = 0.925V$$

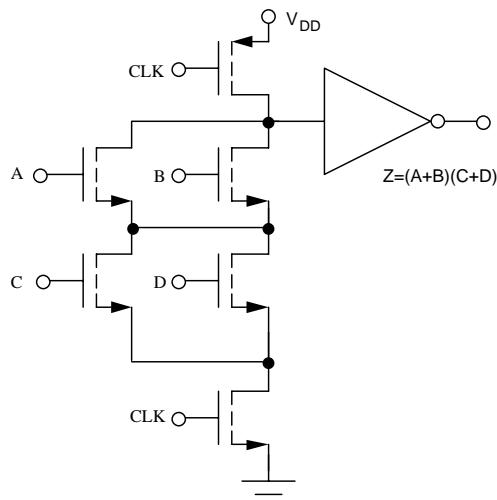
$$R \geq \frac{2V_{IH}}{NM_H} = \frac{2(1.41)}{0.925} = 3.05 \quad | \quad C_1 \geq 83.05C_2$$

7.92

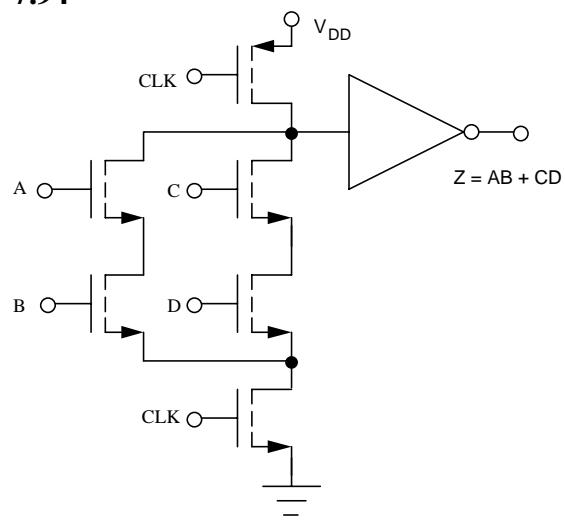
$$Z = A_0 + A_1 + A_2$$



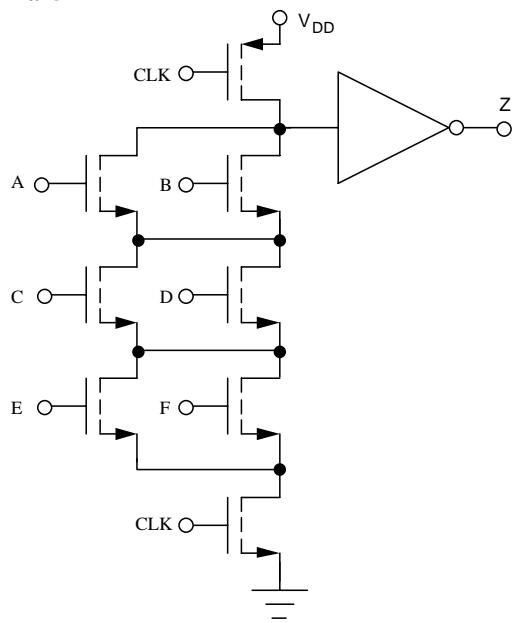
7.93



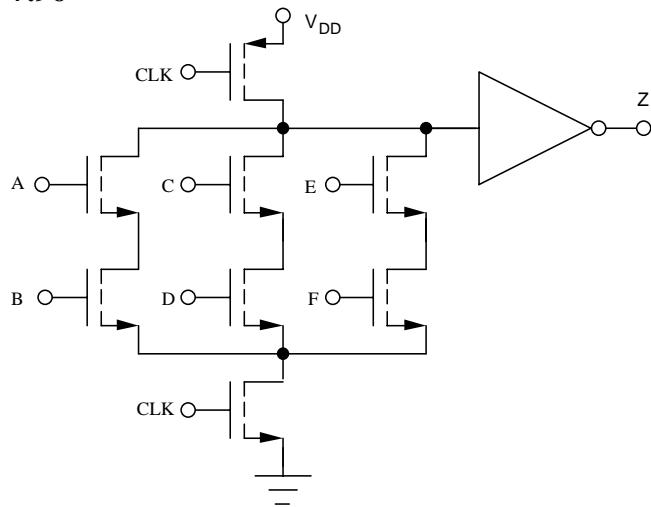
7.94



7.95



7.96



7.97

$$N_{opt} = \ln \frac{C_L}{C_o} = \ln(4000) = 8.29 \rightarrow N = 8 \quad | \quad \beta = (4000)^{\frac{1}{8}} = 2.82.$$

The relative sizes of the 8 inverters are : 1, 2.82, 7.95, 22.4, 63.2, 178, 503, 1420.

Each inverter has a delay of $2.82 \tau_o$. The total delay is $8(2.82 \tau_o) = 22.6 \tau_o$

7.98

$$N_{opt} = \ln \frac{C_L}{C_o} = \ln \left(\frac{10 pF}{100 fF} \right) = 4.61 \rightarrow N = 4 \quad | \quad \beta = (100)^{\frac{1}{4}} = 3.16.$$

The relative sizes of the 4 inverters are : 1, 3.16, 10.0, 31.6

Each inverter has a delay of $3.16\tau_o$. The total delay is $4(3.16\tau_o) = 12.6\tau_o$

Note, $N=5$ yields $\beta = 2.51$ and the total delay is $5(2.51\tau_o) = 12.6\tau_o$.

However, the area will be significantly larger. See Prob. 7.100.

7.99

$$N_{opt} = \ln \frac{C_L}{C_o} = \ln \left(\frac{40 pF}{50 fF} \right) = 6.69 \rightarrow N = 6 \quad | \quad \beta = (800)^{\frac{1}{6}} = 2.82.$$

The relative sizes of the 8 inverters are : 1, 2.82, 7.95, 22.4, 63.2, 178, 503, 1420.

Each inverter has a delay of $2.82\tau_o$. The total delay is $8(2.82\tau_o) = 22.6\tau_o$.

Note, $N=7$ yields $\beta = 2.60$ and the total delay is $7(2.60\tau_o) = 18.2\tau_o$.

However, the area will be significantly larger. See Prob. 7.100.

7.100

$$A_T = A_o (1 + \beta + \beta^2 + \dots + \beta^{N-1}) = A_o \frac{\beta^N - 1}{\beta - 1}$$

$$\text{For } N = 6, \beta = 1000^{1/6} = 3.1623 \quad | \quad A = A_o \frac{1000 - 1}{3.1623 - 1} = 462A_o$$

$$\text{For } N = 7, \beta = 1000^{1/7} = 2.6827 \quad | \quad A = A_o \frac{1000 - 1}{2.6827 - 1} = 594A_o$$

Since the two values of N give similar delays, $N = 6$ would be used because of it requires significantly less area.

7.101

$$(a) R_{onn} = \frac{1}{K_n (V_{GS} - V_{TN})} = \left[\left(\frac{20}{1} \right) (100 \times 10^{-6}) (2.5 - 0.6) \right]^{-1} = 263 \Omega$$

$$(b) R_{onp} = \frac{1}{K_p |V_{GS} - V_{TP}|} = \left[\left(\frac{20}{1} \right) (40 \times 10^{-6}) - 2.5 + 0.6 \right]^{-1} = 658 \Omega$$

(c) A resistive channel exists connecting the source and drain.

7.102

$$G_{on} = G_{onn} + G_{onp} = K_n(V_{GSN} - V_{TN})^* ((V_{GSN} - V_{TN}) > 0) + K_p(V_{TP} - V_{GSP})^* ((V_{TP} - V_{GSP}) > 0)$$

$$V_{GSN} = 2.5 - V_I \quad V_{SBN} = V_I \quad V_{GSP} = -V_I \quad V_{BSN} = 2.5 - V_I$$

$$V_{TN} = [0.6 + 0.5(\sqrt{V_I + 0.6} - \sqrt{0.6})] \quad V_{TP} = [-0.6 - 0.5(\sqrt{2.5 - V_I + 0.6} - \sqrt{0.6})]$$

(a) R_{on} will be the largest for $V_I = 1$ V

$$V_{TN} = 0.845V \quad V_{TP} = -0.937V$$

$$G_{on} = \frac{10}{1}(10^{-4})(2.5 - 1 - 0.845) + \frac{10}{1}(4 \times 10^{-5})(-0.937 + 1) \rightarrow R_{on} = 1470\Omega$$

(b) R_{on} will be the largest for the V_I at which the NMOS transistor just cuts off :

$$2.5 - V_I = [0.6 + 0.5(\sqrt{V_I + 0.6} - \sqrt{0.6})] \rightarrow V_I = 1.554V \quad V_{TN} = 0.947V \quad V_{TP} = -0.834V$$

$$G_{on} = \frac{10}{1}(4 \times 10^{-5})(-0.834 + 1.554) \rightarrow R_{on} = 3470\Omega$$

7.103

$$G_{on} = G_{onn} + G_{onp} = K_n(V_{GSN} - V_{TN})^* ((V_{GSN} - V_{TN}) > 0) + K_p(V_{TP} - V_{GSP})^* ((V_{TP} - V_{GSP}) > 0)$$

$$V_{GSN} = 2.5 - V_I \quad V_{SBN} = V_I \quad V_{GSP} = -V_I \quad V_{BSN} = 2.5 - V_I$$

$$V_{TN} = [0.75 + 0.5(\sqrt{V_I + 0.6} - \sqrt{0.6})] \quad V_{TP} = [-0.75 - 0.5(\sqrt{2.5 - V_I + 0.6} - \sqrt{0.6})]$$

The worst cases occur approximately at the point where the PMOS or NMOS transistors just cut off.

$$\text{The NMOS transistor cuts off for } 2.5 - V_I = [0.75 + 0.5(\sqrt{V_I + 0.6} - \sqrt{0.6})] \rightarrow V_I = 1.426V$$

$$V_{TP} = -1.01V \quad \frac{1}{250} = \left(\frac{W}{L}\right)_p (4 \times 10^{-5})(-1.01 + 1.426) \rightarrow \left(\frac{W}{L}\right)_p = \frac{240}{1}$$

$$\text{The PMOS transistor cuts off for } V_I = [0.75 + 0.5(\sqrt{2.5 - V_I + 0.6} - \sqrt{0.6})] \rightarrow V_I = 1.074V$$

$$V_{TN} = -1.01V \quad \frac{1}{250} = \left(\frac{W}{L}\right)_N (10^{-4})(2.5 - 1.074 - 1.01) \rightarrow \left(\frac{W}{L}\right)_p = \frac{96.2}{1}$$

7.104

(a) The output of the first NMOS transistor will be

$$V_I = 2.5 - V_{TN} = 2.5 - [0.75 + 0.5(\sqrt{V_I + 0.6} - \sqrt{0.6})] \rightarrow V_I = 1.399V \mid V_{TN} = 1.10V$$

The output of the other gates reaches this same value. All three nodes = 1.40 V.

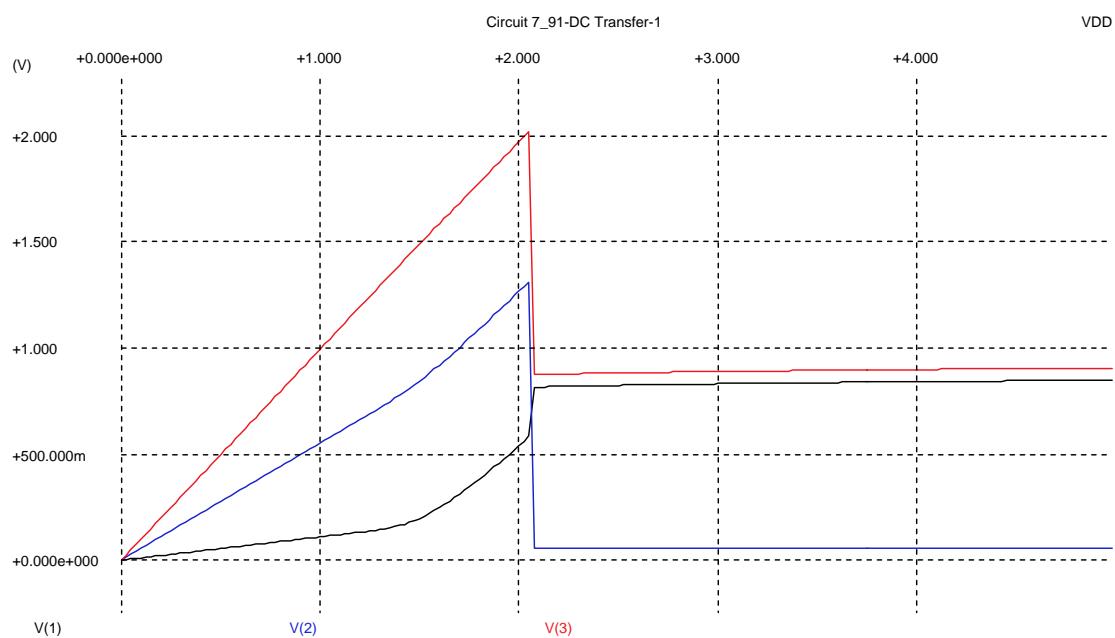
For the PMOS transistors, the node voltages will all be 2.5 V.

(b) The node voltages would all be + 2.5 V.

7.105

*Figure 7.38(b) - CMOS Latchup
VDD 1 0
RC 1 2 25
RL 3 4 2000
RN 2 3 2000
RP 4 0 500
Q1 3 4 0 NBJT
Q2 4 3 2 PBJT
.DC VDD 0 5 .01
.MODEL NBJT NPN BF=60 BR=.25 IS=1E-15
.MODEL PBJT PNP BF=60 BR=.25 IS=1E-15
.PROBE I(VDD) V(1) V(2) V(3) V(4)
.OPTIONS ABSTOL=1E-12 RELTOL=1E-6 VNTOL=1E-6
.END

Simulation results from B2SPICE

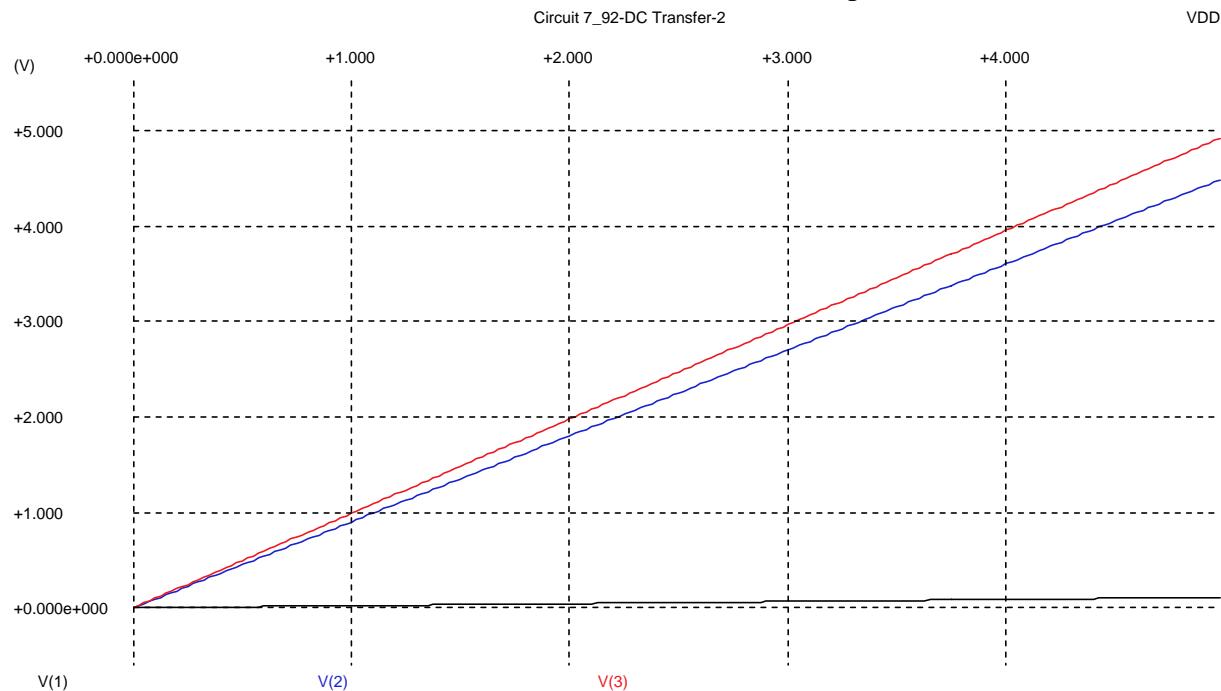


7.106

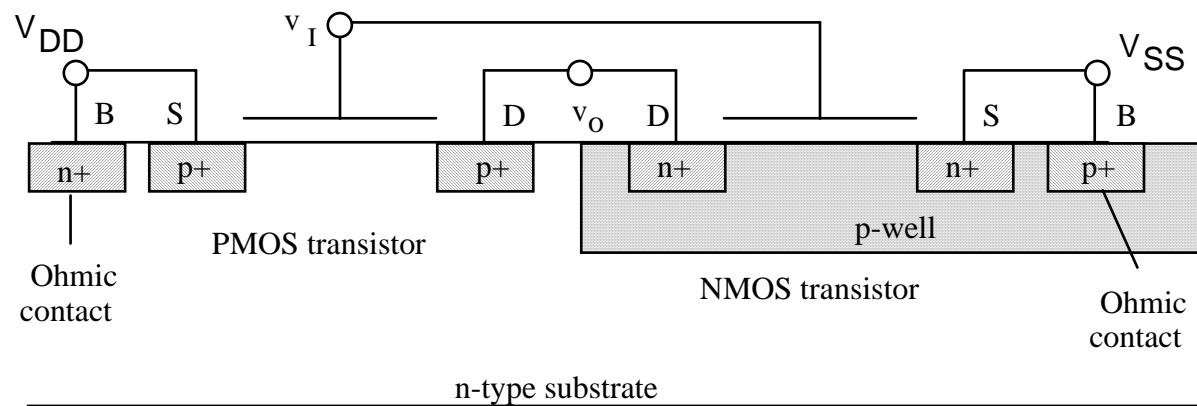
*Figure 7.39(b) - CMOS Latchup
VDD 1 0
RC 1 2 25
RL 3 4 2000
RN 2 3 200
RP 4 0 50
Q1 3 4 0 NBJT
Q2 4 3 2 PBJT
.DC VDD 0 5 .01
.MODEL NBJT NPN BF=60 BR=.25 IS=1E-15
.MODEL PBJT PNP BF=60 BR=.25 IS=1E-15
.PROBE I(VDD) V(1) V(2) V(3) V(4)

```
.OPTIONS ABSTOL=1E-12 RELTOL=1E-6 VNTOL=1E-6
.END
```

Simulation results from B2SPICE – Latchup does not occur!



7.107



7.108

$$(a) V_{IH} = \frac{2K_R(V_{DD} - V_{TN} + V_{TP})}{(K_R - 1)\sqrt{1+3K_R}} - \frac{(V_{DD} - K_R V_{TN} + V_{TP})}{(K_R - 1)}$$

$$V_{IH} = \frac{2K_R(V_{DD} - V_{TN} + V_{TP}) - (V_{DD} - K_R V_{TN} + V_{TP})\sqrt{1+3K_R}}{(K_R - 1)\sqrt{1+3K_R}} = \frac{0}{0}$$

$$\lim_{K_R \rightarrow 1} V_{IH} = \lim_{K_R \rightarrow 1} \frac{2(V_{DD} - V_{TN} + V_{TP}) - (V_{DD} - K_R V_{TN} + V_{TP})\frac{3}{2\sqrt{1+3K_R}} + V_{TN}\sqrt{1+3K_R}}{\sqrt{1+3K_R} + \frac{3}{2}\frac{(K_R - 1)}{\sqrt{1+3K_R}}}$$

$$\lim_{K_R \rightarrow 1} V_{IH} = \frac{2(V_{DD} - V_{TN} + V_{TP}) - (V_{DD} - V_{TN} + V_{TP})\frac{3}{4} + 2V_{TN}}{2} = \frac{5V_{DD} + 3V_{TN} + 5V_{TP}}{8}$$

$$V_{OL} = \frac{2V_{IH} - V_{DD} - V_{TN} - V_{TP}}{2} = \frac{V_{DD} - V_{TN} + V_{TP}}{8}$$

$$(b) V_{IL} = \frac{2\sqrt{K_R}(V_{DD} - V_{TN} + V_{TP}) - (V_{DD} - K_R V_{TN} + V_{TP})}{(K_R - 1)\sqrt{K_R + 3}}$$

$$\lim_{K_R \rightarrow 1} V_{IL} = \frac{2\sqrt{K_R}(V_{DD} - V_{TN} + V_{TP}) - (V_{DD} - K_R V_{TN} + V_{TP})\sqrt{K_R + 3}}{(K_R - 1)\sqrt{K_R + 3}} = \frac{0}{0}$$

$$\lim_{K_R \rightarrow 1} V_{IL} = \lim_{K_R \rightarrow 1} \frac{\frac{2}{2\sqrt{K_R}}(V_{DD} - V_{TN} + V_{TP}) - (V_{DD} - K_R V_{TN} + V_{TP})\frac{1}{2\sqrt{K_R + 3}} + V_{TN}\sqrt{K_R + 3}}{\sqrt{K_R + 3} + \frac{1}{2}\frac{(K_R - 1)}{\sqrt{K_R + 3}}}$$

$$\lim_{K_R \rightarrow 1} V_{IL} = \frac{(V_{DD} - V_{TN} + V_{TP}) - (V_{DD} - V_{TN} + V_{TP})\frac{1}{4} + 2V_{TN}}{2} = \frac{3V_{DD} + 5V_{TN} + 3V_{TP}}{8}$$

$$V_{OH} = \frac{2V_{IH} + V_{DD} - V_{TN} - V_{TP}}{2} = \frac{7V_{DD} + V_{TN} - V_{TP}}{8}$$

$$NM_L = V_{IL} - V_{OL} = \frac{3V_{DD} + 5V_{TN} + 3V_{TP}}{8} - \frac{V_{DD} - V_{TN} + V_{TP}}{8} = \frac{V_{DD} + 3V_{TN} + V_{TP}}{4}$$

$$NM_H = V_{OH} - V_{IH} = \frac{7V_{DD} + V_{TN} - V_{TP}}{8} - \frac{5V_{DD} + 3V_{TN} + 5V_{TP}}{8} = \frac{V_{DD} - V_{TN} - 3V_{TP}}{4}$$

7.109

(a) For $V_{DD} = 5V$, $V_{TN} = 1V$, $V_{TP} = -1V$

$$\tau_p = \frac{0.322C}{K_n} \mid \frac{d\tau_p}{dK_n} = -\frac{0.322C}{K_n^2} = -\frac{\tau_p}{K_n} \mid S_{K_n}^{\tau_p} = \frac{K_n}{\tau_p} \frac{d\tau_p}{dK_n} = -1$$

$$\frac{\Delta\tau_p}{\tau_p} \approx S_{K_n}^{\tau_p} \frac{\Delta K_n}{K_n} = -\frac{\Delta K_n}{K_n} = -(-0.25) = +0.25 \mid \text{A 25% decrease in } K_n \text{ will cause}$$

a 25% increase in propagation delay.

(b) Assuming a symmetrical inverter with $V_{DD} = 5V$ and $V_{TN} = 0.75V$,

$$\tau_p = \frac{C}{K_n(V_{DD} - V_{TN})} \left[\ln \left(4 \frac{V_{DD} - V_{TN}}{V_{DD}} - 1 \right) + \frac{2V_{TN}}{V_{DD} - V_{TN}} \right]$$

$$\tau_p = \frac{C}{K_n(5 - 0.75)} \left[\ln \left(4 \frac{5 - 0.75}{5} - 1 \right) + \frac{2(0.75)}{5 - 0.75} \right] = \frac{0.289C}{K_n}$$

$$\frac{d\tau_p}{dV_{TN}} = \frac{\tau_p}{(V_{DD} - V_{TN})} + \frac{C}{K_n(V_{DD} - V_{TN})} \left[\frac{-4}{\frac{V_{DD}}{V_{DD} - V_{TN}} - 1} + \frac{2V_{DD}}{(V_{DD} - V_{TN})^2} \right]$$

$$\frac{d\tau_p}{dV_{TN}} = \frac{0.289C}{(5 - 0.75)K_n} + \frac{C}{K_n(5 - 0.75)} \left[\frac{\left(\frac{-4}{5}\right)}{\left(4 \frac{5 - 0.75}{5} - 1\right)} + \frac{2(5)}{(5 - 0.75)^2} \right] = \frac{0.120C}{K_n}$$

$$S_{V_{TN}}^{\tau_p} = \frac{V_{TN}}{\tau_p} \frac{d\tau_p}{dV_{TN}} = \frac{0.75K_n}{0.289C} \left(\frac{0.120C}{K_n} \right) = 0.311$$

$$\frac{\Delta\tau_p}{\tau_p} \approx S_{K_n}^{\tau_p} \frac{\Delta V_{TN}}{V_{TN}} = 0.311 \left(\frac{0.1}{0.75} \right) = 0.0415 = 4.15\%.$$

A 13% increase in V_{TN} causes an 4.2% increase in τ_p .

7.110

*PROBLEM 7.110 - INVERTER DELAY VS RISETIME

VDD 1 0 DC 2.5

V1 2 0 PULSE (0 2.5 0 0.1N 0.1N 50N 100N)

MN1 3 2 0 0 MOSN W=1U L=1U AS=4P AD=4P

MP1 3 2 1 1 MOSP W=1U L=1U AS=4P AD=4P

C1 3 0 1PF

*

V2 4 0 PULSE (0 2.5 0 0.2N 0.2N 50N 100N)

MN3 5 4 0 0 MOSN W=1U L=1U AS=4P AD=4P

MP3 5 4 1 1 MOSP W=1U L=1U AS=4P AD=4P

C3 5 0 1PF

*

```

V3 6 0 PULSE (0 2.5 0 0.5N 0.5N 50N 100N)
MN5 7 6 0 0 MOSN W=1U L=1U AS=4P AD=4P
MP5 7 6 1 1 MOSP W=1U L=1U AS=4P AD=4P
C5 7 0 1PF
*
V4 8 0 PULSE (0 2.5 0 1N 1N 50N 100N)
MN7 9 8 0 0 MOSN W=1U L=1U AS=4P AD=4P
MP7 9 8 1 1 MOSP W=1U L=1U AS=4P AD=4P
C7 9 0 1PF
*
V5 10 0 PULSE (0 2.5 0 2N 2N 50N 100N)
MN9 11 10 0 0 MOSN W=1U L=1U AS=4P AD=4P
MP9 11 10 1 1 MOSP W=1U L=1U AS=4P AD=4P
C9 11 0 1PF
*
.OP
.TRAN 0.025N 50N
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99
+LAMBDA=.02 TOX=41.5N
+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5
+LAMBDA=.05 TOX=41.5N
+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
.PROBE V(2) V(3) V(4) V(5) V(6) V(7) V(8) V(9) V(10) V(11)
.END

```

t_r	τ_p
0.1 ns	14.6 ns
0.2 ns	14.7 ns
0.5 ns	14.7 ns
1 ns	14.8 ns
5 ns	15.8 ns

CHAPTER 8

8.1

$$(a) 256\text{Mb} = 2^8(2^{10})(2^{10}) = 268,435,456 \text{ bits}$$

$$(b) 1\text{Gb} = (2^{10})^3 = 1,073,741,824 \text{ bits}$$

$$(c) 256\text{Mb} = 2^8(2^{10})(2^{10}) = 2^{28} \quad | \quad 128\text{kb} = 2^7(2^{10}) = 2^{17} \quad | \quad \frac{2^{28}}{2^{17}} = 2^{11} = 2048 \text{ blocks}$$

8.2

$$I \leq \frac{1mA}{2^{28} \text{ bits}} = 3.73 \frac{pA}{bit}$$

8.3

$$(a) P = CV_{DD}^2 f = 64(10\text{pF})(3.3)^2(1\text{GHz}) = 6.97 \text{ W}$$

$$(b) P = CV_{DD}^2 f = 64(10\text{pF})(2.5)^2(3\text{GHz}) = 12 \text{ W}$$

8.4

$$P = CV_{DD}^2 f = \left(\frac{2^{30}}{2}\right)(100\text{fF})(2.5V)^2\left(\frac{1}{0.012s}\right) = 28.0 \text{ mW}$$

8.5

$$\text{"1"} = V_{DD} = 3 \text{ V} \quad | \quad \text{"0": } \frac{3-V_o}{10^{10}} = \frac{2}{1}(100 \times 10^{-6})\left(3 - 0.75 - \frac{V_o}{2}\right)V_o \rightarrow V_o = 0.667 \mu\text{V} \quad | \quad \text{"0"} = 0.667 \mu\text{V}$$

8.6

*PROBLEM 8.6 - 6-T Cell

VDD 1 0 DC 3

MN1 3 2 0 0 MOSN W=4U L=2U AS=16P AD=16P

MP1 3 2 1 1 MOSP W=10U L=2U AS=40P AD=40P

MN2 2 3 0 0 MOSN W=4U L=2U AS=16P AD=16P

MP2 2 3 1 1 MOSP W=10U L=2U AS=40P AD=40P

MN3 3 0 0 0 MOSN W=4U L=2U AS=16P AD=16P

MN4 2 0 0 0 MOSN W=4U L=2U AS=16P AD=16P

.IC V(3)=1.55V V(2)=1.45V V(1)=3

.OP

.TRAN 0.025N 10N UIC

.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99

+LAMBDA=.02 TOX=41.5N

+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P

.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5

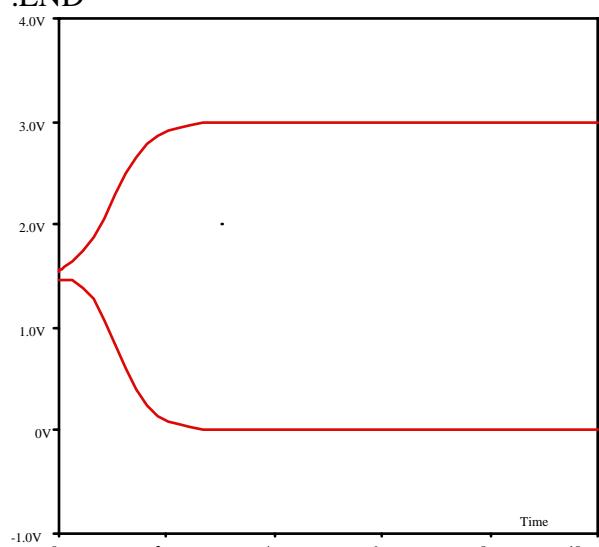
+LAMBDA=.05 TOX=41.5N

+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P

.PRINT TRAN V(2) V(3)

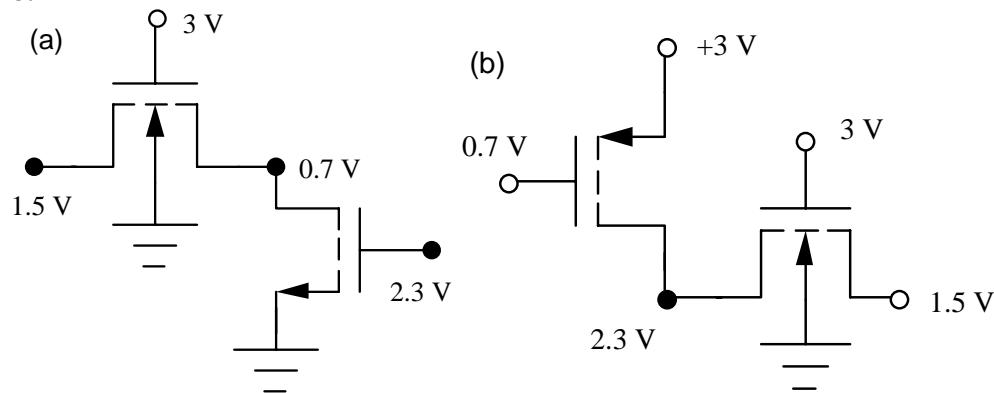
.PROBE V(2) V(3)

.END



Result: $t = 1.5 \text{ ns}$

8.7



First Case : Both transistors are in the linear region

$$I_{DS} = 25 \times 10^{-6} \left(\frac{1}{1} \right) \left(2.3 - 0.7 - \frac{0.7}{2} \right) 0.7 = 21.88 \mu A$$

$$21.88 \mu A = 25 \times 10^{-6} \left(\frac{W}{L} \right) \left(3 - 0.7 - 0.7 - \frac{0.8}{2} \right) 0.8 \rightarrow \left(\frac{W}{L} \right) \leq 0.911 = \frac{1}{1.10}$$

Second Case : Both transistors are in the linear region

$$10 \times 10^{-6} \left(\frac{1}{1} \right) \left(0.7 - 3 - (-0.7) - \frac{(-0.7)}{2} \right) (-0.7) = 25 \times 10^{-6} \left(\frac{W}{L} \right) \left(3 - 1.5 - 0.7 - \frac{0.8}{2} \right) 0.8 \rightarrow \left(\frac{W}{L} \right) \leq \frac{1.09}{1}$$

$$\text{So } \left(\frac{W}{L} \right) \leq \frac{1}{1.10}$$

8.8

*Problem 8.8 - WRITING THE CMOS SRAM
VWL 6 0 DC 0 PULSE(0 3 1NS 1NS 1NS 100NS)

VDD 3 0 DC 3

VBL1 4 0 DC 0

VBL2 5 0 DC 3

CBL1 4 0 500FF

CBL2 5 0 500FF

*Storage Cell

MCN1 2 1 0 0 MOSN W=1U L=1U AS=4P AD=4P

MCP1 2 1 3 3 MOSP W=1U L=1U AS=4P AD=4P

MCN2 1 2 0 0 MOSN W=1U L=1U AS=4P AD=4P

MCP2 1 2 3 3 MOSP W=1U L=1U AS=4P AD=4P

MA1 4 6 2 0 MOSN W=1U L=1U AS=4P AD=4P

MA2 5 6 1 0 MOSN W=1U L=1U AS=4P AD=4P

*

.OP

.TRAN 0.01NS 20NS

.NODESET V(1)=3 V(2)=0

.MODEL MOSN NMOS KP=2.5E-5 VTO=.70 GAMMA=0.5

+LAMBDA=.05 TOX=20N

+CGSO=4E-9 CGDO=4E-9 CJ=2.0E-4 CJSW=5.0E-10

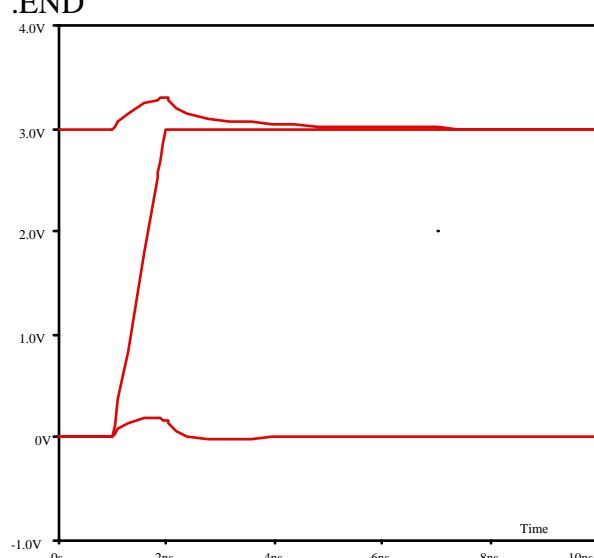
.MODEL MOSP PMOS KP=1.0E-5 VTO=-.70 GAMMA=0.75

+LAMBDA=.05 TOX=20N

+CGSO=4E-9 CGDO=4E-9 CJ=2.0E-4 CJSW=5.0E-10

.PROBE V(1) V(2) V(3) V(4) V(5) V(6)

.END



Small voltage transients occur on both cell storage nodes which die out in 5 - 7 ns.

8.9

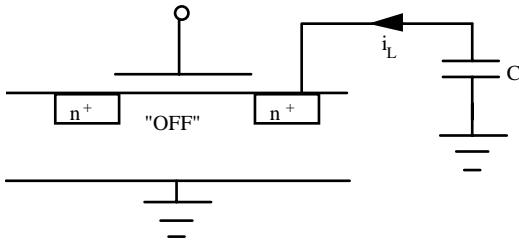
(a) The transistor will fully discharge C_C : $V_{C0} = 0 \text{ V}$

$$V_{C1} = 2.5 - V_{TN} = 2.5 - 0.6 - 0.5(\sqrt{V_{C1} + 0.6} - \sqrt{0.6}) \rightarrow V_{C1} = 1.55 \text{ V} \quad "1" = 1.55 \text{ V}$$

$$\text{For } V_{C1} = 2.5 \text{ V}, V_{TN} = 0.6 + 0.5(\sqrt{2.5 + 0.6} - \sqrt{0.6}) = 1.09 \text{ V} \quad V_{W/L} \geq 2.5 + 1.09 = 3.59 \text{ V}$$

8.10

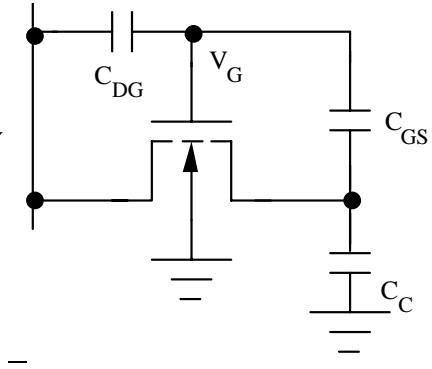
For "0" = 0V, the bias across the source-substrate junction is 0 V, so the leakage current would be 0 and the "0" state is undisturbed. For a "1" corresponding to a positive voltage, a reverse bias across the source-substrate junction, and the diode leakage current will tend to destroy the "1" state.



8.11

$$V_C = 2.5 - V_{TN} = 2.5 - 0.7 - 0.5(\sqrt{V_C + 0.6} - \sqrt{0.6}) \rightarrow V_C = 1.47 \text{ V}$$

$$\Delta V_C = \frac{\frac{1}{sC_c}}{\frac{1}{sC_c} + \frac{1}{sC_{GS}}} \Delta V_{W/L} = \frac{\Delta V_{W/L}}{1 + \frac{C_c}{C_{GS}}} = \frac{-2.5}{1 + \frac{75fF}{100fF}} = -1.43 \text{ V}$$



8.12

$$Q_I = 60fF(0V) + 7.5pF(2.5V) \quad | \quad Q_F = 7.56pF(V_F) \quad | \quad Q_F = Q_I \rightarrow V_F = \frac{7.5pF}{7.56pF} 2.5V$$

$$V_F = 2.48 \text{ V} \quad | \quad \Delta V = \frac{7.5pF}{7.56pF} 2.5V - 2.5V = -2.5 \frac{0.06}{1.56} = -19.8 \text{ mV}$$

8.13

$$(a) "1" = +3.3 \text{ V} \quad | \quad V_C = -V_{TP} = 0.7 + 0.5(\sqrt{3.3 - V_C + 0.6} - \sqrt{0.6}) \rightarrow V_C = 1.14 \text{ V} \quad "0" = 1.14 \text{ V}$$

$$(b) "1" = +2.5 \text{ V} \quad | \quad V_C = -V_{TP} = 0.7 + 0.5(\sqrt{2.5 - V_C + 0.6} - \sqrt{0.6}) \rightarrow V_C = 1.03 \text{ V} \quad "0" = 1.03 \text{ V}$$

8.14

Note that the simulation results in Fig. 9.28 assume that the word line is also driven higher than 3 V. For this case:

$$(a) V_C = 5 - V_{TN} = 5 - 0.7 - 0.5(\sqrt{V_C + 0.6} - \sqrt{0.6}) \rightarrow V_C = 3.66 V$$

$$(b) V_{TN} = 0.7 - 0.5(\sqrt{1.3 + 0.6} - \sqrt{0.6}) = 1.00 V$$

$$V_{GS} - V_{TN} = 5 - 1.3 - 1.00 = 2.7 V \quad | \quad V_{DS} = 3.7 - 1.3 = 2.4 V \rightarrow \text{linear region}$$

$$i_{DS} = 60 \times 10^{-6} \left(\frac{1}{1} \right) \left(5 - 1.3 - 1.00 - \frac{2.4}{2} \right) 2.4 = 216 \mu A \text{ which agrees with the text.}$$

8.15

$$(a) "0" = +0 V \quad | \quad V_C = 3 - V_{TN} = 3 - 0.7 - 0.5(\sqrt{V_C + 0.6} - \sqrt{0.6}) \rightarrow V_C = 1.90 V \quad | \quad "1" = 1.90 V$$

(b) A "0" will have 0 V across the drain - substrate junction, so no leakage occurs.

A "1" will have a reverse bias of 1.9 V across the junction, so the junction leakage will tend to destroy the "1" level. (Note that this discussion ignores subthreshold leakage through the FET which has not been discussed in the text.)

8.16

$$(a) "1" = +5 V \quad | \quad V_C = -V_{TP} = 0.8 + 0.65(\sqrt{5 - V_C + 0.6} - \sqrt{0.6}) \rightarrow V_C = 1.60 V \quad | \quad "0" = +1.60 V$$

$$(b) V_{TP} = -0.8 - 0.65(\sqrt{5 + 0.6} - \sqrt{0.6}) = -1.83 V \quad | \quad V_{WL} \leq -1.83 V$$

8.17

$$\text{Original: } i_D = 60 \times 10^{-6} \left(\frac{1}{1} \right) \left(3 - 1.3 - 1 - \frac{0.6}{2} \right) 0.6 = 14.4 \mu A$$

$$\text{New: } i_D = 60 \times 10^{-6} \left(\frac{1}{1} \right) \left(5 - 1.3 - 1 - \frac{2.4}{2} \right) 2.4 = 216 \mu A.$$

$$\text{Gate drive terms: } \frac{5 - 1.3 - 1 - 1.2}{3 - 1.3 - 1 - 0.3} = \frac{1.5}{0.4} = 3.75 \quad | \quad V_{DS} \text{ ratio: } \frac{2.4}{0.6} = 4$$

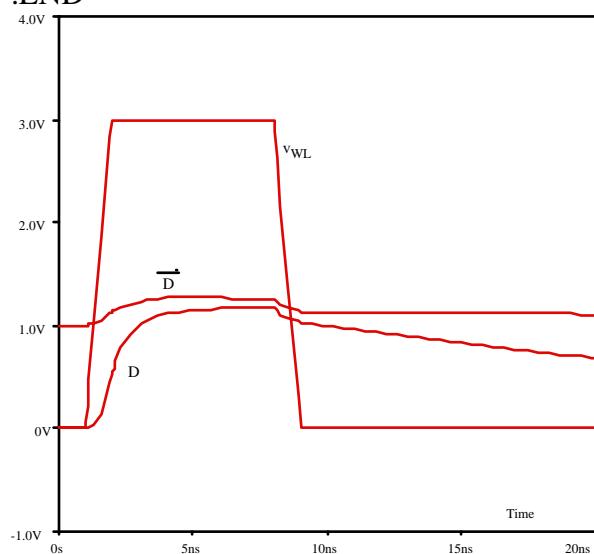
Improved gate drive yields a 3.75 times improvement, although it is reduced by the larger V_{DS} term. Improved drain - source voltage yields a 4 times improvement. $4 \times 3.75 = 15$.

8.18

$$P = CV_{DD}^2 f = (0.5)(2^{30})(100 \text{fF})(2.5V)^2 \left(\frac{1}{0.01s} \right) = 33.6 \text{ mW}$$

8.19

*Problem 8.19 - 4-T Refresh SRAM
VWL 3 0 DC 0 PULSE(0 3 1NS 1NS 1NS 6NS)
VBL 4 0 DC 3
VBLB 5 0 DC 3
CC1 1 0 50FF
CC2 2 0 50FF
*Storage Cell
MCN1 2 1 0 0 MOSN W=4U L=2U AS=16P AD=16P
MCN2 1 2 0 0 MOSN W=4U L=2U AS=16P AD=16P
MA1 4 3 2 0 MOSN W=4U L=2U AS=16P AD=16P
MA2 5 3 1 0 MOSN W=4U L=2U AS=16P AD=16P
.IC V(1)=0 V(2)=1 V(3)=0 V(4)=3 V(5)=3
.OP
.TRAN 0.01NS 20NS UIC
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99
+LAMBDA=.02 TOX=41.5N
+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
.PROBE V(1) V(2) V(3) V(4) V(5)
.END



Note the very slow recovery due to relatively high threshold and gamma values relative to the power supply voltage.

8.20

*Problem 8.20 4-T READ ACCESS
VPC 7 0 DC 3 PULSE(3 0 1NS .5NS .5NS 100NS)
VWL 6 0 DC 0 PULSE(0 3 2NS .5NS .5NS 100NS)
VDD 3 0 DC 3
CBL1 4 0 1PF
CBL2 5 0 1PF
*Storage Cell
MCN1 2 1 0 0 MOSN W=4U L=2U AS=16P AD=16P
MCN2 1 2 0 0 MOSN W=4U L=2U AS=16P AD=16P

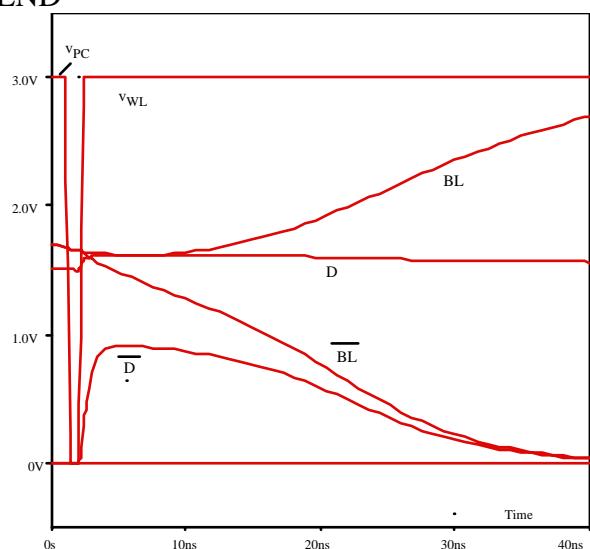
MA1 4 6 2 0 MOSN W=4U L=2U AS=16P AD=16P
 MA2 5 6 1 0 MOSN W=4U L=2U AS=16P AD=16P
 CC1 1 0 50FF
 CC2 2 0 50FF
 *

*Sense Amplifier

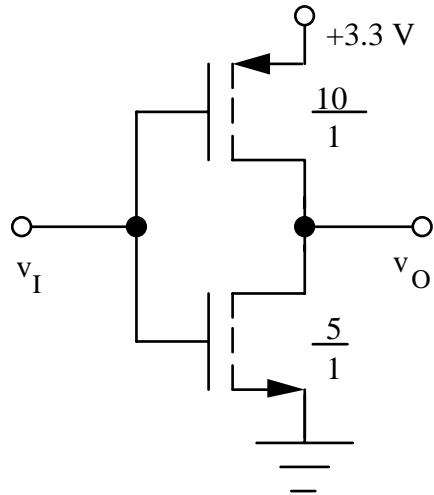
MSN1 4 5 0 0 MOSN W=4U L=2U AS=16P AD=16P
 MSP1 4 5 3 3 MOSP W=4U L=2U AS=16P AD=16P
 MSN2 5 4 0 0 MOSN W=4U L=2U AS=16P AD=16P
 MSP2 5 4 3 3 MOSP W=4U L=2U AS=16P AD=16P
 MRS 5 7 4 0 MOSN W=4U L=2U AS=16P AD=16P
 *

.OP

.TRAN 0.01NS 40NS UIC
 .IC V(1)=1.5 V(2)=0 V(3)=3 V(4)=1.7 V(5)=1.7 V(6)=0 V(7)=3
 .MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99
 +LAMBDA=.02 TOX=41.5N
 +CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
 .MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5
 +LAMBDA=.05 TOX=41.5N
 +CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
 .PROBE V(1) V(2) V(3) V(4) V(5) V(6) V(7)
 .END



8.21



Each inverter will have $v_I = v_O$.

Equating inverter drain currents:

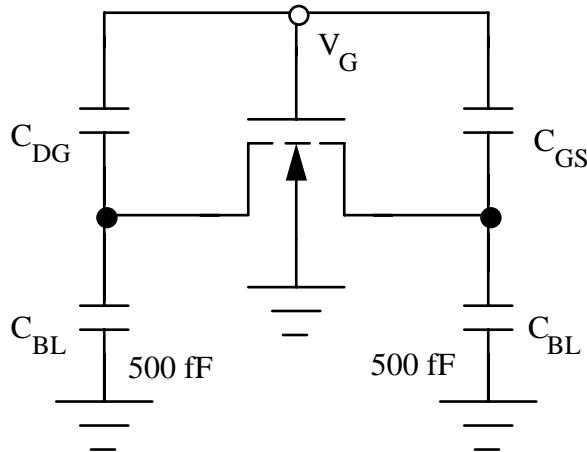
$$\left(\frac{100 \times 10^{-6}}{2}\right)\left(\frac{5}{1}\right)(v_I - 0.7)^2 = \left(\frac{40 \times 10^{-6}}{2}\right)\left(\frac{10}{1}\right)(3.3 - v_I - 0.7)^2$$

$$\rightarrow v_O = v_I = 1.597 \text{ V}$$

Sense amp current = $2i_{DS} = 402 \mu\text{A}$

$$P = 1024(3.3\text{V})(402 \mu\text{A}) = 1.36 \text{ W}$$

8.22



The precharge transistor is operating in the linear region with $V_{DS} = 0$

$$C_{GS} = \frac{1}{2} C_{ox}^'' WL + C_{GSO}W$$

$$C_{GS} = \frac{1}{2} \frac{3.9(8.854 \times 10^{-14} \text{ F/cm})}{2 \times 10^{-6} \text{ cm}} (10^{-3} \text{ cm})(10^{-4} \text{ cm}) + (4 \times 10^{-11} \text{ F/cm})(10^{-3} \text{ cm}) = 48.6 \text{ fF}$$

$$\Delta V(s) = \frac{\frac{1}{sC_{BL}} - \Delta V_G(s)}{\frac{1}{sC_{GS}} + \frac{1}{sC_{BL}}} \rightarrow \Delta V = \frac{\Delta V_G}{\frac{C_{BL}}{C_{GS}} + 1} = \frac{-3}{\frac{500}{48.6} + 1} = 0.266 \text{ V}$$

This value provides a good estimate of the drop observed in Fig. 8.25.

8.23

The precharge transistor is operating in the linear region with $V_{DS} = 0$

$$C_{GS} = \frac{1}{2} C_{ox} WL + C_{GSO} W$$

$$C_{GS} = \frac{1}{2} \frac{3.9(8.854 \times 10^{-14} F/cm)}{2 \times 10^{-6} cm} (10^{-3} cm)(10^{-4} cm) + (4 \times 10^{-11} F/cm)(10^{-3} cm) = 48.6 fF$$

Using $C_{BL} = 500 fF$ as in the previous problem,

$$\Delta V(s) = \frac{\frac{1}{sC_{BL}} - \frac{1}{sC_{GS}}}{\frac{1}{sC_{GS}} + \frac{1}{sC_{BL}}} \Delta V_G(s) \rightarrow \Delta V = \frac{\Delta V_G}{\frac{C_{BL}}{C_{GS}} + 1} = \frac{3}{\frac{500}{48.6} + 1} = 0.266 V$$

This value provides a good estimate of the observed change in Fig. 8.29.

The source - substrate diode will clamp the voltage to $\Delta V \leq 0.7 V$.

8.24

The bitline will charge to an initial voltage of $V_{BL} = 3 - V_{TN}$

$$V_{TN} = 0.7 + 0.5(\sqrt{3 - V_{TN}} + 0.6) - \sqrt{0.6} \rightarrow V_{TN} = 1.10V \mid V_{BL} = 1.90V$$

The initial charge Q_I on C_{BL} : $Q_I = 10^{-12} F(1.9V) = 1.9 pC$

After charge sharing: $V_{BL} = \frac{1.9 pC}{1.05 pF} = 1.81V$. The voltage will be restored to 1.90V

by the transistor. The total charge delivered through the transistor is

$$\Delta Q = 0.09V(1.05 pF) = 0.0945 pC \mid \Delta v_O = \frac{9.45 \times 10^{-14} C}{10^{-13} F} = 0.945 V$$

This sense amplifier provides a voltage gain of $A_V = \frac{0.945}{0.09} = 10.5$

8.25

*PROBLEM 8.24 Charge Transfer Sense Amplifier

VSW 5 0 DC 0 PULSE(0 3 2NS .5NS .5NS 100NS)

VGG 3 0 DC 3

CL 2 0 100FF

CBL 4 0 1PF

CC 6 0 50FF

M1 2 3 4 0 MOSN W=100U L=2U

M2 4 5 6 0 MOSN W=8U L=2U

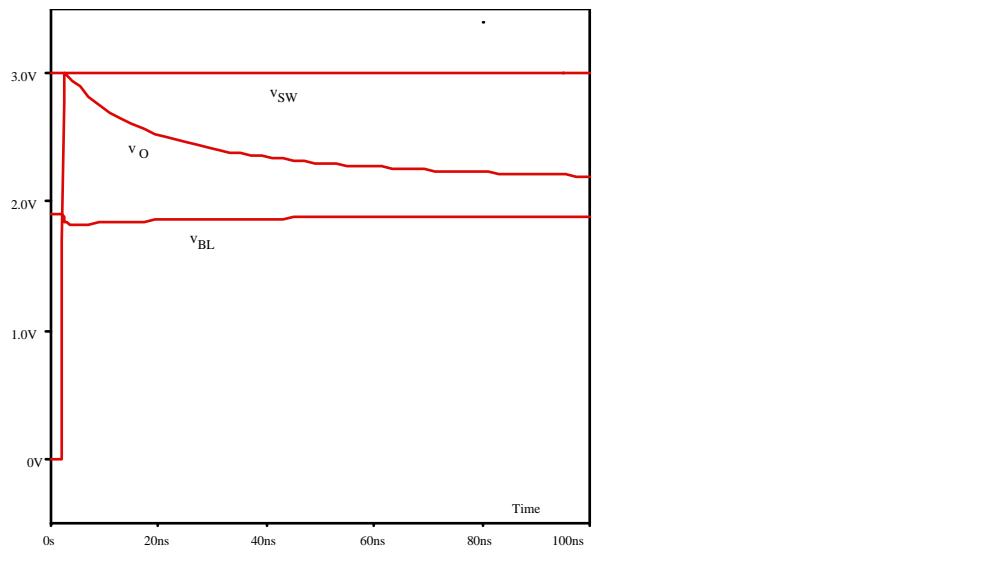
.IC V(2)=3 V(4)=1.9

.TRAN 0.02NS 100NS UIC

.MODEL MOSN NMOS KP=25U VTO=0.7 GAMMA=0.5 PHI=0.6

.PROBE V(2) V(3) V(4) V(5) V(6)

.END



8.26

*PROBLEM 8.26 - Cross-Coupled Latch

VDD 1 0 DC 3.3

MN1 3 2 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP1 3 2 1 1 MOSP W=2U L=1U AS=16P AD=16P

MN2 2 3 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP2 2 3 1 1 MOSP W=2U L=1U AS=16P AD=16P

CBL1 3 0 1PF

CBL2 2 0 1PF

.IC V(3)=1V V(2)=1.25V V(1)=5

.OP

.TRAN 0.05N 50N UIC

.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99

+LAMBDA=.02 TOX=41.5N

+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P

.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5

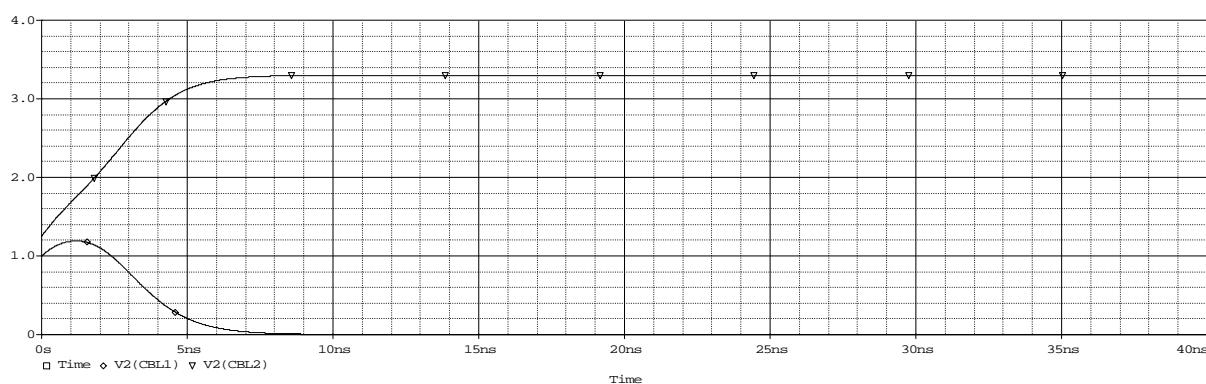
+LAMBDA=.05 TOX=41.5N

+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P

.PRINT TRAN V(2) V(3)

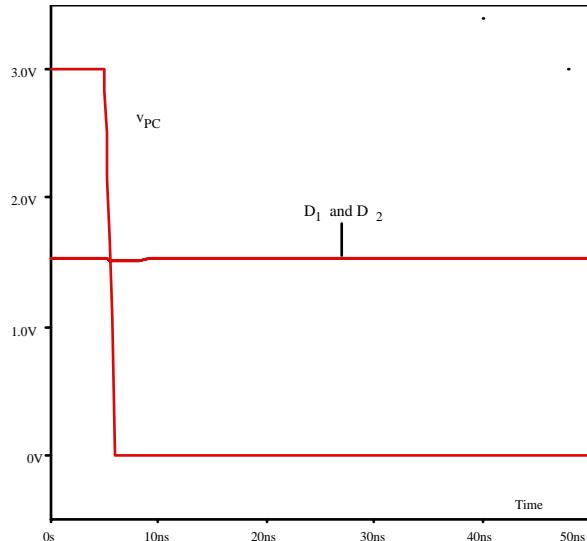
.PROBE V(2) V(3)

.END



8.27

*PROBLEM 8.27 - Cross-Coupled Latch
VDD 1 0 DC 3
VSW 4 0 DC 0 PULSE(3 0 5NS 1NS 1NS 100NS)
MPC 3 4 2 0 MOSN W=20U L=2U AS=80P AD=80P
MN1 3 2 0 0 MOSN W=4U L=2U AS=16P AD=16P
MP1 3 2 1 1 MOSP W=8U L=2U AS=32P AD=32P
MN2 2 3 0 0 MOSN W=4U L=2U AS=16P AD=16P
*MN2 2 3 0 0 MOSN W=4.4U L=2U AS=17.6P AD=17.6P
MP2 2 3 1 1 MOSP W=8U L=2U AS=32P AD=32P
CBL1 3 0 400FF
CBL2 2 0 400FF
.OP
.TRAN 0.05N 50N
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99
+LAMBDA=.02 TOX=41.5N
+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5
+LAMBDA=.05 TOX=41.5N
+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
.PROBE V(2) V(3) V(4)
.END



The latch is perfectly balanced in Part (a) and the voltage levels remain symmetrical even after the PC transistor turns off. This would not happen in the real case because of small asymmetries and noise in the latch. Even a small capacitive imbalance will cause the latch to assume a preferred state. Try setting $C_{BL2} = 425$ fF in Part (a) for example. The asymmetry in the latch in Part (b) causes it to switch to a preferred state.

8.28

*PROBLEM 8.28 - Clocked NMOS Sense Amplifier

VPC 2 0 DC 0 PULSE(3 0 1NS .5NS .5NS 250NS)

VWL 6 0 DC 0 PULSE(0 3 2NS .5NS .5NS 250NS)

VLC 9 0 DC 0 PULSE(0 3 3NS .5NS .5NS 250NS)

VDD 3 0 DC 3

CBL1 5 0 2PF

CBL2 4 0 2PF

*Storage Cell

MA1 5 6 1 0 MOSN W=2U L=2U AS=8P AD=8P

CC 1 0 100FF

*Dummy Cell

MA2 4 6 7 0 MOSN W=2U L=2U AS=8P AD=8P

CD 7 0 50FF

*Sense Amplifier

MPC 5 2 4 0 MOSN W=10U L=2U AS=40P AD=40P

ML1 3 2 4 0 MOSN W=10U L=2U AS=40P AD=40P

ML2 3 2 5 0 MOSN W=10U L=2U AS=40P AD=40P

MS1 5 4 8 0 MOSN W=50U L=2U AS=200P AD=200P

MS2 4 5 8 0 MOSN W=50U L=2U AS=200P AD=200P

MLC 8 9 0 0 MOSN W=50U L=2U AS=200P AD=200P

*

.OP

.TRAN 0.01NS 250NS

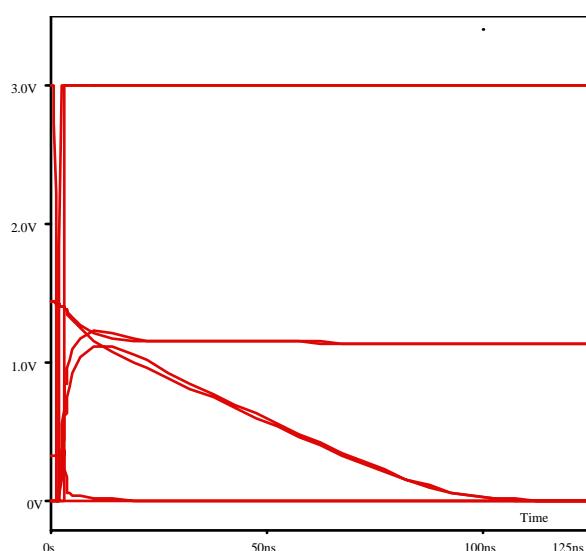
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99

+LAMBDA=.02 TOX=41.5N

+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P

.PROBE V(1) V(2) V(3) V(4) V(5) V(6) V(7) V(8) V(9)

.END



With only a 3 V power supply, the maximum bit-line differential is only 1.14 V which is achieved in 120 ns. (This is relatively slow due to the discharge of large bitline capacitances and the relatively large threshold voltage of the NMOS transistors.)

8.29

*PROBLEM 8.29 - Clocked NMOS Sense Amplifier

VPC 2 0 DC 0 PULSE(5 0 1NS .5NS .5NS 250NS)

VWL 6 0 DC 0 PULSE(0 5 2NS .5NS .5NS 250NS)

VLC 9 0 DC 0 PULSE(0 5 3NS .5NS .5NS 250NS)

VDD 3 0 DC 5

CBL1 5 0 2PF

CBL2 4 0 2PF

*Storage Cell

MA1 5 6 1 0 MOSN W=2U L=2U AS=8P AD=8P

CC 1 0 100FF

*Dummy Cell

MA2 4 6 7 0 MOSN W=2U L=2U AS=8P AD=8P

CD 7 0 50FF

*Sense Amplifier

MPC 5 2 4 0 MOSN W=10U L=2U AS=40P AD=40P

ML1 3 2 4 0 MOSN W=10U L=2U AS=40P AD=40P

ML2 3 2 5 0 MOSN W=10U L=2U AS=40P AD=40P

MS1 5 4 8 0 MOSN W=50U L=2U AS=200P AD=200P

MS2 4 5 8 0 MOSN W=50U L=2U AS=200P AD=200P

MLC 8 9 0 0 MOSN W=50U L=2U AS=200P AD=200P

*

.OP

.TRAN 0.01NS 250NS

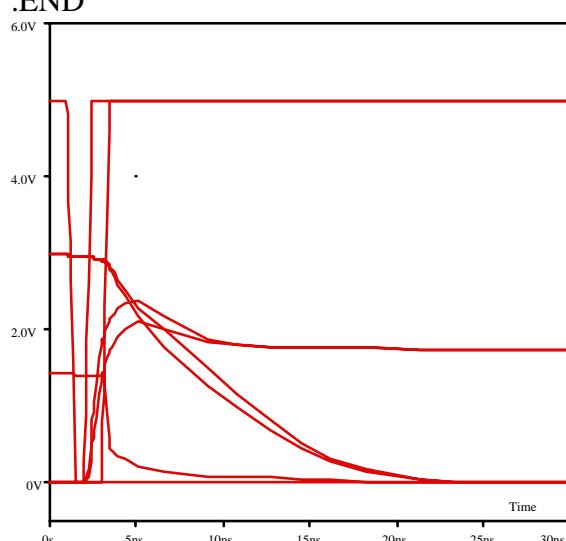
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99

+LAMBDA=.02 TOX=41.5N

+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P

.PROBE V(1) V(2) V(3) V(4) V(5) V(6) V(7) V(8) V(9)

.END



With the 5 V power supply, the maximum bit-line differential is 1.75 V. A 1.5 V differential is achieved in approximately 15 ns, which is much faster than the 3 V case.

8.30

*PROBLEM 8.30 - Cascaded Inverter Pair

VDD 1 0 DC 3

VI 2 0 DC 0

MN1 3 2 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP1 3 2 1 1 MOSP W=2U L=1U AS=16P AD=16P

MN2 4 3 0 0 MOSN W=2U L=1U AS=16P AD=16P

MP2 4 3 1 1 MOSP W=2U L=1U AS=16P AD=16P

.OP

.DC VI 0 3 0.001

.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99

+LAMBDA=.02 TOX=41.5N

+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P

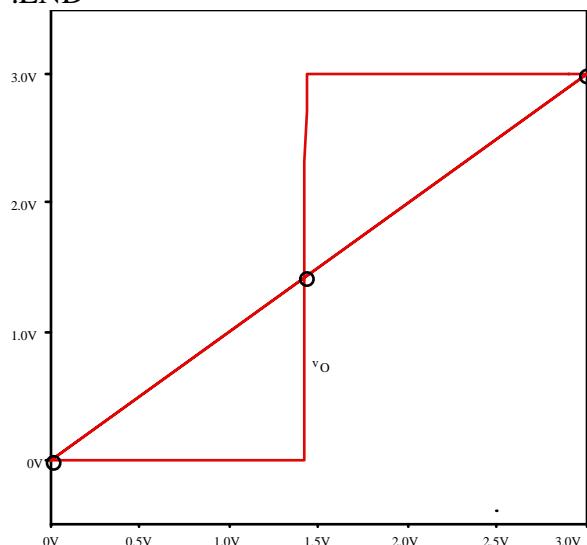
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5

+LAMBDA=.05 TOX=41.5N

+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P

.PROBE V(2) V(3) V(4)

.END



Results: 0 V, 1.429 V, 3 V

8.31

(a) The array requires: $(12 \text{ transistors}/\text{row})(2^{12} \text{ rows}) + (1 \text{ load transistor}/\text{row})(2^{12} \text{ rows}) = 13(2^{12}) = 53,248$ transistors. The 24 inverters require an additional 48 transistors.

N = 53,296 transistors | (b) The number is the same.

8.32

(a) NMOS Pass Transistor Tree : $2 \times (2^0 + 2^1 + 2^2 + 2^3 + 2^4 + 2^5 + 2^6) = 254$ Transistors

2 logic inverters per level = 14 inverters = 28 transistors.

Total = 282 Transistors

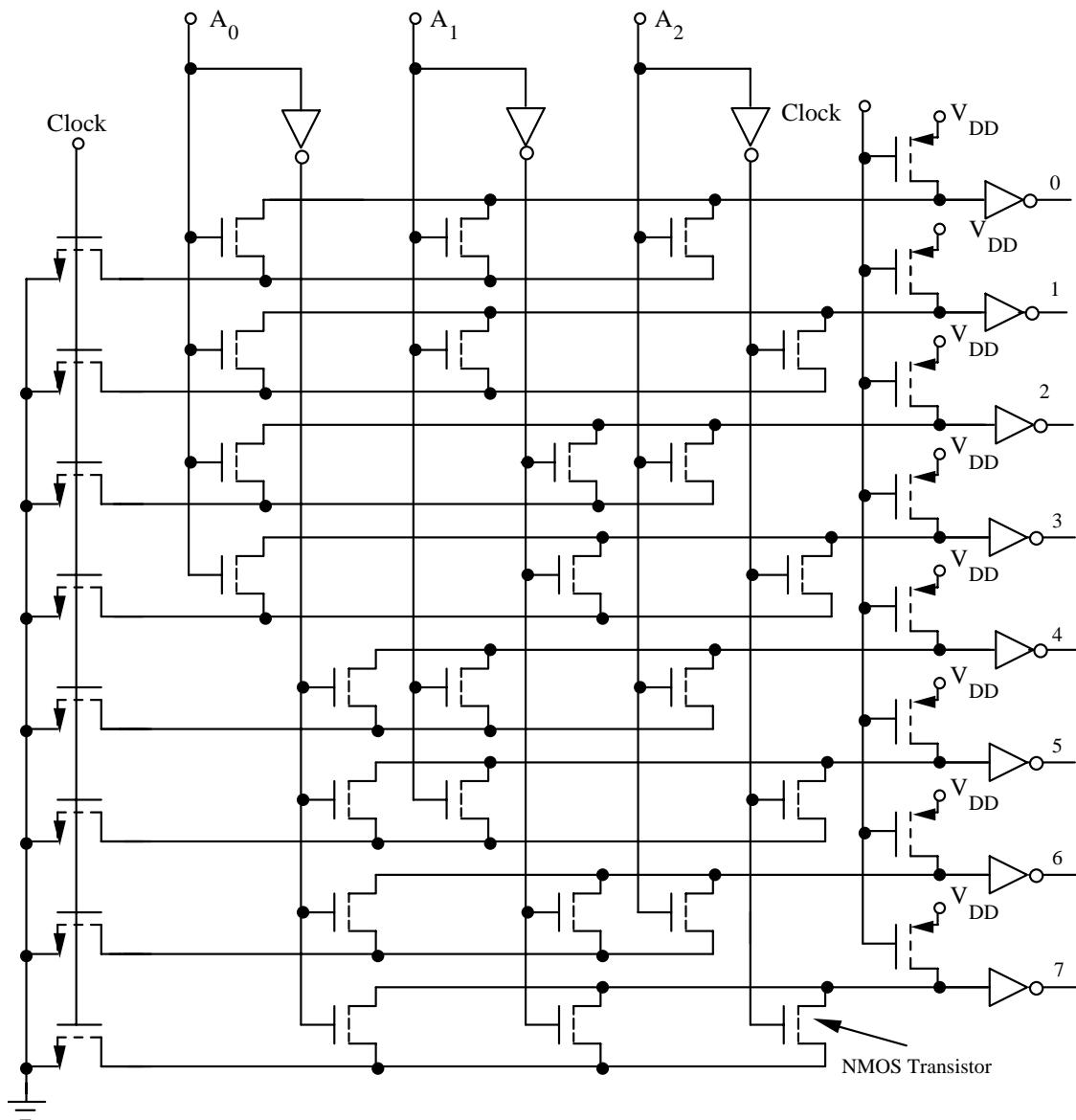
(b) An estimate : 128 data bits requires 128 7 - input gates for data selectors;

1 - 128 input NOR gate; 14 address bit inverters

Total = $128(8) + 1(129) + 14(2) = 1181$ transistors without looking closely at the logic detail.

A number of additional inverters may be needed, and the 128 input gate can likely be replaced with a smaller NOR tree.

8.33



8.34

(a) The output of the first NMOS transistor will be

$$V_1 = 5 - V_{TN} = 5 - \left[0.75 + 0.55 \left(\sqrt{V_1 + 0.6} - \sqrt{0.6} \right) \right] \rightarrow V_1 = 3.55V \mid V_{TN} = 1.45V$$

The output of the other gates reaches this same value. All three nodes = 3.55V.

(b) The node voltages will all be + 5 V.

8.35

Charge sharing occurs. Assuming C_2 and C_3 are discharged (the worst case)

$$(a) V_B = \frac{C_1 V_{DD} + C_2(0)}{C_1 + C_2} = \frac{2C_2 V_{DD}}{2C_2 + C_2} = \frac{2}{3} V_{DD} \mid \text{Node B drops to } \frac{2}{3} V_{DD}.$$

$$(b) V_B = \frac{(C_1 + C_2) \frac{2}{3} V_{DD} + C_3(0)}{C_1 + C_2 + C_3} = \frac{3C_2 \left(\frac{2}{3} V_{DD} \right)}{2C_2 + C_2 + C_2} = \frac{V_{DD}}{2} \mid \text{Node B drops to } \frac{1}{2} V_{DD}.$$

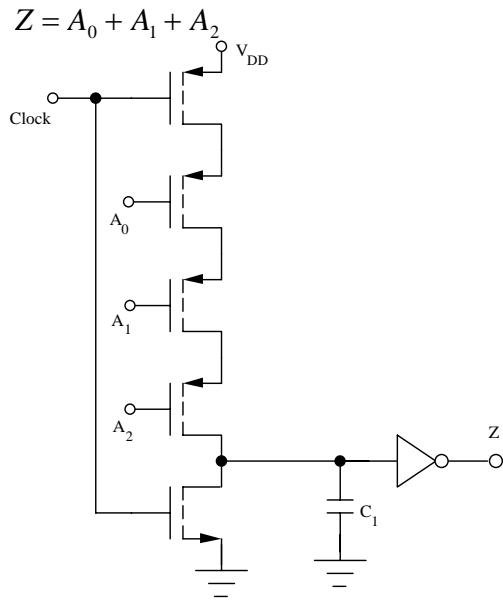
$$(c) V_B = \frac{C_1 V_{DD}}{C_1 + C_2 + C_3} = \frac{R C_2 V_{DD}}{R C_2 + C_2 + C_2} = \frac{R}{R+2} V_{DD} \geq V_{IH} \text{ where } R = \frac{C_1}{C_2}$$

$$R(V_{DD} - V_{IH}) \geq 2V_{IH} \quad \text{or} \quad R \geq \frac{2V_{IH}}{V_{DD} - V_{IH}}$$

Using $V_{DD} = 5V$, $V_{TN} = 0.7V$, $V_{TP} = -0.7V$ in Eq. (7.9):

$$V_{IH} = \frac{5(5) + 3(0.7) + 5(-0.7)}{8} = 2.95V \mid R \geq \frac{2V_{IH}}{V_{DD} - V_{IH}} = \frac{2(2.95)}{2.05} = 2.88 \mid C_1 \geq 2.88C_2$$

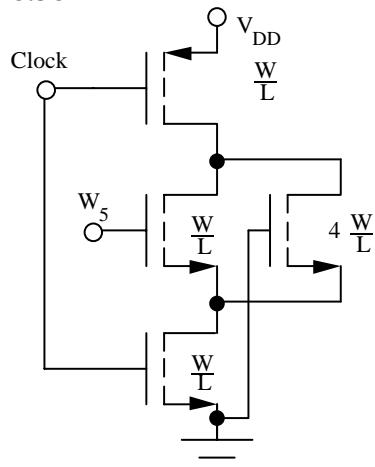
8.36



8.37

	B_7	B_6	B_5	B_4	B_3	B_2	B_1	B_0
W_0	1	0	1	1	0	0	0	0
W_1	0	1	0	0	0	1	1	0
W_2	1	1	0	0	0	1	0	0
W_3	0	0	1	0	1	0	1	1
W_4	0	0	0	0	1	1	1	0
W_5	0	1	0	0	0	0	0	0

8.38



*PROBLEM 8.38 - Simplified ROM Cross-Section

VCLK 1 0 DC 0 PULSE(0 5 2.5NS 1NS 1NS 25NS)

VW5 3 0 DC 0 PULSE(0 5 4.5NS 1NS 1NS 25NS)

VDD 5 0 DC 5

MPC 4 1 5 5 MOSP W=4U L=2U AS=16P AD=16P

MNC 2 1 0 0 MOSN W=4U L=2U AS=16P AD=16P

MW5 4 3 2 0 MOSN W=4U L=2U AS=16P AD=16P

MWW 4 0 2 0 MOSN W=16U L=2U AS=64P AD=64P

.OP

.TRAN 0.01NS 15NS

.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99

+LAMBDA=.02 TOX=41.5N

+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P

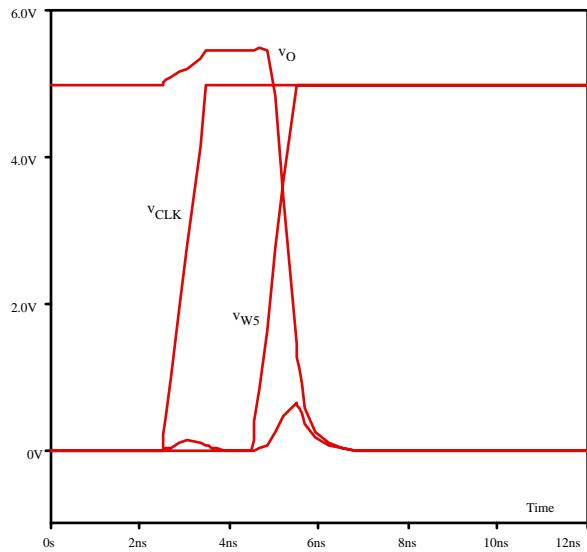
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5

+LAMBDA=.05 TOX=41.5N

+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P

.PROBE V(1) V(2) V(3) V(4) V(5)

.END



8.39

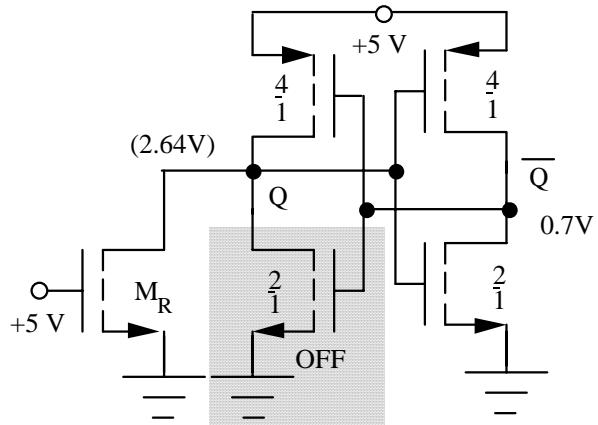
	B_5	B_4	B_3	B_2	B_1	B_0
W_1	0	0	1	0	1	0
W_2	1	0	0	1	0	1
W_3	0	1	1	1	0	1

8.40

	B_2	B_1	B_0
$\overline{W_0}$	1	0	1
$\overline{W_1}$	1	1	0
$\overline{W_2}$	1	0	1
$\overline{W_3}$	0	1	0

Note that the input lines are active low.

8.41



Regenerative switching of the cell will take place when the voltage at Q is pulled low enough by transistor M_R that the voltage at \bar{Q} rises above the NMOS transistor threshold voltage.

Equating drain currents for this condition yields the value of V_Q . It appears that

the NMOS transistor will be in the linear region, and the PMOS transistor will be saturated.

For $V_{DD} = 5V$, $\frac{4 \times 10^{-5}}{2} \left(\frac{4}{1} \right) \left(5 - V_Q - 0.7 \right)^2 = 10^{-4} \left(\frac{2}{1} \right) \left(V_Q - 0.7 - \frac{0.7}{2} \right) 0.7 \rightarrow V_Q = 2.64V$ which agrees with

the assumptions. Now, M_R must be large enough to force $V_Q = 2.64V$. M_R and the PMOS load transistor are both in the linear region.

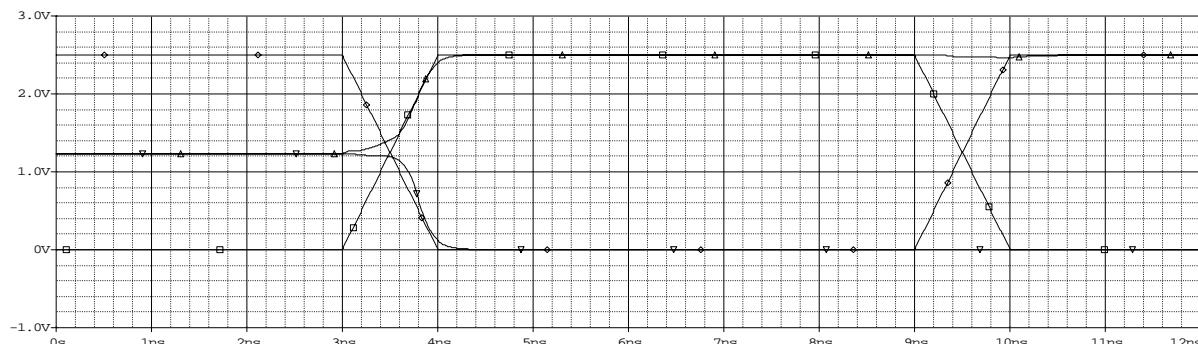
$$4x10^{-5} \left(\frac{4}{1} \right) \left(5 - 0.7 - 0.7 - \frac{2.36}{2} \right) 2.36 \leq 10^{-4} \left(\frac{W}{L} \right)_R \left(5 - 0.7 - \frac{2.64}{2} \right) 2.64 \rightarrow \left(\frac{W}{L} \right)_R \geq \frac{1.16}{1}$$

8.42

The inputs are active in the low voltage state. V_1 low sets the latch and V_2 low resets the latch. $V_1 = \bar{S}$ $V_2 = \bar{R}$.

8.43

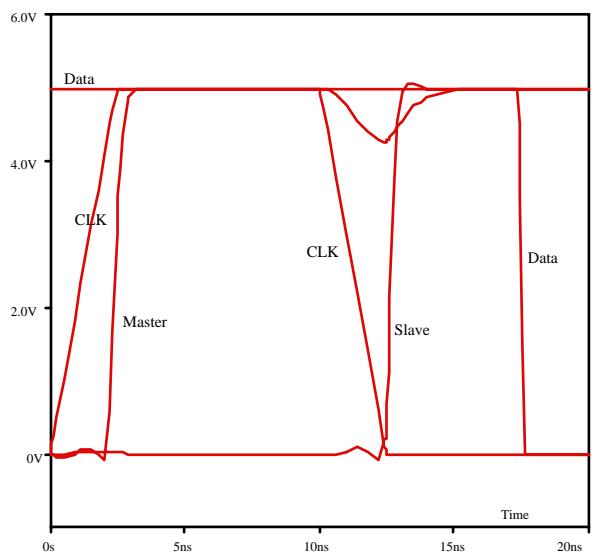
*PROBLEM 8.43 - D-Latch
VDD 7 0 DC 2.5
VI 1 0 DC 2.5
VCLK 2 0 DC 0 PULSE(0 2.5 3NS 1NS 1NS 5NS)
VNCLK 3 0 DC 0 PULSE(2.5 0 3NS 1NS 1NS 5NS)
MTN1 1 2 4 0 MOSN W=2U L=1U AS=16P AD=16P
MTP1 1 3 4 7 MOSP W=2U L=1U AS=16P AD=16P
MIN1 5 4 0 0 MOSN W=2U L=1U AS=16P AD=16P
MIP1 5 4 7 7 MOSP W=2U L=1U AS=16P AD=16P
MIN2 6 5 0 0 MOSN W=2U L=1U AS=16P AD=16P
MIP2 6 5 7 7 MOSP W=2U L=1U AS=16P AD=16P
MTN2 6 3 4 0 MOSN W=2U L=1U AS=16P AD=16P
MTP2 6 2 4 7 MOSP W=2U L=1U AS=16P AD=16P
.OP
.TRAN 0.01N 12N
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99
+LAMBDA=.02 TOX=41.5N
+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5
+LAMBDA=.05 TOX=41.5N
+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
.PROBE V(1) V(2) V(3) V(4) V(5) V(6)
.END



8.44

```
*PROBLEM 8.44 - Master-Slave Flip-Flop
VDD 10 0 DC 5
VI 1 0 DC 5 PWL(0 5 17.4NS 5 17.6NS 0 30NS 0)
VCLK 2 0 DC 0 PULSE(0 5 0NS 2.5NS 2.5NS 7.5NS)
VNCLK 3 0 DC 0 PULSE(5 0 0NS 2.5NS 2.5NS 7.5NS)
MTN1 1 2 4 0 MOSN W=4U L=2U AS=16P AD=16P
MTP1 1 3 4 10 MOSP W=4U L=2U AS=16P AD=16P
MIN1 5 4 0 0 MOSN W=4U L=2U AS=16P AD=16P
MIP1 5 4 10 10 MOSP W=4U L=2U AS=16P AD=16P
MIN2 6 5 0 0 MOSN W=4U L=2U AS=16P AD=16P
MIP2 6 5 10 10 MOSP W=4U L=2U AS=16P AD=16P
MTN2 6 3 4 0 MOSN W=4U L=2U AS=16P AD=16P
MTP2 6 2 4 10 MOSP W=4U L=2U AS=16P AD=16P
*
MTN3 6 3 7 0 MOSN W=4U L=2U AS=16P AD=16P
MTP3 6 2 7 10 MOSP W=4U L=2U AS=16P AD=16P
MIN3 8 7 0 0 MOSN W=4U L=2U AS=16P AD=16P
MIP3 8 7 10 10 MOSP W=4U L=2U AS=16P AD=16P
MIN4 9 8 0 0 MOSN W=4U L=2U AS=16P AD=16P
MIP4 9 8 10 10 MOSP W=4U L=2U AS=16P AD=16P
MTN4 9 2 7 0 MOSN W=4U L=2U AS=16P AD=16P
MTP4 9 3 7 10 MOSP W=4U L=2U AS=16P AD=16P
.IC V(1)=5 V(2)=0 V(3)=5 V(4)=0 V(5)=5 V(6)=0 V(7)=0
+ V(8)=5 V(9)=0 V(10)=5
.TRAN 0.05N 20N UIC
.MODEL MOSN NMOS KP=5E-5 VTO=0.91 GAMMA=0.99
+LAMBDA=.02 TOX=41.5N
+CGSO=330P CGDO=330P CJ=3.9E-4 CJSW=510P
.MODEL MOSP PMOS KP=2E-5 VTO=-0.77 GAMMA=0.5
+LAMBDA=.05 TOX=41.5N
+CGSO=315P CGDO=315P CJ=2.0E-4 CJSW=180P
.PROBE V(1) V(2) V(3) V(4) V(6) V(7) V(9)
.END
```

The flip-flop operates normally. Data is transferred to the master following the first clock transition and to the slave after the second clock transition. The maximum rise and fall times are highly dependent upon the position of the data transition edge. It is interesting to experiment with the data delay to see the effect. At some point the flip-flop will fail.



CHAPTER 9

9.1

Since $V_{REF} = -1.25V$, and $v_I = -1.6V$, Q_1 is off and Q_2 is conducting.

$$v_{C1} = 0 \text{ V and } v_{C2} = -\alpha_F I_{EE} R_C \cong -I_{EE} R_C = -(2mA)(350\Omega) = -0.700 \text{ V}$$

9.2

$$\frac{I_{C2}}{I_{C1}} = \exp\left(\frac{\Delta V_{BE}}{V_T}\right) \Rightarrow \Delta V_{BE} = 0.025 \ln \frac{0.995\alpha_F I_{EE}}{0.005\alpha_F I_{EE}} = 0.132V$$

$$(a) v_I = V_{REF} + \Delta V_{BE} = -1.25 + 0.132 = -1.12 \text{ V}$$

$$v_I = V_{REF} + \Delta V_{BE} = -1.25 - 0.132 = -1.38 \text{ V}$$

$$(b) v_I = V_{REF} + \Delta V_{BE} = -2.00 + 0.132 = -1.87 \text{ V}$$

$$v_I = V_{REF} + \Delta V_{BE} = -2.00 - 0.132 = -2.13 \text{ V}$$

9.3

Since $V_{REF} = -2V$, and $v_I = -1.6V$, Q_2 is off and Q_1 is conducting.

$$v_{C2} = 0 \text{ V and } v_{C1} = -\alpha_F I_{EE} R_C \cong -I_{EE} R_C = -(2.5mA)(700\Omega) = -1.75 \text{ V}$$

Note that Q_1 is beginning to enter the saturation region of operation, but $V_{BC} = +0.15 \text{ V}$ is not really enough to turn on the collector-base diode. (See Problems 9.5 or 5.61.)

9.4

$$v_I = V_{REF} + 0.3V \Rightarrow Q_1 \text{ on; } Q_2 \text{ off. } I_{C1} = \alpha_F I_{EE} \cong I_{EE} = 0.3mA \quad | \quad I_{C2} = 0$$

$$v_{C1} = 0 - I_{C1}(R_l + R_C) = -0.3mA(3.33k\Omega + 2k\Omega) = -1.60 \text{ V}$$

$$v_{C2} = 0 - I_{C1}R_l = -0.3mA(3.33k\Omega) = -0.999 \text{ V}$$

9.5

With $V_{BE} = 0.7$ and $V_{BC} = 0.3$, the transistor is technically in the saturation region, but calculating the currents using the transport model in Eq. (5.13) yields

$$\beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.98}{1-0.98} = 49 \quad | \quad \beta_R = \frac{\alpha_R}{1-\alpha_R} = \frac{0.2}{1-0.2} = 0.25$$
$$i_C = 10^{-15} \left[\exp\left(\frac{0.7}{0.025}\right) - \exp\left(\frac{0.3}{0.025}\right) \right] - \frac{10^{-15}}{0.25} \left[\exp\left(\frac{0.3}{0.025}\right) - 1 \right] = 1.446 \text{ mA}$$
$$i_E = 10^{-15} \left[\exp\left(\frac{0.7}{0.025}\right) - \exp\left(\frac{0.3}{0.025}\right) \right] + \frac{10^{-15}}{49} \left[\exp\left(\frac{0.7}{0.025}\right) - 1 \right] = 1.476 \text{ mA}$$
$$i_B = \frac{10^{-15}}{49} \left[\exp\left(\frac{0.7}{0.025}\right) - 1 \right] + \frac{10^{-15}}{0.25} \left[\exp\left(\frac{0.3}{0.025}\right) - 1 \right] = 29.52 \mu\text{A}$$

At 0.3 V, the collector-base junction is not heavily forward-biased compared to the base-emitter junction, and $I_C = 48.99I_B \approx \beta_F I_B$. The transistor still acts as if it is operating in the forward-active region.

9.6

(a) For Q_2 off, $V_H = 0$ V. For Q_2 on, $I_C \approx I_E$ and

$$I_E = \frac{-0.2 - 0.7 - (-2)}{1.1 \times 10^4} = 100 \mu\text{A} \quad V_L \approx -4000I_E = -0.400 \text{ V}$$

(b) Yes, these voltages are symmetrically positioned above and below V_{REF} , i. e. $V_{REF} \pm 0.2$ V, and the current will be fully switched. See Parts (d) and (e).

$$(c) \text{For } v_I = 0, I_C \approx I_E = \frac{0 - 0.7 - (-2)}{1.1 \times 10^4} = 118 \mu\text{A} \quad R = \frac{0.4V}{118\mu\text{A}} = 3.39 \text{ k}\Omega$$

(d) Q_2 is cutoff. Q_1 is saturated with $V_{BC} = +0.4$ V.

(e) Q_1 is cutoff. Q_2 is saturated with $V_{BC} = +0.2$ V.

(f) 0.2 V and 0.4 V are not large enough to heavily saturate Q_1 or Q_2 . Although the transistors are technically operating in the saturation region, the transistors still behave as if they are in the forward-active region. (See problem 10.5).

9.7

$$(a) \text{For } v_I = V_L, I_E = \frac{-0.2 - 0.7 - (-2)}{1.1 \times 10^4} = 100 \mu A \quad | \quad V_L \approx -4000I_E = -0.400 V$$

$$\text{For } v_I = V_H = 0V, I_C \approx I_E = \frac{0 - 0.7 - (-2)}{1.1 \times 10^4} = 118 \mu A \quad | \quad R = \frac{0.4V}{118 \mu A} = 3.39 k\Omega$$

$$\bar{P} = 2V \left(\frac{100 \mu A + 118 \mu A}{2} \right) = 218 \mu W$$

$$(b) R_{EE} = \frac{R_{EE}}{5} = \frac{11k\Omega}{5} = 2.20 k\Omega \quad | \quad R_{C1} = \frac{R_{C1}}{5} = \frac{4k\Omega}{5} = 800 \Omega \quad | \quad R_{C2} = \frac{R_{C2}}{5} = \frac{3.39k\Omega}{5} = 678 \Omega$$

9.8

$$V_H = 0 - V_{BE} = -0.7 V \quad | \quad V_L = -(5mA)(200\Omega) - 0.7 = -1.70 V$$

$$V_{REF} = \frac{V_H + V_L}{2} = -1.2 V \quad | \quad \Delta V = (5mA)(200\Omega) = 1.00 V$$

9.9

$$V_H = 0 - V_{BE} = -0.7 V \quad | \quad V_L = -(1mA)(600\Omega) - 0.7 = -1.30 V$$

$$V_{REF} = \frac{V_H + V_L}{2} = -1.0 V \quad | \quad \Delta V = (1mA)(600\Omega) = 0.600 V$$

9.10

$$I_{EE} = 4(0.3mA) = 1.2 mA \quad | \quad I_3 = I_4 = 4(0.1mA) = 0.4 mA \quad | \quad R_C = \frac{2k\Omega}{4} = 500\Omega$$

9.11

$$(a) R_C = \frac{\Delta V}{I_{EE}} = \frac{0.8V}{0.3mA} = 2.67 k\Omega \quad | \quad V_H = 0 - V_{BE} = -0.7 V \quad | \quad V_L = -0.8 - V_{BE} = -1.5 V$$

$$V_{REF} = \frac{V_H + V_L}{2} = -1.10 V$$

$$(b) NM_H = NM_L = \frac{\Delta V}{2} - V_T \left[1 + \ln \left(\frac{\Delta V}{V_T} - 1 \right) \right] = \frac{0.8}{2} - 0.025V \left[1 + \ln \left(\frac{0.8}{0.025} - 1 \right) \right] = 0.289 V$$

(c) For Q₁: V_{CB} = -0.8 - (-0.7) = -0.1 V which represents a slight forward bias, but it is not enough to turn on the diode. For Q₂: V_{CB} = -0.8 - (-1.10) = +0.3 V which represents a reverse bias. Both values are satisfactory for operation of the logic gate.

9.12

(b) For Q_1 on and Q_2 off, $I_{C1} = \alpha_F I_{EE} \approx I_{EE} = 0.3mA$ | $I_{C2} = 0$

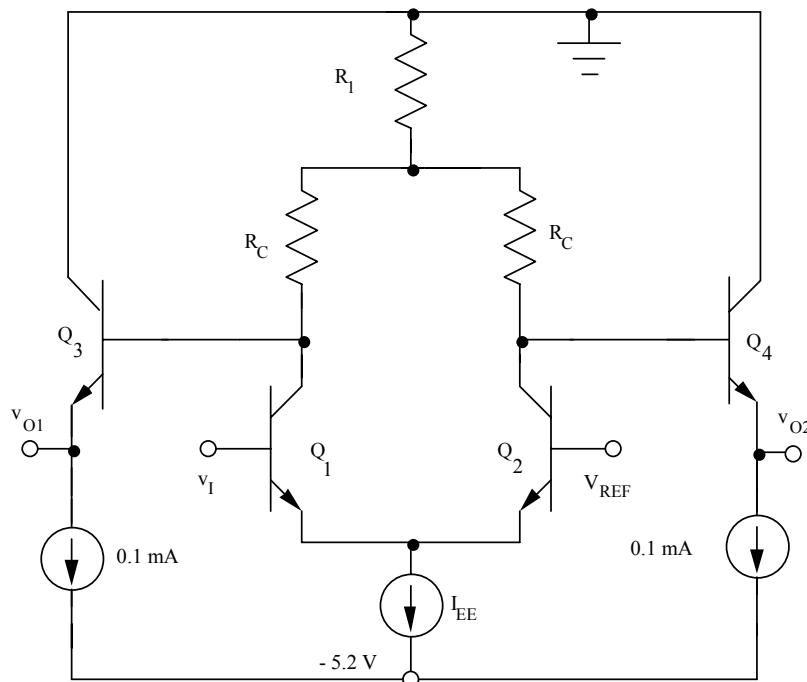
$$V_L = 0 - I_{C1}(R_i + R_C) - 0.7V = -0.3mA(3.33k\Omega + 2k\Omega) - 0.7V = -2.30 V$$

$$V_H = 0 - I_{C1}R_i - 0.7V = -0.3mA(3.33k\Omega) - 0.7 = -1.70 V$$

$$\Delta V = V_H - V_L = 0.600 V$$

(c) $\frac{V_H + V_L}{2} = -2.0V = V_{REF}$ | Yes, the input and output voltage levels are

compatible with each other and are symmetrically placed around V_{REF} .



9.13

(a) See Prob. 9.12

$$(b) \Delta V = \alpha_F I_{EE} R_C \approx I_{EE} R_C \quad | \quad R_C = \frac{0.4V}{1.5mA} = 267 \Omega$$

$$V_H = 0 - \alpha_F I_{EE} R_i - V_{BE} \approx -I_{EE} R_i - V_{BE} = -1.5mA(800) - 0.7V = -1.90 V$$

$$V_L = 0 - \alpha_F I_{EE} (R_i + R_C) - V_{BE} \approx -I_{EE} (R_i + R_C) - V_{BE} = -1.5mA(1067) - 0.7V = -2.30 V$$

$$V_{REF} = \frac{V_H + V_L}{2} = \frac{-1.90 - 2.30}{2} = -2.10 V$$

9.14

$\Delta V = \Delta V_{BE} + \Delta i_{B4} R_C$ | Let the Fanout = N; $\beta_F = 30$. Then there will be N base

$$\text{currents that must be supplied from emitter-follower transistor } Q_4 : \Delta i_{E4} = N \frac{I_{EE}}{\beta_F + 1}$$

$$\Delta V_{BE} = V_T \ln \frac{I_{C4} + \Delta I_{C4}}{I_{C4}} = V_T \ln \frac{I_{E4} + \Delta I_{E4}}{I_{E4}} = V_T \ln \left(1 + \frac{\Delta I_{E4}}{I_{E4}} \right) = 0.025 \ln \left[1 + N \frac{I_{EE}}{(\beta_F + 1) I_{E4}} \right]$$

$$\Delta i_{B4} = \frac{\Delta i_{E4}}{\beta_F + 1} = N \frac{I_{EE}}{(\beta_F + 1)^2}$$

$$\Delta V = \Delta V_{BE} + \Delta i_{B4} R_C = 0.025 \ln \left(1 + N \frac{0.3mA}{31(0.1mA)} \right) + N \frac{0.3mA}{(31)^2} 2k\Omega \quad | \quad \Delta V \leq 0.025$$

$$0.025 = 0.025 \ln \left(1 + \frac{3N}{31} \right) + \frac{0.6N}{(31)^2} \quad | \quad \text{Using MATLAB or HP-Solver : } N \leq 11.01 \rightarrow N = 11$$

9.15

$$R'_{C1} = 8R_{C1} = 8(1.85k\Omega) = 14.8 \text{ k}\Omega \quad | \quad R'_{C2} = 8R_{C2} = 8(2k\Omega) = 16.0 \text{ k}\Omega$$

$$R'_{EE} = 8R_{EE} = 8(11.7k\Omega) = 93.6 \text{ k}\Omega \quad | \quad R' = 8R = 8(42k\Omega) = 336 \text{ k}\Omega$$

9.16

$$(a) R'_{C1} = \frac{R_{C1}}{8} = \frac{1850\Omega}{8} = 231 \text{ }\Omega \quad | \quad R'_{C2} = \frac{R_{C2}}{8} = \frac{2000\Omega}{8} = 250 \text{ }\Omega$$

$$R'_{EE} = \frac{R_{EE}}{8} = \frac{11.7k\Omega}{8} = 1.46 \text{ k}\Omega \quad | \quad R' = \frac{R}{8} = \frac{42k\Omega}{8} = 5.25 \text{ k}\Omega$$

$$(b) R'_{C1} = 5R_{C1} = 5(1.85k\Omega) = 9.25 \text{ k}\Omega \quad | \quad R'_{C2} = 5R_{C2} = 5(2k\Omega) = 10.0 \text{ k}\Omega$$

$$R'_{EE} = 5R_{EE} = 5(11.7k\Omega) = 58.5 \text{ k}\Omega \quad | \quad R' = 5R = 5(42k\Omega) = 210 \text{ k}\Omega$$

9.17

$$\Delta V = \alpha_F I_{EE} R_C \approx I_{EE} R_C = 0.2mA(2k\Omega) = 0.400 V$$

$$V_H = 0 - \alpha_F I_{EE} R_i - V_{BE} \approx -I_{EE} R_i - V_{BE} = -0.2mA(2k\Omega) - 0.7V = -1.10 V$$

$$V_L = 0 - \alpha_F I_{EE} (R_i + R_C) - V_{BE} \approx -I_{EE} (R_i + R_C) - V_{BE} = -0.2mA(4k\Omega) - 0.7V = -1.50 V$$

$$V_{REF} = \frac{V_H + V_L}{2} = \frac{-1.10 - 1.50}{2} = -1.30 V$$

$$NM_L = NM_H = \frac{\Delta V}{2} - V_T \left[1 + \ln \left(\frac{\Delta V}{V_T} - 1 \right) \right] = \frac{0.4}{2} - 0.025V \left[1 + \ln \left(\frac{0.4}{0.025} - 1 \right) \right] = 0.107 V$$

$$I_{E3} + I_{E4} = \frac{[V_H - (-2)] + [V_L - (-2)]}{R} = \frac{(4 - 1.10 - 1.50)V}{50k\Omega} = 28.0 \mu A$$

$$\bar{P} = 28\mu A(2V) + 0.2mA(5.2V) = 1.10 mW$$

9.18

$$NM_H = \frac{\Delta V}{2} - V_T \left[1 + \ln \left(\frac{\Delta V}{V_T} - 1 \right) \right] \quad | \quad 0.1V = \frac{\Delta V}{2} - 0.025V \left[1 + \ln(40\Delta V - 1) \right]$$

Solving by trial - and - error, HP - Solver, or MATLAB : $\Delta V = 0.383 V$

```
function f=dv15(v)
f=4-20*v+1+log(40*v-1);
fzero('dv15',0.5) yields ans = 0.3831
```

9.19

(a) The change in V_{BE} will be neglected : $\Delta V_{BE} = V_T \ln \frac{0.8I_C}{I_C} = -5.6mV$

$$V_H = 0 - V_{BE} = 0 - 0.7 = -0.7 V - \text{no change}$$

$$V_L = 0 - \alpha_F I_{EE} R_C - V_{BE} \approx -I_{EE} R_C - V_{BE} = -0.3mA(1.2)(2k\Omega) - 0.7V = -1.42 V$$

V_L has dropped by 0.12V. | $\Delta V = 0.3mA(1.2)(2k\Omega) = 0.72 V$

$$NM_H = NM_L = \frac{\Delta V}{2} - V_T \left[1 + \ln \left(\frac{\Delta V}{V_T} - 1 \right) \right] = \frac{0.72}{2} - 0.025V \left[1 + \ln \left(\frac{0.72}{0.025} - 1 \right) \right] = 0.252 V$$

(b) At node A : $V_H = 0 - V_{BE} = 0 - 0.7 = -0.7 V - \text{no change}$

$$V_L = 0 - \alpha_F I_{EE} R_C - V_{BE} \approx -I_{EE} R_C - V_{BE} = -\frac{-1.0 - 0.7 - (-5.2)}{1.2(11.7k\Omega)} V(1.2)(2k\Omega) - 0.7V = -1.30 V$$

V_L also has not changed! | Similar results hold at node B because the voltages are set by resistor ratios.

$$NM_H = NM_L = \frac{\Delta V}{2} - V_T \left[1 + \ln \left(\frac{\Delta V}{V_T} - 1 \right) \right] = \frac{0.6}{2} - 0.025V \left[1 + \ln \left(\frac{0.6}{0.025} - 1 \right) \right] = 0.197 V, \text{ unchanged}$$

9.20

$$(a) V_H = -0.7V \quad | \quad \Delta V = 0.8V \quad | \quad V_L = -0.8 - 0.7 = -1.5V \quad | \quad V_{REF} = \frac{V_H + V_L}{2} = -1.1V$$

$$R_{EE} = \frac{-1.1 - 0.7 - (-5.2)}{0.3} \frac{V}{mA} = 11.3 \text{ k}\Omega \quad | \quad R_{C2} = \frac{0.8V}{0.3mA} = 2.67 \text{ k}\Omega$$

$$I_{E1} = \frac{-0.7 - 0.7 - (-5.2)}{11.3} \frac{V}{k\Omega} = 0.336mA \quad | \quad R_{C1} = \frac{0.8V}{0.336mA} = 2.38 \text{ k}\Omega$$

$$(b) NM_H = NM_L = \frac{0.8}{2} - 0.025V \left[1 + \ln \left(\frac{0.8}{0.025} - 1 \right) \right] = 0.289 \text{ V}$$

$$(c) V_{CB1} = -0.8 - (-0.7) = -0.1V \quad | \quad V_{CB2} = -0.8 - (-1.1) = +0.3V$$

The collector - base junction of Q₂ is reverse - biased by 0.3 V. Although the collector - base junction of Q₁ is forward - biased by 0.1 V, this is not large enough to cause a problem. Therefore the voltages are acceptable.

9.21

$$NM_H = \frac{\Delta V}{2} - V_T \left[1 + \ln \left(\frac{\Delta V}{V_T} - 1 \right) \right]$$

$$\text{For room temperature, } V_T = 0.025V : 0.1V = \frac{\Delta V}{2} - 0.025V \left[1 + \ln \left(\frac{\Delta V}{0.025} - 1 \right) \right] \rightarrow \Delta V = 0.383V$$

$$\text{For } -55^\circ C, V_T = 0.0188V : 0.1V = \frac{\Delta V}{2} - 0.0188V \left[1 + \ln \left(\frac{\Delta V}{0.0188} - 1 \right) \right] \rightarrow \Delta V = 0.346V$$

$$\text{For } +75^\circ C, V_T = 0.0300V : 0.1V = \frac{\Delta V}{2} - 0.0300V \left[1 + \ln \left(\frac{\Delta V}{0.0300} - 1 \right) \right] \rightarrow \Delta V = 0.413V$$

$$\Delta V = 0.413 \text{ V}$$

9.22

In the original circuit : $V_H = -2mA(2k\Omega) - 0.7V = -1.1V$ | $\Delta V = 2mA(2k\Omega) = 0.4V$

$V_L = -1.1V - \Delta V = -1.5V$. V_H and V_L are symmetrically placed about V_{REF} .

$$R_{EE} = \frac{-1.3 - 0.7 - (-5.2)}{0.2} \frac{V}{mA} = 16.0 \text{ } k\Omega. R_i \text{ and } R_{C2} \text{ remain unchanged.}$$

$$\text{For } Q_1 \text{ on and } Q_2 \text{ off : } I_{EE} = \frac{-1.1 - 0.7 - (-5.2)}{16.0} \frac{V}{k\Omega} = 0.2125mA$$

$$V_{L1} = -(0.2125mA)(2k\Omega + R_{C1}) - 0.7V \mid V_{L1} = -1.5V \rightarrow R_{C1} = 1.77 \text{ } k\Omega$$

Note that there are only 3 variables (R_i , R_{C1} and R_{C2}) and four voltage levels.

Thus we cannot force them all to the desired level. For this design,

$$V_{H2} = -(0.2125mA)(2k\Omega) - 0.7V = -1.125V \text{ rather than the desired } -1.10V$$

9.23

$$V_{EQ} = \frac{60k\Omega}{60k\Omega + 44k\Omega}(-5.2V) = -3.0V \mid R_{EQ} = 60k\Omega \parallel 44k\Omega = 25.38k\Omega$$

$$I_{BS} = \frac{-3.0 - 0.7 - (-5.2)}{25.38 + (\beta_F + 1)30} \frac{V}{k\Omega} \mid I_{EE} = \beta_F I_{BS} = \beta_F \frac{-3.0 - 0.7 - (-5.2)}{25.38 + (\beta_F + 1)30} \frac{V}{k\Omega}$$

$$\text{For large } \beta_F, I_{EE} = \frac{-3.0 - 0.7 - (-5.2)}{30} \frac{V}{k\Omega} = 50.0 \mu A \mid \text{Active region operation}$$

$$\text{requires } V_{CBS} \geq 0V \mid V_{CBS} = V_{REF} - V_{BE2} - V_{BS} = V_{REF} - 0.7V - (-3V)$$

$$V_{REF} - 0.7V - (-3V) \geq 0 \rightarrow V_{REF} \geq -2.30 \text{ V}$$

9.24

The base of Q_S must not be higher than $V_L - 0.7 = -0.2mA(4k\Omega) - 0.7 - 0.7 = -2.2V$

$$\text{Design choice - Choose } V_B = -3 \text{ V. Assume } \beta_F = 50. \mid I_B = \frac{200\mu A}{50} = 4\mu A$$

$$R_E = \frac{V_B - V_{EE}}{I_E} = \frac{-3 - (-5.2)}{0.204mA} = 10.8 \text{ } k\Omega \rightarrow R_E = 11 \text{ } k\Omega$$

$$\text{Choose } I_{R2} = 20\mu A. \quad R_2 = \frac{0 - (-3)}{20\mu A} = 150 \text{ } k\Omega \rightarrow R_2 = 150 \text{ } k\Omega$$

$$I_{R1} = I_{R2} - I_B = 16\mu A. \quad R_1 = \frac{-3 - (-5.2)}{16\mu A} = 138 \text{ } k\Omega \rightarrow R_1 = 136 \text{ } k\Omega$$

9.25

*PROBLEM 9.25 - ECL INVERTER VTC

VIN 2 0 DC -1.3

VREF 4 0 -1.0

VEE 8 0 -5.2

Q1 1 2 3 NBJT

Q2 5 4 3 NBJT

Q3 0 1 6 NBJT

Q4 0 5 7 NBJT

REE 3 8 11.7K

RC1 0 1 1.85K

RC2 0 5 2K

R3 6 8 42K

R4 7 8 42K

.DC VIN -1.3 -0.7 .01

.TEMP -55 25 85

.MODEL NBJT NPN BF=40 BR=0.25 VA=50

.PROBE V(2) V(1) V(5) V(6) V(7)

.PRINT DC V(2) V(6) V(7)

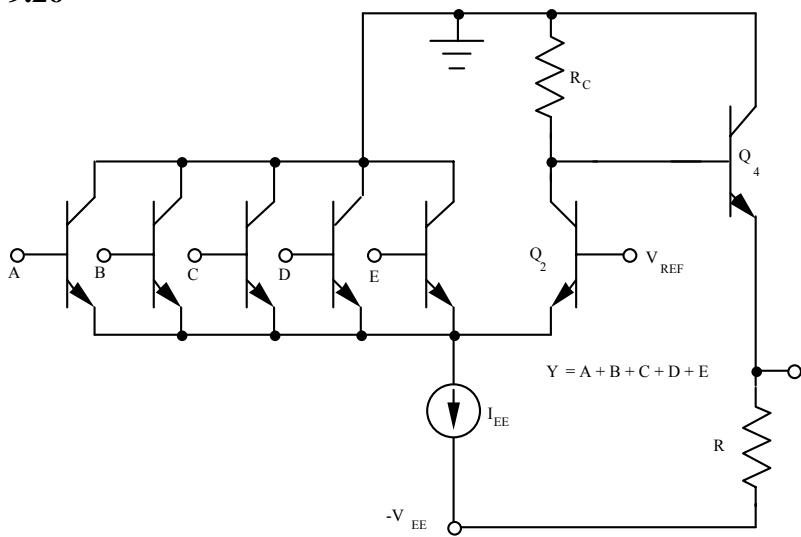
.END

T	-55C	+25C	+85C
V_T	0.0188 V	0.0257 V	0.0309 V
V_H	-0.846 V	-0.724 V	-0.629 V
V_L	-1.40 V	-1.30 V	-1.22 V
ΔV	0.554 V	0.576 V	0.591 V
V_{REF}	-1.00 V	-1.00 V	-1.00 V
V_{IH}	-0.918 V	-0.895 V	-0.880 V
V_{OH}	-0.865 V	-0.750 V	-0.660 V
V_{IL}	-1.08 V	-1.10 V	-1.12 V
V_{OL}	-1.38 V	-1.27 V	-1.19 V
N_{MH}	0.053 V	0.145 V	0.220 V
N_{ML}	0.300 V	0.170 V	0.070 V

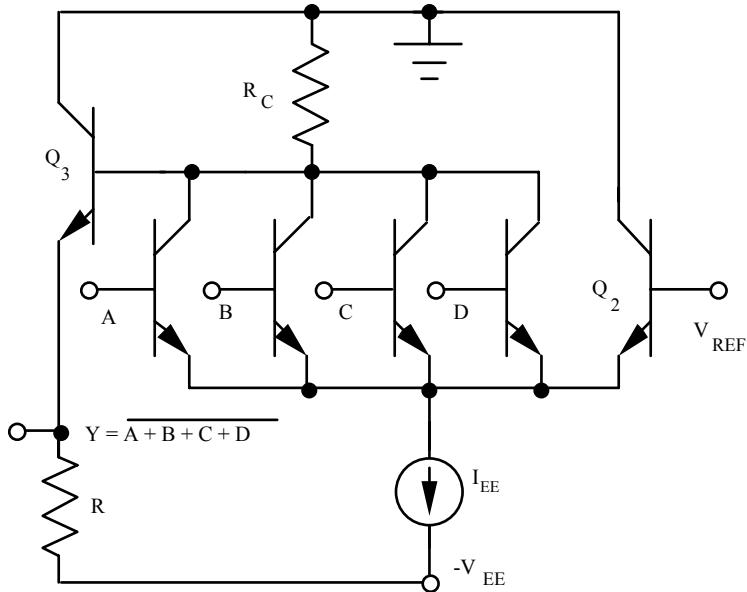
V_{IH} , V_{OH} , V_{OL} , and V_{IL} were calculated from Eqns. 9.27 - 9.30.

With a fixed reference voltage, the noise margins change with temperature and can become zero for a large enough temperature change.

9.26



9.27



9.28

$$(a) \text{For } Q_4 \text{ on, } I_{C4} = \alpha_F I_{E4} \cong I_{E4} = \frac{-0.7 - (-2.5)}{840} = 2.14 \text{ mA}$$

$$V_L = 1.0V - (2.14mA)(390\Omega) - 0.7V = -0.540\text{ V}$$

For Q_4 off, and neglecting the base current in Q_5 , $V_H = 1.0 - 0.7 = +0.300\text{ V}$

$$(b) \text{ For } V_A = 0.3V, I_{C2} = \alpha_F I_{E2} \cong I_{E2} = \frac{0.3 - 0.7 - (-2.5)}{840} = 2.50 \text{ mA}$$

$$\Delta V = 0.30 - (-0.54) = 0.84V \quad | \quad R = \frac{\Delta V}{I_{C2}} = \frac{0.84V}{2.50mA} = 336 \Omega$$

9.29

$$(a) \text{For } Q_4 \text{ on, } I_{C4} = \alpha_F I_{E4} \cong I_{E4} = \frac{-0.7 - (-3.2)}{840} = 2.98 \text{ mA}$$

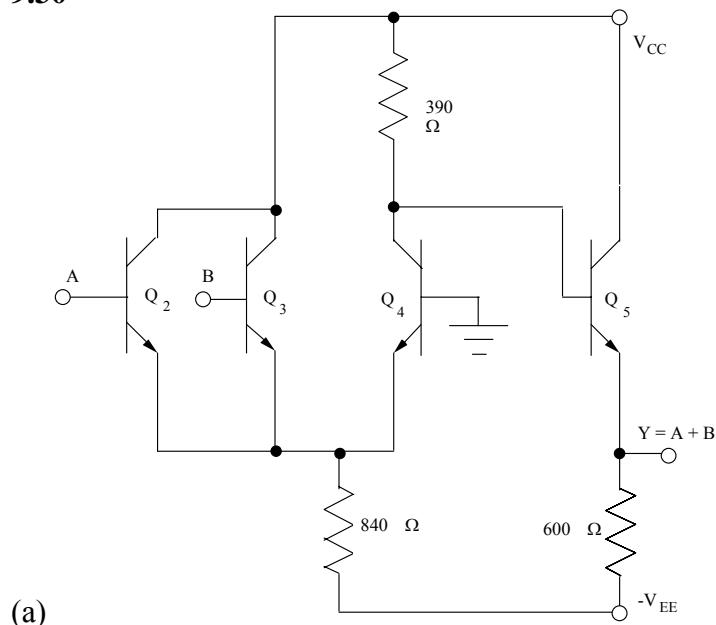
$$V_L = 1.3V - (2.98 \text{ mA})(390 \Omega) - 0.7V = -0.56 \text{ V}$$

For Q_4 off, and neglecting the base current in Q_5 , $V_H \cong 1.3 - 0.7 = +0.60 \text{ V}$

$$(b) \text{For } v_A = 0.6V, I_{C2} = \alpha_F I_{E2} \cong I_{E2} = \frac{0.6 - 0.7 - (-3.2)}{840} = 3.69 \text{ mA}$$

$$\Delta V = 0.60 - (-0.56) = 1.16V \quad | \quad R = \frac{\Delta V}{I_{C2}} = \frac{1.16V}{3.69 \text{ mA}} = 314 \Omega$$

9.30



(a)

(b) The NOR output is taken from the collectors of Q_2/Q_3 , and the 390Ω resistor, Q_5 , and the 600Ω resistor are removed.

9.31

$$v_O^{\min} = -I_{EE} R_L = -(2.5 \text{ mA})(1.2k\Omega) = -3.00 \text{ V} \quad | \quad I_E = I_{EE} + \frac{v_O}{R_L} = 2.5 \text{ mA} + \frac{4 - 0.7}{1.2k\Omega} = 5.25 \text{ mA}$$

$V_{BC} = 4 - 5 = -1 \text{ V}$, so the transistor is in the forward-active region.

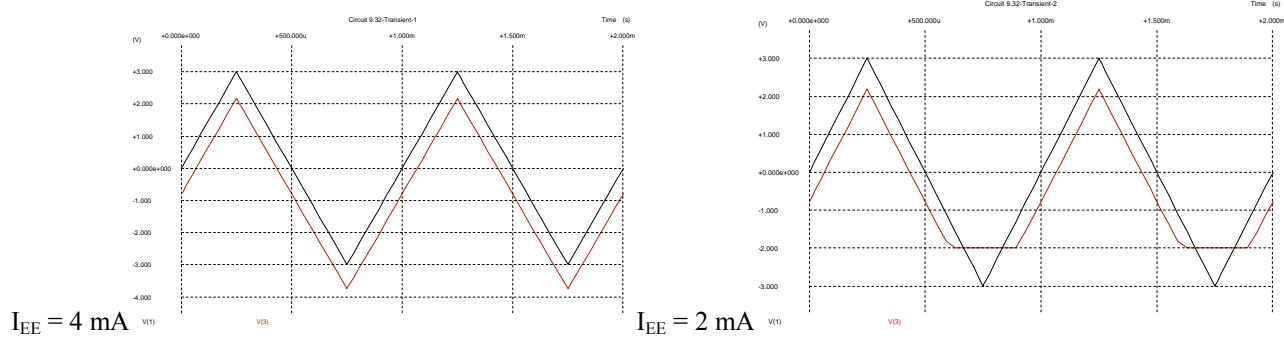
$$I_B = \frac{I_E}{\beta_F + 1} = \frac{5.25 \text{ mA}}{50 + 1} = 0.103 \text{ mA} \quad \text{and} \quad I_C = \beta_F I_B = 5.15 \text{ mA.}$$

9.32

$$(a-b) \text{ See Problem 9.33} \quad (c) I_{EE} \geq -\frac{(V_I - 0.7)V}{1k\Omega} = \frac{3.7V}{1k\Omega} = 3.7 \text{ mA}$$

9.33

Simulation Results from B²SPICE



9.34

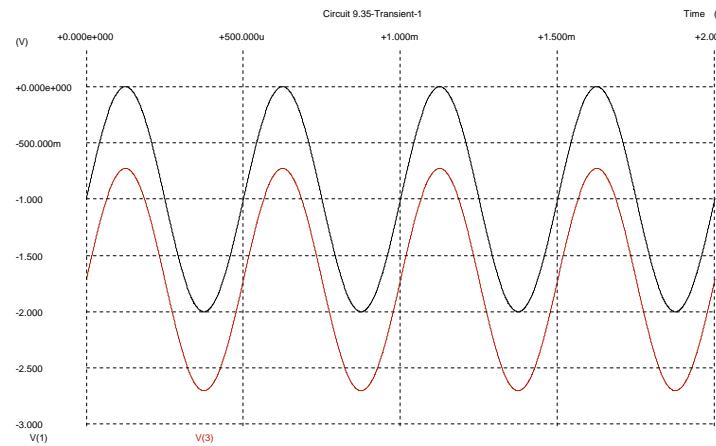
$$(a) v_o = v_i - 0.7V = (-1.7 + \sin 2000\pi t) V$$

$$(b) v_o^{\min} = -2.7V \quad | \quad -I_{EE}R_L \leq -2.7V \rightarrow I_{EE} \geq \frac{2.7V}{20k\Omega} = 0.13 \text{ mA} \text{ with no safety margin.}$$

The transistor will cut off at the bottom of the input waveform for $I_{EE} = 0.13 \text{ mA}$.

9.35

Simulation results from B²SPICE



9.36

$$(a) \text{The transistor cuts off for } v_o^{\min} = -I_{EE}R_L = -(0.5 \text{ mA})(1k\Omega) = -0.5 \text{ V. So } v_i \geq -0.5 + 0.7 = +0.2 \text{ V.}$$

For $v_o > 1.5 \text{ V}$, the transistor enters the saturation region of operation.

Therefore: $0.2 \text{ V} \leq v_i \leq 1.5 \text{ V}$.

$$(b) v_o^{\min} = -1.5 - 0.7 = -2.2 \text{ V. We need } -I_{EE}R_L \leq -2.2 \text{ V} \rightarrow I_{EE} \geq \frac{2.2 \text{ V}}{1k\Omega} = 2.2 \text{ mA}$$

9.37

$$v_o^{\min} = -10 - 0.7 = -10.7 \text{ V. We need } -I_{EE}R_L \leq -10.7 \text{ V} \rightarrow I_{EE} \geq \frac{10.7 \text{ V}}{1k\Omega} = 10.7 \text{ mA}$$

9.38

Assuming Q_i off and using voltage division, $-12 = -15 \frac{2000}{2000 + R_E} \Rightarrow R_E = 500 \Omega$

$$I_E = \frac{12}{2000} + \frac{12 - (-15)}{500} = 60 \text{ mA}$$

9.39

(a) $v_O^{\min} = -10 - 0.7 = -10.7 \text{ V}$. We need $-15V\left(\frac{4.7k\Omega}{4.7k\Omega + R_E}\right) \leq -10.7V$

$$R_E \leq \frac{(15 - 10.7)(4.7k\Omega)}{10.7} = 1.89 \text{ k}\Omega \quad | \quad I_E = \frac{v_I - 0.7}{R_L} + \frac{v_I - 0.7 - V_{EE}}{R_E}$$

$$(b) I_E = \frac{-0.7}{4700} + \frac{-0.7 - (-15)}{1890} = 7.43 \text{ mA} \quad | \quad (c) I_E = \frac{-10 - 0.7}{4700} + \frac{-10 - 0.7 - (-15)}{1890} = 0 \text{ mA}$$

9.40

(a) See the solution to Problem 9.41.

$$(b) v_O = v_I - 0.7V = (-2.2 + 1.5\sin 2000\pi t)V$$

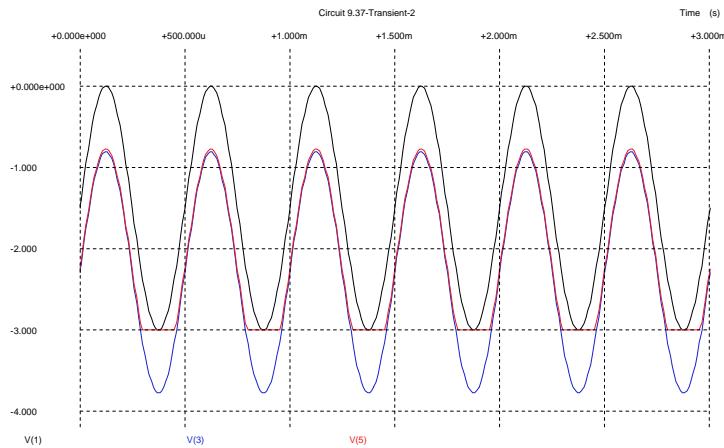
$$(c) v_I^{\max} = -1.5 + 1.5 = 0V \quad | \quad v_O^{\max} = -0.7V \quad |$$

$$I_E = \frac{v_O}{R_L} + \frac{v_O - V_{EE}}{R_E} \quad | \quad I_E^{\max} = \frac{-0.7}{4700} + \frac{-0.7 - (-6)}{1300} = 3.93 \text{ mA}$$

$$(d) v_O^{\min} = -2.2 - 1.5 = -3.7V \quad | \quad I_E^{\min} = \frac{-3.7}{4700} + \frac{-3.7 - (-6)}{1300} = 0.982 \text{ mA}$$

$$(e) \text{We need } -6V\left(\frac{4.7k\Omega}{4.7k\Omega + R_E}\right) \leq -3.7V \rightarrow R_E \leq \frac{4.7k\Omega(6 - 3.7)}{3.7} = 2920 \Omega$$

9.41 Simulation results from B²SPICE



9.42

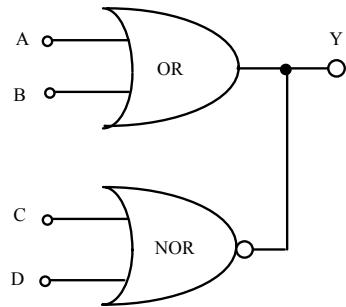
The outputs act as a "wired - or" connection.

$$\text{For } v_I = -0.7V, v_{O1} = v_{O2} = -0.7 V \quad | \quad I_{E3} = 0 \quad | \quad I_{E4} = 0.1mA + 0.1mA = 0.200 mA$$

$$\text{For } v_I = -1.3V, v_{O1} = v_{O2} = -0.7 V \quad | \quad I_{E3} = 0.1mA + 0.1mA = 0.200 mA \quad | \quad I_{E4} = 0$$

9.43

$$Y = A + \bar{B} \quad | \quad Z = \bar{A} + B$$

9.44**9.45**

For Fig. 9.21, $P \cong 0.5mA(5.2V) = 2.6mW = 2600\mu W$. For $20\mu W$, the power must be reduced by 130X. The currents must be reduced by 130X and the resistors must increase by this factor to keep the logic swing the same: $R_C = 130(2k\Omega) = 260k\Omega$.

Using Eq. (9.54), $\tau_p = 0.69(260k\Omega)(2pF) = 359 ns$ - rather slow!

9.46

$$R'_C = \frac{R_C}{2} = \frac{2k\Omega}{2} = 1k\Omega \quad | \quad \Delta V = 0.3mA(1k\Omega) = 0.3V \quad | \quad V_H = 0 - 0.7 = -0.7V$$

$$V_L = V_H - 0.3V = -1.0V \quad | \quad V_{REF} = \frac{-0.7 - 1.0}{2}V = -0.850 V \quad | \quad P \cong 0.5mA(5.2V) = 2.6mW$$

$$\tau_p = 0.69(1k\Omega)(2pF) = 1.38ns \quad | \quad PDP = 2.6mW(1.38ns) = 3.59 pJ$$

9.47

$$\Delta V = 0.15mA(2k\Omega) = 0.3V \quad | \quad V_H = 0 - 0.7 = -0.7V$$

$$V_L = V_H - 0.3V = -1.0V \quad | \quad V_{REF} = \frac{-0.7 - 1.0}{2}V = -0.850 V \quad | \quad P \cong 0.25mA(5.2V) = 1.30mW$$

$$\tau_p = 0.69(2k\Omega)(2pF) = 2.76ns \quad | \quad PDP = 1.30mW(2.76ns) = 3.59 pJ$$

9.48

(a) At the outputs: $V_H = 0 \text{ V}$ | $V_{REF} = V_H - 0.7 - \frac{\Delta V}{2} \rightarrow \Delta V = 2(0 - 0.7 - (-1)) = 0.6V$

$V_L = V_H - \Delta V = 0 - .6 = -0.600 \text{ V}$. Ignoring the base currents, the average power is

$$P \approx \left[\frac{(-1.7 - (-3.3))Y}{1.6k\Omega} + \frac{(-1.0 - (-3.3))Y}{3.2k\Omega} \right] 3.3V = 5.67 \text{ mW}$$

$$R_{C2} = \frac{\Delta V}{I_{EE2}} = \frac{0.6}{\frac{-1 - 0.7 - (-3.3)}{1600}} = 600 \Omega \quad | \quad R_{C1} = \frac{\Delta V}{I_{EE1}} = \frac{0.6}{\frac{-0.7 - 0.7 - (-3.3)}{1600}} = 505 \Omega$$

(b) $\bar{Y} = \overline{A+B+C}$ (c) 5 versus 6 transistors

9.49

At the outputs: $V_H = 0 \text{ V}$ | $V_L = V_H - \Delta V = 0 - .4 = -0.400 \text{ V}$.

At the base of Q_D: $V_H \rightarrow V_{BD} = 0 - 0.7 = -0.7V$ | $V_L \rightarrow V_{BD} = -0.4 - 0.7 = -1.10V$

$$V_{REF} = \frac{-0.7 - 1.1}{2} = -0.90V \quad | \quad V_{EE} \leq V_{REF} - 0.7 - 0.6 = -0.9 - 0.7 - 0.6 = -2.20 \text{ V}$$

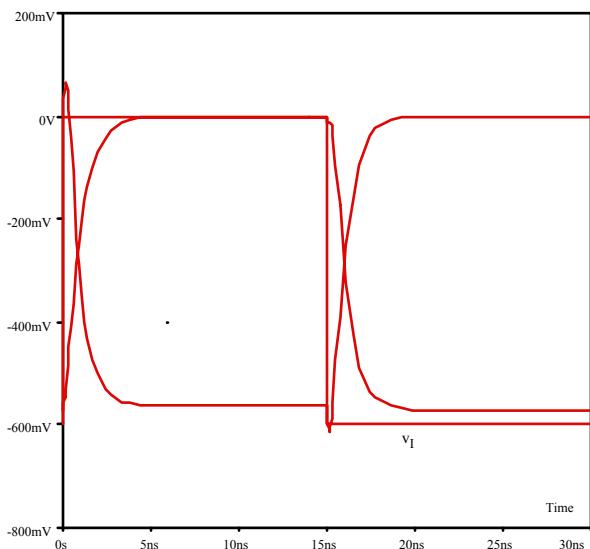
$$\text{For } V_{EE} = -2.20V: R_B = \frac{-0.9 - (-2.2)}{1} \frac{V}{mA} = 1.30 \text{ k}\Omega$$

$$R_E = \frac{[-0.9 - 0.7 - (-2.2)] + [-0.7 - 0.7 - (-2.2)]}{2} \frac{V}{1 \text{ mA}} = 700 \Omega$$

$$R_{C1} = \frac{0.4V}{\frac{-0.7 - 0.7 - (-2.2)}{700} A} = 350 \Omega \quad | \quad R_{C2} = \frac{0.4V}{\frac{-0.9 - 0.7 - (-2.2)}{700} A} = 467 \Omega$$

9.50

*PROBLEM 9.50 - ECL DELAY
VIN 1 0 PULSE(-0.6 0 0 .01NS .01NS 15NS)
VB 8 0 -0.6
VREF 6 0 -1.0
VEE 7 0 -3.3
QA 0 1 2 NBJT
QB 0 8 2 NBJT
QC 0 8 2 NBJT
QD 4 2 3 NBJT
QE 5 6 3 NBJT
RB 2 7 3.2K
RE 3 7 1.6K
RC1 0 4 505
RC2 0 5 600
.OP
.TRAN 0.1N 30N
.MODEL NBJT NPN BF=40 BR=0.25
+IS=5E-16 TF =0.15NS TR=15NS
+CJC=0.5PF CJE=.25PF CJS=1.0PF
+RB=100 RC=5 RE=1
.PROBE V(2) V(1) V(4) V(5) V(6)
.END



Result: $\tau_P = 0.95$ ns

9.51

One approach is to scale all the resistor values. To reduce the power from 2.7 mW to 1.0 mW, the resistor values should all be increased a factor of 2.7.

$$R_{C1} = 2.7(1.85k\Omega) = 5.00 k\Omega \quad | \quad R_{C2} = 2.7(2k\Omega) = 5.40 k\Omega$$

$$R_{EE} = 2.7(11.7k\Omega) = 31.6 k\Omega \quad | \quad R = 2.7(42k\Omega) = 113 k\Omega$$

9.52

Voltage levels remain unchanged: $V_{REF} = -1 V$, $V_H = -0.7 V$, $V_L = -1.3 V$, $I_{EE} = 0.3 mA$

$$R_{EE} = \frac{-1 - 0.7 - (-2)}{0.3} \frac{V}{mA} = 1 k\Omega \quad | \quad R_{C1} = \frac{0.6V}{-0.7 - 0.7 - (-2)} \frac{A}{1 k\Omega} = \frac{0.6V}{0.6mA} = 1 k\Omega$$

$$\bar{I} \cong 2 \frac{-1 - (-2)}{10} \frac{V}{k\Omega} + \frac{0.3 + 0.6}{2} mA = 0.650mA \quad | \quad P = 0.65mA(2V) = 1.30 mW \text{ (-28%)}$$

Note that this gate will now have quite asymmetrical delays at the two outputs since the two collector resistors differ by a factor of two in value.

9.53

The circuit is the pnp version of the ECL gate in Fig. P9.48. | Y = ABC

9.54

$$V_L = 0 \quad | \quad V_H = V_L + \Delta V = +0.6V \quad | \quad V_{REF} = \frac{0.7 + 1.3}{2} = +1.0V \quad | \quad I = \frac{1mW}{3V} = 333\mu A$$

$$\text{The average voltage at the emitter of } Q_D \text{ is } \frac{(1 + 0.7) + (0.7 + 0.7)}{2} = 1.55V$$

$$R_E = \frac{(3 - 1.55)V}{0.9(333\mu A)} = 4.84 k\Omega \quad | \quad R_B = \frac{(3 - 1)V}{0.1(333\mu A)} = 60.1 k\Omega \quad | \quad R_C = \frac{0.6V}{\frac{(3 - 1.7)V}{4.84k\Omega}} = 2.23 k\Omega$$

9.55

*Problem 9.55(a) - PNP ECL GATE DELAY

VI 4 0 PULSE(0.6 0 0 .01NS .01NS 25NS)

VB 7 0 DC 0.6

VREF 6 0 DC 1.0

VEE 1 0 DC 3

QA 0 4 3 PBJT

QB 0 7 3 PBJT

QC 0 7 3 PBJT

QD 0 3 2 PBJT

QE 5 6 2 PBJT

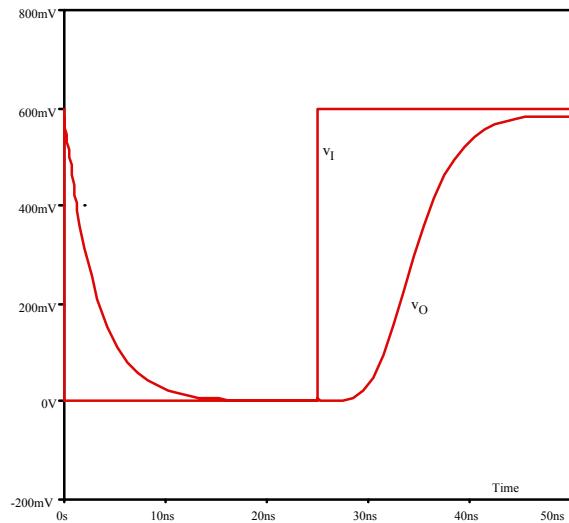
RB 1 3 60.1K

RE 1 2 4.84K

```

RC 5 0 2.23K
.OP
.TRAN 0.1N 50N
.MODEL PBJT PNP BF=40 BR=0.25 IS=5E-16
+TF =0.15NS TR=15NS
+CJC=0.5PF CJE=.25PF CJS=1.0PF
+RB=100 RC=5 RE=1
.PROBE V(4) V(3) V(5)
.END

```



Result: $\tau_p = 6.0\text{ns}$. This delay is dominated by a slow charge up at the base of Q_D .

```

*Problem 9.55(b) - Prob. 9.4
VIN 1 0 PULSE( -2.3 -1.7 0 .01NS .01NS 15NS)
VREF 6 0 -2.0
IEE 2 0 0.0003
Q1 3 1 2 NBJT
Q2 4 6 2 NBJT
R1 0 5 3.33K
RC1 5 3 2K
RC2 5 4 2K
.OP
.TRAN 0.1N 30N
.MODEL NBJT NPN BF=40 BR=0.25 IS=5E-16 TF =0.15NS TR=15NS
+CJC=0.5PF CJE=.25PF CJS=1.0PF RB=100 RC=5 RE=1
.PROBE V(1) V(3) V(4)
.END

```

Result: $\tau_p = 2.4 \text{ ns}$.

```

*Problem 9.55(c) - Fig. P9.16
VIN 1 0 PULSE( -1.5 -1.1 0 .01NS .01NS 15NS)
VREF 6 0 DC -1.30
IEE 2 0 DC 0.0002

```

```

Q1 3 1 2 NBJT
Q2 4 6 2 NBJT
Q3 0 3 7 NBJT
Q4 0 4 8 NBJT
R1 0 5 2K
RC1 5 3 2K
RC2 5 4 2K
RE1 7 9 50K
RE2 8 9 50K
VEE 9 0 DC -2
.OP
.TRAN 0.1N 30N
.MODEL NBJT NPN BF=40 BR=0.25 IS=1E-17 TF =0.15NS TR=15NS
+CJC=0.5PF CJE=.25PF CJS=1.0PF RB=100 RC=5 RE=1
.PROBE V(1) V(3) V(4) V(7) V(8)
.END
Result:  $\tau_p = 3.0$  ns.

```

9.56

Applying the transport model,

$$\begin{aligned}
I_C &= I_S \left[\exp\left(\frac{V_{BE}}{V_T}\right) - \exp\left(\frac{V_{BC}}{V_T}\right) \right] - \frac{I_S}{\beta_F} \left[\exp\left(\frac{V_{BC}}{V_T}\right) - 1 \right] \\
I_B &= \frac{I_S}{\beta_F} \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right] + \frac{I_S}{\beta_R} \left[\exp\left(\frac{V_{BC}}{V_T}\right) - 1 \right] \\
I_C &= 10^{-15} \left[\exp\left(\frac{0.2}{0.025}\right) - \exp\left(\frac{-4.8}{0.025}\right) \right] - \frac{10^{-15}}{0.25} \left[\exp\left(\frac{-4.8}{0.025}\right) - 1 \right] = 2.98 \text{ pA} \\
I_B &= \frac{10^{-15}}{40} \left[\exp\left(\frac{0.2}{0.025}\right) - 1 \right] + \frac{10^{-15}}{0.25} \left[\exp\left(\frac{-4.8}{0.025}\right) - 1 \right] = 74.5 \text{ fA}
\end{aligned}$$

Although the transistor is technically in the forward-active region, (and operating with $I_C = \beta_F I_B$), it is essentially off - its terminal currents are zero for most practical purposes.

9.57

$$\begin{aligned}
\text{For } I_C = 0, V_{CESAT} &= V_T \ln\left(\frac{1}{\alpha_R}\right) \frac{1 + \frac{I_C}{(\beta_R + 1)I_B}}{1 - \frac{I_C}{\beta_F I_B}} = V_T \ln\left(\frac{1}{\alpha_R}\right) \\
V_{CESAT} &= V_T \ln\left(\frac{\beta_R + 1}{\beta_R}\right) = 0.025 \ln\left(\frac{1.25}{0.25}\right) = 0.402 \text{ V}
\end{aligned}$$

9.58

(a) For the Transport model with $V_{BE} = V_{BC}$, the transport current $i_T = 0$:

$$I_C = \frac{I_S}{\beta_R} \left[\exp\left(\frac{V_{BC}}{V_T}\right) - 1 \right] \text{ and } I_E = \frac{I_S}{\beta_F} \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right] \Rightarrow \frac{I_C}{I_E} = \frac{\beta_F}{\beta_R} = \frac{40}{0.25} = 160$$

$$(b) v_{BE} = V_B - 0.6 \quad | \quad v_{BC} = V_B - 0.8 = v_{BE} - 0.2$$

$$i_E = I_S \left[\exp \frac{v_{BE}}{V_T} - \exp \frac{v_{BC}}{V_T} \right] + \frac{I_S}{\beta_F} \left[\exp \frac{v_{BE}}{V_T} - 1 \right]$$

$$i_E = I_S \left[\exp \frac{v_{BE}}{V_T} - \exp \frac{v_{BE}}{V_T} \exp \frac{-0.2}{V_T} \right] + \frac{I_S}{\beta_F} \left[\exp \frac{v_{BE}}{V_T} - 1 \right]$$

$$i_E \cong I_S \left[\exp \frac{v_{BE}}{V_T} \right] + \frac{I_S}{\beta_F} \left[\exp \frac{v_{BE}}{V_T} \right] = I_S \left(1 + \frac{1}{\beta_F} \right) \exp \frac{v_{BE}}{V_T} = \frac{I_S}{\alpha_F} \left[\exp \frac{v_{BE}}{V_T} \right]$$

$$i_C = I_S \left[\exp \frac{v_{BE}}{V_T} - \exp \frac{v_{BE}}{V_T} \exp \frac{-0.2}{V_T} \right] - \frac{I_S}{\beta_R} \left[\exp \frac{v_{BE} - 0.2}{V_T} - 1 \right]$$

$$i_C \cong I_S \left[\exp \frac{v_{BE}}{V_T} \right] \quad | \quad \frac{i_C}{i_E} = \alpha_F = \frac{40}{41} = 0.976$$

$$(c) \frac{i_C}{i_E} = -1 \rightarrow i_B = i_E - i_C = 2i_E \quad | \quad \text{Both junctions will be forward-biased. Neglect}$$

$$\text{the -1 terms: } \frac{I_S}{\beta_F} \exp \frac{v_{BE}}{V_T} + \frac{I_S}{\beta_R} \exp \frac{v_{BC}}{V_T} = 2I_S \left(\exp \frac{v_{BE}}{V_T} - \exp \frac{v_{BC}}{V_T} \right) + 2 \frac{I_S}{\beta_F} \exp \frac{v_{BE}}{V_T}$$

$$v_{BE} - v_{BC} = V_T \ln \frac{2 + \frac{1}{\beta_R}}{2 + \frac{1}{\beta_F}} = 0.025V \ln \frac{2 + \frac{1}{0.25}}{2 + \frac{1}{40}} = 27.2mV$$

$$(v_B - v_I) - (v_B - 0.8) = 27.7mV \quad | \quad v_I = 0.773 V$$

9.59

(a) For the default value of $\beta_F = 40$,

$$I_C = \beta_F I_B \Rightarrow \text{Forward-active region} \quad | \quad V_{BE} \approx V_T \ln \frac{I_C}{I_S} = 0.025V \ln \frac{10^{-3}A}{10^{-15}A} = 0.691V$$

(b) $I_C < \beta_F I_B \Rightarrow \text{saturation region}$; V_{BE} is given by Eqn. 5.45

$$V_{BE} = V_T \ln \frac{I_B + (1 - \alpha_R)I_C}{I_S \left[\frac{1}{\beta_F} + (1 - \alpha_R) \right]} = V_T \ln \frac{I_B + \left(\frac{1}{\beta_R + 1} \right) I_C}{I_S \left[\frac{1}{\beta_F} + \left(\frac{1}{\beta_R + 1} \right) \right]}$$

$$V_{BE} = 0.025V \ln \frac{25 \times 10^{-6} + \left(\frac{1}{0.25 + 1} \right) 10^{-3}}{10^{-15} \left[\frac{1}{80} + \left(\frac{1}{0.25 + 1} \right) \right]} = 0.691V$$

$$(c) I_C < \beta_F I_B \Rightarrow \text{saturation region} \quad | \quad V_{BE} = 0.025V \ln \frac{10^{-3} + \left(\frac{1}{0.25 + 1} \right) 10^{-3}}{10^{-15} \left[\frac{1}{40} + \left(\frac{1}{0.25 + 1} \right) \right]} = 0.710V$$

9.60

$$\alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{1}{2} \quad | \quad \frac{I_C}{I_B} = \frac{1mA}{25\mu A} = 40$$

$$(a) V_{CESAT} = V_T \ln \left(\frac{1}{\alpha_R} \right) \frac{1 + \frac{I_C}{(\beta_R + 1)I_B}}{1 - \frac{I_C}{\beta_F I_B}} = (0.025V) \ln \left[\left(\frac{3}{2} \right) \frac{1 + \frac{40}{2}}{1 - \frac{40}{60}} \right] = 114 \text{ mV}$$

$$(b) \frac{I_C}{I_B} = \frac{1mA}{40\mu A} = 25 \quad | \quad V_{CESAT} = (0.025V) \ln \left[\left(\frac{3}{2} \right) \frac{1 + \frac{25}{2}}{1 - \frac{25}{60}} \right] = 88.7 \text{ mV}$$

9.61

$$\alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{2}{3} \quad | \quad \frac{I_C}{I_B} = \frac{1mA}{25\mu A} = 40$$

$$(a) V_{CESAT} = V_T \ln \left(\frac{1}{\alpha_R} \right) \frac{1 + \frac{I_C}{(\beta_R + 1)I_B}}{1 - \frac{I_C}{\beta_F I_B}} = (0.025V) \ln \left[\left(\frac{3}{2} \right) \frac{1 + \frac{40}{3}}{1 - \frac{40}{50}} \right] = 117 \text{ mV}$$

$$(b) V_{CESAT} = (0.025V) \ln \left[\left(\frac{3}{2} \right) \frac{1 + \frac{40}{3}}{1 - \frac{40}{100}} \right] = 89.5 \text{ mV}$$

9.62

$$\alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{0.25}{1.25} = 0.2$$

$$(a) \Gamma = \exp \left(\frac{V_{CESAT}}{V_T} \right) = \exp \left(\frac{0.2V}{0.025V} \right) = 2980 \quad (b) \Gamma = \exp \left(\frac{V_{CESAT}}{V_T} \right) = \exp \left(\frac{0.1V}{0.025V} \right) = 54.6$$

$$I_B \geq \frac{I_C}{\beta_F} \left[\frac{1 + \frac{\beta_F}{\beta_R \Gamma}}{1 - \frac{1}{\alpha_R \Gamma}} \right] = \frac{I_C}{40} \left[\frac{1 + \frac{40}{0.25(2980)}}{1 - \frac{1}{0.2(2980)}} \right] = \frac{I_C}{37.9} \quad I_B \geq \frac{I_C}{\beta_F} \left[\frac{1 + \frac{\beta_F}{\beta_R \Gamma}}{1 - \frac{1}{\alpha_R \Gamma}} \right] = \frac{I_C}{40} \left[\frac{1 + \frac{40}{0.25(54.6)}}{1 - \frac{1}{0.2(54.6)}} \right] = \frac{I_C}{9.25}$$

$$I_B \geq \frac{I_C}{\beta_{FOR}} = \frac{1}{37.9} \left(\frac{5 - 0.2}{2k\Omega} \right) = 63.3 \text{ } \mu A \quad I_B \geq \frac{I_C}{\beta_{FOR}} = \frac{1}{9.25} \left(\frac{5 - 0.1}{2k\Omega} \right) = 265 \text{ } \mu A$$

9.63

$$\alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{0.25}{1.25} = 0.2 \quad \Gamma = \exp \left(\frac{V_{CESAT}}{V_T} \right) = \exp \left(\frac{0.1V}{0.025V} \right) = 54.6$$

$$I_B \geq \frac{I_C}{\beta_F} \left[\frac{1 + \frac{\beta_F}{\beta_R \Gamma}}{1 - \frac{1}{\alpha_R \Gamma}} \right] = \frac{I_C}{40} \left[\frac{1 + \frac{40}{0.25(54.6)}}{1 - \frac{1}{0.2(54.6)}} \right] = \frac{I_C}{9.25}$$

$$I_B \geq \frac{I_C}{\beta_{FOR}} = \frac{1}{9.25} \left(\frac{5 - 0.1}{3.6k\Omega} \right) = 147 \text{ } \mu A$$

9.64

$$\text{For } I_C = 0, V_{CESAT} = V_T \ln\left(\frac{1}{\alpha_R}\right) = V_T \ln\left(\frac{\beta_R + 1}{\beta_R}\right) = 0.025 \ln\left(\frac{1.25}{0.25}\right) = 40.2 \text{ mV}$$

$$\text{For } I_E = 0, V_{ECSAT} = V_T \ln\left(\frac{1}{\alpha_F}\right) = V_T \ln\left(\frac{\beta_F + 1}{\beta_F}\right) = 0.025 \ln\left(\frac{41}{40}\right) = 0.617 \text{ mV}$$

9.65

$$\alpha_F = \frac{\beta_F}{\beta_F + 1} = \frac{40}{41} = 0.976 \quad \alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{0.25}{1.25} = 0.200$$

$$\tau_s = \frac{0.976(0.4ns + 0.2(12ns))}{1 - 0.976(0.2)} = 3.40ns \quad i_{CMAX} \cong \frac{5V}{2k\Omega} = 2.5 \text{ mA}$$

$$t_s = (3.40ns) \ln \frac{2mA - (-0.5mA)}{\frac{2.5mA}{40} - (-0.5mA)} = 5.07 \text{ ns}$$

9.66

$$V_H = V_{CC} = 3.0 \text{ V} \quad V_L = V_{CESAT} = 0.15$$

$$V_{IL} = 0.7 - V_{CESAT} = 0.7 - 0.04V = 0.66V \quad V_{IH} \cong V_{BESAT2} = 0.8 \text{ V}$$

$$v_I = 3V : I_{B1} = \frac{3 - 0.7 - 0.8}{4} \frac{V}{k\Omega} = 375\mu A \quad | \quad I_{B2} = 1.25I_{B1} = 469\mu A$$

$$v_I = 0.15V : I_{IL} = -\frac{3 - 0.8 - 0.15}{4} \frac{V}{k\Omega} = -513\mu A \quad | \quad I_{C2SAT} = \frac{3 - 0.15}{2000} A = 1.43mA$$

$$1.43mA + N(513\mu A) \leq 40(469\mu A) \rightarrow N \leq 33.8 \rightarrow N \leq 33.$$

9.67

$$v_I = V_H : I = \frac{5 - 0.7 - 0.8}{(0.8)4k\Omega} + \frac{5 - 0.15}{(0.8)2k\Omega} = 4.13mA \quad | \quad P = 5(4.13mA) = 20.6 \text{ mW}$$

$$v_I = V_L : I = \frac{5 - 0.8 - 0.15}{(1.2)4k\Omega} = 0.844mA \quad | \quad P = 5(0.844mA) = 4.22 \text{ mW}$$

$$P_{\max} = 20.6 \text{ mW} \quad | \quad P_{\min} = 4.22 \text{ mW}$$

9.68

Using Eqs. 9.44 and 9.47: $V_{CC} - i_C R_C = V_T \ln\left(\frac{1}{\alpha_R}\right) \frac{1 + \frac{i_C}{(\beta_R + 1)i_B}}{1 - \frac{i_C}{\beta_F i_B}}$

$$5 - 2000i_C = 0.025 \ln\left(\frac{1}{.2}\right) \frac{1 + \frac{i_C}{1.25(1.09mA)}}{1 - \frac{i_C}{40(1.09mA)}} \rightarrow i_C = 2.4659 \text{ mA}$$

$$v_{CESAT} = 5 - 2000i_C = 0.0682V$$

9.69

$$V_H = 2.5 \text{ V} \quad | \quad V_L = V_{CESAT} = 0.15 \text{ V}$$

$$V_{IL} = 0.7 - V_{CESAT} = 0.55V \quad | \quad V_{OL} \cong V_L = 0.15V$$

$$V_{IH} \cong V_{BESAT_2} = 0.8 \text{ V} \quad | \quad V_{OH} \cong V_H = 2.5 \text{ V}$$

$$NM_L = 0.55 - 0.15 = 0.40 \text{ V} \quad NM_H = 2.5 - 0.8 = 1.7 \text{ V}$$

9.70

For $v_I = V_H$, we require $V_{CC} = V_{BE2SAT} + V_{BC1} + I_{B1}R_B = 0.8 + 0.7 + \Delta V = 1.5V + \Delta V$

where ΔV is the voltage across the base resistor. ΔV must be large enough to absorb

V_{BE} process variations and to establish the base current. 0.5 V should be sufficient.

Thus $V_{CC} = 2.0 \text{ V}$ or more is acceptable.

9.71

The VTC transitions are set by the values of v_{BE} and v_{BESAT} and are not changed by the power supply voltage. (b) $V_{IL} = 0.66 \text{ V}$ and $V_{IH} = 0.80 \text{ V}$. But $V_{OH} \cong V_H = 3 \text{ V}$ and $V_{OL} \cong V_L = 0.15 \text{ V}$. (c) $NM_H = 3 - 0.8 = 2.2 \text{ V}$ | $NM_L = 0.66 - 0.15 = 0.51 \text{ V}$.

9.72

We need to reduce the currents by a factor of 11.2. Thus, $R_B = 11.2 (4k\Omega) = 44.8 \text{ k}\Omega$ and $R_C = 11.2 (2k\Omega) = 22.4 \text{ k}\Omega$

9.73 (a)

*Problem 9.73 - Prototype TTL Inverter +Delay

VI 1 0 DC 0 PWL(0 0 0.2N 5 25N 5 25.2N 0 +50N 0)

VCC 5 0 DC 5

Q1 3 2 1 NBJT

Q2 4 3 0 NBJT

RB 5 2 4K

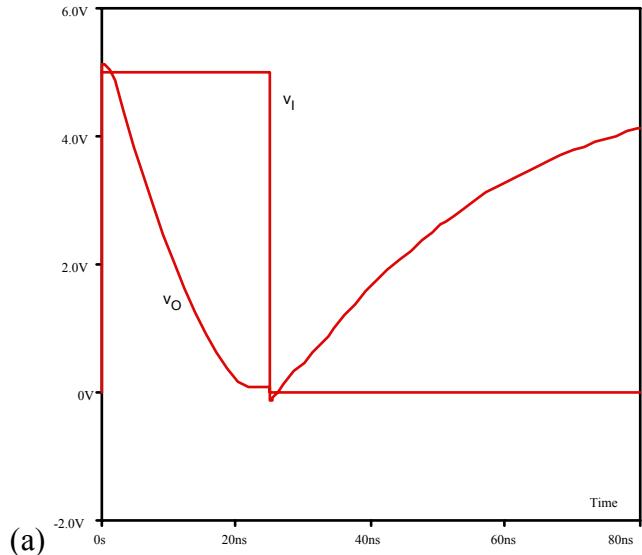
RC 5 4 2K

*RB 5 2 45.2K

```

*RC 5 4 22.6K
.OP
.TRAN .1N 80N
.MODEL NBJT NPN BF=40 BR=0.25 +IS=5E-16 TF=0.15NS TR=15NS
+CJC=0.5PF CJE=2.5PF CJS=1.0PF +RB=100 RC=5 RE=1
.PROBE V(1) V(2) V(3) V(4)
.END

```



Results: (a) $\tau_p = 2.9 \text{ ns}$ (b) $\tau_p = 15.8 \text{ ns}$.

9.74

$$(a) V_H = 5V \quad | \quad V_L = V_{CE2SAT} = 0.15V$$

$$v_I = V_L = 0.15V, \quad I_{IN} = -\frac{5 - 0.15 - 0.6}{4000} = -1.06 \text{ mA}$$

$v_I = V_H = 5V, \quad I_{IN} = -I_s \approx 0$ where I_s is the diode saturation current.

$$(b) I_B = \frac{5 - 0.8 - 0.6}{4000} = 0.90mA; \quad \frac{5 - 0.15}{2000} + N(1.06mA) \leq 40(0.9mA), \quad N \leq 31.$$

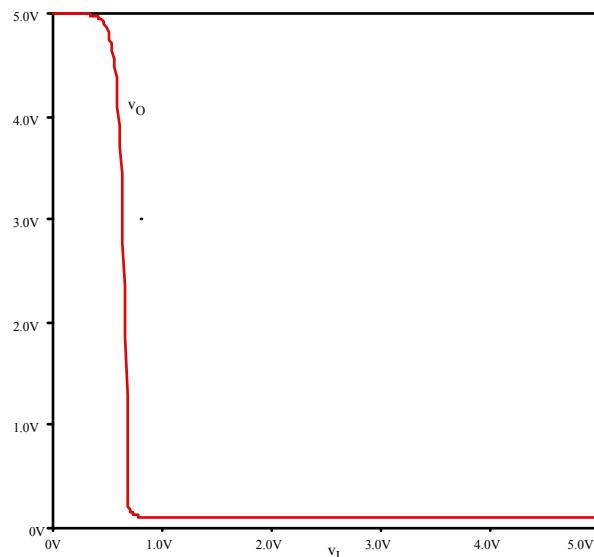
(c) -1.06 mA compared to -1.01 mA and 0 mA compared to 0.22 mA.

9.75

If we assume that the diode on-voltage is 0.7 V to match the base-emitter voltage of the BJT, then the VTC will be the same as that in Fig. 9.35. Both VTCs will be the same.

9.76

*Figure 9.76 - Prototype TTL Inverter
VTC's
VI 1 0 DC 0
VCC 5 0 DC 5
*DTL
D1A 6 1 D1
D2A 6 7 D1
RBA 5 6 4K
RCA 5 8 2K
Q2A 8 7 0 NBJT
*TTL
Q1B 3 2 1 NBJT
Q2B 4 3 0 NBJT
RBB 5 2 4K
RCB 5 4 2K
.DC VI 0 5 .01
.MODEL NBJT NPN BF=40 BR=0.25
IS=5E-16 TF =0.15NS TR=15NS
+CJC=0.5PF CJE=.25PF CJS=1.0PF
RB=100 RC=5 RE=1
.MODEL D1 D IS=5E-16 TT=0.15NS
CJO=1PF
.PROBE V(1) V(2) V(3) V(4) V(6) V(7)
V(8)
.END

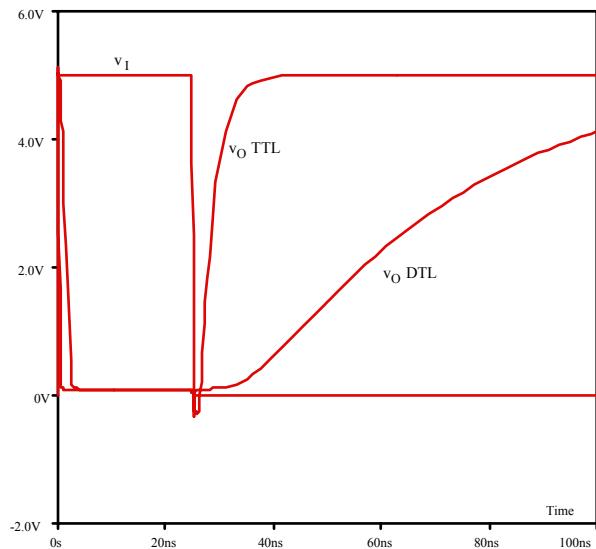


The TTL transition is sharper (more abrupt) and is shifted by approximately 50 mV.

9.77

*Figure 9.77 - Prototype Inverter Delays
VI 1 0 DC 0 PWL(0 0 0.2N 5 25N 5 25.2N 0 5 50N 0)
VCC 5 0 DC 5
*DTL
D1A 6 1 D1
D2A 6 7 D1
RBA 5 6 4K
RCA 5 8 2K
Q2A 8 7 0 NBJT
*TTL
Q1B 3 2 1 NBJT
Q2B 4 3 0 NBJT
RBB 5 2 4K
RCB 5 4 2K
.OP
.TRAN 0.1N 100N
.MODEL NBJT NPN BF=40 BR=0.25 IS=5E-16 TF =0.15NS TR=15NS
+CJC=0.5PF CJE=.25PF CJS=1.0PF RB=100 RC=5 RE=1
.MODEL D1 D IS=5E-16 TT=0.15NS CJO=1PF

```
.PROBE V(1) V(2) V(3) V(4) V(6) V(7) V(8)
.END
```



The fall time of the output of the TTL gate is somewhat slower than the DTL gate since transistor Q_1 must come out of saturation. However, the rise time of the DTL gate is extremely slow because there is no reverse base current to remove the charge from the transistor base.

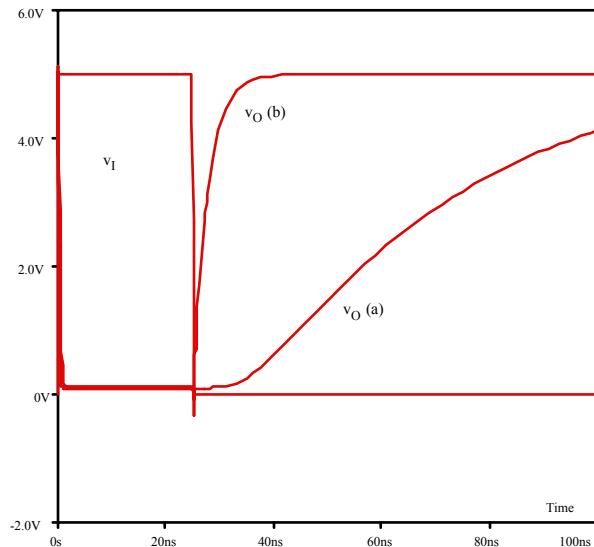
9.78

*Figure 9.78 - DTL Inverter Delays
 VI 1 0 DC 0 PWL(0 0 0.2N 5 25N 5 25.2N 0 50N 0)
 VCC 5 0 DC 5

*DTLA
 D1A 6 1 D1
 D2A 6 7 D1
 RBA 5 6 4K
 RCA 5 8 2K
 Q2A 8 7 0 NBJT

*DTL-B
 D1B 2 1 D1
 D2B 2 3 D1
 Q2B 4 3 0 NBJT
 RBB 5 2 4K
 RCB 5 4 2K
 RB1 3 0 1K

.OP
 .TRAN 0.1N 100N
 .MODEL NBJT NPN BF=40 BR=0.25 IS=5E-16 TF =0.15NS TR=15NS
 +CJC=0.5PF CJE=.25PF CJS=1.0PF RB=100 RC=5 RE=1
 .MODEL D1 D IS=5E-16 TT=0.15NS CJO=1PF
 .PROBE V(1) V(2) V(3) V(4) V(6) V(7) V(8)
 .END



Without the $1-k\Omega$ resistor, the rise time of the DTL gate is extremely slow because there is no reverse base current to remove the charge from the transistor base. The resistor provides an initial reverse base current of -0.7 mA to turn off the transistor and significantly reduces the rise time and propagation delay.

9.79

See problem 9.80.

9.80

*Figure 9.79 - Inverter VTC

VI 1 0 DC 0

VCC 6 0 DC 3.3

Q1 3 2 1 NBJT

Q2 5 3 4 NBJT

Q3 5 4 0 NBJT

R1 6 2 4K

R2 6 5 2K

R3 4 0 3K

.OP

.DC VI 0 3.3 0.01

.MODEL NBJT NPN BF=40 BR=0.25

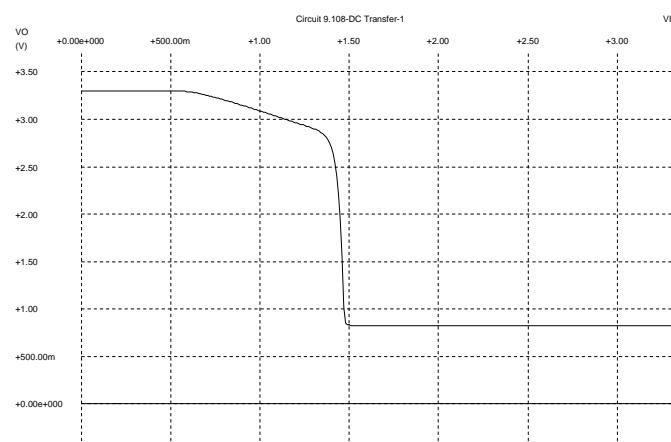
IS=1E-16 TF =0.15NS TR=15NS

+CJC=0.5PF CJE=.25PF CJS=1.0PF

RB=100 RC=5 RE=1

.PROBE V(1) V(2) V(3) V(4) V(5)

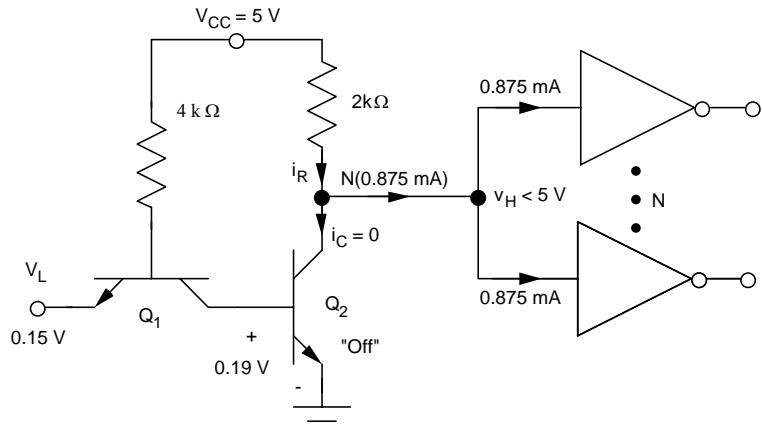
.END



The first break point occurs when the input reaches a voltage large enough to just start turning on Q_2 , at approximately $V_{CESAT1} + V_{BE2} = 0.04V + 0.6V = 0.64V$. The second breakpoint begins when the input reaches $V_{CESAT1} + V_{BE2} + V_{BE3} = 0.04V + 0.7 + 0.6V = 1.34V$. Note

that the shallow slope is set by the ratio of $R_2/R_3 = 2/3$, and also note that Q_3 cannot saturate. From the B2SPICE simulation, $V_H = 3.3$ V, $V_L \approx V_{BE3} + V_{CESAT2} = 0.82$ V, $V_{IH} = 1.38$ V, $V_{OL} = 0.84$ V, $V_{IL} = 1.38$ V, $V_{OH} = 2.82$ V. $NM_H = 2.82 - 1.38 = 1.54$ V. $NM_L = 1.38 - 0.84 = 0.54$ V.

9.81

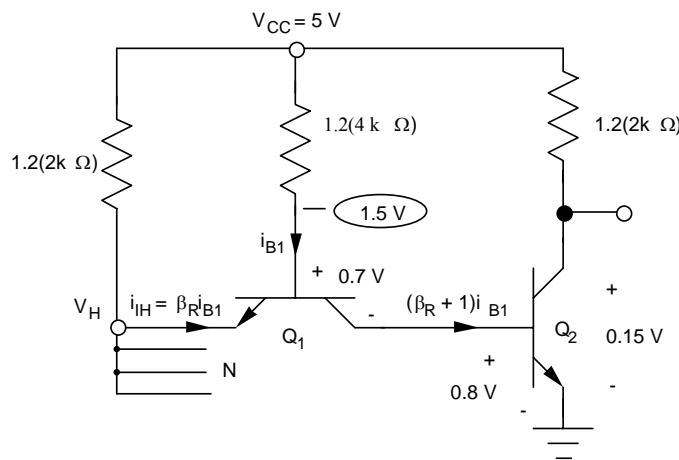


From the analysis in the text, we see that the fanout is limited by the V_H condition.

$$i_{B1} = \frac{5 - 0.7 - 0.8}{4} \frac{V}{k\Omega} = 0.875 \text{ mA} \quad | \quad i_{E1} = -\beta_R i_{B1} = -0.875 \text{ mA}$$

$$5 - 2000(N)(0.875 \times 10^{-3}) \geq 1.5 \rightarrow N \leq 2 \rightarrow \text{Fanout} = 2$$

9.82



From the analysis in the text, we see that the fanout is limited by the V_H condition.

$$i_{B1} = \frac{5 - 0.7 - 0.8}{4(1.2)} \frac{V}{k\Omega} = 0.729mA \quad | \quad i_{E1} = -\beta_R i_{B1} = -0.25(0.729mA) = 0.182mA$$

$$5 - 2000(1.2)(N)(0.182 \times 10^{-3}) \geq 1.5 \rightarrow N \leq 8.01 \rightarrow \text{Fanout} = 8$$

$$i_{B1} = \frac{5 - 0.7 - 0.8}{4(0.8)} \frac{V}{k\Omega} = 1.09mA \quad | \quad i_{E1} = -\beta_R i_{B1} = -0.25(1.09mA) = 0.273mA$$

$$5 - 2000(0.8)(N)(0.273 \times 10^{-3}) \geq 1.5 \rightarrow N \leq 8.01 \rightarrow \text{Fanout} = 8$$

The result is independent of the tolerance if the resistors track each other.

Note that Eq. 9.83 also yields $N = 8$ if more digits are used in the calculation.

9.83

From the analysis in the text, we see that the fanout is limited by the V_H condition.

$$i_{B1} = \frac{5 - 0.7 - 0.8}{R_B} \quad i_{E1} = -\beta_R i_{B1} = -0.25i_{B1}$$

$$5 - 2000(N)(0.25) \frac{5 - 0.7 - 0.8}{R_B} \geq 1.5 \rightarrow R_B \geq 5 k\Omega$$

9.84

(a) Q_4 is in the forward - active region with $I_E = (\beta_F + 1)I_B$

$$I_E = 101 \frac{5 - 0.7 - 0.6}{1600} = 234 mA$$

$$(b) Q_4 saturates; I_E = I_B + I_C = \frac{5 - 0.8 - 0.6}{1600} + \frac{5 - 0.6 - 0.15}{130} = 34.9 mA$$

9.85

(a) $P_D = 5V(234mA) = 1.17 W$ (b) $P_D = 5V(34.9mA) = 0.175 W$

9.86

*Figure 9.86 - TTL Output Current

VCC 5 0 DC 5

RB 5 3 1.6K

RS 5 4 130

Q1 4 3 2 NBJT

D1 2 1 D1

IL 1 0 DC 0

.DC IL 0 30MA 0.01MA

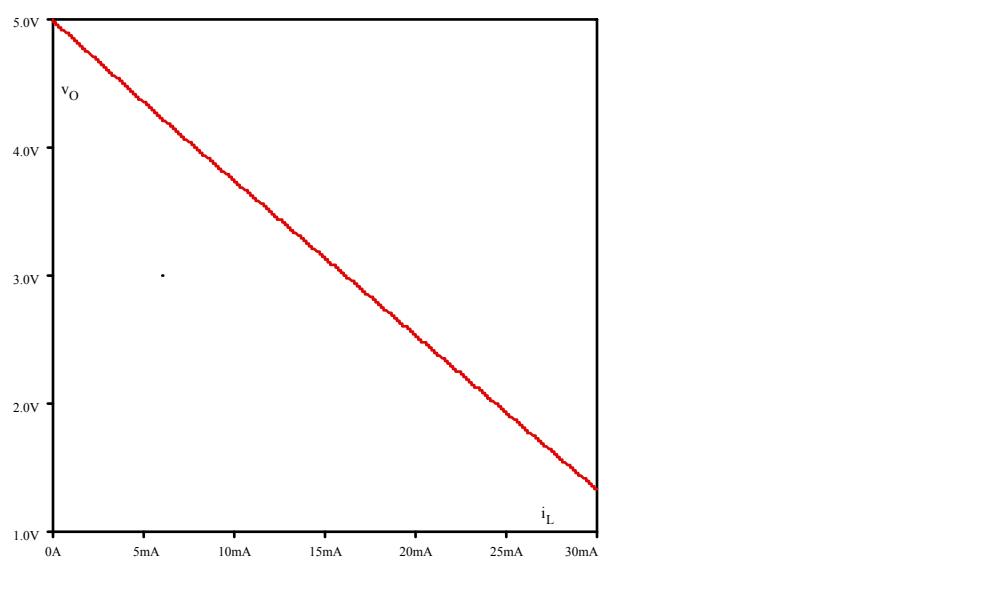
.MODEL NBJT NPN BF=40 BR=0.25 IS=5E-16 TF =0.15NS TR=15NS

+CJC=0.5PF CJE=.25PF CJS=1.0PF RB=100 RC=5 RE=1

.MODEL D1 D IS=5E-16

.PROBE V(1) V(2) V(3) V(4)

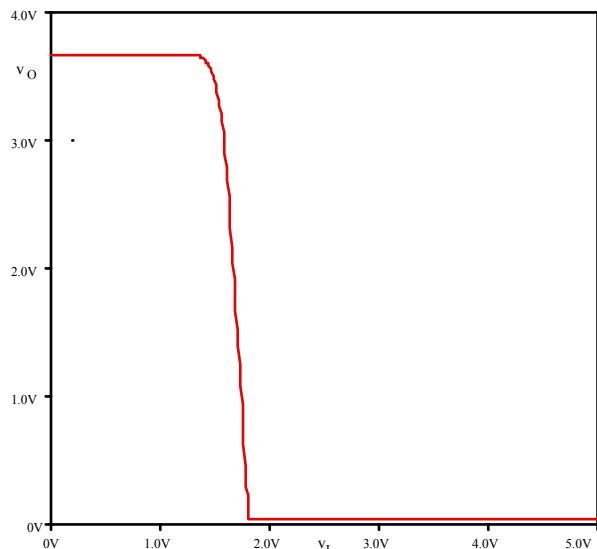
.END



9.87

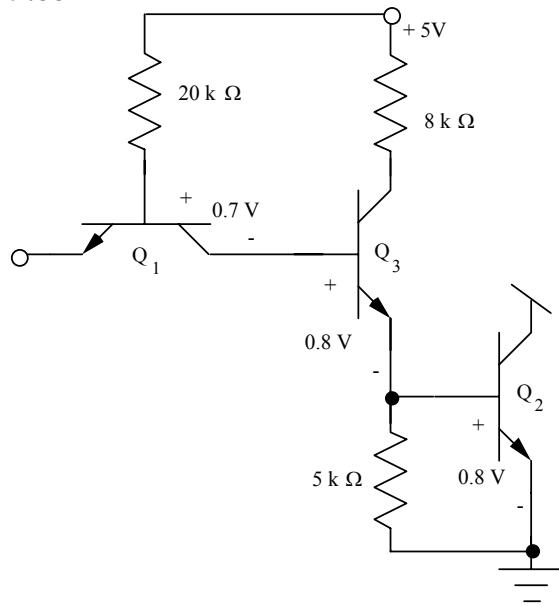
*Problem 9.87 - Modified TTL Inverter VTC

```
VI 1 0 DC 0
VCC 9 0 DC 5
Q1 2 8 1 NBJT
Q2 4 3 0 NBJT
Q3 6 2 3 NBJT
Q4 7 6 5 NBJT
D1 5 4 DN
RB 9 8 4K
RC 9 6 1.6K
RS 9 7 130
RL 4 0 100K
Q5 10 11 0 NBJT
RB5 3 11 3K
RC5 3 10 1K
.DC VI 0 5 .01
.MODEL NBJT NPN BF=40 BR=0.25 IS=1E-17 TF =0.25NS TR=25NS
+CJC=.6PF CJE=.6PF CJS=1.25PF RB=100 RC=5 RE=1
.MODEL DN D
.PROBE V(1) V(2) V(3) V(4) V(5) V(6)
.END
```



In the modified TTL circuit, Q_3 cannot start conducting until its base reaches at least $V_{BE5} + V_{BE6} = 1.2$ V.

9.88



(a) $v_I = V_H : Q_4 \text{ off} - I_{B4} = 0 = I_{C4} \quad | \quad Q_2 \text{ saturated with } I_{C4} = 0$

$$I_{B1} = \frac{(5 - 0.7 - 0.8 - 0.8)V}{20k\Omega} = 135 \mu A \quad | \quad I_{E1} = -\beta_R I_{B1} = -0.25(135 \mu A) = -33.8 \mu A$$

$$I_{C1} = -169 \mu A \quad | \quad I_{C3} = \frac{(5 - 0.15 - 0.8)V}{8k\Omega} = 506 \mu A$$

$$I_{E3} = 506 \mu A + 169 \mu A = 675 \mu A \quad | \quad I_{B2} = 675 \mu A - \frac{0.8V}{5k\Omega} = 515 \mu A$$

(b) $v_I = V_L : Q_2, Q_3 \text{ off}; Q_4 \text{ on}$

$$I_{B1} = \frac{(5 - 0.8 - 0.15)V}{20k\Omega} = 203 \mu A = I_{E1} \quad | \quad I_{C1} = 0$$

9.89

See Problem 9.90.

9.90

*Problem 9.90 - Low Power TTL Inverter

VTC versus Temperature

```

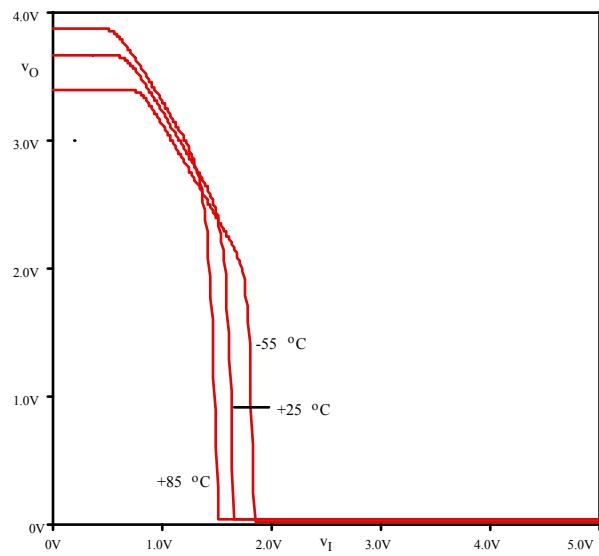
VI 1 0 DC 0
VCC 9 0 DC 5
Q1 2 8 1 NBJT
Q2 4 3 0 NBJT
Q3 6 2 3 NBJT
Q4 7 6 5 NBJT
D1 5 4 DN
RB 9 8 20K
RC 9 6 8K
RS 9 7 650
RL 4 0 100K
RE 3 0 5K
.DC VI 0 5 .01
.TEMP -55 25 85

```

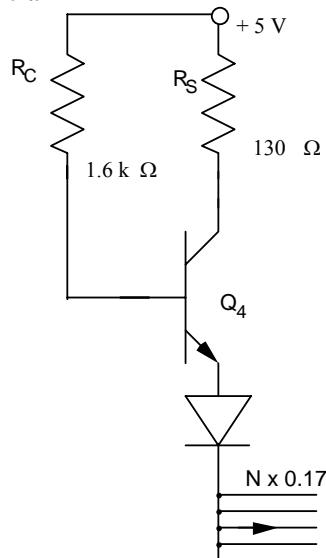
```

.MODEL NBJT NPN BF=40 BR=0.25 IS=1E-
17 TF =0.25NS TR=25NS
+CJC=0.6PF CJE=.6PF CJS=1.25PF RB=100
RC=5 RE=1
.MODEL DN D
.PROBE V(1) V(2) V(3) V(4) V(5) V(6)
.END

```



9.91



$$V_H = 5 - 0.7 - 0.7 - \frac{N(I_{IH})}{\beta_F + 1} R_C$$

$$V_H = 3.6 - \frac{N(0.17mA)}{40 + 1} (1600)$$

$$V_H \geq 2.4V \rightarrow N \leq 180$$

9.92

For small β_R , fanout is limited by the $v_O = V_L$ case ($v_I = V_H$).

$$i_{B3} = (\beta_R + 1)i_{B1} = 1.05 \frac{(5 - 0.7 - 0.8 - 0.8)V}{5k\Omega} = 567\mu A$$

$$i_{B2} = i_{E3} - i_{R_E} = \frac{(5 - 0.15 - 0.8)V}{2k\Omega} + 567\mu A - \frac{0.8V}{1.25k\Omega} = 1.95mA$$

$$i_{IL} = -i_{E1} = -i_{B1} = \frac{(5 - 0.8 - 0.15)V}{5k\Omega} = 0.810mA \quad | \quad \alpha_R = \frac{\beta_R}{1 + \beta_R} = \frac{0.05}{1.05} = 0.0476$$

$$\text{Using Eq. 9.61, } \Gamma = \exp\left(\frac{0.15V}{0.025V}\right) = 403.4 \rightarrow \beta_{FOR} = 20 \frac{1 - \frac{1}{0.0476(403.4)}}{1 + \frac{20}{0.05} \frac{1}{403.4}} = 9.52$$

$$N(0.810mA) \leq 9.52(1.95mA) \rightarrow N = 22$$

9.93

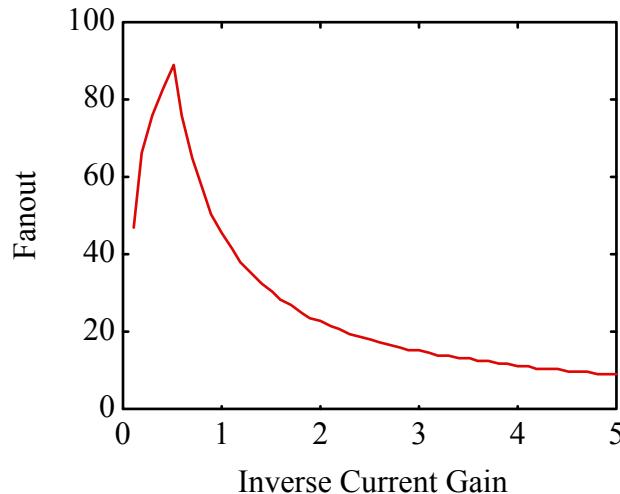
For the $v_O = V_L$ case, the equations are given in Problem 9.92. For $v_O = V_H$,

$$V_H = 5 - I_{B4}R_C - 0.7 - 0.7 \geq 2.4V$$

$$I_{IH} = \beta_R \left(\frac{5 - 0.7 - 0.8 - 0.8}{4000} \right) = \beta_R \left(\frac{2.7}{4000} \right)$$

$$I_{B4} = \frac{NI_{IH}}{\beta_F + 1} = \frac{N\beta_R}{\beta_F + 1} \left(\frac{2.7}{4000} \right)$$

$$N \leq \frac{1.2(\beta_F + 1)(4000)}{2.7\beta_R(1600)}$$

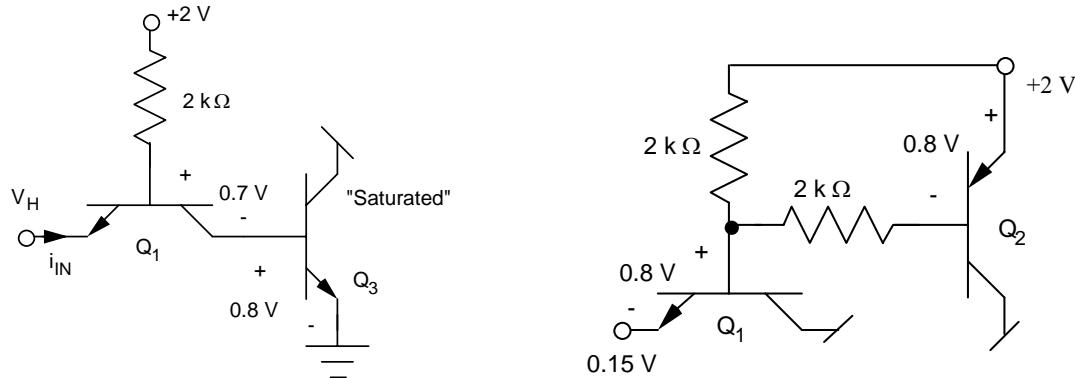


```

function [N,X]=P993
br=0;
bf=40;
g=exp(.15/.025);
for i=1:50
    br=br+.1;
    ar=br/(1+br);
    ib3=(1+br)*675;
    ib2=1730+ib3;
    bfor=40*(1-1/(ar*g))/(1+bf/(br*g));
    N1=fix(bfor*ib2/1013);
    N2=1.2*(bf+1)*4000/(2.7*br*1600);
    N(i)=min(N1,N2);
    X(i)=0.1*i;
end
»[Y,X]=p993;
»plot(X,Y)

```

9.94



$$(a) V_H = 2 - V_{ECSAT2} = 2 - 0.15 = 1.85 \text{ V} \quad | \quad V_L = V_{CESAT3} = 0.15 \text{ V}$$

$$(b) i_{IH} : i_{B2} \approx 0 \quad | \quad i_{IH} = 0.25 \frac{(2 - 0.7 - 0.8)V}{2k\Omega} = 62.5 \mu\text{A}$$

$$i_{IL} = -i_{B1} = -\frac{(2 - 0.8 - 0.15)V}{2k\Omega} - \frac{(2 - 0.8 - 0.8 - 0.15)V}{2k\Omega} = -650 \mu\text{A}$$

(c) Assume $\beta_{FOR} \leq 28.3$

$$\text{For the pnp transistor : } N(62.5\mu\text{A}) \leq 28.3 \frac{(2 - 0.8 - 0.8 - 0.15)V}{2k\Omega} \rightarrow N = 56$$

$$\text{For the npn transistor : } N(650\mu\text{A}) \leq 28.3(1.25) \frac{(2 - 0.7 - 0.8)V}{2k\Omega} \rightarrow N = 13$$

9.95

$$(a) V_L = V_{CESAT_3} = 0.15 \text{ V} \quad | \quad V_H = 2 - V_{BE2} = 2 - 0.7 = 1.3 \text{ V}$$

$$(b) v_I = 0.15V : i_{IL} = -(i_{B1} + i_{C1}) = -\left(\frac{2 - 0.8 - 0.15}{10000} + \frac{2 - 0.15 - 0.15}{12000}\right) = -247 \mu A$$

$$v_I = 1.3V : i_{IL} = \beta_R i_{B1} = 0.25 \left(\frac{2 - 0.7 - 0.8}{10^4} \right) = 12.5 \mu A$$

$$(c) \text{ Using } \beta_{FOR} = 28.3 : i_L = i_{B2} + i_{C2} = \frac{2 - 0.8 - 0.15}{6000} + \frac{2 - 0.15 - 0.15}{1000} = 1.875mA$$

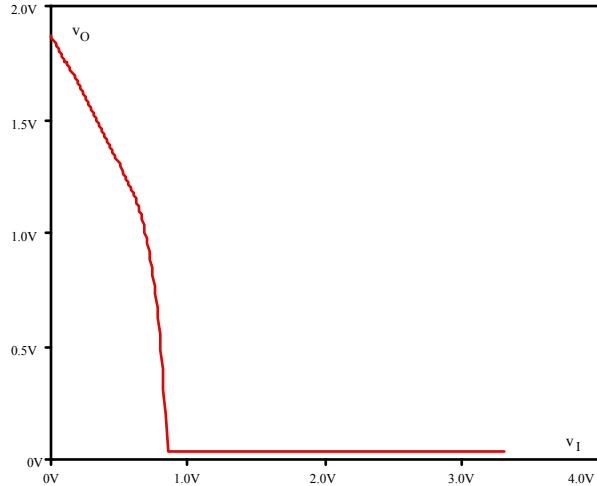
$$i_{B3} = \frac{2 - 0.8}{12000} + 1.25 \left(\frac{2 - 0.7 - 0.8}{10000} \right) = 162.5 \mu A$$

$$28.3(0.1625mA) \geq N(0.247mA) + 1.875mA \rightarrow N = 11$$

9.96

$$(a) Y = \overline{ABC} \quad (b) V_L = V_{CESAT_3} = 0.15 \text{ V} \quad | \quad V_H = 3.3 - V_{BE1} - V_D = 3.3 - 1.4 = 1.9 \text{ V}$$

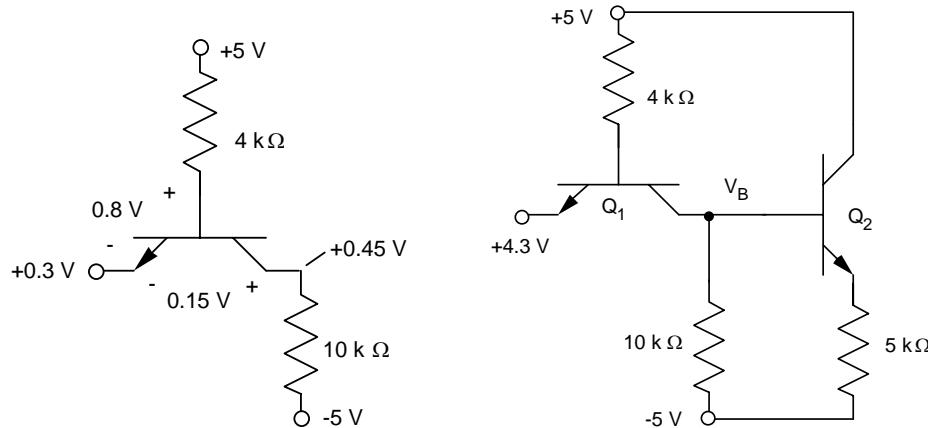
$$(c) v_I = 1.9V, \text{ input diode is off and } i_{IH} = 0. \quad v_I = 0.15V, \quad i_{IL} = -\frac{3.3 - 0.7 - 0.15}{6000} = -408 \mu A$$



The VTC starts to decrease immediately because Q₂ is ready to conduct due to the 0.7-V drop across the input diode. When the input has increased to approximately 0.7 V, Q₃ begins to conduct and the output drops rapidly. The VTC is much sloppier than that of the corresponding TTL gate. For this particular circuit V_{IL} = 0 and V_{IH} = 0.8 V. Based upon our definitions, NM_L = 0. However, the initial slope can be reduced by changing the ratio R_C/R₂ so that V_{IL} = 0.7 V.

9.97

(a) If either input A or input B is low, V_{B2} will be low. Q_2 will be off, Q_3 will be on and Y will be low. Therefore $\bar{Y} = \bar{A} + \bar{B} \rightarrow Y = AB$.



$$(b) V_H = 5 - I_{B5}R_2 - V_{BE5} \approx 5 - V_{BE5} = 5 - 0.7 = 4.30 \text{ V}$$

$$V_L = 5 - \alpha_F I_{E3} R_2 - I_{B5} R_2 - V_{BE5} \approx 5 - I_{E3} R_2 - V_{BE5}$$

$$I_{E3} = \frac{+0.7 - 0.7 - (-5)}{5000} = 1.00 \text{ mA} \quad | \quad V_L = 5 - 0.001(4000) - 0.7 = +0.300 \text{ V}$$

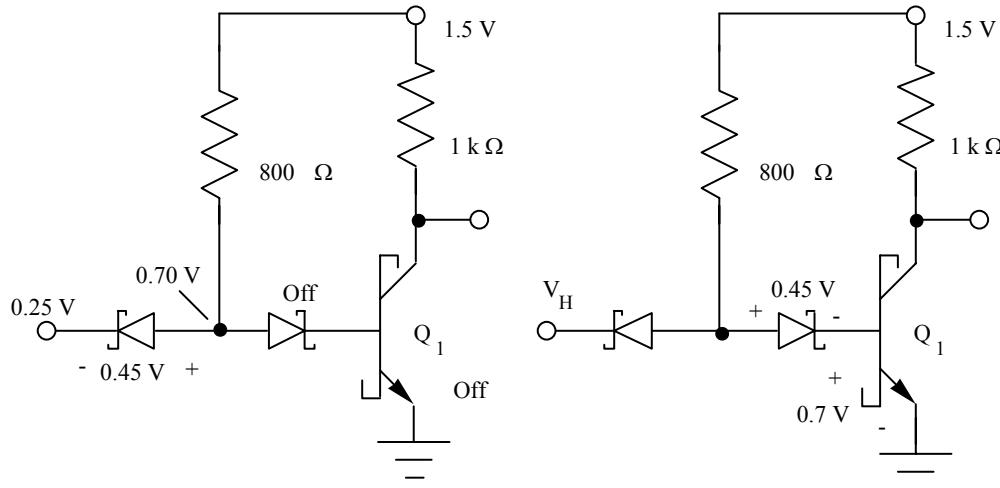
$$(c) v_I = 4.3V : 1.25 \left(\frac{5 - 0.7 - V_B}{4000} \right) = \frac{V_B - (-5)}{10000} + \frac{V_B - 0.7 - (-5)}{5000} \frac{1}{41} \rightarrow V_B = 1.97V$$

$$I_{B1} = \frac{5 - 0.7 - 1.97}{4000} = 582 \mu\text{A} \quad | \quad I_{E1} = -0.25 I_{B1} = -146 \mu\text{A} \quad | \quad I_{IH} = 146 \mu\text{A}$$

$$v_I = 0.3V : I_{B1} = \frac{5 - 0.8 - 0.3}{4000} = 975 \mu\text{A} \quad | \quad I_{C1} = -\frac{0.3 + 0.15 - (-5)}{10000} = -545 \mu\text{A}$$

$$I_{E1} = I_{B1} + I_{C1} = 430 \mu\text{A} \quad | \quad I_{IL} = -430 \mu\text{A}$$

9.98



(a) $V_H = V_{CC} = 1.5 \text{ V}$ | $V_L = "V_{CESAT1}" = 0.7 - 0.45 = 0.25 \text{ V}$

(b) For $v_I = 1.5 \text{ V}$, the input diode is off, and $I_{IH} = 0$.

$$\text{For } v_I = 0.25 \text{ V}, I_{IL} = \frac{1.5 - 0.45 - 0.25}{800} = 1.00 \text{ mA}$$

(c) Note that Q_1 operates as if it were in the forward-active region:

$$\beta_F I_{B1} \geq N I_{IL} + I_{R_2} \quad | \quad 40 \left(\frac{1.5 - 0.45 - 0.70}{800} \right) \geq N(0.001) + \frac{1.5 - 0.25}{1000} \rightarrow N = 16$$

9.99

$$v_{BE} + v_{D2} - v_{D1} = v_{CE} \quad | \quad \text{For } v_{D2} \cong v_{D1}, v_{CE} = v_{BE} = 0.7 \text{ V}$$

$$i_C = i_{CC} + i_{D1} \quad | \quad i_B = i_{BB} - i_{D1} \quad | \quad i_C = \beta_F i_B$$

$$i_{CC} + i_{D1} = \beta_F (i_{BB} - i_{D1}) \rightarrow i_{D1} = \frac{\beta_F i_{BB} - i_{CC}}{\beta_F + 1} = \frac{20(0.25) - 1}{21} \text{ mA} = 0.191 \text{ mA}$$

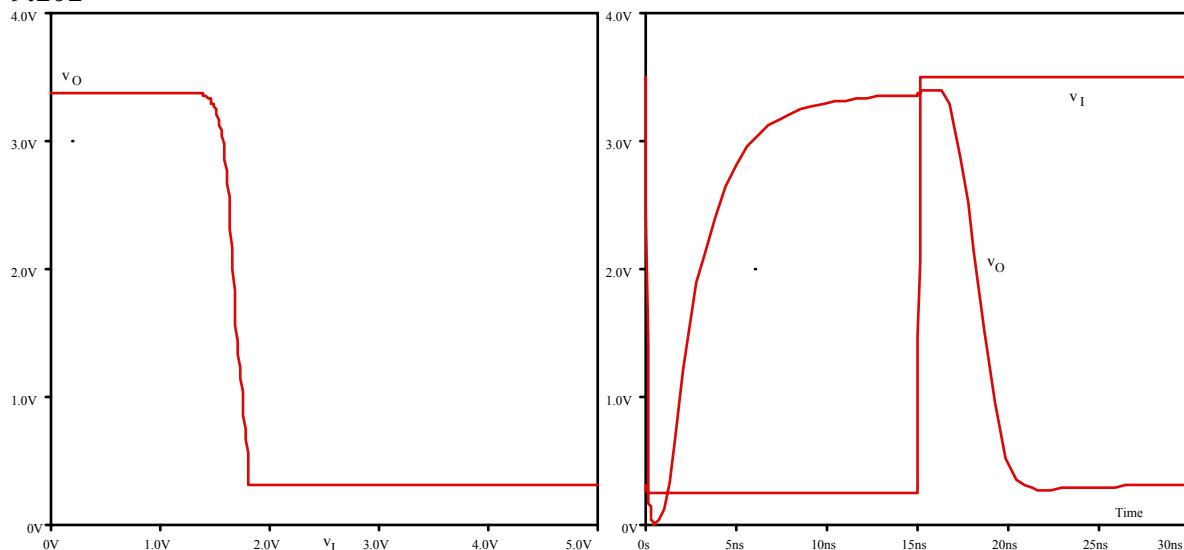
$$i_{D2} = i_{BB} - i_{D1} = 0.25 - 0.191 = 0.059 \text{ mA} \quad | \quad i_C = 20i_B = 20i_{D2} = 1.18 \text{ mA}$$

9.100

In this circuit as drawn, the collector-base junction of Q_1 is bypassed by a Schottky diode. Q_1 will be "off" with $V_{BC} = +0.45 \text{ V}$.

$$i_{B1} = \frac{5 - 0.45 - 0.7}{4000} = 963 \mu\text{A} \quad | \quad I_{IN} = 0 \quad | \quad i_{B2} = i_{B1} = 963 \mu\text{A}$$

9.101

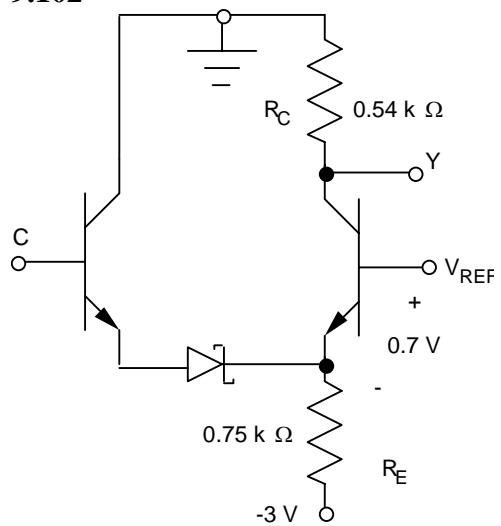


Result: $\tau_p = 3.0 \text{ ns}$

*Problem 9.101 - Schottky TTL Inverter VTC
 VI 1 0 DC 3.5 PWL(0 3.5 0.2N 0.25 15N 0.25 15.2N 3.5 30N 3.5)

VCC 9 0 DC 5
Q1 2 8 1 NBJT
D1 2 8 DS
Q2 4 3 0 NBJT
D2 3 4 DS
Q3 6 2 3 NBJT
D3 2 6 DS
Q4 7 5 4 NBJT
Q5 7 6 5 NBJT
D5 6 7 DS
RB 9 8 2.8K
RC 9 6 900
RS 9 7 50
R5 5 0 3.5K
RL 4 0 100K
Q6 10 11 0 NBJT
D6 11 10 DS
R2 3 11 500
R6 3 10 250
.OP
.DC VI 0 5 .01
.TRAN .025N 30N
.MODEL NBJT NPN BF=40 BR=0.25 IS=1E-17 TF =0.15NS TR=15NS
+CJC=1PF CJE=.5PF CJS=1PF RB=100 RC=10 RE=1
.MODEL DS D IS=1E-12
.PROBE V(1) V(2) V(3) V(4) V(5) V(6)
.END

9.102

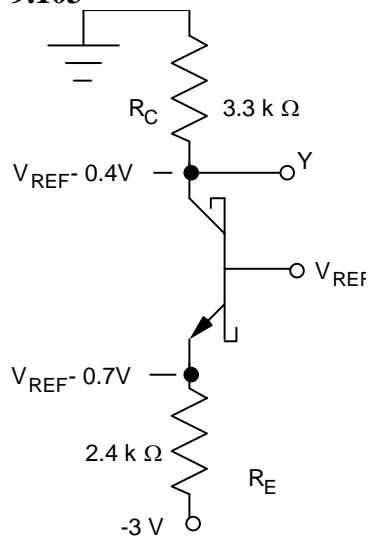


$$Y = A + B + C \quad | \quad V_H = 0 \text{ V} \quad | \quad V_L = -540I_C = -540 \frac{V_{REF} - 0.7 - (-3)}{750} = -0.72(V_{REF} + 2.3)$$

$$\frac{V_H + V_L}{2} = V_{REF} - 0.7 + 0.4 + 0.7 = V_{REF} + 0.4$$

$$\frac{0 - 0.72(V_{REF} + 2.3)}{2} = V_{REF} + 0.4 \rightarrow V_{REF} = -0.903 \text{ V} \quad | \quad V_L = -0.72(-0.903 + 2.3) = -1.01 \text{ V}$$

9.103



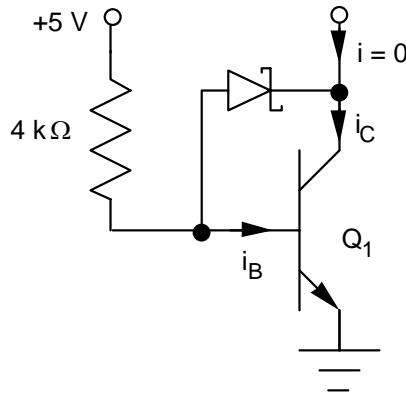
$$Y = A + B + C \quad | \quad V_H = 0 \text{ V} \quad | \quad V_L = V_{REF} - 0.4$$

$$\frac{V_H + V_L}{2} = V_{REF} \quad | \quad \frac{0 + (V_{REF} - 0.4)}{2} = V_{REF} \rightarrow V_{REF} = -0.40 \text{ V} \quad | \quad V_L = -0.80 \text{ V}$$

9.104

The circuit can be modeled by a normal BJT with a Schottky diode in parallel with the collector base junction. If i_C and i_B are defined to be the collector- and base-currents of the BJT,

$$i_C + i_B = \frac{5 - 0.7}{4000} = 1.075 \text{ mA} \quad | \quad i_C \cong \beta_F i_B \rightarrow i_B = \frac{1.075 \text{ mA}}{40} = 26.9 \mu\text{A} \quad | \quad i_C = 1.05 \text{ mA}$$



9.105

If we assume 50% of the gates are switching (an over estimate),

$$(a) P = \frac{50W}{0.5(50 \times 10^6)} = 2 \mu\text{W/gate} \quad | \quad \tau_p = 1 \text{ ns} \quad | \quad PDP = (2 \mu\text{W})(1 \text{ ns}) = 2 \text{ fJ}$$

(b) $PDP = (0.1 \text{ mW})(0.1 \text{ ns}) = 10 \text{ fJ}$ | The result in Part (a) is off the graph!

9.106

If we assume 50% of the gates are switching (an over estimate),

$$(a) P = \frac{100W}{0.5(200 \times 10^6)} = 1 \mu\text{W/gate} \quad | \quad \tau_p = 0.25 \text{ ns} \quad | \quad PDP = (1 \mu\text{W})(0.25 \text{ ns}) = 0.25 \text{ fJ}$$

(b) $PDP = (0.1 \text{ mW})(0.1 \text{ ns}) = 10 \text{ fJ}$ | The result in Part (a) is off the graph!

9.107

$$(a) \tau_p = \frac{PDP}{P} = \frac{0.5 \text{ pJ}}{0.3 \text{ mW}} = 1.67 \text{ ns} \quad (b) P = \frac{PDP}{\tau_p} = \frac{0.5 \text{ pJ}}{1 \text{ ns}} = 0.5 \text{ mW}$$

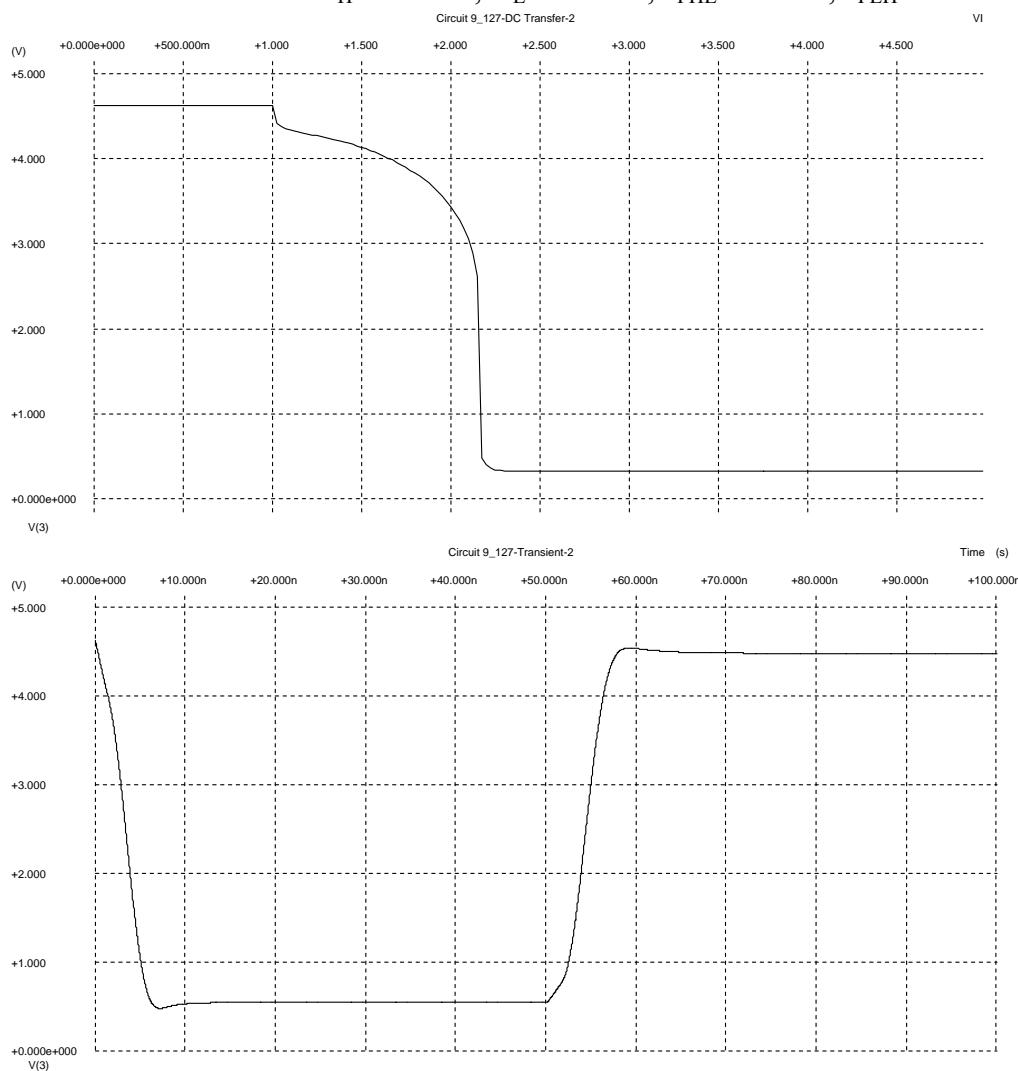
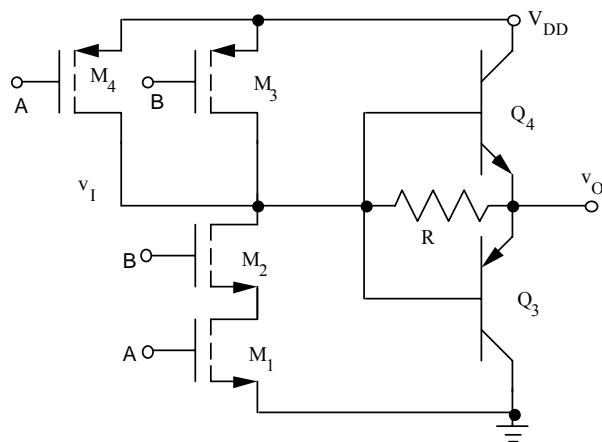
9.109

$$(a) PDP = (0.7 \text{ ns})(40 \text{ mW}) = 28 \text{ pJ} \quad | \quad \tau_p = \frac{PDP}{P} = \frac{28 \text{ pJ}}{10 \text{ mW}} = 2.8 \text{ ns}$$

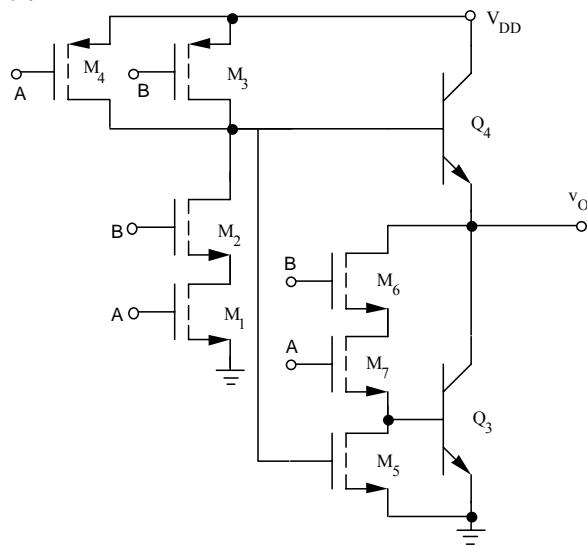
$$(b) P = \frac{PDP}{\tau_p} = \frac{28 \text{ pJ}}{0.2 \text{ ns}} = 140 \text{ mW}$$

9.110

Results from B²SPICE: $V_H = 4.48 \text{ V}$, $V_L = 0.54 \text{ V}$, $\tau_{PHL} = 3.3 \text{ ns}$, $\tau_{PLH} = 4.4 \text{ ns}$.

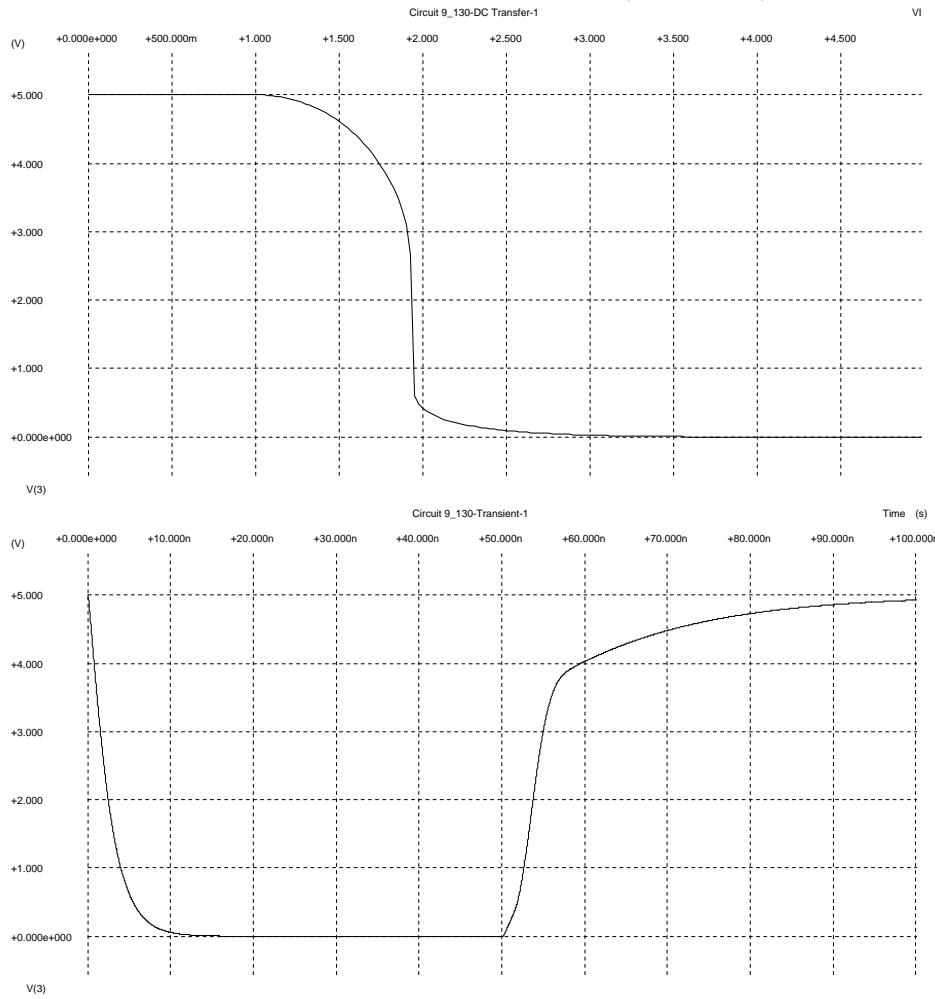
**9.111**

9.112

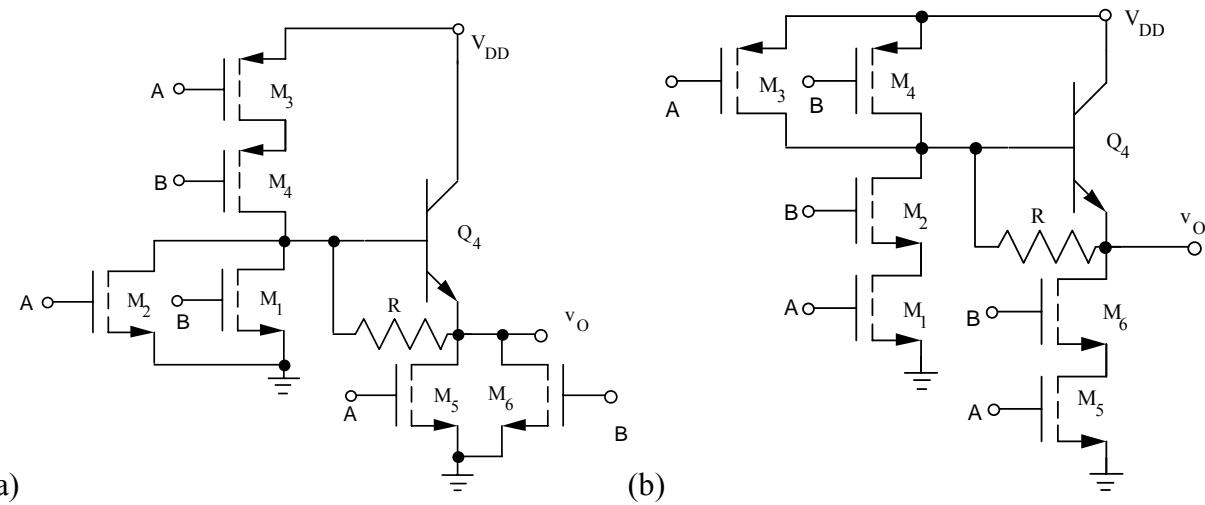


9.113

Results from B²SPICE with $R = 4 \text{ k}\Omega$; $V_H = 5 \text{ V}$, $V_L = 0 \text{ V}$, $\tau_{PHL} = 1.9 \text{ ns}$, $\tau_{PLH} = 4.1 \text{ ns}$.

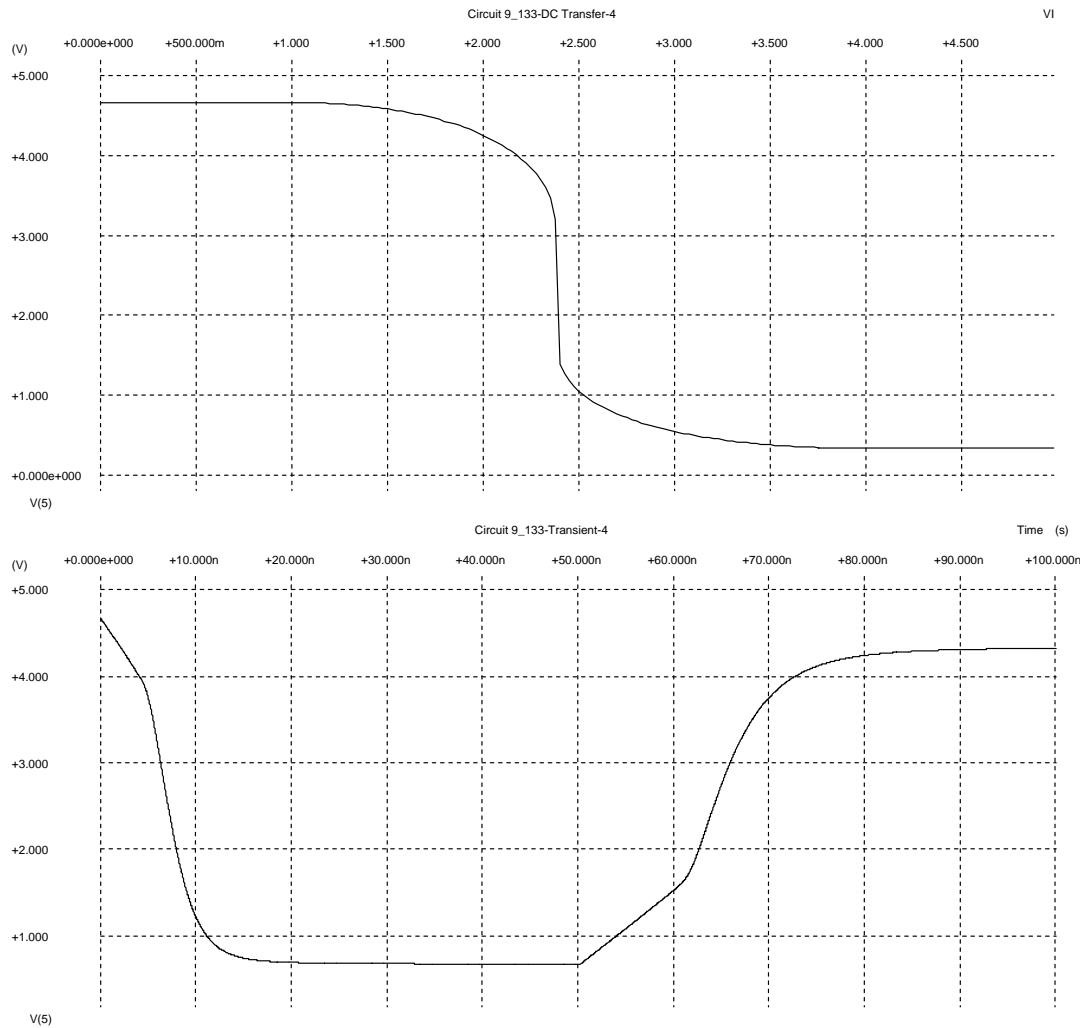


9.114



9.115

Results from B²SPICE: $V_H = 4.7 \text{ V}$, $V_L = 0.34 \text{ V}$, $\tau_{PHL} = 7.0 \text{ ns}$, $\tau_{PLH} = 14 \text{ ns}$.



CHAPTER 10

10.1

A/C temperature	current amplitude
Automobile	current phase
coolant temperature	power
gasoline level	power factor
oil pressure	spectrum
sound intensity	Fan speed
inside temperature	Humidity
Battery charge level	Lawn mower speed
Battery voltage	Light intensity
Fluid level	Oven temperature
Computer display	Refrigerator temperature
hue	Sewing machine speed
contrast	Stereo volume
brightness	Stove temperature
Electrical variables	Time
voltage amplitude	TV picture brightness
voltage phase	TV sound level
	Wind velocity

10.2

(a) $20 \log(120) = 41.6 \text{ dB}$ | $20 \log(60) = 35.6 \text{ dB}$ | $20 \log(50000) = 94.0 \text{ dB}$

$20 \log(100000) = 100 \text{ dB}$ | $20 \log(0.90) = -0.915 \text{ dB}$

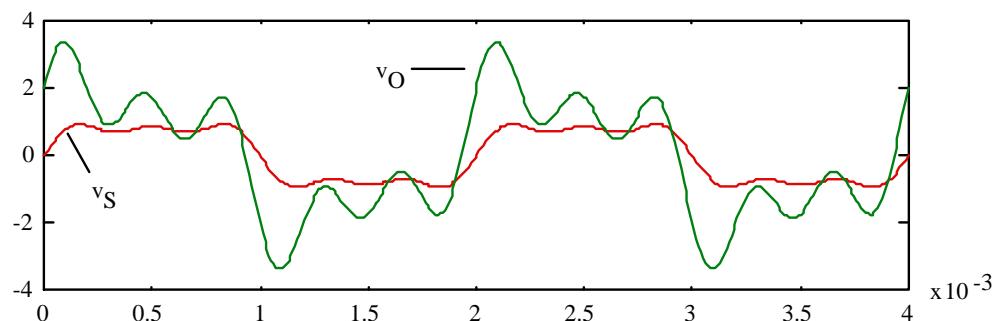
(b) $20 \log(600) = 55.6 \text{ dB}$ | $20 \log(3000) = 69.5 \text{ dB}$ | $20 \log(10^6) = 120 \text{ dB}$

$20 \log(200000) = 106 \text{ dB}$ | $20 \log(0.95) = -0.446 \text{ dB}$

(c) $10 \log(2 \times 10^9) = 93.0 \text{ dB}$ | $10 \log(4 \times 10^5) = 56.0 \text{ dB}$

$10 \log(6 \times 10^8) = 87.8 \text{ dB}$ | $10 \log(10^{10}) = 100 \text{ dB}$

10.3 (a)



- (b) 500 Hz: $1\angle 0^\circ$ | 1500 Hz: $0.333\angle 0^\circ$ | 2500 Hz: $0.200\angle 0^\circ$
(c) 500 Hz: $2\angle 30^\circ$ | 1500 Hz: $1\angle 30^\circ$ | 2500 Hz: $1\angle 30^\circ$
(d) 500 Hz: $2\angle 30^\circ$ | 1500 Hz: $3\angle 30^\circ$ | 2500 Hz: $5\angle 30^\circ$
(e) Yes
-

10.4

$$V_s = 0.0025V \quad | \quad P_o = 40W \quad | \quad V_o = \sqrt{2P_oR_L} = \sqrt{2(40)(8)} = 25.3V$$

$$|A_v| = \frac{25.3}{0.0025} = 10100 \quad | \quad 20 \log (10100) = 80.1 dB$$

$$I_s = \frac{0.0025V}{5k\Omega + 50k\Omega} = 45.45nA \quad | \quad I_o = \frac{V_o}{8\Omega} = \frac{25.3V}{8\Omega} = 3.162A$$

$$|A_i| = \frac{3.162A}{45.45nA} = 6.96 \times 10^7 \quad | \quad 20 \log (3.48 \times 10^7) = 157 dB$$

$$A_p = \frac{40W}{\frac{.0025V(45.45nA)}{2}} = 7.04 \times 10^{11} \quad | \quad 10 \log (7.04 \times 10^{11}) = 118 dB$$

10.5

$$V_s = 0.01V \quad | \quad P_o = 20mW \quad | \quad V_o = \sqrt{2P_oR_L} = \sqrt{2(0.02)(8)} = 0.566V$$

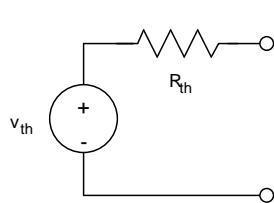
$$|A_v| = \frac{0.566}{.01} = 56.6 \quad | \quad 20 \log (56.6) = 35.0 dB$$

$$I_s = \frac{0.01V}{2k\Omega + 50k\Omega} = 192nA \quad | \quad I_o = \frac{V_o}{8\Omega} = \frac{0.566V}{8\Omega} = 70.8mA$$

$$|A_i| = \frac{70.8mA}{192nA} = 3.68 \times 10^5 \quad | \quad 20 \log (3.68 \times 10^5) = 111 dB$$

$$A_p = \frac{0.02W}{\frac{.01V(192nA)}{2}} = 2.08 \times 10^7 \quad | \quad 10 \log (2.08 \times 10^7) = 73.2 dB$$

10.6



(a) $v_{th} = v_{oc} = 0.768\sqrt{2} = 1.09 V$

$$v_o = \frac{R_L}{R_{th} + R_L} v_{th} \rightarrow R_{th} = R_L \frac{v_{th} - v_o}{v_o} = 430 \left(\frac{0.768 - 0.721}{0.721} \right) = 28.0 \Omega$$

(b) $v_{th} = v_{oc} = 0.760\sqrt{2} = 1.08 V$

$$v_o = \frac{R_L}{R_{th} + R_L} v_{th} \rightarrow R_{th} = R_L \frac{v_{th} - v_o}{v_o} = 1040 \left(\frac{0.760 - 0.740}{0.740} \right) = 28.1 \Omega$$

(c) 1.09 V and 1.08 V \rightarrow 9% error and 8% error

10.7 G4 laptop – 1 V, 28 Ω.

10.8

$$(a) V_o = \sqrt{2R_L P_o} = \sqrt{2(8)(20)} = 17.9V$$

$$P_i = \frac{V_i^2}{2R_i} = \frac{1^2}{40066} = 25.0\mu W \quad | \quad I_i = \frac{1V}{20000\Omega + 32\Omega} = 49.9\mu A \quad | \quad I_o = \frac{17.9V}{8\Omega} = 2.24A$$

$$A_v = \frac{V_o}{V_i} = \frac{17.9V}{1V} = 17.9 \quad | \quad A_p = \frac{20W}{25\mu W} = 8.00 \times 10^5 \quad | \quad A_i = \frac{2.24A}{49.9\mu A} = 4.49 \times 10^4$$

(b) $V_o = 17.9 V$; recommend ± 20 -V supplies

10.9

$$V = \sqrt{2PR} \quad | \quad I = \sqrt{\frac{2P}{R}}$$

The 24-Ω case represents a good trade off between voltage and current.

R (Ω)	V (V)	I (mA)
8	1.27	158
24	2.19	91.3
1000	14.1	14.1

10.10

In the dc steady state, the internal circuit voltages cannot exceed the power supply limits.

(a) +15 V (b) -9 V

10.11

$$(a) \text{ For } V_B = 0.6V, V_o = +8V \quad | \quad A_v = \left. \frac{dv_o}{dv_I} \right|_{v_I=0.6V} = \frac{12-4}{0.5-0.7} = -40$$

$$|A_v| = 32 \text{ dB} \quad \angle A_v = 180^\circ \quad | \quad V_M \leq 0.100 \text{ V for linear operation}$$

$$(b) v_I(t) = (0.6 + 0.1 \sin 1000t) V \quad v_o(t) = (8 - 4 \sin 1000t) V$$

10.12

(a) For $V_B = 0.5V$, $V_o = +12V$ | $\frac{dv_o}{dv_i}$ is different for positive and negative values of

$V_M \sin 1000t$. Thus, the gain is different for positive and negative signal excursions and the output will always be a distorted sine wave. This is not a useful choice of bias point for the amplifier.

(b) For $V_B = 1.1V$, $V_o = +2V$ and $\frac{dv_o}{dv_i} = 0$. The gain is zero for this bias point.

Thus this is also not a useful choice of bias point for the amplifier.

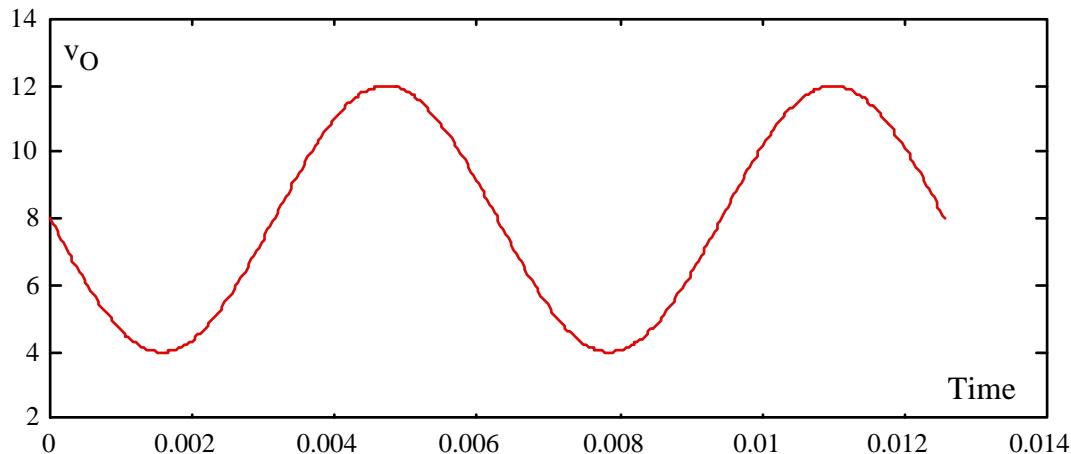
10.13

$$(a) \text{For } V_B = 0.8V, V_o = +3V \mid A_v = \left. \frac{dv_o}{dv_i} \right|_{v_i=0.8V} = \frac{4-2}{0.7-0.9} = -10$$

$|A_v| = 20dB \angle A_v = 180^\circ \mid V_M \leq 0.100 V$ for linear operation

$$(b) \text{For } V_B = 0.2V, V_o = +14V \mid A_v = \left. \frac{dv_o}{dv_i} \right|_{v_i=0.8V} = 0$$

The output signal will be distorted regardless of the value of V_M .

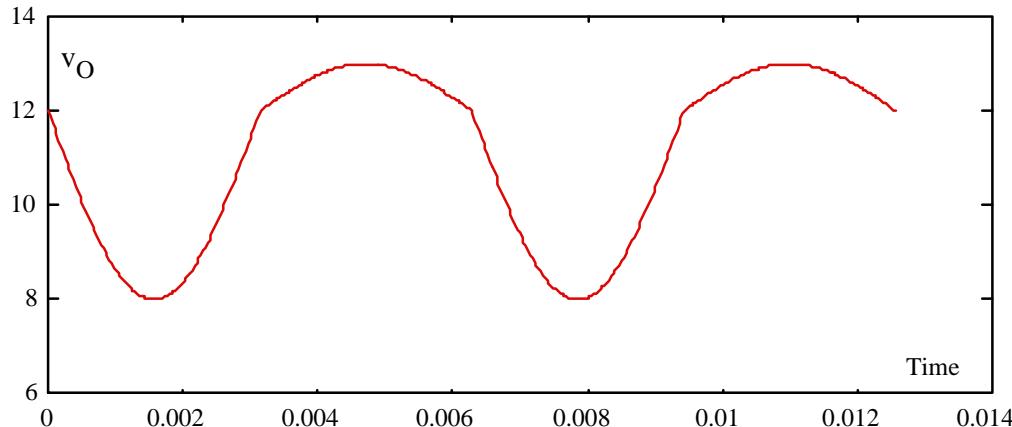
10.14

The amplifier is operating in a linear region. $v_O = 8 - 4 \sin 1000t$ volts There are only two spectral components: 8 V at dc and -4 V at 159 Hz

10.15

For $\sin 1000t \geq 0$, $v_o = 12 - 4 \sin 1000t$

For $\sin 1000t < 0$, $v_o = 12 - 1 \sin 1000t$



Using the MATLAB FFT capability with a fundamental frequency of $1000/2$ Hz:

```
t=linspace(0,2*pi/1000,1000);  
y=12-4*sin(1000*t).*(sin(1000*t)>=0)-sin(1000*t).*(sin(1000*t)<0);  
z=fftshift(fft(y))/1000;
```

yields the following series:

$$v_o(t) = 11.05 - 2.50 \sin(1000t) + 0.638 \cos(2000t) + 0.127 \cos(4000t) + 0.0546 \cos(6000t)$$

Note:
It is worth plotting this function to see if it is correct.

The Fourier coefficients may also be calculated directly using MATLAB. For example, for the cosine terms:

Define a function:

```
function y=four(t)  
y=cos(fn*1000*t).*(12-4*sin(1000*t).*(sin(1000*t)>=0)-  
sin(1000*t).*(sin(1000*t)<0));  
  
global fn  
fn=0; quad('four',0,pi/500)*1000/pi
```

10.16

$$v_i = 0.004 \sin 2000\pi t \text{ V} \quad | \quad A_v = \frac{5V}{0.004V} = 1250 \quad | \quad \text{Third and fifth harmonics are present.}$$

$$\text{THD} = 100 \frac{\sqrt{0.25^2 + 0.10^2}}{5} \% = 5.39 \%$$

10.17

At the input signal frequency: $v_i = 0.25 \sin 1200\pi t \text{ V} \quad | \quad v_o = 4 \sin 1200\pi t \text{ V}$

$$A_v = \frac{4V}{0.25V} = 16 \quad | \quad \text{Second and third harmonics are present. THD} = 100 \frac{\sqrt{0.4^2 + 0.2^2}}{4} \% = 11.2 \%$$

10.18 (a)

```
w=200*pi*linspace(0,0.001,512);
v=6+4*sin(w).*(sin(w)>=0)+2*sin(w).*sin(w)<0;
s=fft(v)/512;
vmag=sqrt(s.*conj(s));
vmag(1:3)
ans = 6.6354 1.4985 0.2129
```

dc component: 6.64 V fundamental: 1.50 V 2nd harmonic: 0.213 V

(b) Define m-files for a(n) and b(n)

```
function f=an(t);
global n;
ftemp=6+(4*sin(2000*pi*t)).*(t<=0.0005)+(2*sin(2000*pi*t)).*(t>0.0005);
f=ftemp.*cos(2000*n*pi*t);

function f=bn(t);
global n;
ftemp=6+(4*sin(2000*pi*t)).*(t<=0.0005)+(2*sin(2000*pi*t)).*(t>0.0005);
f=ftemp.*sin(2000*n*pi*t);
```

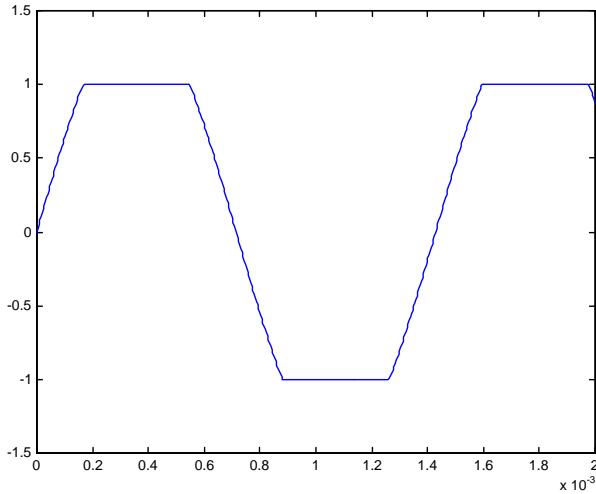
Then n=0; quad('an',0,0.001) ans: 13.27

Then n=1; quad('bn',0,0.001) ans 3.000 etc

f = 6.63 + 3sin(2000 t) - 0.4244cos(4000 t) -0.0849cos(8000 t)

10.19

```
t=linspace(0,0.002,512);
y=max(-1,min(1,1.5*sin(1400*pi*t)));
plot(t,y)
```



```
w=1400*pi*linspace(0,0.001428571,512);
y=max(-1,min(1,1.5*sin(w)));
s=fft(y)/512;
ymag=sqrt(s.*conj(s));
y2=ymag.*ymag;
sumy2=sum(y2)-2*y2(1)-2*y2(2);
thd=100*sqrt(sumy2)/(2*y2(2))
```

thd = 18.3929 %

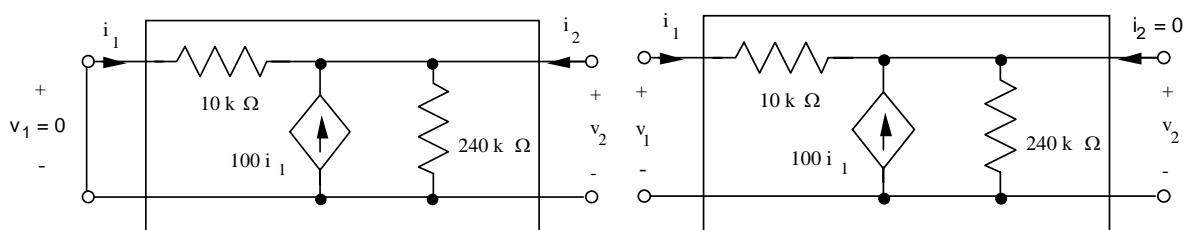
10.20

$$g_{11} = \left. \frac{i_1}{v_1} \right|_{i_2=0} : v_1 = 10^4 i_1 + 101 i_1 (240k\Omega) \rightarrow g_{11} = 4.124 \times 10^{-8} S = 4.12 \times 10^{-8} S$$

$$g_{12} = \left. \frac{i_1}{i_2} \right|_{v_1=0} : i_1 = -\frac{240k\Omega}{240k\Omega + 10k\Omega} (i_2 + 100i_1) \rightarrow g_{12} = -9.90 \times 10^{-3}$$

$$g_{21} = \left. \frac{v_2}{v_1} \right|_{i_2=0} : v_2 = 101i_1 (240k\Omega) \quad | \quad i_1 = g_{11}v_1 \rightarrow g_{21} = 1.00$$

$$g_{22} = \left. \frac{v_2}{i_2} \right|_{v_1=0} : i_2 = \frac{v_2}{240k\Omega} + \frac{v_2}{10k\Omega} + 100 \frac{v_2}{10k\Omega} \rightarrow g_{22} = 99.0 \Omega$$



10.21

$$g_{11} = \frac{1}{24.25 M\Omega} \quad g_{12} = -9.897 \times 10^{-3} \quad g_{21} = 0.9996 \quad g_{22} = 98.97 \Omega$$

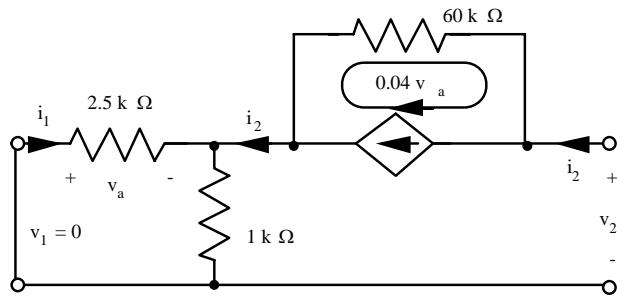
10.22

$$g_{11} = \left. \frac{\mathbf{i}_1}{\mathbf{v}_1} \right|_{\mathbf{i}_2=0} = \frac{1}{2.5k\Omega + 1k\Omega} = 0.286 \text{ mS} \quad | \quad g_{12} = \left. \frac{\mathbf{i}_1}{\mathbf{i}_2} \right|_{\mathbf{v}_1=0} = -\frac{1k\Omega}{2.5k\Omega + 1k\Omega} = -0.286$$

$$g_{21} = \left. \frac{\mathbf{v}_2}{\mathbf{v}_1} \right|_{\mathbf{i}_2=0} : \mathbf{v}_2 = \mathbf{v}_1 \frac{1k\Omega}{2.5k\Omega + 1k\Omega} + \mathbf{v}_1 \frac{2.5k\Omega}{2.5k\Omega + 1k\Omega} (-0.04)(60k\Omega) \rightarrow g_{21} = -1710$$

$$g_{22} = \left. \frac{\mathbf{v}_2}{\mathbf{i}_2} \right|_{\mathbf{v}_1=0} : \mathbf{v}_2 = (\mathbf{i}_2 - 0.04 \mathbf{v}_a) 60k\Omega + \mathbf{i}_2 (1k\Omega \parallel 2.5k\Omega) \quad | \quad \mathbf{v}_a = -\mathbf{i}_2 (1k\Omega \parallel 2.5k\Omega)$$

$$g_{22} = 1.78 \times 10^6 \Omega$$



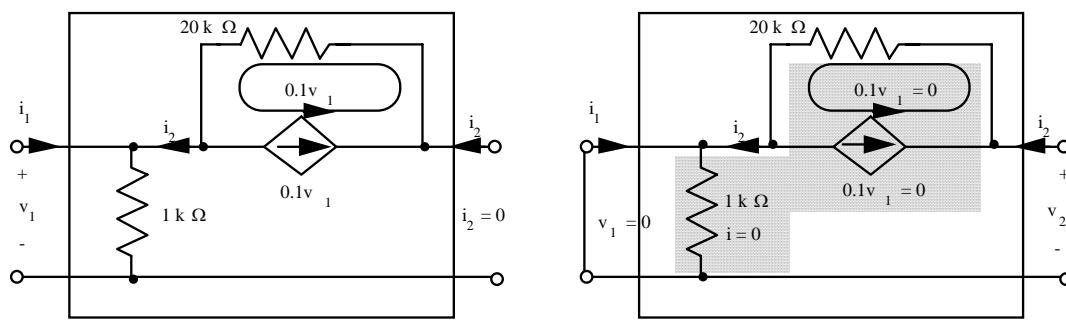
10.23

$$g_{11} = \left. \frac{i_1}{v_1} \right|_{i_2=0} : v_1 = 10^3 i_1 \rightarrow g_{11} = 1.00 \times 10^{-3} S$$

$$g_{12} = \left. \frac{i_1}{i_2} \right|_{v_1=0} : i_1 = -i_2 \rightarrow g_{12} = -1.00$$

$$g_{21} = \left. \frac{v_2}{v_1} \right|_{i_2=0} : v_2 = v_1 + 0.1v_1(20k\Omega) \quad | \quad v_1 = 2001v_1 \rightarrow g_{21} = 2001$$

$$g_{22} = \left. \frac{v_2}{i_2} \right|_{v_1=0} : i_2 = \frac{v_2}{20k\Omega} \rightarrow g_{22} = 20 k\Omega$$



10.24

$$g_{11} = \frac{1}{1.000 \text{ } k\Omega} \quad g_{12} = -1.000 \quad g_{21} = 2001 \quad g_{22} = 20.00 \text{ } k\Omega$$

10.25

$$(a) V_o = V_s \frac{R_{in}}{R_{in} + R_s} A \frac{R_L}{R_L + R_{out}} \quad | \quad A = 10^{\frac{54}{20}} = 501.2$$

$$A_v = \frac{10^6}{10^3 + 10^6} (501.2) \frac{16}{0.5 + 16} = 485.5 \quad | \quad A_{\text{v dB}} = 20 \log(485.5) = 53.7 \text{ dB}$$

$$A_i = \frac{I_o}{I_s} = \frac{\frac{16}{V_s}}{\frac{10^3 + 10^6}{V_s}} = 3.041 \times 10^7 \quad | \quad A_{\text{idB}} = 20 \log(3.041 \times 10^7) = 150 \text{ dB}$$

$$A_p = \frac{V_o I_o}{V_s I_s} = \frac{485.5 V_s \frac{485.5 V_s}{16}}{V_s \frac{V_s}{10^3 + 10^6}} = 485.5 (3.041 \times 10^7) = 1.478 \times 10^{10}$$

$$A_{\text{pdB}} = 10 \log(1.478 \times 10^{10}) = 102 \text{ dB}$$

$$(b) 1 = \frac{V_o^2}{2(16)} \rightarrow V_o = 5.657 \text{ V} \quad | \quad V_s = \frac{5.657}{485.5} = 11.65 \text{ mV}$$

$$(c) R_{\text{out}} \text{ and } R_L \text{ see the same current. } P = \frac{I_o^2}{2} R_L \rightarrow \frac{I_o^2}{2} = \frac{1}{16}$$

$$P_{R_{\text{out}}} = \frac{I_o^2}{2} R = \frac{1}{16} 0.5 = 31.25 \text{ mW} \quad | \quad P_{R_{\text{in}}} = \frac{I_s^2}{2} R_{in} = \left(\frac{0.01165}{10^3 + 10^6} \right)^2 \frac{10^6}{2} = 67.7 \text{ pW}$$

$$P = 31.25 \text{ mW} + 67.7 \text{ pW} = 31.3 \text{ mW}$$

10.26

$$(a) V_o = V_s \frac{R_{in}}{R_{in} + R_s} A \frac{R_L}{R_L + R_{out}} = V_s \frac{1000}{1000 + 1000} \left(10^{\frac{54}{20}} \right) \frac{16}{16 + 16} = 125 \text{ V}_s$$

$$1 = \frac{V_o^2}{2(16)} \rightarrow V_o = 5.66 \text{ V} \quad | \quad V_s = \frac{5.66}{125} = 45.3 \text{ mV}$$

(b) Since R_{out} and R_L have the same current and same value, the power dissipated in R_{out} is 1 W.

$$\text{The power lost in } R_{\text{in}} \text{ is } \left(\frac{45.3 \text{ mV}}{2} \right)^2 \frac{1}{2(1000)} = 0.257 \mu\text{W} \quad | \quad P_D = 0.257 \mu\text{W} + 1.00 \text{ W} = 1.00 \text{ W}$$

10.27

$$i_o = \sqrt{\frac{2P_o}{R_L}} = \sqrt{\frac{2(0.1W)}{24\Omega}} = 91.3 \text{ mA} \quad | \quad v = i_o(28 + 24)\Omega = 4.75 \text{ V}$$

$$P_D = \frac{i_o v}{2} = 217 \text{ mW} \quad | \quad P_L = \frac{i_o^2 R_{out}}{2} = \frac{(91.3 \text{ mA})^2 (28\Omega)}{2} = 117 \text{ mW}$$

10.28

$$i_o = \sqrt{\frac{2P_o}{R_L}} = \sqrt{\frac{2(0.1W)}{1000\Omega}} = 14.1 \text{ mA} \quad | \quad v = i_o(28 + 1000)\Omega = 14.5 \text{ V}$$

$$P_D = \frac{i_o v}{2} = 103 \text{ mW} \quad | \quad P_L = \frac{i_o^2 R_{out}}{2} = \frac{(14.1 \text{ mA})^2 (28\Omega)}{2} = 2.78 \text{ mW}$$

10.29

$$R_{in} = \infty \quad | \quad R_{out} = 0 \Omega \quad | \quad v_o = Av_s = -2000v_s \quad | \quad v_o = 0.01V(-2000) = -20 \text{ V}$$

$$P = \frac{V_o^2}{2R_L} = \frac{20^2}{2(16)} = 12.5 \text{ W} \quad | \quad A_p = \frac{12.5W}{0} = \infty$$

10.30

$$A_v = -10^{\frac{77}{20}} = -7079 \quad | \quad -7079 = \frac{20k\Omega}{20k\Omega + 1k\Omega} A \frac{2k\Omega}{2k\Omega + 0.1k\Omega} \rightarrow A = -7805$$

$$A = -7800 \quad | \quad A_{dB} = 20 \log(7800) = 77.8 \text{ dB}$$

10.31

$$i_1 = i_s \frac{R_s}{R_s + R_{in}} \quad i_o = \beta i_1 \frac{R_{out}}{R_{out} + R_L} \quad A_i = \beta \frac{R_{out}}{R_{out} + R_L} \frac{R_s}{R_s + R_{in}} \quad R_{in} = 0 \quad R_{out} = \infty$$

10.32

$$I_o = I_s \frac{R_s}{R_s + R_{in}} \beta \frac{R_{out}}{R_{out} + R_L} \quad | \quad 200 = \frac{200k\Omega}{200k\Omega + 10k\Omega} \beta \frac{300k\Omega}{300k\Omega + 47k\Omega} \rightarrow \beta = 243$$

10.33

$$R_{in} = 0 \Omega \quad | \quad R_{out} = \infty \quad | \quad P = \frac{I_o^2}{2} R_L = \frac{[10^{-6} A(5000)]^2}{2} 10^4 \Omega = 125 \text{ mW} \quad | \quad A_p = \frac{125 \text{ mW}}{0} = \infty$$

10.34

$$V_o = V_s \frac{R_{in}}{R_{in} + R_s} A \frac{R_{in}}{R_{in} + R_{out}} A \frac{R_L}{R_L + R_{out}}$$

$$A_v = \frac{5000}{5000+1000}(-1200) \frac{5000}{5000+500}(-1200) \frac{100}{100+500} = +1.82 \times 10^5$$

$$A_{vdb} = 20 \log(1.82 \times 10^5) = 105 \text{ dB}$$

$$A_i = \frac{I_o}{I_s} = \frac{1.82 \times 10^5 V_s}{100} \frac{1}{\frac{V_s}{6000}} = +1.09 \times 10^7 \quad | \quad A_{idB} = 20 \log(1.36 \times 10^7) = 141 \text{ dB}$$

$$A_p = \frac{1.82 \times 10^5 V_s (1.09 \times 10^7 I_s)}{V_s I_s} = +1.98 \times 10^{12} \quad | \quad A_{pdB} = 10 \log(1.98 \times 10^{12}) = 123 \text{ dB}$$

10.35

$$A_p = \frac{V_o I_o}{V_s I_s} = \frac{\frac{V_o}{R_L}}{\frac{V_s}{R_s + R_{in}}} = \left(\frac{V_o}{V_s}\right)^2 \frac{R_s + R_{in}}{R_L}$$

$$A_{pdB} = 10 \log \left[\left(\frac{V_o}{V_s} \right)^2 \frac{R_s + R_{in}}{R_L} \right] = 10 \log \left(\frac{V_o}{V_s} \right)^2 + 10 \log \left(\frac{R_s + R_{in}}{R_L} \right)$$

$$A_{pdB} = 20 \log \left(\frac{V_o}{V_s} \right) - 10 \log \left(\frac{R_L}{R_s + R_{in}} \right) = A_{vdb} - 10 \log \left(\frac{R_L}{R_s + R_{in}} \right)$$

$$A_p = \frac{V_o I_o}{V_s I_s} = \frac{I_o R_L I_o}{I_s (R_s + R_{in}) I_s} = \left(\frac{I_o}{I_s} \right)^2 \frac{R_L}{R_s + R_{in}}$$

$$A_{idB} = 10 \log \left[\left(\frac{I_o}{I_s} \right)^2 \frac{R_L}{R_s + R_{in}} \right] = 10 \log \left(\frac{I_o}{I_s} \right)^2 + 10 \log \left(\frac{R_L}{R_s + R_{in}} \right)$$

$$A_{pdB} = 20 \log \left(\frac{I_o}{I_s} \right) + 10 \log \left(\frac{R_L}{R_s + R_{in}} \right) = A_{idB} + 10 \log \left(\frac{R_L}{R_s + R_{in}} \right)$$

$$\text{Note: } A_{pdB} = \frac{A_{vdb} + A_{idB}}{2}$$

10.36

$$(a) A_i(s) = \frac{3x10^9 s^2}{(s^2 + 51s + 50)(s^2 + 13000s + 3x10^7)} = \frac{3x10^9 s^2}{(s+1)(s+50)(s+3000)(s+10000)}$$

Zeros : s = 0, s = 0 | Poles : s = -1, s = -50, s = -3000, s = -10000

$$(b) A_v(s) = \frac{10^5(s^2 + 51s + 50)}{s^5 + 1000s^4 + 50000s^3 + 20000s^2 + 13000s + 3x10^7} \quad | \quad \text{Zeros : } s = -1, s = -50$$

Using MATLAB to find the poles:

`Av=[1 1000 50000 20000 13000 3e7];`

`roots(Av)`

`ans = -947.24 -52.13 -9.170 4.27 + j6.93 4.27 - j6.93`

10.37

$$\frac{V_o}{V_s} = \frac{R_2}{R_1 + R_2} \left(\frac{1}{1 + \frac{s}{\omega_H}} \right) \quad | \quad A_{mid} = \frac{R_2}{R_1 + R_2} = \frac{1.5k\Omega}{1k\Omega + 1.5k\Omega} = 0.600 \quad | \quad A_{mid-dB} = -4.44 \text{ dB}$$

$$f_H = \frac{1}{2\pi(R_1 \parallel R_2)C} = \frac{1}{2\pi(1k\Omega \parallel 1.5k\Omega)0.01\mu F} = 26.5 \text{ kHz}$$

10.38

$$\frac{V_o}{V_s} = \frac{R_2}{R_1 + R_2} \left(\frac{1}{1 + \frac{s}{\omega_H}} \right) \quad | \quad A_{mid} = \frac{R_2}{R_1 + R_2} = \frac{100k\Omega}{10k\Omega + 100k\Omega} = 0.909 \quad | \quad A_{mid-dB} = -0.828 \text{ dB}$$

$$f_H = \frac{1}{2\pi(R_1 \parallel R_2)C} = \frac{1}{2\pi(10k\Omega \parallel 100k\Omega)0.01\mu F} = 1.75 \text{ kHz}$$

10.39

$$(a) A_{mid} \geq 10^{\frac{-0.5}{20}} = 0.944 \quad | \quad \frac{R_2}{560 + R_2} \geq 0.944 \rightarrow R_2 \geq 9440\Omega \quad | \quad \text{Choose } R_2 = 10 \text{ k}\Omega$$

$$C = \frac{1}{2\pi(R_1 \parallel R_2)f_H} = \frac{1}{2\pi(560\Omega \parallel 10k\Omega)20\text{kHz}} = 0.015 \text{ }\mu F$$

$$(b) R_2 = 10 \text{ k}\Omega \quad | \quad C = 15.0 \text{ nF}$$

10.40

$$\frac{V_o}{V_s} = \frac{R_2}{R_1 + R_2} \left(\frac{s}{s + \omega_L} \right) \quad | \quad A_{mid} = \frac{R_2}{R_1 + R_2} = \frac{20k\Omega}{10k\Omega + 20k\Omega} = 0.667 \quad | \quad A_{mid-dB} = -3.52 \text{ dB}$$

$$f_L = \frac{1}{2\pi(R_1 + R_2)C} = \frac{1}{2\pi(10k\Omega + 20k\Omega)0.01\mu F} = 531 \text{ Hz}$$

10.41

$$\frac{V_o}{V_s} = \frac{R_2}{R_1 + R_2} \left(\frac{s}{s + \omega_L} \right) \quad | \quad A_{mid} = \frac{R_2}{R_1 + R_2} = \frac{78k\Omega}{10k\Omega + 78k\Omega} = 0.886 \quad | \quad A_{mid-dB} = -1.05 \text{ dB}$$

$$f_L = \frac{1}{2\pi(R_1 + R_2)C} = \frac{1}{2\pi(10k\Omega + 78k\Omega)0.01\mu F} = 181 \text{ Hz}$$

10.42

$$(a) A_{mid} \geq 10^{\frac{-0.5}{20}} = 0.944 \quad | \quad \frac{R_2}{330\Omega + R_2} \geq 0.944 \rightarrow R_2 \geq 5560\Omega \quad | \quad \text{Choose } R_2 = 7.5 \text{ k}\Omega$$

$$C = \frac{1}{2\pi(R_1 + R_2)f_L} = \frac{1}{2\pi(330\Omega + 7500\Omega)20\text{kHz}} = 1.02 \text{ nF}$$

$$(b) R_2 = 7.5 \text{ k}\Omega \quad | \quad C = 1.0 \text{ nF} \quad | \quad \text{Checking: } f_L = 20.3 \text{ kHz}$$

10.43

$$A_v = \frac{2\pi x 10^7 s}{(s + 20\pi)(s + 2\pi x 10^4)} = \frac{1000s}{(s + 20\pi) \left(1 + \frac{s}{2\pi x 10^4} \right)} \quad | \quad A_{mid} = +1000 = 60 \text{ dB}$$

$$f_L = \frac{20\pi}{2\pi} = 10 \text{ Hz} \quad | \quad f_H = \frac{2\pi x 10^4}{2\pi} = 10 \text{ kHz} \quad | \quad BW = 10\text{kHz} - 10\text{Hz} = 9.99 \text{ kHz}$$

Bandpass Amplifier

10.44

$$A_v = \frac{10^4 s}{s + 200\pi} \quad | \quad \text{High-pass Amplifier} \quad | \quad A_{mid} = +10^4 = 80 \text{ dB}$$

$$f_L = \frac{200\pi}{2\pi} = 100 \text{ Hz} \quad | \quad f_H = \infty \quad | \quad BW = \infty$$

10.45

$$A_v = \frac{2\pi x 10^6}{s + 200\pi} = \frac{10^4}{1 + \frac{s}{200\pi}} \rightarrow \text{Low-pass Amplifier} \quad | \quad A_{mid} = +10^4 = 80 \text{ dB}$$

$$f_L = 0 \text{ Hz} \quad | \quad f_H = \frac{200\pi}{2\pi} = 100 \text{ Hz} \quad | \quad BW = 100\text{Hz} - 0\text{Hz} = 100 \text{ Hz}$$

10.46

$$A_v(s) = \frac{10^7 s}{s^2 + 10^5 s + 10^{14}} = 10^2 \frac{10^5 s}{s^2 + 10^5 s + 10^{14}} = A_{mid} \frac{s \frac{\omega_o}{Q}}{s^2 + s \frac{\omega_o}{Q} + \omega_o^2}$$

Bandpass Amplifier | $A_{mid} = 100 = 40 \text{ dB}$ | $f_o = \frac{10^7}{2\pi} = 1.592 \text{ MHz}$ | $Q = \frac{\omega_o}{10^5} = 100$

$$\text{BW} = \frac{1.592 \text{ MHz}}{100} = 15.92 \text{ kHz} \quad \text{For a high Q circuit:}$$

$$f_L \approx f_o - \frac{BW}{2} = 1.592 \text{ MHz} - 15.92 \text{ kHz} = 1.584 \text{ MHz}$$

$$f_H \approx f_o + \frac{BW}{2} = 1.592 \text{ MHz} + 15.92 \text{ kHz} = 1.600 \text{ MHz}$$

10.47

$$A_v(s) = -20 \frac{s^2 + 10^{12}}{s^2 + 10^4 s + 10^{12}} = A_{mid} \frac{s^2 + \omega_o^2}{s^2 + s \frac{\omega_o}{Q} + \omega_o^2} \quad \text{| Notch Filter}$$

Note: $A_v(s) = -20 \left(1 - \frac{s \frac{\omega_o}{Q}}{s^2 + s \frac{\omega_o}{Q} + \omega_o^2} \right)$ where $\frac{s \frac{\omega_o}{Q}}{s^2 + s \frac{\omega_o}{Q} + \omega_o^2}$ is a bandpass function.

$$A_{mid} = -20 = 20 \text{ dB} \text{ but } A_v = 0 \text{ at } f_o \quad | \quad f_o = \frac{\omega_o}{2\pi} = \frac{10^6}{2\pi} = 159.2 \text{ kHz} \quad | \quad Q = \frac{\omega_o}{10^4} = 100$$

$$\text{The width of the null} = \text{BW} = \frac{159.2 \text{ kHz}}{100} = 1.592 \text{ kHz} \quad \text{| For a high Q circuit:}$$

$$f_L \approx f_o - \frac{BW}{2} = 159.2 \text{ Hz} - 1.592 \text{ kHz} = 157.6 \text{ kHz}$$

$$f_H \approx f_o + \frac{BW}{2} = 159.2 \text{ Hz} + 1.592 \text{ kHz} = 160.8 \text{ kHz}$$

10.48

$$A_v(s) = \frac{4\pi^2 x 10^{14} s^2}{(s+20\pi)(s+50\pi)(s+2\pi x 10^5)(s+2\pi x 10^6)}$$

$$A_v(s) = \frac{10^3 s^2}{(s+20\pi)(s+50\pi)\left(1 + \frac{s}{2\pi x 10^5}\right)\left(1 + \frac{s}{2\pi x 10^6}\right)} \quad | \quad A_{mid} = 1000 = 60 \text{ dB}$$

Zeros: $s = 0, s = 0$ | Poles: $s = -20\pi, s = -50\pi, s = -2\pi x 10^5, s = -2\pi x 10^6$

$$\text{For } s \gg 50\pi, A_v(s) \approx \frac{10^3}{\left(1 + \frac{s}{2\pi x 10^5}\right)\left(1 + \frac{s}{2\pi x 10^6}\right)}$$

Since the two high frequency poles are separated in frequency by a decade,

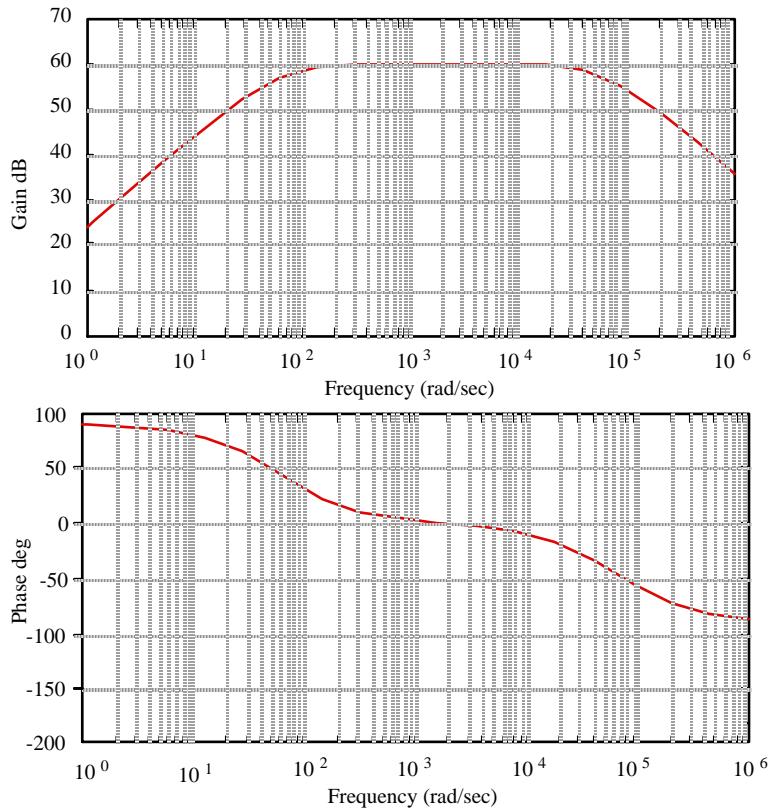
$$f_H \approx \frac{2\pi x 10^5}{2\pi} = 100 \text{ kHz} \quad | \quad \text{However, we are not that lucky at low frequencies.}$$

$$\text{For } s \ll 2\pi x 10^5, A_v(s) \approx \frac{10^3 s^2}{(s+20\pi)(s+50\pi)} \quad | \quad |A_v(j\omega_L)| = \frac{10^3 \omega_L^2}{\sqrt{(\omega_L^2 + (20\pi)^2)(\omega_L^2 + (50\pi)^2)}} = \frac{10^3}{\sqrt{2}}$$

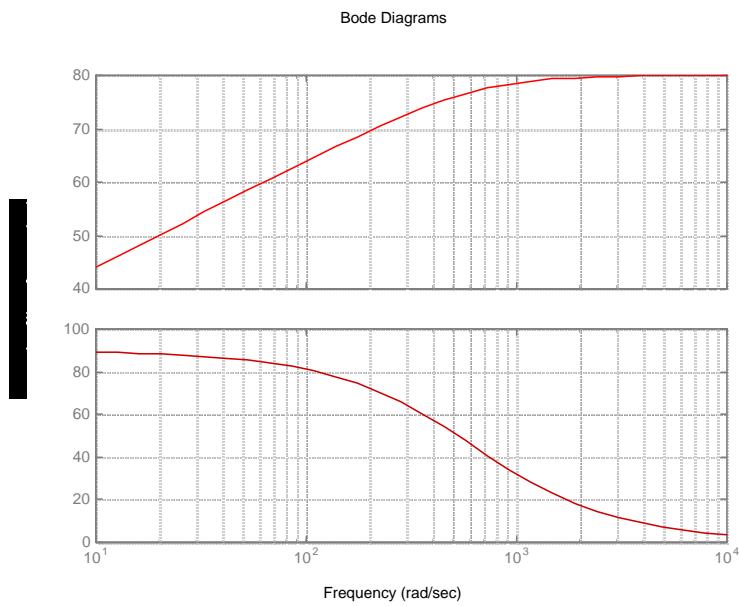
$$\omega_L^4 - [(20\pi)^2 + (50\pi)^2]\omega_L^2 - (20\pi)^2(50\pi)^2 = 0 \rightarrow \omega_L = \pm 178 \quad | \quad f_L = \frac{178}{2\pi} = 28.3 \text{ Hz}$$

10.49

Using MATLAB: $n=[2e7*\pi \ 0]$; $d=[1 \ (20*\pi+2e4*\pi) \ 40e4*\pi^2]$; bode(n,d)

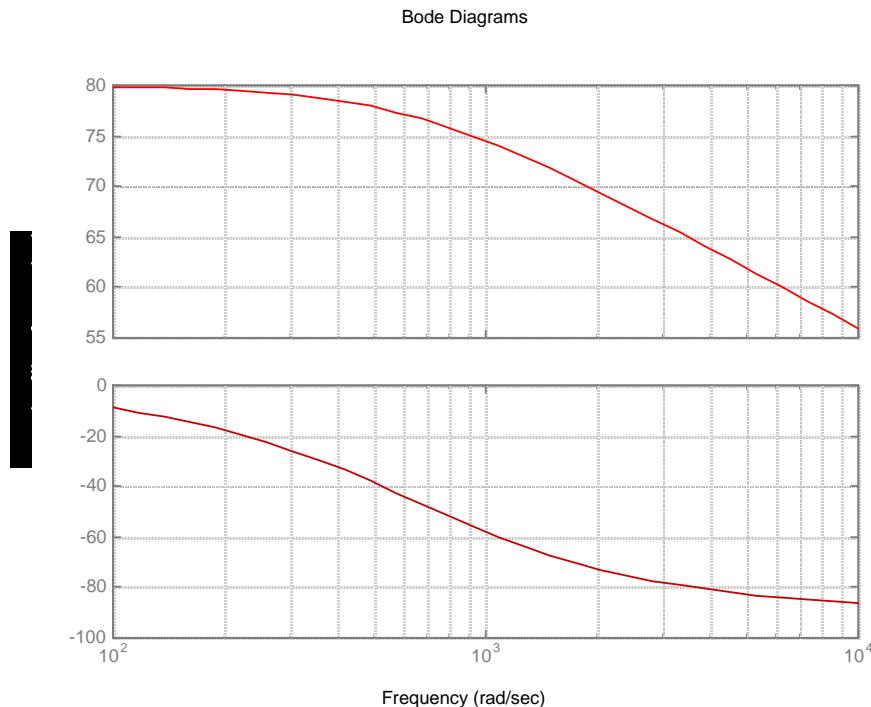
**10.50**

Using MATLAB: $n=[1e4 \ 0]$; $d=[1 \ 200*\pi]$; bode(n,d)



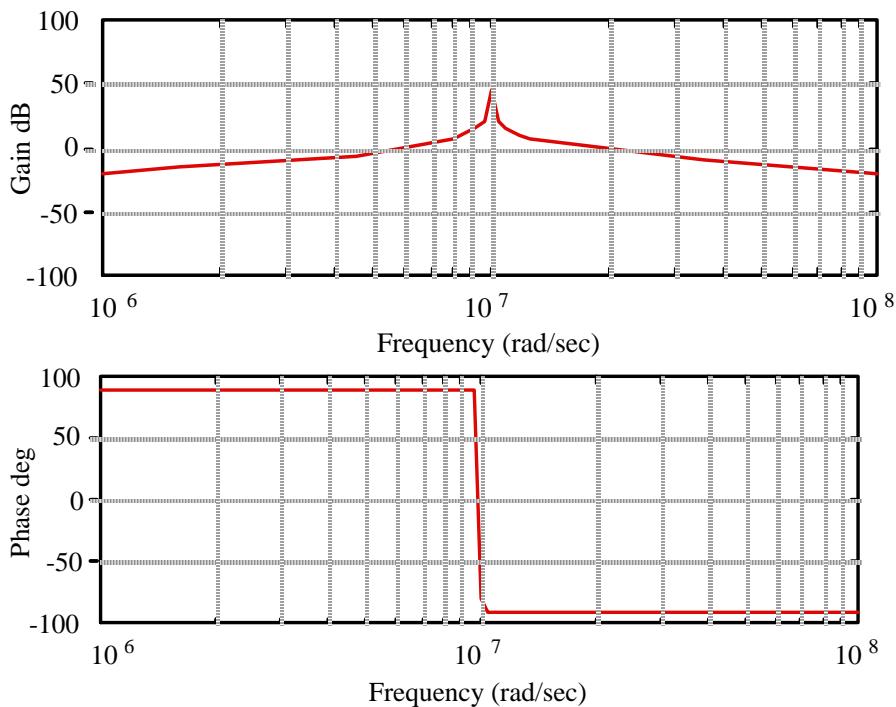
10.51

Using MATLAB: $n=[2e6*pi]$; $d=[1 200*pi]$; $bode(n,d)$



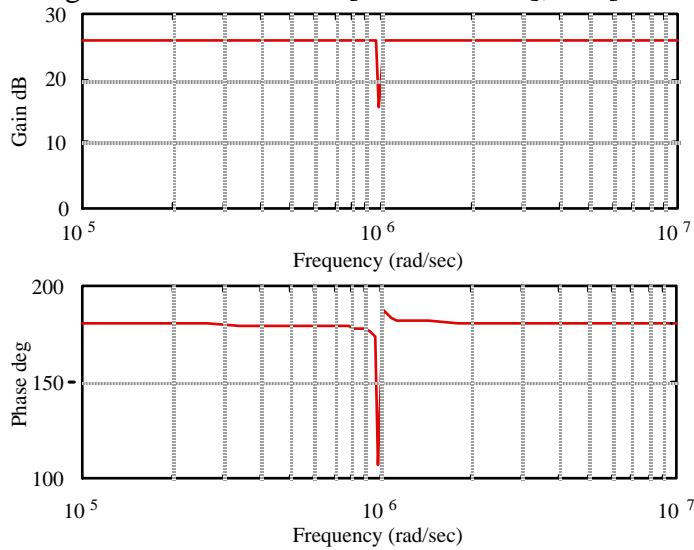
10.52

Using MATLAB: $n=[1e7 0]$; $d=[1 1e5 1e14]$; $bode(n,d)$



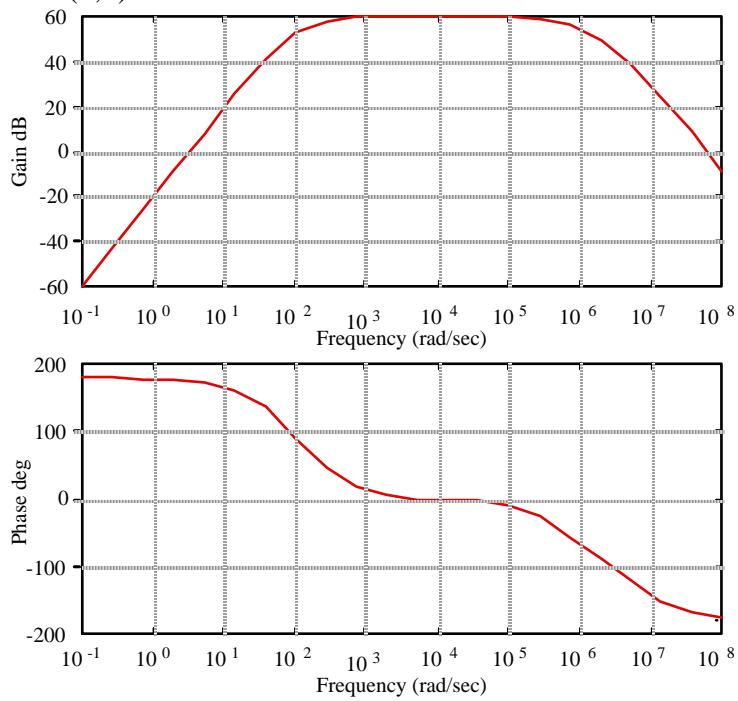
10.53

Using MATLAB: $n=[-20 \ 0 \ -2e13]; \ d=[1 \ 1e4 \ 1e12]; \ bode(n,d)$

**10.54**

Using MATLAB:

```
n=[4e14*pi^2 0 0];
p1=[1 20*pi]; p2=[1 50*pi]; p3=[1 2e5*pi]; p4=[1 2e6*pi];
d=conv(conv(p1,p2),conv(p3,p4));
bode(n,d)
```



10.55

Using MATLAB:

```
n=[2e7*pi 0]; d=conv([1 20*pi],[1 2e4*pi]); w=2*pi*[5 500 50000];
a=freqs(n,d,w); am=abs(a); ap=angle(a)*180/pi
```

Magnitudes: 447.2135 998.5526 196.1161

Phases: 63.4063 -1.7166 -78.6786

(a) $v_o = 0.447 \sin(10\pi t + 63.4^\circ) V$

(b) $v_o = 0.999 \sin(1000\pi t - 1.72^\circ) V$

(c) $v_o = 0.196 \sin(10^5 \pi t - 78.7^\circ) V$

10.56

$$A_v(s) = \frac{10^4 s}{s + 200\pi} \quad | \quad A_v(j\omega) = \frac{10^4 j\omega}{j\omega + 200\pi} = \frac{10^4 jf}{jf + 100}$$

$$|A_v(j\omega)| = \frac{10^4 f}{\sqrt{f^2 + 100^2}} \quad | \quad \angle A_v(j\omega) = 90^\circ - \tan^{-1} \frac{f}{100}$$

(a) 1 Hz: $|A_v(j\omega)| = 100 \quad | \quad \angle A_v(j\omega) = 89.4^\circ \quad | \quad v_o = 0.03 \sin(2\pi t + 89.4^\circ) V$

(b) 50 Hz: $|A_v(j\omega)| = 4472 \quad | \quad \angle A_v(j\omega) = 63.4^\circ \quad | \quad v_o = 1.34 \sin(100\pi t + 63.4^\circ) V$

(c) 5 kHz: $|A_v(j\omega)| = 9998 \quad | \quad \angle A_v(j\omega) = 1.15^\circ \quad | \quad v_o = 3.00 \sin(10^4 \pi t + 1.15^\circ) V$

10.57

Using MATLAB:

```
n=[1e4 0]; d=[1 200*pi]; w=2*pi*[2 2000 200000];
```

```
a=freqs(n,d,w); am=abs(a); ap=angle(a)*180/pi
```

Magnitudes: 2.0000e+02 9.9875e+03 1.0000e+04

Phases: 88.8542 2.8624 0.0286

(a) $v_o = 2.00 \sin(4\pi t + 88.9^\circ) mV$

(b) $v_o = 0.999 \sin(4000\pi t + 2.86^\circ) V$

(c) $v_o = 0.100 \sin(4 \times 10^5 \pi t + 0.0286^\circ) V$

10.58

Using MATLAB:

```
n=[-1e7 0]; d=[1 1e5 1e14];
w=2*pi*[1.59e6 1e6 5e6];
a=freqs(n,d,w);
am=abs(a)
ap=angle(a)*180/pi
Magnitudes: 98.1550 1.0381 0.3542
Phases: -168.9767 -90.5948 90.2029
```

$$(a) v_o = 0.393 \sin(3.18 \times 10^6 \pi t - 169^\circ) V$$

$$(b) v_o = 4.15 \sin(2 \times 10^6 \pi t - 90.6^\circ) mV$$

$$(c) v_o = 1.42 \sin(10^7 \pi t + 90.2^\circ) mV$$

10.59

Using MATLAB:

```
n=[-20 0 -2e13]; d=[1 1e4 1e12];
w=2*pi*[1.59e5 5e4 2e5];
a=freqs(n,d,w);
am=abs(a)
ap=angle(a)*180/pi
Magnitudes: 3.8242 19.9999 19.9953
Phases: 101.0233 179.8003 -178.7570
(a) v_o = 0.956 \sin(3.18 \times 10^5 \pi t + 101^\circ) mV
(b) v_o = 5.00 \sin(10^5 \pi t + 180^\circ) V
(c) v_o = 5.00 \sin(4 \times 10^5 \pi t - 179^\circ) V
```

10.60

Using MATLAB:

```
n=[4e14*pi^2 0 0];
p1=[1 20*pi]; p2=[1 50*pi]; p3=[1 2e5*pi]; p4=[1 2e6*pi];
d=conv(conv(p1,p2),conv(p3,p4));
w=2*pi*[5 500 50000];
a=freqs(n,d,w);
am=abs(a)
ap=angle(a)*180/pi
Magnitudes: 87.7058 998.5400 893.3111
Phases: 142.1219 3.6930 -29.3873
(a) v_o = 175 \sin(10 \pi t + 142^\circ) mV
(b) v_o = 2.00 \sin(1000 \pi t + 3.69^\circ) V
(c) v_o = 1.79 \sin(10^5 \pi t - 29.4^\circ) V
```

10.61

$$(a) A_{mid} = +10^{\frac{26}{20}} = +20 \quad | \quad A_v = \frac{20}{1 + \frac{s}{2\pi x (5 \times 10^6)}} = \frac{20}{1 + \frac{s}{10^7 \pi}} = \frac{2 \times 10^8 \pi}{s + 10^7 \pi}$$

$$(b) A_v = -\frac{2 \times 10^8 \pi}{s + 10^7 \pi}$$

10.62

$$(a) A_{mid} = +10^{\frac{40}{20}} = +100 \quad | \quad A_v(s) = 100 \frac{s}{(s + 400\pi) \left(1 + \frac{s}{2\pi x 10^5} \right)} = \frac{2\pi x 10^7 s}{(s + 400\pi)(s + 2\pi x 10^5)}$$

$$(b) A_v(s) = -\frac{2\pi x 10^7 s}{(s + 400\pi)(s + 2\pi x 10^5)}$$

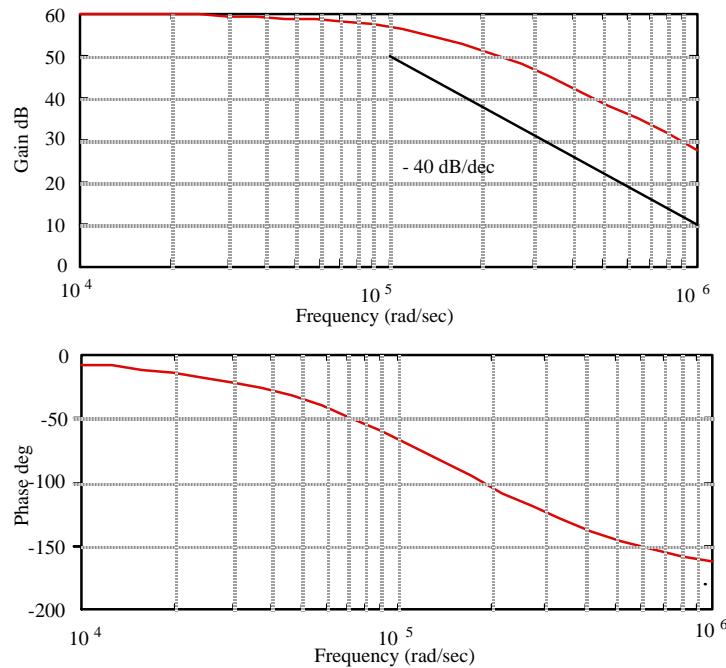
10.63

$$A_v(s) = -1000 \left(\frac{50000\pi}{s + 50000\pi} \right)^2 = -1000 \left(\frac{1}{1 + \frac{s}{50000\pi}} \right)^2 \quad | \quad A_{\text{mid}} = -1000$$

$$f_H = 0.64 \quad f_1 = 0.644(25\text{kHz}) = 16.1 \text{ kHz} \quad | \quad 2 \left(-20 \frac{\text{dB}}{\text{dec}} \right) = -40 \frac{\text{dB}}{\text{dec}}$$

Using MATLAB:

```
n=1000*(50000*pi)^2;
d=[1 2*50000*pi (50000*pi)^2];
bode(n,d)
```



10.64

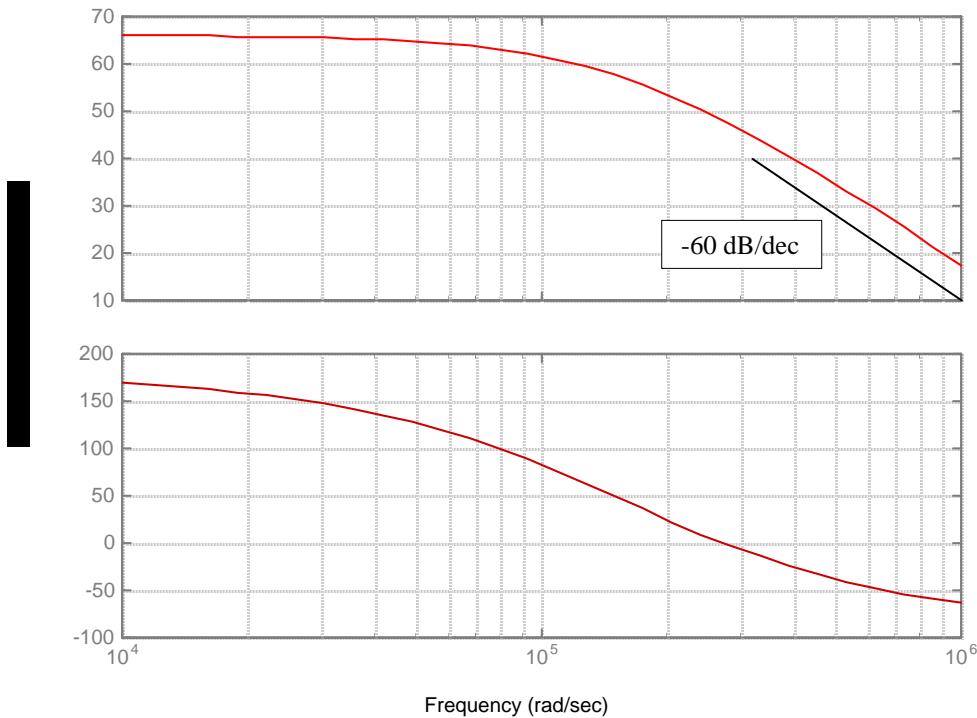
$$A_v(s) = A_o \left(\frac{\omega_1}{s + \omega_1} \right)^3 \quad | \quad |A_v(j\omega_H)| = A_o \left(\frac{\omega_1}{\sqrt{\omega_H^2 + \omega_1^2}} \right)^3 = \frac{A_o}{\sqrt{2}} \quad | \quad \text{BW} = f_H$$

$$\sqrt{2}^{\frac{1}{3}} = \sqrt{1 + \left(\frac{f_H}{f_1} \right)^2} \rightarrow f_H = f_1 \sqrt{2^{\frac{1}{3}} - 1} = 25 \text{ kHz} (0.5098) = 12.8 \text{ kHz} \quad | \quad 3 \left(-20 \frac{\text{dB}}{\text{dec}} \right) = -60 \frac{\text{dB}}{\text{dec}}$$

Using MATLAB:

```
n=2000*(50000*pi)^3;
d=[1 3*50000*pi 3*(50000*pi)^2 (50000*pi)^3];
bode(n,d)
```

Bode Diagrams



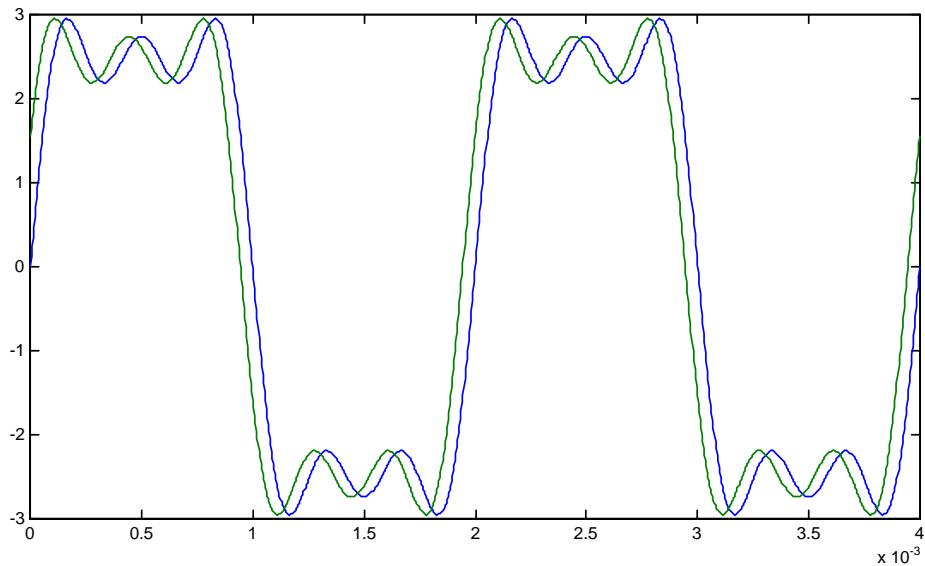
10.65

(a) To avoid distortion of the waveform, the phase shift must be proportional to frequency. 30° at 1500 Hz and 50° at 2500 Hz.

(b) $v_o = 3.16\sin(1000\pi t + 10^\circ) + 1.05\sin(3000\pi t + 30^\circ) + 0.632\sin(5000\pi t + 50^\circ)$

(c) Using MATLAB:

```
t=linspace(0,.004);  
a=10^(10/20);  
vs=sin(1000*pi*t)+0.333*sin(3000*pi*t)+0.200*sin(5000*pi*t);  
vo=A*(sin(1000*pi*t+pi/18)+0.333*sin(3000*pi*t+3*pi/18)+0.2*sin(5000*pi*t+5*pi/18));  
plot(t,A*vs,t,vo)
```



CHAPTER 11

11.1

$$v_o = v_s \frac{1M\Omega}{1M\Omega + 5k\Omega} (1000) \frac{1k\Omega}{1k\Omega + 0.5\Omega} \quad | \quad A_v = \frac{v_o}{v_s} = 990 \text{ or } 59.9 \text{ dB}$$

$$i_s = \frac{v_s}{1M\Omega + 5k\Omega} \text{ and } i_o = \frac{990v_s}{1k\Omega} \quad | \quad A_i = \frac{i_o}{i_s} = \frac{990}{1000} 10^6 = 9.9 \times 10^5 \text{ or } 120 \text{ dB}$$

$$A_p = A_v A_i = 990 (9.9 \times 10^5) = 9.8 \times 10^8 \text{ or } 89.9 \text{ dB} \quad | \quad v_s = \frac{v_o}{A_v} = \frac{5V}{990} = 5.05 \text{ mV}$$

11.2

$$v_o = v_s \frac{5k\Omega}{5k\Omega + 5k\Omega} (31.6) \frac{1k\Omega}{1k\Omega + 1k\Omega} \text{ and } A_v = \frac{v_o}{v_s} = 7.91 \text{ or } 18.0 \text{ dB}$$

$v_s = \frac{v_o}{A_v} = \frac{10V}{7.91} = 1.27 \text{ V}$ Since R_{out} has the same value as R_L , the power

dissipated in R_{out} is also 0.5W. The power dissipated in R_{id} will be

$$P_I = \frac{V_{id}^2}{2R_{id}} = \frac{\left(\frac{V_s}{2}\right)^2}{2R_{id}} = \frac{V_s^2}{8R_{id}} \text{ where } V_s = \frac{V_o}{7.91} \text{ and } V_o = \sqrt{2(0.5W)(1000\Omega)} = 31.6V$$

$$P_I = \frac{4^2}{8(5000)} = 0.4 \text{ mW. The total power dissipated in the amplifier is}$$

$$P = 500 \text{ mW} + 0.4 \text{ mW} = 500 \text{ mW.}$$

11.3

$$0.99mV \geq 1mV \frac{R_{id}}{R_{id} + 50k\Omega} \Rightarrow R_{id} \geq 4.95 M\Omega$$

11.4

$$I_o = \sqrt{\frac{2(100W)}{50\Omega}} = 2A \text{ and } \frac{I_o^2 R_{out}}{2} \leq 5W \text{ or } R_{out} \leq 2.5\Omega$$

11.5

$$v_{id} = \frac{v_o}{A} = \frac{10V}{10^5} = 0.1 \text{ mV} \quad | \quad \frac{10V}{A} \leq 10^{-6}V \text{ requires } A \geq 10^7 \text{ or } 140 \text{ dB}$$

11.6

$$v_{id} = \frac{v_o}{A} = \frac{15V}{10^6} = 15 \mu V \quad | \quad \frac{15V}{A} \leq 10^{-6}V \text{ requires } A \geq 15 \times 10^6 \text{ or } 144 \text{ dB} \quad | \quad i_+ = \frac{15\mu V}{1M\Omega} = 15 pA$$

11.7

$$(a) A_v = -\frac{R_2}{R_l} = -\frac{220k\Omega}{4.7k\Omega} = -46.8 \quad | \quad 20\log(46.8) = 33.4 \text{ dB} \quad | \quad R_{in} = R_l = 4.7 k\Omega \quad | \quad R_{out} = 0 \Omega$$

$$(b) A_v = -\frac{R_2}{R_l} = -\frac{2.2M\Omega}{47k\Omega} = -46.8 \quad | \quad 20\log(46.8) = 33.4 \text{ dB} \quad | \quad R_{in} = R_l = 47 k\Omega \quad | \quad R_{out} = 0 \Omega$$

11.8

$$(a) A_v = -\frac{R_2}{R_l} = -\frac{120k\Omega}{12k\Omega} = -10.0 \quad | \quad 20\log(10.0) = 20.0 \text{ dB} \quad | \quad R_{in} = R_l = 12 k\Omega \quad | \quad R_{out} = 0 \Omega$$

$$(b) A_v = -\frac{R_2}{R_l} = -\frac{330k\Omega}{140k\Omega} = -2.36 \quad | \quad 20\log(2.36) = 7.46 \text{ dB} \quad | \quad R_{in} = R_l = 140 k\Omega \quad | \quad R_{out} = 0 \Omega$$

$$(c) A_v = -\frac{R_2}{R_l} = -\frac{240k\Omega}{4.3k\Omega} = -55.8 \quad | \quad 20\log(55.8) = 34.9 \text{ dB} \quad | \quad R_{in} = R_l = 4.3 k\Omega \quad | \quad R_{out} = 0 \Omega$$

11.9

$$A_v = -\frac{R_2}{R_l} = -\frac{8200\Omega}{750\Omega} = -10.9 \quad | \quad V_o = -10.9(0.05V) = -0.547V \quad | \quad v_o(t) = -0.547 \sin(4638t) V$$

$$I_s = \frac{V_s}{R_l} = \frac{0.05V}{750\Omega} = 66.7 \mu A \quad | \quad i_s(t) = 66.7 \sin(4638t) \mu A$$

11.10

$$(a) A_v = -\frac{110k\Omega}{22k\Omega} = -5 \quad v_o = A_v v_s = 0 \quad (b) V_o = A_v V_s = -5(0.22V) = -1.10 V$$

$$(c) v_o = [-5(0.15V)] \sin 2500\pi t = -0.75 \sin 2500\pi t V \quad (d) v_o = (-1.10 + 0.75 \sin 2500\pi t) V$$

$$(e) I_s = \frac{0.22V}{22k\Omega} = 10.0 \mu A \quad i_s = \left[\frac{0.15V}{22k\Omega} \right] \sin 2500\pi t = 6.82 \sin 2500\pi t \mu A \quad i_s = (10.0 - 6.82 \sin 2500\pi t) \mu A$$

$$(f) i_o = -i_s \quad I_o = -10.0 \mu A \quad i_o = -6.82 \sin 2500\pi t \mu A \quad i_o = (-10.0 + 6.82 \sin 2500\pi t) \mu A$$

$$(g) v_o = 0$$

$$\boxed{11.11 \quad v_o = -i_{TH} R}$$

11.12

$$R_{in} = R_l = 1.5 k\Omega \quad | \quad A_v = -\frac{R_2}{R_l} = -10^{\frac{40}{20}} = -100 \rightarrow R_2 = 100R_l = 150k\Omega$$

The resistors exist as standard values.

11.13

$$R_{in} = R_l = 30 \text{ k}\Omega \quad | \quad A_v = -\frac{R_2}{R_l} = -10^{\frac{26}{20}} = -20 \rightarrow R_2 = 20R_l = 600 \text{ k}\Omega$$

Using the closest values from Appendix A, $R_l \rightarrow 30.1 \text{ k}\Omega$ and $R_2 \rightarrow 604 \text{ k}\Omega$

The values for the final design are $A_v = -\frac{604 \text{ k}\Omega}{30.1 \text{ k}\Omega} = -20.1$ and $R_{in} = 30.1 \text{ k}\Omega$

11.14

$$R_{in} = R_l = 100 \text{ k}\Omega \quad | \quad A_v = -\frac{R_2}{R_l} = -10^{\frac{12}{20}} = -15.8 \rightarrow R_2 = 15.8R_l = 1.58 \text{ M}\Omega$$

Using the closest 1% values from Appendix A, $R_l \rightarrow 100 \text{ k}\Omega$ and $R_2 \rightarrow 1.00 \text{ M}\Omega + 576 \text{ k}\Omega$

The values for the final design are $A_v = -\frac{1.576 \text{ M}\Omega}{100 \text{ k}\Omega} = -15.8$ and $R_{in} = 100 \text{ k}\Omega$

If we used 5% values, we could select 100 kΩ and 1.6 MΩ.

11.15

$$A_v = 1 + \frac{R_2}{R_l} = 1 + \frac{750 \text{ k}\Omega}{8.2 \text{ k}\Omega} = 92.5 \quad | \quad 20 \log(92.5) = 39.3 \text{ dB} \quad | \quad R_{in} = \infty \quad | \quad R_{out} = 0 \text{ }\Omega$$

11.16

$$(a) A_v = 1 + \frac{R_2}{R_l} = 1 + \frac{120 \text{ k}\Omega}{24 \text{ k}\Omega} = 6.00 \quad | \quad 20 \log(6.00) = 15.6 \text{ dB} \quad | \quad R_{in} = \infty \quad | \quad R_{out} = 0 \text{ }\Omega$$

$$(b) A_v = 1 + \frac{R_2}{R_l} = 1 + \frac{300 \text{ k}\Omega}{15 \text{ k}\Omega} = 21.0 \quad | \quad 20 \log(21.0) = 26.4 \text{ dB} \quad | \quad R_{in} = \infty \quad | \quad R_{out} = 0 \text{ }\Omega$$

$$(c) A_v = 1 + \frac{R_2}{R_l} = 1 + \frac{360 \text{ k}\Omega}{4.3 \text{ k}\Omega} = 84.7 \quad | \quad 20 \log(84.7) = 38.6 \text{ dB} \quad | \quad R_{in} = \infty \quad | \quad R_{out} = 0 \text{ }\Omega$$

11.17

$$A_v = 1 + \frac{R_2}{R_l} = 1 + \frac{8200 \Omega}{910 \Omega} = 10.0 \quad | \quad V_o = 10.0(0.05V) = 0.500V \quad | \quad v_o(t) = 0.500 \sin 9125t \text{ V}$$

11.18

$$(a) A_v = 1 + \frac{110k\Omega}{22k\Omega} = +6 \quad v_o = 6v_s = 0 \quad (b) V_o = A_v V_s = 6(0.33V) = +1.98 \text{ V}$$

$$(b) v_o = [6(0.18V)] \sin 3250\pi t = 1.08 \sin 3250\pi t \text{ V}$$

$$(d) v_o = (1.98 - 1.08 \sin 3250\pi t) \text{ V} \quad (e) i_s = 0$$

$$(f) i_o = +\frac{v_o}{R_1 + R_2} = \frac{1.98V}{132k\Omega} = 15.0 \mu\text{A} \quad i_o = 8.18 \sin 3250\pi t \mu\text{A} \quad i_o = (15.0 + 8.18 \sin 3250\pi t) \mu\text{A}$$

$$(g) v_o = (0.33 - 0.18 \sin 3250\pi t) V$$

11.19

$$(a) A_v^{nom} = 1 + \frac{R_2}{R_1} = 1 + \frac{47k\Omega}{0.18k\Omega} = 262 \quad | \quad 20 \log(262) = 48.4 \text{ dB}$$

$$R_{in} = 10k\Omega + \infty = \infty \quad | \quad R_{out} = 0 \Omega$$

$$(b) A_v^{\max} = 1 + \frac{47k\Omega(1.1)}{0.18k\Omega(0.9)} = 320 \quad | \quad A_v^{\min} = 1 + \frac{47k\Omega(0.9)}{0.18k\Omega(1.1)} = 215$$

$$\frac{A_v^{\max} - A_v^{nom}}{A_v^{nom}} = \frac{320 - 262}{262} = 0.22 \quad | \quad \frac{A_v^{\min} - A_v^{nom}}{A_v^{nom}} = \frac{215 - 262}{262} = -0.18$$

$$(c) Tolerances: +22\%, -18\% \quad (d) \frac{320}{215} = 1.49 : 1$$

(e) function count=c;

```
c=0;
for i=1:500,
    r1=180*(1+0.2*(rand-0.5));
    r2=47000*(1+0.2*(rand-0.5));
    a=1+r2/r1;
    anom=1+47000/180;
    if (a>=0.95*anom & a<=1.05*anom), c=c+1; end;
end
c
```

Executing this function twenty times yields 44% .

11.20

$$A_v = 1 + \frac{R_2}{R_1} = 10^{\frac{32}{20}} = 39.8 \rightarrow R_2 = 38.8R_1$$

There are many possible pairs of values in Appendix A. Two choices are

$R_1 \rightarrow 3.09 \text{ k}\Omega$ and $R_2 \rightarrow 121 \text{ k}\Omega$ or $R_1 \rightarrow 6.19 \text{ k}\Omega$ and $R_2 \rightarrow 243 \text{ k}\Omega$

The values for the final design are $A_v = 1 + \frac{121 \text{ k}\Omega}{3.09 \text{ k}\Omega} = 40.2$

11.21

$$A_v = 1 + -\frac{R_2}{R_1} = 10^{\frac{26}{20}} = 20 \rightarrow R_2 = 19R_1$$

There are many possible pairs of values in Appendix A. Two choices are

$R_1 \rightarrow 1.05 \text{ k}\Omega$ and $R_2 \rightarrow 200 \text{ k}\Omega$ or $R_1 \rightarrow 10.5 \text{ k}\Omega$ and $R_2 \rightarrow 200 \text{ k}\Omega$

The values for the final design are $A_v = 1 + \frac{200 \text{ k}\Omega}{1.05 \text{ k}\Omega} = 20.0$

11.22

$$A_v = 1 + -\frac{R_2}{R_1} = 10^{\frac{6}{20}} = 2.00 \rightarrow R_2 = R_1. \text{ Any value could theoretically be used, but}$$

we don't want a heavy load on a real op amp, so we should choose the resistors to be at least in the $10 - \text{k}\Omega$ range or so. A third $100 - \text{k}\Omega$ resistor is added in shunt with the input as in Fig. P11.23(b). $R_1 \rightarrow 10.0 \text{ k}\Omega$, $R_2 \rightarrow 10.0 \text{ k}\Omega$, and $R_3 \rightarrow 100 \text{ k}\Omega$

The values for the final design are $A_v = 1 + \frac{10.0 \text{ k}\Omega}{10.0 \text{ k}\Omega} = 2.00$ and $R_{in} = 100 \text{ k}\Omega$

11.23

$$(a) A_v = -\frac{R_2}{R_1} = -\frac{100 \text{ k}\Omega}{20 \text{ k}\Omega} = -5.00 \quad | \quad R_{in} = R_1 = 20 \text{ k}\Omega$$

$$(b) A_v = 1 + \frac{R_2}{R_1} = 1 + \frac{100 \text{ k}\Omega}{20 \text{ k}\Omega} = +6.00 \quad | \quad R_{in} = 47 \text{ k}\Omega \parallel \infty = 47 \text{ k}\Omega$$

$$(c) A_v = -\frac{R_2}{R_1} = -\frac{0}{36 \text{ k}\Omega} = 0 \quad | \quad R_{in} = R_1 = 36 \text{ k}\Omega$$

(This is not a very useful circuit except possibly as an "electronic ground".)

11.24

$$v_o = -\frac{R_3}{R_1}v_1 - \frac{R_3}{R_2}v_2 = -\frac{51 \text{ k}\Omega}{1 \text{ k}\Omega}v_1 - \frac{51 \text{ k}\Omega}{2 \text{ k}\Omega}v_2 = -51v_1 - 25.5v_2$$

$$v_o(t) = [-51(0.01)]\sin 3770t + [-25.5(0.04)]\sin 10000t$$

$$v_o(t) = (-0.510 \sin 3770t - 1.02 \sin 10000t) V \text{ and } v_o(t) \equiv 0$$

11.25

$$(a) v_o = (0) \left\lfloor -\frac{R}{2R} v_s \right\rfloor + (1) \left\lfloor -\frac{R}{4R} v_s \right\rfloor + (1) \left\lfloor -\frac{R}{8R} v_s \right\rfloor + (0) \left\lfloor -\frac{R}{16R} v_s \right\rfloor = -0.3750 \sin 4000\pi t \text{ V}$$

$$(b) v_o = (1) \left\lfloor -\frac{R}{2R} v_s \right\rfloor + (0) \left\lfloor -\frac{R}{4R} v_s \right\rfloor + (1) \left\lfloor -\frac{R}{8R} v_s \right\rfloor + (1) \left\lfloor -\frac{R}{16R} v_s \right\rfloor = -0.6875 \sin 4000\pi t \text{ V}$$

(c) $v_o = -A \sin 4000\pi t \text{ V}$ where the amplitude A is in the table below:

0000	0	0100	-0.250 V	1000	-0.5000 V	1100	-0.7500 V
0001	-0.0625 V	0101	-0.3125 V	1001	-0.5625 V	1101	-0.8125 V
0010	-0.1250 V	0110	-0.3750 V	1010	-0.6250 V	1110	-0.8750 V
0011	-0.1875 V	0111	-0.4375 V	1011	-0.6875 V	1111	-0.9375 V

11.26

$$R_{on} = \frac{1}{K_n' \left(\frac{W}{L} \right) (V_{GS} - V_{TN} - V_{DS})} \quad | \quad \text{The worst-case condition for the switches occurs}$$

for the one with $V_{DS} \neq 0$ and $V_{SB} = 0$. If $V_{REF} = 3V$ and $R_{on} = 0.01(10k\Omega) = 100\Omega$

$$V_D = 3V \text{ and } V_S = 3V \frac{10k\Omega}{10k\Omega + 100\Omega} = 2.97V \quad | \quad V_{DS} = 0.03V$$

$$V_{TN} = 1 + 0.5(\sqrt{2.97 + 0.6} - \sqrt{0.6}) = 1.56V$$

$$\left(\frac{W}{L} \right) = \frac{1}{5 \times 10^{-5} (100) [5 - 2.97 - 1.56 - 0.03]} = \left(\frac{455}{1} \right)$$

$$\text{When the grounded transistor is on, } V_{DS} = 0 \quad | \quad \left(\frac{W}{L} \right) = \frac{1}{5 \times 10^{-5} (100) [5 - 1 - 0]} = \left(\frac{50}{1} \right)$$

11.27

$$(a) \text{Using Eq. 11.32, } A_v = -\frac{R_2}{R_1} = -\frac{10R}{R} = -10$$

$$(b) R_{in2} = \left. \frac{v_2}{i_2} \right|_{v_1=0} = 11R = 110 \text{ k}\Omega \quad | \quad R_{in1} = \left. \frac{v_1}{i_1} \right|_{v_2=0} = R = 10 \text{ k}\Omega$$

$$(c) v_o = -10(v_1 - v_2) = -30 + 15 \cos 8300\pi t \text{ V} \quad (d) v_o = -30 + 30 \cos 8300\pi t \text{ V}$$

11.28

$$V_1 = 3.2 \text{ V} \quad | \quad V_2 = 3.1 \text{ V} \quad | \quad V_o = -\frac{R_2}{R_1}(V_1 - V_2) = -\frac{10R}{R}(3.2 - 3.1) = -1.00 \text{ V}$$

$$I_o = \frac{(3.20 - 2.82)V}{100k\Omega} = 3.80 \mu\text{A} \quad | \quad V_+ = 3.1V \frac{10R}{R + 10R} = 2.82 \text{ V} \quad | \quad V_- = V_+ = 2.82 \text{ V}$$

$$I_1 = \frac{V_1 - V_-}{100k\Omega} = \frac{3.2 - 2.82}{100} \frac{\text{V}}{k\Omega} = 3.80 \mu\text{A} \quad | \quad I_2 = \frac{V_2 - V_+}{100k\Omega} = \frac{3.1 - 2.82}{100} \frac{\text{V}}{k\Omega} = 2.80 \mu\text{A}$$

Checking : $I_2 = \frac{V_2}{R + 10R} = \frac{3.1V}{110k\Omega} = 2.82 \mu\text{A}$ which agrees within roundoff error.

11.29

$$A_v = -\left(\frac{R_4}{R_3}\right)\left(1 + \frac{R_2}{R_1}\right) = -\left(\frac{10k\Omega}{10k\Omega}\right)\left(1 + \frac{100k\Omega}{2k\Omega}\right) = -51$$

$$v_o = A_v(v_1 - v_2) = [-51(0.1)]\sin 2000\pi t + (-51)(2 - 2.1) = (5.1 - 5.1\sin 2000\pi t) \text{ V}$$

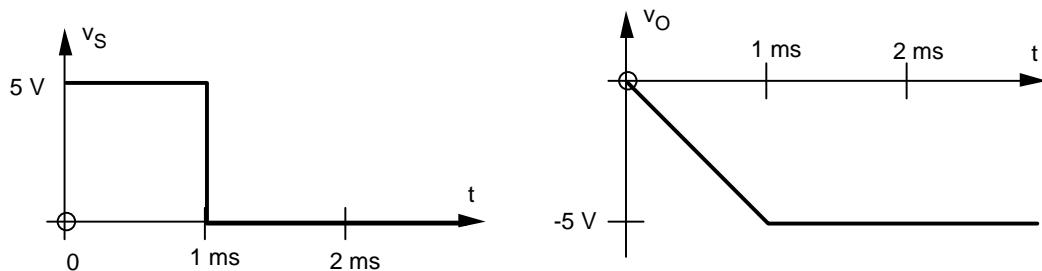
11.30

$$A_v = -\left(\frac{R_4}{R_3}\right)\left(1 + \frac{R_2}{R_1}\right) = -\left(\frac{20k\Omega}{10k\Omega}\right)\left(1 + \frac{100k\Omega}{20k\Omega}\right) = -12$$

$$v_o = A_v(v_1 - v_2) = -12(4 - 0.1\sin 4000\pi t - 3.5) = (-6 + 1.2\sin 4000\pi t) \text{ V}$$

11.31

$$v_o(t) = -\frac{1}{RC} \int_0^t v_s(\tau) d\tau + v_c(0^+) = -\frac{1}{10k\Omega(0.005\mu\text{F})} \int 0.1\sin 2000\pi\tau d\tau + 0 = 0.318\cos 2000\pi t \text{ V}$$

11.32**11.33**

$$(a) A_v = -\left(\frac{R_2}{R_1}\right) \frac{1}{1 + \frac{s}{\omega_H}} \quad | \quad A_v(0) = -\frac{R_2}{R_1} = -\frac{10k\Omega}{2k\Omega} = -5 \quad | \quad f_H = \frac{1}{2\pi R_2 C} = \frac{1}{2\pi(10k\Omega)(0.001\mu\text{F})} = 15.9 \text{ kHz}$$

$$(b) A_v(0) = -\frac{R_2}{R_1} = -\frac{56k\Omega}{2.7k\Omega} = -20.7 \quad | \quad f_H = \frac{1}{2\pi R_2 C} = \frac{1}{2\pi(56k\Omega)(100\text{pF})} = 28.4 \text{ kHz}$$

11.34

$$(a) R_{in} = R_l = 10 \text{ k}\Omega \quad | \quad A_v(0) = -10^{\frac{20}{20}} = -10 \rightarrow R_2 = 10R_l = 100 \text{ k}\Omega$$

$$C = \frac{1}{2\pi R_2 f_H} = \frac{1}{2\pi(100\text{k}\Omega)(20\text{kHz})} = 79.6 \text{ pF}$$

(b) If the input resistance specification is most critical,

$$R_l = 10 \text{ k}\Omega \quad | \quad R_2 = 10R_l = 100 \text{ k}\Omega \quad | \quad C = 82 \text{ pF} \rightarrow f_H = 19.4 \text{ kHz}$$

If the cutoff frequency specification is most critical,

$$C = 82 \text{ pF} \rightarrow f_H = 19.9 \text{ kHz} \quad | \quad R_l = 9.76 \text{ k}\Omega \quad | \quad R_2 = 10R_l = 97.6 \text{ k}\Omega$$

11.35

$$sCV_s = -\frac{V_o}{R} \quad | \quad T(s) = \frac{V_o}{V_s} = -sRC$$

11.36

$$v_o(t) = -RC \frac{dv_s(t)}{dt} = -(100\text{k}\Omega)(0.02\mu\text{F}) \frac{d}{dt} 2\cos 3000\pi t = +37.7 \sin 3000\pi t \text{ V}$$

11.37

$$A_v(s) = -\frac{Z_2(s)}{Z_1(s)} \quad Z_2 = R_2 \quad Z_1(s) = \frac{R_l}{sCR_l + 1} \quad A_v(s) = -\frac{R_2}{R_l} \left(1 + \frac{s}{\omega_L}\right) \quad \text{for } \omega_L = \frac{1}{R_l C}$$

11.38

$$(a) A_v = -\frac{R_2}{R_l} = -\frac{120\text{k}\Omega}{20\text{k}\Omega} = -6.00 \quad | \quad R_{in} = R_l = 20 \text{ k}\Omega$$

Note that the 100 - kΩ resistor does not affect the circuit because v₋ = 0.

$$(b) A_v = 1 + \frac{R_2}{R_l} = 1 + \frac{120\text{k}\Omega}{15\text{k}\Omega} = +9.00 \quad | \quad R_{in} = 75\text{k}\Omega \parallel \infty = 75 \text{ k}\Omega$$

$$(c) A_v = -\frac{R_2}{R_l} = -\frac{0}{36\text{k}\Omega} = 0 \quad | \quad R_{in} = R_l = 160 \text{ k}\Omega$$

(This is not a very useful circuit except possibly as an "electronic ground".)

11.39

Equating currents at the inverting input node (virtual ground):

$$\frac{v_s}{10k\Omega} = -\frac{v_o}{100k\Omega + (20k\Omega \parallel 100k\Omega)} \frac{20k\Omega}{100k\Omega + 20k\Omega}$$

$$A_v = \frac{v_o}{v_s} = -\frac{116.7k\Omega(120k\Omega)}{10k\Omega(20k\Omega)} = -70.0 \quad R_{in} = 10 k\Omega \quad R_{out} = 0$$

11.40

The inverting terminal of the op amp represents a virtual ground (0 V).

$$(a) I_o = I_D = \frac{V_- - (-V_{EE})}{R} = \frac{0 - (-10)}{10} = 1 A$$

(b) Saturation requires $V_{DS} \geq V_{GS} - V_{TN}$ where $V_{DS} = V_{DD} - V_- = V_{DD}$ and

$$V_{GS} - V_{TN} = \sqrt{\frac{2I_D}{K_n}} = \sqrt{\frac{2(1)}{0.25}} = 2.83V \rightarrow V_{DD} \geq 2.83 V$$

$$(c) P_R = I^2 R = (1)^2 10 = 10W. \text{ So the resistor must dissipate } 10 W.$$

A 15 - W resistor would provide a reasonable safety margin.

11.41

The inverting terminal of the op amp represents a virtual ground (0 V).

$$(a) I_o = I_C = \alpha_F I_E = \left(\frac{\beta_F}{1 + \beta_F} \right) \left[\frac{V_- - (-V_{EE})}{R} \right] = \left(\frac{30}{31} \right) \left[\frac{0 - (-15)}{30} \right] = 0.484 A$$

$$(b) V_o = V_- + V_{BE} = 0 + V_{BE} = V_{BE} = V_T \ln \frac{I_C}{I_S} = 0.025V \ln \frac{0.484}{10^{-13}} = 0.730V$$

(c) Forward - active region operation requires $V_{CE} \geq V_{BE}$ but $V_{CE} = V_{CC} - V_- = V_{CC}$
Therefore $V_{CC} \geq 0.730 V$.

$$(d) P_R = I^2 R = (0.484)^2 30 = 7.03W. \text{ So the resistor must dissipate } 7.03 W.$$

A 10W resistor would provide a reasonable safety margin.

$$P_D = I_C V_{CE} + I_B V_{BE} = 0.484(15) + \frac{0.484}{30} 0.730 = 7.27 W.$$

11.42

$$(a) A_v(s) = -\frac{Z_2(s)}{Z_1(s)} \quad Z_2 = \frac{1}{sC} \quad Z_1(s) = R \quad A_v(s) = -\frac{1}{sRC}, \text{ an inverting integrator.}$$

$$(b) \frac{\mathbf{V}_s - \mathbf{V}_+}{R} + \frac{\mathbf{V}_o - \mathbf{V}_+}{KR} = sC\mathbf{V}_+ \quad \text{and} \quad \mathbf{V}_+ = \mathbf{V}_- = \mathbf{V}_o \frac{R_i}{R_i + KR_i} = \frac{\mathbf{V}_o}{1+K}$$

Combining these expressions yields: $A_v(s) = \frac{\mathbf{V}_o}{\mathbf{V}_s} = +\frac{1+K}{sRC}$, a noninverting integrator.

11.43

$$V_- = V_o \frac{R_i}{R_i + 9R_i} = \frac{V_o}{10} \quad | \quad \frac{V_s - V_+}{R} + \frac{V_o - V_+}{10R} = sC\mathbf{V}_+ \quad | \quad V_+ = V_-$$

$$V_s = \left(sCR + \frac{11}{10} \right) \frac{V_o}{10} \quad | \quad \frac{V_o}{V_s} = \frac{100}{10sCR + 11} \quad \text{-- The circuit becomes a low-pass filter.}$$

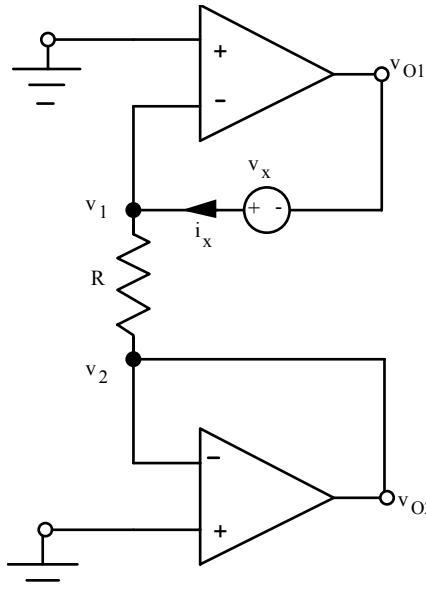
Note: The pole moves to the right half plane if the tolerances go the other way.

$$\text{For example, if } KR_i = 10R_i \text{ and } KR = 9R, \quad \frac{V_o}{V_s} = \frac{99}{9sCR - 1}$$

11.44

(a) Applying ideal op-amp assumption 1, the voltage at the top end of R is v_1 and the voltage at the bottom end of R is v_2 . Applying op-amp assumption 2, the current i_o must also equal the current in R, so

$$i_o = \frac{\mathbf{v}_1 - \mathbf{v}_2}{R}$$



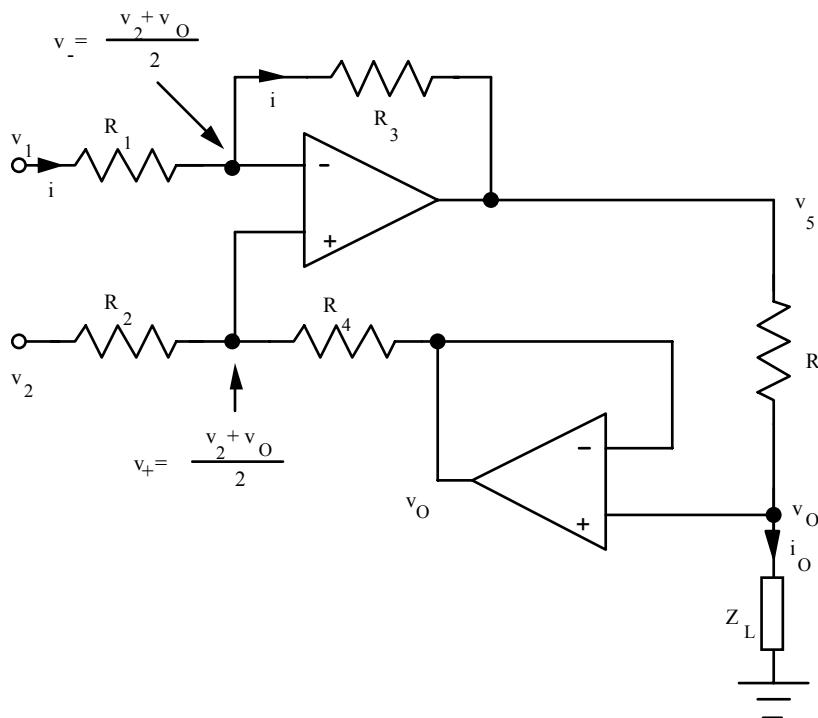
$$(b) i_x = \frac{0V - 0V}{R} = 0 \quad | \quad R_{out} = \frac{\mathbf{v}_x}{i_x} = \infty$$

$$\mathbf{v}_{o1} = A(0 - (\mathbf{v}_{o1} + \mathbf{v}_x)) \quad \mathbf{v}_{o2} = A(0 - \mathbf{v}_{o2}) \Rightarrow \mathbf{v}_{o2} = 0$$

$$\mathbf{v}_{o1} = -\mathbf{v}_x \frac{A}{1+A} \quad | \quad \mathbf{v}_1 = \mathbf{v}_{o1} + \mathbf{v}_x = \frac{\mathbf{v}_x}{1+A}$$

$$i_x = \frac{\mathbf{v}_1 - \mathbf{v}_2}{R} = \frac{\mathbf{v}_x}{(1+A)R} \quad | \quad R_{out} = \frac{\mathbf{v}_x}{i_x} = (1+A)R$$

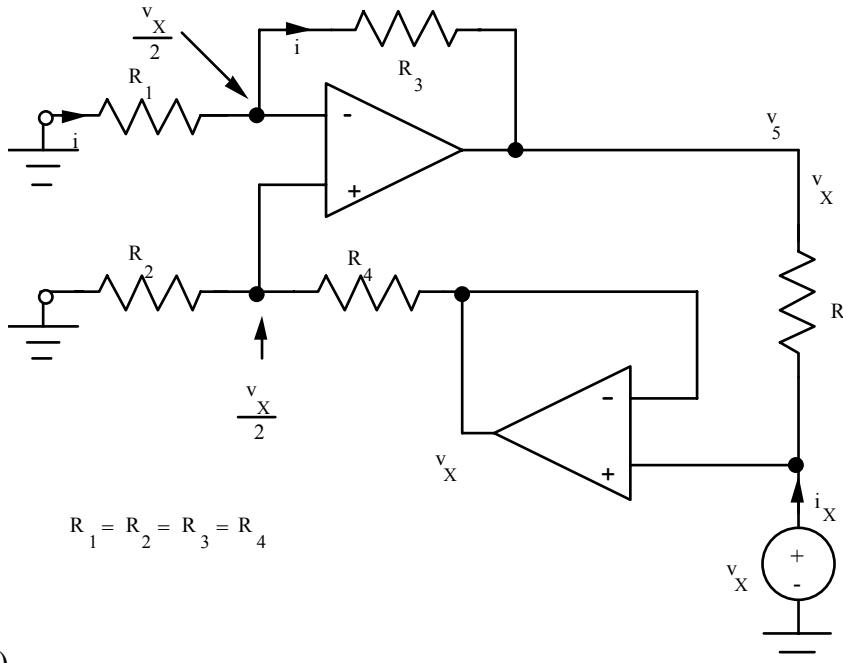
11.45



(a)

$$\mathbf{i}_o = \frac{\mathbf{v}_5 - \mathbf{v}_o}{R} \quad | \quad \mathbf{v}_5 = \mathbf{v}_- - \mathbf{i} R_3 = \mathbf{v}_- - \frac{\mathbf{v}_1 - \mathbf{v}_-}{R_1} R_3 = 2\mathbf{v}_- - \mathbf{v}_1 \quad \text{since } R_1 = R_3$$

$$\mathbf{v}_- = \frac{\mathbf{v}_2 + \mathbf{v}_o}{2} \quad \text{and} \quad \mathbf{v}_5 = \mathbf{v}_2 - \mathbf{v}_1 + \mathbf{v}_o \quad | \quad \mathbf{i}_o = \frac{\mathbf{v}_2 - \mathbf{v}_1 + \mathbf{v}_o - \mathbf{v}_o}{R} = \frac{\mathbf{v}_2 - \mathbf{v}_1}{R}$$



(b)

$$\mathbf{i}_x = \frac{\mathbf{v}_x - \mathbf{v}_5}{R} = \frac{\mathbf{v}_x - \mathbf{v}_x}{R} = 0 \quad | \quad R_{out} = \frac{\mathbf{v}_x}{\mathbf{i}_x} = \infty \quad (\text{an ideal current source})$$

11.46

(a) Using voltage division since $\mathbf{i}_+ = 0$, $v_2 = v_4 + 6 \frac{4.99k\Omega}{4.99k\Omega + 5.00k\Omega}$

$$v_2 = v_4 + (6 - v_4) \frac{4.99k\Omega}{4.99k\Omega + 5.00k\Omega} = 0.5005v_4 + 2.997V$$

$$\text{Since } v_{id} = 0, v_1 = v_2 \text{ and } v_5 = v_1 - \frac{4 - v_1}{5k\Omega} (5.01k\Omega)$$

$$\text{Solving for } v_5 \text{ yields } v_5 = 1.992V + 1.002v_4$$

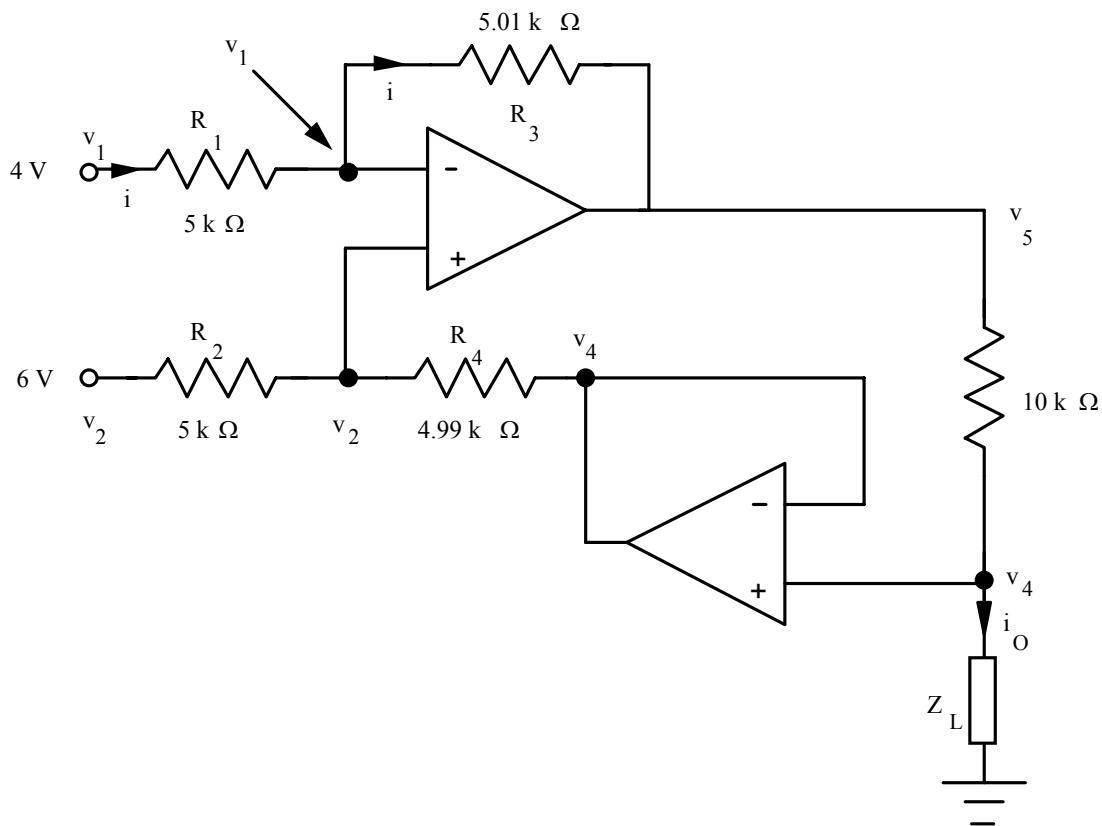
$$i_o = \frac{v_5 - v_4}{10k\Omega} = 199\mu A + 2 \times 10^{-7}v_4$$

v_4 is unknown; let us assume $2 \times 10^{-7}v_4 \ll 199 \times 10^{-6}A$

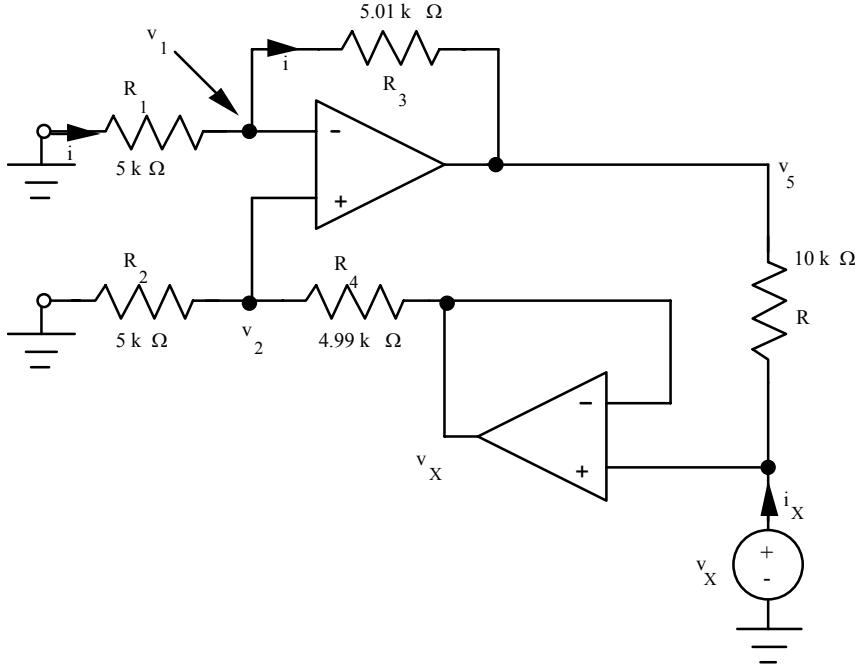
which requires $v_4 \ll 995V$. So for $v_4 < 100V$, which should almost always be true in transistor circuits, $i_o = 199\mu A$.

For $Z_L = 10 k\Omega$, $v_4 = 1.99 V$, $v_2 = 3.99 V$, $v_1 = 3.99 V$, $v_5 = 3.99 V$

Note that $v_5 - v_4 = 2 V = (6V - 4V)$



11.46 (b)



$R_{out} = \frac{v_x}{i_x}$ and $i_x = \frac{v_x - v_5}{10k\Omega}$ So we need to find i_x , and hence v_5 , in terms of v_x

$$v_1 = v_2 = v_x \frac{5.00k\Omega}{4.99k\Omega + 5.00k\Omega} = 0.5005v_x$$

$$v_5 = v_1 + i(5.01k\Omega) = v_1 + \frac{v_1}{5k\Omega}(5.01k\Omega) = 2.002v_1 = 1.002v_x$$

$$i_x = \frac{v_x - v_5}{10k\Omega} = \frac{v_x - 1.002v_x}{10k\Omega} = -\frac{0.002v_x}{10k\Omega} \text{ and } R_{out} = -5M\Omega! \text{ A negative output resistance!}$$

11.47

$$I_L = I_S + \frac{V_o - I_L R_L}{R_l} \quad V_o = I_L R_L + I_S R_2 \quad I_L = I_S \left(1 + \frac{R_2}{R_l} \right)$$

$$V_s = I_S R_2 + I_L R_L = I_S \left[R_2 + R_L \left(1 + \frac{R_2}{R_l} \right) \right] \quad R_m = R_2 + R_L \left(1 + \frac{R_2}{R_l} \right)$$

Apply test voltage v_x to the output with $I_S = 0$. Then $v_+ = v_x$,

$$v_o = v_x, \text{ and } i_x = i_- + \frac{v_x - v_x}{R_l} = 0 + 0 = 0. \quad R_{out} = \infty$$

For finite gain : $R_{out} = \frac{v_x}{i_x}$ where $i_x = \frac{v_x - v_o}{R_l}$ and $v_o = v_x \frac{A}{1+A}$

$$v_x - v_o = \frac{v_x}{1+A} \quad \text{and} \quad R_{out} = R_l(1+A)$$

11.48

Using the result from Prob. 11.47,

$$R_{in} = R_2 + R_L \left(1 + \frac{R_2}{R_1} \right) = 1k\Omega + 3.6k\Omega \left(1 + \frac{1k\Omega}{10k\Omega} \right) = 4.96 \text{ k}\Omega \quad R_{out} = \infty$$

11.49

Applying op-amp assumption 1 to the circuit below, the voltage at the top of R_2 is v_{O2} , and applying op-amp assumption 2,

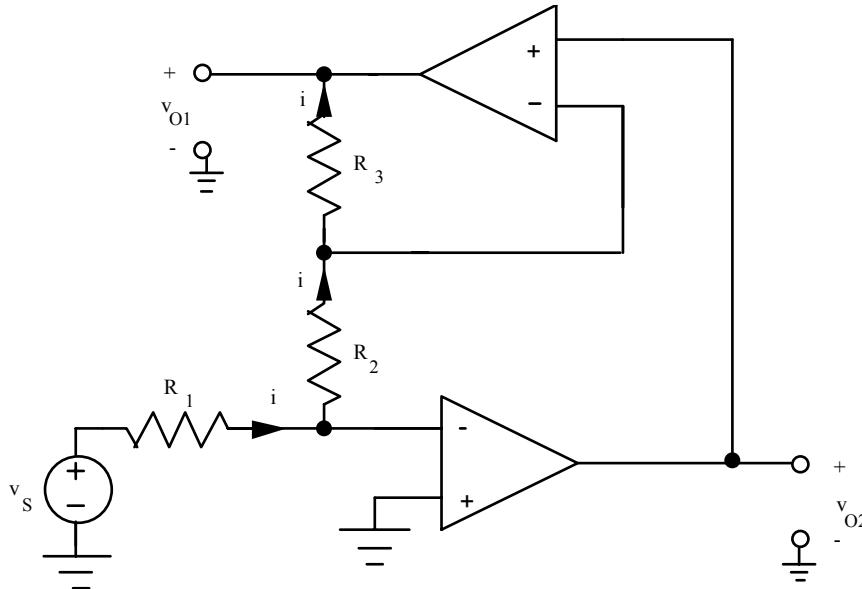
$$\frac{v_s}{R_1} = -\frac{v_{O2}}{R_2} \quad \text{or} \quad v_{O2} = -v_s \frac{R_2}{R_1}$$

Since the op-amp input currents are zero, and

$$i = \frac{v_s}{R_1}, \quad v_{O1} = -iR_2 - iR_3 = -\left(\frac{R_2}{R_1} + \frac{R_3}{R_1} \right)v_s$$

Alternatively, the voltage at the bottom of R_2 is zero, so

$$v_{O1} = \left(1 + \frac{R_3}{R_2} \right) v_{O2} = \left(1 + \frac{R_3}{R_2} \right) \left(-\frac{R_2}{R_1} \right) v_s = -\left(\frac{R_2}{R_1} + \frac{R_3}{R_1} \right) v_s$$



11.50

$$R_{in} = \frac{v_s}{i_s} \quad i_s = \frac{v_s - v_o}{15k\Omega} \quad v_o = \left(1 + \frac{30k\Omega}{2k\Omega} \right) v_s = 16v_s \quad i_s = \frac{v_s - 16v_s}{15k\Omega} = \frac{-15v_s}{15k\Omega} \quad R_{in} = -1k\Omega$$

11.51

An n-bit DAC requires (n+1) resistors. Ten bits requires 11 resistors.

$$\frac{2^{10}R}{R} = \frac{2^{10}}{1} \quad \text{or} \quad 1024 : 1$$

A wide range of resistor values is required but it could be done.

For R = 1 kΩ, 1024R = 1.024 MΩ.

11.52

$$V_o = -V_{REF} \left(\frac{R}{4R} + \frac{R}{8R} \right) = -3.0 \left(\frac{1}{4} + \frac{1}{8} \right) = -1.1250 \text{ V}$$

$$V_o = -V_{REF} \left(\frac{R}{2R} + \frac{R}{16R} \right) = -3.0 \left(\frac{1}{2} + \frac{1}{16} \right) = -1.6875 \text{ V}$$

0000	0.0000 V	1000	-1.5000 V
0001	-0.1875 V	1001	-1.6875 V
0010	-0.3750 V	1010	-1.875 V
0011	-0.5625 V	1011	-2.0625 V
0100	-0.7500 V	1100	-2.2500 V
0101	0.9375 V	1101	-2.4375 V
0110	-1.1250 V	1110	-2.6250 V
0111	-1.3125 V	1111	-2.8125 V

11.53

Taking successive Thévenin equivalent circuits at each ladder node yields:

	V _{TH}	R _{TH}	v _O
0001	V _{REF} /16	R	-0.3125 V
0010	V _{REF} /8	R	-0.6250 V
0100	V _{REF} /4	R	-1.250 V
1000	V _{REF} /2	R	-2.500 V

11.54

The ADC code is equivalent to $(2^{-1} + 2^{-3} + 2^{-5} + 2^{-7} + 2^{-9} + 2^{-10} + 2^{-13})x V_{FS} = 0.66711426 x V_{FS}$

The ADC input may be anywhere in the range :

$$\left(0.66711426 \pm \frac{1}{2} \text{ LSB} \right) x V_{FS} = 3.4154625V \pm 0.15625mV \quad | \quad 3.415469V \leq V_x \leq 3.415781V$$

11.55

$$(a) 1 \text{ LSB} = \frac{2V}{2^{20} \text{ bits}} = 1.90735 \mu\text{V}$$

$$(b) \frac{1.63V}{2V} 2^{20} = 854589.4 \text{ bits} \rightarrow 854589_{10} = 11010000101000111101_2$$

$$(c) \frac{0.997003V}{2V} 2^{20} = 522716.7 \text{ bits} \rightarrow 522717_{10} = 0111111100111011101_2$$

11.56

The time corresponding to 1 LSB is $T_{LSB} = \frac{0.2s}{2^{20} \text{ bits}} = 190.7 \text{ ns} \quad | \quad 0.1T_{LSB} = 19.1 \text{ ns}$

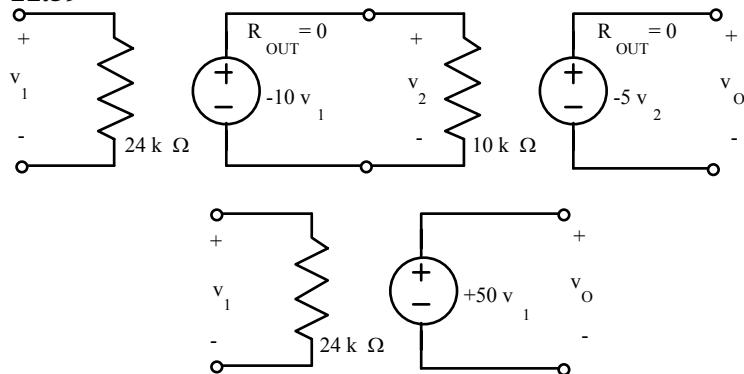
11.57

$$V_o(\omega) = \frac{1}{RC} \int_0^{T_T} v(t) dt = \frac{1}{RC} \int_0^{T_T} V_M \cos(\omega t + \theta) dt = \frac{V_M}{\omega RC} \int_{\theta}^{\omega T_T + \theta} \cos x dx = \frac{V_M}{\omega RC} [\sin(\omega T_T + \theta) - \sin \theta]$$

$$\text{For } \theta = 0, V_o(\omega) = \frac{V_M}{RC} \frac{\sin \omega T_T}{\omega} = \frac{V_M T_T}{RC} \left(\frac{\sin \omega T_T}{\omega T_T} \right)$$

11.58 Combine amplifiers A & B; Combine amplifiers B & C

11.59



$$A_v = 50, R_{in} = 24 \text{ k}\Omega, R_{out} = 0$$

11.60

$$A_v = \left(-\frac{240k\Omega}{24k\Omega} \right) \left(-\frac{50k\Omega}{10k\Omega} \right) = +50 \quad | \quad R_{in} = R_{inA} = 24 \text{ k}\Omega \quad | \quad R_{out} = R_{outB} = 0$$

11.61

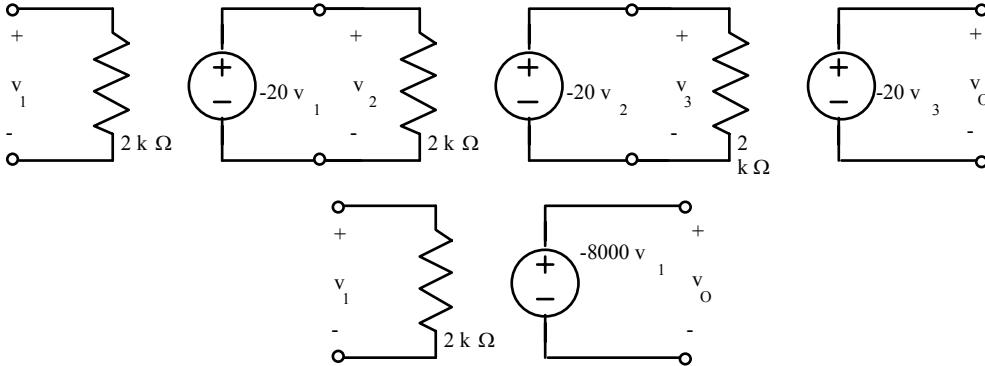
$$A_v = \left(1 + \frac{390k\Omega}{47k\Omega} \right) \left(1 + \frac{100k\Omega}{24k\Omega} \right) = +48.0 \quad | \quad R_{in} = R_{inA} = \infty \quad | \quad R_{out} = R_{outB} = 0$$

11.62

$$(a) A_v = \left(1 + \frac{120k\Omega}{20k\Omega}\right) \left(-\frac{120k\Omega}{20k\Omega}\right) = -42.0 \quad | \quad R_{in} = R_{inA} = \infty \quad | \quad R_{out} = R_{outB} = 0$$

$$(b) A_v = \left(-\frac{120k\Omega}{20k\Omega}\right) \left(1 + \frac{120k\Omega}{20k\Omega}\right) = -42.0 \quad | \quad R_{in} = R_{inA} = 20 k\Omega \quad | \quad R_{out} = R_{outB} = 0$$

11.63



$$A_v = \left(-\frac{40k\Omega}{2k\Omega}\right) \left(-\frac{40k\Omega}{2k\Omega}\right) \left(-\frac{40k\Omega}{2k\Omega}\right) = (-20)^3 = -8000 \quad | \quad R_{in} = R_{inA} = 2 k\Omega \quad | \quad R_{out} = R_{outC} = 0$$

11.64

$$A_v = \left(-\frac{40k\Omega}{3.9k\Omega}\right) \left(-\frac{40k\Omega}{3.9k\Omega}\right) \left(-\frac{40k\Omega}{3.9k\Omega}\right) = \left(-\frac{40k\Omega}{3.9k\Omega}\right)^3 = -1080 \quad | \quad R_{in} = R_{inA} = 3.9 k\Omega \quad | \quad R_{out} = R_{outC} = 0$$

11.65

$$A_v = \left(-\frac{40k\Omega}{R}\right) \left(-\frac{40k\Omega}{R}\right) \left(-\frac{40k\Omega}{R}\right) = \left(-\frac{40k\Omega}{R}\right)^3 \quad | \quad A_v = -10^{\frac{40}{20}} = -100$$

$$R = \frac{40k\Omega}{\sqrt[3]{100}} = 8.62 k\Omega \quad | \quad R_{in} = R_{inA} = 8.62 k\Omega \quad | \quad R_{out} = R_{outC} = 0$$

11.66

$$(a) A_v = \left(-\frac{470k\Omega}{47k\Omega}\right) \left(-\frac{150k\Omega}{15k\Omega}\right) \left(-\frac{270k\Omega}{18k\Omega}\right) = -1500 \quad | \quad R_{in} = R_{inA} = 47 k\Omega \quad | \quad R_{out} = R_{outC} = 0$$

(b) Moving from left to right,

$$0.010 \text{ V}, 0 \text{ V}, -10(.01) = -0.100 \text{ V}, 0 \text{ V}, -10(-0.100) = +1.00 \text{ V}, 0 \text{ V}, -15(1.00) = -15.0 \text{ V},$$

The eighth node is the ground node at 0 V.

11.67

$$A_v^{nom} = \left(-\frac{470k\Omega}{47k\Omega} \right) \left(-\frac{150k\Omega}{15k\Omega} \right) \left(-\frac{270k\Omega}{18k\Omega} \right) = -1500$$

$$A_v^{\max} = \left[-\frac{470k\Omega}{47k\Omega} \left(\frac{1.05}{0.95} \right) \right] \left[-\frac{150k\Omega}{15k\Omega} \left(\frac{1.05}{0.95} \right) \right] \left[-\frac{270k\Omega}{18k\Omega} \left(\frac{1.05}{0.95} \right) \right] = -2025$$

$$A_v^{\min} = \left[-\frac{470k\Omega}{47k\Omega} \left(\frac{0.95}{1.05} \right) \right] \left[-\frac{150k\Omega}{15k\Omega} \left(\frac{0.95}{1.05} \right) \right] \left[-\frac{270k\Omega}{18k\Omega} \left(\frac{0.95}{1.05} \right) \right] = -1011$$

$$R_{in}^{nom} = R_{inA} = 47 k\Omega \quad R_{in}^{\max} = 47k\Omega(1.05) = 49.4 k\Omega \quad R_{in}^{\min} = 47k\Omega(0.95) = 44.7 k\Omega$$

$$R_{out}^{nom} = R_{out}^{\max} = R_{out}^{\min} = R_{outC} = 0$$

11.68

$$A_v = \left(1 + \frac{39k\Omega}{3k\Omega} \right) \left(1 + \frac{39k\Omega}{3k\Omega} \right) \left(1 + \frac{39k\Omega}{3k\Omega} \right) = +2744 \quad | \quad R_{in} = 1M\Omega \parallel \infty = 1 M\Omega \quad | \quad R_{out} = R_{outC} = 0$$

2.00 mV, 2.00 mV, 28.0 mV, 28.0 mV, 392 mV, 392 mV, 5.49 V, 0 V (Ground node)

11.69

$$A_v = \left(1 + \frac{39k\Omega}{1k\Omega} \right) \left(1 + \frac{39k\Omega}{1k\Omega} \right) \left(1 + \frac{39k\Omega}{1k\Omega} \right) = +64000 \quad | \quad R_{in} = 2M\Omega \parallel \infty = 2 M\Omega \quad | \quad R_{out} = R_{outC} = 0$$

2.00 mV, 2.00 mV, 80.0 mV, 80.0 mV, 3.20V, 3.20 V, 128 V (not realistic), 0 V

11.70

$$A_v^{nom} = \left(1 + \frac{39k\Omega}{3k\Omega} \right)^3 = +2744$$

$$A_v^{\max} = \left[\left(1 + \frac{39k\Omega}{3k\Omega} \right) \left(\frac{1.02}{0.98} \right) \right]^3 = +3094 \quad A_v^{\min} = \left[\left(1 + \frac{39k\Omega}{3k\Omega} \right) \left(\frac{0.98}{1.02} \right) \right]^3 = +2434$$

$$R_{in}^{nom} = 1M\Omega \parallel \infty = 1 M\Omega \quad R_{in}^{\max} = 1M\Omega(1.02) = 1.02 M\Omega \quad R_{in}^{\min} = 1M\Omega(0.98) = 980 k\Omega$$

$$R_{out}^{nom} = R_{out}^{\max} = R_{out}^{\min} = R_{outC} = 0$$

11.71

$$A_v = \left(1 + \frac{150k\Omega}{15k\Omega} \right) \left(-\frac{420k\Omega}{21k\Omega} \right) \left(1 + \frac{100k\Omega}{20k\Omega} \right) = -1320 \quad | \quad R_{in} = 75k\Omega \parallel \infty = 75 k\Omega \quad | \quad R_{out} = R_{outC} = 0$$

5.00 mV, 5.00 mV, 55.0 mV, 0 V, -1.10 V, -1.10V, -6.60 V, 0 V (Ground node)

11.72

$$A_v^{nom} = \left(1 + \frac{150k\Omega}{15k\Omega}\right) \left(-\frac{420k\Omega}{21k\Omega}\right) \left(1 + \frac{100k\Omega}{20k\Omega}\right) = -1320$$

$$A_v^{\max} = \left[\left(1 + \frac{150k\Omega}{15k\Omega}\right) \left(\frac{1.01}{0.99}\right)\right] \left[\left(-\frac{420k\Omega}{21k\Omega}\right) \left(\frac{1.01}{0.99}\right)\right] \left[\left(1 + \frac{100k\Omega}{20k\Omega}\right) \left(\frac{1.01}{0.99}\right)\right] = -1402$$

$$A_v^{\min} = \left[\left(1 + \frac{150k\Omega}{15k\Omega}\right) \left(\frac{0.99}{1.01}\right)\right] \left[\left(-\frac{420k\Omega}{21k\Omega}\right) \left(\frac{0.99}{1.01}\right)\right] \left[\left(1 + \frac{100k\Omega}{20k\Omega}\right) \left(\frac{0.99}{1.01}\right)\right] = -1243$$

$$R_{in}^{nom} = R_{inA} = 75 \text{ k}\Omega \quad R_{in}^{\max} = 75k\Omega(1.01) = 75.8 \text{ k}\Omega \quad R_{in}^{\min} = 75k\Omega(0.99) = 74.3 \text{ k}\Omega$$

$$R_{out}^{nom} = R_{out}^{\max} = R_{out}^{\min} = R_{outC} = 0$$

11.73

$$(a) C_2 = C = 0.005\mu F \quad | \quad C_1 = 2C = 0.01\mu F \quad | \quad R = \frac{1}{\sqrt{2}\omega_o C} = \frac{1}{\sqrt{2}(40000\pi)(0.005\mu F)} = 1.13 \text{ k}\Omega$$

For $Q = \frac{1}{\sqrt{2}}$: $A_v(s) = \frac{\omega_o^2}{s^2 + \sqrt{2}\omega_o s + \omega_o^2}$ | $A(0) = 1$ | $|A(j\omega_o)| = \frac{1}{\sqrt{2}} \rightarrow \omega_H = \omega_o!$ | $f_H = 20 \text{ kHz}$

(b) For $f_o = 40 \text{ kHz}$: $C' \rightarrow \frac{C}{2}$: $C_1' = 0.005 \mu F$ | $C_2' = 0.0025 \mu F$ | $R = 1.13 \text{ k}\Omega$

11.74

(a)

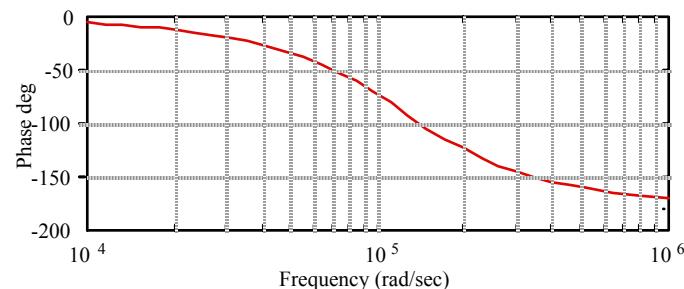
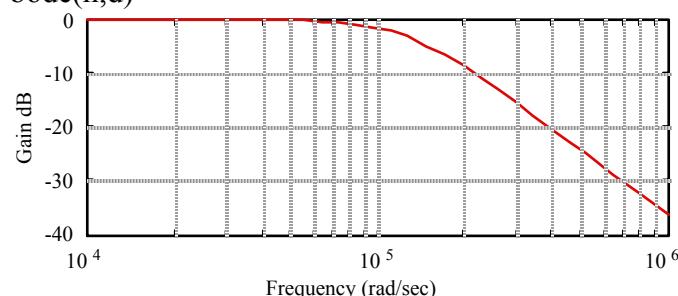
$r1=1130; r2=1130; c1=1e-8; c2=5e-9;$

$\omega_0=1/sqrt(r1*r2*c1*c2)$

$n=\omega_0*\omega_0;$

$d=[1 2/(r1*c1) \omega_0*\omega_0];$

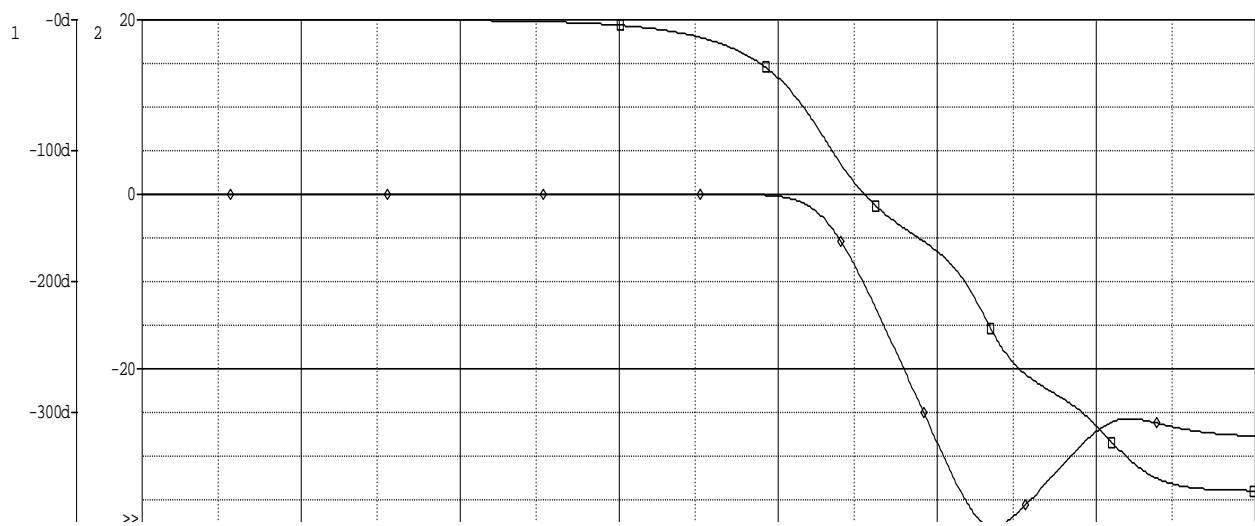
bode(n,d)



(b)

*PROBLEM 11.74 - Low-pass Filter

```
R_R1      $N_0002 $N_0001 1.13k
C_C1      $N_0002 $N_0003 0.01UF
V_V1      $N_0004 0 18V
V_V2      0 $N_0005 18V
R_R2      $N_0006 $N_0002 1.13k
V_VS      $N_0006 0 DC 0V AC 1V
C_C2      0 $N_0001 0.005UF
X_U1      $N_0001 $N_0003 $N_0004 $N_0005 $N_0003 uA741
.AC DEC 40 1 1MEG
.PRINT AC IM(VS) IP(VS) VDB(6) VP(6)
.PROBE I(VS) V(6)
.END
```



(c) The magnitude response is very similar to the ideal case. However, note bumps in the phase plot and the excess phase shift as one approaches the f_T of the amplifier. In this case, it is not causing a problem, but for higher gain filters the situation would be different. See Probs. 11.82 & 11.84.

11.75

Using Eq. 11.47: $\mathbf{V}_1(s) = \frac{G_1 \mathbf{V}_s(s)(sC_2 + G_2)}{s^2 C_1 C_2 + sC_2(G_1 + G_2) + G_1 G_2} \quad | \quad \mathbf{I}_s = G_1(\mathbf{V}_s - \mathbf{V}_1)$

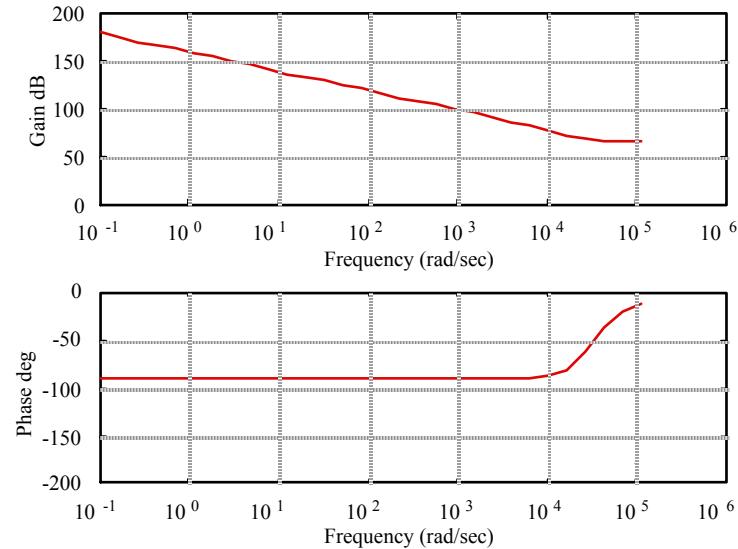
$$\mathbf{I}_s = G_1 \mathbf{V}_s \left(1 - \frac{G_1(sC_2 + G_2)}{s^2 C_1 C_2 + sC_2(G_1 + G_2) + G_1 G_2} \right) = G_1 \mathbf{V}_s \frac{s^2 C_1 C_2 + sC_2 G_2}{s^2 C_1 C_2 + sC_2(G_1 + G_2) + G_1 G_2}$$

$$Z_s(s) = \frac{\mathbf{V}_s}{\mathbf{I}_s} = R_i \frac{s^2 C_1 C_2 + sC_2(G_1 + G_2) + G_1 G_2}{s^2 C_1 C_2 + sC_2 G_2} = R_i \frac{s^2 + s \frac{\omega_o}{Q} + \omega_o^2}{s \left(s + \frac{1}{R_2 C_1} \right)}$$

$$\omega_o^2 = \frac{1}{R_1 R_2 C_1 C_2} \quad | \quad \frac{\omega_o}{Q} = \frac{1}{C_1} \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

11.76

```
r1=2260; r2=2260; c1=2e-8; c2=1e-8;
wsq=1/(r1*r2*c1*c2);
n=r1*[1 2/(r1*c1) wsq];
d=[1 1/(r1*c1) 0];
bode(n,d)
```



11.77

$$G_1 \mathbf{V}_s = (sC_1 + G_1 + G_2) \mathbf{V}_1 - s(KC_1 + G_2) \mathbf{V}_2$$

$$0 = -G_2 \mathbf{V}_1 + (sC_2 + G_2) \mathbf{V}_2$$

$$\mathbf{V}_o = K \mathbf{V}_2 \quad | \quad \frac{\mathbf{V}_o}{\mathbf{V}_s} = \frac{K}{s^2 R_1 R_2 C_1 C_2 + s[R_1 C_1(1-K) + C_2(R_1 + R_2)] + 1}$$

$$\omega_o = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}} \quad | \quad Q = \left[\frac{1-K}{R_2 C_2} + \frac{1}{(R_1 \| R_2) C_1} \right]$$

$$\text{For } R_1 = R_2 = R \text{ and } C_1 = C_2 = C, \quad \omega_o = \frac{1}{RC} \quad Q = \frac{\omega_o^2}{3-K} \quad S_K^o = \frac{K}{3-K}$$

11.78

$$\omega_o = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}} \quad | \quad S_{R_1}^{\omega_o} = \frac{R_1}{\omega_o} \frac{\partial \omega_o}{\partial R_1} = \frac{R_1}{\omega_o} \frac{1}{\sqrt{R_2 C_1 C_2}} \left(-\frac{1}{2} \right) (R_1)^{-\frac{3}{2}} = \frac{R_1}{\omega_o} \left(-\frac{1}{2} \frac{\omega_o}{R_1} \right) = -\frac{1}{2}$$

$$S_{R_1}^{\omega_o} = -\frac{1}{2} \quad | \quad \text{By symmetry, } S_{C_1}^{\omega_o} = -\frac{1}{2}$$

11.79

$$\text{For } C_1 = C = C_2 : \quad \omega_o = \frac{1}{C \sqrt{R_1 R_2}} \quad | \quad Q = \frac{1}{2} \sqrt{\frac{R_2}{R_1}} \quad | \quad \omega_o = \frac{1}{2 R_1 C Q}$$

$$S_Q^{\omega_o} = \frac{Q}{\omega_o} \frac{\partial \omega_o}{\partial Q} = \frac{Q}{\omega_o} \left(-\frac{1}{2 R_1 C Q^2} \right) = \frac{Q}{\omega_o} \left(-\frac{\omega_o}{Q} \right) = -1 \quad | \quad S_Q^{\omega_o} = -1$$

11.80

As noted in Design Example 11.8, the maximally flat response corresponds to $Q = \frac{1}{\sqrt{2}}$.

$$\text{For } Q = \frac{1}{\sqrt{2}} : \quad A_V(s) = \frac{\omega_o^2}{s^2 + \sqrt{2}\omega_o s + \omega_o^2} \quad | \quad A(0) = 1 \quad | \quad |A(j\omega_o)| = \frac{1}{\sqrt{2}} \rightarrow \omega_H = \omega_o \quad | \quad \therefore f_H = 1 \text{ kHz}$$

$$R_1 = R = R_2 \text{ and } C_1 = 2C_2 = 2C \text{ yields } Q = \frac{1}{\sqrt{2}} \quad | \quad \omega_o = \frac{1}{\sqrt{2R^2 C^2}} = \frac{1}{\sqrt{2}RC}$$

$$RC = \frac{1}{2\pi\sqrt{2}(1000)} = 1.125 \times 10^{-4} \quad | \quad \text{For } C = 0.001 \mu F, R = 112.5 k\Omega. \text{ The}$$

nearest 5% value is 110 kΩ. The nearest 1% value is 113 kΩ. Using 1% values,
 $C_1 = 0.002 \mu F \quad | \quad C_2 = 0.001 \mu F \quad | \quad R_1 = R_2 = 113 \text{ k}\Omega$

11.81

Using the $R_1 = R_2 = R$ and $C_1 = C_2 = C$ case, $A_{HP}(s) = K \frac{s^2}{s^2 + s \frac{\omega_o}{Q} + \omega_o^2}$

$$\omega_o = \frac{1}{RC} \quad | \quad Q = \frac{1}{3-K} \quad | \quad Q = 1 \rightarrow K = 2 \quad | \quad A_{HP}(s) = 2 \frac{s^2}{s^2 + s\omega_o + \omega_o^2}$$

We need to find the relationship between ω_L and ω_o .

$$\frac{2}{\sqrt{2}} = 2 \frac{\omega_L^2}{\sqrt{(\omega_o^2 - \omega_L^2)^2 + (\omega_L \omega_o)^2}} \rightarrow \omega_o^4 - 2\omega_o^2\omega_L^2 + \omega_L^4 + \omega_o^2\omega_L^2 = 2\omega_L^4 \quad | \quad \omega_L^4 + \omega_o^2\omega_L^2 - \omega_o^4 = 0$$

$$\omega_L^2 = \frac{-\omega_o^2 \pm \sqrt{\omega_o^4 + 4\omega_o^4}}{2} \rightarrow \omega_L^2 = \omega_o^2 \frac{\sqrt{5} - 1}{2} \quad | \quad \omega_L = 0.7862\omega_o \quad | \quad 2\pi(20\text{kHz}) = 0.7862\omega_o$$

$$\omega_o = 1.599 \times 10^5 \quad | \quad RC = \frac{1}{\omega_o} = 6.256 \times 10^{-6} \quad | \quad \text{For } C = 270 \text{ pF}, R = 23.17 \text{ k}\Omega$$

The nearest 1% resistor value is $23.2 \text{ k}\Omega$.

Final design : $C_1 = C_2 = 270 \text{ pF}$ | $R_1 = R_2 = 23.2 \text{ k}\Omega$

11.82

$$(a) Q = \frac{1}{2} \sqrt{\frac{R_2}{R_{th}}} = \frac{1}{2} \sqrt{\frac{200\text{k}\Omega}{1\text{k}\Omega}} = \frac{10}{\sqrt{2}} \quad | \quad f_o = \frac{1}{2\pi\sqrt{10^3(2 \times 10^5)(2.2 \times 10^{-10})^2}} = 51.2 \text{ kHz}$$

$$BW = \frac{f_o}{Q} = 7.23 \text{ kHz} \quad A_v(f_o) = \frac{1}{2} \frac{R_2}{R_{th}} = 100 \text{ or } 40 \text{ dB}$$

$$(b) K_M = \frac{3.3\text{k}\Omega}{1\text{k}\Omega} = 3.3 \quad | \quad R_{th} = 3.3(1\text{k}\Omega) = 3.3 \text{ k}\Omega \quad | \quad R_2 = 3.3(200\text{k}\Omega) = 660 \text{ k}\Omega$$

$$C_1 = C_2 = \frac{220 \text{ pF}}{3.3} = 66.7 \text{ pF}$$

$$(c) K_F = \frac{2f_o}{f_o} = 2 \quad | \quad C_1 = C_2 = \frac{220 \text{ pF}}{2} = 110 \text{ pF} \quad | \quad R_{th} = 1 \text{ k}\Omega \quad | \quad R_2 = 200 \text{ k}\Omega$$

11.83

$$(a) BW = \frac{f_o}{Q} = \frac{1000 \text{ Hz}}{5} = 200 \text{ Hz} \quad | \quad C_1 = C_2 = C \quad | \quad Q = \frac{1}{2} \sqrt{\frac{R_2}{R_{th}}} = 5 \rightarrow \frac{R_2}{R_{th}} = 100$$

$$\text{Choose } R_{th} = 1 \text{ k}\Omega \rightarrow R_2 = 100 \text{ k}\Omega \quad | \quad C = \frac{1}{\omega_o \sqrt{R_{th} R_2}} = \frac{1}{2\pi(10^3)(10^4)} = 0.0159 \text{ }\mu\text{F}$$

$\omega_o = \frac{1}{10R_{th}C}$: Checking the nearest standard values:

$C = 0.015 \text{ }\mu\text{F} \rightarrow R_{th} = 1.06 \text{ k}\Omega$ - not good; $C = 0.01 \text{ }\mu\text{F} \rightarrow R_{th} = 1.6 \text{ k}\Omega \quad | \quad R_2 = 160 \text{ k}\Omega$

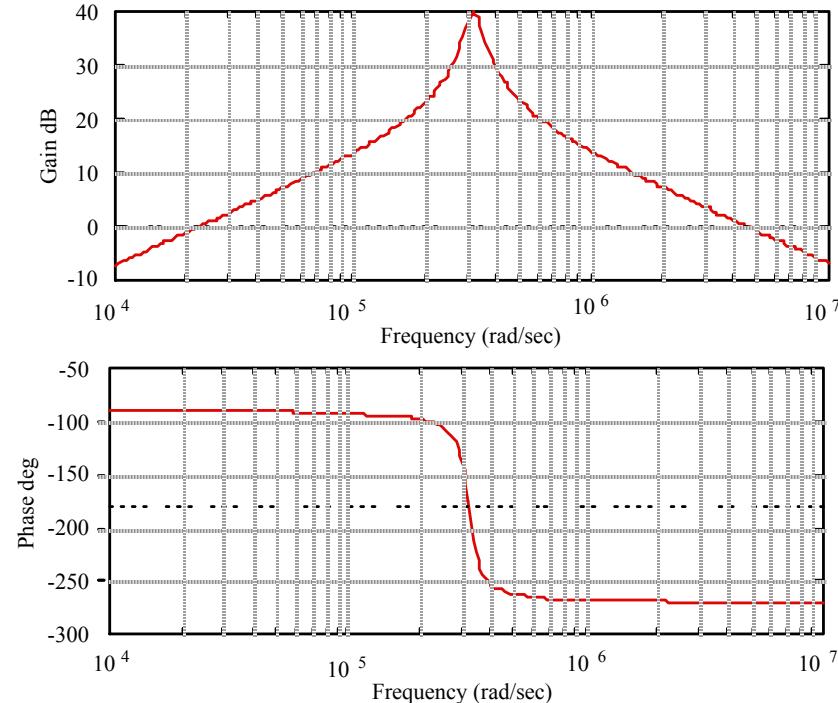
Choose $R_l = 1.6 \text{ k}\Omega$ with $R_3 = \infty$.

$$(b) C' = \frac{C}{2.25} = 0.004 \text{ }\mu\text{F} \quad | \quad R_l = 1.6 \text{ k}\Omega \quad | \quad R_2 = 160 \text{ k}\Omega \quad | \quad R_3 = \infty$$

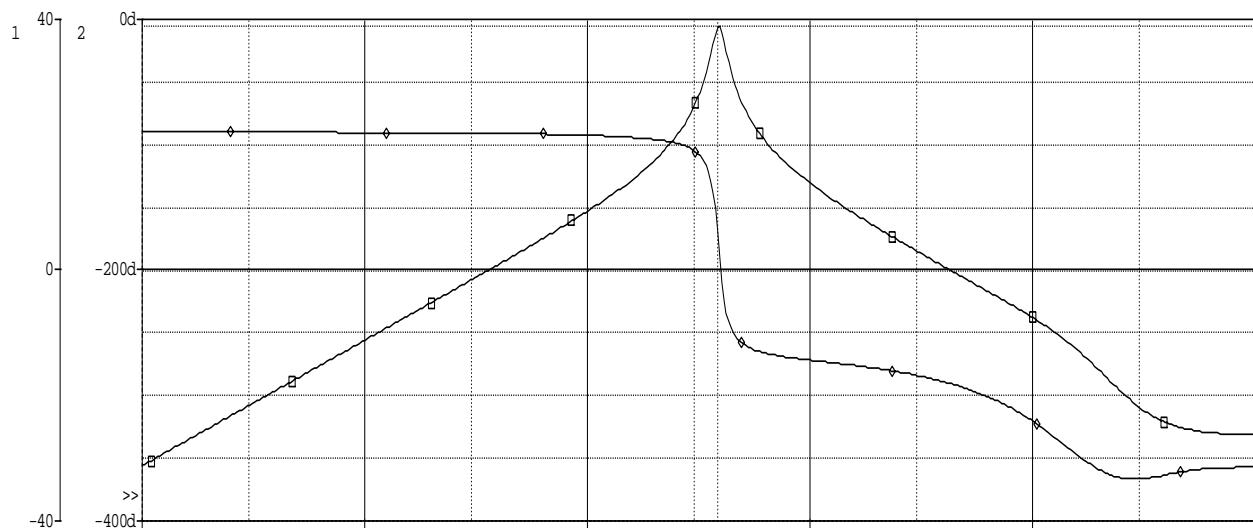
11.84

(a)

```
r1=1000; r2=2e5; c=2.2e-10;
wo=1/sqrt(r1*r2*c*c); q=sqrt(r2/r1)/2;
n=[-2*q*wo 0]; d=[1 wo/q wo*wo];
w=logspace(4,7,300);
bode(n,d,w)
```



(b) SPICE Simulation Results



SPICE yields: $f_0 = 38.9$ kHz, $Q = 8.1$, Center frequency gain = 38.8 dB. These values are off due to the finite bandwidth of the op-amp and its excess phase shift at the center frequency of the filter. The center frequency is substantially shifted.

11.85

$$(a) BW = \frac{\omega_o}{Q} = \frac{1}{3} \quad | \quad \omega_L = 0.833 \frac{rad}{s} \quad | \quad \omega_H = 1.167 \frac{rad}{s}$$

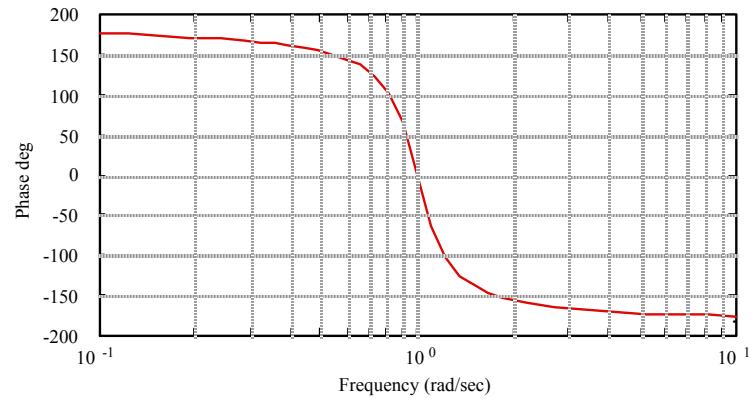
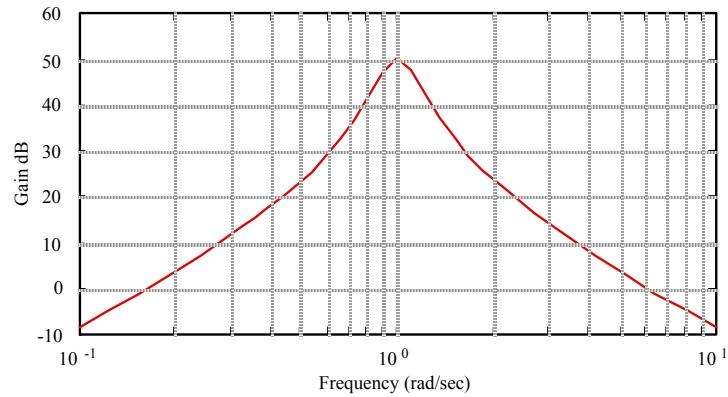
$$BW' = BW \sqrt{2^{\frac{1}{2}} - 1} = 0.215 \frac{rad}{s} \quad | \quad \omega'_o = \omega_o = 1 \frac{rad}{s} \quad | \quad Q' = \frac{1}{0.215} = 4.65$$

$$C_1 = C_2 = C: \quad \omega_o = \frac{1}{C\sqrt{R_{th}R_2}} \quad | \quad Q = \frac{1}{2}\sqrt{\frac{R_2}{R_{th}}} \quad | \quad \frac{1}{R_{th}C} = 2Q\omega_o$$

$$(b) A_{BP}(s) = \left(\frac{R_{th}}{R_1}\right)^2 \left(\frac{-2Qs\omega_o}{s^2 + s\frac{\omega_o}{Q} + 1} \right)^2 = \left(\frac{R_{th}}{R_1}\right)^2 \left(\frac{-6s}{s^2 + \frac{s}{3} + 1} \right)^2 \quad | \quad \text{For } R_3 = \infty, A_{BP}(s) = \left(\frac{-6s}{s^2 + \frac{s}{3} + 1} \right)^2$$

11.86

n=conv([-6 0],[-6,0]); d=conv([1 1/3 1],[1 1/3 1]); bode(n,d)



11.87

Using normalized frequency and $R_3 = \infty$: $5 \text{ kHz} \rightarrow \omega_o = 1$ and $6 \text{ kHz} \rightarrow \omega_o = 1.1$

$$A_{BP}(s) = \left(\frac{-10s}{s^2 + 0.2s + 1} \right) \left(\frac{-12s}{s^2 + 0.24s + 1.44} \right) = \frac{120s^2}{s^4 + 0.44s^3 + 2.484s^2 + 0.528s + 1.44}$$

At the new center frequency $s = j\omega_o$, $-0.44\omega_o^3 + 0.528\omega_o = 0 \rightarrow \omega_o = 1.095$

and $|A(j\omega_o)| = 1429 = 63.1 \text{ dB}$

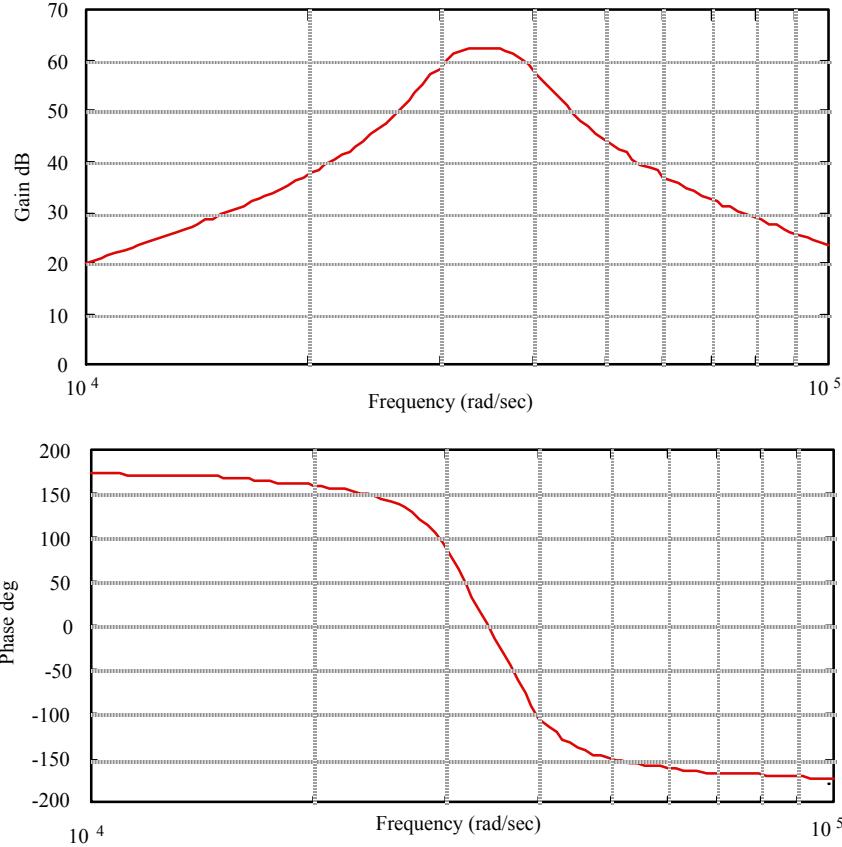
The bandwidth points can be found using MATLAB:

```
w=linspace(.9,1.5,250);
[m,p,w]=bode([120 0 0],[1 .44 2.484 .528 1.44],w);
20*log10(max(m))
ans = 63.098
((20*log10(a))>60.098).*(w.');
```

From this last vector one can easily find: $\omega_o = 1.095$ or $f_o = 5.48 \text{ kHz}$, $\omega_L = 0.970$ or $f_o = 4.85 \text{ kHz}$, $\omega_H = 1.237$ or $f_o = 6.19 \text{ kHz}$, $BW = 1.34 \text{ kHz}$, $Q = 4.09$

11.88

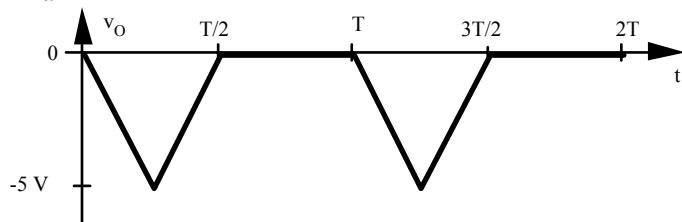
```
w1=2*pi*5000; q1=5; w2=2*pi*6000; q2=5;
n1=[-2*q1*w1 0]; d1=[1 w1/q1 w1*w1];
n2=[-2*q2*w2 0]; d2=[1 w2/q2 w2*w2];
n=conv(n1,n2); d=conv(d1,d2);
w=logspace(4,5,100);
bode(n,d,w)
```

**11.89**

Using $A_{BP} = 20 \text{ dB}$ at the center frequency : $R_{in} = R_1 = 10 \text{ k}\Omega$ | $10 = KQ = \frac{R_2}{R_1}$

$$R_2 = 100 \text{ k}\Omega \quad | \quad K = \frac{10}{Q} = 2 \quad | \quad R = KR_1 = 20 \text{ k}\Omega \quad | \quad C = \frac{1}{\omega_o R} = \frac{1}{2\pi(600\text{Hz})20\text{k}\Omega} = 0.0133 \mu\text{F}.$$

11.90 Q is independent of C in the Tow-Thomas biquad. $S_C^Q = 0$.

11.91**11.92**

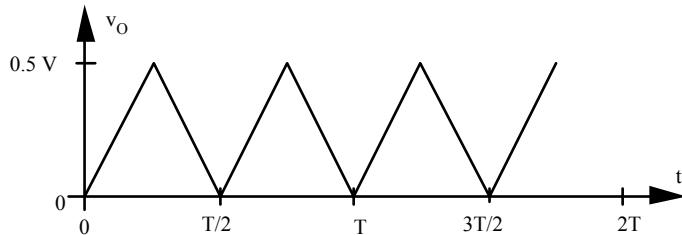
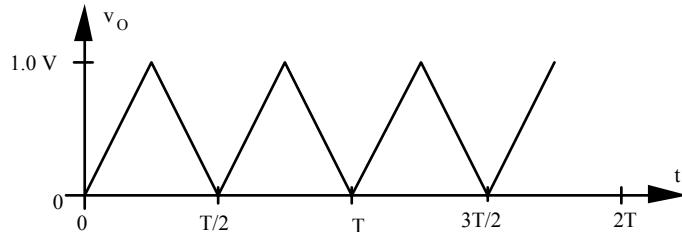
The waveform going into the low-pass filter is the same as that in Prob. 11.91 except the amplitude will be $V_M = 1V \left(-\frac{8.2k\Omega}{2.7k\Omega} \right) = -3.037 V$.

The average value of the waveform is $\bar{V} = \left(-\frac{10k\Omega}{10k\Omega} \right) \frac{\frac{1}{2} \frac{T}{2} (-3.037)}{T} = +0.759 V$.

11.93

The Fourier series converges very rapidly since only the even terms exist for $n \geq 2$ and the terms decrease as $1/n^2$. Thus the RMS value will be dominated by the first term ($n = 1$).

$$\text{Require: } \frac{\pi}{2} \frac{1}{\sqrt{1+\left(\frac{\omega}{\omega_o}\right)^2}} \leq 0.01 \quad | \quad (50\pi)^2 \leq 1 + \left(\frac{\omega}{\omega_o}\right)^2 \quad | \quad \omega_o \geq \frac{\omega}{157} = \frac{120\pi}{157} = 2.40 \text{ Hz}$$

11.94**11.95**

11.96

*Figure P11.94 - RECTIFIER
 VS 1 0 PWL(0 0 1M 1 3M -1 5M 1 7M -1 8M 0)
 R1 1 2 10K
 R2 4 5 10K
 R3 5 6 10K
 R4 2 4 10K
 R5 1 5 20K
 D1 3 2 DIODE
 D2 4 3 DIODE
 EOP1 3 0 0 2 1E5
 EOP2 6 0 0 5 1E5
 .MODEL DIODE D IS=1E-12A
 .TRAN .01M 8M
 .PRINT TRAN V(6)
 .PROBE V(1) V(2) V(3) V(4) V(5) V(6)
 .END

11.97

*Figure P11.95 - RECTIFIER
 VS 1 0 PWL(0 0 1M 1 3M -1 5M 1 7M -1 8M 0)
 R1 0 2 10K
 R2 4 5 10K
 R3 5 6 20K
 R4 2 4 10K
 D1 3 2 DIODE
 D2 4 3 DIODE
 EOP1 3 0 1 2 1E5
 EOP2 6 0 1 5 1E5
 .MODEL DIODE D IS=1E-12A
 .TRAN .01M 8M
 .PRINT TRAN V(6)
 .PROBE V(1) V(2) V(3) V(4) V(5) V(6)
 .END

11.98

$$\frac{V_1}{10k\Omega} = I_s \exp \frac{-V_{o1}}{V_T} \quad | \quad V_{o1} = -V_T \ln \frac{V_1}{10^4 I_s} \quad | \quad V_{o2} = -V_T \ln \frac{V_2}{10^4 I_s}$$

$$V_{o3} = -(V_{o1} + V_{o2}) = V_T \left(\ln \frac{V_1}{10^4 I_s} + \ln \frac{V_2}{10^4 I_s} \right) = V_T \ln \frac{V_1 V_2}{10^8 I_s^2}$$

$$V_o = -10^4 I_D = -10^4 I_s \exp \frac{V_D}{V_T} = -10^4 I_s \exp \left(\ln \frac{V_1 V_2}{10^8 I_s^2} \right) = -\frac{V_1 V_2}{10^4 I_s}$$

11.99

Simplify the circuit by taking a Thevenin equivalent of the 5V source and two $10k\Omega$

$$\text{resistors: } V_{TH} = 5V \frac{10k\Omega}{10k\Omega + 10k\Omega} = 2.5V \quad | \quad R_{TH} = 10k\Omega \parallel 10k\Omega = 5k\Omega$$

$$V_o = 5V - \text{Using superposition: } V_+ = 2.5 \frac{100k\Omega}{100k\Omega + 5k\Omega} + 5 \frac{5k\Omega}{100k\Omega + 5k\Omega} = 2.62V$$

$$V_o = 0V : V_+ = 2.5 \frac{100k\Omega}{100k\Omega + 5k\Omega} = 2.38V \quad V_N = 2.62 - 2.38 = 0.24V$$

11.100

$$V_o = -10V : V_+ = -10 \frac{4.3k\Omega}{4.3k\Omega + 39k\Omega} = -0.993 V$$

$$V_o = 10V : V_+ = 10 \frac{4.3k\Omega}{4.3k\Omega + 39k\Omega} = 0.993 V$$

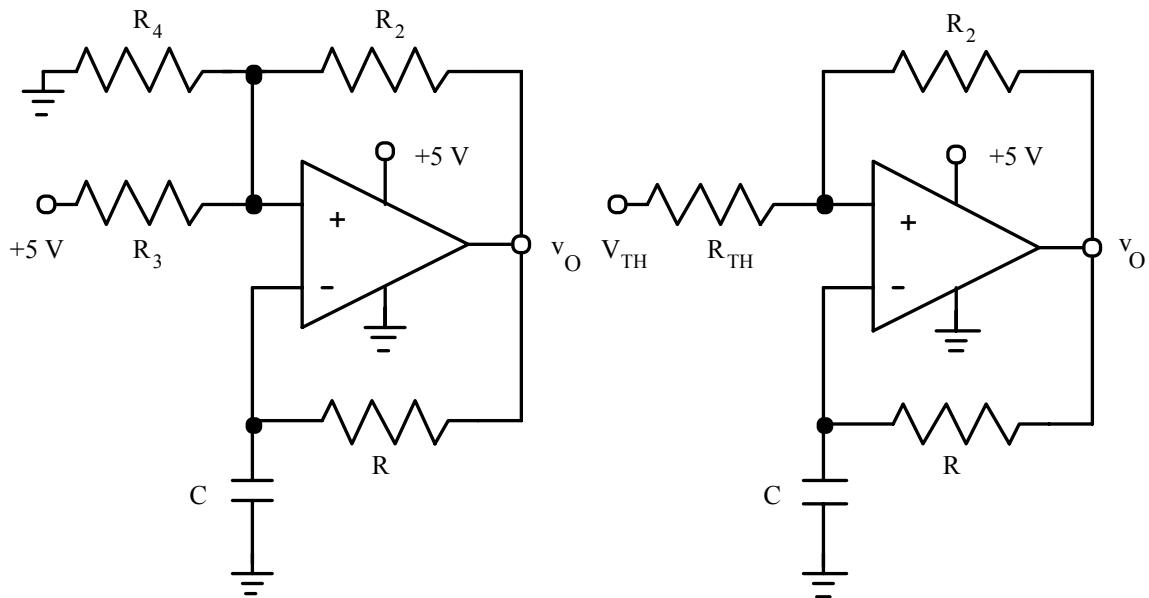
$$V_N = 0.993 - (-0.993) = 1.99 V$$

11.101

$$\text{For } V_o = 4.3 + 0.6 = 4.9V : V_+ = 4.9 \frac{4.3k\Omega}{4.3k\Omega + 39k\Omega} = 0.487 V$$

$$\text{For } V_o = -4.3 - 0.6 = -4.9V : V_+ = -4.9 \frac{4.3k\Omega}{4.3k\Omega + 39k\Omega} = -0.487 V$$

$$V_N = 0.487 - (-0.487) = 0.974 V$$

11.102

$$\text{For } V_O = 0: \quad V_+ = V_{TH} \frac{R_2}{R_{TH} + R_2} = 1 - \frac{0.05}{2} = 0.975V \quad | \quad R_{TH} = R_3 \| R_4 \quad | \quad V_{TH} = 5 \frac{R_4}{R_3 + R_4}$$

$$\text{For } V_O = 5: \quad V_+ = V_{TH} \frac{R_2}{R_{TH} + R_2} + 5 \frac{R_{TH}}{R_{TH} + R_2} = 1 + \frac{0.05}{2} = 1.025V$$

$$\text{Subtracting: } 5 \frac{R_{TH}}{R_{TH} + R_2} = 0.05V \rightarrow \frac{R_{TH}}{R_{TH} + R_2} = 0.01 \rightarrow \frac{R_2}{R_{TH}} = 99$$

$$\frac{V_{TH} \frac{R_2}{R_{TH} + R_2}}{\frac{R_{TH}}{R_{TH} + R_2}} = \frac{0.975}{0.01} \rightarrow V_{TH} \frac{R_2}{R_{TH}} = 97.5 \rightarrow V_{TH} = \frac{97.5}{99} = 0.985V$$

$$0.985 = 5 \frac{R_4}{R_3 + R_4} \rightarrow \frac{R_3}{R_4} = 4.077 \quad | \quad \text{Choosing } R_4 = 2k\Omega \rightarrow R_3 = 8.154k\Omega$$

$$R_{TH} = 8.154k\Omega \| 2k\Omega = 1.606k\Omega \quad | \quad R_2 = 99(1.606k\Omega) = 159k\Omega$$

Choosing standard values: $R_2 = 160 \text{ k}\Omega \quad | \quad R_3 = 8.2k\Omega \quad | \quad R_4 = 2 \text{ k}\Omega$

11.103

$$\text{For } v_O = +12V: \quad V_+ = 6 \frac{24k\Omega}{3.4k\Omega + 24k\Omega} + 12 \frac{3.4k\Omega}{3.4k\Omega + 24k\Omega} = 6.74 \text{ V}$$

$$\text{For } v_O = 0V: \quad V_+ = 6 \frac{24k\Omega}{3.4k\Omega + 24k\Omega} = 5.26 \text{ V}$$

$$v(t) = V_F - (V_F - V_I) \exp\left(-\frac{t}{RC}\right)$$

$$6.74 = 12 - (12 - 5.26) \exp\left(-\frac{T_1}{RC}\right) \rightarrow T_1 = 6200(3.3 \times 10^{-8}) \ln \frac{6.74}{5.26} = 50.7 \mu s$$

$$5.26 = 0 - (0 - 6.74) \exp\left(-\frac{T_2}{RC}\right) \rightarrow T_2 = 6200(3.3 \times 10^{-8}) \ln \frac{6.74}{5.26} = 50.7 \mu s$$

$$f = \frac{1}{50.7 \mu s + 50.7 \mu s} = 9.86 \text{ kHz}$$

11.104

$f = 0$. The circuit does not oscillate. $V_O = 0$ is a stable state.

11.105

$$(a) \text{ Let } R_1 = R_2 \quad | \quad \beta = \frac{R_1}{R_1 + R_2} = \frac{1}{2} \quad | \quad T = 2RC \ln \frac{1+\beta}{1-\beta} = 2RC \ln 3 = 2.197RC$$

During steady-state oscillation, the maximum output current from the op-amp is

$$I = \frac{5}{R_1 + R_2} + \frac{5 - (-2.5)}{R} \quad | \quad \text{Let } R = R_1 = R_2 \quad | \quad \frac{5}{2R} + \frac{7.5}{R} \leq 1mA \rightarrow R \geq 10k\Omega$$

$$RC = \frac{0.001s}{2.197} = 4.55 \times 10^{-4} s \quad | \quad \text{Selecting } C = 0.015\mu F, R = 30.3k\Omega \rightarrow 30 k\Omega \text{ (5% values)}$$

$$\text{Final values: } R = R_1 = R_2 = 30 k\Omega \quad | \quad C = 0.015 \mu F \quad | \quad f = \frac{1}{2.197(30 k\Omega)(0.015\mu F)} = 1.01 kHz$$

$$(b) \beta = \frac{1}{1 + \frac{R_2}{R_1}} \quad | \quad \beta_{\max} = \frac{1}{1 + \frac{30k\Omega(0.95)}{30k\Omega(1.05)}} = 0.525 \quad | \quad \beta_{\min} = \frac{1}{1 + \frac{30k\Omega(1.05)}{30k\Omega(0.95)}} = 0.475$$

$$T_{\max} = 2(30k\Omega)(1.05)(0.015\mu F)(1.1) \ln \frac{1+0.525}{1-0.525} = 1.213 \times 10^{-3} s \rightarrow f_{\min} = 825 Hz$$

$$T_{\min} = 2(30k\Omega)(0.95)(0.015\mu F)(0.90) \ln \frac{1+0.475}{1-0.475} = 7.949 \times 10^{-4} s \rightarrow f_{\max} = 1.26 kHz$$

$$(c) \text{ For } v_o = +4.75V : V_+ = 4.75\beta = \frac{4.75}{2} = 2.375V$$

$$\text{For } v_o = -5.25V : V_+ = -5.25\beta = \frac{-5.25}{2} = -2.625V$$

$$v(t) = V_F - (V_F - V_I) \exp\left(-\frac{t}{RC}\right)$$

$$2.375 = 4.75 - (4.75 - (-2.625)) \exp\left(-\frac{T_1}{RC}\right) \rightarrow T_1 = RC \ln \frac{7.375}{2.375} = 1.133RC$$

$$-2.625 = -5.25 - (-5.25 - 2.375) \exp\left(-\frac{T_2}{RC}\right) \rightarrow T_2 = RC \ln \frac{7.625}{2.625} = 1.066RC$$

$$T = 2.199RC = 2.199(30k\Omega)(0.015\mu F) = 9.896 \times 10^{-4} s \rightarrow f = 1.01 kHz - \text{Very little change}$$

11.106

For a triangular waveform with peak amplitude V_s and $\omega_o = 2000\pi$:

$$v(t) = \sum_{n=1}^{\infty} \frac{8V_s}{n^2\pi^2} \sin \frac{n\pi}{2} \sin n\omega_o t$$

For the low - pass filter: $A_v(s) = -\frac{1}{1 + \frac{s}{3000\pi}}$ | $A_v(jf) = \frac{1}{\sqrt{1 + \left(\frac{f}{1500}\right)^2}}$

$$|A_v(j1000)| = 0.832 \quad |A_v(j3000)| = 0.447 \quad |A_v(j5000)| = 0.287$$

For a 5 - V fundamental: $\frac{8V_s}{\pi^2} \cdot 0.832 = 5 \rightarrow V_s = \frac{1}{0.832} \frac{5}{8} \pi^2 = 7.41 \text{ V}$

This series contains only odd harmonics: For $n = 2$, $V_{2000} = 0$.

For $f = 3 \text{ kHz}$, $n = 3$: $V_{3000} = 0.447 \left(\frac{5}{0.832} \right) \frac{1}{3^2} = 0.298 \text{ V}$

For $f = 5 \text{ kHz}$, $n = 5$: $V_{5000} = 0.287 \left(\frac{5}{0.832} \right) \frac{1}{5^2} = 69.0 \text{ mV}$

11.107

$$T = RC \ln \frac{1 + \frac{V_{on}}{V_{CC}}}{1 - \beta} \quad | \quad \beta = \frac{15k\Omega}{15k\Omega + 27k\Omega} = 0.357 \quad | \quad (51k\Omega)(0.033\mu F) \ln \frac{1 + \frac{0.6}{10}}{1 - 0.357} = 841 \mu s$$

$$T_r = RC \ln \frac{1 + \beta \frac{V_{CC}}{V_{EE}}}{1 - \frac{V_{on}}{V_{EE}}} = (51k\Omega)(0.033\mu F) \ln \frac{1 + 0.357 \left(\frac{10}{10} \right)}{1 - \frac{0.6}{10}} = 416 \mu s$$

11.108

$$T = RC \ln \frac{1 + \frac{V_{on}}{V_{CC}}}{1 - \beta} \quad | \quad T_r = RC \ln \frac{1 + \beta \frac{V_{CC}}{V_{EE}}}{1 - \frac{V_{on}}{V_{EE}}} \quad | \quad \ln \frac{1 + \frac{V_{on}}{V_{CC}}}{1 - \beta} = \frac{T}{T_r} \ln \frac{1 + \beta \frac{V_{CC}}{V_{EE}}}{1 - \frac{V_{on}}{V_{EE}}}$$

$$\ln \frac{1 + \frac{0.6}{5}}{1 - \beta} = \frac{10\mu s}{5\mu s} \ln \frac{1 + \beta \left(\frac{5}{5}\right)}{1 - \frac{0.6}{5}} \quad | \quad \ln \left(\frac{1.12}{1 - \beta} \right) = 2 \ln \frac{1 + \beta}{0.88} \quad | \quad \left(\frac{1.12}{1 - \beta} \right) = \left(\frac{1 + \beta}{0.88} \right)^2$$

$$\text{MATLAB gives } \beta = 0.6998 \rightarrow \frac{R_1}{R_2} = 2.33 \quad | \quad R_2 = 13 \text{ k}\Omega \quad | \quad R_2 = 30.3 \text{ k}\Omega \rightarrow 30 \text{ k}\Omega$$

$$RC = \frac{10^{-5}}{\ln \frac{1 + \frac{0.6}{5}}{1 - 0.6998}} = 7.595 \mu s \quad | \quad C = 150 \text{ pF} \quad | \quad R = 50.6 \text{ k}\Omega \rightarrow 51 \text{ k}\Omega$$

CHAPTER 12

12.1

$$(a) A = 10^{\frac{86}{20}} = 2.00 \times 10^4 \quad | \quad A_{v-ideal} = 1 + \frac{150k\Omega}{12k\Omega} = 13.5$$

$$A_v = \frac{A}{1 + A\beta} = \frac{2.00 \times 10^4}{1 + 2.00 \times 10^4 \left(\frac{12k\Omega}{162k\Omega} \right)} = 13.49$$

$$FGE = \frac{13.5 - 13.49}{13.5} = 6.75 \times 10^{-4} \text{ or } 0.0675\% \quad | \quad \text{Note: } FGE \approx \frac{1}{A\beta} = 6.75 \times 10^{-4}$$

$$(b) A_{v-ideal} = 1 + \frac{150k\Omega}{1.2k\Omega} = 126 \quad | \quad A_v = \frac{2.00 \times 10^4}{1 + 2.00 \times 10^4 \left(\frac{1.2k\Omega}{151.2k\Omega} \right)} = 125$$

$$A\beta = 2.00 \times 10^4 \left(\frac{1.2k\Omega}{151.2k\Omega} \right) = 159 \gg 1 \quad | \quad FGE \approx \frac{1}{A\beta} = 6.30 \times 10^{-3}$$

12.2

$$(a) A = 10^{\frac{100}{20}} = 10^5 \quad | \quad A_{v-ideal} = 1 + \frac{47k\Omega}{5.6k\Omega} = 9.393$$

$$A_v = \frac{A}{1 + A\beta} = \frac{10^5}{1 + 10^5 \left(\frac{5.6k\Omega}{52.6k\Omega} \right)} = 9.392$$

$$GE = \frac{1}{\beta(1 + A\beta)} = 8.82 \times 10^{-4} \quad FGE = \frac{1}{1 + A\beta} = 9.39 \times 10^{-5}$$

$$(b) A = 10^{\frac{94}{20}} = 5.01 \times 10^4 \quad | \quad A_{v-ideal} = 1 + \frac{47k\Omega}{5.6k\Omega} = 9.393$$

$$A_v = \frac{A}{1 + A\beta} = \frac{5.01 \times 10^4}{1 + 5.01 \times 10^4 \left(\frac{5.6k\Omega}{52.6k\Omega} \right)} = 9.391$$

$$GE = \frac{1}{\beta(1 + A\beta)} = 1.76 \times 10^{-3} \quad FGE = \frac{1}{1 + A\beta} = 1.87 \times 10^{-4}$$

12.3

$$(a) A = 10^{\frac{92}{20}} = 3.98 \times 10^4 \quad | \quad A_{v-ideal} = -\frac{220k\Omega}{22k\Omega} = -10$$

$$A_v = -\frac{R_2}{R_l} \left(\frac{A\beta}{1 + A\beta} \right) = -10 \left[\frac{3.98 \times 10^4 \left(\frac{22k\Omega}{242k\Omega} \right)}{1 + 3.98 \times 10^4 \left(\frac{22k\Omega}{242k\Omega} \right)} \right] = -9.997$$

$$FGE = \frac{10 - 9.997}{10} = 2.76 \times 10^{-4} \text{ or } 0.0276\% \quad | \quad \text{Note: } FGE \cong \frac{1}{A\beta} = 2.76 \times 10^{-4}$$

$$(b) A_{v-ideal} = -\frac{220k\Omega}{1.1k\Omega} = -200 \quad | \quad A_v = -\frac{R_2}{R_l} \left(\frac{A\beta}{1 + A\beta} \right) = -200 \left[\frac{3.98 \times 10^4 \left(\frac{1.1k\Omega}{221.1k\Omega} \right)}{1 + 3.98 \times 10^4 \left(\frac{1.1k\Omega}{221.1k\Omega} \right)} \right] = -199.0$$

$$A\beta = 3.98 \times 10^4 \left(\frac{1.1k\Omega}{221.1k\Omega} \right) = 198 \gg 1 \quad | \quad FGE \cong \frac{1}{A\beta} = 5.05 \times 10^{-3}$$

12.4

$$(a) A = 10^{\frac{94}{20}} = 5.01 \times 10^4 \quad | \quad A_{v-ideal} = -\frac{47k\Omega}{4.7k\Omega} = -10$$

$$A_v = -\frac{R_2}{R_l} \left(\frac{A\beta}{1 + A\beta} \right) = -10 \left[\frac{5.01 \times 10^4 \left(\frac{4.7k\Omega}{51.7k\Omega} \right)}{1 + 5.01 \times 10^4 \left(\frac{4.7k\Omega}{51.7k\Omega} \right)} \right] = -9.998$$

$$GE = -\frac{R_2}{R_l} \left(\frac{1}{1 + A\beta} \right) = \frac{-10}{1 + 5.01 \times 10^4 \left(\frac{4.7k\Omega}{51.7k\Omega} \right)} = -2.20 \times 10^{-3} \quad | \quad FGE = \frac{1}{1 + A\beta} = 2.20 \times 10^{-4}$$

$$(b) A = 10^{\frac{100}{20}} = 10^5 \quad | \quad A_{v-ideal} = -\frac{47k\Omega}{4.7k\Omega} = -10$$

$$A_v = -\frac{R_2}{R_l} \left(\frac{A\beta}{1 + A\beta} \right) = -10 \left[\frac{10^5 \left(\frac{4.7k\Omega}{51.7k\Omega} \right)}{1 + 10^5 \left(\frac{4.7k\Omega}{51.7k\Omega} \right)} \right] = -9.999$$

$$GE = -\frac{R_2}{R_l} \left(\frac{1}{1 + A\beta} \right) = \frac{-10}{1 + 10^5 \left(\frac{4.7k\Omega}{51.7k\Omega} \right)} = -1.10 \times 10^{-3} \quad | \quad FGE = \frac{1}{1 + A\beta} = 1.10 \times 10^{-4}$$

12.5

$$A_{CL} = 10^{\frac{46}{20}} = 200 \rightarrow \frac{R_2}{R_1} = 200 \quad | \quad \beta \equiv \frac{1}{1 + \frac{R_2}{R_1}} = \frac{1}{201}$$

$$FGE \equiv \frac{1}{A\beta} < 0.001 \quad | \quad A > \frac{201}{0.001} = 2.01 \times 10^5 \text{ or } 106 \text{ dB}$$

12.6

$$FGE = 1 - \frac{A}{1+A} = \frac{1}{1+A} \leq 10^{-4} \text{ requires } A \geq 10,000 \text{ (80 dB)}$$

12.7

$$\frac{1}{\beta} = A_v = 10^{\frac{32}{20}} = 39.8 \quad | \quad FGE \equiv \frac{1}{A\beta} < 0.002 \quad | \quad A > \frac{39.8}{0.002} = 1.99 \times 10^4 \text{ or } 86 \text{ dB}$$

12.8

$$A_v = 1 + \frac{R_2}{R_1} \quad | \quad A_v^{nom} = 1 + \frac{99R_1}{R_1} = 100 \quad | \quad A_v^{\max} = 1 + \frac{99R_1(1+0.0001)}{R_1(1-0.0001)} = 100.02$$

$$A_v^{\min} = 1 + \frac{99R_1(1-0.0001)}{R_1(1+0.0001)} = 98.98 \quad | \quad \frac{1}{A\beta} < 0.001 \quad | \quad A > 10^6 \text{ or } 120 \text{ dB}$$

12.9

Driving the output of the circuit in Fig. 12.3 with a current source of value i_x :

$$\mathbf{i}_x = \mathbf{i}_o + \mathbf{i}_2 \quad | \quad \mathbf{i}_2 = \frac{\mathbf{v}_x}{R_1 + R_2} ; \quad \mathbf{i}_o = \frac{\mathbf{v}_x - A\mathbf{v}_{id}}{R_o} ; \quad \mathbf{v}_{id} = -\mathbf{i}_2 R_1$$

$$\mathbf{i}_o = \frac{\mathbf{v}_x + A\mathbf{i}_2 R_1}{R_o} = \mathbf{v}_x \frac{1 + A\beta}{R_o} \quad \text{where} \quad \beta = \frac{R_1}{R_1 + R_2}$$

$$\mathbf{i}_x = \mathbf{v}_x \frac{1 + A\beta}{R_o} + \frac{\mathbf{v}_x}{R_1 + R_2} \quad \text{and} \quad R_{out} = \frac{\mathbf{v}_x}{\mathbf{i}_x} = \frac{R_o}{1 + A\beta} \parallel (R_1 + R_2)$$

12.10

$$\text{Assuming } i_- \ll i_2 : \quad \beta = \frac{R_1}{R_1 + R_2} = \frac{1}{48} \quad | \quad i_- = -i_x = -\frac{v_x}{R_{id}(1 + A\beta)} = -\frac{0.1V}{10^6 \Omega \left(1 + 10^5 \frac{1}{48}\right)} = -48.0 \text{ pA}$$

$$i_i \equiv i_2 = \frac{v_o}{R_1 + R_2} = \frac{0.1V(1+47)}{48k\Omega} = 100 \mu A \quad \text{and} \quad \mathbf{i}_- \ll \mathbf{i}_2$$

12.11

$$(a) A = 10^{\frac{86}{20}} = 2.00 \times 10^4 \quad | \quad 1 + A\beta = 1 + 2.00 \times 10^4 \left(\frac{12k\Omega}{162k\Omega} \right) = 1482$$

$$A_v = \frac{A}{1 + A\beta} = \frac{2.00 \times 10^4}{1482} = 13.49 \quad | \quad R_{in} = 250k\Omega (1 + A\beta) = 371 M\Omega$$

$$R_{out} = \frac{250\Omega}{(1 + A\beta)} = 169 m\Omega \quad | \quad \text{Note that } A_{v-ideal} = 1 + \frac{150k\Omega}{12k\Omega} = 13.5$$

$$(b) A_{v-ideal} = 1 + \frac{150k\Omega}{1.2k\Omega} = 126 \quad | \quad 1 + A\beta = 1 + 2.00 \times 10^4 \left(\frac{1.2k\Omega}{151.2k\Omega} \right) = 159.7$$

$$A_v = \frac{A}{1 + A\beta} = \frac{2.00 \times 10^4}{160.7} = 124 \quad | \quad R_{in} = 250k\Omega (1 + A\beta) = 39.9 M\Omega \quad | \quad R_{out} = \frac{250\Omega}{(1 + A\beta)} = 156 \Omega$$

12.12

$$(a) A = 10^{\frac{100}{20}} = 10^5 \quad | \quad 1 + A\beta = 1 + 10^5 \left(\frac{5.6k\Omega}{5.6k\Omega + 47k\Omega} \right) = 10647$$

$$A_v = \frac{A}{1 + A\beta} = \frac{10^5}{10647} = 9.392 \quad | \quad R_{in} = 400k\Omega (1 + A\beta) = 10.6 M\Omega$$

$$R_{out} = \frac{200\Omega}{(1 + A\beta)} = 18.8 m\Omega \quad | \quad \text{Note that } A_{v-ideal} = 1 + \frac{47k\Omega}{5.6k\Omega} = 9.393$$

$$(b) A = 10^{\frac{94}{20}} = 5.01 \times 10^4 \quad | \quad 1 + A\beta = 1 + 5.01 \times 10^4 \left(\frac{5.6k\Omega}{5.6k\Omega + 47k\Omega} \right) = 5335$$

$$A_v = \frac{A}{1 + A\beta} = \frac{5.01 \times 10^4}{5335} = 9.391 \quad | \quad R_{in} = 400k\Omega (1 + A\beta) = 2.13 M\Omega$$

$$R_{out} = \frac{200\Omega}{(1 + A\beta)} = 37.5 m\Omega \quad | \quad \text{Note that } A_{v-ideal} = 1 + \frac{47k\Omega}{5.6k\Omega} = 9.393$$

12.13

$$(a) A = 10^{\frac{100}{20}} = 10^5 \quad | \quad 1 + A\beta = 1 + 10^5 \left(\frac{5.6k\Omega}{5.6k\Omega + 47k\Omega} \right) = 10647 \quad | \quad A_{v-ideal} = -\frac{47k\Omega}{5.6k\Omega} = -8.393$$

$$A_v = -\frac{R_2}{R_i} \left(\frac{A\beta}{1 + A\beta} \right) = -8.393 \frac{10646}{10647} = -8.392 \quad | \quad R_{in} = R_i + R_{id} \left| \frac{R_2}{1 + A} \right| = 5.60 \text{ k}\Omega$$

$$R_{out} = \frac{200\Omega}{(1 + A\beta)} = 18.8 \text{ m}\Omega$$

$$(b) A = 10^{\frac{94}{20}} = 5.01 \times 10^4 \quad | \quad 1 + A\beta = 1 + 5.01 \times 10^4 \left(\frac{5.6k\Omega}{5.6k\Omega + 47k\Omega} \right) = 5335$$

$$A_v = -\frac{R_2}{R_i} \left(\frac{A\beta}{1 + A\beta} \right) = -8.393 \frac{5334}{5335} = -8.391 \quad | \quad R_{in} = R_i + R_{id} \left| \frac{R_2}{1 + A} \right| = 5.60 \text{ k}\Omega$$

$$R_{out} = \frac{200\Omega}{(1 + A\beta)} = 37.5 \text{ m}\Omega$$

12.14

$$(a) A = 10^{\frac{94}{20}} = 5.01 \times 10^4 \quad | \quad 1 + A\beta = 1 + 5.01 \times 10^4 \left(\frac{4.7k\Omega}{4.7k\Omega + 47k\Omega} \right) = 4555 \quad | \quad A_{v-ideal} = -\frac{47k\Omega}{4.7k\Omega} = -10$$

$$A_v = -\frac{R_2}{R_i} \left(\frac{A\beta}{1 + A\beta} \right) = -10 \frac{4554}{4555} = -9.998 \quad | \quad R_{in} = R_i + R_{id} \left| \frac{R_2}{1 + A} \right| = 4.70 \text{ k}\Omega$$

$$R_{out} = \frac{100\Omega}{(1 + A\beta)} = 21.6 \text{ m}\Omega$$

$$(b) A = 10^{\frac{100}{20}} = 10^5 \quad | \quad 1 + A\beta = 1 + 10^5 \left(\frac{4.7k\Omega}{4.7k\Omega + 47k\Omega} \right) = 9092 \quad | \quad A_{v-ideal} = -\frac{47k\Omega}{4.7k\Omega} = -10$$

$$A_v = -\frac{R_2}{R_i} \left(\frac{A\beta}{1 + A\beta} \right) = -10 \frac{9091}{9092} = -9.999 \quad | \quad R_{in} = R_i + R_{id} \left| \frac{R_2}{1 + A} \right| = 4.70 \text{ k}\Omega$$

$$R_{out} = \frac{100\Omega}{(1 + A\beta)} = 11.0 \text{ m}\Omega$$

12.15

$$\text{Setting } v_2 = 0, \quad R_{in1} = R_{id}(1 + A\beta) = (500k\Omega) \left(1 + 4 \times 10^4 \frac{2R_i}{2R_i + 49R_i} \right) = 785 \text{ M}\Omega$$

$$\text{By symmetry, } R_{in2} = R_{in1} = 785 \text{ M}\Omega \quad | \quad R_{out} = R_{out3} = \frac{R_o}{(1 + A\beta)} = \frac{75}{\left(1 + \frac{4 \times 10^4}{2} \right)} = 3.75 \text{ m}\Omega$$

12.16

Op-amp parameters: $R_{id} = 500 \text{ k}\Omega$, $R_o = 35 \Omega$, $A = 50,000$

Amplifier Requirements: $A_V = 200$, $R_{in} \geq 200 \text{ M}\Omega$, $R_{out} \leq 0.2 \Omega$.

We must immediately discard the inverting amplifier case. $R_{in} = R_1$ requires $R_1 \geq 200 \text{ M}\Omega$ which can be achieved, but then R_2 must be $200 R_1 \geq 40 \text{ G}\Omega$ which is out of the question (see values in Appendix A). So, working with the non-inverting amplifier:

$$A_V = 200 \Rightarrow \beta = \frac{R_1}{R_1 + R_2} = \frac{1}{200} \quad \text{and} \quad A\beta = \frac{50000}{200} = 250 \gg 1$$

$$R_{out} = \frac{R_o}{1 + A\beta} \approx \frac{35}{250} = 0.14 \Omega \quad \text{meets the specification}$$

$$R_{in} = R_{id}(1 + A\beta) \approx 500 \text{ k}\Omega(250) = 125 \text{ M}\Omega \quad \text{does not meet the requirements.}$$

So the specifications cannot be met using a single-stage amplifier built using the op-amp that was specified in the problem.

12.17

The non-inverting amplifier is the only one that can hope to achieve both the required gain and with such a high value of input resistance:

$$A_V = \frac{1}{\beta} = 200 \quad \text{and} \quad A\beta = \frac{10^4}{200} = 50$$

$$R_{in} = R_{id}(1 + A\beta) = 1 \text{ M}\Omega(51) = 51 \text{ M}\Omega \quad \text{- too small}$$

$$R_{out} = \frac{R_o}{(1 + A\beta)} = \frac{100 \Omega}{51} = 1.96 \Omega \quad \text{- too large}$$

If the gain specification is met, the input and output resistance specifications will not be met.

12.18

The open-circuit voltage is $\mathbf{v}_{th} = \mathbf{v}_s \left(-\frac{R_2}{R_1} \right) \left(\frac{A\beta}{1 + A\beta} \right)$. Checking the loop-gain:

$$A\beta = (5 \times 10^4) \left(\frac{6.8 \text{ k}\Omega}{6.8 \text{ k}\Omega + 110 \text{ k}\Omega} \right) = 2910 \gg 1 \quad \text{so} \quad \mathbf{v}_{th} = \mathbf{v}_s \left(-\frac{R_2}{R_1} \right) = -\mathbf{v}_s \left(\frac{110 \text{ k}\Omega}{6.8 \text{ k}\Omega} \right) = -16.2 \mathbf{v}_s$$

$$R_{th} = R_{out} = \frac{R_o}{1 + A\beta} \approx \frac{R_o}{A\beta} = \frac{250 \Omega}{2910} = 85.9 \text{ m}\Omega$$

12.19

The open circuit voltage is $v_{th} = \frac{A}{1+A\beta} v_s$. Checking the loop gain:

$$A\beta = 10^4 \left(\frac{0.39k\Omega}{0.39k\Omega + 56k\Omega} \right) = 69.2 \gg 1 \text{ so } v_{th} \approx v_s \left(1 + \frac{R_2}{R_1} \right) = v_s \left(1 + \frac{56k\Omega}{0.39k\Omega} \right) = 145 v_s$$

$$\text{or more exactly: } v_{th} = v_s \frac{A}{1+A\beta} = v_s \frac{10^4}{1+69.2} = 143 v_s \quad | \quad R_{th} = R_{out} = \frac{R_o}{1+A\beta} = \frac{200\Omega}{70.2} = 2.85 \Omega$$

12.20

Applying the definition of fractional gain error:

$$FGE = \frac{-\frac{R_2}{R_1} - \left[-\frac{R_2(1 \pm \varepsilon)}{R_1(1 \mp \varepsilon)} \right] \frac{A\beta}{1+A\beta}}{-\frac{R_2}{R_1}} = 1 - \left[\frac{(1 \pm \varepsilon)}{(1 \mp \varepsilon)} \right] \frac{A\beta}{1+A\beta} \approx 1 - (1 \pm 2\varepsilon) \frac{A\beta}{1+A\beta}$$

$$FGE \approx 1 - \frac{A\beta}{1+A\beta} \mp 2\varepsilon \frac{A\beta}{1+A\beta} = \frac{1}{1+A\beta} \mp 2\varepsilon \frac{A\beta}{1+A\beta}$$

$$\text{For } A\beta \gg 1, FGE \approx \frac{1}{A\beta} \mp 2\varepsilon \text{ which must be } \leq 0.01. \quad A = 10^{\frac{106}{20}} = 2.00 \times 10^5$$

$$\frac{1}{A\beta} \mp 2\varepsilon = \frac{1}{(2 \times 10^5) \frac{1}{1000}} \mp 2\varepsilon \leq 0.01 \quad | \quad \text{Taking the positive sign, } 2\varepsilon \leq 0.005 \text{ and } \varepsilon \leq 0.25\%$$

12.21

Using the results from Prob. 12.20,

$$A_v = 10^{\frac{54}{20}} = 501 \quad | \quad \text{For } A\beta = \frac{4 \times 10^4}{501} = 79.8 \gg 1, \text{ so } FGE \approx \frac{1}{A\beta} \mp 2\varepsilon \text{ which must be } \leq 0.02$$

$$\frac{1}{A\beta} \mp 2\varepsilon = \frac{1}{79.8} \mp 2\varepsilon \leq 0.02 \quad | \quad \text{Taking the positive sign, } 2\varepsilon \leq 0.00747 \text{ and } \varepsilon \leq 0.374\%$$

12.22

$$V_+ = 3V \frac{99k\Omega}{10.1k\Omega + 99k\Omega} = 2.722 V \quad | \quad \frac{3 - 2.722}{9.9k\Omega} = \frac{2.722 - V_o}{101k\Omega} \quad | \quad V_o = -0.111 V \quad | \quad V_o^{ideal} = 0 V$$

12.23

$$V_+ = 4.05V \frac{99k\Omega}{10.1k\Omega + 99k\Omega} = 3.675 \text{ V} \quad | \quad \frac{3.95 - 3.675}{9.9k\Omega} = \frac{3.675 - V_o}{101k\Omega} \quad | \quad V_o = 0.869 \text{ V}$$

For matched resistors, $V_o^{ideal} = -10(V_1 - V_2) = -10(3.95 - 4.05) = +1.00 \text{ V}$

$$\varepsilon = 100\% \left(\frac{1 - 0.869}{1} \right) = 13.1\%$$

12.24

$$(a) v_{ic} = \frac{v_1 + v_2}{2} = 10 \sin 120\pi t \text{ V} \quad \text{and} \quad v_{id} = v_1 - v_2 = 0.50 \sin 5000\pi t \text{ V}$$

$$(b) v_+ = \mathbf{v}_{ic} \frac{99k\Omega}{10.1k\Omega + 99k\Omega} = 0.90742 \mathbf{v}_{ic} \quad | \quad \mathbf{i} = \frac{\mathbf{v}_{ic} - \mathbf{v}_-}{9.9k\Omega} = \frac{\mathbf{v}_{ic} - \mathbf{v}_+}{9.9k\Omega} = \frac{0.09258}{9.9k\Omega} \mathbf{v}_{ic}$$

$$\mathbf{v}_o = \mathbf{v}_- - \mathbf{i}(101k\Omega) = \mathbf{v}_+ - \mathbf{i}(101k\Omega) = 0.90742 \mathbf{v}_{ic} - \frac{0.09258}{9.9k\Omega} \mathbf{v}_{ic}(101k\Omega)$$

$$\mathbf{v}_o = -0.037 \mathbf{v}_{ic} \quad \text{and} \quad A_{cm} = \frac{\mathbf{v}_o}{\mathbf{v}_{ic}} = -0.037 \quad | \quad \text{The value of } A_{dm} = -10 \text{ is not}$$

affected by the small tolerances. (c) $CMRR = \left| \frac{A_{dm}}{A_{cm}} \right| = 270$ - a paltry 48.6 dB

$$(d) v_o = A_{dm} v_{id} + A_{cm} v_{ic} = -0.370 \sin(120\pi t) - 5.00 \sin(5000\pi t) \text{ V}$$

12.25

$$V_{IC} = \frac{5 + 5.01}{2} = 5.005 \text{ V}. \quad \text{The maximum equivalent input error is}$$

$$\frac{V_{IC}}{CMRR} = \frac{5.005}{10^4} = 0.500 \text{ mV}, \quad \text{but the sign is unknown. Therefore the meter reading may be anywhere in the range } 9.50 \text{ mV} \leq V_{meter} \leq 10.5 \text{ mV.}$$

12.26

$$(a) V_1 = 15V \frac{30k\Omega}{10k\Omega + 30k\Omega} = 11.25 V \quad | \quad V_2 = 15V \frac{10k\Omega}{10k\Omega + 30k\Omega} = 3.75 V$$

$$V_1 - V_2 = 15V \frac{20k\Omega}{10k\Omega + 30k\Omega} = 7.50 V \quad | \quad V_{CM} = \frac{V_1 + V_2}{2} = \frac{11.25 + 3.75}{2} = 7.50V.$$

The maximum equivalent input error is $\frac{V_{CM}}{CMRR}$. We need $\frac{V_{CM}}{CMRR} < 10^{-4}(V_1 - V_2)$

$$CMRR > \frac{10^4(7.5V)}{7.5V} = 10^4 \text{ or } 80 \text{ dB.}$$

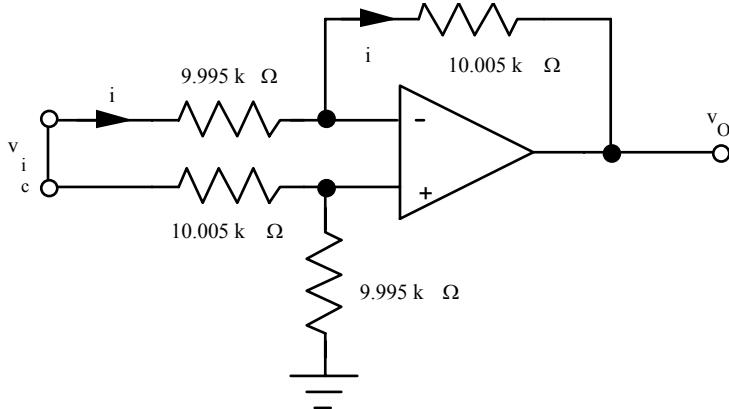
$$(b) V_1 = 15V \frac{10.2k\Omega}{20.2k\Omega} = 7.574 V \quad | \quad V_2 = 15V \frac{10k\Omega}{20.2k\Omega} = 7.426 V$$

$$V_1 - V_2 = 15V \frac{200\Omega}{20.2k\Omega} = 0.1485 V \quad | \quad V_{CM} = \frac{V_1 + V_2}{2} = 7.50V.$$

$$\text{We need } \frac{V_{CM}}{CMRR} < 10^{-4}(V_1 - V_2) \text{ or } CMRR > \frac{10^4(7.5V)}{0.1485V} = 5.05 \times 10^5 \text{ or } 114 \text{ dB.}$$

12.27

One worst-case tolerance assignment is given below. The second is found by reversing the pairs of resistor values.



$$v_+ = v_{ic} \frac{9.995}{10.005 + 9.995} = 0.49975v_{ic} \quad | \quad i = \frac{v_{ic} - v_-}{9.995k\Omega} = \frac{v_{ic} - v_+}{9.995k\Omega} = \frac{0.50025}{9.995k\Omega} v_{ic}$$

$$v_o = v_- - i(10.005k\Omega) = v_+ - i(10.005k\Omega) = 0.49975v_{ic} - \frac{0.50025}{9.995k\Omega} v_{ic}(10.005k\Omega)$$

$$v_o = -0.001v_{ic} \text{ and } A_{cm} = \frac{v_o}{v_{ic}} = -0.001 \quad | \quad \text{The value of } A_{dm} = 1 \text{ is not affected by the}$$

$$\text{small tolerances. } CMRR = \left| \frac{A_{dm}}{A_{cm}} \right| = 1000 \quad | \quad CMRR_{dB} = 60 \text{ dB}$$

12.28

Setting $V_2 = 0$, $R_{in1} = R_{id}(1 + A\beta) \parallel 2R_{ic} = (1M\Omega) \left(1 + 7.5 \times 10^4 \frac{2k\Omega}{2k\Omega + 24k\Omega}\right) \parallel 2(500M\Omega) = 852 M\Omega$

By symmetry, $R_{in2} = R_{in1} = 852 M\Omega$ | $R_{out} = R_{out3} = \frac{R_o}{(1 + A\beta)} = \frac{100}{\left(1 + \frac{75000}{2}\right)} = 2.67 \text{ m}\Omega$

12.29

$$V_2 = V_a = 4.99V \quad | \quad V_3 = V_b = 5.01V \quad | \quad V_1 = V_2 + \frac{V_2 - V_3}{200\Omega} (4.9k\Omega) = 4.500$$

$$V_4 = V_3 - \frac{V_2 - V_3}{200\Omega} (4.9k\Omega) = 5.500 \quad | \quad V_6 = V_4 \frac{9.99k\Omega}{10.01k\Omega + 9.99k\Omega} = 2.7473V$$

$$\frac{V_1 - V_5}{9.99k\Omega} = \frac{V_5 - V_o}{10.01k\Omega} \quad | \quad V_5 = V_6 \quad | \quad V_o = 0.991 V$$

$$i_1 = -\frac{V_2 - V_3}{200\Omega} - \frac{V_1 - V_5}{9.99k\Omega} = -75.4 \mu\text{A} \quad | \quad i_2 = \frac{V_2 - V_3}{200\Omega} - \frac{V_4}{10.01k\Omega + 9.99k\Omega} = -375 \mu\text{A}$$

$$i_3 = \frac{V_5 - V_o}{10.01k\Omega} = +175 \mu\text{A}$$

The common - mode and differential - mode inputs to the differential subtractor are

$$V_{cm} = \frac{V_1 + V_4}{2} = 5V \quad \& \quad V_{dm} = V_1 - V_4 = -1V \text{ with } V_1 = -0.5V \text{ and } V_4 = +0.5V$$

The subtractor outputs for the common - mode and differential - mode inputs are :

$$CM : V_5 = V_6 = 5 \frac{9.99k\Omega}{10.01k\Omega + 9.99k\Omega} = 2.4975V \quad | \quad \frac{V_1 - V_5}{9.99k\Omega} = \frac{V_5 - V_o^{cm}}{10.01k\Omega} \quad | \quad V_o^{cm} = -0.0100 V$$

$$DM : V_5 = V_6 = 0.5 \frac{9.99k\Omega}{10.01k\Omega + 9.99k\Omega} = 0.24975V \quad | \quad \frac{V_1 - V_5}{9.99k\Omega} = \frac{V_5 - V_o^{dm}}{10.01k\Omega} \quad | \quad V_o^{dm} = 1.00 V$$

$$A_{dm} = \frac{1.00}{-0.02} = -50.0 \quad | \quad A_{cm} = \frac{-0.01}{5} = -0.002 \quad | \quad CMRR = \left| \frac{A_{dm}}{A_{cm}} \right| = 25000 \text{ or } 88.0 \text{ dB}$$

12.30

$$V_2 = V_a = 3.00V \quad | \quad V_3 = V_b = 3.00V \quad | \quad V_1 = V_2 + \frac{V_2 - V_3}{200\Omega} (4.9k\Omega) = 3.00V$$

$$V_4 = V_3 - \frac{V_2 - V_3}{200\Omega} (4.9k\Omega) = 3.00V \quad | \quad V_6 = V_4 \frac{9.99k\Omega}{10.01k\Omega + 9.99k\Omega} = 1.4985V$$

$$\frac{V_1 - V_5}{9.99k\Omega} = \frac{V_5 - V_o}{10.01k\Omega} \quad | \quad V_5 = V_6 \quad | \quad V_o = -6.01 mV$$

$$i_1 = -\frac{V_2 - V_3}{200\Omega} - \frac{V_1 - V_5}{9.99k\Omega} = -150 \mu A \quad | \quad i_2 = \frac{V_2 - V_3}{200\Omega} - \frac{V_4}{10.01k\Omega + 9.99k\Omega} = -150 \mu A$$

$$i_3 = \frac{V_5 - V_o}{10.01k\Omega} = +149 \mu A$$

$$V_o = A_{dm}v_{id} + A_{cm}v_{ic} \quad | \quad -6.01 \times 10^{-3} = -50(3 - 3) + A_{cm} \frac{3+3}{2} \quad | \quad A_{cm} = -2.00 \times 10^{-3}$$

$$CMRR = \left| \frac{A_{dm}}{A_{cm}} \right| = \frac{50}{2.00 \times 10^{-3}} = 2.50 \times 10^4 \text{ or } 88.0 dB \quad | \quad \text{It has been assumed that}$$

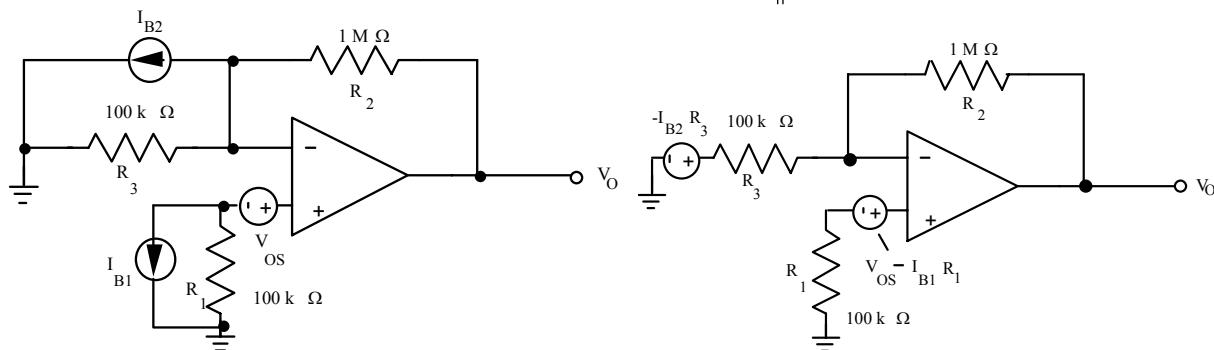
the value of A_{dm} is not affected by the small tolerances. See solution to Prob. 12.29.

12.31

$$V_o = (V_{os} - I_{B1}R_1) \left(1 + \frac{R_2}{R_3} \right) - I_{B2}R_3 \left(-\frac{R_2}{R_3} \right) = (V_{os} - I_{B1}R_1) \left(1 + \frac{R_2}{R_3} \right) + I_{B2}R_2$$

$$V_o = (\pm 0.001 - 10^{-7}10^5) \left(1 + \frac{10^6}{10^5} \right) + 0.95 \times 10^{-7}10^6 = \pm 0.011 - .015V. \text{ Worst case } V_o = -0.026 V.$$

Ideal output = 0 V. Error = -26 mV. Yes, R_1 should be $R_2 \parallel R_3 = 90.9 k\Omega$.



12.32

$$V_o = (V_{os} - I_{B1}R_1) \left(1 + \frac{R_2}{R_3}\right) - I_{B2}R_3 \left(-\frac{R_2}{R_3}\right) = (V_{os} - I_{B1}R_1) \left(1 + \frac{R_2}{R_3}\right) + I_{B2}R_2$$

$$V_o = [\pm 0.01 - 2 \times 10^{-7} (10^5)] \left[1 + \frac{510k\Omega}{100k\Omega}\right] + 2.5 \times 10^{-7} (510k\Omega) = \pm 0.061 + 0.0055V$$

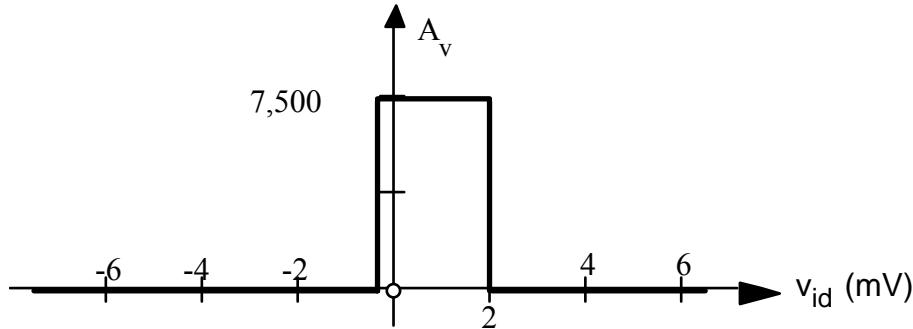
Worst case $V_o = +0.066.5$ mV. Ideal output = 0 V. Error = 66.5 mV. Yes, R_1 should be $R_2||R_3 = 90.9$ k Ω .

12.33

$$v_o = A_v(v_{id} + V_{os}) \mid A_v = \frac{dv_o}{dv_{id}} = \frac{10 - (-5)}{2 - 0} \frac{V}{mV} = +7500$$

When $v_o = 0$, $v_{id} = -V_{os}$ and so $V_{os} = -0.667$ mV.

12.34



12.35

For $I_{B2} = 0$: Since v_+ must = $v_- = V_{os}$, the current through C is $i_C(t) = \frac{V_{os}}{R}$

$$v_o(t) = V_{os} + \frac{1}{C} \int_0^t i_C(t) dt = V_{os} + \frac{1}{C} \int_0^t \frac{V_{os}}{R} dt = V_{os} + \frac{V_{os}}{RC} t$$

For $V_{os} = 0$, $i_C(t) = I_{B2}$ since $v_- = v_+ = 0$.

$$v_o(t) = \frac{1}{C} \int_0^t i_C(t) dt = \frac{1}{C} \int_0^t I_{B2} dt = \frac{I_{B2}}{C} t \quad | \text{ Summing these two results yields}$$

$$\text{Eq. (11.103): } v_o(t) = V_{os} + \frac{V_{os}}{RC} t + \frac{I_{B2}}{C} t \quad | \text{ Note that } v_c(0) = 0 \text{ for both cases.}$$

12.36

$$40dB = 100 = 1 + \frac{R_2}{R_1} \quad \text{or} \quad \frac{R_2}{R_1} = 99 \quad | \quad \text{For bias current compensation, } R_1 \parallel R_2 = 10k\Omega$$

$$\frac{R_1 R_2}{R_1 + R_2} = \frac{R_2}{1 + \frac{R_2}{R_1}} = 10k\Omega \quad | \quad R_2 = 10k\Omega(1+99) = 1.00 M\Omega \quad \text{and} \quad R_1 = \frac{1M\Omega}{99} = 10.1k\Omega$$

The nearest 5% values would be 1 MΩ and 10 kΩ.

12.37

$$(a) \text{Ideal } V_o = -0.005V \left(1 + \frac{100k\Omega}{1.1k\Omega}\right) = -0.460V$$

$$(b) V_o = (-0.005V - 0.001V) \frac{A}{1 + A\beta} = (-0.005V - 0.001V) \frac{10^4}{1 + 10^4 \frac{1.1k\Omega}{101.1k\Omega}} = -0.546V$$

$$(c) \text{Error} = \frac{-0.460 - (-0.546)}{-0.460} = -0.187 \quad \text{or} \quad -18.7\%$$

12.38

Inverting Amplifier: $v_o = A_v v_s = -6.2v_s$ as long as $|v_o| \leq 10V$ as constrained by the op-amp power supply voltages

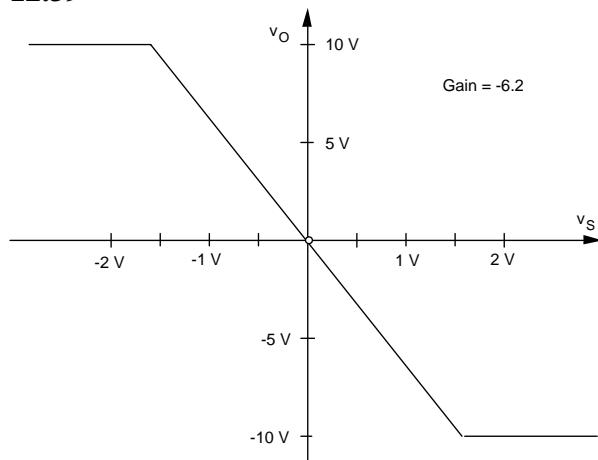
(a) $V_o = -6.2(1) = -6.2V$, feedback loop is working and $V_- = 0$

(b) $V_o = -6.2(-3) = +18V$; V_o saturates at $V_o = +10V$

The feedback loop is "broken" since the open-loop gain is now 0.

(The output voltage does not change when the input changes so $A = 0$)

$$\text{By superposition, } V_- = -3 \frac{6.2k\Omega}{7.2k\Omega} + 10 \frac{1k\Omega}{7.2k\Omega} = -1.19V$$

12.39

12.40

Inverting Amplifier: $v_o = A_v v_s = -10v_s$ as long as $|v_o| \leq 10V$ as constrained by the op - amp power supply voltages

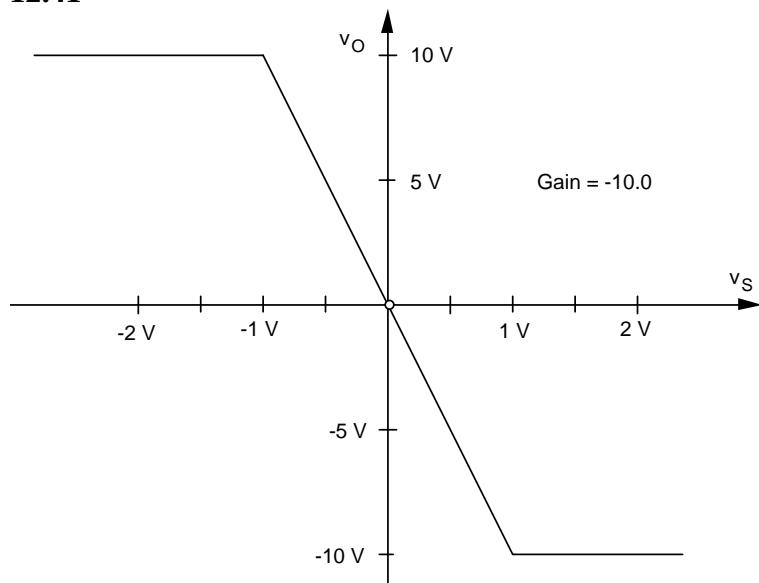
(a) $V_o = -10(0.5) = -5.00$ V, the feedback loop is working, and $V_- = 0$

(b) $V_o = -10(1.2) = -12.0$ V; V_o saturates at $V_o = +10$ V

The feedback loop is "broken" since the open - loop gain is now 0.

(The output voltage does not change when the input changes so $A = 0$)

$$\text{By superposition, } V_- = 1.2 \frac{10k\Omega}{11k\Omega} - 10 \frac{1k\Omega}{11k\Omega} = 0.182 \text{ V}$$

12.41**12.42**

Noninverting Amplifier: $v_o = A_v v_s = +40v_s$ as long as $|v_o| \leq 15V$

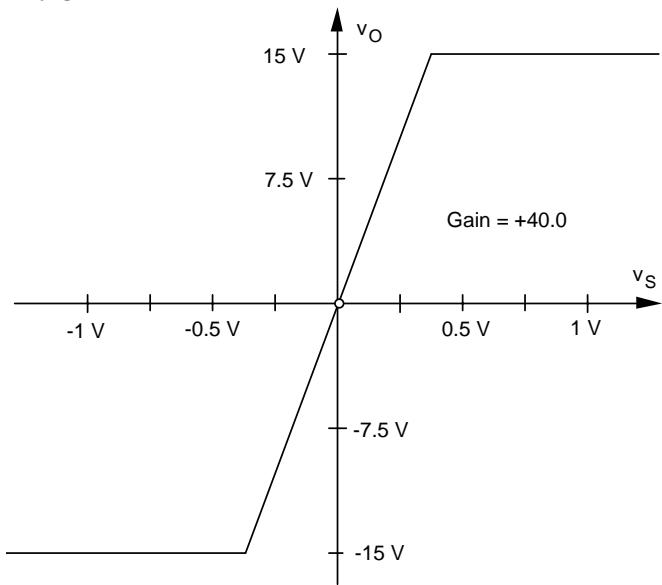
(a) $V_o = 40(0.25V) = +10$ V, the feedback loop is working, and $V_{ID} = 0$

(b) $V_o = 40(0.5V) = 20$ V; V_o saturates at $V_o = +15$ V

The feedback loop is "broken" since the open - loop gain is now 0.

(The output voltage does not change when the input changes so $A = 0$)

$$V_{ID} = V_+ - V_- = 0.5V - 15 \frac{1k\Omega}{1k\Omega + 39k\Omega} = 0.125V.$$

12.43**12.44**

Noninverting Amplifier: $v_o = A_v v_s = +43.9 v_s$ as long as $|v_o| \leq 15V$

(a) $V_o = 43.9(0.25V) = +11.0V$, feedback loop is working, and $V_{ID} = 0$

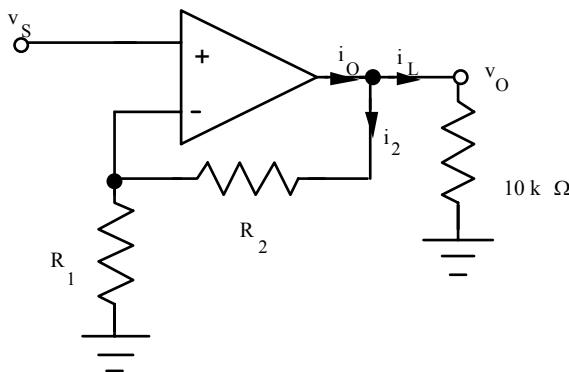
(b) $V_o = 43.9(0.5V) = 22.0V$; V_o saturates at $V_o = +15V$

The feedback loop is "broken" since the open-loop gain is now 0.

(The output voltage does not change when the input changes so $A = 0$)

$$V_{ID} = V_+ - V_- = 0.5V - 15 \frac{0.91k\Omega}{0.91k\Omega + 39k\Omega} = 0.158 V.$$

12.45



$i_o = i_L + i_2$ and $|i_o| \leq 1.5mA$. The output voltage requirement gives $|i_L| \leq \frac{10V}{10k\Omega} = 1.00mA$

which leaves 0.500mA as the maximum value of i_2 . $i_2 = \frac{10V}{R_l + R_2}$ gives $(R_l + R_2) \geq 20k\Omega$

The closed - loop gain of 40 db ($A_v = 100$) requires $\frac{R_2}{R_l} = 99$.

The closest ratio from the resistor tables appears to be $\frac{R_2}{R_1} = 100$ which is within 1%

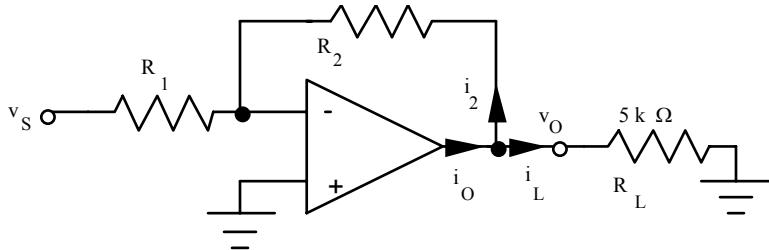
of the desired ratio. (This is close enough since we are using 5% resistors.)

There are many many choices that meet both $\frac{R_2}{R_1} = 100$ and $(R_l + R_2) \geq 20k\Omega$.

However, the choice, $R_l = 200\Omega$ and $R_2 = 20k\Omega$ is not acceptable because its minimum value does not meet the requirements : $20.2k\Omega(1 - 0.05) = 19.2k\Omega$.

The smallest acceptable pair is $R_l = 220\Omega$ and $R_2 = 22k\Omega$.

12.46



$$i_o = i_L + i_2 \leq 4 \text{ mA} \quad \text{and} \quad i_L = \frac{15V}{5k\Omega} = 3 \text{ mA} \quad \text{so} \quad i_2 \leq 1 \text{ mA}$$

$$i_2 = \frac{v_o}{R_2} \leq 1 \text{ mA} \quad \text{requires} \quad R_2 \geq \frac{15}{.001} = 15k\Omega$$

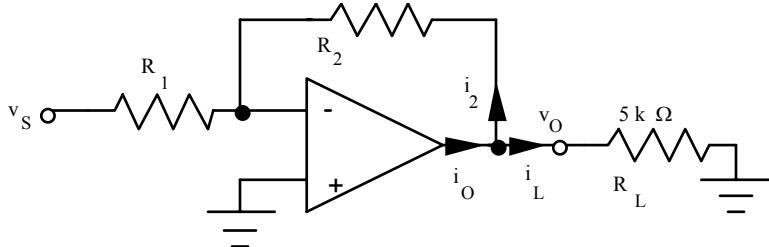
To account for the resistor tolerance, $0.95R_2 \geq 15k\Omega$ requires $R_2 \geq 15.8k\Omega$. For $A_v = 46 \text{ dB} = 200$, $R_2 = 200 R_1$, and one acceptable resistor pair would be $R_1 = 1 \text{ k}\Omega$ and $R_2 = 20 \text{ k}\Omega$. Many acceptable choices exist. An input resistance constraint might set a lower limit on R_1 .

12.47

The maximum base current is limited to 5 mA, so the maximum emitter current is limited to

$$I_E = (\beta_F + 1)I_B = 51(5 \text{ mA}) = 255 \text{ mA}. \quad \text{Since} \quad I_E = \frac{10V}{R}, \quad R \geq \frac{10V}{255 \text{ mA}} = 39.2 \Omega$$

12.48



$$i_o = i_L + i_2 \leq \frac{10V}{4k\Omega} = 2.5 \text{ mA} \quad \text{and} \quad i_L = \frac{10V}{5k\Omega} = 2 \text{ mA} \quad \text{so} \quad i_2 \leq 0.5 \text{ mA}$$

$$R_2 \geq \frac{10V}{0.5 \text{ mA}} = 20k\Omega \quad A_v = 46 \text{ dB} \Rightarrow \frac{R_2}{R_1} = 200$$

One possible choice would be $R_2 = 20 \text{ k}\Omega$ and $R_1 = 100 \Omega$. However, the op-amp would not be able to supply enough output current if tolerances are taken into account. Better choices would be $R_2 = 22 \text{ k}\Omega$ and $R_1 = 110 \Omega$ or $R_2 = 200 \text{ k}\Omega$ and $R_1 = 1 \text{ k}\Omega$ which would give the amplifier a much higher input resistance.

$$(b) V = \frac{|v_{o,\max}|}{200} = \frac{10V}{200} = 50 \text{ mV} \quad (c) R_{in} = R_1 = 110 \Omega \text{ and } 1 \text{ k}\Omega \text{ for the two designs given above.}$$

12.49

Using the expressions in Table 12.1:

$$\text{First stage: } \beta = \frac{24k\Omega}{24k\Omega + 240k\Omega} = \frac{1}{11} \quad | \quad A_{v1} = -\frac{R_2}{R_1} \left(\frac{A\beta}{1 + A\beta} \right) = -\frac{240k\Omega}{24k\Omega} \left(\frac{\frac{10^5}{11}}{1 + \frac{10^5}{11}} \right) = -10.0$$

$$R_{in1} = R_1 + \left(R_{id} \left| \frac{R_2}{1 + A\beta} \right. \right) = 24k\Omega + 500k\Omega \left| \frac{240k\Omega}{1 + 10^5} \right. = 24.0 \text{ k}\Omega \quad | \quad R_{out1} = \frac{R_o}{1 + A\beta} = \frac{100}{1 + \frac{10^5}{11}} = 11.0 \text{ m}\Omega$$

$$\text{Second stage: } \beta = \frac{10k\Omega}{10k\Omega + 50k\Omega} = \frac{1}{6} \quad | \quad A_{v2} = -\frac{50k\Omega}{10k\Omega} \left(\frac{\frac{10^5}{6}}{1 + \frac{10^5}{6}} \right) = -5.00$$

$$R_{in2} = 10k\Omega + 500k\Omega \left| \frac{240k\Omega}{1 + 10^5} \right. = 10.0 \text{ k}\Omega \quad | \quad R_{out2} = \frac{100}{1 + \frac{10^5}{6}} = 6.00 \text{ m}\Omega$$

Overall amplifier :

$$A_v = -10.0 \frac{10k\Omega}{10.0k\Omega + 11.0m\Omega} (-5.00) = +50.0 \quad | \quad R_{in} = 24.0 \text{ k}\Omega \quad | \quad R_{out} = 6.00 \text{ m}\Omega$$

For all practical purposes, the numbers the same. $R_{out} = 6.00 \text{ m}\Omega$ is a good approximation of 0Ω , and $A_v = -10.0(-5.00) = +50.0$

12.50

Use the expressions in Table 12.1.

$$\beta_1 = \frac{47k\Omega}{47k\Omega + 390k\Omega} = 0.010755 \quad | \quad A_{v1} = \frac{A}{1 + A\beta_1} = \frac{10^5}{1 + 10^5(0.010755)} = \frac{10^5}{10756} = +9.30$$

$$\beta_2 = \frac{24k\Omega}{24k\Omega + 100k\Omega} = 0.19355 \quad | \quad A_{v1} = \frac{A}{1 + A\beta_2} = \frac{10^5}{1 + 10^5(0.19355)} = \frac{10^5}{19356} = +5.17$$

$$A_v = (9.30)(5.17) = 48.1$$

$$R_{in} = R_{id1}(1 + A\beta) = 250k\Omega(10756) = 2.69 \text{ G}\Omega \quad | \quad R_{out} = \frac{R_{o2}}{1 + A\beta_2} = \frac{200}{19356} = 10.3 \text{ m}\Omega$$

12.51

Use the expressions in Table 12.1.

$$\beta_1 = \beta_2 = \frac{20k\Omega}{20k\Omega + 120k\Omega} = \frac{1}{7} \quad | \quad A_{v1} = \frac{A}{1 + A\beta_1} = \frac{10^5}{1 + (10^5/7)} = \frac{10^5}{14287} = +7.00$$

$$A_{v2} = -\frac{R_2}{R_1} \left(\frac{A\beta_2}{1 + A\beta_1} \right) = -6 \left(\frac{14286}{14287} \right) = -6.00 \quad | \quad A_v = (7.00)(-6.00) = -42.0$$

$$R_{in} = R_{id1} (1 + A\beta_1) = 250k\Omega (14287) = 3.57 G\Omega \quad | \quad R_{out} = \frac{R_{o2}}{1 + A\beta_2} = \frac{200}{14287} = 14.0 m\Omega$$

12.52

Use the expressions in Table 12.1. The three individual amplifier stages are the same.

$$\beta = \frac{2k\Omega}{2k\Omega + 40k\Omega} = \frac{1}{21} \quad | \quad A = 10^{\frac{92}{20}} = 5.01 \times 10^4 \quad | \quad A_v = -\frac{R_2}{R_1} \left(\frac{A\beta}{1 + A\beta} \right) = -\frac{40k\Omega}{2k\Omega} \frac{\frac{5.01 \times 10^4}{21}}{1 + \frac{5.01 \times 10^4}{21}} = -20.0$$

$$R_{in} = R_1 + \left(R_{id} \parallel \frac{R_2}{1 + A} \right) = 2k\Omega + 500k\Omega \parallel \frac{40k\Omega}{1 + 5.01 \times 10^4} = 2.00 k\Omega \quad | \quad R_{out} = \frac{R_o}{1 + A\beta} = \frac{300\Omega}{1 + \frac{5.01 \times 10^4}{21}} = 126 m\Omega$$

$$\text{For the overall amplifier: } A_v = \left(-20.0 \frac{2k\Omega}{2k\Omega + 126m\Omega} \right) \left(-20.0 \frac{2k\Omega}{2k\Omega + 126m\Omega} \right) (-20.0) = -8000$$

$$R_{in} = 2.00 k\Omega \quad | \quad R_{out} = 126 m\Omega$$

12.53

$50^2 < 5000 < 50^3$ | Three stages will be required to keep the gain of each stage ≤ 50 .

However, the input and output resistance requirements may further constrain the

gains and must be checked as well. $A = 10^{\frac{85}{20}} = 1.778 \times 10^4$

$$\text{For } R_{out} = \frac{R_o}{1 + A\beta} : \frac{100\Omega}{1 + A\beta} \leq 0.1\Omega \rightarrow A\beta \geq 999 \rightarrow \beta \geq 0.0562 \rightarrow \frac{1}{\beta} \leq 17.8.$$

$$\text{For } R_{in} = R_{id} (1 + A\beta) \parallel 2R_{ic} : 1M\Omega (1 + A\beta) \parallel 2G\Omega \geq 10M\Omega \rightarrow A\beta \geq 9 \rightarrow \frac{1}{\beta} \leq 1976$$

$17.8(50)(50) > 5000$ so three stages is still sufficient.

12.54

$$\mathbf{V}_s = \mathbf{V}_o \frac{Z_1}{Z_1 + Z_2} = \mathbf{V}_o \frac{\frac{R_1}{R_2}}{R_1 + \frac{SC}{R_2 + \frac{1}{SC}}} = \mathbf{V}_o \frac{(SCR_2 + 1)R_1}{(SCR_2 + 1)R_1 + R_2}$$

$$A_v(s) = \frac{\mathbf{V}_o}{\mathbf{V}_s} = \left(1 + \frac{R_2}{R_1}\right) \frac{SC(R_1 \| R_2) + 1}{SCR_2 + 1}$$

12.55

$$A_v(s) = -\frac{R_2}{R_1} \frac{1}{sCR_2 + 1} \quad | \quad A_v(0) = -\frac{R_2}{R_1} \quad | \quad f_H = \frac{1}{2\pi CR_2}$$

$$A_v^{nom} = -\frac{330k\Omega}{10k\Omega} = -33 \quad | \quad A_v^{\max} = -\frac{330k\Omega(1.1)}{10k\Omega(0.9)} = -40.3 \quad | \quad A_v^{\min} = -\frac{330k\Omega(0.9)}{10k\Omega(1.1)} = -27.0$$

$$f_H^{nom} = \frac{1}{2\pi(10^{-10})(3.3 \times 10^5)} = 4.83kHz \quad | \quad f_H^{\max} = \frac{1}{2\pi(10^{-10})(0.5)(3.3 \times 10^5)(0.9)} = 10.7kHz$$

$$f_H^{\min} = \frac{1}{2\pi(10^{-10})(1.2)(3.3 \times 10^5)(1.1)} = 3.65kHz$$

12.56

-60db/decade requires 3 poles - 3 x (-20db/decade). Using three identical

amplifiers: $A_v = \sqrt[3]{1000} = 10$ and $f_{H1} = \frac{f_{H3}}{\sqrt[3]{2^3 - 1}} = 1.96(20kHz) = 39.2kHz$.

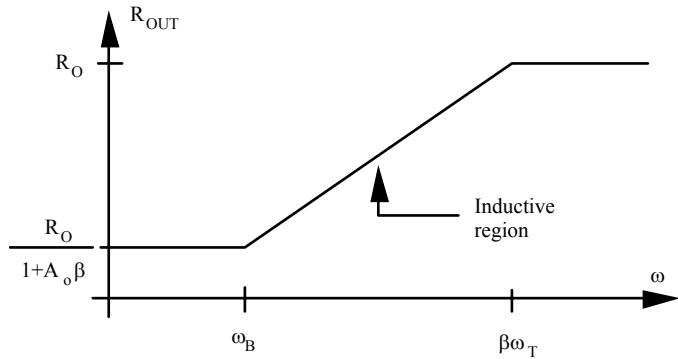
$$R_2 = 10R_1 \quad | \quad f_H = \frac{1}{2\pi R_2 C} \quad | \quad R_2 C = \frac{1}{2\pi(39.2 \times 10^3)} = 4.06 \times 10^{-6}s$$

Try $C = 270 pF$. $R_2 = \frac{1}{2\pi f_H C} = 15.0 k\Omega$, $R_1 = 1.5k\Omega$

12.57

$$A(s) = \frac{\omega_T}{s + \omega_B} \quad | \quad \omega_T = A_o \omega_B \quad | \quad Z_{out} = \frac{R_o}{1 + A(s)\beta} = \frac{R_o}{1 + \frac{\omega_T}{s + \omega_B}\beta} = R_o \frac{s + \omega_B}{s + \omega_B + \omega_T\beta}$$

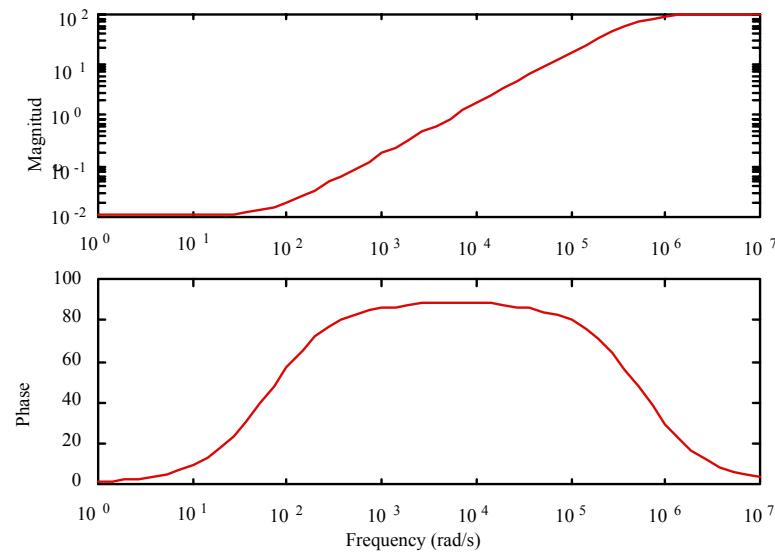
$$Z_{out} = R_o \frac{s + \omega_B}{s + \omega_B(1 + A_o\beta)} = \frac{R_o}{(1 + A_o\beta)} \frac{1 + \frac{s}{\omega_B}}{1 + \frac{s}{\omega_B(1 + A_o\beta)}} \approx \frac{R_o}{(1 + A_o\beta)} \frac{1 + \frac{s}{\omega_B}}{1 + \frac{s}{\beta\omega_T}}$$



12.58

Using MATLAB:

```
b=1/11; ro=100; wt=2*pi*1e6; wb=wt/1e5;
n=ro*[1 wb]; d=[1 b*wt]; w=logspace(0,7);
r=freqs(n,d,w);
mag=abs(r); phase=angle(r)*180/pi;
subplot(212); semilogx(w,phase)
subplot(211); loglog(w,mag)
```



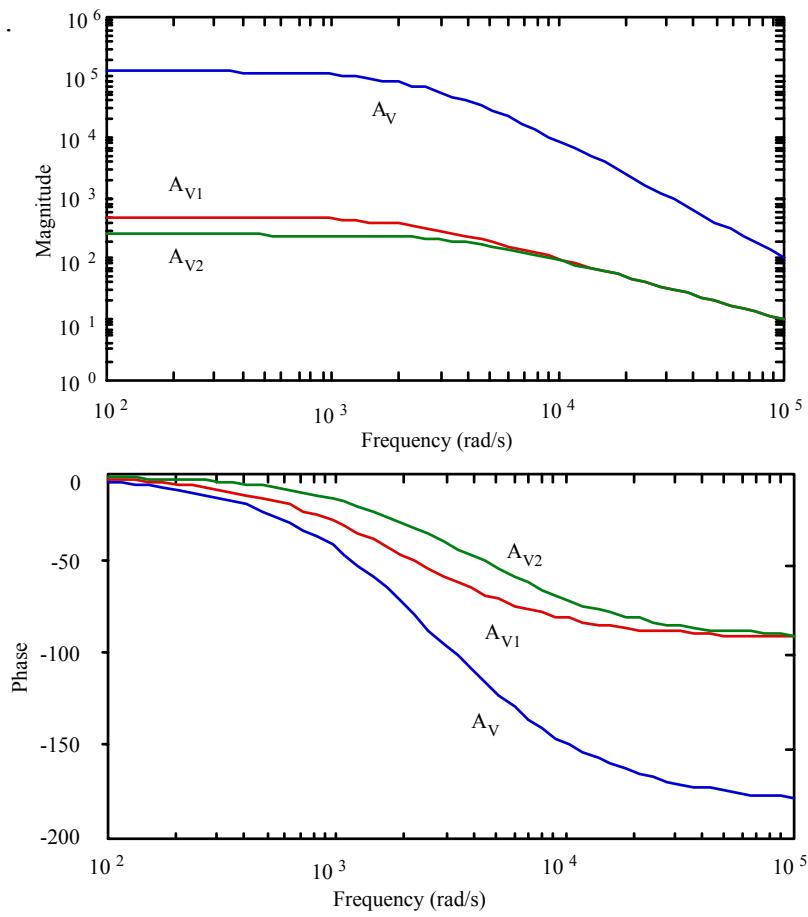
12.59

$$\begin{aligned}
Z_{in} &= R_1 + \left(R_{id} \left\| \frac{R_2}{1+A(s)} \right\| \right) = R_1 + \left(R_{id} \left\| \frac{R_2}{1+\frac{\omega_T}{s+\omega_B}} \right\| \right) = R_1 + \left(R_{id} \left\| R_2 \frac{(s+\omega_B)}{s+\omega_B+\omega_T} \right\| \right) \\
Z_{in} &= R_1 + \frac{R_{id} R_2 \frac{(s+\omega_B)}{s+\omega_B+\omega_T}}{R_{id} + R_2 \frac{(s+\omega_B)}{s+\omega_B+\omega_T}} = R_1 + \frac{R_{id} R_2 (s+\omega_B)}{R_{id} (s+\omega_B+\omega_T) + R_2 (s+\omega_B)} \\
Z_{in} &= R_1 + \frac{R_{id} R_2 \omega_B \left(1 + \frac{s}{\omega_B} \right)}{R_{id} \omega_B (1+A_o) + R_2 \omega_B + s(R_{id} + R_2)} = R_1 + \frac{R_{id} \frac{R_2}{(1+A_o)} \left(1 + \frac{s}{\omega_B} \right)}{R_{id} + \frac{R_2}{(1+A_o)} \left(1 + \frac{s}{\omega_B (1+A_o)} \frac{R_{id} + R_2}{R_{id} + \frac{R_2}{(1+A_o)}} \right)} \\
Z_{in} &= R_1 + \left(R_{id} \left\| \frac{R_2}{(1+A_o)} \right\| \right) \frac{\left(1 + \frac{s}{\omega_B} \right)}{1 + \frac{s}{\omega_B (1+A_o)} \frac{R_{id} + R_2}{R_{id} + \frac{R_2}{(1+A_o)}}}
\end{aligned}$$

12.60

Using MATLAB:

```
n1=1e6; d1=[1 2000];  
n2=1e6; d2=[1 4000];  
n3=1e12; d3=[1 6000 8e6];  
w=logspace(2,5);  
[m1,p1,w]=bode(n1,d1,w);  
[m2,p2,w]=bode(n2,d2,w);  
[m3,p3,w]=bode(n3,d3,w);  
subplot(211)  
loglog(w,m1,w,m2,w,m3)  
subplot(212)  
semilogx(w,p1,w,p2,w,p3)
```



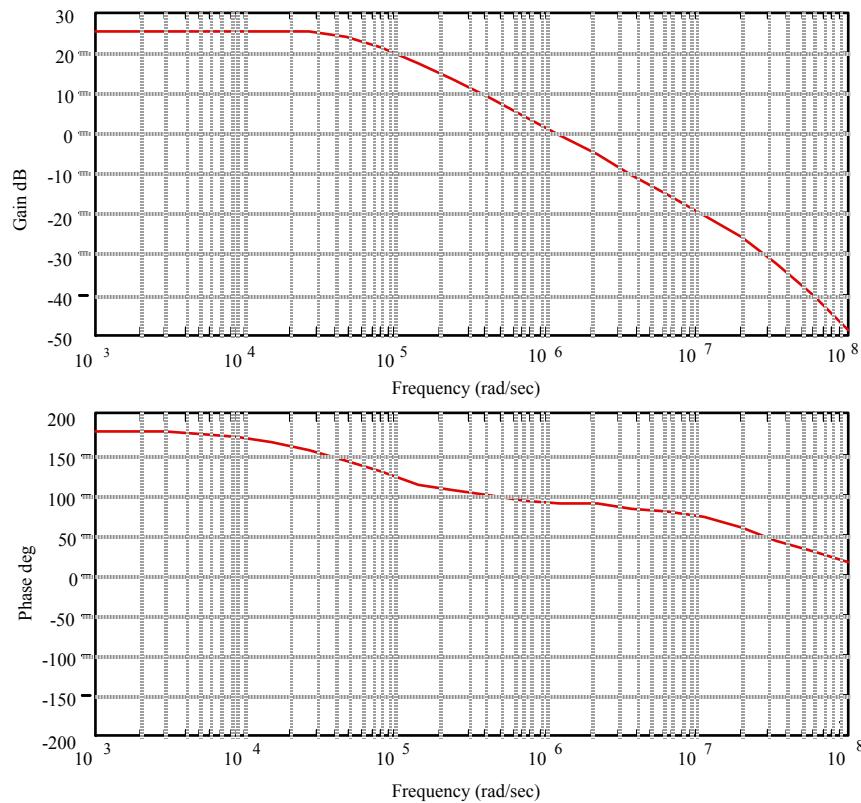
12.61

$$A_v = -\frac{Z_2}{Z_1} \frac{A\beta}{1+A\beta} \quad | \quad \beta = \frac{Z_1}{Z_1 + Z_2} \quad | \quad A = \frac{\omega_T}{s+\omega_o} \quad | \quad Z_1 = R_1 \quad | \quad Z_2 = \frac{R_2}{sCR_2+1}$$

$$A_v(s) = -\frac{\frac{R_2}{R_1} \omega_T}{s^2 R_2 C + s \left(1 + \frac{R_2}{R_1} + R_2 C (\omega_o + \omega_T) \right) + \omega_o \left(1 + \frac{R_2}{R_1} \right) + \omega_T}$$

$$A_v(s) = -\frac{3.653 \times 10^{13}}{s^2 + 3.142 \times 10^7 s + 1.916 \times 10^{12}}$$

Using MATLAB: bode(-3.653e13,[1 3.142e7 1.916e12])



12.62

(a) $\frac{V_s(s)}{R} = -sCV_o(s)$ | $A_v(s) = \frac{V_o(s)}{V_s(s)} = -\frac{1}{sRC}$ which is the transfer function of an integrator

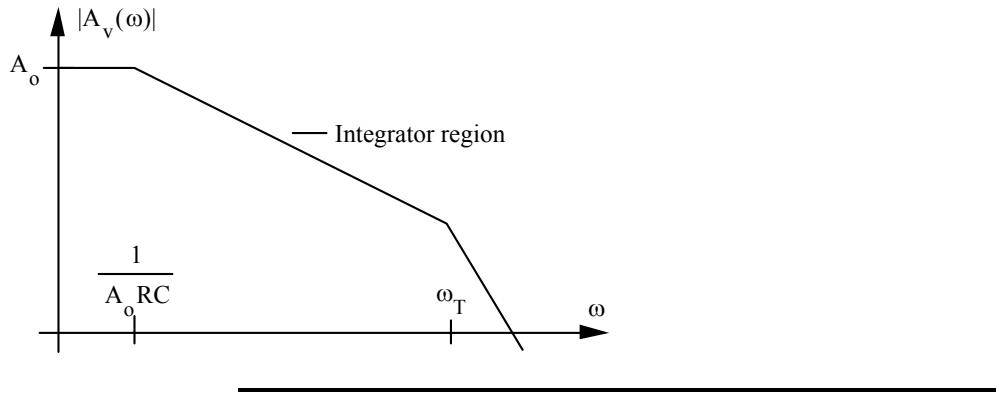
(b) Generalizing Eq. (11.122): $A_v(s) = -\frac{Z_2}{Z_1} \frac{A(s)\beta}{1 + A(s)\beta}$ | $Z_2 = \frac{1}{sC}$ | $Z_1 = R_l$ | $\beta = \frac{Z_1}{Z_1 + Z_2}$

$$\beta = \frac{R_l}{R_l + \frac{1}{sC}} = \frac{sCR}{sCR + 1} \quad | \quad A(s)\beta = \frac{\omega_T}{s + \omega_B} \frac{sRC}{sRC + 1} \quad | \quad A_v(s) = -\frac{1}{sRC} \frac{\frac{\omega_T}{s + \omega_B} \frac{sRC}{sRC + 1}}{1 + \frac{\omega_T}{s + \omega_B} \frac{sRC}{sRC + 1}}$$

$$A_v(s) = -\frac{1}{sRC} \frac{sRC\omega_T}{(s + \omega_B)(sRC + 1) + sRC\omega_T} = -\frac{\omega_T}{(s + \omega_B)(sRC + 1) + sRC\omega_T}$$

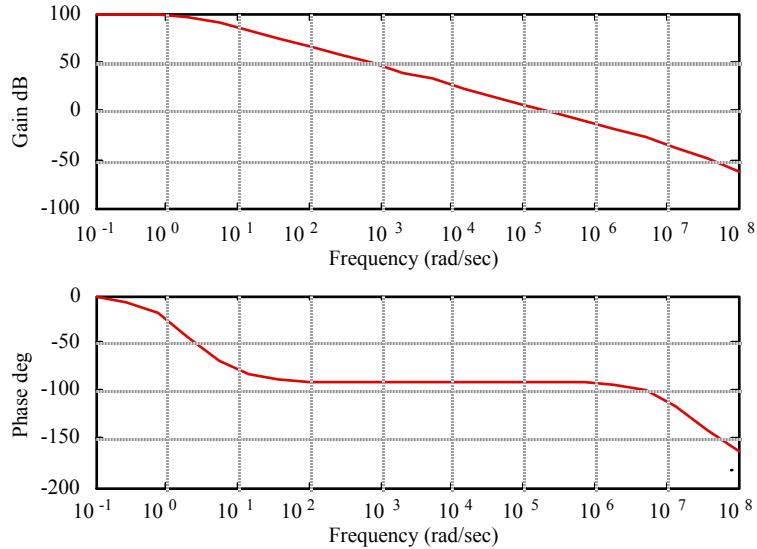
$$A_v(s) = -\frac{\frac{\omega_T}{RC}}{s^2 + s\left(\omega_B + \omega_T + \frac{1}{RC}\right) + \frac{\omega_B}{RC}} \cong -\frac{\frac{\omega_T}{RC}}{(s + \omega_T)\left(s + \frac{\omega_B}{\omega_T RC}\right)} = -\frac{\frac{\omega_T}{RC}}{(s + \omega_T)\left(s + \frac{1}{A_o RC}\right)}$$

using dominant root factorization where it is assumed $\omega_T \gg \omega_B$ and $\omega_T \gg \frac{1}{RC}$.



12.63

```
wrc=1/(1e4*470e-12); wt=2*pi*5e6; wb=2*pi*50;
n=wt*wrc; d=[1 wt+wb+wrc wb*wrc];
bode(n,d)
```

**12.64**

$$\beta = \frac{2k\Omega}{2k\Omega + 40k\Omega} = \frac{1}{21} \quad | \quad A\beta = \frac{10^5}{21} = 4760 \gg 1$$

$$(a) A_v = -\frac{R_2}{R_1} = -\frac{40k\Omega}{2k\Omega} = -20 \quad | \quad f_H = \beta f_T = \frac{3 \times 10^6 \text{ Hz}}{21} = 143 \text{ kHz}$$

$$(b) A_v = (-20)^3 = -8000 \text{ (78 dB)} \quad | \quad f_{H3} = 0.51 f_H = 72.9 \text{ kHz}$$

12.65

The table below follows the approach used in Table 12.6. The only change is the required gain is $A_v = 10^{\frac{85}{20}} = 1.778 \times 10^4$.

Cascade of Identical Non-Inverting Amplifiers					
# of Stages	$A_v(0)$	f_H	f_H	R_{IN}	R_{OUT}
	Gain per Stage	Single Stage	N Stages		
	$1/\beta$	$\beta \times f_T$			
1	2.00E+04	5.00E+01	5.000E+01	6.00E+09	8.33E+00
2	1.41E+02	7.07E+03	4.551E+03	7.08E+11	7.06E-02
3	2.71E+01	3.68E+04	1.878E+04	3.69E+12	1.36E-02
4	1.19E+01	8.41E+04	3.658E+04	8.41E+12	5.95E-03
5	7.25E+00	1.38E+05	5.320E+04	1.38E+13	3.62E-03
6	5.21E+00	1.92E+05	6.717E+04	1.92E+13	2.60E-03
7	4.12E+00	2.43E+05	7.839E+04	2.43E+13	2.06E-03
8	3.45E+00	2.90E+05	8.724E+04	2.90E+13	1.72E-03
9	3.01E+00	3.33E+05	9.415E+04	3.33E+13	1.50E-03
10	2.69E+00	3.71E+05	9.951E+04	3.71E+13	1.35E-03
11	2.46E+00	4.06E+05	1.037E+05	4.06E+13	1.23E-03
12	2.28E+00	4.38E+05	1.068E+05	4.38E+13	1.14E-03

We see from the spreadsheet that a cascade of seven identical stages is required to achieve the bandwidth specification. Fortunately, it also meets the input and output resistance specs. For the non-inverting amplifier cascade:

$$A_v = 1 + \frac{R_2}{R_1} = 4.12 \rightarrow \frac{R_2}{R_1} = 3.12$$

A similar spreadsheet for the cascade of identical inverting amplifiers indicates that it is impossible to meet the bandwidth requirement.

12.66

(a) From Problem 11.99, $A_v = 1 + \frac{R_2}{R_1} = 4.12 \rightarrow \frac{R_2}{R_1} = 3.12$ | Exploring the 5% resistor

tables, we find $R_2 = 62k\Omega$ and $R_1 = 20k\Omega$ yields $\frac{R_2}{R_1} = 3.10$ as a reasonable pair.

The nominal gain of the cascade is then $A_v = (4.10)^7 = 1.948 \times 10^4$.

$A_v = 86db \pm 1dB \Rightarrow 1.778 \times 10^4 \leq A_v \leq 2.239 \times 10^4$ and the gain is well within this range.

Many amplifiers will probably fail due to tolerances with 5% resistors. A Monte Carlo analysis would tell us. If we resort to 1% resistors to limit the tolerance spread,

$R_2 = 30.9 k\Omega$ and $R_1 = 10.0 k\Omega$ is one of many possible pairs.

(b) For $R_2 = 62k\Omega$ and $R_1 = 20k\Omega$, $\beta = \frac{1}{4.1}$ | $f_{H1} = \beta f_T = \frac{5 \times 10^6}{4.1} = 1.22 MHz$

$$f_H = 1.22 MHz \sqrt{2^{\frac{1}{7}} - 1} = 394 kHz$$

12.67/12.68

One possibility: Use a cascade of two non-inverting amplifiers, and shunt the input of the first amplifier to define the input resistance.

60db $\rightarrow A_v = 1000$ | A single - stage amplifier with a gain of 1000 would have a bandwidth of only 5 kHz using this op - amp. Two stages should be sufficient if R_{in} and R_{out} can also be met. A design with $f_{H2} \gg f_{H1}$ will be tried.

First stage : Non - inverting with bandwidth of 20 kHz

$$\beta_1 = \frac{f_{H1}}{f_T} = \frac{20\text{kHz}}{5\text{MHz}} = 0.004 \quad | \quad A_{v1} = \frac{1}{\beta_1} = 250 \rightarrow A_{v2} = 4 \rightarrow \beta_2 = 0.25 \rightarrow f_{H2} = 1.25\text{MHz}$$

Since $f_{H2} \gg f_{H1}$, $f_H = f_{H1} = 20\text{kHz}$. $A_o = 85\text{dB} = 17800$

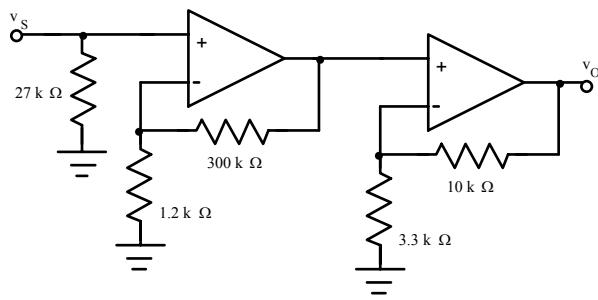
$$\text{Checking } R_{out} = \frac{R_{o2}}{1 + A_o \beta_2} = \frac{100}{1 + 17800(0.25)} = 0.0225\Omega \text{ which is ok.}$$

Choosing resistors from the Appendix, a possible set is

Amplifier 1: $R_1 = 1.2k\Omega$, $R_2 = 300k\Omega$ and shunt the input with $R_3 = 27k\Omega$

Amplifier 2: $R_1 = 3.3k\Omega$, $R_2 = 10k\Omega$

$$\text{Checking gain: } A_v = \frac{17800}{1 + \frac{17800}{251}} \left(\frac{17800}{1 + \frac{17800}{4.03}} \right) = 997.5 = 60.0\text{dB}$$



12.69

```
function sg=Prob103(tol);
sg=0;
for j=1:10
ao=100000; ft=1e6*sqrt(2^(1/6)-1);
for i=1:500,
    r1=22000*(1+2*tol*(rand-0.5));r2=130000*(1+2*tol*(rand-0.5));
    beta=r1/(r1+r2);g1=ao/(1+ao*beta); b1=beta*ft;
    r1=22000*(1+2*tol*(rand-0.5));r2=130000*(1+2*tol*(rand-0.5));
    beta=r1/(r1+r2);g2=ao/(1+ao*beta); b2=beta*ft;
    r1=22000*(1+2*tol*(rand-0.5));r2=130000*(1+2*tol*(rand-0.5));
    beta=r1/(r1+r2);g3=ao/(1+ao*beta); b3=beta*ft;
    r1=22000*(1+2*tol*(rand-0.5));r2=130000*(1+2*tol*(rand-0.5));
    beta=r1/(r1+r2);g4=ao/(1+ao*beta); b4=beta*ft;
    r1=22000*(1+2*tol*(rand-0.5));r2=130000*(1+2*tol*(rand-0.5));
    beta=r1/(r1+r2);g5=ao/(1+ao*beta); b5=beta*ft;
    r1=22000*(1+2*tol*(rand-0.5));r2=130000*(1+2*tol*(rand-0.5));
    beta=r1/(r1+r2);g6=ao/(1+ao*beta); b6=beta*ft;
    gain(i)=g1*g2*g3*g4*g5*g6; bw(i)=(b1+b2+b3+b4+b5+b6)/6;
end;
sg=sg+sum(gain<1e5 | bw<5e4);
end;
end
```

(a) For 5000 test cases with tol = 0.05, 33.5% of the amplifiers failed to meet either the gain or bandwith requirement.

(b) For 10000 test cases with tol = 0.015, 0.1% of the amplifiers failed to meet either the gain or bandwith requirement.

12.70

$$(a) \left(\frac{1}{\beta}\right)^N = G \rightarrow \beta = \frac{1}{G^{\frac{1}{N}}} \quad | \quad f_{H1} = \beta f_T \quad | \quad f_H = \frac{f_T}{G^{\frac{1}{N}}} \sqrt{2^{\frac{1}{N}} - 1} \quad | \quad \frac{f_H}{f_T} = \frac{\sqrt{2^{\frac{1}{N}} - 1}}{G^{\frac{1}{N}}} = \frac{(2^z - 1)^{\frac{1}{2}}}{G^z} \text{ for } Z = \frac{1}{N}$$

$$\text{For } 2^z = e^{z \ln 2} \text{ and } G^z = e^{z \ln G}: \quad \frac{d}{dz} \left(\frac{f_H}{f_T} \right) = \frac{G^z \left[\frac{1}{2} (2^z - 1)^{\frac{1}{2}} 2^z \ln 2 \right] - (2^z - 1)^{\frac{1}{2}} G^z \ln G}{G^{2z}}$$

$$\text{Setting } \frac{d}{dz} \left(\frac{f_H}{f_T} \right) = 0 \rightarrow G^z \left[\frac{1}{2} (2^z - 1)^{\frac{1}{2}} 2^z \ln 2 \right] - (2^z - 1)^{\frac{1}{2}} G^z \ln G = 0 \rightarrow 2^z \ln 2 = 2(2^z - 1) \ln G$$

$$2^z = -\frac{2 \ln G}{\ln 2 - 2 \ln G} \rightarrow Z \ln 2 = \ln \left(-\frac{2 \ln G}{\ln 2 - 2 \ln G} \right)$$

$$Z = \frac{\ln \left(-\frac{\ln G}{\ln G - \ln \sqrt{2}} \right)}{\ln 2} \rightarrow N_{opt} = \frac{\ln 2}{\ln \left(\frac{\ln G}{\ln G - \ln \sqrt{2}} \right)}$$

$$(b) N_{opt} = \frac{\ln 2}{\ln \left(\frac{\ln 10^5}{\ln 10^5 - \ln \sqrt{2}} \right)} = 22.7 \text{ which agrees with the spreadsheet in Table 12.8}$$

$$f_{Hopt} = 106.0 \text{ kHz}$$

12.71

$$\beta_{nom} = \frac{22k\Omega}{22k\Omega + 130k\Omega} = \frac{1}{6.91} \quad A\beta = \frac{5 \times 10^4}{6.91} = 7240 \gg 1$$

$$(a) A_v^{nom} = 1 + \frac{R_2}{R_1} = 1 + \frac{130k\Omega}{22k\Omega} = 6.91$$

$$A_v^{\max} = 1 + \frac{R_2}{R_1} = 1 + \frac{130k\Omega(1.05)}{22k\Omega(0.95)} = 7.53 \quad | \quad A_v^{\min} = 1 + \frac{R_2}{R_1} = 1 + \frac{130k\Omega(0.95)}{22k\Omega(1.05)} = 6.35$$

$$f_H^{nom} = \beta_{nom} f_T = \frac{10^6 \text{ Hz}}{6.91} = 145 \text{ kHz} \quad | \quad f_H^{\max} = \frac{10^6 \text{ Hz}}{6.35} = 157 \text{ kHz} \quad | \quad f_H^{\min} = \frac{10^6 \text{ Hz}}{7.53} = 133 \text{ kHz}$$

12.72

```
function [gain,bw]=Prob1272a
ao=50000; ft=1e6;
for i=1:500,
    r1=22000*(1+0.1*(rand-0.5));
    r2=130000*(1+0.1*(rand-0.5));
    beta=r1/(r1+r2);
    gain(i)=ao/(1+ao*beta); bw(i)=beta*ft;
end;
end

[gain,bw]=prob1272a;
mean(gain)    ans = 6.9140    std(gain)      ans = 0.2339
mean(bw)      ans = 1.4478e+05   std(bw)       ans = 4.8969e+03
```

Three sigma limits: $6.21 \leq A_V \leq 7.62$ $130 \text{ kHz} \leq BW \leq 159 \text{ kHz}$

```
function [gain,bw]=Prob1272b
for i=1:500,
    ao=100000*(1+1.0*(rand-0.5));
    ft=2e6*(1+1.0*(rand-0.5));
    r1=22000*(1+0.1*(rand-0.5));
    r2=130000*(1+0.1*(rand-0.5));
    beta=r1/(r1+r2);
    gain(i)=ao/(1+ao*beta); bw(i)=beta*ft;
end;
end
```

```
[gain,bw]=prob1272b;
mean(gain)    ans = 6.9201    std(gain)      ans = 0.2414
mean(bw)      ans = 2.8925e+05   std(bw)       ans = 8.5536e+04
```

Note that the bandwidth is essentially a uniform distribution.

3σ : $6.20 \leq A_V \leq 7.64$ 98.9% of the values fall between: $146 \text{ kHz} \leq BW \leq 439 \text{ kHz}$

12.73

$$SR \geq V_o \omega = (15V)(2\pi)(2 \times 10^4 \text{ Hz}) = 1.89 \times 10^6 \frac{V}{s} \text{ or } 1.89 \frac{V}{\mu s}$$

12.74

$$f = \frac{SR}{2\pi V_o} = \frac{10V}{10^{-6}s} \frac{1}{20\pi V} = 159 \text{ kHz}$$

12.75

The negative transition requires the largest slew rate : $SR = \frac{\Delta V}{\Delta t} = \frac{20V}{2\mu s} = 10 \frac{V}{\mu s}$

12.76

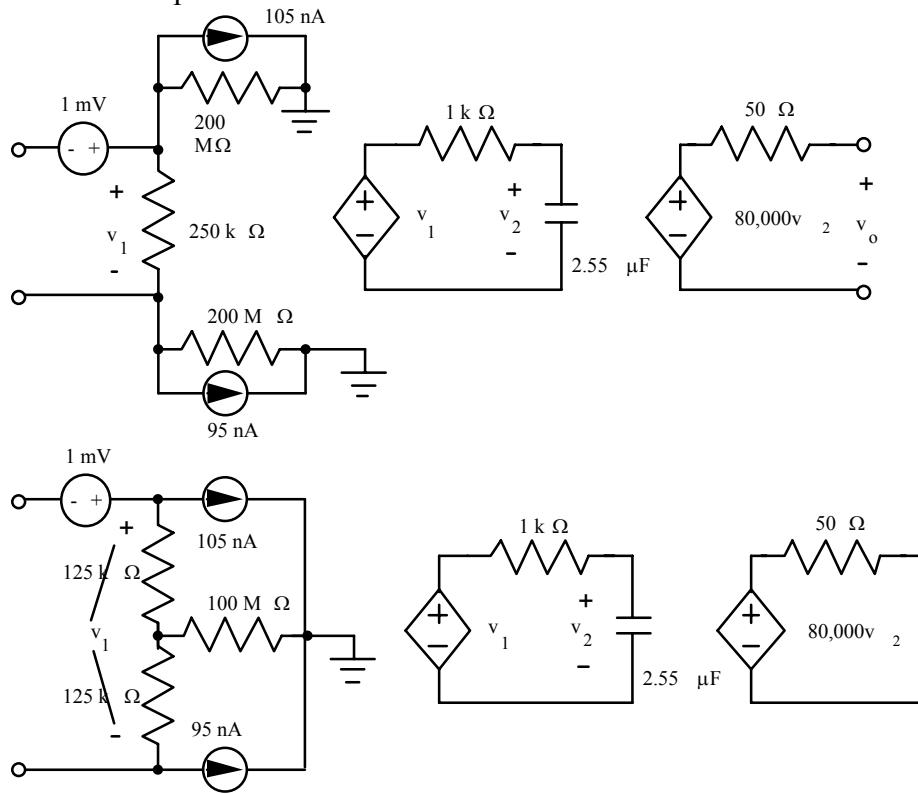
(a) For the circuit in Fig. 12.26: $R_{id} = 250 k\Omega$ | $R = 1 k\Omega$ – an arbitrary choice

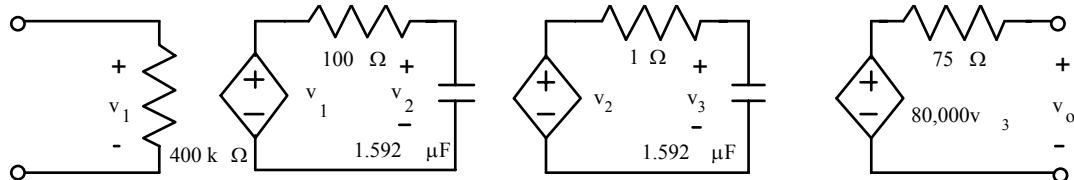
$$\omega_B = \frac{2\pi(5 \times 10^6)}{8 \times 10^4} = 125\pi \text{ rad/s} \quad | \quad C = \frac{1}{\omega_B R} = \frac{1}{(125\pi)1000} = 2.55 \mu F \quad | \quad R_o = 50\Omega \quad | \quad A_o = 80,000$$

(b) Add a resistor from each input terminal to ground of value $2R_{IC} = 1 G\Omega$.

See Prob. 11.111 for schematics.

12.77 Two possibilities:



12.78

$$\omega_1 : C = \frac{1}{\omega_1 R_1} = \frac{1}{2\pi(10^3)(100)} = 1.592 \mu F \text{ -- setting } R_1 \text{ arbitrarily to } 100 \Omega.$$

$$\omega_2 : R_2 = \frac{1}{\omega_2 C} = \frac{1}{2\pi(10^5)(1.592 \mu F)} = 1 \Omega \text{ -- Using the same value of } C.$$

12.79

*PROBLEM 12.79 - Six-Stage Amplifier

VS 1 0 AC 1

XA1 1 2 0 AMP

XA2 2 3 0 AMP

XA3 3 4 0 AMP

XA4 4 5 0 AMP

XA5 5 6 0 AMP

XA6 6 7 0 AMP

.SUBCKT AMP 1 2 7

RID 1 3 1E9

RO 6 2 50

E2 6 7 5 7 1E5

E1 4 7 1 3 1

R 4 5 1K

C 5 7 15.915UF

R2 2 3 130K

R1 3 7 22K

.ENDS

.TF V(7) VS

.AC DEC 40 1 1MEG

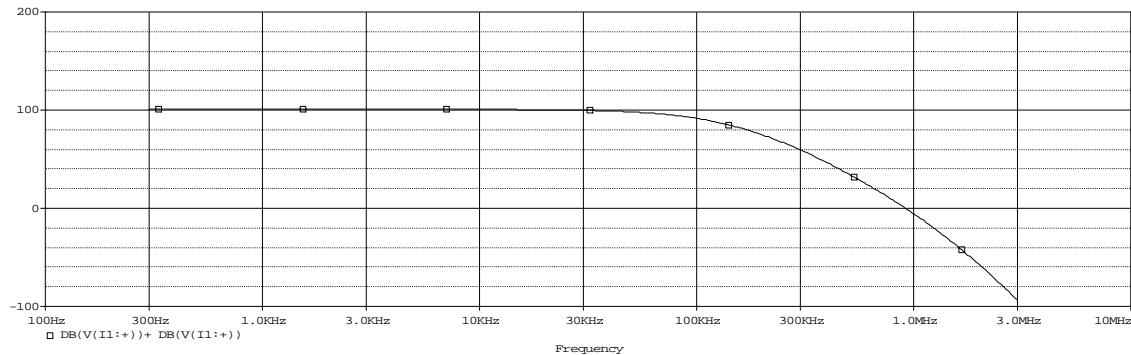
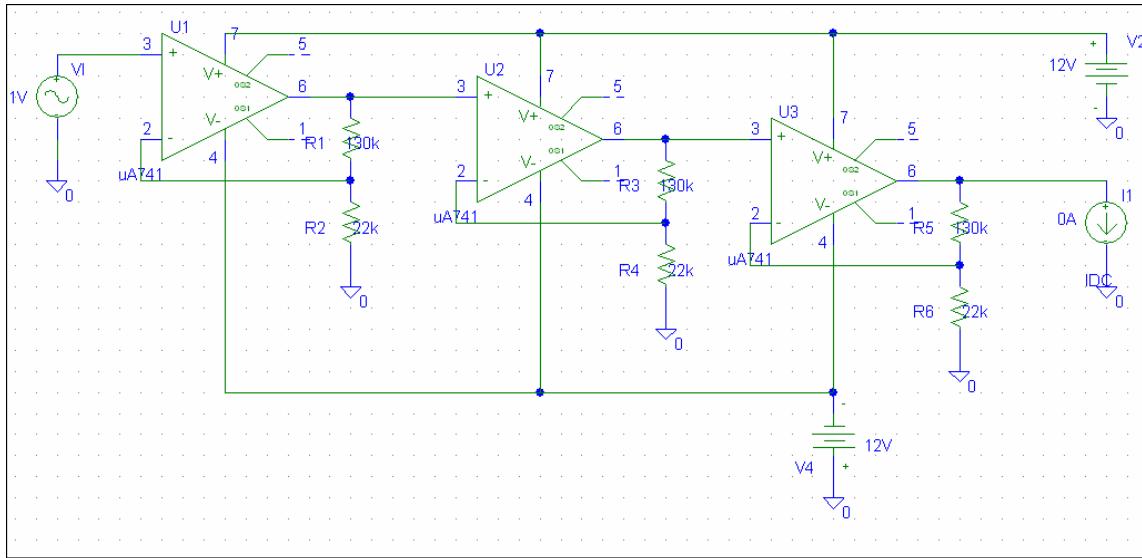
.PRINT AC V(1) V(2) V(3) V(4) V(5) V(6) V(7)

.PROBE V(1) V(2) V(3) V(4) V(5) V(6) V(7)

.END

12.80

Student PSPICE cannot handle 6 copies of the uA741 op amp, but since all the stages are the same, we can square the output from a 3-stage version or cube the output from a two-stage model.



From the SPICE graph, BW = 54.3 kHz.

12.81

*PROBLEM 12.81 - Six Stage Amplifier

VS 1 0 AC 1
XA1 1 2 0 AMP
XA2 2 3 0 AMP
XA3 3 4 0 AMP
XA4 4 5 0 AMP
XA5 5 6 0 AMP
XA6 6 7 0 AMP
.SUBCKT AMP 1 2 8
 RID 1 3 1E9
 RO 7 2 50
 E2 7 8 6 8 1E5
 *Two dummy loops provide separate control of Gain & BW tolerances
 G1 8 4 1 3 .001
 R11 4 8 RG 1000
 E1 5 8 4 8 1
 RC 5 6 1000
 C 6 8 CC 15.915UF
 *
 R2 2 3 RR 130K
 R1 3 8 RR 22K
.ENDS
.MODEL RR RES (R=1 DEV=5%)
.MODEL RG RES (R=1 DEV=50%)
.MODEL CC CAP (C=1 DEV=50%)
.AC DEC 20 1E3 1E6
.PROBE V(7)
.PRINT AC V(7)
.MC 1000 AC V(7) MAX OUTPUT(EVERY 20)
*.MC 1000 AC V(7) MAX OUTPUT(RUNS 77 573 597 777)
.END

Maximum gain = 103 dB; Minimum gain = 98.5 dB

Maximum Bandwidth = 65 kHz; Minimum bandwidth = 38 kHz (These are approximate.)

12.82

$$R_{id} = 10^{10} \Omega \quad C = \frac{1}{2\pi(1000\Omega)(20\text{MHz})} = 7.96 \text{ pF} \quad A = 4 \times 10^6 \quad R_o \text{ not specified}$$

12.83

$A \geq 118 \text{ dB}$ $\text{CMRR} \geq 80 \text{ dB}$ $\text{PSRR} \geq 100 \text{ dB}$ $V_{os} \leq 1.5 \text{ mV}$

$I_B \leq 8.8 \text{ nA}$ $I_{os} \leq 2.2 \text{ nA}$ Power Supplies $\pm 18 \text{ V}$ maximum

Nominal values only : $R_{id} = 10^{10} \Omega$ $\text{SR} = 12.5 \text{ V}/\mu\text{s}$ nominal $f_T = 20 \text{ MHz}$

12.84

(a) Use the expressions in Tables 12.1 and 12.2.

$$A = 10^{\frac{100}{20}} = 10^5 \quad | \quad \beta_A = \frac{47k\Omega}{47k\Omega + 470k\Omega} = \frac{1}{11} \quad | \quad \beta_B = \frac{15k\Omega}{15k\Omega + 150k\Omega} = \frac{1}{11} \quad | \quad \beta_C = \frac{18k\Omega}{18k\Omega + 270k\Omega} = \frac{1}{16}$$

$$A_{vA} = -\frac{R_2}{R_1} \left(\frac{A\beta}{1+A\beta} \right) = -\frac{470k\Omega}{47k\Omega} \frac{\frac{10^5}{11}}{1+\frac{10^5}{11}} = -10.0 \quad A_{vB} = -\frac{R_2}{R_1} \left(\frac{A\beta}{1+A\beta} \right) = -\frac{150k\Omega}{15k\Omega} \frac{\frac{10^5}{11}}{1+\frac{10^5}{11}} = -10.0$$

$$A_{vC} = -\frac{R_2}{R_1} \left(\frac{A\beta}{1+A\beta} \right) = -\frac{270k\Omega}{18k\Omega} \frac{\frac{10^5}{16}}{1+\frac{10^5}{16}} = -15.0 \quad A_v = -10.0^2 (-15) = -1500$$

$$R_{in} = R_{inA} = R_1 + \left(R_{id} \parallel \frac{R_2}{1+A} \right) = 47k\Omega + 1M\Omega \parallel \frac{470k\Omega}{1+10^5} = 47.0 \text{ k}\Omega$$

$$R_{out} = R_{outC} = \frac{R_o}{1+A\beta} = \frac{250\Omega}{1+\frac{10^5}{16}} = 40.0 \text{ m}\Omega$$

$$f_{HA} = f_{HB} = \beta_A f_T = \frac{2 \text{ MHz}}{11} = 182 \text{ kHz} \quad f_{HC} = \beta_C f_T = \frac{2 \text{ MHz}}{16} = 125 \text{ kHz}$$

For the overall amplifier : $A_v = -1500 \quad | \quad R_{in} = 47.0 \text{ k}\Omega \quad | \quad R_{out} = 40.0 \text{ m}\Omega$

Using the definition of bandwidth :

$$\sqrt{\frac{10}{1+\left(\frac{f_H}{182 \text{ kHz}}\right)^2}} \sqrt{\frac{10}{1+\left(\frac{f_H}{182 \text{ kHz}}\right)^2}} \sqrt{\frac{15}{1+\left(\frac{f_H}{125 \text{ kHz}}\right)^2}} = \frac{1500}{\sqrt{2}} \rightarrow f_H = 79.9 \text{ kHz}$$

$$(b) v_s = 50.0 \text{ mV} \quad | \quad v_{OA} = -10v_s = -500 \text{ mV} \quad | \quad v_{OB} = -10v_{OA} = +5.00 \text{ V} \quad |$$

$$v_o = -15v_{OB} = -75.0 \text{ V} > 18 \text{ V} \rightarrow v_o = -18 \text{ V} \quad | \quad v_{-A} = \frac{v_{OA}}{-10^5} = +5.00 \mu\text{V} \quad | \quad v_{-B} = \frac{v_{OB}}{-10^5} = -50.0 \mu\text{V}$$

The output of the third amplifier is saturated at -18 V, and the inverting input is no longer near

$$\text{ground potential. Using superposition, } v_{-C} = 5V \frac{270k\Omega}{18k\Omega + 270k\Omega} + (-18V) \frac{18k\Omega}{18k\Omega + 270k\Omega} = +3.56 \text{ V}$$

The remaining three nodes are $V_+ = +18 \text{ V}$ $V_- = -18 \text{ V}$ and $V_{gnd} = 0 \text{ V}$.

12.85

$$A = 10^{\frac{100}{20}} = 10^5 \quad | \quad \beta_A = \frac{47k\Omega}{47k\Omega + 470k\Omega} = \frac{1}{11} \quad | \quad \beta_B = \frac{15k\Omega}{15k\Omega + 150k\Omega} = \frac{1}{11}$$

$$\beta_C = \frac{18k\Omega}{18k\Omega + 270k\Omega} = \frac{1}{16} \quad A\beta >> 1 \quad A_v^{nom} \cong \left(-\frac{470k\Omega}{47k\Omega} \right) \left(-\frac{150k\Omega}{15k\Omega} \right) \left(-\frac{270k\Omega}{18k\Omega} \right) = -1500$$

$$A_v^{\max} \cong -1500 \left(\frac{1.05}{0.95} \right)^3 = -2025 \quad A_v^{\min} \cong -1500 \left(\frac{0.95}{1.05} \right)^3 = -1111 \quad R_{in}^{nom} \cong R_{inA}^{nom} = 47.0 \text{ k}\Omega$$

$$R_{in}^{\max} \cong R_{inA}^{\max} = 47.0 \text{ k}\Omega (1.05) = 49.4 \text{ k}\Omega \quad R_{in}^{\min} \cong R_{inA}^{\min} = 47.0 \text{ k}\Omega (0.95) = 44.7 \text{ k}\Omega$$

$$R_{out}^{nom} \cong R_{outC}^{nom} = \frac{R_o}{1 + A\beta} = \frac{250\Omega}{1 + \frac{10^5}{16}} = 40.0 \text{ m}\Omega$$

$$R_{out}^{\max} \cong R_{outC}^{\max} = \frac{R_o}{1 + A\beta^{\min}} = \frac{250\Omega}{1 + \frac{10^5}{17.6}} = 43.9 \text{ m}\Omega \quad R_{out}^{\min} \cong R_{outC}^{\min} = \frac{R_o}{1 + A\beta^{\max}} = \frac{250\Omega}{1 + \frac{10^5}{14.6}} = 36.4 \text{ m}\Omega$$

$$f_{HA} = f_{HB} = \beta_A f_T = \frac{2 \text{ MHz}}{11} = 182 \text{ kHz} \quad f_{HC} = \beta_C f_T = \frac{2 \text{ MHz}}{16} = 125 \text{ kHz}$$

Using the definition of bandwidth :

$$\frac{10}{\sqrt{1 + \left(\frac{f_H}{182 \text{ kHz}} \right)^2}} \frac{10}{\sqrt{1 + \left(\frac{f_H}{182 \text{ kHz}} \right)^2}} \frac{15}{\sqrt{1 + \left(\frac{f_H}{125 \text{ kHz}} \right)^2}} = \frac{1500}{\sqrt{2}} \rightarrow f_H = 79.8 \text{ kHz}$$

$$f_{HA}^{\max} = f_{HB}^{\max} = \beta_A f_T = \frac{2 \text{ MHz}}{10.0} = 200 \text{ kHz} \quad f_{HC} = \beta_C f_T = \frac{2 \text{ MHz}}{14.6} = 137 \text{ kHz}$$

$$\frac{9.048}{\sqrt{1 + \left(\frac{f_H^{\max}}{200 \text{ kHz}} \right)^2}} \frac{9.048}{\sqrt{1 + \left(\frac{f_H^{\max}}{200 \text{ kHz}} \right)^2}} \frac{13.57}{\sqrt{1 + \left(\frac{f_H^{\max}}{137 \text{ kHz}} \right)^2}} = \frac{1111}{\sqrt{2}} \rightarrow f_H^{\max} = 87.5 \text{ kHz}$$

$$f_{HA}^{\max} = f_{HB}^{\max} = \beta_A f_T = \frac{2 \text{ MHz}}{12.0} = 167 \text{ kHz} \quad f_{HC} = \beta_C f_T = \frac{2 \text{ MHz}}{17.6} = 114 \text{ kHz}$$

$$\frac{11.05}{\sqrt{1 + \left(\frac{f_H^{\max}}{167 \text{ kHz}} \right)^2}} \frac{11.05}{\sqrt{1 + \left(\frac{f_H^{\max}}{167 \text{ kHz}} \right)^2}} \frac{16.58}{\sqrt{1 + \left(\frac{f_H^{\max}}{114 \text{ kHz}} \right)^2}} = \frac{2025}{\sqrt{2}} \rightarrow f_H^{\max} = 73.0 \text{ kHz}$$

12.86

(a) Use the expressions in Tables 12.1 and 12.2. Three identical gain blocks.

$$A = 10^{\frac{106}{20}} = 2.00 \times 10^5 \quad | \quad \beta = \frac{3k\Omega}{3k\Omega + 39k\Omega} = \frac{1}{14} \quad | \quad A\beta = 14286 \quad | \quad A_{vl} = \frac{A}{1 + A\beta} = 14.0$$

$$A_v = 14.0^3 = 2744$$

$$R_{in} = R_{inA} = 1M\Omega \parallel R_{id}(1 + A\beta) = 1M\Omega \parallel 500k\Omega(1 + 14286) = 1.00 M\Omega$$

$$R_{out} = R_{outC} = \frac{R_o}{1 + A\beta} = \frac{300\Omega}{1 + 14286} = 21.0 m\Omega$$

$$f_{H1} = \beta_A f_T = \frac{5MHz}{14} = 357kHz \quad f_H = f_{H1} \sqrt{2^{\frac{1}{3}} - 1} = 182kHz$$

For the overall amplifier : $A_v = +2740 \quad | \quad R_{in} = 1.00 M\Omega \quad | \quad R_{out} = 21.0 m\Omega \quad | \quad f_H = 182kHz$

(b) $v_I = 5.00 mV \quad | \quad v_{OA} = 14v_I = 70.0 mV \quad | \quad v_{OB} = 14v_{OA} = 980 mV \quad |$

$$v_O = 14v_{OB} = 13.7V > 12V \rightarrow v_O = 12.0 V \quad | \quad v_{-A} = \frac{v_{OA}}{14} = +5.00 mV \quad | \quad v_{-B} = \frac{v_{OB}}{14} = 70.0 mV$$

The output of the third amplifier is saturated at 12 V, and the inverting and non-inverting inputs are no longer equal. $v_{-C} = 12V \frac{3k\Omega}{3k\Omega + 39k\Omega} = 0.857 V. \quad V_+ = +12 V \quad V_- = -12 V \quad V_{gnd} = 0 V$

12.87

(a) Use the expressions in Tables 12.1 and 12.2. Three identical gain blocks.

$$A = 10^{\frac{106}{20}} = 2.00 \times 10^5 \quad | \quad \beta = \frac{1.5k\Omega}{1.5k\Omega + 39k\Omega} = \frac{1}{27} \quad | \quad A\beta = 7407 \quad | \quad A_{vl} = \frac{A}{1 + A\beta} = 27.0$$

$$A_v = 27.0^3 = 19700$$

$$R_{in} = R_{inA} = 1.5M\Omega \parallel R_{id}(1 + A\beta) = 1.5M\Omega \parallel 500k\Omega(1 + 14286) = 1.50 M\Omega$$

$$R_{out} = R_{outC} = \frac{R_o}{1 + A\beta} = \frac{300\Omega}{1 + 7407} = 38.8 m\Omega$$

$$f_{H1} = \beta_A f_T = \frac{5MHz}{27} = 185kHz \quad f_H = f_{H1} \sqrt{2^{\frac{1}{3}} - 1} = 94.3kHz$$

For the overall amplifier : $A_v = +19700 \quad | \quad R_{in} = 1.50 M\Omega \quad | \quad R_{out} = 38.8 m\Omega \quad | \quad f_H = 94.3 kHz$

(b) $v_I = 5.00 mV \quad | \quad v_{OA} = 27v_I = 135 mV \quad | \quad v_{OB} = 27v_{OA} = 3.65 V \quad |$

$$v_O = 27v_{OB} = 98.4V > 12V \rightarrow v_O = 12.0 V \quad | \quad v_{-A} = \frac{v_{OA}}{27} = +5.00 mV \quad | \quad v_{-B} = \frac{v_{OB}}{27} = 135 mV$$

The output of the third amplifier is saturated at 12 V, and the inverting and non-inverting inputs are no longer equal. $v_{-C} = 12V \frac{1.5k\Omega}{1.5k\Omega + 39k\Omega} = 0.444 V. \quad V_+ = +12 V \quad V_- = -12 V \quad V_{gnd} = 0 V$

12.88

Three identical stages: $\beta_{nom} = \frac{3k\Omega}{3k\Omega + 39k\Omega} = \frac{1}{14}$ $A\beta = \frac{2 \times 10^5}{14} = 14286 >> 1$

$$A_v^{nom} = \left(1 + \frac{R_2}{R_1}\right)^3 = \left(1 + \frac{39k\Omega}{3k\Omega}\right)^3 = 2740$$

$$A_v^{\max} = \left[1 + \frac{39k\Omega(1.02)}{3k\Omega(0.98)}\right]^3 = 3070 \quad | \quad A_v^{\min} = \left[1 + \frac{39k\Omega(0.98)}{3k\Omega(1.02)}\right]^3 = 2460$$

$$R_{in}^{nom} = 1 M\Omega \quad | \quad R_{in}^{\max} = 1 M\Omega(1.02) = 1.02 M\Omega \quad | \quad R_{in}^{\min} = 1 M\Omega(0.98) = 980 k\Omega$$

$$R_{out}^{nom} = \frac{300}{1 + 14286} = 21.0 M\Omega \quad | \quad R_{out}^{\max} = \frac{300}{1 + \frac{2 \times 10^5}{14.53}} = 21.8 M\Omega \quad | \quad R_{out}^{\min} = \frac{300}{1 + \frac{2 \times 10^5}{13.49}} = 20.2 M\Omega$$

$$f_H^{nom} = \beta_{nom} f_T = \frac{5 MHz}{14} = 357 kHz \quad | \quad f_H^{\max} = \frac{5 MHz}{13.49} = 371 kHz \quad | \quad f_H^{\min} = \frac{5 MHz}{14.53} = 344 kHz$$

12.89

(a) Use the expressions in Tables 12.1 and 12.2.

$$A = 10^{20} = 10^4 \quad | \quad \beta_A = \frac{10k\Omega}{10k\Omega + 39k\Omega} = \frac{1}{4.9} \quad | \quad \beta_B = \frac{2k\Omega}{2k\Omega + 200k\Omega} = \frac{1}{101} \quad | \quad \beta_C = \frac{10k\Omega}{10k\Omega + 39k\Omega} = \frac{1}{4.9}$$

$$A_{vC} = A_{vA} = \frac{A}{1 + A\beta} = \frac{10000}{1 + \frac{10000}{4.9}} = +4.90 \quad A_{vB} = -\frac{R_2}{R_1} \left(\frac{A\beta}{1 + A\beta} \right) = -\frac{200k\Omega}{2k\Omega} \frac{\frac{10^4}{101}}{1 + \frac{10^4}{101}} = -99.0$$

$$A_v = 4.90^2 (-99.0) = -2380 \quad R_{in} = R_{inA} = R_{id}(1 + A\beta) = 300k\Omega \left(1 + \frac{10000}{4.9} \right) = 613 M\Omega$$

$$R_{out} = R_{outC} = \frac{R_o}{1 + A\beta} = \frac{250\Omega}{1 + \frac{10^4}{4.9}} = 98.0 m\Omega$$

$$f_{HC} = f_{HA} = \beta_A f_T = \frac{3MHz}{4.9} = 612kHz \quad f_{HC} = \beta_C f_T = \frac{3MHz}{101} = 29.7kHz$$

For the overall amplifier : $A_v = -2380 \quad | \quad R_{in} = 613 M\Omega \quad | \quad R_{out} = 98.0 m\Omega$

Using the definition of bandwidth :

$$\sqrt{\frac{4.9}{1 + \left(\frac{f_H}{612kHz} \right)^2}} \sqrt{\frac{99}{1 + \left(\frac{f_H}{29.7kHz} \right)^2}} \sqrt{\frac{4.9}{1 + \left(\frac{f_H}{612kHz} \right)^2}} = \frac{2380}{\sqrt{2}} \rightarrow f_H = 29.6 kHz$$

Note that the bandwidth is controlled by amplifier B because it's bandwidth is much smaller than the others.

$$(b) v_I = 00.0 mV \quad | \quad v_{OA} = 4.9v_{OS} = +49.0 mV \quad | \quad v_{OB} = -100v_{OA} + 101(10mV) = -3.89V \quad |$$

$$v_O = 4.9(v_{OB} + .010) = -19.0V < -15V \rightarrow v_O = -15 V \quad | \quad v_{-A} = \frac{v_{OA}}{4.9} = 10.0 mV \quad | \quad v_{-B} = \frac{v_{OB}}{-10^4} = +389 \mu V$$

$$v_{-C} = -\frac{15V}{4.9} = -3.06 V \quad \text{The remaining three nodes are } V_+ = +15 V \quad V_- = -15 V \quad \text{and } V_{gnd} = 0 V.$$

12.90

$$A = 10^{\frac{80}{20}} = 10^4 \quad | \quad \beta_C = \beta_A = \frac{10k\Omega}{10k\Omega + 39k\Omega} = \frac{1}{4.9} \quad | \quad \beta_B = \frac{2k\Omega}{2k\Omega + 200k\Omega} = \frac{1}{101}$$

$$A\beta \gg 1 \quad A_v^{nom} \cong \left(1 + \frac{39k\Omega}{10k\Omega}\right)^2 \left(-\frac{200k\Omega}{2k\Omega}\right) = -2401$$

$$A_v^{\max} \cong \left(1 + \frac{39k\Omega}{10k\Omega} \left(\frac{1.10}{0.90}\right)\right)^2 \left(-\frac{200k\Omega}{2k\Omega} \left(\frac{1.10}{0.90}\right)\right) = -4064$$

$$A_v^{\min} \cong \left(1 + \frac{39k\Omega}{10k\Omega} \left(\frac{0.90}{1.10}\right)\right)^2 \left(-\frac{200k\Omega}{2k\Omega} \left(\frac{0.90}{1.10}\right)\right) = -1437$$

$$R_{in}^{nom} = R_{id}(1 + A\beta) = 300k\Omega \left[1 + 10^4 \left(\frac{1}{4.9}\right)\right] = 612 M\Omega$$

$$R_{in}^{\max} = 300k\Omega \left[1 + 10^4 \left(\frac{1}{4.19}\right)\right] = 716 M\Omega \quad R_{in}^{\min} = 300k\Omega \left[1 + 10^4 \left(\frac{1}{5.77}\right)\right] = 521 M\Omega$$

$$R_{out}^{nom} \cong R_{outC}^{nom} = \frac{R_o}{1 + A\beta} = \frac{200\Omega}{1 + \frac{10^4}{4.9}} = 98.0 m\Omega$$

$$R_{out}^{\max} \cong R_{outC}^{\max} = \frac{R_o}{1 + A\beta^{\min}} = \frac{200\Omega}{1 + \frac{10^4}{5.77}} = 115 m\Omega \quad R_{out}^{\min} \cong R_{outC}^{\min} = \frac{R_o}{1 + A\beta^{\max}} = \frac{200\Omega}{1 + \frac{10^4}{4.19}} = 83.4 m\Omega$$

$$f_{HA} = f_{HB} = \beta_A f_T = \frac{3 MHz}{4.9} = 612 kHz \quad f_{HC} = \beta_B f_T = \frac{3 MHz}{101} = 29.7 kHz$$

The bandwidth is controlled by the narrow bandwidth stage.

$$f_H^{nom} = 29.7 kHz \quad f_H^{\min} = \beta_B^{\min} f_T = \frac{3 MHz}{123} = 24.3 kHz \quad f_H^{\max} = \beta_B^{\max} f_T = \frac{3 MHz}{82.8} = 36.2 kHz$$

CHAPTER 13

13.1

Assuming linear operation : $v_{BE} = 0.700 + 0.005 \sin 2000\pi t$ V

$$v_{ce} = \left[\left(\frac{5mV}{8mV} \right) (-1.65V) \right] \sin 2000\pi t = -1.03 \sin 2000\pi t$$
 V

$$v_{CE} = 5.00 - 1.03 \sin 2000\pi t$$
 V; $10 - 3300I_C \geq 0.700 \rightarrow I_C \leq 2.82$ mA

13.2

Assuming linear region operation :

$$v_{GS} = 3.50 + 0.25 \sin 2000\pi t$$
 V

$$v_{ds} = \left[\left(\frac{0.25V}{0.50V} \right) (-2V) \right] \sin 2000\pi t = -1.00 \sin 2000\pi t$$
 V

$$v_{DS} = 4.80 - 1.00 \sin 2000\pi t$$
 V

$$v_{DS} \geq v_{GS} - V_{TN} \rightarrow 10 - 3300I_D - 1.00 \sin 2000\pi t \geq 3.50 + 0.25 \sin 2000\pi t - 1$$

$$\text{For } \sin 2000\pi t = 1, I_D \leq \frac{10 - 1 - 3.5 - 0.25 + 1}{3300} \frac{V}{\Omega} = 1.89$$
 mA

13.3

(a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a coupling capacitor that couples the ac component of the signal at the collector to the output v_O . C_3 is a bypass capacitor. (b) The signal voltage at the top of resistor R_4 will be zero.

13.4

(a) C_1 is a bypass capacitor. C_2 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_3 is a coupling capacitor that couples the ac component of the signal at the collector to output v_O . (b) The signal voltage at the base will be $v_b = 0$.

13.5

(a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a bypass capacitor. C_3 is a coupling capacitor that couples the ac component of the signal at the collector to output v_O . (b) The signal voltage at the emitter will be $v_e = 0$.

13.6

(a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a bypass capacitor. C_3 is a coupling capacitor that couples the ac component of the signal at the drain to output v_O . (b) The signal voltage at the source will be $v_s = 0$.

13.7

(a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a coupling capacitor that couples the ac component of the signal at the drain to output v_O .

13.8

(a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a bypass capacitor. C_3 is a coupling capacitor that couples the ac component of the signal at the drain to output v_O . (b) The signal voltage at the source will be $v_S = 0$.

13.9

(a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a bypass capacitor. C_3 is a coupling capacitor that couples the ac component of the signal at the collector to output v_O . (b) The signal voltage at the emitter will be $v_E = 0$.

13.10

(a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a coupling capacitor that couples the signal from the emitter of Q_1 back to the node joining R_1 and R_2 . C_3 is a coupling capacitor that couples the ac component of the signal at the emitter to the output v_O . (b) The signal voltage at the collector will be zero.

13.11

(a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a bypass capacitor. C_3 is a coupling capacitor that couples the ac component of the signal at the drain to the output v_O . (b) The signal voltage at the top of R_4 will be zero.

13.12

(a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a coupling capacitor that couples the ac component of the signal at the drain to output v_O .

13.13

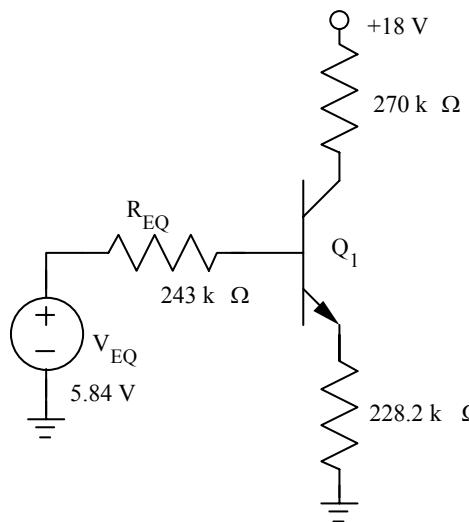
(a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a coupling capacitor that couples the ac component of the signal at the drain to the output v_O .

13.14

dc voltage sources produce constant values of output voltage. Hence no signal voltage can appear at the terminals of the source. The signal component of the voltage is forced to be zero, and a direct path to ground is provided for signal currents.

13.15

NPN Common-Emitter Amplifier



$$V_{EQ} = 18V \frac{360k\Omega}{360k\Omega + 750k\Omega} = 5.84 V$$

$$R_{EQ} = R_l \parallel R_2 = 360k\Omega \parallel 750k\Omega = 243 k\Omega$$

$$5.84 = 243 \times 10^3 I_B + 0.7 + 91(228.2 \times 10^3) I_B$$

$$I_B = 0.245 \mu A \quad | \quad I_C = 90I_B = 22.0 \mu A$$

$$V_{CE} = 18 - 2.7 \times 10^5 I_C - 2.28 \times 10^5 I_E = 6.99 V$$

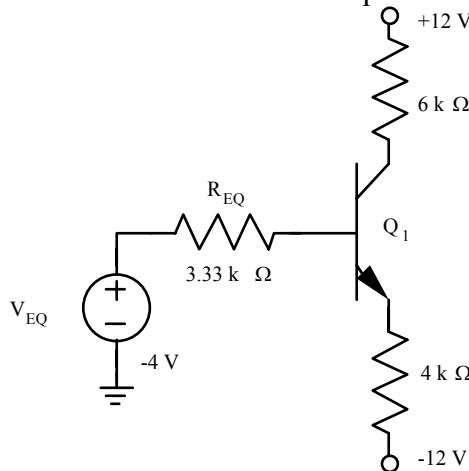
$$Q\text{-point: } (22.0 \mu A, 6.99 V)$$

13.16

SPICE results: (a) (22.5 μA , 6.71 V) (b) (22.6 μA , 6.69 V) The discrepancies between the results in Probs. 13.15 and 13.16 arise because $V_{BE} = 0.575$ V with $I_S = 5$ fA. Very little changes occurs with the addition of V_A .

13.17

NPN Common-Emitter Amplifier



$$V_{EQ} = -12V + 24V \frac{5k\Omega}{5k\Omega + 10k\Omega} = -4 V$$

$$R_{EQ} = R_l \parallel R_2 = 5k\Omega \parallel 10k\Omega = 3.33 k\Omega$$

$$-4 = 3300 I_B + 0.7 + 76(4000) I_B - 12$$

$$I_B = 23.8 \mu A \quad | \quad I_C = 75I_B = 1.78 mA$$

$$V_{CE} = 12 - 6000 I_C - 4000 I_E - (-12) = 6.08 V$$

$$Q\text{-point: } (1.78 mA, 6.08 V)$$

13.18

*Problem 13.17 - NPN Common-Emitter Amplifier

VCC 7 0 DC 12

VEE 8 0 DC -12

R1 3 8 5K

R2 7 3 10K

RE 4 8 4K

RC 7 5 6K

Q1 5 3 4 NBJT

.OP

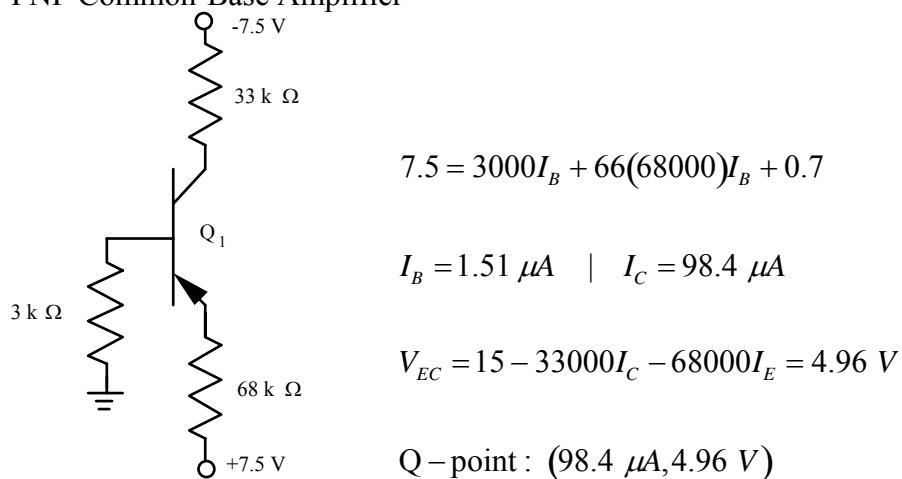
.MODEL NBJT NPN IS=1E-15 BF=75 VA=75

.END

Results: IC 1.78E-03 VCE 6.14E+00 VBE 7.28E-01

13.19

PNP Common-Base Amplifier



13.20

*Problem 13.19 - PNP Common-Base Amplifier

VEE 1 0 DC 7.5

VCC 5 0 DC -7.5

RC 5 4 33K

RB 3 0 3K

RE 1 2 68K

Q1 4 3 2 PBJT

.OP

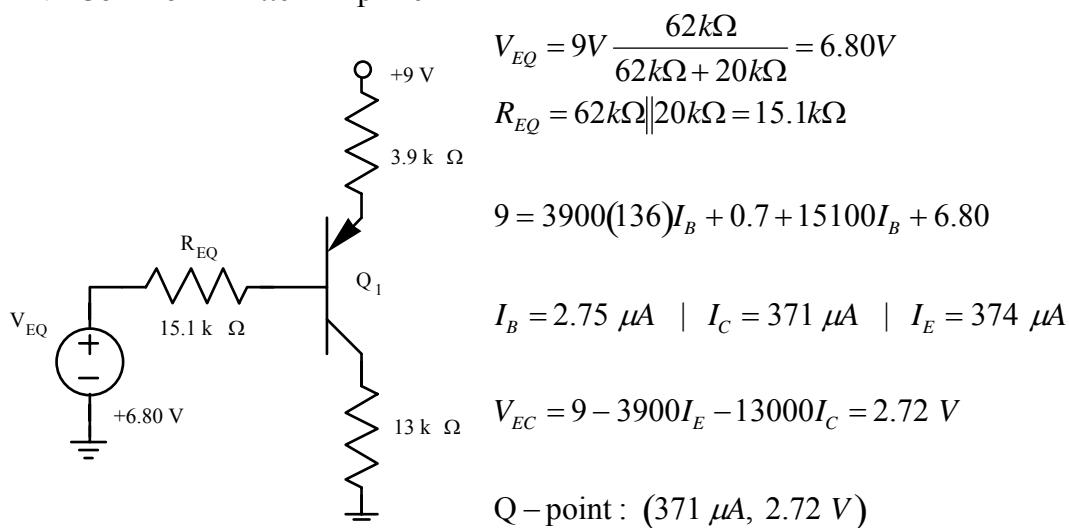
.MODEL PBJT PNP IS=1E-16 BF=65 VA=75

.END

Results: IC -9.83E-05 VCE -4.97E+00 VBE -7.13E-01

13.21

PNP Common-Emitter Amplifier



13.22

*Problem 13.21 - PNP Common-Emitter Amplifier

VCC 4 0 DC 9

RC 1 0 13K

R2 2 0 62K

R1 4 2 20K

RE 4 3 3.9K

Q1 1 2 3 PBJT

.OP

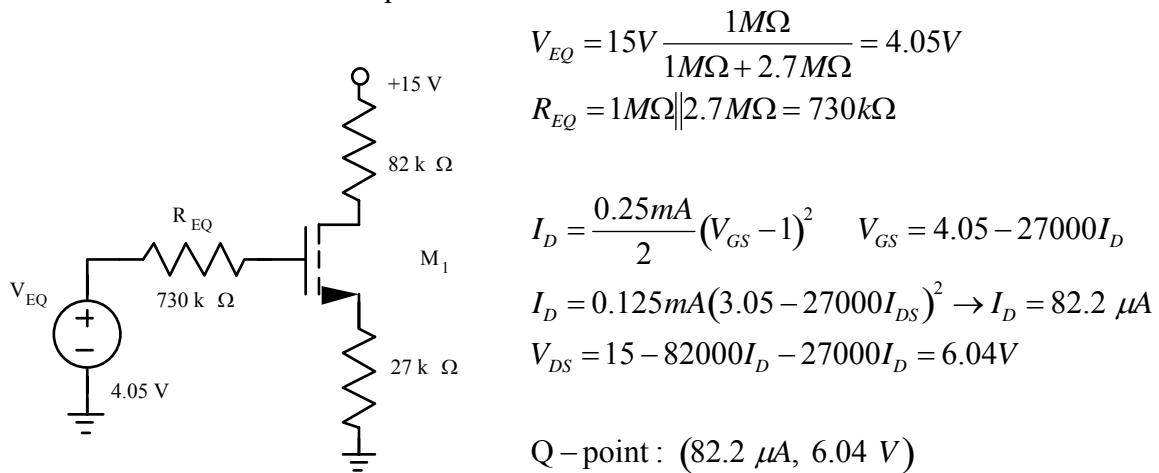
.MODEL PBJT PNP IS=1E-15 BF=135 VA=75

.END

Results: IC -3.73E-04 VCE -2.68E+00 VBE -6.88E-01

13.23

NMOS Common-Source Amplifier



13.24

*Problem 13.23 - NMOS Common-Source Amplifier

VDD 4 0 DC 15

RD 4 3 82K

R2 4 2 2.7MEG

R1 2 0 1MEG

R4 1 0 27K

M1 3 2 1 1 NFET

.OP

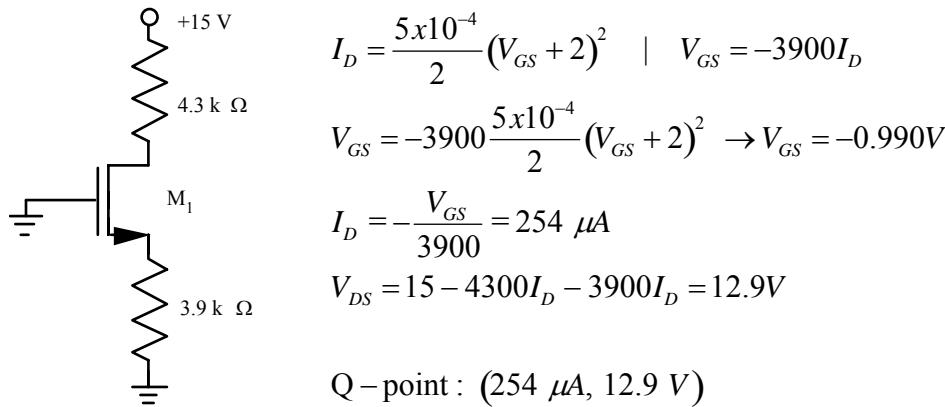
.MODEL NFET NMOS KP=250U VTO=1

.END

Results: ID 8.29E-05 VDS 5.96E+00 VGS 1.81E+00

13.25

Depletion-mode NMOS Common-Gate Amplifier



13.26

*Problem 13.25 - Depletion-mode NMOS Common-Gate Amplifier

VDD 3 0 DC 15

RD 3 2 4.3K

R1 1 0 3.9K

M1 2 0 1 1 NDMOS

.OP

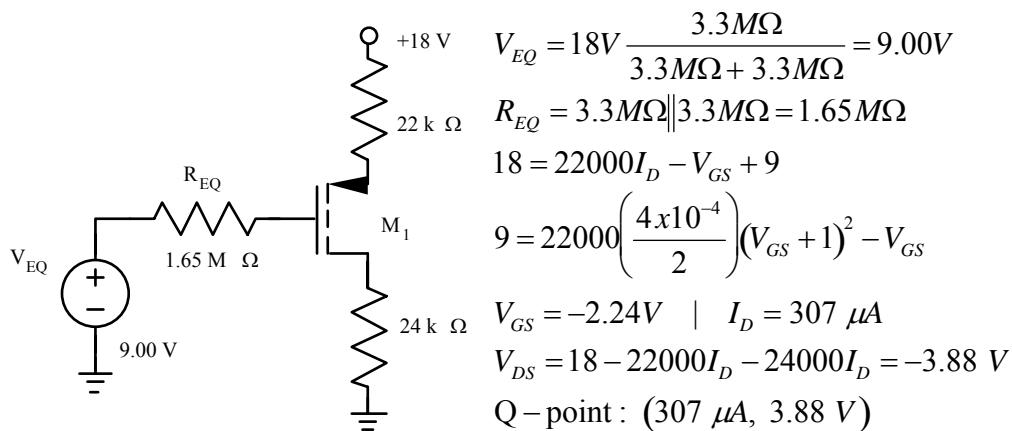
.MODEL NDMOS NMOS KP=500U VTO=-2

.END

Results: ID 2.54E-04 VDS 1.29E+01 VGS -9.92E-01

13.27

PMOS Common-Source Amplifier



13.28

*Problem 13.27 - PMOS Common-Source Amplifier

VDD 4 0 DC 18

RD 1 0 24K

R2 4 2 3.3MEG

R1 2 0 3.3MEG

R4 4 3 22K

M1 1 2 3 3 PFET

.OP

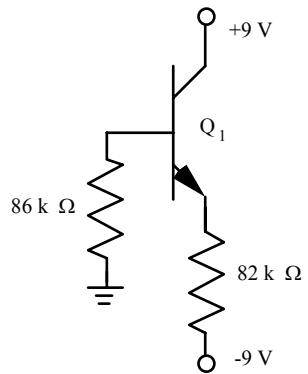
.MODEL PFET PMOS KP=400U VTO=-1

.END

Results: ID -3.07E-04 VDS -3.86E+00 VGS -2.24E+00

13.29

NPN Common-Collector Amplifier



$$9 = 86000I_B + 101(82000)I_B + 0.7$$

$$I_B = 0.992 \mu A \quad | \quad I_C = 99.2 \mu A$$

$$V_{CE} = 18 - 82000I_E = 18 - 82000(100 \mu A) = 9.80 V$$

$$Q\text{-point: } (99.2 \mu A, 9.80 V)$$

13.30

*Problem 13.29 - NPN Common-Collector Amplifier

VCC 5 0 DC 9

VEE 8 0 DC -9

R1 3 6 43K

R2 6 0 43K

RE 4 8 82K

Q1 5 3 4 NBJT

.OP

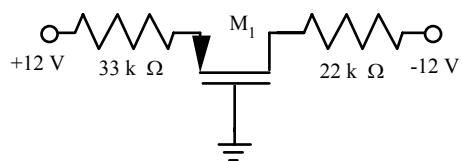
.MODEL NBJT NPN IS=1E-16 BF=100 VA=75

.END

Results: IC 9.93E-05 VCE 9.79E+00 VBE 7.12E-01

13.31

PMOS Common-Gate Amplifier



$$I_D = \frac{12 + V_{GS}}{33000} = \frac{200 \times 10^{-6}}{2} (V_{GS} - 1)^2$$

$$V_{GS} = -0.84 V \quad | \quad I_D = 338 \mu A$$

$$V_{DS} = -(12 - 33000I_D - 22000I_D + 12)$$

$$V_{DS} = -5.41 V$$

$$Q\text{-point: } (338 \mu A, -5.41 V)$$

13.32

*Problem 13.31 - PMOS Common-Gate Amplifier

VDD 4 0 DC 12

VSS 1 0 DC -12

RD 2 1 22K

R1 4 3 33K

M1 2 0 3 3 PFET

.OP

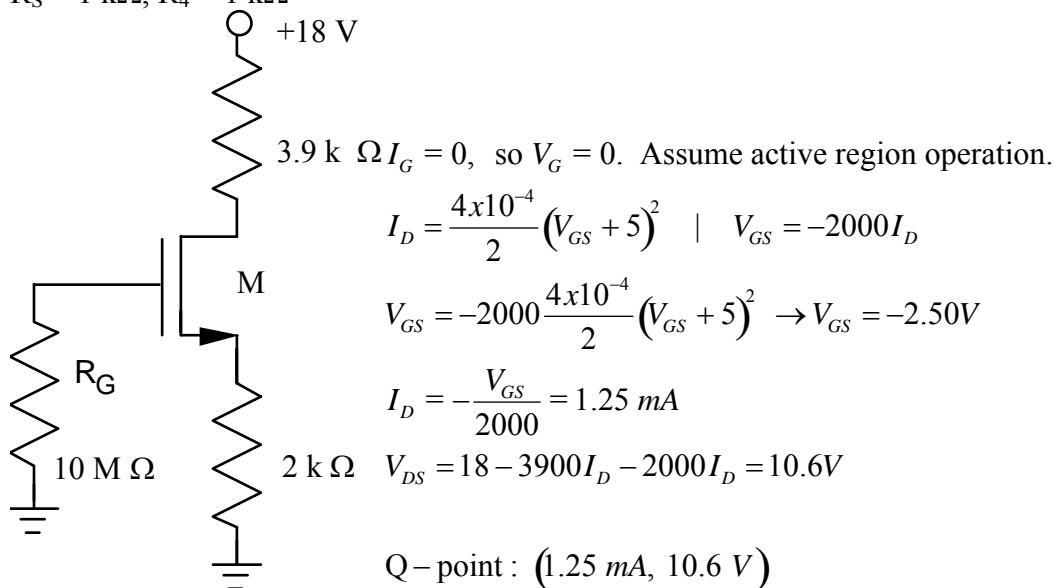
.MODEL PFET PMOS KP=200U VTO=+1

.END

Results: ID -3.38E-04 VDS -5.40E+00 VGS -8.39E-01

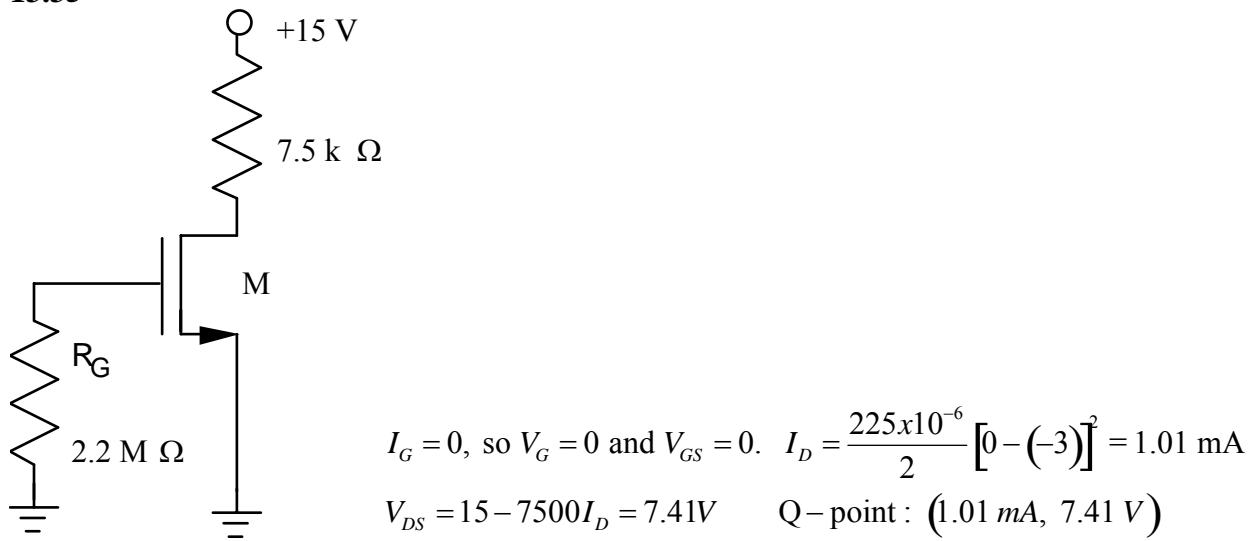
13.33

$R_S = 1 \text{ k}\Omega$, $R_4 = 1 \text{ k}\Omega$



13.34 SPICE results: The Q-point is the same (1.25 mA, 10.6 V).

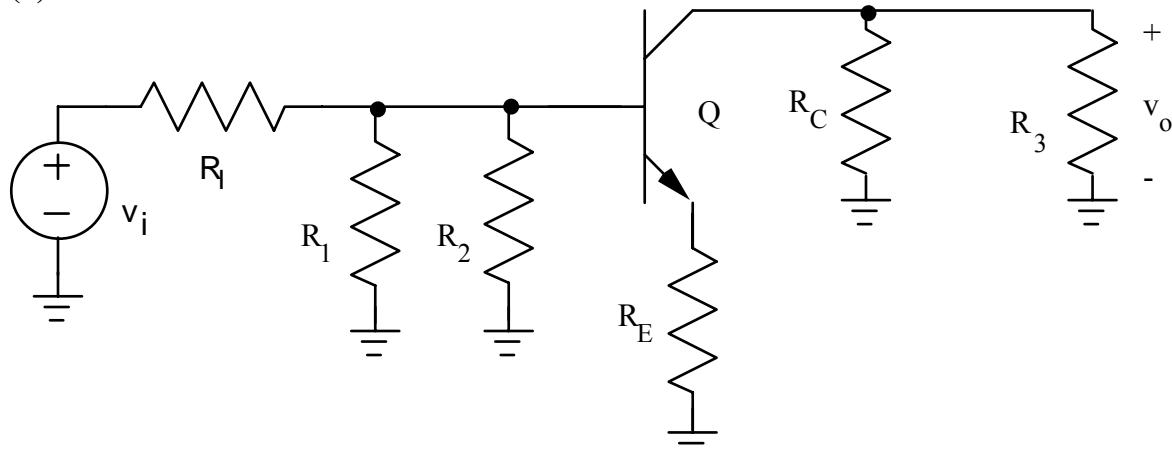
13.35



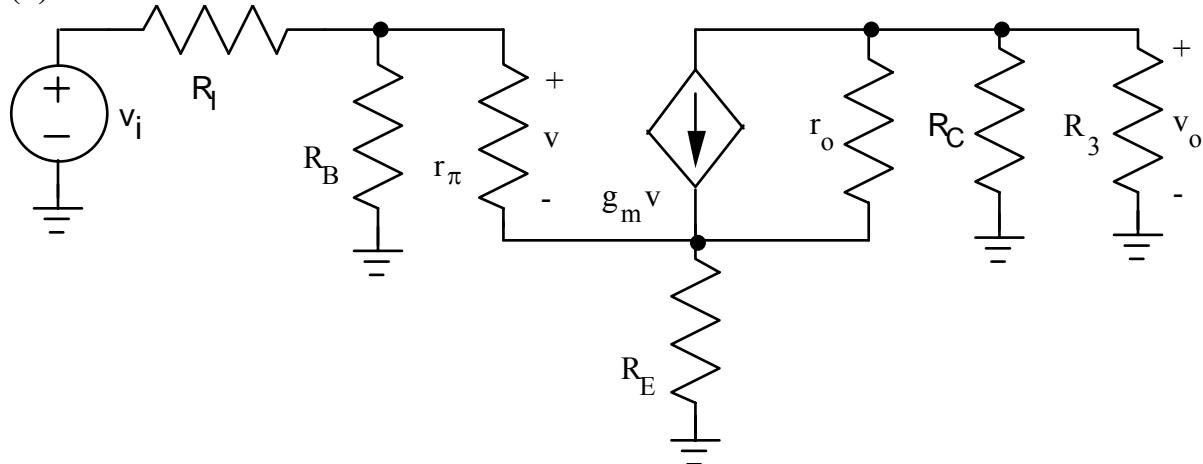
13.36 SPICE results: The Q-point is the same (1.01 mA , 7.41 V).

13.37

(a)



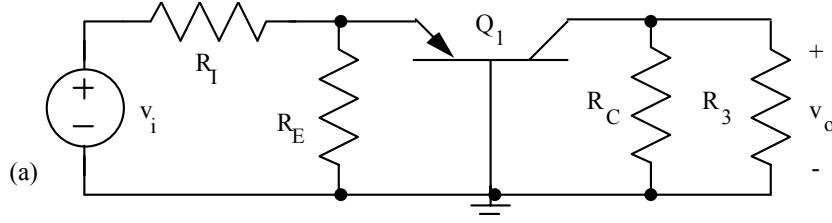
(b)



(c) C_1 is a coupling capacitor that couples the ac component of v_i into the amplifier. C_2 is a coupling capacitor that couples the ac component of the signal at the collector to the output v_o . C_3 is a bypass capacitor.

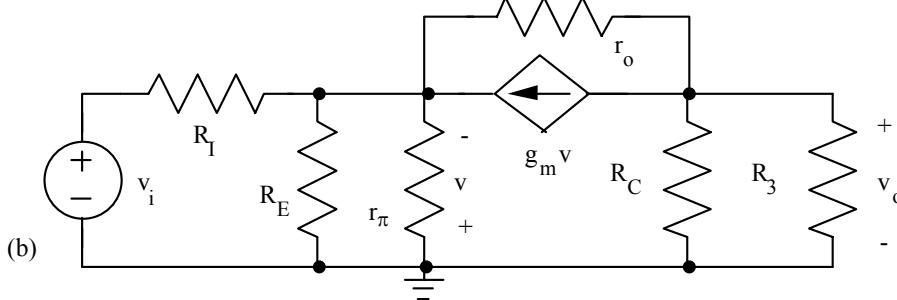
13.38(a)

Figure P13.4



(a)

(c)



(b)

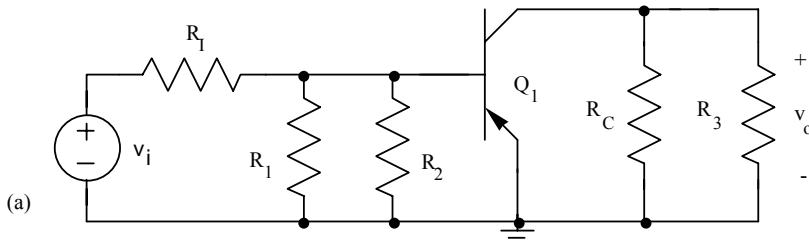
$C_1 - \text{Bypass}$

$C_2 - \text{Coupling}$

$C_3 - \text{Coupling}$

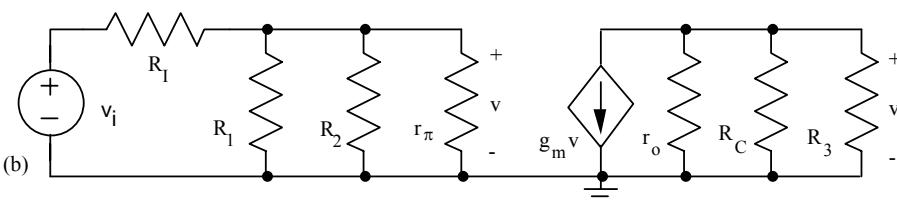
13.38(b)

Figure P13.5



(a)

(c)



(b)

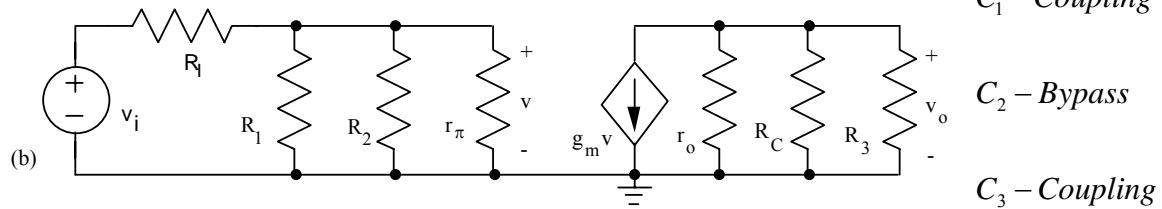
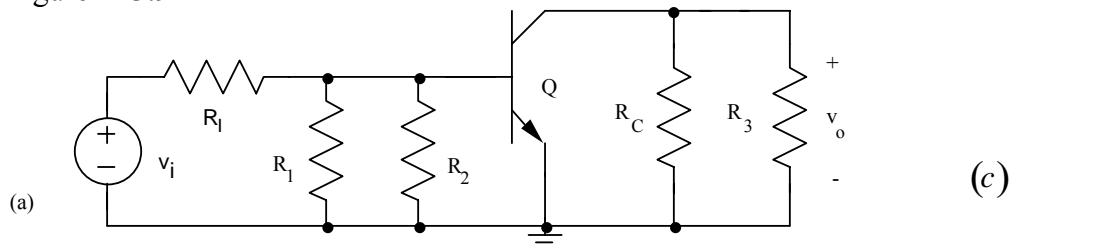
$C_1 - \text{Coupling}$

$C_2 - \text{Bypass}$

$C_3 - \text{Coupling}$

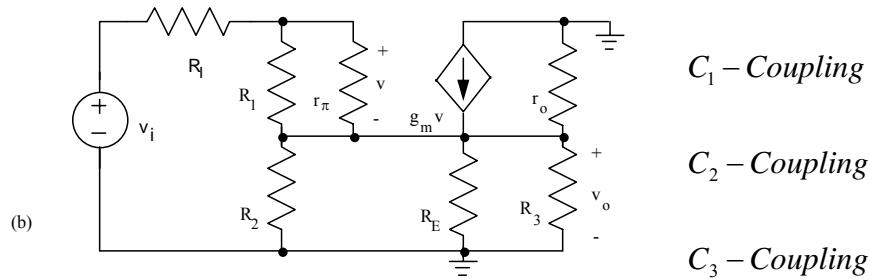
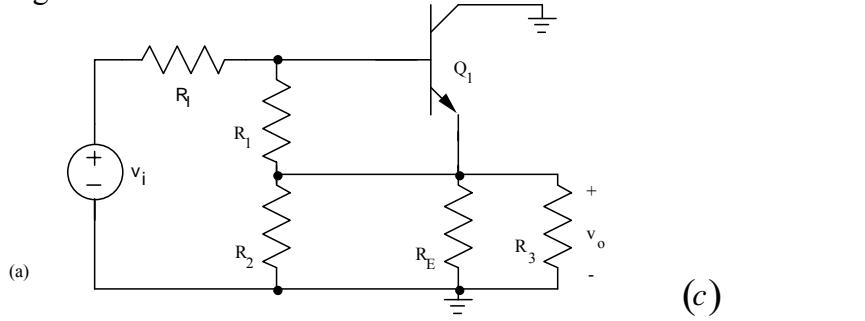
13.39(a)

Figure P13.9



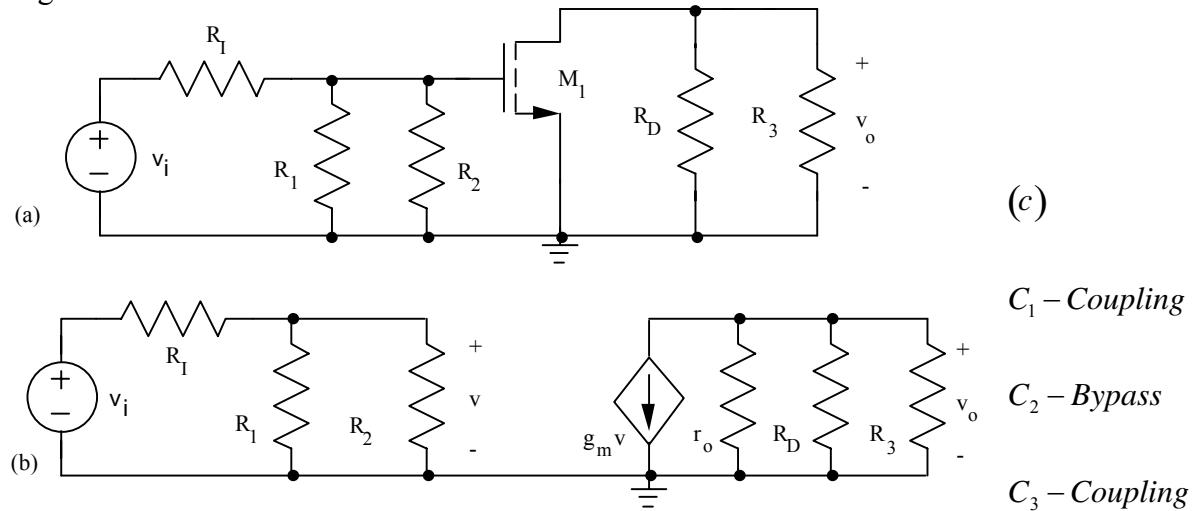
13.39(b)

Figure P13.10



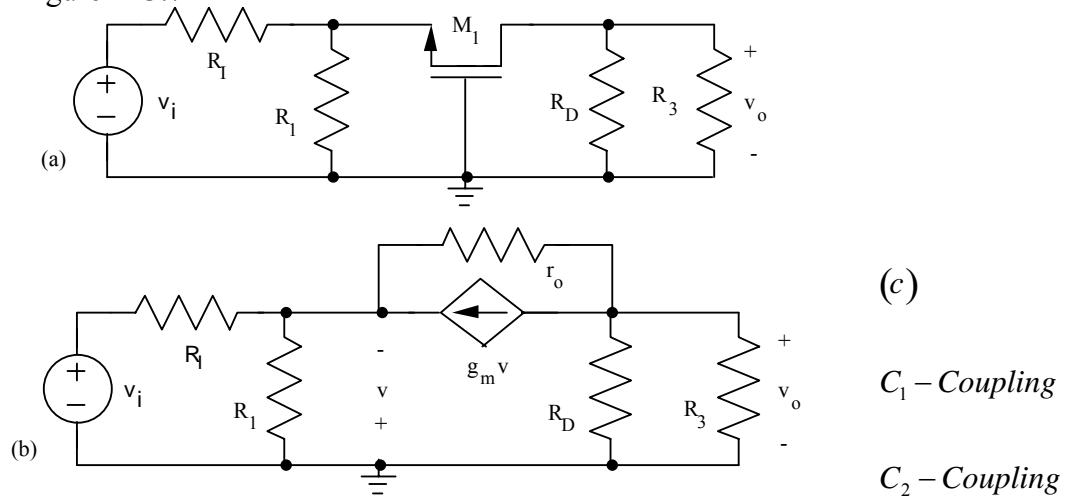
13.40(a)

Figure P13.6



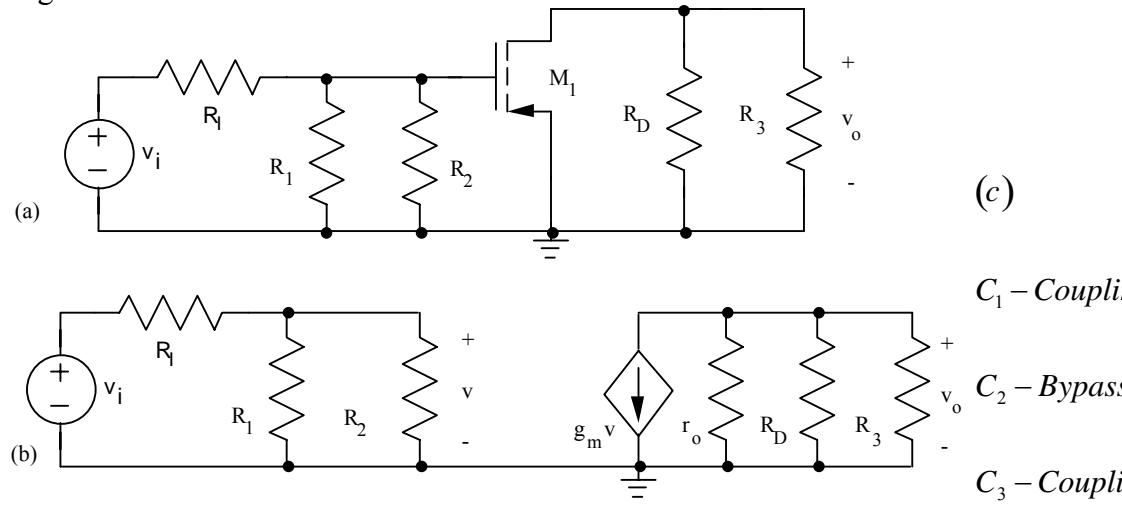
13.40(b)

Figure P13.7



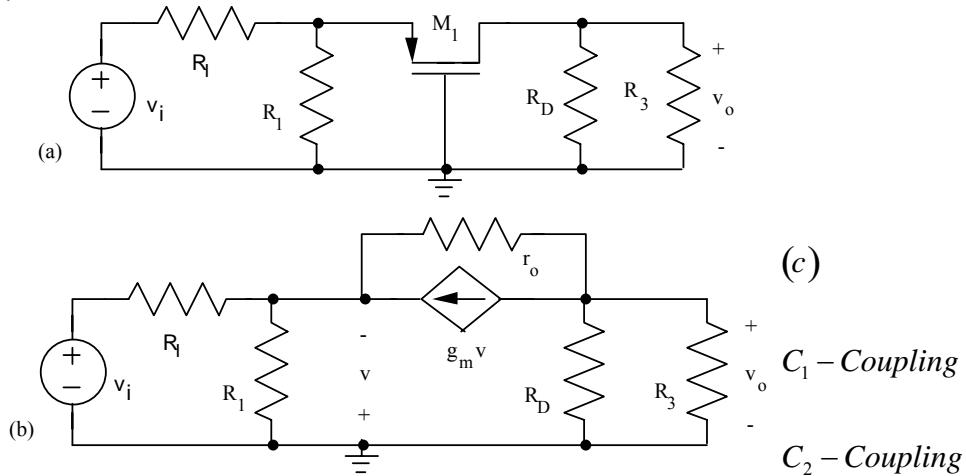
13.41(a)

Figure P13.8



13.42(a)

Figure P13.12



13.43

R_i : Thévenin equivalent source resistance; R_1 : base bias voltage divider; R_2 : base bias voltage divider; R_E and R_4 : emitter bias resistors - determine the emitter current; R_C : collector bias resistor - sets the collector-emitter voltage; R_3 : load resistor

13.44

R_i : Thévenin equivalent source resistance; R_1 : gate bias voltage divider; R_2 : gate bias voltage divider; R_4 : source bias resistor - sets source current; R_D : drain bias resistor - sets drain-source voltage; R_3 : load resistor

13.45

R_I : Thévenin equivalent source resistance; R_1 : base bias voltage divider; R_2 : base bias voltage divider; R_E : emitter bias resistor - determines the emitter current; R_C : collector bias resistor - sets the collector-emitter voltage; R_3 : load resistor

13.46

$$(a) r_d = \frac{V_T}{I_D + I_S} \quad | \quad I_D = 10^{-14} \left(\exp\left(\frac{0.6}{0.025}\right) - 1 \right) = 264.9 \mu A \quad | \quad r_d = \frac{0.025}{264.9 \mu A + 10 fA} = 94.4 \Omega$$

$$(b) I_D = 0 \quad r_d = \frac{0.025}{10 fA} = 2.50 T\Omega \quad (c) \frac{0.025}{I_D + I_S} > 10^{15} \rightarrow I_D + I_S < 2.5 \times 10^{-17} A$$

$$V_D < V_T \ln \frac{I_D + I_S}{I_S} = 0.025 \ln \frac{2.5 \times 10^{-17}}{10^{-14}} = -0.150 V$$

13.47

$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23}}{1.60 \times 10^{-19}} T = 8.63 \times 10^{-5} T \quad | \quad r_d \equiv \frac{V_T}{I_D} = 1000 V_T$$

T	75K	100K	200K	300K	400K
V _T	6.47 mV	8.63 mV	17.3 mV	25.9 mV	34.5 mV
r _d	6.47 Ω	8.63 Ω	17.3 Ω	25.9 Ω	34.5 Ω

13.48

$$(a) \exp\left(\frac{0.005}{0.025}\right) - 1 = 0.221 \quad | \quad \frac{0.005}{0.025} = 0.200 \rightarrow +10.7\% \text{ error}$$

$$\exp\left(-\frac{0.005}{0.025}\right) - 1 = -0.181 \quad | \quad -\frac{0.005}{0.025} = -0.200 \rightarrow -9.37\% \text{ error}$$

$$(b) \exp\left(\frac{0.010}{0.025}\right) - 1 = 0.492 \quad | \quad \frac{0.010}{0.025} = 0.400 \rightarrow +23.0\% \text{ error}$$

$$\exp\left(-\frac{0.010}{0.025}\right) - 1 = -0.330 \quad | \quad -\frac{0.010}{0.025} = -0.400 \rightarrow -17.5\% \text{ error}$$

13.49

$$(a) I_C = \frac{g_m}{40} = \frac{0.03}{40} = 0.750 mA = 750 \mu A \quad (b) I_C = \frac{g_m}{40} = \frac{250 \times 10^{-6}}{40} = 6.25 \mu A$$

$$(c) I_C = \frac{g_m}{40} = \frac{50 \times 10^{-6}}{40} = 1.25 \mu A$$

13.50

$$I_C = \frac{\beta_o V_T}{r_\pi} = \frac{75(0.025V)}{10^4 \Omega} = 187.5 \mu A \quad | \quad \text{Q-point: } (188 \mu A, V_{CE} \geq 0.7 V)$$

$$g_m = 40I_C = 40(1.875 \times 10^{-4}) = 7.50 mS \quad | \quad r_o = \frac{V_A + V_{CE}}{I_C} \approx \frac{V_A}{I_C} = \frac{100V}{187.5 \mu A} = 533 k\Omega$$

13.51

$$I_C = \frac{\beta_o V_T}{r_\pi} = \frac{125(0.025V)}{2 \times 10^6 \Omega} = 1.56 \mu A \quad | \quad \text{Q-point: } (1.56 \mu A, V_{CE} \geq 0.7 V)$$

$$g_m = 40I_C = 40(1.56 \times 10^{-6}) = 62.4 \mu S \quad | \quad r_o = \frac{V_A + V_{CE}}{I_C} \approx \frac{V_A}{I_C} = \frac{75V}{1.56 \mu A} = 48.1 M\Omega$$

13.52

$$I_C = \frac{\beta_o V_T}{r_\pi} = \frac{100(0.025V)}{250k\Omega} = 10 \mu A \quad | \quad \text{Q-point: } (10 \mu A, V_{CE} \geq 0.7 V)$$

$$g_m = 40I_C = 40(10^{-5}) = 0.400 mS \quad | \quad r_o = \frac{V_A + V_{CE}}{I_C} \approx \frac{V_A}{I_C} = \frac{100V}{10 \mu A} = 10 M\Omega$$

13.53

$$I_C = \frac{\beta_o V_T}{r_\pi} = \frac{75(0.025V)}{10^6 \Omega} = 1.875 \mu A \quad | \quad \text{Q-point: } (1.88 \mu A, V_{CE} \geq 0.7 V)$$

$$g_m = 40I_C = 40(1.875 \times 10^{-6}) = 75.0 \mu S \quad | \quad r_o = \frac{V_A + V_{CE}}{I_C} \approx \frac{V_A}{I_C} = \frac{100V}{1.875 \mu A} = 53.3 M\Omega$$

13.54

$$r_o = \frac{V_A + V_{CE}}{I_C} ; \text{ solving for } V_A : V_A = I_C r_o - V_{CE}$$

Using the values from row 1: $V_A = 0.002(40000) - 10 = 70 \text{ V}$

Using the values from the second row: $\beta_o = g_m r_\pi = 0.12(500) = 60$ and $\beta_F = \beta_o = 60$.

$$\text{Row 1: } g_m = 40I_C = 40(0.002) = 0.08 \text{ S} \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{60}{0.08} = 750 \Omega$$

$$\mu_f = g_m r_o = 0.08(40000) = 3200$$

$$\text{Row 2: } I_C = \frac{g_m}{40} = \frac{0.12}{40} = 3 \text{ mA} \quad | \quad r_o = \frac{V_A + V_{CE}}{I_C} = \frac{80}{0.003} = 26.7 \text{ k}\Omega$$

$$\mu_f = g_m r_o = 0.12(26700) = 3200$$

$$\text{Row 3: } g_m = \frac{\beta_o}{r_\pi} = \frac{60}{4.8 \times 10^5} = 1.25 \times 10^{-4} \text{ S} \quad | \quad I_C = \frac{g_m}{40} = \frac{1.25 \times 10^{-4}}{40} = 3.13 \mu\text{A}$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{80}{3.13 \times 10^{-6}} = 25.6 \text{ M}\Omega \quad | \quad \mu_f = g_m r_o = 1.25 \times 10^{-4}(25.6 \times 10^6) = 3200$$

13.55

$$(a) \exp\left(\frac{0.005}{0.025}\right) - 1 = 0.221 \quad | \quad \frac{0.005}{0.025} = 0.200 \rightarrow +10.7\% \text{ error}$$

$$\exp\left(-\frac{0.005}{0.025}\right) - 1 = -0.181 \quad | \quad -\frac{0.005}{0.025} = -0.200 \rightarrow -9.37\% \text{ error}$$

$$(b) \exp\left(\frac{0.0075}{0.025}\right) - 1 = 0.350 \quad | \quad \frac{0.0075}{0.025} = 0.300 \rightarrow +16.7\% \text{ error}$$

$$\exp\left(-\frac{0.0075}{0.025}\right) - 1 = -0.259 \quad | \quad -\frac{0.0075}{0.025} = -0.300 \rightarrow -13.6\% \text{ error}$$

$$(c) \exp\left(\frac{0.0025}{0.025}\right) - 1 = 0.105 \quad | \quad \frac{0.0025}{0.025} = 0.100 \rightarrow +5.17\% \text{ error}$$

$$\exp\left(-\frac{0.0025}{0.025}\right) - 1 = -0.0952 \quad | \quad -\frac{0.0025}{0.025} = -0.100 \rightarrow -4.84\% \text{ error}$$

13.56

$$(a) \beta_F = \frac{I_C}{I_B} \cong \frac{350\mu\text{A}}{4\mu\text{A}} \cong 90 \quad | \quad \beta_o = \frac{\Delta I_C}{\Delta I_B} \cong \frac{600\mu\text{A} - 125\mu\text{A}}{6\mu\text{A} - 2\mu\text{A}} \cong 120$$

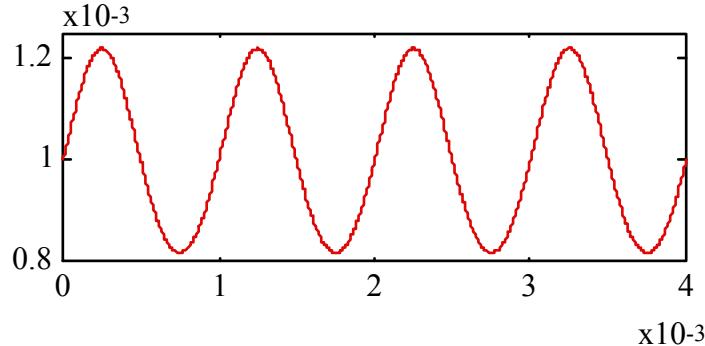
$$(b) \beta_F \cong \frac{750\mu\text{A}}{8\mu\text{A}} \cong 95 \quad | \quad \beta_o \cong \frac{900\mu\text{A} - 600\mu\text{A}}{4\mu\text{A}} \cong 75$$

13.57(a)

```

t=linspace(0,.004,1024);
ic=.001*exp(40*.005*sin(2000*pi*t));
IC=fft(ic);
z=abs(IC(1:26)/1024);
z(1)
ans = 0.001
plot(t,ic)

```



```

z([5 9 13])
ans = 0.0001  0.0000  0.0000

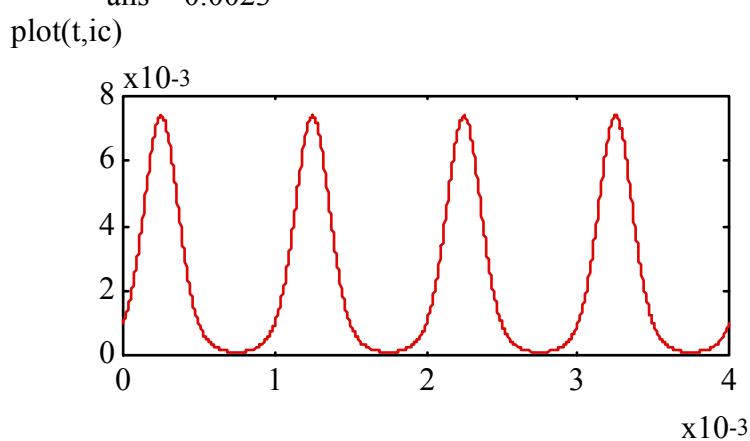
```

13.57(b)

```

t=linspace(0,.004,1024);
ic=.001*exp(40*.005*sin(2000*pi*t));
IC=fft(ic);
z=abs(IC(1:26)/1024);
z(1)
ans = 0.0023
plot(t,ic)

```



```

z([5 9 13])
ans = 0.0016  0.0007  0.0002

```

13.58 (a)

NAME	Q1
MODEL	NBJT
IB	2.21E-05
IC	1.78E-03
VBE	7.28E-01
VBC	-5.41E+00
VCE	6.14E+00
BETADC	8.04E+01
GM	6.87E-02
RPI	1.17E+03
RX	0.00E+00
RO	4.52E+04
BETAAC	8.04E+01

$$T = 27^\circ C \quad | \quad V_T = 8.625 \times 10^{-5} (300) = 25.9 mV$$

$$g_m = \frac{I_C}{V_T} = \frac{1.78 mA}{25.9 mV} = 68.7 mS$$

$$\beta_o = \beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) = 75 \left(1 + \frac{6.14}{75} \right) = 81.1$$

$$r_\pi = \frac{\beta_o}{g_m} = \frac{81.1}{0.0687} = 1180 \Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{75 + 6.14}{1.78 mA} = 45.6 k\Omega$$

13.58(b)

MODEL PBJT
 IB -2.69E-06
 IC -3.73E-04
 VBE -6.88E-01
 VBC 1.99E+00
 VCE -2.68E+00
 BETADC 1.39E+02
 GM 1.44E-02
 RPI 9.61E+03
 RX 0.00E+00
 RO 2.06E+05
 BETAAC 1.39E+02

$$T = 27^\circ C \quad | \quad V_T = 8.625 \times 10^{-5} (300) = 25.9 mV$$

$$g_m = \frac{I_C}{V_T} = \frac{0.373 mA}{25.9 mV} = 14.4 mS$$

$$\beta_o = \beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) = 135 \left(1 + \frac{2.68}{75} \right) = 140$$

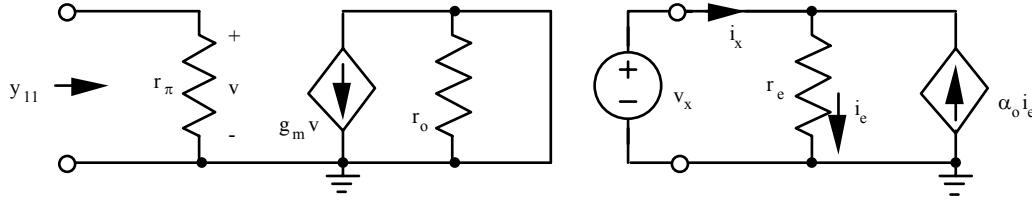
$$r_\pi = \frac{\beta_o}{g_m} = \frac{140}{0.0144} = 9.72 k\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{75 + 2.68}{0.373 mA} = 208 k\Omega$$

Note: The SPICE model actually is using V_{CB} instead of V_{CE} in the current gain calculations.

$$(a) \beta_o = 75 \left(1 + \frac{5.41}{75} \right) = 80.4 \quad (b) \beta_o = 135 \left(1 + \frac{1.99}{75} \right) = 139$$

13.59



For the hybrid pi model: $y_{11} = \frac{1}{r_\pi}$

For the T - model: $i_x = \frac{v_x}{r_e} - \alpha_o \frac{v_x}{r_e} = \frac{1 - \alpha_o}{r_e} v_x$

$$y_{11} = \frac{i_x}{v_x} = \frac{1 - \alpha_o}{r_e} = \frac{1 - \frac{\beta_o}{\beta_o + 1}}{r_e} = \frac{1}{(\beta_o + 1)r_e} \rightarrow r_\pi = (\beta_o + 1)r_e$$

$$r_e = \frac{r_\pi}{(\beta_o + 1)} = \frac{\beta_o}{g_m(\beta_o + 1)} = \frac{\alpha_o}{g_m} = \frac{\alpha_o V_T}{I_C} = \frac{V_T}{I_E}$$

13.60

$$g_m = 40(50\mu A) = 2.00 mS \quad | \quad r_\pi = \frac{100}{2.00 mS} = 50 k\Omega \quad | \quad r_o = \frac{75V + 10V}{50\mu A} = 1.70 M\Omega$$

$$R_{BB} = R_B \| r_\pi = 100 k\Omega \| 50 k\Omega = 33.3 k\Omega$$

$$A_v = -\left(\frac{33.3 k\Omega}{33.3 k\Omega + 0.75 k\Omega}\right)(2 mS)(1.70 M\Omega \| 100 k\Omega \| 100 k\Omega) = -95.0$$

13.61

For $\beta_o = 100$, see Prob. 13.60.

$$r_\pi = \frac{60}{2.00 mS} = 30 k\Omega \quad | \quad R_{BB} = R_B \| r_\pi = 100 k\Omega \| 30 k\Omega = 23.1 k\Omega$$

$$A_v = -\left(\frac{23.1 k\Omega}{23.1 k\Omega + 0.75 k\Omega}\right)(2 mS)(1.70 M\Omega \| 100 k\Omega \| 100 k\Omega) = -94.1$$

$-95.0 \leq A_v \leq -94.1$ – only a small variation

13.62

$$g_m = 40(2.5 mA) = 0.100 S \quad | \quad r_\pi = \frac{75}{0.1 S} = 750 \Omega \quad | \quad r_o = \frac{50 + 7.5}{2.5} \frac{V}{mA} = 23.0 k\Omega$$

$$R_{BB} = R_B \| r_\pi = 4.7 k\Omega \| 750 \Omega = 647 \Omega$$

$$A_v = \left(\frac{647 \Omega}{50 \Omega + 647 \Omega}\right)(-0.100 S)(23.0 k\Omega \| 4.3 k\Omega \| 10 k\Omega) = -247$$

13.63

$$g_m = 40(1\mu A) = 40\mu S \quad | \quad r_\pi = \frac{40}{40\mu S} = 1M\Omega \quad | \quad r_o = \frac{50+1.5}{1} \frac{V}{\mu A} = 51.5M\Omega$$

$$R_{BB} = R_B \| r_\pi = 5M\Omega \| 1M\Omega = 833k\Omega$$

$$A_v = \left(\frac{833k\Omega}{10k\Omega + 833k\Omega} \right) (-40\mu S) (51.5M\Omega \| 1.5M\Omega \| 3.3M\Omega) = -40.0$$

13.64

SPICE Results: $I_C = 248 \mu A$, $V_{CE} = 3.30 V$, $A_V = -15.1 \text{ dB}$ -- I_C differs by 1.2% - A_V is off by 0.5%

13.65

$$[10(V_{CC})]^N = [10(9)]^N \geq 20000 \rightarrow N \geq \frac{\log(20000)}{\log(90)} = 2.20 \rightarrow N = 3$$

(or quite possibly 2 by droping a larger fraction of the supply voltage across R_C)

13.66

*Problem 13.21 - PNP Common-Emitter Amplifier - Figure P13.5

VCC 7 0 DC 9

VI 1 0 AC 1

RI 1 2 1K

C1 2 3 100U

R1 7 3 20K

R2 3 0 62K

RE 7 4 3.9K

C 7 4 100U

RC 5 0 13K

C3 5 6 100U

R3 6 0 100K

Q1 5 3 4 PBJT

.OP

.MODEL PBJT PNP IS=1E-15 BF=135 VA=75

.AC DEC 10 100Hz 10000Hz

.PRINT AC VM(6) VDB(6) VP(6)

.END

Results: $I_C = 373 \mu A$, $V_{EC} = 2.68V$, $A_V = -134$

Hand calculations in Prob. 13.21 yielded (371 μA , 2.72V)

$$g_m = 40(371\mu A) = 14.8mS \quad | \quad r_\pi = \frac{135}{14.8mS} = 9.12k\Omega \quad | \quad r_o = \infty$$

$$R_B = R_1 \| R_2 = 20k\Omega \| 62k\Omega = 15.1k\Omega \quad | \quad R_{BB} = 15.1k\Omega \| 9.12k\Omega = 5.69k\Omega$$

$$A_v = -\left(\frac{5.69k\Omega}{1k\Omega + 5.69k\Omega} \right) (14.8mS) (\infty \| 13k\Omega \| 100k\Omega) = -145$$

SPICE A_v result is somewhat lower because r_O is included.

13.67

$$A_v \approx -10V_{CC} = -10(12) = -120$$

13.68

$$A_v \approx -10(V_{CC} + V_{EE}) = -10(15 + 15) = -300$$

13.69

$$A_v = -10(V_{CC} + V_{EE}) = -10(1.5 + 1.5) = -30; \text{ This estimate says no.}$$

However, if we look a bit deeper,

$$A_v = -40(I_C R_C) = -40V_{R_C}, \text{ and we let } V_{R_C} = \frac{(V_{CC} + V_{EE})}{2} = 1.5V,$$

then we can achieve A_v = -40(1.5) = -60.

So, with careful design, we can probably achieve a gain of 50.

13.70

Using our rule - of - thumb estimate,

$$A_v \approx -10V_{CC} = -10(1.5) = -15 \quad | \quad A_v = -10(1) = -10$$

Note that this result assumes that I_C varies with V_{CC}.

13.71

$$(a) i_c = \frac{5V}{10k\Omega} = 0.5 \text{ mA, but } i_c \leq 0.2I_C \text{ for small - signal operation. So } I_C \geq 5i_c = 2.5 \text{ mA.}$$

$$(b) V_{CC} \geq V_{BE} + i_c R_L + I_C R_L = 0.7 + 5 + 25 = 30.7 \text{ V}$$

13.72

$$A_v = 40 \text{ dB} = 100 \quad | \quad v_o = 100v_{be} = 100(0.005V) = 0.500V.$$

13.73

For common-emitter stage: $A_v = 50dB \rightarrow A_v = -316$

$$|v_{be}| = \frac{15V}{316} = 47.5mV \text{ which is far too big for small-signal operation.}$$

This will be significant distortion of the sine wave.

13.74

$$(a) V_{EQ} = -9 + \frac{20k\Omega}{62k\Omega + 20k\Omega} 18 = -4.61V \quad | \quad R_{EQ} = 20k\Omega \parallel 62k\Omega = 15.1k\Omega$$

$$I_B = \frac{-4.61 - 0.7 - (-9)}{15.1k\Omega + 136(3.9k\Omega)} = 6.76\mu A \quad | \quad I_C = 135I_B = 913\mu A$$

$$V_{CE} = 9 - 13000I_C - 3900I_E - (-9) = 2.54V$$

$$g_m = 40I_C = 0.0365S \quad | \quad r_\pi = \frac{135}{g_m} = 3.70k\Omega \quad | \quad r_o = \infty \quad | \quad R_L = 13k\Omega \parallel 100k\Omega = 11.5k\Omega$$

$$A_v = -\left(\frac{2.97k\Omega}{1k\Omega + 2.97k\Omega}\right)(0.0365)(11.5k\Omega) = -314$$

(b) For $V_{CC} = 18V$, the answers are the same: $I_C = 913\mu A \quad | \quad V_{EC} = 2.54V \quad | \quad A_v = -314$

13.75

Using the information from Row 1:

$$\frac{1}{\lambda} = I_D r_o - V_{DS} = (8 \times 10^{-4})(4 \times 10^4) - 6 = 26V; \lambda = 0.0385V^{-1}$$

$$\text{From Row 2: } K_n = \frac{g_m^2}{2I_D(1 + \lambda V_{DS})} = \frac{(2 \times 10^{-4})^2}{2(5 \times 10^{-5})(1 + \frac{6}{26})} = 3.25 \times 10^{-4} \frac{A}{V^2}$$

$$\text{Row 1: } g_m = \sqrt{2K_n I_D (1 + \lambda V_{DS})} = \sqrt{2(3.25 \times 10^{-4})(8 \times 10^{-4})(1 + \frac{6}{26})} = 8 \times 10^{-4} S$$

$$\mu_f = g_m r_o = 8 \times 10^{-4}(4 \times 10^4) = 32$$

$$0.2(V_{GS} - V_{TN}) = 0.2 \sqrt{\frac{2I_D}{K_n(1 + \lambda V_{DS})}} = 0.2 \sqrt{\frac{2(8 \times 10^{-4})}{3.25 \times 10^{-4}(1 + \frac{6}{26})}} = 0.40V$$

$$\text{Row 2: } r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{26 + 6}{5 \times 10^{-5}} = 640 k\Omega \quad | \quad \mu_f = g_m r_o = 2 \times 10^{-4} (6.4 \times 10^5) = 128$$

$$0.2(V_{GS} - V_{TN}) = 0.2 \sqrt{\frac{2I_D}{K_n(1 + \lambda V_{DS})}} = 0.2 \sqrt{\frac{2(5 \times 10^{-5})}{3.25 \times 10^{-4} \left(1 + \frac{6}{26}\right)}} = 0.10V$$

$$\text{Row 3: } g_m = \sqrt{2K_n I_D (1 + \lambda V_{DS})} = \sqrt{2(3.25 \times 10^{-4})(10^{-2}) \left(1 + \frac{6}{26}\right)} = 2.83 \times 10^{-3} S$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{26 + 6}{0.01} = 3.2 k\Omega \quad | \quad \mu_f = g_m r_o = 2.83 \times 10^{-3} (3.2 \times 10^3) = 9.06$$

$$0.2(V_{GS} - V_{TN}) = 0.2 \sqrt{\frac{2I_D}{K_n(1 + \lambda V_{DS})}} = 0.2 \sqrt{\frac{2(10^{-2})}{3.25 \times 10^{-4} \left(1 + \frac{6}{26}\right)}} = 1.41V$$

MOSFET Small-Signal Parameters				
I _D	g _m (S)	r _o (Ω)	μ _f	Small-Signal Limit v _{gs} (V)
0.8 mA	0.0008	40,000	32	0.40
50 μA	0.0002	640,000	128	0.10
10 mA	0.00283	3200	9.06	1.41

13.76

$$\mu_f = \left(\frac{1}{\lambda} + V_{DS}\right) \sqrt{\frac{2K_n(1 + \lambda V_{DS})}{I_D}} \approx \left(\frac{1}{\lambda}\right) \sqrt{\frac{2K_n}{I_D}} = \left(\frac{1}{\lambda}\right) \sqrt{\frac{2K'_n}{I_D} \left(\frac{W}{L}\right)}$$

$$\frac{W}{L} = (\mu_f \lambda)^2 \frac{I_D}{2K'_n} = [250(0.02)]^2 \frac{2 \times 10^{-4}}{2(5 \times 10^{-5})} = \frac{50}{1}$$

$$V_{GS} - V_{TN} \approx \sqrt{\frac{2I_D}{K_n}} = \sqrt{\frac{2(2 \times 10^{-4})}{50(5 \times 10^{-5})}} = 0.160 V$$

13.77

$$\mu_f = \left(\frac{1}{\lambda} + V_{DS} \right) \sqrt{\frac{2K_n(1+\lambda V_{DS})}{I_D}} \cong \left(\frac{1}{\lambda} \right) \sqrt{\frac{2K_n}{I_D}} + \left(\frac{1}{.02} \right) \sqrt{\frac{2(2.5 \times 10^{-4})}{I_D}} \leq 1 \rightarrow I_D \geq 1.25 A$$

13.78

$$g_m = \frac{2I_D}{V_{GS} - V_{TN}} \quad | \quad I_D = \frac{(0.005)(0.5)}{2} = 1.25 mA \quad | \quad \frac{W}{L} = \frac{2I_D}{K'_n(V_{GS} - V_{TN})^2} = \frac{2(1.25mA)}{4 \times 10^{-5}(0.5)^2} = \frac{250}{1}$$

13.79

$$(1+0.2)^2 - 1 = 0.44 \quad | \quad 2(0.2) = 0.40 \rightarrow 10\% \text{ error}$$

$$(1+0.4)^2 - 1 = 0.96 \quad | \quad 2(0.4) = 0.80 \rightarrow 20\% \text{ error}$$

13.80

From the results of Problem 13.24:

$$ID = 8.29E-05, VGS = 1.81E+00, VDS=5.96E+00, GM = 2.04E-04, GDS = 0.00E+00$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(82.9 \mu A)}{1.81 - 1} = 205 \mu S \quad | \quad \lambda = 0 \rightarrow r_o = \infty \quad | \quad g_{ds} = \frac{1}{r_o} = 0$$

13.81

From the results of Problem 13.28:

$$ID = 3.07E-04, VGS = -2.24E+00, VDS=-3.86E+00, GM = 4.96E-04, GDS = 0.00E+00$$

$$g_m = \frac{2I_D}{|V_{GS} - V_{TP}|} = \frac{2(307 \mu A)}{|-2.24 + 1|} = 495 \mu S \quad | \quad \lambda = 0 \rightarrow r_o = \infty \quad | \quad g_{ds} = \frac{1}{r_o} = 0$$

13.82

$$R_{out} = \frac{R_D r_o}{R_D + r_o} \quad | \quad \text{Using } V_{DS} = \frac{V_{DD}}{2} \quad | \quad R_D = \frac{9V}{I_D} \quad | \quad r_o = \frac{50V + 9V}{I_D} \rightarrow R_{out} = \frac{7.8V}{I_D}$$

$$I_D = \frac{7.8V}{50k\Omega} = 156 \mu A \rightarrow R_D = 57.6 k\Omega \quad | \quad r_o = 378 k\Omega \quad | \quad \text{Q-point: } (156 \mu A, 9 V)$$

13.83

Virtually any Q-point is possible. R_{IN} is set by R_G which can be any value desired since there is no gate current. (Note this is not the case with a BJT for which base current must be considered.)

13.84

Note that $i_G \approx 0$ for this device.

Load line: $400 = 133000i_p + v_{PK}$ and $v_{GK} = -1.5V$

Two points (i_p, v_{PK}) : (3mA, 0V) and (0mA, 400V) \rightarrow Q-pt: (1.4 mA, 215 V)

$$r_o = \frac{250V - 200V}{2.15mA - 1.25mA} = 55.6k\Omega \quad | \quad g_m = \frac{2.3mA - 0.7mA}{-1V - (-2V)} = 1.6mS \quad | \quad \mu_f = 89.0$$

$$A_v = -g_m(R_p \parallel r_o) = -1.6mS(133k\Omega \parallel 55.6k\Omega) = -62.7$$

13.85

$$\text{BJT: } I_C = g_m V_T = 0.5S(0.025V) = 12.5mA \quad | \quad \text{MOSFET: } I_D = \frac{g_m^2}{2K_n} = \frac{(0.5S)^2}{2(25mA/V^2)} = 5 A!$$

The BJT can achieve the required transconductance at a 400 times lower current than the MOSFET. For a given power supply voltage, the BJT will therefore use 400 times less power.

Note, however, that r_π is small for the BJT: $r_\pi = \frac{60}{0.5} = 120\Omega$ (versus ∞ for the FET).

13.86

Since a relatively high input resistance is required at a relatively high current, a FET should be used. If a BJT were selected, it would be very difficult to achieve the required input resistance because its value of r_π is low:

$$r_\pi = \frac{\beta_o V_T}{I_C} = \frac{100(0.025V)}{10mA} = 250 \Omega$$

13.87

$$40(V_A + V_{CE}) = \left(\frac{1}{\lambda} + V_{DS}\right) \sqrt{\frac{2K_n(1 + \lambda V_{DS})}{I_D}}$$

$$40(35) = 60 \sqrt{\frac{2(0.025)(1.2)}{I_D}} \rightarrow I_D = 111 \mu A \quad | \quad \mu_f = 40(35) = 1400$$

13.88

$$\mu_f \approx \frac{V_A}{V_T} = 40V_A = 40(50) = 2000 \quad | \quad g_m = \frac{I_C}{V_T} = 40I_C = 40(2 \times 10^{-4}) = 8.00 mS$$

$$\mu_f \approx \frac{2}{\lambda(V_{GS} - V_{TN})} = \frac{2}{0.02(0.5)} = 200 \quad | \quad g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(2 \times 10^{-4})}{0.5} = 0.800 mS$$

13.89

Either transistor could be used. For a BJT operating in the common-emitter configuration or an FET operating in the common-source configuration:

$$\text{For the BJT : } R_{in} \approx r_\pi \quad | \quad \text{BJT : } I_C = \frac{\beta_o V_T}{r_\pi} = \frac{100(0.025V)}{75\Omega} = 33.3 \text{ mA} \quad - \text{ A fairly high current}$$

For the FET : $R_{in} = R_G$ and setting $R_G = 75 \Omega$ is satisfactory, particularly if a depletion-mode FET is available.

The input of a CE circuit operating at a much lower current could also be swamped by the addition of a $75\text{-}\Omega$ resistor in parallel with its input. (Note that common-base and common-gate amplifiers from Chapter 14 could also be used.)

13.90

(a) $A_v = 10^{\frac{26}{20}} = 20.0$. Either a BJT or MOSFET can achieve the required gain. However, based upon the material in Chapter 13, an FET should be chosen since the input voltage of 0.25 V is 50 time larger than the permissible value for v_{be} (0.005 V) for the BJT. For the FET, a value of $V_{GS} - V_{TN} = 1.25$ V will satisfy the small-signal limit with $v_{gs} = 0.25$ V. (The generalized common-emitter stage with emitter degeneration can also satisfy the requirements.) (b) The FET is also best for this case, since the amplifier will see input signals much greater than the 5-mV limit of the BJT.

13.91

$$A_v \approx -\frac{V_{DD}}{V_{GS} - V_{TN}} = -\frac{(12)}{1} = -12 \text{ or } 21.6 \text{ dB}$$

13.92

$$v_d = \frac{15}{2} = 7.5V_{peak} \quad | \quad 15dB \rightarrow A_v = -5.62 \quad | \quad v_{gs} = \frac{7.5V}{5.62} = 1.34V \quad | \quad V_{GS} - V_{TN} \geq 5(1.34) = 6.70V$$

Yes, it is possible although the required value of $(V_{GS} - V_{TN})$ is getting rather large.

13.93

$$|A_v| \approx \frac{V_{DD}}{V_{GS} - V_{TN}} \quad | \quad \frac{9}{V_{GS} - V_{TN}} \geq 30 \rightarrow V_{GS} - V_{TN} \leq 0.300 \text{ V}$$

13.94

$$\text{For } V_{DS} = \frac{V_{DD}}{2}, A_v = -\frac{V_{DD}}{V_{GS} - V_{TN}} \quad | \quad 30 = \frac{15}{V_{GS} - V_{TN}} \quad | \quad V_{GS} - V_{TN} = 0.5 \text{ V}$$

$$I_D = \frac{1mA}{2} (V_{GS} - V_{TN})^2 = 125 \mu\text{A} \quad | \quad \text{Q-point : } (125 \mu\text{A}, 7.5 \text{ V})$$

13.95

$$v_{gs} \leq 0.2(V_{GS} - V_{TN}) \text{ requires } (V_{GS} - V_{TN}) \geq \frac{0.1}{0.2} = 0.5V$$

$A_v = 35dB \rightarrow A_v = -56.2$. Using the rule - of - thumb estimate to select V_{DD} :

$$A_v = -\frac{V_{DD}}{V_{GS} - V_{TN}} \quad \text{and} \quad V_{DD} = 56.2(0.5V) = 28V$$

13.96

$$v_{gs} \leq 0.2(V_{GS} - V_{TN}) \text{ requires } (V_{GS} - V_{TN}) \geq \frac{0.5}{0.2} = 2.5V$$

$A_v = 20dB \rightarrow A_v = -10$. Using the rule - of - thumb estimate to select V_{DD} :

$$A_v = -\frac{V_{DD}}{V_{GS} - V_{TN}} \quad \text{and} \quad V_{DD} = 10(2.5) = 25V$$

13.97

$$\text{We desire } \left(\frac{V_{DD}}{V_{GS} - V_{TN}}\right)^N \geq 1000 \quad | \quad \left(\frac{10}{V_{GS} - V_{TN}}\right)^N \geq 1000$$

For $V_{GS} - V_{TN} = 1V$, $N = 3$ meets the requirements, but with no safety margin.

For $V_{GS} - V_{TN} = 0.75V$, $N = 3$ easily meets the requirements.

13.98

$$\text{For the bias network : } V_{EQ} = 10V \frac{430k\Omega}{430k\Omega + 560k\Omega} = 4.343V \quad | \quad R_{EQ} = 430k\Omega \parallel 560k\Omega = 243k\Omega$$

$$I_D = \frac{5 \times 10^{-4}}{2} (V_{GS} - 1)^2 \quad | \quad V_{GS} = 4.343 - 2 \times 10^4 I_D \rightarrow V_{GS} = 1.72V \quad | \quad I_D = 131\mu A$$

$V_{DS} = 10 - 63k\Omega(131\mu A) = 1.75V \geq V_{GS} - V_{TN}$ so active region assumption is ok.

$$g_m = \sqrt{2(5 \times 10^{-4})(131\mu A)} = 362\mu S \quad | \quad r_o = \frac{\left(\frac{1}{0.0133} + 1.75\right)}{131\mu A} = 586k\Omega$$

$$A_v = -\frac{243k\Omega}{243k\Omega + 1k\Omega} (362\mu S)(586k\Omega \parallel 43k\Omega \parallel 100k\Omega) = -10.3$$

13.99

$$g_m = \sqrt{2 \left(500 \frac{\mu A}{V^2} \right) (100\mu A) (1 + 0.02(5))} = 332\mu S \quad | \quad r_o = \frac{50 + 5V}{100\mu A} = 550k\Omega$$

$$A_v = -\left(\frac{6.8M\Omega}{6.8M\Omega + 0.1M\Omega} \right) (332\mu S)(550k\Omega \parallel 50k\Omega \parallel 120k\Omega) = -10.9$$

13.100

$$g_m^{\max} = \sqrt{2(700\mu A/V^2)(100\mu A)} = 374\mu S \quad | \quad g_m^{\min} = \sqrt{2(300\mu A/V^2)(100\mu A)} = 245\mu S$$

$$A_v = -\left(\frac{6.8M\Omega}{6.8M\Omega + 0.1M\Omega}\right)(g_m) \left(550k\Omega \parallel 50k\Omega \parallel 120k\Omega\right) = (-32.7k\Omega)(g_m)$$

$$A_v^{\max} = -12.2 \quad | \quad A_v^{\min} = -8.01$$

13.101

$$g_m = \sqrt{2(100\mu A/V^2)(10\mu A)(1+0.02(5))} = 46.9\mu S \quad | \quad r_o = \frac{50+5V}{10\mu A} = 5.50M\Omega$$

$$A_v = -\left(\frac{10M\Omega}{10M\Omega + 0.1M\Omega}\right)(46.9\mu S) \left(5.50M\Omega \parallel 560k\Omega \parallel 2.2M\Omega\right) = -19.2$$

13.102

$$g_m = \sqrt{2K_n I_{DS}(1+\lambda V_{DS})} = \sqrt{2(0.001)(0.002)(1+0.015(7.5))} = 2.11 \times 10^{-3} S$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_{DS}} = \frac{\frac{1}{0.015} + 7.5}{0.002} = 37.1k\Omega$$

$$A_{vt} = -g_m(r_o \parallel R_D \parallel R_3) = -2.11 \times 10^{-3} (37.1k\Omega \parallel 3.9k\Omega \parallel 270k\Omega) = -7.35$$

$$A_v = \frac{10M\Omega}{10k\Omega + 10M\Omega} A_{vt} = -7.34$$

13.103

*Problem 13.103 - NMOS Common-Source Amplifier - Figure P13.6

VDD 7 0 DC 15

*FOR OUTPUT RESISTANCE

*VO 6 0 AC 1

*VI 1 0 AC 0

VI 1 0 AC 1

RI 1 2 1K

C1 2 3 100UF

R1 3 0 1MEG

R2 7 3 2.7MEG

R4 4 0 27K

C2 4 0 100UF

RD 7 5 82K

C3 5 6 100UF

R3 6 0 470K

M1 5 3 4 4 NFET

.OP

.MODEL NFET NMOS KP=250U VTO=1

.AC LIN 1 1000 1000

.PRINT AC VM(6) VDB(6) VP(6) IM(VI) IP(VI)

*.PRINT AC IM(C3) IP(C3)

.END

Results: ID = 8.29E-05 VGS = 1.81E+00 VDS = 5.96E+00

VM(6) = 1.420E+01 VP(6) = -1.800E+02 IM(VI) = 1.369E-06 IP(VI) = -1.800E+02

VM(3) = 9.986E-01 VP(3) = 1.248E-04 IM(C3) = 1.220E-05 IP(C3) = -1.800E+02

$$A_v = -14.6 \quad | \quad R_{in} = \frac{VM(3)}{IM(VI)} = \frac{0.9986}{1.369\mu A} = 729 \text{ k}\Omega \quad | \quad R_{out} = \frac{1}{IM(C3)} = \frac{1}{12.20\mu A} = 82.0 \text{ k}\Omega$$

13.104

*Problem 13.104 - PMOS Common-Source Amplifier - Figure P13.8

VDD 7 0 DC 18

*FOR OUTPUT RESISTANCE

*VO 6 0 AC 1

*VI 1 0 AC 0

*

VI 1 0 AC 1

RI 1 2 1K

C1 2 3 100U

R2 7 3 3.3MEG

R1 3 0 3.3MEG

R4 7 4 22K

C2 7 4 100U

RD 5 0 24K

C3 5 6 100U

R3 6 0 470K

M1 5 3 4 4 PFET

.OP

.MODEL PFET PMOS KP=400U VTO=-1

.AC LIN 1 1000 1000

.PRINT AC VM(6) VDB(6) VP(6) IM(VI) IP(VI) VM(3) VP(3)

*.PRINT AC IM(C3) IP(C3)

.END

Results: ID = 3.07E-04 VGS = -2.24E+00 VDS = -3.86E+00

VM(6) = 12.76E+01 VP(6) = -1.799E+02 IM(VI) = 6.057E-07 IP(VI) = -1.800E+02

VM(3) = 9.994E-01 VP(3) = 5.523E-05 IM(C3) = 4.167E-05 IP(C3) = -1.800E+02

$$A_v = -12.8 \mid R_{in} = \frac{VM(3)}{IM(VI)} = \frac{0.9994V}{0.6057\mu A} = 1.65 M\Omega \mid R_{out} = \frac{1}{IM(C3)} = \frac{1}{41.67\mu A} = 24.0 k\Omega$$

13.105

*Problem 13.105 - Depletion-mode NMOS Common-Source Amplifier - Figure P13.11

VDD 7 0 DC 18

*FOR OUTPUT RESISTANCE

*VO 6 0 AC 1

*VI 1 0 AC 0

*

VI 1 0 AC 1

RI 1 2 10K

C1 2 3 100UF

RG 3 0 10MEG

R1 4 0 2K

C3 4 0 100UF

RD 7 5 3.9K

C2 5 6 100UF

R3 6 0 36K

J1 5 3 4 NFET

.OP

.MODEL NFET NMOS KP=400U VTO=-5

.AC LIN 1 1000 1000

.PRINT AC VM(6) VDB(6) VP(6) IM(VI) IP(VI) VM(3) VP(3)

*.PRINT AC IM(C2) IP(C2)

.END

Results: ID = 1.25E-03 VGS = -2.50E+00 VDS = -1.06E+01

VM(6) = 3.515E+00 VP(6) = -1.799E+02 IM(VI) = 9.991E-08 IP(VI) = -1.800E+02

VM(3) = 9.990E-01 VP(3) = 9.106E-06 IM(C3) = 2.564E-04 IP(C3) = -1.800E+02

$$A_v = -3.52 \quad | \quad R_{in} = \frac{VM(3)}{IM(VI)} = \frac{0.9990V}{99.91nA} = 10.0 M\Omega \quad | \quad R_{out} = \frac{1}{IM(C3)} = \frac{1}{256.4\mu A} = 3.90 k\Omega$$

13.106

SPICE Results: Q-point: (1.01 mA, 7.41 V), $A_v = 15.1$ dB, $R_{in} = 2.20 M\Omega$, $R_{out} = 7.50 k\Omega$

13.107

$$g_m = 40(50\mu A) = 2.00mS \quad | \quad r_\pi = \frac{100}{2.00mS} = 50k\Omega \quad | \quad r_o = \frac{75V + 10V}{50\mu A} = 1.70M\Omega$$

$$R_{in} = R_B \parallel r_\pi = 100k\Omega \parallel 50k\Omega = 33.3k\Omega \quad | \quad R_{out} = 1.7M\Omega \parallel 100k\Omega = 94.4k\Omega$$

13.108

$$R_{in} = R_B \parallel r_\pi \quad | \quad r_\pi^{\min} = \frac{60}{40(50\mu A)} = 30k\Omega \quad | \quad r_\pi^{\max} = \frac{100}{40(50\mu A)} = 50k\Omega$$

$$R_{in}^{\min} = R_B \parallel r_\pi = 100k\Omega \parallel 30k\Omega = 23.1k\Omega \quad | \quad R_{in}^{\max} = R_B \parallel r_\pi = 100k\Omega \parallel 50k\Omega = 33.3k\Omega$$

$$R_{out} = R_C \parallel r_o = 100k\Omega \parallel \frac{75+10}{50\mu A} = 100k\Omega \parallel 1.7M\Omega = 94.4k\Omega \text{ independent of } \beta_o$$

13.109

$$r_\pi = \frac{40(0.025V)}{1\mu A} = 1.00M\Omega \quad | \quad r_o = \frac{50+1.5}{1} \frac{V}{\mu A} = 51.5M\Omega$$

$$R_{in} = R_B \parallel r_\pi = 5M\Omega \parallel 1M\Omega = 833k\Omega \quad | \quad R_{out} = R_C \parallel r_o = 1.5M\Omega \parallel 51.5M\Omega = 1.46M\Omega$$

13.110

$$r_\pi = \frac{75(0.025V)}{2.5mA} = 750\Omega \quad | \quad r_o = \frac{50+7.5}{2.5} \frac{V}{mA} = 23.0k\Omega$$

$$R_{in} = R_B \parallel r_\pi = 4.7k\Omega \parallel 0.75k\Omega = 647\Omega \quad | \quad R_{out} = R_C \parallel r_o = 4.3k\Omega \parallel 23k\Omega = 3.62k\Omega$$

13.111

From Prob. 13.98 : Q - Point = (131μA, 1.75V)

$$R_{in} = R_l \parallel R_2 = 430k\Omega \parallel 560k\Omega = 243k\Omega \quad | \quad R_{out} = 43k\Omega \parallel r_o$$

$$r_o = \frac{\left(\frac{1}{0.0133} + 1.75\right)V}{0.131mA} = 587k\Omega \quad | \quad R_{out} = 43k\Omega \parallel 587k\Omega = 40.1k\Omega$$

13.112

$$R_{in} = R_G = 6.8M\Omega \quad | \quad R_{out} = 50k\Omega \parallel r_o$$

$$r_o = \frac{(50+5)V}{0.1mA} = 550k\Omega \quad | \quad R_{out} = 50k\Omega \parallel 550k\Omega = 45.8k\Omega$$

13.113

$R_{in} = R_G = 6.8M\Omega$ which is independent of K_n | $R_{out} = R_D \parallel r_o$

$$r_o = \frac{\left(\frac{1}{0.02} + 5\right)V}{0.1mA} = 550k\Omega \quad | \quad R_{out} = 50k\Omega \parallel 550k\Omega = 45.8k\Omega, \text{ also independent of } K_n$$

13.114

$$R_{in} = R_G = 10M\Omega \quad | \quad R_{out} = R_D \parallel r_o \quad | \quad r_o = \frac{\left(\frac{1}{0.02} + 5\right)V}{10\mu A} = 5.50 M\Omega$$

$$R_{out} = 560k\Omega \parallel 5.50 M\Omega = 508 k\Omega$$

13.115

$$R_{in} = R_G = 1M\Omega \quad | \quad R_{out} = R_D \parallel r_o \quad | \quad r_o = \frac{\left(\frac{1}{0.015} + 7.5\right)V}{2mA} = 37.1 k\Omega$$

$$R_{out} = 3.9k\Omega \parallel 37.1k\Omega = 3.53 k\Omega$$

13.116

$$g_m = 40(50\mu A) = 2.00mS \quad | \quad r_\pi = \frac{100}{2.00mS} = 50k\Omega \quad | \quad r_o = \frac{75V + 10V}{50\mu A} = 1.70M\Omega$$

$$R_{BB} = R_B \parallel r_\pi = 100k\Omega \parallel 50k\Omega = 33.3k\Omega$$

$$v_{th} = -v_i \left(\frac{33.3k\Omega}{33.3k\Omega + 0.75k\Omega} \right) (2mS)(1.70M\Omega \parallel 100k\Omega) = -185v_i$$

$$R_{th} = 1.70M\Omega \parallel 100k\Omega = 94.4 k\Omega$$

13.117

$$g_m = 40(2.5mA) = 100mS \quad | \quad r_\pi = \frac{75}{100mS} = 750\Omega \quad | \quad r_o = \frac{50V + 7.5V}{2.5mA} = 23.0k\Omega$$

$$R_{BB} = R_B \parallel r_\pi = 4.7k\Omega \parallel 0.75k\Omega = 647\Omega$$

$$v_{th} = -v_i \left(\frac{647\Omega}{647\Omega + 50\Omega} \right) (100mS)(23.0k\Omega \parallel 4.3k\Omega) = -336v_i$$

$$R_{th} = 23.0k\Omega \parallel 4.3k\Omega = 3.62 k\Omega$$

13.118

$$g_m = \sqrt{2(500\mu A/V^2)(100\mu A)(1 + 0.02(5))} = 332\mu S \quad | \quad r_o = \frac{(50 + 5)V}{100\mu A} = 550k\Omega$$

$$v_{th} = -v_i \left(\frac{6.8M\Omega}{6.8M\Omega + 0.1M\Omega} \right) (332\mu S)(550k\Omega \parallel 50k\Omega) = -15.0v_i$$

$$R_{th} = 550k\Omega \parallel 50k\Omega = 45.8 k\Omega$$

13.119

$$g_m = \sqrt{2(100\mu A/V^2)(10\mu A)(1+0.02(5))} = 46.9\mu S \quad | \quad r_o = \frac{(50+5)V}{10\mu A} = 5.50 M\Omega$$

$$v_{th} = -v_i \left(\frac{10M\Omega}{10M\Omega + 0.1M\Omega} \right) (46.9\mu S)(5.50 M\Omega \| 560k\Omega) = -23.6v_i$$

$$R_{th} = 5.50 M\Omega \| 560k\Omega = 508 k\Omega$$

13.120

SPICE Results: Q-point: (242 μA , 3.61 V), $A_v = 31.1$ dB, $R_{in} = 14.8$ k Ω , $R_{out} = 9.81$ k Ω

13.121

$$0 = 10000I_B + 0.7 + 66(1615)I_B - 5 \quad I_B = 36.9 \mu A \quad | \quad I_C = 65I_B = 2.40 mA$$

$$V_{CE} = 5 - 1000I_C - 1615I_E - (-5) = 3.66 V \quad Q\text{-point: } (2.40 mA, 3.66 V)$$

$$g_m = 40(2.40mA) = 96.0mS \quad | \quad r_\pi = \frac{65}{96.0mS} = 677 \Omega \quad | \quad r_o = \frac{50V + 3.66V}{2.40mA} = 22.4 k\Omega$$

$$R_{in} = R_B \| r_\pi (1 + g_m R_E) = 10k\Omega \| 677\Omega [1 + 0.096(15)] = 1.42 k\Omega$$

$$A_v = -\left(\frac{1.42k\Omega}{0.33k\Omega + 1.42k\Omega} \right) \frac{96.0mS}{1 + 0.096(15)} (1k\Omega \| 220k\Omega) = -31.8$$

$$R_{out} = 1k\Omega \| 22.4k\Omega [1 + 0.096(15)] = 982 \Omega$$

13.122

SPICE Results: Q-point: (2.39 μA , 3.69 V), $A_v = 29.7$ dB, $R_{in} = 1.49$ k Ω , $R_{out} = 977$ Ω

The results agree closely with the hand calculations in Prob. 13.121. The small disagreements arise from the differences between the two methods.

13.123

$$0 = 10^6 I_B + 0.7 + 66(161.5k\Omega)I_B - 5 \quad I_B = 0.369 \mu A \quad | \quad I_C = 65I_B = 24.0 \mu A$$

$$V_{CE} = 5 - 1000I_C - 1615I_E - (-5) = 3.66 V \quad Q\text{-point: } (24.0 \mu A, 3.66 V)$$

$$g_m = 40(24.0\mu A) = 0.959mS \quad | \quad r_\pi = \frac{65}{0.959mS} = 67.8 k\Omega \quad | \quad r_o = \frac{50V + 3.66V}{24.0\mu A} = 2.24 M\Omega$$

$$R_{in} = R_B \| r_\pi (1 + g_m R_E) = 1M\Omega \| 67.8k\Omega [1 + 0.959mS(1.5k\Omega)] = 142 k\Omega$$

$$A_v = -\left(\frac{142k\Omega}{0.33k\Omega + 142k\Omega} \right) \frac{0.959mS}{1 + 0.959mS(1.5k\Omega)} (100k\Omega \| 220k\Omega) = -27.0$$

$$R_{out} = 100k\Omega \| 2.24 M\Omega [1 + 0.959mS(1.5k\Omega)] = 98.2 k\Omega$$

13.124

SPICE Results: Q-point: (24.6 μ A, 3.52 V), $A_v = 28.4$ dB, $R_{in} = 148$ k Ω , $R_{out} = 98.1$ k Ω
The results agree closely with the hand calculations in Prob. 13.123. The small disagreements arise from the fact that the results are slightly different.

13.125

SPICE Results: Q-point: (251 μ A, 4.45 V), $A_v = 16.3$ dB, $R_{in} = 1.00$ M Ω , $R_{out} = 28.7$ k Ω
The results agree closely with the hand calculations in Ex. 13.10.

13.126

*Problem 13.126 - NMOS Common-Source Amplifier - Figure P13.98

VDD 7 0 DC 10

*FOR OUTPUT RESISTANCE

*VO 6 0 AC 1

*VI 1 0 AC 0

*

VI 1 0 AC 1

RI 1 2 1K

C1 2 3 100U

R1 3 0 430K

R2 7 3 560K

R4 4 0 20K

C3 4 0 100U

RD 7 5 43K

C2 5 6 100U

R3 6 0 100K

M1 5 3 4 4 NFET

.OP

.MODEL NFET NMOS KP=500U VTO=1 LAMBDA=0.0133

.AC LIN 1 1000 1000

.PRINT AC VM(6) VDB(6) VP(6) VM(3) VP(3) IM(VI) IP(VI)

*.PRINT AC IM(C2) IP(C2)

.END

Results: ID = 1.31E-04 VDS = 1.73E+00

VM(6) = 1.044E+01 VP(6) = -1.800E+02 IM(VI) = 4.094E-06 IP(VI) = -1.800E+02

VM(3) = 9.959E-01 VP(3) = 3.734E-04 IM(C3) = 2.496E-05 IP(C3) = -1.800E+02

$$A_v = -10.4 \quad | \quad R_{in} = \frac{VM(3)}{IM(VI)} = \frac{0.9959V}{4.094\mu A} = 243 \text{ k}\Omega \quad | \quad R_{out} = \frac{1}{IM(C3)} = \frac{1}{24.96\mu A} = 40.1 \text{ k}\Omega$$

13.127

$$I_B = 3.71\mu A \quad I_C = 241\mu A \quad I_E = 245\mu A \quad V_{CE} = 3.67V$$

$$P_{R_B} = I_B^2 R_B = (3.71\mu A)^2 (100k\Omega) = 1.38 \text{ } \mu W \quad | \quad P_{R_C} = I_C^2 R_C = (241\mu A)^2 (10k\Omega) = 0.581 \text{ } mW$$

$$P_{R_E} = I_E^2 R_E = (245\mu A)^2 (16k\Omega) = 0.960 \text{ } mW$$

$$P_{BJT} = I_C V_{CE} + I_B V_{BE} = (241\mu A)(3.67V) + (3.71\mu A)(0.7V) = 0.887 \text{ } mW$$

$$P_S = 5V(241\mu A) + (-5V)(-245\mu A) = 2.43 \text{ } mW \quad | \quad P_S = P_{R_B} + P_{R_C} + P_{R_E} + P_Q$$

13.128

$$I_D = 250\mu A \quad V_{DS} = 4.75V$$

$$P_{JFET} = I_D V_{DS} = (250\mu A)(4.75V) = 1.19 \text{ } mW \quad | \quad P_{R_D} = I_D^2 R_D = (250\mu A)^2 (27k\Omega) = 1.69 \text{ } mW$$

$$P_{R_4} = I_D^2 R_4 = (250\mu A)^2 (2k\Omega) = 0.125 \text{ } mW \quad | \quad P_{R_G} = 0$$

$$P_S = 12V(250\mu A) = 3.00 \text{ } mW \quad | \quad P_{JFET} + P_{R_D} + P_{R_4} + P_{R_G} = 3.00 \text{ } mW$$

13.129

Using the values from Prob. 13.17:

$$I_B = 23.8\mu A \quad I_C = 1.78mA \quad I_E = 1.81mA \quad V_{CE} = 6.08V \quad V_B = -4.09V$$

$$P_{R_1} = \frac{V_1^2}{R_1} = \frac{(-4.09 - (-12))^2 V^2}{5000\Omega} = 12.5 \text{ } mW \quad | \quad P_{R_2} = \frac{V_2^2}{R_2} = \frac{(12 - (-4.09))^2 V^2}{10000\Omega} = 25.9 \text{ } mW$$

$$P_{R_C} = I_C^2 R_C = (1.78mA)^2 (6k\Omega) = 19.0 \text{ } mW \quad | \quad P_{R_E} = I_E^2 R_E = (1.81mA)^2 (4k\Omega) = 13.0 \text{ } mW$$

$$P_{BJT} = I_C V_{CE} + I_B V_{BE} = (1.78mA)(6.08V) + (23.8\mu A)(0.7V) = 10.8 \text{ } mW$$

$$P_S = 12V \left[1.78mA + \frac{12 - (-4.09)V}{10000\Omega} \right] + 12V \left[1.81mA + \frac{-4.09 - (-12)V}{5000\Omega} \right] = 81.3 \text{ } mW$$

$$P_S = P_{R_1} + P_{R_2} + P_{R_C} + P_{R_E} + P_{BJT} = 81.2 \text{ } mW$$

13.130

Using the values from Prob. 13.19:

$$I_B = 1.51\mu A \quad I_C = 98.4\mu A \quad I_E = 99.9\mu A \quad V_{CE} = 4.96V$$

$$P_{R_B} = I_B^2 R_B = (1.51\mu A)^2 3k\Omega = 6.84 \text{ } nW \quad | \quad P_{R_C} = I_C^2 R_C = (98.4\mu A)^2 (33k\Omega) = 0.320 \text{ } mW$$

$$P_{R_E} = I_E^2 R_E = (99.9\mu A)^2 (68k\Omega) = 0.679 \text{ } mW$$

$$P_{BJT} = I_C V_{CE} + I_B V_{BE} = (98.4\mu A)(4.96V) + (1.51\mu A)(0.7V) = 0.489 \text{ } mW$$

$$P_S = 7.5(98.4\mu A) + 7.5V(99.9\mu A) = 1.49 \text{ } mW \quad | \quad P_S = P_{R_B} + P_{R_C} + P_{R_E} + P_{BJT} = 1.49 \text{ } mW$$

13.131

Using the values from Prob. 13.23: $I_D = 82.2\mu A$ $V_{DS} = 6.04V$

$$P_{FET} = I_D V_{DS} = (82.2\mu A)(6.04V) = 0.497 \text{ mW} \quad | \quad P_{R_D} = I_D^2 R_D = (82.2\mu A)^2 (82k\Omega) = 0.554 \text{ mW}$$

$$P_{R_4} = I_D^2 R_4 = (82.2\mu A)^2 (27k\Omega) = 0.182 \text{ mW} \quad | \quad I_2 = \frac{15V}{3.7M\Omega} = 4.05\mu A$$

$$P_{R_1} = I_2^2 R_1 = (4.05\mu A)^2 (1M\Omega) = 16.4 \mu W \quad | \quad P_{R_2} = I_2^2 R_2 = (4.05\mu A)^2 (2.7M\Omega) = 44.3 \mu W$$

$$P_S = 15V(82.2\mu A + 4.05\mu A) = 1.29 \text{ mW} \quad | \quad P_{FET} + P_{R_D} + P_{R_4} + P_{R_1} + P_{R_2} = 1.29 \text{ mW}$$

13.132

Using the values from Prob. 13.27: $I_D = 307\mu A$ $V_{SD} = 3.88V$

$$P_{FET} = I_D V_{SD} = (307\mu A)(3.88V) = 1.19 \text{ mW} \quad | \quad P_{R_D} = I_D^2 R_D = (307\mu A)^2 (24k\Omega) = 2.26 \text{ mW}$$

$$P_{R_4} = I_D^2 R_4 = (307\mu A)^2 (22k\Omega) = 2.07 \text{ mW} \quad | \quad I_2 = \frac{18V}{6.6M\Omega} = 2.73\mu A$$

$$P_{R_1} = I_2^2 R_1 = (2.73\mu A)^2 (3.3M\Omega) = 24.6 \mu W \quad | \quad P_{R_2} = I_2^2 R_2 = (2.73\mu A)^2 (3.3M\Omega) = 24.6 \mu W$$

$$P_S = 18V(307\mu A + 2.73\mu A) = 5.58 \text{ mW} \quad | \quad P_{FET} + P_{R_D} + P_{R_4} + P_{R_1} + P_{R_2} = 5.57 \text{ mW}$$

13.133

Using the values from Prob. 13.33: $I_D = 1.25mA$ $V_{DS} = 10.6V$

$$P_{FET} = I_D V_{DS} = (1.25mA)(10.6V) = 13.3 \text{ mW} \quad | \quad P_{R_D} = I_D^2 R_D = (1.25mA)^2 (3.9k\Omega) = 6.09 \text{ mW}$$

$$P_{R_S} = I_D^2 R_S = (1.25mA)^2 (1k\Omega) = 1.56 \text{ mW} \quad | \quad P_{R_4} = I_D^2 R_4 = (1.25mA)^2 (1k\Omega) = 1.56 \text{ mW}$$

$$P_{R_G} = I_G^2 R_G = 0 \quad P_S = 18V(1.25mA) = 22.5 \text{ mW} \quad | \quad P_{FET} + P_{R_D} + P_{R_S} + P_{R_1} = 22.5 \text{ mW}$$

13.134

$$I_C = \frac{V_{CC}}{3R_C} \quad | \quad i_c \leq 0.2I_C \quad | \quad v_c = i_c R_C \leq 0.2 \frac{V_{CC}}{3R_C} R_C = \frac{V_{CC}}{15}$$

13.135

$$|i_d| \leq 0.4I_D \quad | \quad I_D = \frac{500 \times 10^{-6}}{2} (0 - (-1.5))^2 = 563 \mu A$$

$$|v_{gs}| \leq 0.2(V_{GS} - V_{TN}) = 0.2(0 - (-1.5)) = 0.3 V$$

$$v_{ds} = i_d R_D \leq 0.4(563\mu A)(15k\Omega) = 3.38 V$$

To insure saturation: $v_{DS} \geq v_{GS} - V_{TN} = v_{gs} - V_{TN} = 0.3 - (-1.5) = 1.8 V$

$$V_{DD} \geq 1.8 + 3.38 + (563\mu A)(15k\Omega) = 13.6 V$$

13.136

Assuming $\frac{V_{CC}}{2} \gg V_{CESAT}$:

$$|v_o| \leq \frac{V_{CC}}{2} \quad |P_{dc}| = V_{CC} \left(\frac{V_{CC}}{2R_L} \right) = \frac{V_{CC}^2}{2R_L} \quad |P_{ac}| = \frac{1}{2} \left(\frac{V_{CC}}{2} \right)^2 \frac{1}{R_L} = \frac{V_{CC}^2}{8R_L} \quad |\varepsilon| = 100\% \frac{\frac{V_{CC}^2}{8R_L}}{\frac{V_{CC}^2}{2R_L}} = 25\%$$

13.137

The Q - point from problem 13.21 is (371μA, 2.72V).

$$|v_o| \leq g_m |v_{be}| (r_o \| R_C \| R_3) = 40 (371\mu A) (5mV) (\infty \| 13k\Omega \| 100k\Omega) = 0.854 V$$

13.138

The Q - point from Problem 13.23 is (82.2μA, 6.04V).

$$|i_d| \leq 0.4I_D = 32.9\mu A \quad |v_{ds}| \leq 0.4I_D (r_o \| R_D \| R_3) = 32.9\mu A (\infty \| 82k\Omega \| 470k\Omega) = 2.30V$$

13.139

The Q - point from Problem 13.27 is (307μA, 3.88V).

$$|i_d| \leq 0.4I_D = 307\mu A \quad |v_o| \leq 0.4I_D (r_o \| R_L \| R_3) = 307\mu A (\infty \| 24k\Omega \| 470k\Omega) = 2.80V$$

Checking the bias point : $V_{R_D} = 307\mu A (24k\Omega) = 7.37V \quad | \quad 2.80 < 7.37 \quad \& \quad 2.80 < 3.88 - 1$

13.140

The Q - point from problem 13.17 is (1.78mA, 6.08V).

$$|i_c| \leq 0.2I_C = 0.356 mA \quad |v_c| \leq 0.2I_C (r_o \| R_C \| R_3) = 0.356mA (\infty \| 6k\Omega \| 100k\Omega) = 2.02V$$

13.141

The Q - point from problem 13.33 is (1.25 mA, 10.6 V). Neglecting r_o ,

$$|i_d| \leq 0.4I_D = 0.500mA \quad |v_d| \leq 0.4I_D (R_D \| R_3) = 0.500mA (3.9k\Omega \| 36k\Omega) = 1.76 V$$

13.142

The Q - point from problem 13.35 is (1.01 mA, 7.41 V).

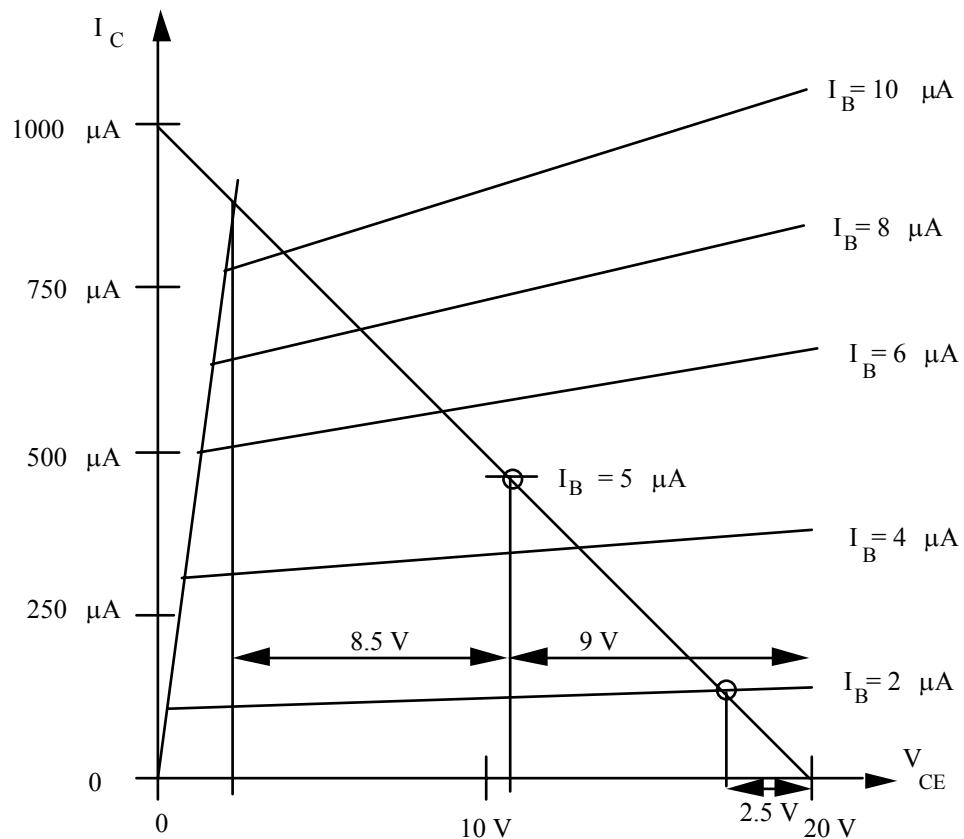
$$|i_d| \leq 0.4I_D = 0.404mA \quad |v_d| \leq 0.4I_D (R_D \| R_3) = 0.404mA (7.5k\Omega \| 220k\Omega) = 2.93 V$$

13.143

$V_{CE} = 20 - 20000I_C$: Two points on the load line ($0mA, 20V$) , ($1mA, 0V$)

At $I_B = 2\mu A$, the maximum swing is approximately 2.5 V limited by V_{RE} .

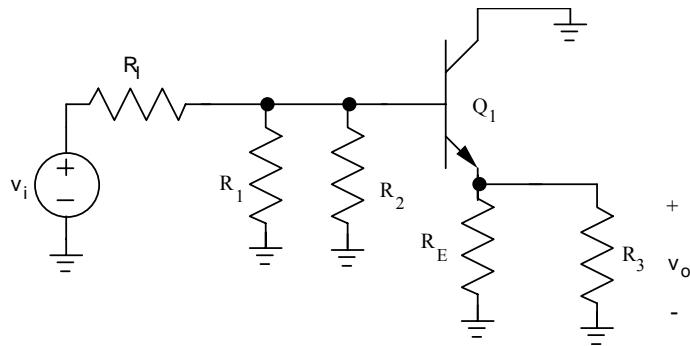
For $I_B = 5\mu A$, the maximum swing is approximately - 8.5 V limited by V_{CE} .



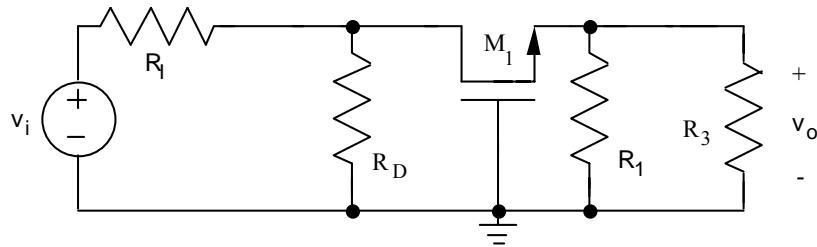
CHAPTER 14

14.1

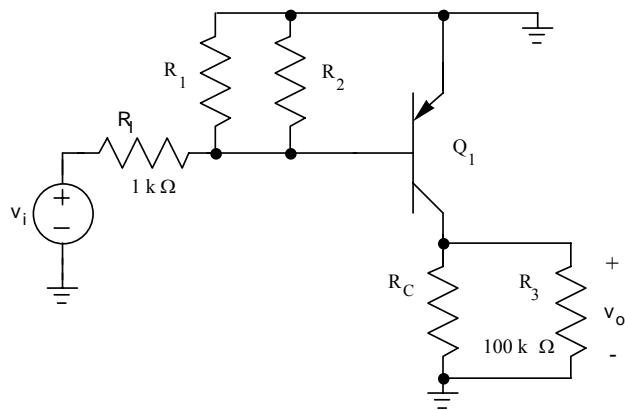
(a) Common-collector Amplifier (npn) (emitter-follower)



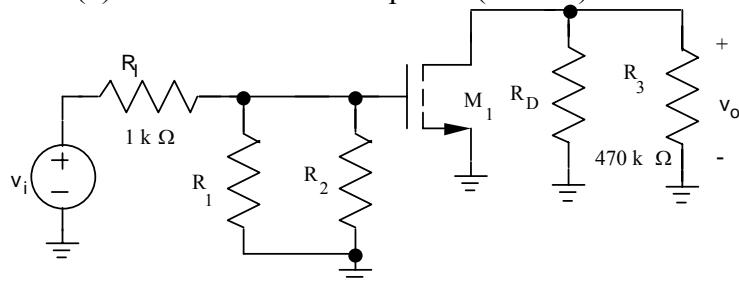
(b) Not a useful circuit because the signal is injected into the drain of the transistor.



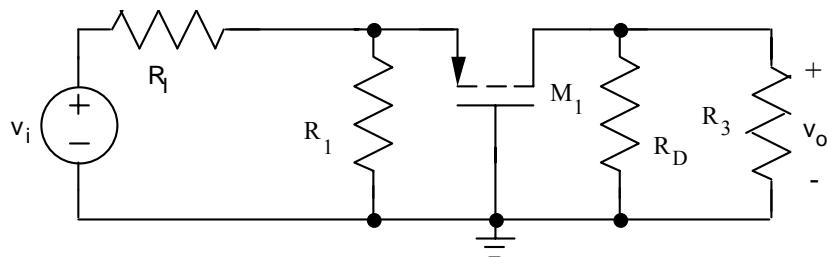
(c) Common-emitter Amplifier (pnp)



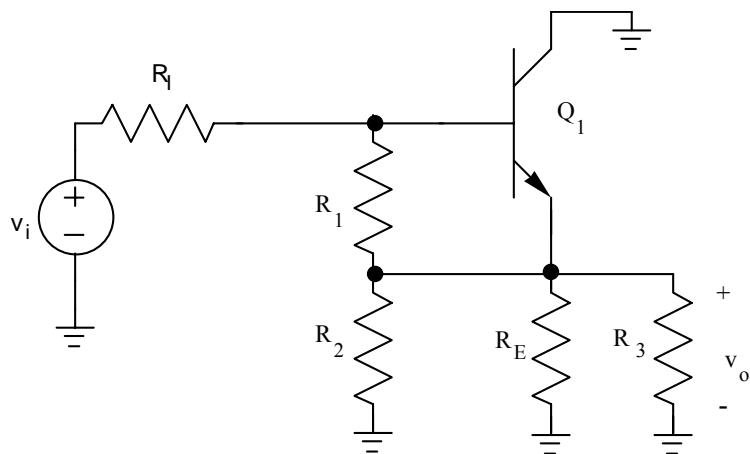
14.1 (d) Common-source Amplifier (NMOS)



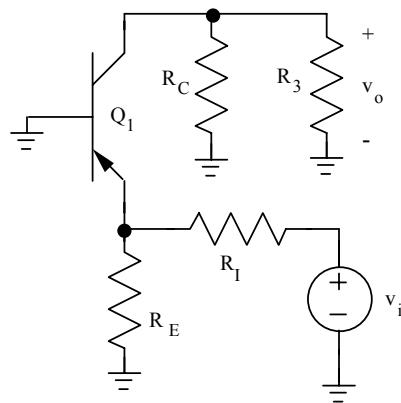
(e) Common-gate Amplifier (PMOS)



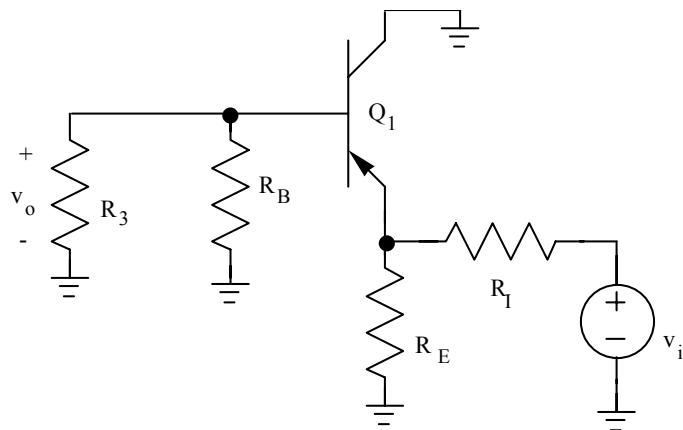
(f) Common-collector Amplifier (emitter-follower) (npn)



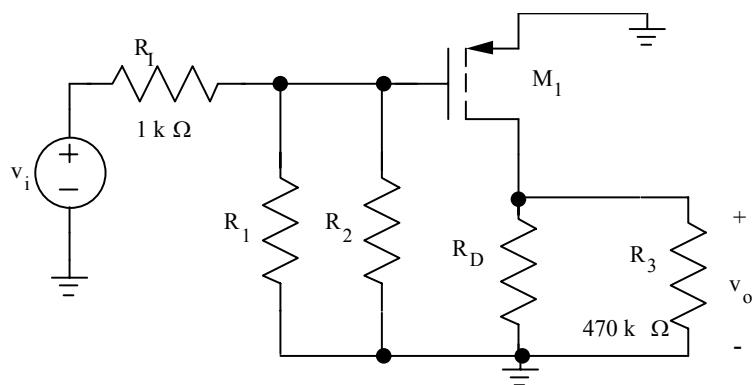
14.1(h) Common-base Amplifier (pnp)



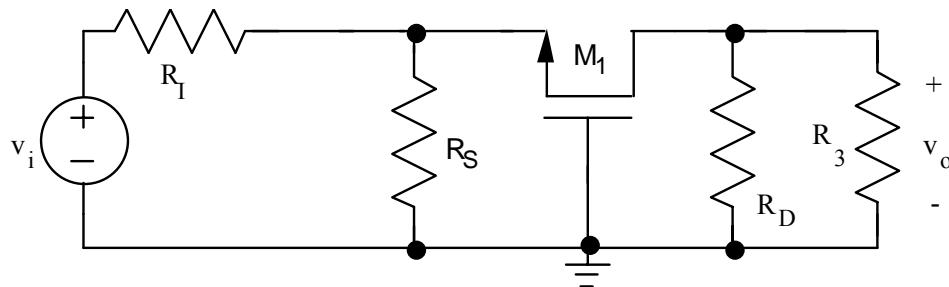
(i) Not a useful circuit since the signal is being taken out of the base terminal.



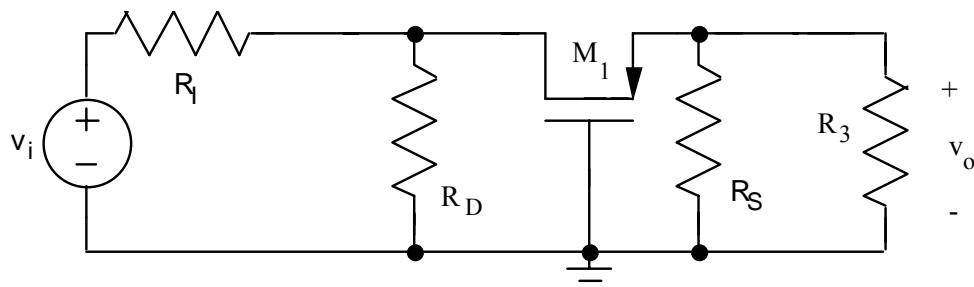
(j) Common-source Amplifier (PMOS)



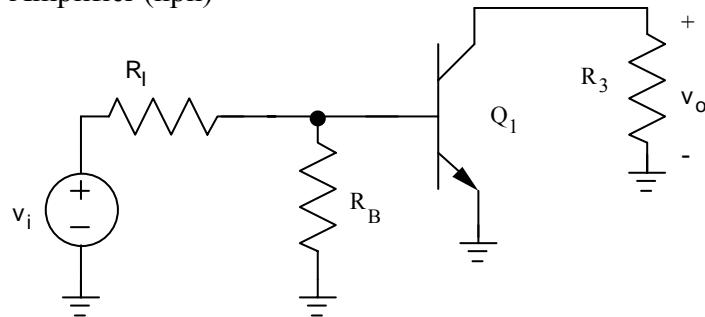
14.1(k) Common-gate Amplifier (Depletion-mode NMOS)



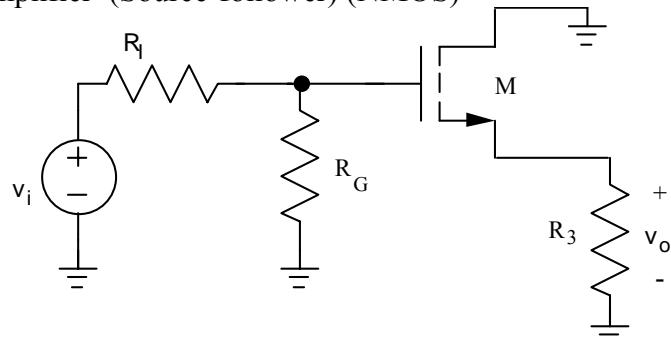
(l) Not a useful circuit because the signal is injected into the drain of the transistor.



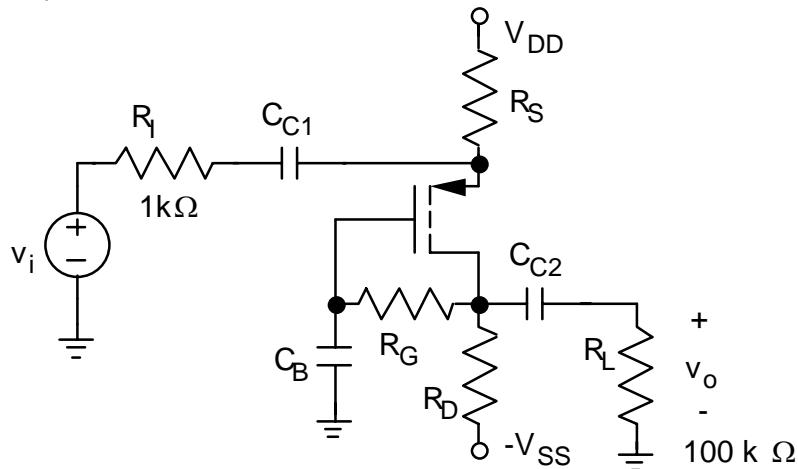
(n) Common-emitter Amplifier (npn)



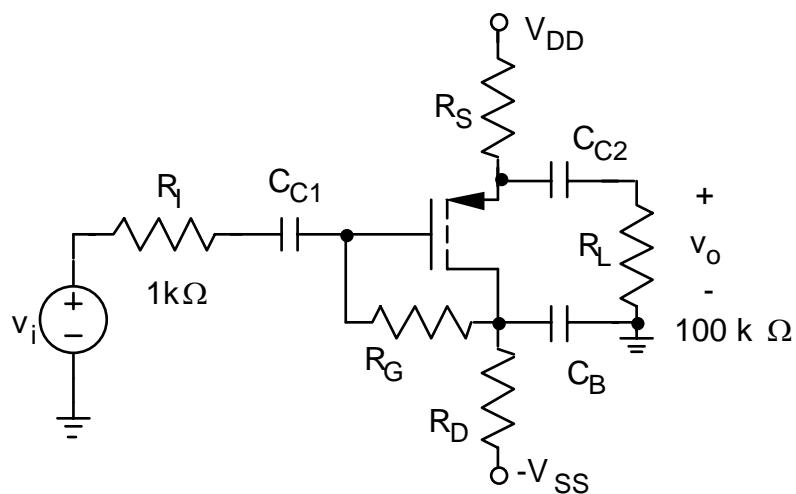
(o) Common-drain Amplifier (Source-follower) (NMOS)



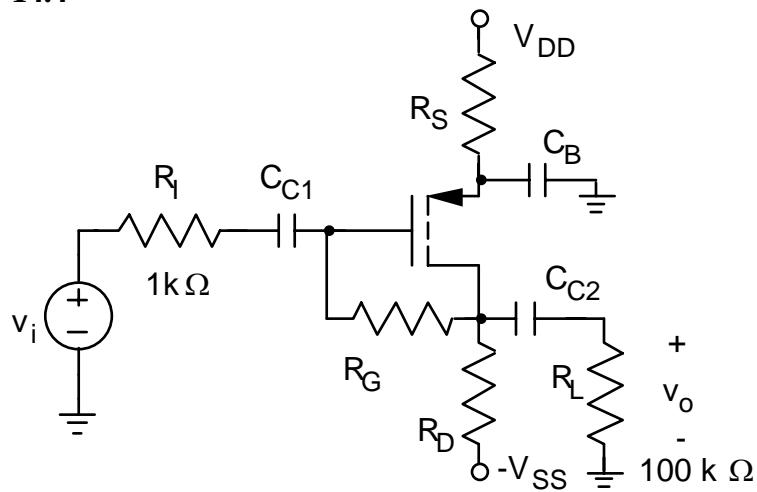
14.2



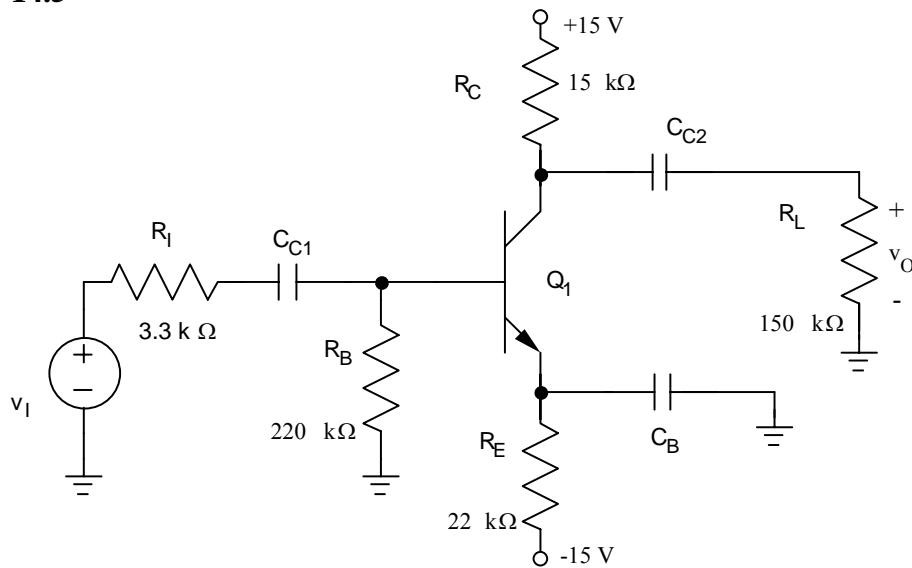
14.3



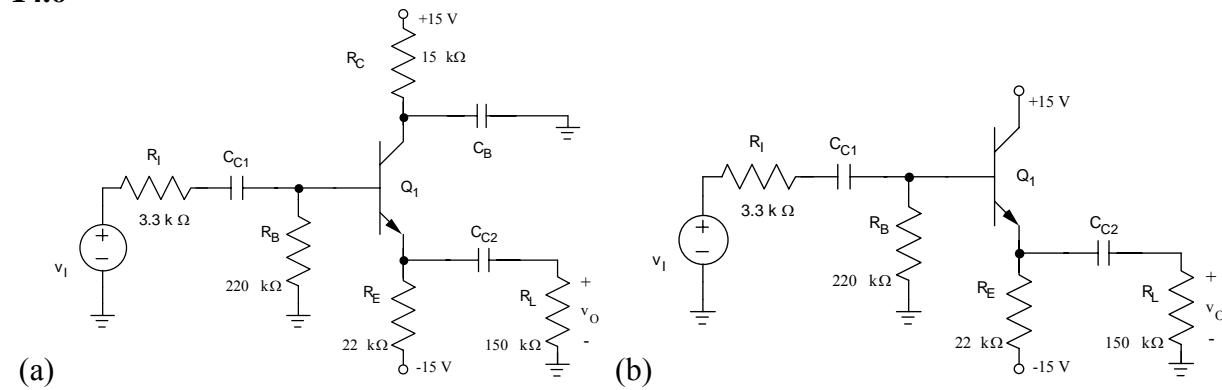
14.4



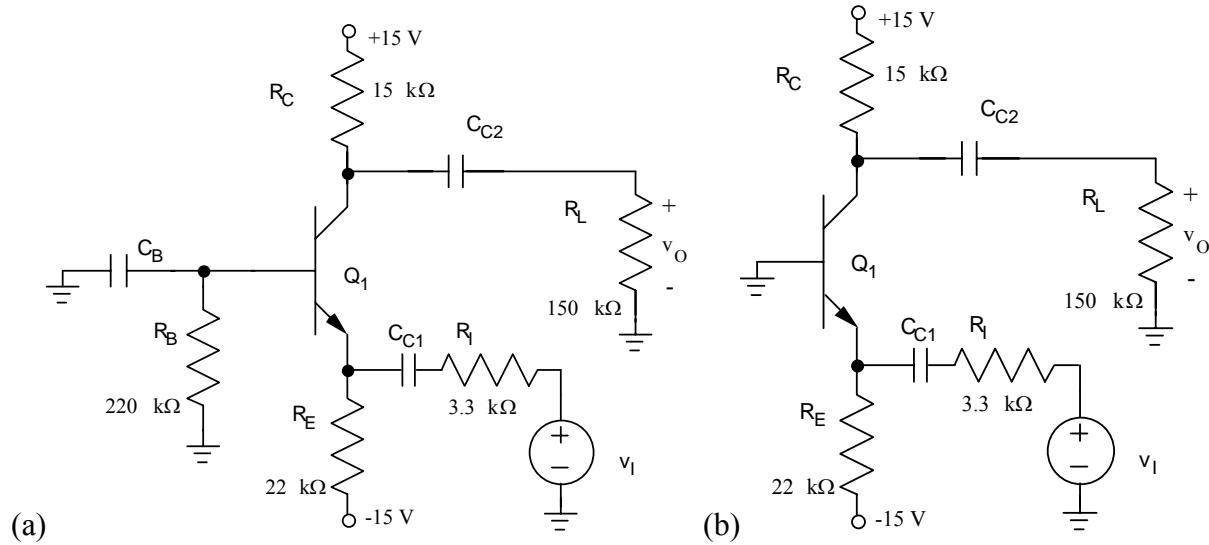
14.5



14.6



14.7



14.8

$$(a) \text{ Neglecting } R_{out} : A_{vt} = -\frac{g_m R_L}{1 + g_m R_S} = -\frac{(0.005S)(2000\Omega)}{1 + (0.005S)(330\Omega)} = -3.77$$

$$A_v = A_{vt} \frac{R_G}{R_I + R_G} = -3.77 \left(\frac{2M\Omega}{75k\Omega + 2M\Omega} \right) = -3.64 \quad | \quad R_{in} = R_G = 2M\Omega$$

$$R_{out} = r_o (1 + g_m R_S) = 10k\Omega [1 + (0.005S)(330\Omega)] = 26.5 k\Omega \gg 2k\Omega$$

$$A_i = -R_G \frac{g_m}{1 + g_m R_S} = -2M\Omega \frac{0.005S}{1 + (0.005S)(330\Omega)} = -3770$$

$$(b) A_v = -g_m \left(R_L \| r_o \left(\frac{R_G}{R_I + R_G} \right) \right) = -(0.005S)(2k\Omega \| 10k\Omega) \left(\frac{2M\Omega}{75k\Omega + 2M\Omega} \right) = -8.03$$

$$R_{in} = R_G = 2M\Omega \quad | \quad R_{out} = r_o = 10.0 k\Omega \quad | \quad A_i = -R_G g_m = -2M\Omega(0.005S) = -10000$$

14.9

$$(a) g_m = 0.02S \quad | \quad r_\pi = \frac{75}{.02} = 3750\Omega$$

$$R_{in} = R_B \parallel [r_\pi + (\beta_o + 1)R_E] = 15k\Omega \parallel [3750\Omega + 76(300\Omega)] = 9.58 k\Omega$$

$$\text{Neglecting } R_{out} : A_v = A_{vt} \left(\frac{R_{in}}{R_I + R_{in}} \right) = -\frac{\beta_o R_L}{r_\pi + (\beta_o + 1)R_E} \left(\frac{R_{in}}{R_I + R_{in}} \right)$$

$$A_v = -\frac{75(12k\Omega)}{3750\Omega + 76(300\Omega)} \left(\frac{9.58k\Omega}{500\Omega + 9.58 k\Omega} \right) = -32.2$$

$$R_{out} \cong r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 100k\Omega \left[1 + \frac{75(300\Omega)}{(15k\Omega \parallel 500\Omega) + 3750\Omega + 300\Omega} \right] = 596 k\Omega >> 12k\Omega$$

$$A_i = -\beta_o \frac{R_B}{R_B + r_\pi + (\beta_o + 1)R_E} = -75 \frac{15k\Omega}{15k\Omega + 3750\Omega + 76(300\Omega)} = -27.1$$

$$(b) g_m = 0.02S \quad | \quad r_\pi = \frac{75}{.02} = 3750\Omega$$

$$R_{in} = R_B \parallel [r_\pi + (\beta_o + 1)R_E] = 15k\Omega \parallel [3750\Omega + 76(620\Omega)] = 11.6 k\Omega$$

$$\text{Neglecting } R_{out} : A_v = A_{vt} \left(\frac{R_{in}}{R_I + R_{in}} \right) = -\frac{\beta_o R_L}{r_\pi + (\beta_o + 1)R_E} \left(\frac{R_{in}}{R_I + R_{in}} \right)$$

$$A_v = -\frac{75(12k\Omega)}{3750\Omega + 76(620\Omega)} \left(\frac{11.6k\Omega}{500\Omega + 11.6k\Omega} \right) = -17.0$$

$$R_{out} \cong r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 100k\Omega \left[1 + \frac{75(620\Omega)}{(15k\Omega \parallel 500\Omega) + 3750\Omega + 620\Omega} \right] = 1060 k\Omega >> 12k\Omega$$

$$A_i = -\beta_o \frac{R_B}{R_B + r_\pi + (\beta_o + 1)R_E} = -75 \frac{15k\Omega}{15k\Omega + 3750\Omega + 76(620\Omega)} = -17.1$$

14.10

$$(a) \text{For large } \beta_o : A_v \cong -\frac{R_L}{R_E} = -\frac{8.2k\Omega \parallel 47k\Omega}{330\Omega + 680\Omega} = -6.91 \quad | \quad (b) \text{Place a bypass capacitor in}$$

parallel with the 330Ω resistor. Then $A_v \cong -\frac{R_L}{R_E} = -\frac{8.2k\Omega \parallel 47k\Omega}{680\Omega} = -10.3 \quad | \quad (c) \text{Place a}$

bypass capacitor in parallel with the 680Ω resistor. Then $A_v \cong -\frac{8.2k\Omega \parallel 47k\Omega}{330\Omega} = -21.2$

(d) Place a bypass capacitor from the emitter to ground. (e) $A_v \cong -10(V_{CC} + V_{EE}) = -240.$

14.11

$$R_{in} = r_\pi + (\beta_o + 1)R_E = 250 \text{ k}\Omega$$

$$A_v = -\frac{\beta_o R_L}{r_\pi + (\beta_o + 1)R_E} = -\frac{75R_L}{250\text{k}\Omega} = -10 \rightarrow R_L = 33.3 \text{ k}\Omega \rightarrow 33 \text{ k}\Omega$$

$$\text{Assuming } (\beta_o + 1)R_E \gg r_\pi, R_E \approx \frac{250 \text{ k}\Omega}{\beta_o + 1} = \frac{250 \text{ k}\Omega}{76} = 3.29 \text{ k}\Omega \rightarrow 3.3 \text{ k}\Omega$$

As indicated above, the nearest 5% values would be 33 kΩ and 3.3 kΩ.

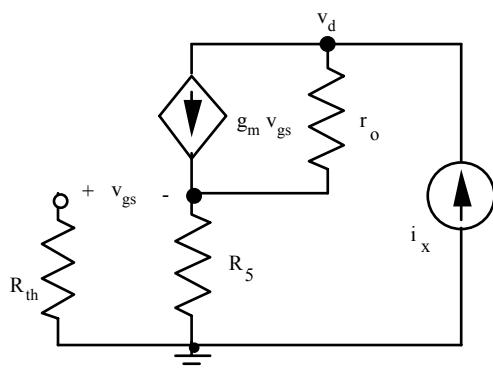
14.12

$$R_{in} = r_\pi = 250 \text{ k}\Omega \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{\beta_o V_T}{I_C} \quad | \quad I_C = \frac{\beta_o V_T}{r_\pi} = \frac{75(0.025V)}{250\text{k}\Omega} = 7.50 \mu\text{A}$$

$$A_v = -g_m R_L \left(\frac{r_\pi}{R_{th} + r_\pi} \right) = -\frac{\beta_o R_L}{R_{th} + r_\pi} = -\frac{75R_L}{100\Omega + 250\text{k}\Omega} = -10 \quad | \quad R_L = 33.3 \text{ k}\Omega \rightarrow 33 \text{ k}\Omega$$

The closest 5% value is $R_L = 33 \text{ k}\Omega$.

14.13



$$\begin{bmatrix} i_x - g_m v_{gs} \\ + g_m v_{gs} \end{bmatrix} = \begin{bmatrix} g_o & -g_o \\ -g_o & g_o + G_S \end{bmatrix} \begin{bmatrix} v_d \\ v_s \end{bmatrix} \quad | \quad v_{gs} = -v_s$$

$$\begin{bmatrix} i_x \\ 0 \end{bmatrix} = \begin{bmatrix} g_o & -(g_m + g_o) \\ -g_o & g_m + g_o + G_S \end{bmatrix} \begin{bmatrix} v_d \\ v_s \end{bmatrix}$$

$$\Delta = g_o G_S \quad | \quad v_d = (g_m + g_o + G_S) \frac{i_x}{\Delta} = \frac{(g_m + g_o + G_S)}{g_o G_S} i_x$$

$$R_{out} = \frac{v_d}{i_x} = R_S \left(1 + \frac{g_m}{g_o} + \frac{G_S}{g_o} \right) = R_S \left(1 + \mu_f + \frac{r_o}{R_S} \right)$$

$$R_{out} = r_o + (1 + \mu_f) R_S \approx r_o + \mu_f R_S = r_o (1 + g_m R_S)$$

14.14

$$I_B = \frac{(15 - 0.7)V}{1M\Omega + (100 + 1)100k\Omega} = 1.29 \mu A \quad | \quad I_C = 129 \mu A \quad | \quad V_{CE} = 30 - 39000I_C - 100000I_E = 11.9V$$

Active region is correct. | $r_\pi = \frac{100(0.025V)}{129\mu A} = 19.4k\Omega$ | r_o - no V_A specified - neglect

$$R_L = 500k\Omega \parallel 39k\Omega = 36.2k\Omega \quad | \quad R_{in} = R_B \parallel r_\pi = 1M\Omega \parallel 19.4k\Omega = 19.0k\Omega$$

$$A_v = -g_m R_L \left(\frac{R_{in}}{R_I + R_{in}} \right) = 40(0.129mA)(36.2k\Omega) \left(\frac{19.0k\Omega}{500\Omega + 19.0k\Omega} \right) = -182$$

$$R_{out} = R_C \parallel r_o = 39 k\Omega$$

$$v_{be} = v_i \left(\frac{R_{in}}{R_I + R_{in}} \right) = v_i \left(\frac{19.0k\Omega}{500\Omega + 19.0k\Omega} \right) = 0.974v_i \quad | \quad v_i \leq \frac{0.005V}{0.974} = 5.13 mV$$

$$A_v \cong -10(V_{CC} + V_{EE}) = -10(30) = -300. \quad | \quad \text{A closer estimate is} - 40V_{R_C} = -40(5.03) = -201$$

14.15

$$V_{EQ} = 9 \frac{62k\Omega}{20k\Omega + 62k\Omega} = 6.80V \quad | \quad R_{EQ} = 20k\Omega \parallel 62k\Omega = 15.1k\Omega$$

$$I_B = \frac{(9 - 0.7 - 6.80)V}{15.1k\Omega + (75 + 1)3.9k\Omega} = 4.82\mu A \quad | \quad I_C = 361 \mu A \quad | \quad V_{EC} = 9 - 3900I_E - 8200I_C = 4.61V$$

Active region is correct. | $r_\pi = \frac{75(0.025V)}{361\mu A} = 5.19k\Omega$ | V_A not specified, choose $r_o = \infty$

$$R_{in} = 15.1k\Omega \parallel 5.19k\Omega = 3.86 k\Omega \quad | \quad R_{out} = r_o \parallel 8.2k\Omega = 8.2 k\Omega \quad | \quad g_m = 40I_C = 12.6 mS$$

$$R_L = r_o \parallel 8.2k\Omega \parallel 100k\Omega = 8.2k\Omega \parallel 100k\Omega = 7.58k\Omega$$

$$A_v = -g_m R_L \left(\frac{R_{in}}{R_I + R_{in}} \right) = -(12.6mS)(7.58k\Omega) \left(\frac{3.86k\Omega}{1k\Omega + 3.86k\Omega} \right) = -75.9$$

$$A_i = \frac{R_B}{R_B + r_\pi} (-\beta_o) \frac{R_{out}}{R_{out} + R_3} = \frac{15.1k\Omega}{15.1k\Omega + 5.19k\Omega} (-75) \frac{8.2k\Omega}{8.2k\Omega + 100k\Omega} = -4.23$$

$$v_{be} = v_i \frac{R_{in}}{R_I + R_{in}} = v_i \frac{3.86k\Omega}{1k\Omega + 3.86k\Omega} = 0.794v_i \quad | \quad v_i = \frac{5.00mV}{0.794} = 6.30 mV$$

$A_v \cong -10V_{CC} = -10(9) = -90.$ | The voltage gain is slightly below the rule-of-thumb estimate.

14.16

$$V_{EQ} = 15 \frac{500k\Omega}{1.4M\Omega + 500k\Omega} = 3.95V \quad | \quad R_{EQ} = 500k\Omega \parallel 1.4M\Omega = 368k\Omega$$

$$3.95 = V_{GS} + 27000I_D = 1 + \sqrt{\frac{2I_D}{250 \times 10^{-6}}} + 27000I_D \rightarrow I_D = 79.7\mu A$$

$$V_{DS} = 15 - I_D(75k\Omega + 27k\Omega) = 6.87 V \quad | \quad \text{Active region operation is correct.}$$

$$g_m = \sqrt{2(250 \times 10^{-6})(79.7 \times 10^{-6})} = 0.200mS \quad | \quad \text{Assume } \lambda = 0, r_o = \infty.$$

$$R_L = r_o \parallel 75k\Omega \parallel 470k\Omega \approx 75k\Omega \parallel 470k\Omega = 64.7k\Omega$$

$$R_{in} = R_G = R_1 \parallel R_2 = 368 k\Omega \quad | \quad R_{out} = r_o \parallel 75k\Omega \approx 75k\Omega$$

$$A_v = -g_m R_L \frac{R_{in}}{R_I + R_{in}} = -(0.200mS)(64.7k\Omega) \left(\frac{368k\Omega}{1k\Omega + 368k\Omega} \right) = -12.9$$

$$A_i = R_G(-g_m) \frac{R_D}{R_D + R_3} = 368k\Omega(-0.200mS) \frac{75k\Omega}{75k\Omega + 470k\Omega} = -10.1$$

$$v_{gs} = v_i \frac{R_{in}}{R_I + R_{in}} = v_i \frac{368k\Omega}{1k\Omega + 368k\Omega} = 0.997v_i \quad | \quad V_{GS} - V_{TN} = \sqrt{\frac{2(79.7\mu A)}{250\mu A/V^2}} = 0.798V$$

$$v_{gs} \leq 0.2(V_{GS} - V_{TN}) \rightarrow v_i \leq 0.2 \frac{0.798V}{0.997} = 0.160 V \quad | \quad A_v \approx -\frac{V_{DD}}{V_{GS} - V_{TN}} = -\frac{15}{0.798} = -18.8$$

The rule - of - thumb estimate assumes $V_{R_L} = \frac{V_{DD}}{2}$. We have $V_{R_L} = 79.7\mu A(75k\Omega) = 5.98V = 0.399V_{DD}$

The estimate also doesn't account for the presence of R_3 .

14.17

$$V_{EQ} = 22 \frac{2.2M\Omega}{2.2M\Omega + 2.2M\Omega} = 11.0V \quad | \quad R_G = R_{EQ} = 2.2M\Omega \parallel 2.2M\Omega = 1.10M\Omega$$

Assume active region operation.

$$22 = 22000I_D - V_{GS} + 11 \quad | \quad 11 = 22000I_D + 1 + \sqrt{\frac{2I_D}{400 \times 10^{-6}}} \rightarrow I_D = 391 \mu A$$

$$V_{DS} = -[22 - I_D(22k\Omega + 18k\Omega)] = -6.36 V \quad | \quad \text{Active region operation is correct.}$$

$$g_m = \sqrt{2(400 \times 10^{-6})(391 \times 10^{-6})} = 0.559 mS \quad | \quad \text{Assume } \lambda = 0, r_o = \infty$$

$$R_L = r_o \parallel 18k\Omega \parallel 470k\Omega \approx 18k\Omega \parallel 470k\Omega = 17.3k\Omega \quad | \quad R_{in} = 1.10 M\Omega \quad | \quad R_{out} = r_o \parallel 18k\Omega = 18k\Omega$$

$$A_v = -g_m R_L \left(\frac{R_{in}}{R_I + R_{in}} \right) = -(0.559 mS)(17.3k\Omega) \frac{1.1M\Omega}{22k\Omega + 1.1M\Omega} = -9.48$$

$$A_i = -g_m R_{in} \frac{R_D}{R_D + R_3} = -0.559 mS (1.1M\Omega) \frac{18k\Omega}{18k\Omega + 470k\Omega} = -22.7$$

$$v_{gs} = v_i \frac{R_{in}}{R_I + R_{in}} = v_i \frac{1.1M\Omega}{22k\Omega + 1.1M\Omega} = 0.980v_i \quad | \quad V_{GS} - V_{TN} = \sqrt{\frac{2(391\mu A)}{400\mu A/V^2}} = 1.40V$$

$$v_{gs} \leq 0.2(V_{GS} - V_{TN}) \quad | \quad v_i \leq 0.2 \left(\frac{1.40V}{0.980} \right) = 0.286 V$$

14.18

$$V_{GS} = 0 \rightarrow I_D = \frac{K_n}{2} (V_{TN})^2 = \frac{4 \times 10^{-4}}{2} (-5)^2 = 5.00 mA$$

$$V_{DS} = 16 - 1800I_D = 7.00V \quad | \quad \text{Active region operation is correct.}$$

$$g_m = \sqrt{2(4 \times 10^{-4})(5 \times 10^{-3})} = 2.00 mS \quad | \quad \text{Assume } \lambda = 0, r_o = \infty.$$

$$A_v = -g_m R_L \left(\frac{R_G}{R_I + R_G} \right) = -(2.00 mS)(1.8k\Omega \parallel 36k\Omega) \left(\frac{10M\Omega}{10M\Omega + 5k\Omega} \right) = -3.43$$

$$R_{in} = 10.0 M\Omega \quad | \quad R_{out} = R_D \parallel r_o = 1.80 k\Omega$$

$$A_i = -g_m R_G \left(\frac{R_D}{R_D + R_3} \right) = -2.00 mS (10M\Omega) \left(\frac{1.8k\Omega}{1.8k\Omega + 36k\Omega} \right) = -952$$

$$v_{gs} = v_i \left(\frac{10M\Omega}{10M\Omega + 5k\Omega} \right) \leq 0.2 |V_{GS} - V_{TN}| \rightarrow v_i \leq 1 V$$

14.19

$$I_B = \frac{(12 - 0.7)V}{20k\Omega + (80 + 1)9.1k\Omega} = 14.9\mu A \quad | \quad I_C = 1.19 mA \quad | \quad V_{CE} = 24 - 9100I_E = 13.2 V$$

Active region is correct. $| r_\pi = \frac{80(0.025V)}{1.19mA} = 1.68k\Omega \quad | \quad r_o = \frac{(100+13.2)V}{1.19mA} = 95.1k\Omega$

$$R_L = r_o \| 1M\Omega = 95.1k\Omega \| 1M\Omega = 86.9k\Omega \quad | \quad R_{in} = R_B \| r_\pi = 20k\Omega \| 1.68k\Omega = 1.55 k\Omega \quad | \quad R_{out} = r_o = 95.1 k\Omega$$

$$A_v = -g_m R_L \left(\frac{R_{in}}{R_I + R_{in}} \right) = -40(1.19mA)(86.9k\Omega) \frac{1.55k\Omega}{250\Omega + 1.55k\Omega} = -3560$$

$$A_i = -\beta_o \left(\frac{R_B}{R_B + r_\pi} \right) \left(\frac{r_o}{r_o + R_3} \right) = -80 \left(\frac{20k\Omega}{20k\Omega + 1.68k\Omega} \right) \left(\frac{95.1k\Omega}{95.1k\Omega + 1M\Omega} \right) = -6.41$$

$$v_{be} = v_i \left(\frac{R_{in}}{R_I + R_{in}} \right) = v_i \frac{1.55k\Omega}{250\Omega + 1.55k\Omega} = 0.861v_i \quad | \quad v_i \leq \frac{5.00mV}{0.861} = 5.81 mV$$

14.20

$$r_\pi = \frac{80}{0.4S} = 200\Omega \quad | \quad \text{Assume } V_A = \infty, r_o = \infty.$$

$$R_{in} = R_B \| [r_\pi + (\beta_o + 1)R_L] = 47k\Omega \| [200\Omega + 81(1k\Omega)] = 29.8 k\Omega$$

$$R_{out} = \frac{R_{th} + r_\pi}{\beta_o + 1} = \frac{(47k\Omega \| 10k\Omega) + 200\Omega}{81} = 104 \Omega$$

$$A_v = + \frac{(\beta_o + 1)R_L}{r_\pi + (\beta_o + 1)R_L} \left(\frac{R_{in}}{R_I + R_{in}} \right) = \frac{81(1k\Omega)}{200\Omega + 81(1k\Omega)} \left(\frac{29.8k\Omega}{10k\Omega + 29.8k\Omega} \right) = 0.747$$

$$A_i = +(\beta_o + 1) \left[\frac{R_B}{R_B + r_\pi + (\beta_o + 1)R_L} \right] \left(\frac{r_o}{r_o + R_L} \right) = 81 \frac{47k\Omega}{47k\Omega + 200\Omega + 81(1k\Omega)} = 29.7$$

14.21

$$\text{Assume } \lambda = 0, r_o = \infty. \quad | \quad R_{in} = R_G = 2 M\Omega \quad | \quad R_{out} = \frac{1}{g_m} = 100 \Omega$$

$$A_v = + \frac{g_m R_L}{1 + g_m R_L} \left(\frac{R_{in}}{R_I + R_{in}} \right) = \frac{0.01(2k\Omega)}{1 + 0.01(2k\Omega)} \left(\frac{2 M\Omega}{100k\Omega + 2 M\Omega} \right) = 0.907$$

$$A_i = +g_m R_G \left(\frac{r_o}{r_o + R_L} \right) = 0.01(2 M\Omega) = 2 \times 10^4$$

14.22

Defining v_1 as the source node:

$$(a) 2k\Omega \parallel 100k\Omega = 1.96k\Omega$$

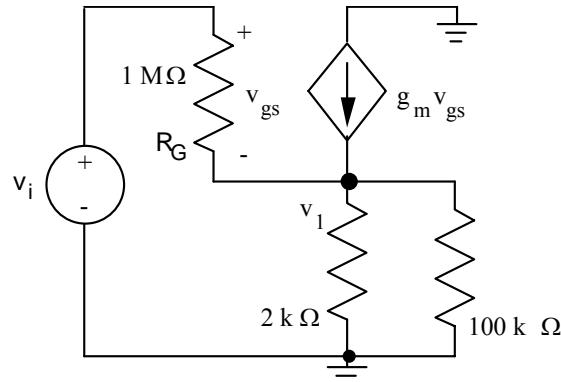
$$\frac{(v_i - v_1)}{10^6} + 3.54 \times 10^{-3}(v_i - v_1) = \frac{v_1}{1960}$$

$$3.541 \times 10^{-3} v_i = 4.051 \times 10^{-3} v_1$$

$$v_1 = 0.874 v_i \quad | \quad A_v = 0.874$$

$$R_{in} = \frac{v_i}{i_i} = \frac{v_i}{10^{-6}(v_i - v_1)} = 7.94 M\Omega$$

Driving the output with current source i_x :



$$R_{out} : i_x = \frac{v_1}{10^6} + \frac{v_1}{2000} + 3.54 \times 10^{-3} v_1$$

$$R_{out} = \frac{v_1}{i_x} = 247 \Omega \quad | \quad (b) R_{in} = \infty$$

14.23

$$V_{EQ} = -12 + 12 \frac{100k\Omega}{100k\Omega + 100k\Omega} = -6.00V \quad | \quad R_{EQ} = 100k\Omega \parallel 100k\Omega = 50.0k\Omega$$

$$I_B = \frac{(-0.7 + 6)V}{50.0k\Omega + (126)(4.7k\Omega)} = 8.25\mu A \quad | \quad I_C = 1.03 mA \quad | \quad V_{CE} = 24 - 2000I_C - 4700I_E = 17.1 V$$

$$\text{Active region is correct.} \quad | \quad r_\pi = \frac{125(0.025V)}{1.03mA} = 3.03k\Omega \quad | \quad r_o = \frac{(50+17.1)V}{1.03mA} = 65.1k\Omega$$

$$R_B = R_I \parallel R_2 = 100k\Omega \parallel 100k\Omega = 50.0k\Omega \quad | \quad R_L = R_3 \parallel R_E \parallel r_o = 24k\Omega \parallel 4.7k\Omega \parallel 65.1k\Omega = 3.71k\Omega$$

$$R_{in} = R_B \left[r_\pi + (\beta_o + 1)R_L \right] = 50.0k\Omega \left[3.03k\Omega + (126)3.71k\Omega \right] = 45.2 k\Omega$$

$$A_v = + \frac{(\beta_o + 1)R_L}{r_\pi + (\beta_o + 1)R_L} \left(\frac{R_{in}}{R_I + R_{in}} \right) = \frac{126(3.71k\Omega)}{3.03k\Omega + 126(3.71k\Omega)} \left(\frac{50.0k\Omega}{500\Omega + 50.0k\Omega} \right) = 0.984$$

$$v_{be} = v_i \left(\frac{R_{in}}{R_I + R_{in}} \right) \left(\frac{r_\pi}{r_\pi + (\beta_o + 1)R_L} \right) = \left(\frac{50.0k\Omega}{500\Omega + 50.0k\Omega} \right) \left[\frac{3.03k\Omega}{3.03k\Omega + 126(3.71k\Omega)} \right] = 6.34 \times 10^3 v_i$$

$$v_i \leq \frac{0.005V}{6.34 \times 10^{-3}} = 0.784 V \quad | \quad R_{out} = R_E \left\| \frac{(R_B \parallel R_I) + r_\pi}{\beta_o + 1} \right\| = 4.7k\Omega \left\| \frac{(50.0k\Omega \parallel 500\Omega) + 3.03k\Omega}{126} \right\| = 27.8 \Omega$$

14.24

$$V_{GS} = 5V \mid I_D = \frac{5 \times 10^{-4}}{2} (5 - 1.5)^2 = 3.06 \text{ mA} \mid V_{DS} = 5 - (-5) = 10V \text{ - Pinchoff region}$$

operation is correct. $\mid g_m = \sqrt{2(5 \times 10^{-4})(3.06 \text{ mA})(1 + 0.02(10))} = 1.92 \text{ mS}$

$$r_o = \frac{\frac{1}{0.02} + 10}{3.06} \frac{V}{mA} = 19.6 \text{ k}\Omega \text{ - Cannot neglect!} \mid R_L = 19.6 \text{ k}\Omega \parallel 100 \text{ k}\Omega = 16.4 \text{ k}\Omega$$

$$R_{in} = R_G = 1 \text{ M}\Omega \mid R_{out} = \frac{1}{g_m} \parallel r_o = 507 \text{ }\Omega$$

$$A_v = +\frac{R_{in}}{R_I + R_{in}} \left(\frac{g_m R_L}{1 + g_m R_L} \right) = +\frac{1 \text{ M}\Omega}{10 \text{ k}\Omega + 1 \text{ M}\Omega} \left(\frac{1.92 \text{ mS}(16.4 \text{ k}\Omega)}{1 + 1.92 \text{ mS}(16.4 \text{ k}\Omega)} \right) = 0.960$$

$$\mathbf{v}_{gs} = \mathbf{v}_i \left(\frac{R_{in}}{R_I + R_{in}} \right) \left(\frac{1}{1 + g_m R_L} \right) = v_i \left[\frac{10^6 \Omega}{10^4 \Omega + 10^6 \Omega} \right] \left[\frac{1}{1 + 1.92 \text{ mS}(16.4 \text{ k}\Omega)} \right] = 0.0305 \mathbf{v}_i$$

$$v_i \leq \frac{0.2(5 - 1.5)}{0.0305} = 23.0 \text{ V} \text{ But, } v_{DS} \text{ must exceed } v_{GS} - V_{TN} \cong V_{GS} - V_{TN} = 4V \text{ for pinchoff.}$$

$$V_{DS} = 10 - v_o = 10 - 0.970v_i \geq 4 \rightarrow v_i \leq 6.19 \text{ V} \text{ - Limited by the Q-point voltages}$$

14.25

$$I_B = \frac{(9 - 0.7)V}{1 \text{ M}\Omega + (100 + 1)430 \text{ k}\Omega} = 187 \text{ nA} \mid I_C = 18.7 \mu\text{A} \mid V_{CE} = 18 - 430000I_E = 9.89 \text{ V}$$

Active region is correct. $\mid r_\pi = \frac{100(0.025V)}{18.7 \mu\text{A}} = 134 \text{ k}\Omega \mid r_o = \frac{(60 + 9.89)V}{18.7 \mu\text{A}} = 3.74 \text{ M}\Omega$ - neglected

In the ac model, R_l appears in parallel with r_π . The circuit appears to be using a transistor with

$$r_\pi' = 500 \text{ k}\Omega \parallel r_\pi = 106 \text{ k}\Omega \text{ and } \beta_o' = g_m r_\pi' = 40(18.7 \mu\text{A})/106 \text{ k}\Omega = 79.0$$

$$R_L = 500 \text{ k}\Omega \parallel 430 \text{ k}\Omega \parallel 500 \text{ k}\Omega = 158 \text{ k}\Omega \mid R_{in} = r_\pi' + (\beta_o' + 1)R_L = 106 \text{ k}\Omega + 79.0(158 \text{ k}\Omega) = 12.6 \text{ M}\Omega$$

$$A_v = \frac{(\beta_o' + 1)R_L}{r_\pi' + (\beta_o' + 1)R_L} \left(\frac{R_{in}}{R_I + R_{in}} \right) = \frac{80.0(158 \text{ k}\Omega)}{106 \text{ k}\Omega + 80.0(158 \text{ k}\Omega)} \left(\frac{12.6 \text{ M}\Omega}{500 \Omega + 12.6 \text{ M}\Omega} \right) = +0.992$$

$$R_{out} = R_E \parallel R_2 \parallel \frac{R_I + r_\pi'}{\beta_o' + 1} = 430 \text{ k}\Omega \parallel 500 \text{ k}\Omega \parallel \frac{500 \Omega + 106 \text{ k}\Omega}{79.0} = 1.34 \text{ k}\Omega$$

$$v_{be} = v_i \frac{r_\pi'}{R_I + r_\pi' + (\beta_o' + 1)R_L} = v_i \frac{106 \text{ k}\Omega}{500 \Omega + 106 \text{ k}\Omega + 80.0(158 \text{ k}\Omega)} = 8.32 \times 10^{-3} v_i$$

$$v_i \leq \frac{0.005V}{8.32 \times 10^{-3}} = 0.601 \text{ V}$$

14.26

$$v_i \leq 0.005(1 + g_m R_L) \quad | \quad R_L = R_E \| R_3 \cong R_E$$

$$v_i \leq 0.005(1 + g_m R_L) = 0.005(1 + g_m R_E) = 0.005\left(1 + \frac{I_C R_E}{V_T}\right)$$

$$v_i \leq 0.005\left(1 + \alpha_F \frac{I_E R_E}{V_T}\right) \cong 0.005\left(1 + \frac{I_E R_E}{V_T}\right)$$

$$v_i \leq 0.005\left(1 + \frac{V_{R_E}}{V_T}\right) = 0.005\left(1 + \frac{V_{R_E}}{0.025}\right) = 0.005 + 0.2V_{R_E}$$

14.27

$$\beta_o = g_m r_\pi = 3.54mS(1M\Omega) = 3540 \quad | \quad R_L = 2k\Omega \| 100k\Omega = 1.96k\Omega$$

$$A_v = \frac{(\beta_o + 1)R_L}{r_\pi + (\beta_o + 1)R_L} = \frac{(3540 + 1)(1.96k\Omega)}{1M\Omega + (3540 + 1)(1.96k\Omega)} = 0.874$$

$$R_{in} = r_\pi + (\beta_o + 1)R_L = 1M\Omega + (3540 + 1)(1.96k\Omega) = 7.94 M\Omega$$

$$R_{out} = 2k\Omega \| \frac{r_\pi}{(\beta_o + 1)} = 2k\Omega \| \frac{10^6}{(3541)} = 247 \Omega$$

14.28

$$(a) v_{be} = v_i - v_o \quad | \quad 0.005 \leq 5 - v_o \rightarrow A_v = \frac{v_o}{v_i} \geq \frac{4.995}{5} = 0.999$$

$$(b) A_v = \frac{(\beta_o + 1)R_E}{r_\pi + (\beta_o + 1)R_E} = \frac{1}{1 + \frac{r_\pi}{(\beta_o + 1)R_E}} = \frac{1}{1 + \frac{\beta_o}{(\beta_o + 1)\beta_o R_E} \frac{r_\pi}{\beta_o R_E}} = \frac{1}{1 + \frac{\alpha_o}{g_m R_E}} = \frac{1}{1 + \frac{V_T}{I_E R_E}}$$

$$\frac{1}{1 + \frac{V_T}{I_E R_E}} \geq 0.999 \rightarrow \frac{V_T}{I_E R_E} \leq 0.001 \rightarrow I_E R_E \geq \frac{0.025V}{0.001} = 25.0 V$$

14.29

$$v_{be} = v_i - v_o = (1 - A_v)v_i \quad | \quad 0.005 \leq (1 - A_v)7.5 \rightarrow A_v = \frac{v_o}{v_i} \geq \frac{7.5 - 0.005}{7.5} = 0.999333$$

$$\text{From Prob. 14.28, } A_v = \frac{1}{1 + \frac{V_T}{I_E R_L}} \quad | \quad R_L = R_E \parallel 500\Omega = \frac{500R_E}{500 + R_E} \quad | \quad A_v = \frac{1}{1 + \frac{V_T}{I_E R_E} \left(\frac{500 + R_E}{500} \right)}$$

$$\frac{1}{1 + \frac{V_T}{I_E R_E} \left(\frac{500 + R_E}{500} \right)} \geq 0.999333 \rightarrow \frac{V_T}{I_E R_E} \left(\frac{500 + R_E}{500} \right) \leq 6.67 \times 10^{-4}$$

$$\frac{500 I_E R_E}{500 + R_E} \geq \frac{0.025V}{6.67 \times 10^{-4}} = 37.5V \quad | \quad V_{CC} \geq I_E R_E + 0.7 + 7.5$$

Some design possibilities are listed in the table below.

R _E	I _E	V _{CC}	V _{CC} I _E
100 Ω	450 mA	53 V	24 W
250 Ω	225 mA	64 V	16 W
360 Ω	179mA	73V	13 W
500 Ω	150 mA	83 V	12 W
750 Ω	125 mA	102 V	13 W
1000 Ω	113mA	120 V	14 W
2000 Ω	93.8 mA	196 V	18 W

Using a result near the minimum-power case in the table: R_E = 510 Ω, I_E = 149 mA and V_{CC} = 85 V.

$$\text{For } \beta_F = 50: \quad I_B \cong \frac{149mA}{51} = 2.92 \text{ mA} \quad | \quad \text{Set } I_{R_1} = 5I_B = 14.6mA \cong 15mA$$

$$R_1 = \frac{V_E + V_{BE}}{I_{R_1}} = \frac{149mA(510\Omega) + 0.7}{15mA} = 5.07k\Omega \rightarrow 5.1 k\Omega \quad | \quad I_{R_2} = I_{R_1} + I_B \cong 18mA$$

$$R_2 = \frac{85 - V_{BE} - V_{BE}}{I_{R_2}} = \frac{8.3V}{18mA} = 462\Omega \rightarrow 470 \Omega$$

It is obviously very difficult to achieve the required level of linearity!

14.30

$$(a) g_m = 40(12.5\mu A) = 0.5mS$$

$$R_{in} = R_4 \left\| \frac{r_\pi}{\beta_o + 1} = R_4 \left\| \frac{\alpha_o}{g_m} = 100k\Omega \right\| \frac{0.99}{0.5mS} = 1.94 k\Omega \right.$$

$$A_v = \frac{g_m R_L}{1 + g_m (R_I \| R_4)} \left(\frac{R_4}{R_I + R_4} \right) = \frac{0.5mS(100k\Omega)}{1 + 0.5mS(50\Omega \| 100k\Omega)} \left(\frac{100k\Omega}{50\Omega + 100k\Omega} \right) = 48.7$$

$$R_{out} = r_o [1 + g_m (R_I \| R_4)] = \frac{60V}{12.5\mu A} [1 + 0.5mS(50\Omega)] = 4.92 M\Omega$$

$$A_i = \alpha_o \left(\frac{R_4}{R_I + R_4} \right) = 0.990 \left(\frac{100k\Omega}{50\Omega + 100k\Omega} \right) = 0.990$$

$$(b) A_v = \frac{0.5mS(100k\Omega)}{1 + 0.5mS(2.2k\Omega \| 100k\Omega)} \left(\frac{100k\Omega}{2.2k\Omega + 100k\Omega} \right) = 23.6 \quad | \quad R_{in} = 1.94k\Omega - \text{no change}$$

$$R_{out} = r_o [1 + g_m (R_I \| R_4)] = \frac{60V}{12.5\mu A} [1 + 0.5mS(2.2\Omega)] = 10.1 M\Omega$$

14.31

$$(a) R_{in} = R_4 \left\| \frac{1}{g_m} = 3k\Omega \right\| \frac{1}{0.5mS} = 1.20 k\Omega \quad | \quad R_{out} = \infty \quad (\text{assume } \lambda = 0)$$

$$A_v = \frac{g_m R_L}{1 + g_m (R_I \| R_4)} \left(\frac{R_4}{R_I + R_4} \right) = \frac{0.5mS(60k\Omega)}{1 + 0.5mS(50\Omega \| 3k\Omega)} \left(\frac{3k\Omega}{50\Omega + 3k\Omega} \right) = +28.8$$

$$A_i = 1 - \frac{R_4}{R_4 + \frac{1}{g_m}} = \frac{3k\Omega}{3k\Omega + 2k\Omega} = 0.600$$

$$(b) A_v = \frac{0.5mS(60k\Omega)}{1 + 0.5mS(5k\Omega \| 3k\Omega)} \left(\frac{3k\Omega}{5k\Omega + 3k\Omega} \right) = +5.81 \quad | \quad R_{in} = 5k\Omega \left\| \frac{1}{0.5mS} = 1.43 k\Omega \right.$$

$$R_{out} = \infty \quad | \quad A_i = \frac{5k\Omega}{5k\Omega + 2k\Omega} = 0.714$$

14.32

The voltage gain is approximately 0. The signal is injected into the collector and taken out of the emitter. This is not a useful amplifier circuit.

14.33

$$I_B = \frac{(12 - 0.7)V}{100k\Omega + (50 + 1)82k\Omega} = 2.64\mu A \quad | \quad I_C = 132 \mu A$$

$$V_{CE} = 24 - 82000I_E - 39000I_C = 7.81 V \quad | \quad \text{Active region operation is correct.}$$

$$g_m = 40I_C = 5.28mS \quad | \quad r_\pi = \frac{\beta_o}{g_m} = 9.47k\Omega \quad | \quad r_o = \frac{(50 + 7.81)V}{132\mu A} = 438k\Omega \text{ - neglected}$$

$$R_I \| R_E = 0.5k\Omega \| 82k\Omega = 497\Omega \quad | \quad R_L = R_C \| R_3 = 39k\Omega \| 100k\Omega = 28.1k\Omega$$

$$A_v = \frac{g_m R_L}{1 + g_m(R_I \| R_E)} \left(\frac{R_E}{R_I + R_E} \right) = \frac{5.28mS(28.1k\Omega)}{1 + 5.28mS(497\Omega)} \left(\frac{82k\Omega}{500\Omega + 82k\Omega} \right) = 40.7$$

$$R_{in} = 82k\Omega \left\| \frac{r_\pi}{\beta_o + 1} = 185 \Omega \quad | \quad A_i = A_v \frac{R_I + R_{in}}{R_3} = 40.7 \frac{500\Omega + 185\Omega}{100k\Omega} = 0.279 \right.$$

$$R_{out} = R_C = 39.0 k\Omega \quad | \quad v_{eb} = v_i \frac{R_{in}}{R_I + R_{in}} \leq 5.00mV \quad | \quad 0.270v_i \leq 5.00mV \quad | \quad v_i \leq 18.5 mV$$

14.34

$$I_B = \frac{(9 - 0.7)V}{1000k\Omega + (50 + 1)820k\Omega} = 194nA \quad | \quad I_C = 9.69 \mu A$$

$$V_{CE} = 18 - 820000I_E - 390000I_C = 6.12 V \quad | \quad \text{Active region is correct.}$$

$$g_m = 40I_C = 0.388mS \quad | \quad r_\pi = \frac{\beta_o}{g_m} = 129k\Omega \quad | \quad r_o = \frac{(50 + 6.12)V}{9.69\mu A} = 5.79M\Omega \text{ - neglected}$$

$$R_I \| R_E = 5k\Omega \| 820k\Omega = 4.97k\Omega \quad | \quad R_L = R_C \| R_3 = 390k\Omega \| 1M\Omega = 281k\Omega$$

$$A_v = \frac{g_m R_L}{1 + g_m(R_I \| R_E)} \left(\frac{R_E}{R_I + R_E} \right) = \frac{0.388mS(281k\Omega)}{1 + 0.388mS(4.97k\Omega)} \left(\frac{820k\Omega}{5k\Omega + 820k\Omega} \right) = 37.0$$

$$R_{in} = 820k\Omega \left\| \frac{r_\pi}{\beta_o + 1} = 2.52 k\Omega \quad | \quad A_i = A_v \frac{R_I + R_{in}}{R_3} = 37.0 \frac{5k\Omega + 2.52k\Omega}{1M\Omega} = 0.278 \right.$$

$$R_{out} \cong R_C = 390 k\Omega \quad | \quad v_{eb} = v_i \frac{R_{in}}{R_I + R_{in}} \leq 5.00mV \quad | \quad 0.335v_i \leq 5.00mV \quad | \quad v_i \leq 14.9 mV$$

14.35

$$V_{GS} = -3900I_D = -3900 \frac{(5 \times 10^{-4})}{2} (V_{GS} + 2)^2 \quad | \quad V_{GS} = -0.975(V_{GS} + 2)^2 \rightarrow V_{GS} = -0.9915V$$

$$I_D = \frac{(5 \times 10^{-4})}{2} (V_{GS} + 2)^2 = 254\mu A \quad | \quad V_{DS} = 16 - 23.9k\Omega I_D = 9.92V \text{ - Pinched off.}$$

$$g_m = \frac{2(254\mu A)}{2 - 0.992} = 0.504mS \quad | \quad R_{in} = 3.9k\Omega \left| \frac{1}{g_m} \right. = 1.32k\Omega \quad | \quad R_{out} \cong R_D = 20k\Omega$$

$$R_L = 20k\Omega \parallel 51k\Omega = 14.4k\Omega$$

$$A_v = \frac{g_m R_L}{1 + g_m (R_I \parallel R_S)} \left(\frac{R_S}{R_I + R_S} \right) = \frac{0.504mS(14.4k\Omega)}{1 + 0.504mS(0.796k\Omega)} \left(\frac{3.9k\Omega}{1k\Omega + 3.9k\Omega} \right) = 4.12$$

$$A_i = A_v \frac{R_I + R_{in}}{R_3} = 4.12 \frac{1k\Omega + 1.32k\Omega}{51k\Omega} = 0.187$$

$$\left| v_{gs} \right| = v_i \frac{1.32k\Omega}{1k\Omega + 1.32k\Omega} \leq 0.2(V_{GS} + 2) \quad | \quad v_i \frac{1.32k\Omega}{1k\Omega + 1.32k\Omega} \leq 0.2(-0.992 + 2) \rightarrow v_i \leq 0.354 V$$

14.36

$$I_D = \frac{(2 \times 10^{-4})}{2} (V_{GS} + 1)^2 \quad | \quad \frac{15 + V_{GS}}{68k\Omega} = 10^{-4} (V_{GS} + 1)^2 \rightarrow V_{GS} = -2.363V$$

$$I_D = \frac{15 + V_{GS}}{68k\Omega} = 186\mu A \quad | \quad V_{DS} = -[30 - (68k\Omega + 43k\Omega)I_D] = -9.35V \quad |$$

Pinchoff region is correct. | $g_m = \frac{2(186\mu A)}{2.36 - 1} = 0.274mS \quad | \quad R_{in} = 68k\Omega \left| \frac{1}{g_m} \right. = 3.46k\Omega$

$$R_{out} \cong R_D = 43k\Omega \quad | \quad R_L = 43k\Omega \parallel 200k\Omega = 35.4k\Omega$$

$$A_v = \frac{R_{in}}{R_I + R_{in}} g_m R_L = \frac{3.46k\Omega}{0.250k\Omega + 3.46k\Omega} (0.274mS)(35.4k\Omega) = 9.05$$

$$A_i = A_v \frac{R_I + R_{in}}{R_3} = 9.05 \left(\frac{3.71k\Omega}{200k\Omega} \right) = 0.168 \quad | \quad \left| v_{gs} \right| = v_i \frac{3.46k\Omega}{0.250k\Omega + 3.46k\Omega} \leq 0.2(V_{SG} - 1)$$

$$v_i \frac{3.46k\Omega}{0.250k\Omega + 3.46k\Omega} \leq 0.2(2.36 - 1) \rightarrow v_i \leq 0.292 V$$

14.37

$$V_{GS} = -10 + (33k\Omega)I_D \quad | \quad V_{GS} = -10 + \frac{(3.3 \times 10^4)(2 \times 10^{-4})}{2}(V_{GS} + 1)^2$$

$$V_{GS} = -2.507 \text{ V} \quad \& \quad I_D = \frac{(2 \times 10^{-4})}{2}(V_{GS} + 1)^2 = 227 \mu\text{A}$$

$V_{DS} = -[20 - I_D(33k\Omega + 24k\Omega)] = -7.06 \text{ V}$ - Active region operation is correct.

$$g_m = \sqrt{2(2 \times 10^{-4})(2.27 \times 10^{-4})} = 3.01 \times 10^{-4} \text{ S} \quad | \quad R_I \| R_S = 0.5k\Omega \| 33k\Omega = 493\Omega$$

Assume $\lambda = 0$, $r_o = \infty$ | $R_L = R_D \| R_3 = 24k\Omega \| 100k\Omega = 19.4k\Omega$

$$A_v = \frac{g_m R_L}{1 + g_m (R_I \| R_S)} \left(\frac{R_S}{R_I + R_S} \right) = \frac{0.301mS(19.4k\Omega)}{1 + 0.301mS(493\Omega)} \left(\frac{33k\Omega}{500\Omega + 33k\Omega} \right) = 5.01$$

$$A_i = 1 - \frac{R_S}{R_S + \frac{1}{g_m}} \left(\frac{R_D}{R_D + R_3} \right) = \frac{33k\Omega}{33k\Omega + 3.32k\Omega} \left(\frac{24k\Omega}{24k\Omega + 100k\Omega} \right) = 0.176$$

$$R_{in} = R_S \left\| \frac{1}{g_m} \right\| = 3.02 \text{ k}\Omega \quad | \quad R_{out} = R_D = 24 \text{ k}\Omega$$

$$\left| v_{gs} \right| = v_i \frac{R_{IN}}{R_I + R_{IN}} \leq 0.2 |V_{GS} + 1| \quad | \quad v_i \frac{3.02 \text{ k}\Omega}{0.5 \text{ k}\Omega + 3.02 \text{ k}\Omega} \leq 0.2(1.51) \rightarrow v_i \leq 0.352 \text{ V}$$

14.38

For $R_{th} \ll \frac{1}{g_m}$, $A_v \approx g_m R_L$ All of the input voltage appears across the gate - source terminals of the transistor.

For $R_{th} \gg \frac{1}{g_m}$, $A_v \approx \frac{R_L}{R_{th}}$ For large R_{th} , all of the Thevenin equivalent source

current, $\frac{v_{th}}{R_{th}}$, goes into the transistor source terminal.

14.39

$$R_{in} = \frac{r_\pi + 1.5k\Omega}{\beta_o + 1} \quad | \quad r_\pi = \frac{75(0.025V)}{1mA} = 1.88k\Omega \quad | \quad R_{in} = \frac{1.88k\Omega + 1.5k\Omega}{76} = 44.5 \Omega$$

14.40

$$g_m = \sqrt{2(1.25mA)(1mA)} = 1.58mS \quad | \quad R_{in} = \frac{1}{g_m} = 633 \Omega$$

14.41

$$(a) R_{out} = r_o \left[1 + \frac{\beta_o R_E}{r_\pi + R_E} \right] \quad | \quad I_E = \frac{15V - 0.7V}{143k\Omega} = 100\mu A \quad | \quad \text{For } \beta_F = 100, I_C = 99.0\mu A$$

$$r_\pi = \frac{100(0.025V)}{99.0\mu A} = 25.3k\Omega \quad | \quad r_o \approx \frac{50V}{99.0\mu A} = 505k\Omega$$

$$R_{out} = 505k\Omega \left[1 + \frac{100(143k\Omega)}{25.3k\Omega + 143k\Omega} \right] = 43.4 M\Omega \quad (b) 0 V$$

$$(c) I_E = \frac{15V - 0.7V}{15k\Omega} = 953\mu A \quad | \quad \text{For } \beta_F = 100, I_C = 944\mu A \quad | \quad r_\pi = \frac{100(0.025V)}{944\mu A} = 2.65k\Omega$$

$$r_o \approx \frac{50V}{944\mu A} = 53.0k\Omega \quad | \quad R_{out} = 53.0k\Omega \left[1 + \frac{100(15k\Omega)}{15k\Omega + 2.65k\Omega} \right] = 4.56 M\Omega \quad | \quad V_{CB} \geq 0 V$$

14.42

$$R_{out} = (\beta_o + 1) r_o = (\beta_o + 1) \left(\frac{V_A + V_{CE}}{I_C} \right) = 126 \left(\frac{50 + 10.7}{49.6\mu A} \right) = 154 M\Omega$$

14.43

$$R_{in} = 350\Omega \quad | \quad A_v = 10^{\frac{43}{20}} = 141 \quad | \quad \text{Low } R_{in}, \text{ large gain}$$

A common - base amplifier can achieve these specifications.

$$R_{in} \approx \frac{1}{g_m} \rightarrow I_C \approx \frac{1}{40(350)} = 71.4 \mu A$$

A common emitter amplifier operating at a higher current is an alternate choice.

$$R_{in} \approx r_\pi \rightarrow I_C \approx \frac{100}{40(350)} = 7.14 mA$$

For both cases, $|A_v| \approx 10V_{CC} \rightarrow V_{CC} = 14 V$

14.44

$$R_{in} = 0.3 M\Omega \quad | \quad A_v = 10^{\frac{46}{20}} = 200 \quad | \quad \text{Fairly large } R_{in}, \text{ large gain}$$

A common - emitter amplifier operating at a low current can achieve both a large gain and input resistance. $A_v \approx 20V_{CC} \rightarrow V_{CC} = 10V$

Achieving this gain with an FET is much more difficult :

$$A_v \approx \frac{V_{DD}}{V_{GS} - V_{TN}} = \frac{V_{DD}}{0.25V} \rightarrow V_{DD} \approx 50V \text{ which is unreasonably large.}$$

14.45

$$R_{in} = 10 M\Omega \quad | \quad A_v = 10^{\frac{26}{20}} = 20 \quad | \quad \text{Large } R_{in}, \text{ moderate gain}$$

These requirements are readily met by a common - source amplifier.

For example, $A_v \approx \frac{V_{DD}}{V_{GS} - V_{TN}} = \frac{15V}{0.5V} = 30$.

A common - emitter stage operating at a low collector current with

an unbypassed emitter resistor $(R_E \approx \frac{10 M\Omega}{100} = 100 k\Omega)$ is a second possibility,

but the circuit will require careful design.

14.46

$$R_{in} = 50 k\Omega \quad | \quad A_v = 10^{\frac{58}{20}} = 792 \quad | \quad \text{A bipolar transistor would be required}$$

for such a large gain. However, this is a large fraction of the BJT amplification factor [i. e. $(40/V)(75V) = 3000$] and will be very difficult to achieve with the information thus far (the active load discussed later is a possibility).

Using our rule - of - thumb for the common - emitter amplifier,

$$|A_v| \approx 10V_{CC} \rightarrow V_{CC} = 80 \text{ V which is too large. Thus, it is not possible is the best answer.}$$

14.47

An inverting amplifier with a gain of 40 dB is most easily achieved with a common - emitter stage : $A_v \approx 10V_{CC} \rightarrow V_{CC} = 10 \text{ V}$. The input resistance can be achieved by shunting the

input with a $5 - \Omega$ resistor. Setting $r_\pi = 5 \Omega$ would require $I_C \approx \frac{100(0.025V)}{5\Omega} = 0.5A$ and would waste a large amount of power to achieve the required input resistance.

It would be better to operate the transistor at a much lower current and "swamp" the input resistance by shunting the input with a $5 - \Omega$ resistor

14.48

A non - inverting amplifier with a gain of 20 and an input resistance of $5 k\Omega$ should be readily achievable with either a common - base or common - gate amplifier with proper choice of operating point. The gain of 10 is easily achieved with either the

FET or BJT design estimate : $A_v \approx \frac{V_{DD}}{V_{GS} - V_{TN}}$ or $A_v \approx 10V_{CC}$. $R_{in} \approx \frac{1}{g_m} = 5 k\Omega$ is within

easy reach of either device. The gain and input resistance can also be easily met with either a common - emitter, or common - source stage with a resistor shunt at the input.

14.49

0 - dB gain corresponds to a follower ($A_v = 1$).

For an emitter - follower, $R_{in} \cong (\beta_o + 1)R_L \cong 101(20k\Omega) = 2.02 M\Omega$. So an BJT cannot meet the input resistance requirement. A source follower provides a gain of approximately 1 and can easily achieve the required input resistance.

14.50

A gain of 0.97 and an input resistance of $400k\Omega$ should be achievable with

either a source - follower or an emitter - follower. For the FET, $A_v \cong \frac{g_m R_L}{1 + g_m R_L} = 0.97$

requires $g_m R_L = 33.3$: $\frac{2I_D R_L}{V_{GS} - V_{TN}} = 33.3 \rightarrow I_D R_L = 8.3V$ for a design with $V_{GS} - V_{TN} = 0.5V$.

The BJT can achieve the required gain with a much lower power supply and can still meet the R_{in} requirement : $R_{in} \cong \beta_o R_L \cong 100(5k\Omega) = 500k\Omega$.

$$A_v \cong \frac{g_m R_L}{1 + g_m R_L} = 0.97 \quad | \quad g_m R_L = 33.3 \rightarrow I_C R_E = 33.3(0.025) = 0.833 V.$$

The requirements can be met with careful bias circuit design and specification of a BJT with minimum current gain of at least 100.

14.51

$A_v = 10^{\frac{66}{20}} = 2,000$. This value of voltage gain approaches the amplification factor of the BJTs : $A_v \leq \mu_f = 40V_A = 40(75) = 3000$. Such a large gain

requirement cannot be met with single - transistor BJT amplifiers using the resistive loaded amplifiers in this chapter (Remember the $10V_{CC}$ limit). FETs typically have much lower values of μ_f and are at an even worse disadvantage.

None of the single - transistor amplifier configurations can meet the gain requirements.

14.52

Such a large output resistance will require either a CE or CB stage or a CS or CG stage.

For a BJT, $R_{out} \leq \beta_o r_o$ $\frac{\beta_o V_A}{I_C} = 10^9 \Omega$ or $I_C = \frac{100(75V)}{10^9 \Omega} = 7.5 \mu A$ using typical

values for β_o and V_A . We need to also see how much voltage is required.

We also need $r_o(1 + g_m R_E) > 10^9 \Omega$ or $40(I_C R_E) \frac{75}{7.5 \mu A} > 10^9 \Omega \rightarrow I_C R_E > 2.5 V$ which is reasonable.

For a MOSFET, $R_{out} = r_o(1 + g_m R_S) \approx g_m r_o R_S = \frac{2R_S}{\lambda(V_{GS} - V_{TN})} = 10^9 \Omega$ For typical values,

$R_S = \frac{10^9(0.01/V)(0.25V)}{2} = 1.25 M\Omega$ Using this value to estimate the required voltage,

$$g_m r_o R_S = \sqrt{2K_n I_D} \frac{R_S}{\lambda I_D} = 10^9 \Omega \rightarrow I_D = \frac{2K_n}{10^{18}} \left(\frac{R_S}{\lambda} \right)^2 = \frac{2(0.001)}{10^{18}} \left(\frac{1.25 \times 10^6}{0.01} \right)^2 = 31.3 \mu A \text{ and}$$

$V_{R_S} = 39 V$ which is getting large. So the BJT appears to be the best choice.

14.53

$$R_{out} = \frac{R_{th} + r_\pi}{\beta_o + 1} \quad | \quad \text{Assuming } R_{th} \approx R_I \text{ and } r_\pi = 0, R_{out} \geq \frac{R_I}{\beta_o + 1} = \frac{250}{151} = 1.66 \Omega$$

14.54

$$R_{in} = r_\pi + (\beta_o + 1)R_E \approx r_\pi + \beta_o R_E = r_\pi(1 + g_m R_E) \quad | \quad r'_\pi = r_\pi(1 + g_m R_E)$$

$$g'_m = \frac{i_c}{v_i} = \frac{\beta_o}{r_\pi + (\beta_o + 1)R_E} \approx \frac{\beta_o}{r_\pi + \beta_o R_E} = \frac{\beta_o}{r_\pi(1 + g_m R_E)} = \frac{g_m}{1 + g_m R_E}$$

$$r'_o = \frac{i_c}{v_c} \Big|_{v_i=0} = r_o \left(1 + \frac{\beta_o R_E}{r_\pi + R_E} \right) \approx r_o \left(1 + \frac{\beta_o R_E}{r_\pi} \right) = r_o(1 + g_m R_E) \text{ for } r_\pi \gg R_E$$

$$\beta'_o = g'_m r'_\pi = \left(\frac{g_m}{1 + g_m R_E} \right) r_\pi(1 + g_m R_E) = \beta_o \quad | \quad \mu'_f = g'_m r'_o = \left(\frac{g_m}{1 + g_m R_E} \right) r_o(1 + g_m R_E) = \mu_f$$

14.55

*Problem 14.55 - Common-Emitter Amplifier 5mV

VCC 6 0 DC 9

VEE 4 0 DC -9

VS 1 0 SIN(0 0.005 1K)

C1 1 2 1U

RB 2 0 10K

RC 6 5 3.6K

RE 3 4 2K

C2 3 0 50U

C3 5 7 1U

```

R3 7 0 10K
Q1 5 2 3 NBJT
.OP
.TRAN 1U 5M
.FOUR 1KHZ V(7)
.MODEL NBJT NPN IS=1E-16 BF=100 VA=70
.PROBE V(7)
.END
*Problem 14.55 - Common-Emitter Amplifier 10mV
VCC 6 0 DC 9
VEE 4 0 DC -9
VS 1 0 SIN(0 0.01 1K)
C1 1 2 1U
RB 2 0 10K
RC 6 5 3.6K
RE 3 4 2K
C2 3 0 50U
C3 5 7 1U
R3 7 0 10K
Q1 5 2 3 NBJT
.OP
.TRAN 1U 5M
.FOUR 1KHZ V(7)
.MODEL NBJT NPN IS=1E-16 BF=100 VA=70
.PROBE V(7)
.END
*Problem 14.55 - Common-Emitter Amplifier 15mV
VCC 6 0 DC 9
VEE 4 0 DC -9
VS 1 0 SIN(0 0.015 1K)
C1 1 2 1U
RB 2 0 10K
RC 6 5 3.6K
RE 3 4 2K
C2 3 0 50U
C3 5 7 1U
R3 7 0 10K
Q1 5 2 3 NBJT
.OP
.TRAN 1U 5M
.FOUR 1KHZ V(7)
.MODEL NBJT NPN IS=1E-16 BF=100 VA=70
.PROBE V(7)
.END

```

Results:

v_i	1 kHz	2 kHz	3 kHz	THD
-------	-------	-------	-------	-----

5 mV	5.8 mV	0.335 mV (5.7%)	0.043 mV (0.74%)	5.9%
10 mV	12.4 mV	1.54 mV (12.5%)	0.258 mV (2.1%)	12.8%
15 mV	20.6 mV	4.32 mV (21%)	1.18 mV (5.4%)	22%

14.56

*Problem 14.56 - Output Resistance

VCC 2 0 DC 10

IB1 0 1 DC 10U

Q1 2 1 0 NBJT

IB2 0 3 DC 10U

RE 4 0 10K

Q2 2 3 4 NBJT

.OP

.DC VCC 10 20 .025

.MODEL NBJT NPN IS=1E-16 BF=60 VA=20

.PRINT DC IC(Q1) IC(Q2)

.PROBE IC(Q1) IC(Q2)

.END

Results: A small value of Early voltage has been used deliberately to accentuate the results. Note that the transistors have significantly different values of β_F because of the collector-emitter voltage differences and low value of VA.

NAME	Q1	Q2
MODEL	NBJT	NBJT
IB	1.00E-05	1.00E-05
IC	8.77E-04	6.72E-04
VBE	7.61E-01	7.61E-01
VBC	-9.24E+00	-2.41E+00
VCE	1.00E+01	3.18E+00
BETADC	8.77E+01	6.72E+01
GM	3.39E-02	2.60E-02
RPI	2.59E+03	2.59E+03
RO	3.33E+04	3.33E+04

$$\text{From SPICE : } R_{out1} = \frac{(20-10)}{(1.17-0.877)} \frac{V}{mA} = 34.1 \text{ k}\Omega \quad | \quad R_{out2} = \frac{(20-10)}{(903-673)} \frac{V}{\mu A} = 43.5 \text{ k}\Omega$$

For circuit 1: $R_{out1} = r_{o1} = 33.3 \text{ k}\Omega$

For circuit 2: $R_{out2} = r_{o2} \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) + (R_{th} + r_\pi) \| R_E$ (See Eq. 14.28)

But $R_{th} = \infty \rightarrow R_{out2} = r_{o2} + R_E = 33.3 \text{ k}\Omega + 10 \text{ k}\Omega = 43.3 \text{ k}\Omega$

14.57

$$R_{th} \equiv r_o \left(1 + \frac{\beta_o R_I}{R_I + r_\pi} \right) = 250k\Omega \left(1 + \frac{100(270\Omega)}{270\Omega + 50k\Omega} \right) = 384 \text{ k}\Omega$$

$$v_{th} = i_{sc} R_{th} = \frac{v_i}{R_I + \frac{\alpha_o}{g_m}} \alpha_o R_{th} = \frac{v_i}{270\Omega + \frac{0.990}{0.002}} 0.990(384 \text{ k}\Omega) \rightarrow v_{th} = 479v_i$$

14.58

$$v_{th} = G_m R_{th} = -\frac{g_m}{1 + g_m R_S} [r_o (1 + g_m R_S)] v_i = -\mu_f v_i = -(0.5mS)(250k\Omega) v_i = -125v_i$$

$$R_{th} = r_o (1 + g_m R_S) = r_o + \mu_f R_S = 250k\Omega + 125(18k\Omega) = 2.50 \text{ M}\Omega$$

14.59

$$v_{th} = v_i \frac{(\beta_o + 1)r_o}{R_I + r_\pi + (\beta_o + 1)r_o} = v_i \frac{1}{\frac{R_I}{(\beta_o + 1)r_o} + \frac{r_\pi}{(\beta_o + 1)r_o} + 1} = v_i \frac{1}{\frac{g_m R_I}{(\beta_o + 1)\mu_f} + \frac{\beta_o}{(\beta_o + 1)\mu_f} + 1} \cong v_i$$

$$R_{th} \cong \frac{R_I + r_\pi}{\beta_o + 1} \| r_o \cong \frac{R_I + r_\pi}{\beta_o + 1} = \frac{R_I}{\beta_o + 1} + \frac{\alpha_o}{g_m}$$

14.60

$$(a) g_{21} = \left. \frac{v_2}{v_1} \right|_{i_2=0} = \frac{g_m R_E}{1 + g_m R_E} \cong 1$$

$$g_{12} = \left. \frac{i_1}{i_2} \right|_{v_1=0} = \left(\frac{1}{\beta_o + 1} \right) \frac{i_e}{i_2} \cong \left(\frac{1}{\beta_o + 1} \right) \frac{R_E}{R_E + \frac{1}{g_m}} = \frac{1}{\beta_o + 1} \left(\frac{g_m R_E}{1 + g_m R_E} \right) \cong \frac{1}{\beta_o}$$

$$(b) g_{21} = 0.960 \quad | \quad g_{12} = 9.51 \times 10^{-3} \quad | \quad g_{21} \gg g_{12}$$

14.61

$$(a) g_{21} = \left. \frac{v_2}{v_1} \right|_{i_2=0} \quad | \quad v_2 = \frac{g_m (R_D \| r_o)}{1 + g_m (R_D \| r_o)} v_1 \quad | \quad g_{21} = \frac{g_m (R_D \| r_o)}{1 + g_m (R_D \| r_o)} \cong 1$$

$$g_{12} = \left. \frac{i_1}{i_2} \right|_{v_1=0} \quad | \quad i_1 =$$

$$(b) g_{21} = \frac{0.2mS(50k\Omega \| 450k\Omega)}{1 + 0.2mS(50k\Omega \| 450k\Omega)} = 0.947 \quad | \quad g_{12} = 0 \quad | \quad g_{21} \gg g_{12}$$

14.62

$$(a) g_{21} = \left. \frac{v_2}{v_1} \right|_{i_2=0} \quad | \quad v_2 = g_m (R_C \| r_o) v_1 \quad | \quad g_{21} = g_m (R_C \| r_o)$$

$$g_{12} = \left. \frac{i_1}{i_2} \right|_{v_1=0} = -\frac{R_C}{r_o + R_C} \quad | \quad \left| \frac{g_{21}}{g_{12}} \right| = g_m \frac{R_C r_o}{r_o + R_C} \frac{r_o + R_C}{R_C} = g_m r_o = \mu_f >> 1$$

$$(b) g_{21} = 3mS(18k\Omega \| 800k\Omega) = 52.8 \quad g_{12} = -\frac{18k\Omega}{18k\Omega + 800k\Omega} = 0.0220$$

14.63

$$(a) g_{21} = \left. \frac{v_2}{v_1} \right|_{i_2=0} = +g_m (R_D \| r_o) \quad | \quad g_{12} = \left. \frac{i_1}{i_2} \right|_{v_1=0} = -\frac{R_D}{R_D + r_o} \quad | \quad g_{21} = -g_m r_o g_{12} \cong -\mu_f g_{12}$$

$$(b) g_{21} = +0.5mS(100k\Omega \| 500k\Omega) = 41.7 \quad | \quad g_{12} = -\frac{100k\Omega}{100k\Omega + 500k\Omega} = -0.167 \quad | \quad g_{21} >> g_{12}$$

14.64

$$(a) g_{21} = \left. \frac{v_2}{v_1} \right|_{i_2=0} \quad | \quad v_2 \cong -\frac{g_m R_C}{1 + g_m R_E} v_1 \quad | \quad g_{21} = -\frac{g_m R_C}{1 + g_m R_E} \quad | \quad g_{12} = \left. \frac{i_1}{i_2} \right|_{v_1=0}$$

$$i_1 \cong -\frac{v_2}{r_o (1 + g_m R_E)} \left(\frac{R_E}{R_E + r_\pi} \right) \cong -\frac{i_2 R_C}{r_o (1 + g_m R_E)} \left(\frac{R_E}{R_E + r_\pi} \right) \quad | \quad g_{12} = -\frac{R_C}{r_o (1 + g_m R_E)} \left(\frac{R_E}{R_E + r_\pi} \right)$$

$$(b) g_{21} = -\frac{2mS(130k\Omega)}{1 + 2mS(12k\Omega)} = -10.4 \quad | \quad g_{12} = -\frac{130k\Omega}{1M\Omega [1 + 2mS(12k\Omega)]} \left(\frac{12k\Omega}{12k\Omega + 50k\Omega} \right) = -1.01 \times 10^{-3}$$

$$g_{21} >> g_{12}$$

14.65

$$(a) g_{21} = \left. \frac{v_2}{v_1} \right|_{i_2=0} \quad | \quad v_2 \cong -\frac{g_m R_D}{1 + g_m R_S} v_1 \quad | \quad g_{21} \cong -\frac{g_m R_D}{1 + g_m R_S}$$

$$g_{12} = \left. \frac{i_1}{i_2} \right|_{v_1=0} \quad | \quad i_1 = 0 \quad | \quad g_{12} = 0 \quad | \quad \frac{g_{12}}{g_{21}} = 0 \quad | \quad g_{21} >> g_{12}$$

$$(b) g_{21} = -\frac{0.75mS(130k\Omega)}{1 + 0.75mS(12k\Omega)} = -9.75 \quad | \quad g_{12} = 0$$

14.66

At the output node v_o : $g_m v_x = (g_o + G_L) v_o - g_o v_x \quad | \quad v_o = \frac{g_m + g_o}{g_o + G_L} v_x$

$$i_x = g_m v_x + g_o (v_x - v_o) \quad | \quad \frac{i_x}{v_x} = g_m + g_o \left(1 - \frac{g_m + g_o}{g_o + G_L} \right) = g_m + g_o \left(\frac{G_L - g_m}{g_o + G_L} \right)$$

$$\frac{i_x}{v_x} = g_m + g_o \left(\frac{G_L - g_m}{g_o + G_L} \right) = G_L \frac{g_m + g_o}{g_o + G_L} \quad | \quad R_{in} = \frac{v_x}{i_x} = \frac{1}{g_m} \frac{1 + \frac{R_L}{r_o}}{1 + \frac{1}{\mu_f}} \cong \frac{1}{g_m} \left(1 + \frac{R_L}{r_o} \right)$$

14.67

$$I_C = 100 \frac{5 - 0.7}{10^4 + 101(10^3)} = 3.87mA \quad | \quad g_m = 40 I_C = 0.155S \quad | \quad r_\pi = \frac{100}{g_m} = 645\Omega$$

$$R_L = 1k\Omega \parallel 20k\Omega = 952\Omega \quad | \quad R_E = 1k\Omega \parallel 20k\Omega = 952\Omega$$

$$A_{v1} = -\frac{\beta_o R_L}{r_\pi + (\beta_o + 1)R_E} = -\frac{100(952\Omega)}{645\Omega + 101(952\Omega)} = -0.984$$

$$A_{v2} = \frac{(\beta_o + 1)R_E}{r_\pi + (\beta_o + 1)R_E} = \frac{101(952\Omega)}{645\Omega + 101(952\Omega)} = 0.993$$

The small - signal requirement limits the output signal to :

$$v_{be} = v_i - v_{o2} = v_i (1 - 0.993) = 0.007v_i \quad | \quad v_i \leq \frac{0.005}{0.007} = 0.714V$$

$$v_{ol} \leq 0.984(0.714V) = 0.703V$$

We also need to check V_{CB} : $V_C = 5 - 3.87mA(1k\Omega) = 1.13V$ and $V_B = -10^4 I_B = -0.387V$.

The total collector - base voltage of the transistor is therefore : $V_{CB} = 1.52V - 0.984v_i - v_i$.

We require $V_{CB} \geq 0$ for forward - active region operation. Therefore : $v_i \leq 0.766 V$.

The small - signal limit is the most restrictive.

14.68

$$(a) V_{EQ} = -15 + 30 \frac{100k\Omega}{100k\Omega + 100k\Omega} = 0V \quad | \quad R_{EQ} = 100k\Omega \parallel 100k\Omega = 50k\Omega$$

$$I_B = \frac{0 - 0.7 - (-15)}{50k\Omega + 126(4.7k\Omega)} = 22.3\mu A \quad | \quad I_C = 2.78 mA \quad | \quad I_E = 2.81 mA$$

$$V_{CE} = 30 - 2000I_C - 4700I_E = 11.4 V$$

$$r_\pi = \frac{125(0.025V)}{2.78mA} = 1.12k\Omega \quad | \quad r_o = \frac{(50+11.4)V}{2.78mA} = 22.1k\Omega$$

$$R_B = R_1 \parallel R_2 = 100k\Omega \parallel 100k\Omega = 50k\Omega \quad | \quad R_L = R_3 \parallel R_E \parallel r_o = 24k\Omega \parallel 4.7k\Omega \parallel 22.1k\Omega = 3.34k\Omega$$

$$R_{in} = R_B \parallel [r_\pi + (\beta_o + 1)R_L] = 50k\Omega \parallel [1.12k\Omega + (126)3.34k\Omega] = 44.7 k\Omega$$

$$A_v = + \frac{(\beta_o + 1)R_L}{r_\pi + (\beta_o + 1)R_L} \left(\frac{R_{in}}{R_I + R_{in}} \right) = \frac{126(3.34k\Omega)}{1.12k\Omega + 126(3.34k\Omega)} \left(\frac{44.7k\Omega}{0.600k\Omega + 44.7 k\Omega} \right) = 0.984$$

$$R_{out} = R_E \parallel r_o \parallel \frac{(R_B \parallel R_I) + r_\pi}{\beta_o + 1} = 4.7k\Omega \parallel 22.1k\Omega \parallel \frac{(44.7k\Omega \parallel 600\Omega) + 1.12k\Omega}{126} = 13.5 \Omega$$

(b) SPICE Results: Q-point: (2.81 mA, 11.1 V), $A_v = 0.984$, $R_{in} = 45.5 k\Omega$, $R_{out} = 13.0 \Omega$

14.69

$$I_B = \frac{(10 - 0.7)V}{1M\Omega + (80 + 1)68k\Omega} = 1.43 \mu A \quad | \quad I_C = 114 \mu A \quad | \quad V_{CE} = 20 - 39000I_C - 68000I_E = 7.71 V$$

$$\text{Active region is correct.} \quad | \quad r_\pi = \frac{81(0.025V)}{114\mu A} = 17.8 k\Omega \quad | \quad r_o = \frac{75 + 7.71}{114\mu A} = 726 k\Omega$$

$$R_L = 500k\Omega \parallel 39k\Omega \parallel 726k\Omega = 34.5k\Omega \quad | \quad R_{in} = R_B \parallel r_\pi = 1M\Omega \parallel 17.8k\Omega = 17.5 k\Omega$$

$$A_v = -g_m R_L \left(\frac{R_{in}}{R_I + R_{in}} \right) = 40(0.114mA)(34.5k\Omega) \left(\frac{17.5k\Omega}{500\Omega + 17.5k\Omega} \right) = -153$$

$$R_{out} = R_C \parallel r_o = 39k\Omega \parallel 726k\Omega = 37.0 k\Omega$$

$$v_{be} = v_i \left(\frac{R_{in}}{R_I + R_{in}} \right) = v_i \left(\frac{17.5k\Omega}{500\Omega + 17.5k\Omega} \right) = 0.972v_i \quad | \quad v_i \leq \frac{0.005V}{0.972} = 5.14 mV$$

$$A_v \cong -10(V_{CC} + V_{EE}) = -10(20) = -200. \quad | \quad \text{A closer estimate is } -40V_{R_C} = -40(4.47) = -178$$

(b) SPICE Results: Q-point: (116 μA , 7.53 V), $A_v = -150$, $R_{in} = 19.6 k\Omega$, $R_{out} = 37.0 k\Omega$

14.70

$$(a) V_{EQ} = 12 \frac{62k\Omega}{62k\Omega + 20k\Omega} = 9.07V \quad | \quad R_{EQ} = 62k\Omega \parallel 20k\Omega = 15.1k\Omega$$

$$I_B = \frac{12 - 0.7 - 9.07}{15.1k\Omega + 76(6.8k\Omega)} = 4.19\mu A \quad | \quad I_C = 314 \mu A \quad | \quad I_E = 319 \mu A$$

$$V_{EC} = 12 - 16000I_C - 6800I_E = 4.81 V$$

$$r_o = \frac{60 + 4.81}{314 \times 10^{-6}} = 206k\Omega \quad | \quad r_\pi = \frac{75(0.025)}{314 \times 10^{-6}} = 5.97k\Omega$$

$$R_L = r_o \parallel 16k\Omega \parallel 100k\Omega = 206k\Omega \parallel 16k\Omega \parallel 100k\Omega = 12.9k\Omega$$

$$R_{in} = 15.1k\Omega \parallel 5.97k\Omega = 4.28 k\Omega \quad | \quad R_{out} = r_o \parallel 16k\Omega = 14.8 k\Omega \quad | \quad g_m = 40I_C = 12.6 mS$$

$$A_v = -g_m R_L \left(\frac{R_{in}}{R_I + R_{in}} \right) = -(12.6mS)(12.9k\Omega) \left(\frac{4.28k\Omega}{1k\Omega + 4.28k\Omega} \right) = -132$$

(b) SPICE Results: Q-point: (309 μA , 4.93 V), $A_v = -127$, $R_{in} = 4.65 k\Omega$ $R_{out} = 14.9 k\Omega$

14.71

$$(a) V_{EQ} = 18 \frac{500k\Omega}{500k\Omega + 1.4M\Omega} = 4.73V \quad | \quad R_{EQ} = R_1 \parallel R_2 = 500k\Omega \parallel 1.4M\Omega = 368k\Omega$$

Assume Active Region Operation

$$4.73 = V_{GS} = 27000I_D \rightarrow 4.73 = 1 + \sqrt{\frac{2I_D}{5 \times 10^{-4}}} + 27000I_D \rightarrow I_D = 113 \mu A$$

$$V_{DS} = 18 - (27000 + 75000)I_D = 6.47 V > 3.73 V \text{ - Active region is correct.}$$

$$r_o = \frac{50 + 6.47}{113 \times 10^{-6}} = 500k\Omega \quad | \quad g_m = \sqrt{2(500 \times 10^{-6})(113 \times 10^{-6})[1 + 0.02(6.47)]} = 357\mu S$$

$$R_L = r_o \parallel R_D \parallel 470k\Omega = 500k\Omega \parallel 75k\Omega \parallel 470k\Omega = 57.3k\Omega$$

$$R_{in} = R_1 \parallel R_2 = 500k\Omega \parallel 1.4M\Omega = 368k\Omega \quad | \quad R_{out} = r_o \parallel 75k\Omega = 65.2 k\Omega$$

$$A_v = -g_m R_L \left(\frac{R_{in}}{R_I + R_{in}} \right) = -(0.357mS)(57.3k\Omega) \left(\frac{368k\Omega}{1k\Omega + 368k\Omega} \right) = -20.4$$

(b) SPICE Results: Q-point: (115 μA , 6.30 V), $A_v = -20.5$, $R_{in} = 368 k\Omega$ $R_{out} = 65.1 k\Omega$

14.72

$$I_D = \frac{(2.5 \times 10^{-4})}{2} (V_{GS} + 1)^2 \quad | \quad \frac{10 + V_{GS}}{33k\Omega} = 1.25 \times 10^{-4} (V_{GS} + 1)^2 \rightarrow V_{GS} = -2.358V$$

$$I_D = \frac{10 + V_{GS}}{33k\Omega} = 232\mu A \quad | \quad V_{DS} = -10 + 0.232mA(24k\Omega) - 2.36 = -6.79V \quad | \quad \text{Pinchoff region is correct.}$$

$$g_m = \sqrt{2(2.5 \times 10^{-4})(2.32 \times 10^{-4})[1 + 0.02(6.79)]} = 0.363mS \quad / \quad R_I \| R_S = 0.5k\Omega \| 33k\Omega = 493\Omega$$

$$r_o = \frac{50 + 6.79}{2.32 \times 10^{-4}} = 245k\Omega \quad R_L = r_o \| R_D \| R_3 = 245k\Omega \| 24k\Omega \| 100k\Omega = 17.9k\Omega \quad / \quad R_{in} = 33k\Omega \left\| \frac{1}{g_m} \right\| = 2.69 k\Omega$$

$$R_{out} = r_o \| R_D = 21.9 k\Omega \quad A_v = \frac{g_m R_L}{1 + g_m (R_I \| R_S)} \left(\frac{R_S}{R_I + R_S} \right) = \frac{0.363mS(17.9k\Omega)}{1 + 0.363mS(0.493k\Omega)} \left(\frac{33k\Omega}{500\Omega + 33k\Omega} \right) = 5.42$$

(b) SPICE Results: Q-point: (234 μ A, -6.67V), $A_v = +5.56$, $R_{in} = 2.69$ k Ω , $R_{out} = 18.1$ k Ω

14.73

$$I_C = 100 \frac{5 - 0.7}{500k\Omega + 500k\Omega + (101)\beta 30k\Omega} = 12.5\mu A \quad | \quad V_{CE} = 5 - I_C(330k\Omega) - (-5) = 5.87V$$

$$r_\pi = \frac{100}{40(12.5\mu A)} = 200k\Omega \quad | \quad r_o = \frac{60 + 5.87}{12.5 \times 10^{-6}} = 5.27M\Omega \quad | \quad R_L = 500k\Omega \| 330k\Omega \| 500k\Omega \| r_o = 139k\Omega$$

$$\text{Absorb } R_I \text{ into the transistor: } r'_\pi = r_\pi \| R_I = 143k\Omega \quad | \quad \beta'_o = g_m r'_\pi = 71.4$$

$$R_{in} = r'_\pi + (\beta'_o + 1)R_L = 143k\Omega + 71.4(139k\Omega) = 10.1 M\Omega$$

$$R_{out} = 330k\Omega \| 500k\Omega \| r_o \| \frac{(R_I \| R_B) + r'_\pi}{\beta'_o + 1} = 1.97 k\Omega$$

$$A_v = + \frac{(\beta'_o + 1)R_L}{(R_I \| R_B) + r'_\pi + (\beta'_o + 1)R_L} = \frac{72.4(139k\Omega)}{1k\Omega + 143k\Omega + 72.4(139k\Omega)} = 0.986$$

(b) SPICE Results: Q-point: (12.7 μ A, 5.78 V), $A_v = +0.986$, $R_{in} = 10.7 M\Omega$, $R_{out} = 2.00$ k Ω

14.74

$$I_B = \frac{(12 - 0.7)V}{100k\Omega + (51)82k\Omega} = 2.69 \mu A \quad | \quad I_C = 135 \mu A \quad | \quad V_{CE} = 24 - 39000I_C - 82000I_E = 7.58 V$$

Active region is correct.

$$g_m = 40(135\mu A) = 5.40 mS \quad | \quad r_\pi = \frac{50(0.025V)}{135\mu A} = 9.26 k\Omega \quad | \quad r_o = \frac{50 + 7.58}{135\mu A} = 427 k\Omega$$

$$R_{th} = R_I \| R_E = 0.5k\Omega \| 82k\Omega = 497\Omega \quad | \quad R_L = r_o(1 + g_m R_{th}) \| R_C \| R_3 = 1.57 M\Omega \| 39k\Omega \| 100k\Omega = 27.6 k\Omega$$

$$A_v = \frac{g_m R_L}{1 + g_m (R_I \| R_E)} \left(\frac{R_E}{R_I + R_E} \right) = \frac{5.40 mS (27.6 k\Omega)}{1 + 5.40 mS (497\Omega)} \left(\frac{82k\Omega}{500\Omega + 82k\Omega} \right) = 40.2$$

$$R_{in} = 82k\Omega \left\| \frac{r_\pi}{\beta_o + 1} \right\| = 181 \Omega \quad | \quad R_{out} = r_o(1 + g_m R_{th}) \| R_C = 38.1 k\Omega$$

(b) SPICE Results: Q-point: (132 μA , 7.79V), $A_v = 39.0$, $R_{in} = 204 \Omega$, $R_{out} = 38.0 k\Omega$

14.75

$$V_{EQ} = 18 \frac{2.2 M\Omega}{2.2 M\Omega + 2.2 M\Omega} = 9.00V \quad | \quad R_{EQ} = R_i \| R_2 = 2.2 m\Omega \| 2.2 M\Omega = 1.10 M\Omega$$

Assume Active Region Operation

$$18 - 9 = 110000I_D - V_{GS} \rightarrow 9 = 1 + \sqrt{\frac{2I_D}{4 \times 10^{-4}}} + 110000I_D \rightarrow I_D = 67.5 \mu A$$

$$V_{DS} = 18 - (110000 + 90000)I_D = 4.50 V > 0.575 V \quad - \text{ Active region is correct.}$$

$$r_o = \frac{50 + 4.50}{67.5 \times 10^{-6}} = 807 k\Omega \quad | \quad g_m = \sqrt{2(400 \times 10^{-6})(67.5 \times 10^{-6})[1 + 0.02(4.50)]} = 243 \mu S$$

$$R_L = r_o \| R_D \| 470k\Omega = 807k\Omega \| 90k\Omega \| 470k\Omega = 69.7k\Omega$$

$$R_{in} = R_i \| R_2 = 2.2 M\Omega \| 2.2 M\Omega = 1.1 M\Omega \quad | \quad R_{out} = r_o \| 90k\Omega = 81.0 k\Omega$$

$$A_v = -g_m R_L \left(\frac{R_{in}}{R_i + R_{in}} \right) = -(0.243 mS)(69.7 k\Omega) \left(\frac{1.1 M\Omega}{1 k\Omega + 1.1 M\Omega} \right) = -16.9$$

(b) SPICE Results: Q-point: (66.7 μA , 4.47V), $A_v = -16.8$, $R_{in} = 1.10 M\Omega$, $R_{out} = 81.0 k\Omega$

14.76

(a) Assume Active Region operation. $V_{GS} = -51000I_D$ $I_D = \frac{5 \times 10^{-4}}{2} (V_{GS} + 2)^2 \rightarrow I_D = 32.2 \mu A$

$$V_{DS} = 15 - (20000 + 51000)I_D = 12.7 V > 0.36 V \text{ - Active Region is correct.}$$

$$g_m = \sqrt{2(5 \times 10^{-4})(32.2 \times 10^{-6})[1 + 0.02(12.70)]} = 0.201 mS \quad | \quad R_{in} = 51 k\Omega \left| \frac{1}{g_m} \right| = 4.53 k\Omega$$

$$r_o = \frac{50 + 12.7}{32.2 \times 10^{-6}} = 1.95 M\Omega \quad | \quad R_{th} = R_I \parallel R_S = 981 \Omega$$

$$R_{out} = r_o (1 + g_m R_{th}) \parallel R_D = 19.8 k\Omega \quad | \quad R_L = R_{out} \parallel 10 k\Omega = 6.65 k\Omega$$

$$A_v = \frac{g_m R_L}{1 + g_m (R_I \parallel R_S)} \left(\frac{R_S}{R_I + R_S} \right) = \frac{0.201 mS (6.65 k\Omega)}{1 + 0.201 mS (0.981 k\Omega)} \left(\frac{51 k\Omega}{1 k\Omega + 51 k\Omega} \right) = 1.10$$

(b) SPICE Results: Q-point: (32.9 μA , 12.7 V), $A_v = +1.10$, $R_{in} = 4.50 k\Omega$, $R_{out} = 19.8 k\Omega$

14.77

The power supply should be +16 V.

(a) Assume Active Region operation. Since there is no negative feedback ($R_S = 0$), we should include the effect of channel-length modulation. $V_{GS} = 0$

$$I_D = \frac{4 \times 10^{-4}}{2} (-5)^2 (1 + 0.02V_{DS}) \text{ and } V_{DS} = 16 - 1800I_D \rightarrow I_D = 5.59 mA$$

$$V_{DS} = 16 - 1800I_D = 5.93 V > 5 V \text{ - Active region is correct.}$$

$$g_m = \sqrt{2(4 \times 10^{-4})(5.59 mA)[1 + 0.02(5.93)]} = 2.24 mS \quad | \quad r_o = \frac{50 + 5.93}{5.59 \times 10^{-3}} = 10.0 k\Omega$$

$$A_v = -g_m R_L \left(\frac{R_G}{R_I + R_G} \right) = -(2.24 mS)(10.0 k\Omega \parallel 1.8 k\Omega \parallel 36 k\Omega) \left(\frac{10 M\Omega}{10 M\Omega + 5 k\Omega} \right) = -3.27$$

$$R_{in} = 10.0 M\Omega \quad | \quad R_{out} = R_D \parallel r_o = 1.52 k\Omega$$

(b) SPICE Results: Q-point: (5.59 mA, -5.93V), $A_v = -3.27$, $R_{in} = 10.0 M\Omega$, $R_{out} = 1.52 k\Omega$

14.78

$$I_B = \frac{(10 - 0.7)V}{33 k\Omega + (80 + 1)7.8 k\Omega} = 14.0 \mu A \quad | \quad I_C = 1.12 mA \quad | \quad V_{CE} = 20 - 7800I_E = 11.3 V$$

Active region is correct. $| r_\pi = \frac{80(0.025V)}{1.12 mA} = 1.79 k\Omega \quad | \quad r_o = \frac{(100 + 11.3)V}{1.12 mA} = 99.4 k\Omega$

$$R_L = r_o \parallel 1 M\Omega = 95.1 k\Omega \parallel 1 M\Omega = 86.8 k\Omega \quad | \quad R_{in} = R_B \parallel r_\pi = 33 k\Omega \parallel 1.79 k\Omega = 1.70 k\Omega \quad | \quad R_{out} = r_o = 99.4 k\Omega$$

$$A_v = -g_m R_L \left(\frac{R_{in}}{R_I + R_{in}} \right) = -40(1.12 mA)(86.8 k\Omega) \frac{1.70 k\Omega}{250 \Omega + 1.70 k\Omega} = -3390$$

(b) Results: Q-point: (1.12 mA, 11.2 V), $A_v = -3440$, $R_{in} = 1.93 k\Omega$, $R_{out} = 98.9 k\Omega$

14.79

Bias forces Active Region operation : $V_{DS} = 6 - (-6) = 12 \text{ V}$ $V_{GS} = 6 \text{ V}$

$$I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS}) = \frac{4 \times 10^{-4}}{2} (6 - 1)^2 [1 + 0.02(12)] = 6.20 \text{ mA}$$

$$g_m = \sqrt{2(4 \times 10^{-4})(6.2 \times 10^{-3})[1 + 0.02(12)]} = 2.48 \text{ mS}$$

$$r_o = \frac{\frac{1}{0.02} + 12}{6.20} \frac{V}{mA} = 10.0 \text{ k}\Omega \quad \text{-- Cannot neglect!} \quad | \quad R_L = 10.0 \text{ k}\Omega \| 100 \text{ k}\Omega = 9.09 \text{ k}\Omega$$

$$R_{in} = R_G = 2 \text{ M}\Omega \quad | \quad R_{out} = \frac{1}{g_m} \| r_o = 388 \text{ }\Omega$$

$$A_v = + \frac{R_{in}}{R_I + R_{in}} \left(\frac{g_m R_L}{1 + g_m R_L} \right) = + \frac{2 \text{ M}\Omega}{10 \text{ k}\Omega + 2 \text{ M}\Omega} \left(\frac{2.48 \text{ mS}(9.09 \text{ k}\Omega)}{1 + 2.48 \text{ mS}(9.09 \text{ k}\Omega)} \right) = 0.953$$

(b) SPICE Results: Q-point: (6.20 mA, 12.0V), $A_v = 0.953$, $R_{in} = 2.00 \text{ M}\Omega$, $R_{out} = 388 \text{ }\Omega$

14.80

$$(a) V_{EQ} = 15 \frac{500 \text{ k}\Omega}{1.4 \text{ M}\Omega + 500 \text{ k}\Omega} = 3.95 \text{ V} \quad | \quad R_{EQ} = 500 \text{ k}\Omega \| 1.4 \text{ M}\Omega = 368 \text{ k}\Omega$$

$$\text{Assume active region} \quad | \quad 3.95 = V_{GS} + 27000 I_D = 1 + \sqrt{\frac{2 I_D}{400 \times 10^{-6}}} + 27000 I_D \rightarrow I_D = 85.1 \mu\text{A}$$

$$V_{DS} = 15 - I_D (75 \text{ k}\Omega + 27 \text{ k}\Omega) = 6.32 \text{ V} \quad | \quad \text{Active region operation is correct.}$$

$$g_m = \sqrt{2(400 \times 10^{-6})(85.1 \times 10^{-6})} = 0.261 \text{ mS} \quad | \quad r_o = \frac{50 + 6.32}{85.1 \mu\text{A}} = 662 \text{ k}\Omega \quad | \quad R_G = R_I \| R_2 = 368 \text{ k}\Omega$$

$$C_1 \geq 10 \frac{1}{2\pi f(R_I + R_G)} = \frac{10}{2\pi(400 \text{ Hz})(1 \text{ k}\Omega + 368 \text{ k}\Omega)} \quad | \quad C_1 \geq 0.0108 \mu\text{F} \rightarrow 0.01 \mu\text{F}$$

$$C_2 \geq 10 \frac{1}{2\pi f(R_S \| \frac{1}{g_m})} = \frac{10}{2\pi(400 \text{ Hz})(27 \text{ k}\Omega \| \frac{1}{0.261 \text{ mS}})} \quad | \quad C_2 \geq 1.19 \mu\text{F} \rightarrow 1.2 \mu\text{F}$$

$$C_3 \geq 10 \frac{1}{2\pi f[(R_D \| r_o) + R_3]} = \frac{10}{2\pi(400 \text{ Hz})(67.4 \text{ k}\Omega + 470 \text{ k}\Omega)} \quad | \quad C_3 \geq 7.40 \text{ nF} \rightarrow 8200 \text{ pF}$$

$$(b) C_2 = \frac{1}{2\pi f(R_S \| \frac{1}{g_m})} = \frac{1}{2\pi(4000 \text{ Hz})(27 \text{ k}\Omega \| \frac{1}{0.261 \text{ mS}})} = 0.0119 \mu\text{F} \rightarrow 0.012 \mu\text{F}$$

14.81

$$(a) V_{EQ} = 12 \frac{62k\Omega}{20k\Omega + 62k\Omega} = 9.07V \quad | \quad R_{EQ} = 20k\Omega \parallel 62k\Omega = 15.1k\Omega$$

$$I_B = \frac{(12 - 0.7 - 9.07)V}{15.1k\Omega + (75 + 1)\beta_0 k\Omega} = 7.16\mu A \quad | \quad I_C = 537 \mu A \quad | \quad V_{EC} = 12 - 3900I_E - 8200I_C = 5.47 V$$

Active region is correct.

$$r_\pi = \frac{75(0.025V)}{537\mu A} = 3.49k\Omega \quad | \quad r_o = \frac{60 + 5.47}{537\mu A} = 122k\Omega \quad | \quad g_m = 40I_C = 21.5 mS$$

$$R_{in} = R_I \parallel R_2 \parallel r_\pi = 15.1k\Omega \parallel 3.49k\Omega = 2.83 k\Omega \quad | \quad R_{out} = r_o \parallel R_C = 122k\Omega \parallel 8.2k\Omega = 7.68 k\Omega$$

$$C_1 \geq 10 \frac{1}{2\pi f(R_I + R_{in})} = \frac{10}{2\pi(100Hz)(1k\Omega + 2.83k\Omega)} \quad | \quad C_1 \geq 4.16 \mu F \rightarrow 0.01 \mu F$$

$$C_2 \geq 10 \frac{1}{2\pi f \left(\frac{R_I \parallel R_{EQ} + r_\pi}{\beta_0 + 1} \right)} = \frac{10}{2\pi(100Hz) \left(\frac{1k\Omega \parallel 15.1k\Omega + 3.49k\Omega}{76} \right)} \quad | \quad C_2 \geq 273 \mu F \rightarrow 270 \mu F$$

$$C_3 \geq 10 \frac{1}{2\pi f [R_{out} + R_3]} = \frac{10}{2\pi(100Hz)(7.68k\Omega + 100k\Omega)} \quad | \quad C_3 \geq 0.148 \mu F \rightarrow 0.15 \mu F$$

$$(b) C_2 = \frac{1}{2\pi f \left(\frac{R_I \parallel R_{EQ} + r_\pi}{\beta_0 + 1} \right)} = \frac{1}{2\pi(1000Hz) \left(\frac{1k\Omega \parallel 15.1k\Omega + 3.49k\Omega}{76} \right)} = 2.73 \mu F \rightarrow 2.7 \mu F$$

14.82

$$I_C = 100 \frac{5 - 0.7}{10^4 + 101(10^3)} = 3.87mA \quad | \quad g_m = 40I_C = 0.155S \quad | \quad r_\pi = \frac{100}{g_m} = 645\Omega \quad | \quad r_o = \infty$$

The capacitors will be negligible at a frequency 10 times the individual break frequencies:

$$R_{eq1} = 10k\Omega \parallel [r_\pi + (\beta_0 + 1)(1k\Omega \parallel 20k\Omega)] = 9.06k\Omega \quad | \quad f_1 = \frac{10}{2\pi(9.06k\Omega)2\mu F} = 87.8 Hz$$

$$R_{eq2} = 20k\Omega + \left[1k\Omega \parallel \frac{r_\pi}{(\beta_0 + 1)} \right] = 20.0k\Omega \quad | \quad f_2 = \frac{10}{2\pi(20.0k\Omega)10\mu F} = 7.96 Hz$$

$$R_{eq3} = R_{out} + 20k\Omega = 21.0k\Omega \quad | \quad f_3 = \frac{10}{2\pi(21.0k\Omega)10\mu F} = 7.56 Hz$$

14.83

$$(a) I_C = \alpha_F I_E = \frac{80}{81} \left(\frac{5 - 0.7}{13.3 \times 10^3} \right) = 319 \mu A \quad | \quad g_m = 40 I_C = 12.8 mS \quad | \quad r_\pi = \frac{80}{g_m} = 6.26 k\Omega \quad | \quad r_o = \infty$$

$$R_{eq1} = 75\Omega + \left[13.3k\Omega \parallel \left(\frac{r_\pi}{(\beta_o + 1)} \right) \right] = 152\Omega \quad | \quad C_1 = \frac{10}{2\pi(50kHz) \parallel 152\Omega} = 0.209 \mu F \rightarrow 0.20 \mu F$$

$$R_{eq2} = R_{out} + 100k\Omega = 8.25k\Omega + 100k\Omega = 108k\Omega \quad | \quad C_2 = \frac{10}{2\pi(50kHz) \parallel 108k\Omega} = 295 pF \rightarrow 270 pF$$

$$(b) C_1 = 0.209 \mu F \left(\frac{50kHz}{100Hz} \right) = 105 \mu F \rightarrow 100 \mu F \quad | \quad C_2 = 295 pF \left(\frac{50kHz}{100Hz} \right) = 0.148 \mu F \rightarrow 0.15 \mu F$$

14.84

$$V_{EQ} = -15 + 15 \frac{51k\Omega}{51k\Omega + 100k\Omega} = -4.87V \quad | \quad R_{EQ} = 51k\Omega \parallel 100k\Omega = 33.8k\Omega$$

$$\text{Assume active region operation} \quad | \quad I_B = \frac{[-4.87 - 0.7 - (-15)]V}{33.8k\Omega + (101)(4.7k\Omega)} = 18.5\mu A \quad | \quad I_C = 1.85 mA$$

$$V_{CE} = 30 - 4700I_E = 21.2 V \quad | \quad g_m = 40(1.85mA) = 7.40mS$$

$$\text{Active region is correct.} \quad | \quad r_\pi = \frac{100(0.025V)}{1.85mA} = 1.35k\Omega \quad | \quad r_o = \frac{(50 + 21.2)V}{1.85mA} = 38.5k\Omega$$

$$R_B = R_i \parallel R_2 = 51k\Omega \parallel 100k\Omega = 33.8k\Omega \quad | \quad R_L = R_3 \parallel R_E \parallel r_o = 24k\Omega \parallel 4.7k\Omega \parallel 38.5k\Omega = 3.57k\Omega$$

$$R_{in} = R_B \parallel [r_\pi + (\beta_o + 1)R_L] = 33.8k\Omega \parallel [1.35k\Omega + (101)3.57k\Omega] = 30.9 k\Omega$$

$$R_{out} = R_E \parallel \frac{(R_B \parallel R_i) + r_\pi}{\beta_o + 1} = 4.7k\Omega \parallel \frac{(33.8k\Omega \parallel 500\Omega) + 1.35k\Omega}{101} = 18.2 \Omega$$

$$C_1 = \frac{10}{2\pi f(R_i + R_{in})} = \frac{10}{2\pi(50Hz)(500\Omega + 30.9k\Omega)} = 1.01\mu F \rightarrow 1.0 \mu F$$

$$C_2 = \frac{10}{2\pi f(R_3 + R_{out})} = \frac{10}{2\pi(50Hz)(24k\Omega + 18.2\Omega)} = 1.33\mu F \rightarrow 1.5 \mu F$$

14.85

Note : $R_s \equiv R_i = 3.9k\Omega$ | Assume active region operation.

$$V_{GS} = -3900I_D = -3900 \frac{(5 \times 10^{-4})}{2} (V_{GS} + 2)^2 \quad | \quad V_{GS} = -0.975(V_{GS} + 2)^2 \rightarrow V_{GS} = -0.9915V$$

$$I_D = \frac{(5 \times 10^{-4})}{2} (V_{GS} + 2)^2 = 254\mu A \quad | \quad V_{DS} = 15 - 23.9k\Omega I_D = 8.92V \text{ - Active region is correct.}$$

$$g_m = \frac{2(254\mu A)}{2 - 0.992} = 0.504mS \quad | \quad r_o = \frac{50 + 8.92}{254 \times 10^{-6}} = 232k\Omega \quad | \quad R_{in} = 3.9k\Omega \quad | \quad \frac{1}{g_m} = 1.32k\Omega$$

$$R_{out} = R_D \parallel r_o [1 + g_m(R_s \parallel R_i)] = 20k\Omega \parallel 232k\Omega [1 + 0.504mS(3.9k\Omega \parallel 1k\Omega)] = 18.8k\Omega$$

$$C_1 = \frac{10}{2\pi f(R_i + R_{in})} = \frac{10}{2\pi(400Hz)(1k\Omega + 1.32k\Omega)} = 1.72\mu F \rightarrow 1.8 \mu F$$

$$C_2 = \frac{10}{2\pi f(R_3 + R_{out})} = \frac{10}{2\pi(400Hz)(100k\Omega + 18.8k\Omega)} = 0.0335\mu F \rightarrow 0.033 \mu F$$

14.86

(a) Use C_2 to set the lower cutoff frequency to 1 kHz. C_1 and C_3 remain negligible at 1 kHz.

$$C_2 = 0.056 \mu F, C_1 = 1800 pF, C_3 = 0.015 \mu F$$

(b) SPICE Results: $f_L = 925$ Hz

14.87

(a) Use C_3 to set the lower cutoff frequency to 2 kHz. C_1 remains negligible at 2 kHz.

$$C_1 = 8200 pF, C_3 = 820 pF$$

(b) Use C_1 to set the lower cutoff frequency to 1 kHz. C_2 and C_3 remain negligible at 1 kHz.

$$C_1 = 0.042 \mu F, C_2 = 1800 pF, C_3 = 0.015 \mu F$$

(c) SPICE Results: For (a) $f_L = 1.96$ kHz. For (b) $f_L = 1.02$ kHz

14.88

$$A_v = \frac{g_m R_L}{1 + g_m R_L} \geq 0.95 \rightarrow g_m R_L \geq 19 \quad | \quad g_m = \sqrt{2 K_n I_D} \quad | \quad V_{GS} - V_{TN} = \sqrt{\frac{2 I_D}{K_n}} = 0.5V$$

$$I_D = \frac{(0.5)^2 (0.03)}{2} = 3.75mA \quad | \quad R_L \geq \frac{19}{\sqrt{2(0.03)(0.00375)}} = 1.27k\Omega$$

$$R_L = R_s \parallel 3k\Omega \rightarrow R_s \geq 2.19k\Omega \quad | \quad V_{SS} = V_{GS} + (3.75mA)R_s \quad | \quad \text{Possible designs:}$$

$2.4k\Omega, 11.5V; 2.7k\Omega, 12.6V; 3.0k\Omega, 13.75V$ - Making a choice which uses a nearly minimum value of supply voltage gives: $V_{SS} = 12 V, R_s = 2.4 k\Omega$

14.89

For a common-emitter amplifier with $R_E = 0$, $R_{in} \equiv r_\pi = \frac{\beta_o V_T}{I_C}$ | $I_C = \frac{100(0.025V)}{75\Omega} = 33.3 \text{ mA}$

14.90

Using Eqn. 14.73: $50 = \frac{R_E}{1 + 40(4.3)}$ → $R_E = 8.65k\Omega$ | $I_C \equiv \frac{4.3V}{R_E} = 497\mu A$

$$50 = g_m R_L \frac{R_{in}}{R_I + R_{in}} \quad | \quad \text{Assuming } R_I = 50\Omega, 50 = \frac{g_m R_L}{2} \rightarrow R_L = \frac{2(50)}{40(497\mu A)} = 5.03k\Omega$$

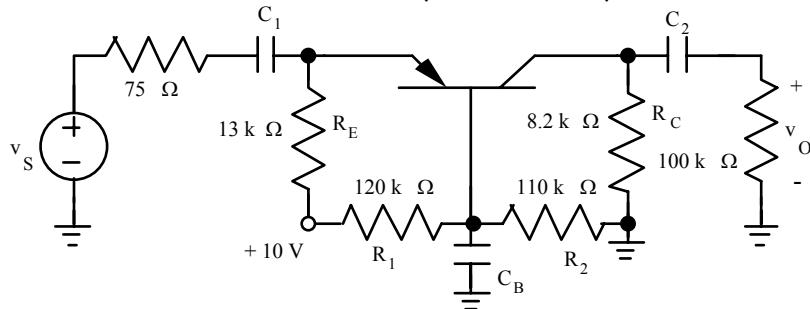
$R_L = R_C \parallel 100k\Omega \rightarrow R_C = 5.30k\Omega$ | $V_{EC} = 5 + 0.7 - I_C R_C = 3.07V$ - Active region is ok.

$$C_1 \gg \frac{1}{2\pi(500\text{kHz})(50\Omega + 50\Omega)} = 3.18nF \rightarrow C_1 = 0.033 \mu F$$

$$C_2 \gg \frac{1}{2\pi(500\text{kHz})(105k\Omega)} = 3.02 pF \rightarrow C_2 = 33 pF$$

14.91

The base voltage should remain half way between the positive and negative power supply voltages. If $V_{EE} = +10V$ and $V_{CC} = 0V$, then V_B should = 5 V which can be obtained using a resistive voltage divider from the +10V supply. We now have the standard four-resistor bias circuit. The base current is $327 \mu A / 80 = 4.08 \mu A$.



Setting the current in R_1 to $10I_B = 40\mu A$, $R_1 = \frac{5V}{40\mu A} = 125k\Omega \rightarrow 120k\Omega$

The current in $R_2 = 11I_B = 44\mu A$, and $R_2 = \frac{5V}{44\mu A} = 114k\Omega \rightarrow 110k\Omega$

Note that the base terminal must now be bypassed with a capacitor.

14.92

Using Eqn. 14.73: $75 = \frac{R_E}{1 + 40(8.3)} \rightarrow R_E = 25.0 k\Omega \quad | \quad I_C \cong \frac{8.3V}{R_E} = 332 \mu A$

$$50 = g_m R_L \frac{R_{in}}{R_I + R_{in}} \quad | \quad 50 = \frac{g_m R_L}{2} \rightarrow R_L = \frac{2(50)}{40(332 \mu A)} = 7.52 k\Omega \quad | \quad R_L = R_C \parallel 100 k\Omega \rightarrow R_C = 8.13 k\Omega$$

$$V_{EC} = 9 + 0.7 - I_C R_C = 6.98 V - \text{Active region is ok.}$$

$$C_1 \gg \frac{1}{2\pi(500 kHz)(75\Omega + 75\Omega)} = 2.12 nF \rightarrow C_2 = 0.022 \mu F$$

$$C_2 \gg \frac{1}{2\pi(500 kHz)(108 k\Omega)} = 2.95 pF \rightarrow C_2 = 30 pF$$

14.93

$$R_{in} \cong \frac{1}{g_m} \rightarrow g_m = \sqrt{2K_n I_D} = 0.1 S \quad | \quad I_D = \frac{0.01}{2K_n} \quad | \quad (a) I_D = \frac{0.01}{2(0.005)} = 1 A$$

$$(b) I_D = \frac{0.01}{2(0.5)} = 10.0 mA \quad | \quad \text{The second FET achieves the desired input resistance}$$

at much lower current and hence much lower power for a given supply voltage.

14.94

$$\frac{1}{g_m} = \frac{V_T}{I_C} = \frac{kT}{qI_C} \propto T$$

$$\text{At } -40^\circ C = 233 K, \frac{1}{g_m} = 50 \Omega \left(\frac{233 k}{300 K} \right) = 38.8 \Omega. \quad | \quad \text{At } +50^\circ C = 323 K, \frac{1}{g_m} = 50 \Omega \left(\frac{323 K}{300 K} \right) = 53.8 \Omega.$$

$$\text{Another approach: At } 27^\circ C = 300 K, I_C = \frac{300 k}{50 q} = \frac{6 k}{q}.$$

$$\text{At } -40^\circ C = 233 K, \frac{1}{g_m} = \frac{233}{6} = 38.8 \Omega. \quad | \quad \text{At } +50^\circ C = 323 K, \frac{1}{g_m} = \frac{323}{6} = 53.8 \Omega.$$

14.95

This analysis assumes that the source and load resistors are fixed, and that only

$$\text{the amplifier parameters are changing. } A_v = g_m R_L \left(\frac{R_{in}}{R_I + R_{in}} \right)$$

$$\text{Since } R_E \gg 75\Omega, R_E \parallel R_I \approx 75\Omega \text{ and } R_{in} \approx R_E \parallel \frac{1}{g_m} \approx \frac{1}{g_m} \quad | \quad A_v \approx \frac{g_m R_L}{1 + g_m R_I}$$

To achieve A_v^{\max} , $R_L \rightarrow R_L^{\max}$, $g_m \rightarrow g_m^{\max}$ which requires

$$I_C \rightarrow I_C^{\max} = 0.988 \frac{(5.25 - 0.7)V}{13k\Omega(0.95)} = 364\mu A \quad | \quad R_L^{\max} = 8.2k\Omega(1.05) \parallel 100k\Omega = 7.93k\Omega$$

$$g_m = 40(364\mu A) = 14.6mS \quad | \quad A_v^{\max} = \frac{14.6mS(7.93k\Omega)}{1 + 0.0146(75)} = 55.3$$

To achieve A_v^{\min} , $R_L \rightarrow R_L^{\min}$, $g_m \rightarrow g_m^{\min}$ which requires

$$I_C \rightarrow I_C^{\min} = 0.988 \frac{(4.75 - 0.7)V}{13k\Omega(1.05)} = 293\mu A \quad | \quad R_L^{\min} = 8.2k\Omega(0.95) \parallel 100k\Omega = 7.23k\Omega$$

$$g_m = 40(293\mu A) = 11.7mS \quad | \quad A_v^{\min} = \frac{11.7mS(7.23k\Omega)}{1 + 0.0117(75)} = 45.1 \quad | \quad 45.1 \leq A_v \leq 55.3$$

The range is only slightly larger than that observed in the Monte Carlo analysis in Table 14.15.

14.96

*Problem 14.96 - Common-Base Amplifier - Monte Carlo Analysis

*Generate Voltage Sources with 5% Tolerances

IEE 0 8 DC 5

REE 8 0 RTOL 1

EEE 6 0 8 0 1

*

ICC 0 9 DC 5

RCC 9 0 RTOL 1

ECC 7 0 9 0 -1

*

VS 1 0 AC 1

RS 1 2 75

C1 2 3 47U

RE 3 6 RTOL 13K

Q1 4 0 3 PBJT

RC 4 7 RTOL 8.2K

C2 4 5 4.7U

R3 5 0 100K

.OP

.AC LIN 1 10KHZ 10KHZ

.PRINT AC VM(5) VP(5)

.MODEL PBJT PNP (BF=80 DEV 25%) (VA = 60 DEV 33.33%)

.MODEL RTOL RES (R=1 DEV 5%)
 .MC 1000 AC VM(5) YMAX
 .END

Results: Mean value $A_v = 47.5$; 3σ limits: $42.5 \leq A_v \leq 52.5$. However, the worst-case values observed in the analysis are $A_v^{\min} = 43.2$ and $A_v^{\max} = 51.9$. The mean is 5% lower than the design value. The width of the distribution is approximately the same as that in Table 14.15.

14.97

(a) This analysis assumes that the source and load resistors are fixed, and that only

the amplifier parameters are changing. $A_v = \frac{g_m R_L}{1 + g_m R_{th}} \left(\frac{R_E}{R_I + R_E} \right)$

$$R_{th} = R_E \| R_I \text{ and } \frac{R_E}{R_I + R_E} = \frac{1}{1 + \frac{R_I}{R_E}}$$

where $R_E = 13.3k\Omega$ and $R_I = 75\Omega$

Since $R_E \gg R_I$, R_{th} and $\frac{R_E}{R_I + R_E}$ are essentially constant. To achieve A_v^{\max} , $R_L \rightarrow R_L^{\max}$, $g_m \rightarrow g_m^{\max}$

$$\text{which requires } I_C \rightarrow I_C^{\max} = 0.988 \frac{(5.10 - 0.7)V}{13.3k\Omega(0.99)} = 330\mu A \mid R_L^{\max} = 8.25k\Omega(1.01) \| 100k\Omega = 7.69k\Omega$$

$$g_m = 40(330\mu A) = 13.2mS \mid A_v^{\max} = \frac{13.2mS(7.69k\Omega)}{1 + 0.0132(75)} \left[\frac{13.3(0.99)}{75 + 13.3(0.99)} \right] = 50.7$$

To achieve A_v^{\min} , $R_L \rightarrow R_L^{\min}$, $g_m \rightarrow g_m^{\min}$ which requires

$$I_C \rightarrow I_C^{\min} = 0.988 \frac{(4.90 - 0.7)V}{13.3k\Omega(1.01)} = 309\mu A \mid R_L^{\min} = 8.25k\Omega(0.99) \| 100k\Omega = 7.55k\Omega$$

$$g_m = 40(309\mu A) = 12.4mS \mid A_v^{\min} = \frac{12.4mS(7.55k\Omega)}{1 + 0.0124(75)} \left[\frac{13.3(1.01)}{75 + 13.3(1.01)} \right] = 48.2$$

(b) Using a Spreadsheet similar to Table 14.16: Mean value $A_v = 49.6$; 3σ limits: $48.2 \leq A_v \leq 50.9$. The worst-case values observed in the analysis are $A_v^{\min} = 48.4$ and $A_v^{\max} = 50.8$.

14.98

*Problem 14.98 - Common-Base Amplifier - Monte Carlo Analysis

*Generate Voltage Sources with 2% Tolerances

IEE 0 8 DC 5

REE 8 0 RTOL 1

EEE 6 0 8 0 1

*

ICC 0 9 DC 5

RCC 9 0 RTOL 1

ECC 7 0 9 0 -1

```

*
VS 1 0 AC 1
RS 1 2 75
C1 2 3 100U
RE 3 6 RR 13.3K
Q1 4 0 3 PBJT
RC 4 7 RR 8.25K
C2 4 5 1U
R3 5 0 100K
.OP
.AC LIN 1 10KHZ 10KHZ
.PRINT AC VM(5) VP(5) IM(VS) IP(VS)
.MODEL PBJT PNP (BF=80 DEV 25%) (VA = 60 DEV 33.33%)
.MODEL RTOL RES (R=1 DEV 2%)
.MODEL RR RES (R=1 DEV 1%)
.MC 1000 AC VM(5) YMAX
*.MC 1000 AC IM(VS) YMAX
.END

```

Results: Mean value: $A_v = 47.2$; 3σ limits: $45.7 \leq A_v \leq 48.5$

Mean value: $R_{in} = 83.4 \Omega$; 3σ limits: $79.5 \Omega \leq R_{in} \leq 87.6 \Omega$

14.99

$$R_{in} = R_E \left| \frac{1}{g_m} \right| = \frac{R_E}{1 + g_m R_E} = \frac{R_E}{1 + 40 I_C R_E} = \frac{R_E}{1 + 40 \frac{80}{81} I_E R_E} = \frac{R_E}{1 + 39.5 I_E R_E}$$

$$I_E R_E = 2.5 - 0.7 = 1.8V \quad | \quad 75 = \frac{R_E}{1 + 39.5(1.8)} \rightarrow R_E = 5.41k\Omega$$

$$I_C = \frac{80}{81} \frac{1.8V}{5.41k\Omega} = 329\mu A \quad | \quad R_{th} = 75\Omega \parallel 5.41k\Omega = 74.0\Omega \quad | \quad g_m = 40(329\mu A) = 13.2mS$$

$$A_v = \frac{g_m R_L}{1 + g_m R_{th}} \left(\frac{R_E}{R_I + R_E} \right) \rightarrow R_L = 7.59k\Omega$$

$7.59k\Omega = R_C \parallel 100k\Omega \rightarrow R_C = 8.21k\Omega \quad | \quad V_C = -2.5V + I_C R_C = +0.201V \quad | \quad$ Oops! We are violating our definition of the forward - active region. If we use the nearest 5% values, $R_E = 5.6k\Omega$ and $R_C = 8.2k\Omega$, $I_C = 318\mu A$ and $V_C = +0.108V$. The transistor is just entering saturation.

14.100

Using a Spreadsheet similar to Table 14.15:

Mean value: $A_v = 0.960$; 3σ limits: $0.942 \leq A_v \leq 0.979$

Mean value: $I_D = 4.91$ mA; 3σ limits: 4.27 mA $\leq I_D \leq 5.55$ mA

Mean value: $V_{DS} = 7.03$ V; 3σ limits: 4.52 V $\leq V_{DS} \leq 9.54$ V

*Problem 14.102 - Common-Drain Amplifier - Fig. 14.34

*Generate Voltage Sources with 5% Tolerances

IDD 0 7 DC 5

RDD 7 0 RTOL 1

EDD 5 0 7 0 1

*

ISS 0 8 DC 20

RSS 8 0 RTOL 1

ESS 6 0 8 0 -1

*

VGG 1 0 DC 0 AC 1

C1 1 2 4.7U

RG 2 0 RTOL 22MEG

RS 3 6 RTOL 3.6K

C2 3 4 68U

R3 4 0 3K

M1 5 2 3 3 NMOSFET

.OP

.AC LIN 1 10KHZ 10KHZ

.DC VGG 0 0 1

.MODEL NMOSFET NMOS (VTO=1.5 DEV 33.33%) (KP=20M DEV 50%) LAMBDA=0.02

.MODEL RTOL RES (R=1 DEV 5%)

.PRINT AC VM(4) VP(4) IM(VGG) IP(VGG)

.MC 1000 DC ID(M1) YMAX

*.MC 1000 DC VDS(M1) YMAX

*.MC 1000 AC IM(VGG) YMAX

*.MC 1000 AC VM(4) YMAX

.END

Results: Mean value: $I_D = 4.97$ mA; 3σ limits: 4.32 mA $\leq I_D \leq 5.62$ mA

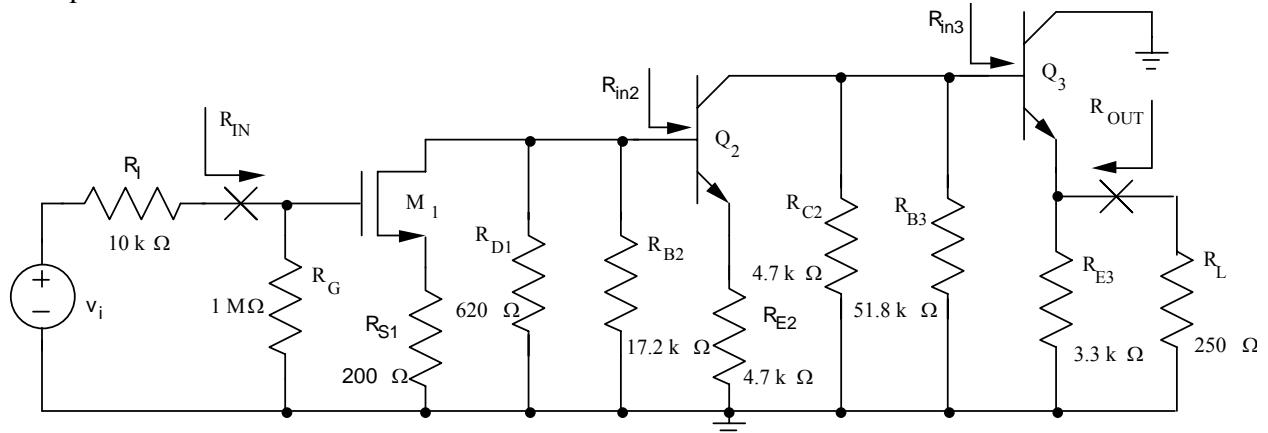
Mean value: $V_{DS} = 7.19$ V; 3σ limits: 6.18 V $\leq V_{DS} \leq 8.20$ V

Mean value: $R_{in} = 22.0$ M Ω ; 3σ limits: 20.3 $\Omega \leq R_{in} \leq 24.0$ Ω

Mean value: $A_v = 0.956$; 3σ limits: $0.936 \leq A_v \leq 0.976$

14.101

ac equivalent circuit



The Q - points and small - signal parameter values have already been found in the text.

$$\text{The bypass capacitors do not affect } R_{in} : R_{in} = R_G = 1 M\Omega \quad | \quad A_v = \left(\frac{R_{in}}{10k\Omega + R_{in}} \right) A_{vt1} A_{vt2} A_{vt3}$$

$$R_{L1} = (620\Omega \parallel 17.2k\Omega) \parallel (r_{\pi2} + (\beta_{o2} + 1)1.6k\Omega) = 598\Omega \parallel (2.39k\Omega + (151)1.6k\Omega) = 597\Omega$$

$$A_{vt1} = -\frac{g_m R_{L1}}{1 + g_m R_{S1}} = -\frac{0.01(597)}{1 + (0.01)200} = -1.99 \quad | \quad R_{L2} = 3.54k\Omega \quad (\text{Eq. 15.7})$$

$$A_{vt2} = -\frac{\beta_{o2} R_{L2}}{r_{\pi2} + (\beta_{o2} + 1)1.6k\Omega} = -\frac{150(3.54k\Omega)}{2.39k\Omega + (151)1.6k\Omega} = -2.18$$

$$A_{vt3} = +0.950 \quad | \quad A_v = -\left(\frac{1M\Omega}{10k\Omega + 1M\Omega} \right) (1.99)(-2.18)(0.950) = +4.08$$

$$R_{out} = (3300\Omega) \left| \left(\frac{R_{th3} + r_{\pi3}}{\beta_{o3} + 1} \right) \right| \quad | \quad R_{th3} = R_{I3} \parallel R_{o2} = R_{I3} \left| \left(r_{o2} \left(1 + \frac{\beta_{o2} R_{E2}}{R_{th2} + r_{\pi2} + R_{E2}} \right) \right) \right| \cong R_{I3} = 4.31k\Omega$$

$$R_{out} = (3.30k\Omega) \left| \left(\frac{4.31 + 1.00}{81} k\Omega \right) \right| = 64.3\Omega$$

14.102

$$M_1 : I_D = \frac{0.01}{2} (V_{GS} + 2)^2 \quad | \quad V_{GS} = -9000I_D \rightarrow V_{GS} = -1.80V$$

$$I_D = \frac{0.01}{2} (-1.8 + 2)^2 = 200 \mu A \quad | \quad V_{DS} = 15 - (15k\Omega + 9k\Omega)I_D = 10.2 V$$

$$g_m = \sqrt{2(10mA/V^2)(0.2mA)} = 2mS \quad | \quad r_o = \frac{(50 + 10.2)V}{0.2mA} = 301k\Omega$$

$$Q_2 : V_{EQ2} = 15 \frac{43k\Omega}{43k\Omega + 160k\Omega} = 3.18V \quad | \quad R_{EQ2} = 160k\Omega \parallel 43k\Omega = 33.9k\Omega$$

$$I_{C2} = 150 \frac{3.18 - 0.7}{33.9k\Omega + 151(1.6k\Omega)} = 1.35 mA \quad | \quad V_{CE2} = 15 - \left(4.7k\Omega + \frac{151}{150} 1.6k\Omega \right) I_C = 6.49 V$$

$$g_{m2} = 40(1.35mA) = 54.0mS \quad | \quad r_{\pi2} = \frac{150}{54.0mS} = 2.78k\Omega \quad | \quad r_{o2} = \frac{(80 + 6.49)V}{1.35mA} = 64.1k\Omega$$

$$Q_3 : V_{EQ3} = 15 \frac{120k\Omega}{120k\Omega + 91k\Omega} = 8.53V \quad | \quad R_{EQ3} = 120k\Omega \parallel 91k\Omega = 51.8k\Omega$$

$$I_{C3} = 80 \frac{8.53 - 0.7}{51.8k\Omega + 81(2.2k\Omega)} = 2.72 mA \quad | \quad V_{CE3} = 15 - \left(\frac{81}{80} 2.2k\Omega \right) I_C = 8.93 V$$

$$g_{m3} = 40(2.72mA) = 109mS \quad | \quad r_{o3} = \frac{(60 + 8.93)V}{2.72mA} = 25.3k\Omega \quad | \quad r_{\pi3} = \frac{80}{109mS} = 734\Omega$$

$$A_v = \left(\frac{R_G}{10k\Omega + R_G} \right) A_{vt1} A_{vt2} A_{vt3}$$

$$A_{vt1} = -(2mS)(301k\Omega \parallel 15k\Omega \parallel 33.9k\Omega \parallel 2.78k\Omega) = -4.36$$

$$A_{vt2} = (-54.0mS) \left[64.1k\Omega \parallel 4.7k\Omega \parallel 51.8k\Omega \parallel (734 + 81(2.2k\Omega \parallel 250\Omega)) \right] = -180$$

$$A_{vt3} = \frac{81(2.2k\Omega \parallel 250\Omega)}{734 + 81(2.2k\Omega \parallel 250\Omega)} = 0.961 \quad | \quad A_v = -4.36(-180)(0.961) \left(\frac{1M\Omega}{10k\Omega + 1M\Omega} \right) = 747$$

$$v_{be3} = v_{b3}(1 - A_{vt3}) = 0.99 A_{vt1} A_{vt2} v_s (1 - A_{vt3}) \leq 5mV \quad | \quad v_s \leq \frac{0.005}{0.99(4.36)(180)(1 - 0.961)} = 165\mu V$$

The gain is actually reduced rather than improved. The signal range increased since the gain was reduced.

14.103

*Problem 14.102/14.103 - Multistage Amplifier – Figure P14.102

VCC 12 0 DC 15

VI 1 0 AC 1

*For output resistance

*VI 1 0 AC 0

*VO 11 0 AC 1

RS 1 2 10K

C1 2 3 22U

RG 3 0 1MEG

M1 5 3 4 4 NMOSFET

RS1 4 0 9K

C2 4 0 22U

RD 12 5 15K

C3 5 6 22U

R1 12 6 160K

R2 6 0 43K

Q2 8 6 7 NBJT1

RC 12 8 4.7K

RE2 7 0 1.6K

C4 7 0 22U

C5 8 9 22U

R3 12 9 91K

R4 9 0 120K

Q3 12 9 10 NBJT2

RE3 10 0 2.2K

C6 10 11 22U

RL 11 0 250

.MODEL NMOSFET NMOS VTO=-2 KP=.01 LAMBDA=0.02

.MODEL NBJT1 NPN IS=1E-16 BF=150 VA=80

.MODEL NBJT2 NPN IS=1E-16 BF=80 VA=60

.OPTIONS TNOM=17.2

.OP

.AC LIN 1 2KHZ 2KHZ

.PRINT AC VM(3) VP(3) IM(VI) IP(VI) VM(11) VP(11) IM(C6) IP(C6)

.END

$$\text{Results : } A_v = VM(11) = +879 \quad | \quad R_{in} = \frac{VM(3)}{IM(VI)} = 1.00 M\Omega \quad | \quad R_{out} = \frac{1}{IM(C6)} = 51.8 \Omega$$

14.104

The bypass capacitors do not affect R_{in} : $R_{in} = R_G = 1 M\Omega$ | $A_v = \left(\frac{R_{in}}{10k\Omega + R_{in}} \right) A_{vt1} A_{vt2} A_{vt3}$

$$R_{L1} = (15k\Omega \parallel 160k\Omega \parallel 43k\Omega) \parallel (r_{\pi 2} + (\beta_{o2} + 1)1.6k\Omega) = 10.4k\Omega \parallel [2.78k\Omega + 151(1.6k\Omega)] = 9.98k\Omega$$

$$A_{vt1} = -\frac{g_{m1} R_{L1}}{1 + g_{m1} R_{S1}} = -\frac{2(9.98k\Omega)}{1 + 2(9k\Omega)} = -1.05$$

$$R_{L2} = (4.7k\Omega \parallel 91k\Omega \parallel 120k\Omega) \parallel [r_{\pi 3} + (\beta_{o3} + 1)(2.2k\Omega \parallel 250\Omega)] = 4.31k\Omega \parallel [734\Omega + 81(225\Omega)] = 3.51k\Omega$$

$$A_{vt2} = -\frac{\beta_{o2} R_{L2}}{r_{\pi 2} + (\beta_{o2} + 1)1.6k\Omega} = -\frac{150(3.51k\Omega)}{2.39k\Omega + (151)1.6k\Omega} = -2.17$$

$$A_{vt3} = \frac{81(2.2k\Omega \parallel 250\Omega)}{734 + 81(2.2k\Omega \parallel 250\Omega)} = 0.961 \quad | \quad A_v = \left(\frac{1M\Omega}{10k\Omega + 1M\Omega} \right) (-1.05)(-2.17)(0.961) = +2.17$$

$$R_{out} = (3300\Omega) \left| \left(\frac{R_{th3} + r_{\pi 3}}{\beta_{o3} + 1} \right) \right| \quad | \quad R_{th3} = R_{I3} \parallel R_{o2} = R_{I3} \left| \left(r_{o2} \left(1 + \frac{\beta_{o2} R_{E2}}{R_{th2} + r_{\pi 2} + R_{E2}} \right) \right) \right| \cong R_{I3} = 4.31k\Omega$$

$$R_{out} = (3.30k\Omega) \left| \left(\frac{4.31 + 1.00}{81} k\Omega \right) \right| = 64.3\Omega$$

14.105

*Problem 14.105 - Use the listing from Problem 14.103, but remove C2 and C4.

Result: $A_v = VM(11) = +2.20$

14.106

$$Q_1 : V_{EQ1} = 15 \frac{100k\Omega}{100k\Omega + 820k\Omega} = 1.63V \quad | \quad R_{EQ1} = 100k\Omega \parallel 820k\Omega = 89.1k\Omega$$

$$I_{C1} = 100 \frac{1.63 - 0.7}{89.1k\Omega + 101(2k\Omega)} = 319 \mu A \quad | \quad V_{CE1} = 15 - \left(18k\Omega + \frac{101}{100} 2k\Omega \right) I_C = 8.61 V$$

$$g_{m1} = 40(319 \mu A) = 12.8mS \quad | \quad r_{\pi 1} = \frac{100}{12.8mS} = 7.81k\Omega \quad | \quad r_{o1} = \frac{(70 + 8.61)V}{319 \mu A} = 246k\Omega$$

$$Q_2 : V_{EQ2} = 15 \frac{43k\Omega}{43k\Omega + 160k\Omega} = 3.18V \quad | \quad R_{EQ2} = 160k\Omega \parallel 43k\Omega = 33.9k\Omega$$

$$I_{C2} = 100 \frac{3.18 - 0.7}{33.9k\Omega + 101(1.6k\Omega)} = 1.27 mA \quad | \quad V_{CE2} = 15 - \left(4.7k\Omega + \frac{101}{100} 1.6k\Omega \right) I_C = 6.98 V$$

$$g_{m2} = 40(1.27mA) = 50.8mS \quad | \quad r_{\pi 2} = \frac{100}{50.8mS} = 1.97k\Omega \quad | \quad r_{o2} = \frac{(70 + 6.98)V}{1.27mA} = 60.6k\Omega$$

$$M_3 : V_{EQ3} = 15 \frac{1.2M\Omega}{1.2M\Omega + 910k\Omega} = 8.53V \quad | \quad R_{EQ3} = 1.2M\Omega \parallel 910k\Omega = 518k\Omega$$

$$8.53 = V_{GS3} + 3000I_{D3} = 1 + \sqrt{\frac{2I_{D3}}{0.001}} + 3000I_{D3} \rightarrow I_{D3} = 1.87mA \quad | \quad V_{GS3} - V_{TN3} = 1.93V$$

$$V_{DS3} = 15 - 3000I_{D3} = 9.39V \quad | \quad g_{m3} = \sqrt{2(0.001)(0.00187)} = 1.93mS$$

$$A_v = \left(\frac{R_{in}}{R_I + R_{in}} \right) A_{vt1} A_{vt2} A_{vt3} \quad | \quad R_{in} = 820k\Omega \parallel 100k\Omega \parallel r_{\pi 1} = 820k\Omega \parallel 100k\Omega \parallel 7.81k\Omega = 7.18k\Omega$$

$$A_{vt1} = -g_{m1}(R_{C1} \parallel R_{B2} \parallel r_{\pi 2}) = -12.8mS(18k\Omega \parallel 33.9k\Omega \parallel 1.97k\Omega) = -21.6$$

$$A_{vt2} = -g_{m2}(R_{C2} \parallel R_{G3}) = -50.8mS(4.7k\Omega \parallel 518k\Omega) = -237$$

$$A_{vt3} = \frac{g_{m3}(R_{E3} \parallel R_L)}{1 + g_{m3}(R_{E3} \parallel R_L)} = \frac{1.93mS(3.0k\Omega \parallel 250\Omega)}{1 + 1.93mS(3.0k\Omega \parallel 250\Omega)} = 0.308$$

$$A_v = \left(\frac{7.18k\Omega}{10k\Omega + 7.18k\Omega} \right) (-21.6)(-237)(0.308) = 659$$

$$v_{gs3} = v_{g3}(1 - A_{vt3}) = \left(\frac{R_{in}}{R_I + R_{in}} \right) A_{vt1} A_{vt2} v_i (1 - A_{v3}) \leq 0.2(V_{GS3} - V_{TN3})$$

$$v_i \leq \frac{0.2(1.93)}{0.418(21.6)(237)(1 - 0.308)} = 261\mu V$$

The gain is reduced rather than improved. The signal range increased since the gain was reduced.

14.107

*Problem 14.107 - Multistage Amplifier – Figure P14.106

VCC 12 0 DC 15

VI 1 0 AC 1

RI 1 2 10K

*For output resistance

*VI 1 0 AC 0

*VO 11 0 AC 1

C1 2 3 22U

R1 12 3 820K

R2 3 0 100K

Q1 5 3 4 NBJT

RE1 4 0 2K

C2 4 0 22U

RC1 12 5 18K

C3 5 6 22U

R3 12 6 160K

R4 6 0 43K

Q2 8 6 7 NBJT

RC 12 8 4.7K

RE2 7 0 1.6K

C4 7 0 22U

C5 8 9 22U

R5 12 9 910K

R6 9 0 1.2MEG

M3 12 9 10 10 NMOSFET

RE3 10 0 3K

C6 10 11 22U

RL 11 0 250

.OP

.AC LIN 1 3KHZ 3KHZ

.MODEL NMOSFET NMOS VTO=1 KP=.001 LAMBDA=0.02

.MODEL NBJT NPN IS=1E-16 BF=100 VA=70

.PRINT AC VM(3) VP(3) IM(VI) IP(VI) VM(11) VP(11) IM(C6) IP(C6)

.END

$$\text{Results : } A_v = VM(11) = +711 \quad | \quad R_{in} = \frac{VM(3)}{IM(VI)} = 8.29 \text{ k}\Omega \quad | \quad R_{out} = \frac{1}{IM(C6)} = 401 \Omega$$

14.108

$$R_{in} = R_1 \parallel R_2 \parallel [r_{\pi 1} + (\beta_{o1} + 1)R_{E1}] = 100k\Omega \parallel 820k\Omega \parallel [7.81k\Omega + 101(2k\Omega)] = 62.66k\Omega$$

$$A_{vt1} = -\frac{\beta_{o1}(R_{C1} \parallel R_{B2} \parallel R_{I2})}{r_{\pi 1} + (\beta_{o1} + 1)R_{E1}} \quad | \quad R_{I2} = r_{\pi 2} + (\beta_{o2} + 1)R_{E2} = 1.97k\Omega + 101(1.6k\Omega) = 164k\Omega$$

$$R_3 \parallel R_4 = 43k\Omega \parallel 160k\Omega = 33.9k\Omega \quad | \quad A_{vt1} = -\frac{100(18k\Omega \parallel 33.9k\Omega \parallel 164k\Omega)}{7.81k\Omega + 101(2k\Omega)} = -6.69$$

$$R_{G3} = R_5 \parallel R_6 = 1.2M\Omega \parallel 910k\Omega = 518k\Omega \quad | \quad A_{vt2} = -\frac{\beta_{o2}(R_{C2} \parallel R_{G3})}{r_{\pi 2} + (\beta_{o2} + 1)R_{E1}} = -\frac{100(4.7k\Omega \parallel 518k\Omega)}{1.97k\Omega + 101(1.6k\Omega)} = -2.85$$

$$A_{vt3} = \frac{g_{m3}(R_{E3} \parallel R_L)}{1 + g_{m3}(R_{E3} \parallel R_L)} = \frac{1.93mS(3.0k\Omega \parallel 250\Omega)}{1 + 1.93mS(3.0k\Omega \parallel 250\Omega)} = 0.308$$

$$A_v = \left(\frac{R_{in}}{10k\Omega + R_{in}} \right) A_{vt1} A_{vt2} A_{vt3} = \left(\frac{62.6k\Omega}{10k\Omega + 62.6k\Omega} \right) (-6.69)(-2.85)(0.308) = 5.05$$

14.109

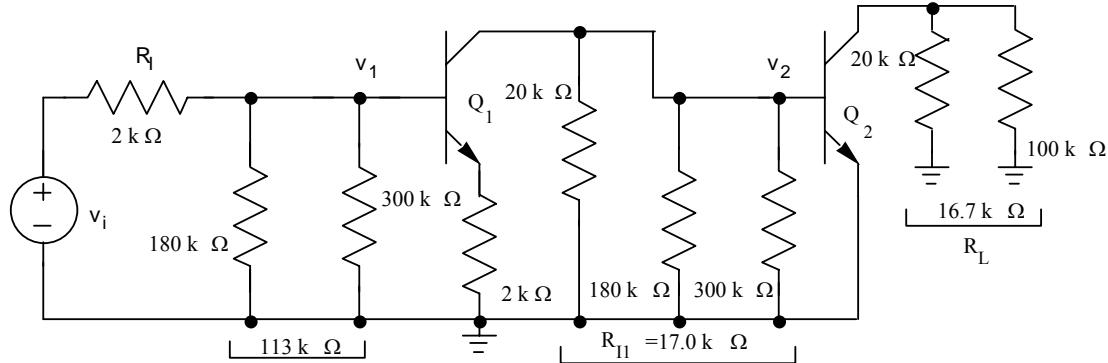
Note that the equivalent circuits are the same for Q_1 and Q_2 .

$$V_{EO} = \frac{180k\Omega}{180k\Omega + 300k\Omega} 15V = 5.63V \quad | \quad R_{EO} = 180k\Omega \parallel 300k\Omega = 113k\Omega$$

$$I_B = \frac{5.63 - 0.7}{113 + 101(20)} \frac{V}{k\Omega} = 2.31\mu A \quad | \quad I_C = 100I_B = 232\mu A \quad | \quad I_E = 101I_B = 234\mu A$$

$$V_{CE} = 15 - 2x10^4 I_E - 2x10^4 I_C = 5.71V$$

$$r_\pi = \frac{100(0.025V)}{232\mu A} = 10.8k\Omega \quad | \quad r_o = \frac{(70 + 5.71)V}{232\mu A} = 326k\Omega$$



$$A_v = \left(\frac{R_{in}}{2k\Omega + R_{in}} \right) A_{vt1} A_{vt2}$$

$$A_{vt1} = \frac{v_2}{v_1} = -\frac{\beta_{o1}(R_{II} \parallel r_{\pi2})}{r_{\pi1} + (\beta_{o1} + 1)R_5} = -\frac{100(17k\Omega \parallel 10.8k\Omega)}{10.8k\Omega + (101)2k\Omega} = -3.10$$

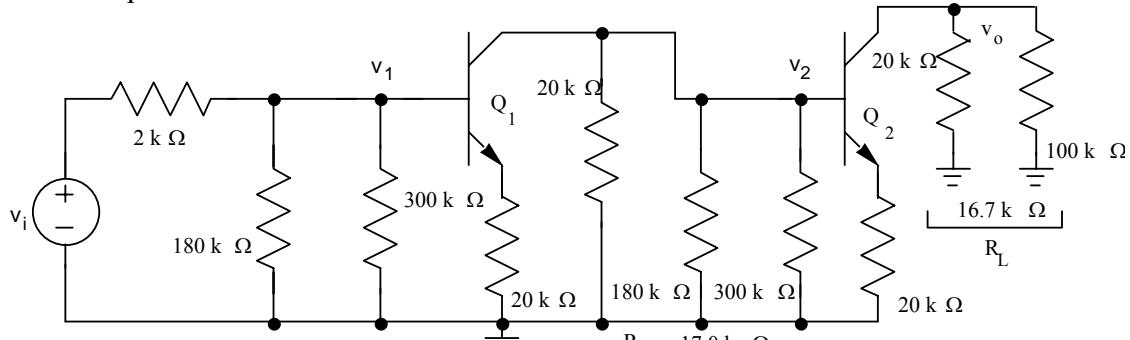
$$A_{vt2} = \frac{v_o}{v_2} = -g_m R_L \quad | \quad R_L = 100k\Omega \parallel 20k\Omega = 16.7k\Omega \quad | \quad A_{vt2} = -40(232\mu A)(16.7k\Omega) = -155$$

$$R_{in} = R_{B1} \parallel (r_{\pi1} + (\beta_{o1} + 1)R_5) = 300k\Omega \parallel 180k\Omega \parallel [10.8k\Omega + (101)2k\Omega] = 73.6k\Omega$$

$$A_v = \left(\frac{73.6k\Omega}{2k\Omega + 73.6k\Omega} \right) (-3.10)(-155) = +468 \quad | \quad R_{out} = 20k\Omega \parallel r_{o2} = 20k\Omega \parallel 326k\Omega = 18.8k\Omega$$

14.110

The ac equivalent circuit from Problem 14.109 becomes:



$$A_{vt1} = \frac{v_2}{v_{bi}} = -\frac{\beta_o (R_{I1} \parallel [r_{\pi 2} + (\beta_{o2} + 1)R_6])}{r_{\pi 1} + (\beta_{o1} + 1)R_5} = -\frac{100 [17k\Omega \parallel (10.8k\Omega + (101)20k\Omega)]}{10.8k\Omega + (101)20k\Omega} = -0.830$$

$$A_{vt2} = \frac{v_o}{v_2} = -\frac{\beta_{o2} R_L}{r_{\pi 2} + (\beta_{o2} + 1)R_6} = -\frac{100(16.7k\Omega)}{10.8k\Omega + (101)20k\Omega} = -0.822$$

$$A_v = \frac{R_{in}}{R_I + R_{in}} A_{vt1} A_{vt2} \quad | \quad R_{in} = 113k\Omega \parallel (r_{\pi 1} + (\beta_{o1} + 1)R_5) = 113k\Omega \parallel (10.8k\Omega + (101)20k\Omega) = 107k\Omega$$

$$A_v = \frac{107k\Omega}{2k\Omega + 107k\Omega} (-0.830)(-0.822) = +0.670$$

The voltage gain is completely lost. | $R_{out} \cong 20k\Omega$

14.111

*Problem 14.111 - Multistage Amplifier – Figure P14.109

VCC 11 0 DC 15

VI 1 0 AC 1

RI 1 2 2K

*For output resistance

*VI 1 0 AC 0

*VO 10 0 AC 1

C1 2 3 10U

R1 3 0 180K

R2 11 3 300K

Q1 6 3 4 NBJT

RE1 4 5 2K

RE2 5 0 18K

C2 5 0 10U

RC1 11 6 20K

C3 6 7 10U

R3 7 0 180K

R4 11 7 300K

Q2 9 7 8 NBJT

RC2 11 9 20K

RE3 8 0 20K

C4 8 0 10U

C5 9 10 10U

RL 10 0 100K

.OP

.AC LIN 1 5KHZ 5KHZ

.MODEL NMOSFET NMOS VTO=1 KP=.001 LAMBDA=0.02

.MODEL NBJT NPN IS=1E-16 BF=100 VA=70

.PRINT AC VM(3) VP(3) IM(VI) IP(VI) VM(10) VP(10) IM(C5) IP(C5)

.END

$$\text{Results : } A_v = VM(10) = +454 \quad | \quad R_{in} = \frac{VM(3)}{IM(VI)} = 74.7 \text{ k}\Omega \quad | \quad R_{out} = \frac{1}{IM(C5)} = 18.8 \text{ k}\Omega$$

14.112

$$A_v = \left(\frac{R_{in}}{2k\Omega + R_{in}} \right) A_{vt1} A_{vt2}$$

$$A_{vt1} = \frac{v_2}{v_1} = -g_{m1}(R_{I1} \| r_{\pi 2}) = -40(232\mu A)(17k\Omega \| 10.8k\Omega) = -61.3$$

$$A_{vt2} = \frac{v_o}{v_2} = -g_{m2}R_L \quad | \quad R_L = 100k\Omega \| 20k\Omega = 16.7k\Omega \quad | \quad A_{vt2} = -40(232\mu A)(16.7k\Omega) = -155$$

$$R_{in} = R_{B1} \| r_{\pi 1} = 300k\Omega \| 180k\Omega \| 10.8k\Omega = 10.0k\Omega$$

$$A_v = \left(\frac{10.0k\Omega}{2k\Omega + 10.0k\Omega} \right) (-61.3)(-155) = +7920 \quad | \quad R_{out} = 20k\Omega \| r_{o2} = 20k\Omega \| 326k\Omega = 18.8k\Omega$$

14.113

$$M1: \text{Assume saturation: } I_D = \frac{0.05}{2} (V_{GS} + 2)^2 \quad \text{and} \quad V_{GS} = -1800I_D$$

$$V_{GS} = -1800 \frac{0.05}{2} (V_{GS} + 2)^2 \quad \text{or} \quad 45V_{GS}^2 + 181V_{GS} + 180 = 0$$

$$V_{GS} = -2.22V, -1.80V \quad | \quad V_{GS} = -1.80 \text{ V and } I_D = 1 \text{ mA}$$

$$V_{DS} = 20 - 15000(0.001) - 1800(0.001) = 3.2 \text{ V} > V_{GS} - V_{TN}$$

$$M2: \text{Assume saturation: } I_D = \frac{0.05}{2} (V_{GS} + 2)^2 \quad \text{and} \quad V_{GS} = -2500I_D$$

$$V_{GS} = -2500 \frac{0.05}{2} (V_{GS} + 2)^2 \quad \text{or} \quad 62.5V_{GS}^2 + 251V_{GS} + 250 = 0$$

$$V_{GS} = -1.83 \text{ V and } I_D = 0.723 \text{ mA}$$

$$V_{DS} = 20 - 2500(0.723 \text{ mA}) = 18.2 \text{ V} > V_{GS} - V_{TN}$$

$$g_{m1} = \sqrt{2(0.05)(0.001)} = 10.0 \text{ mS} \quad | \quad g_{m2} = \sqrt{2(0.05)(7.23 \times 10^{-4})} = 8.50 \text{ mS}$$

$$R_{in} = 1800 \left\| \frac{1}{g_{m1}} \right\| = 1800 \| 100 = 94.7\Omega \quad | \quad R_{out} = 2500 \left\| \frac{1}{g_{m2}} \right\| = 2500 \| 118 = 113\Omega$$

$$A_{vt1} = +g_{m1}(15k\Omega \| 1M\Omega) = 0.01S(14.8k\Omega) = 148$$

$$A_{vt2} = +\frac{g_{m2}(2.5k\Omega \| 10k\Omega)}{1 + g_{m2}(2.5k\Omega \| 10k\Omega)} = +\frac{8.5 \times 10^{-3}(2.5k\Omega \| 10k\Omega)}{1 + 8.5 \times 10^{-3}(2.5k\Omega \| 10k\Omega)} = 0.944$$

$$A_v = A_{vt1} A_{vt2} = +140$$

14.114

$$V_{EQ} = -15 + 30 \frac{100k\Omega}{100k\Omega + 100k\Omega} = 0V \quad | \quad R_{EQ} = 100k\Omega \parallel 100k\Omega = 50k\Omega$$

$$I_B = \frac{0 - 0.7 - (-15)}{50k\Omega + 126(4.7k\Omega)} = 22.3\mu A \quad | \quad I_C = 2.78 mA \quad | \quad I_E = 2.81 mA$$

$$V_{CE} = 30 - 2000I_C - 4700I_E = 11.4 V \quad | \quad r_\pi = \frac{125(0.025V)}{2.78mA} = 1.12k\Omega$$

$$r_o = \frac{(50 + 11.4)V}{2.78mA} = 22.1k\Omega \quad | \quad R_B = R_1 \parallel R_2 = 100k\Omega \parallel 100k\Omega = 50k\Omega$$

$$R_{in} = R_B \parallel [r_\pi + (\beta_o + 1)R_L] = 50k\Omega \parallel [1.12k\Omega + (126)3.34k\Omega] = 44.7 k\Omega$$

$$R_{out} = R_E \parallel r_o \parallel \frac{(R_B \parallel R_I) + r_\pi}{\beta_o + 1} = 4.7k\Omega \parallel 22.1k\Omega \parallel \frac{(44.7k\Omega \parallel 600\Omega) + 1.12k\Omega}{126} = 13.5 \Omega$$

$$R_{1S} = R_I + R_{in} = 45.3k\Omega \quad R_{2S} = R_3 + R_{out} = 24.0k\Omega \quad R_{3S} \cong R_C = 2k\Omega$$

$$f_L \cong \frac{1}{2\pi} \left[\frac{1}{10^{-5}(45.3k\Omega)} + \frac{1}{47 \times 10^{-6}(24.0k\Omega)} \right] = 0.492 Hz \quad \text{SPICE result : } f_L = 0.39 Hz$$

Note that C_3 is not in the signal path and doesn't contribute to f_L .

14.115 Use $C_3 = 2.2 \mu F$

$$I_B = \frac{(10 - 0.7)V}{1M\Omega + (80 + 1)68k\Omega} = 1.43 \mu A \quad | \quad I_C = 114 \mu A \quad | \quad V_{CE} = 20 - 39000I_C - 68000I_E = 7.71 V$$

$$\text{Active region is correct.} \quad | \quad r_\pi = \frac{81(0.025V)}{114\mu A} = 17.8 k\Omega \quad | \quad r_o = \frac{75 + 7.71}{114\mu A} = 726 k\Omega$$

$$R_L = 500k\Omega \parallel 39k\Omega \parallel 726k\Omega = 34.5k\Omega \quad | \quad R_{in} = R_B \parallel r_\pi = 1M\Omega \parallel 17.8k\Omega = 17.5 k\Omega$$

$$A_v = -g_m R_L \left(\frac{R_{in}}{R_I + R_{in}} \right) = 40(0.114mA)(34.5k\Omega) \left(\frac{17.5k\Omega}{500\Omega + 17.5k\Omega} \right) = -153$$

$$R_{out} = R_C \parallel r_o = 39k\Omega \parallel 726k\Omega = 37.0 k\Omega \quad R_{1S} = R_I + R_{in} = 18.0k\Omega \quad R_{3S} = R_{out} + R_3 = 537k\Omega$$

$$R_{2S} = R_E \parallel \frac{(R_B \parallel R_I) + r_\pi}{\beta_o + 1} = 68k\Omega \parallel \frac{(1M\Omega \parallel 500\Omega) + 17.8k\Omega}{81} = 225\Omega$$

$$f_L \cong \frac{1}{2\pi} \left[\frac{1}{2.2\mu F(18.0k\Omega)} + \frac{1}{47\mu F(225\Omega)} + \frac{1}{2.2\mu F(537k\Omega)} \right] = 19.2 Hz \quad \text{SPICE result : } f_L = 18 Hz$$

14.116

$$(a) V_{EQ} = 12 \frac{62k\Omega}{62k\Omega + 20k\Omega} = 9.07V \quad | \quad R_{EQ} = 62k\Omega \parallel 20k\Omega = 15.1k\Omega$$

$$I_B = \frac{12 - 0.7 - 9.07}{15.1k\Omega + 76(6.8k\Omega)} = 4.19\mu A \quad | \quad I_C = 314 \mu A \quad | \quad I_E = 319 \mu A$$

$$V_{EC} = 12 - 16000I_C - 6800I_E = 4.81 V$$

$$r_o = \frac{60 + 4.81}{314 \times 10^{-6}} = 206k\Omega \quad | \quad r_\pi = \frac{75(0.025)}{314 \times 10^{-6}} = 5.97k\Omega$$

$$R_{in} = 15.1k\Omega \parallel 5.97k\Omega = 4.28 k\Omega \quad | \quad R_{out} = r_o \parallel 16k\Omega = 14.8 k\Omega \quad | \quad g_m = 40I_C = 12.6 mS$$

$$R_{IS} = R_I + R_{in} = 5.28k\Omega \quad R_{3S} = R_{out} + R_3 = 115k\Omega$$

$$R_{2S} = R_E \left\| \frac{(R_B \parallel R_I) + r_\pi}{\beta_o + 1} \right\| = 6.8k\Omega \left\| \frac{(15.1k\Omega \parallel 1k\Omega) + 5.97k\Omega}{76} \right\| = 90.0\Omega$$

$$f_L \approx \frac{1}{2\pi} \left[\frac{1}{2.2\mu F(5.28k\Omega)} + \frac{1}{47\mu F(90.0\Omega)} + \frac{1}{10\mu F(115k\Omega)} \right] = 51.5 Hz \quad \text{SPICE result: } f_L = 43.8 Hz$$

14.117

$$V_{EQ} = 18 \frac{500k\Omega}{500k\Omega + 1.4M\Omega} = 4.73V \quad | \quad R_{EQ} = R_1 \parallel R_2 = 500k\Omega \parallel 1.4M\Omega = 368k\Omega$$

Assume Active Region Operation

$$4.73 = V_{GS} = 27000I_D \rightarrow 4.73 = 1 + \sqrt{\frac{2I_D}{5 \times 10^{-4}}} + 27000I_D \rightarrow I_D = 113 \mu A$$

$$V_{DS} = 18 - (27000 + 75000)I_D = 6.47 V > 3.73 V \quad - \text{ Active region is correct.}$$

$$r_o = \frac{50 + 6.47}{113 \times 10^{-6}} = 500k\Omega \quad | \quad g_m = \sqrt{2(500 \times 10^{-6})(113 \times 10^{-6})[1 + 0.02(6.47)]} = 357\mu S$$

$$R_L = r_o \parallel R_D = 500k\Omega \parallel 75k\Omega \parallel 470k\Omega = 57.3k\Omega$$

$$R_{in} = R_1 \parallel R_2 = 500k\Omega \parallel 1.4M\Omega = 368k\Omega \quad | \quad R_{out} = r_o \parallel 75k\Omega = 65.2 k\Omega$$

$$R_{IS} = R_I + R_{in} = 369k\Omega \quad R_{3S} = R_{out} + R_3 = 535k\Omega \quad R_{2S} = R_S \left\| \frac{1}{g_m} = 27k\Omega \right\| \frac{1}{0.357mS} = 2.54k\Omega$$

$$f_L \approx \frac{1}{2\pi} \left[\frac{1}{2.2\mu F(369k\Omega)} + \frac{1}{47\mu F(2.54k\Omega)} + \frac{1}{10\mu F(535k\Omega)} \right] = 1.56 Hz \quad \text{SPICE result: } f_L = 1.22 Hz$$

14.118

$$I_D = \frac{(2.5 \times 10^{-4})}{2} (V_{GS} + 1)^2 \quad | \quad \frac{10 + V_{GS}}{33k\Omega} = 1.25 \times 10^{-4} (V_{GS} + 1)^2 \rightarrow V_{GS} = -2.358V$$

$$I_D = \frac{10 + V_{GS}}{33k\Omega} = 232\mu A \quad | \quad V_{DS} = -10 + 0.232mA(24k\Omega) - 2.36 = -6.79V \quad | \quad \text{Pinchoff region is correct.}$$

$$g_m = \sqrt{2(2.5 \times 10^{-4})(2.32 \times 10^{-4})[1 + 0.02(-6.79)]} = 0.363mS \quad r_o = \frac{50 + 6.79}{2.32 \times 10^{-4}} = 245k\Omega$$

$$R_{in} = 33k\Omega \left\| \frac{1}{g_m} \right\| = 2.69 k\Omega \quad | \quad R_{IS} = R_I + R_{in} = 3.19k\Omega \quad | \quad R_{2S} \cong R_D + R_3 = 124k\Omega$$

$$f_L \cong \frac{1}{2\pi} \left[\frac{1}{10\mu F(2.69k\Omega)} + \frac{1}{47\mu F(124k\Omega)} \right] = 5.94 Hz \quad \text{SPICE result : } f_L = 5.00 Hz$$

14.119

$$I_B = \frac{(12 - 0.7)V}{100k\Omega + (51)82k\Omega} = 2.69 \mu A \quad | \quad I_C = 135 \mu A \quad | \quad V_{CE} = 24 - 39000I_C - 82000I_E = 7.58 V$$

$$\text{Active region is correct.} \quad r_\pi = \frac{50(0.025V)}{135\mu A} = 9.26 k\Omega \quad | \quad r_o = \frac{50 + 7.58}{135\mu A} = 427 k\Omega$$

$$R_{IS} = R_B \left\| [r_\pi + (\beta_o + 1)(R_E \| R_I)] \right\| = 100k\Omega \left\| [9.26k\Omega + (51)(82k\Omega \| 500\Omega)] \right\| = 25.7k\Omega$$

$$R_{2S} = R_I + R_E \left\| \frac{r_\pi}{\beta_o + 1} \right\| = 500 + 82k\Omega \left\| \frac{9.26k\Omega}{51} \right\| = 681\Omega \quad | \quad R_{3S} = R_C + R_3 = 139k\Omega$$

$$f_L \cong \frac{1}{2\pi} \left[\frac{1}{4.7\mu F(25.7k\Omega)} + \frac{1}{47\mu F(681\Omega)} + \frac{1}{10\mu F(139k\Omega)} \right] = 6.40 Hz \quad \text{SPICE result : } f_L = 5.72 Hz$$

14.120

$$\text{Assume Active Region operation.} \quad V_{GS} = -51000I_D \quad I_D = \frac{5 \times 10^{-4}}{2} (V_{GS} + 2)^2 \rightarrow I_D = 32.2 \mu A$$

$$V_{DS} = 15 - (20000 + 51000)I_D = 12.7 V > 0.36 V \quad - \quad \text{Active Region is correct.}$$

$$g_m = \sqrt{2(5 \times 10^{-4})(32.2 \times 10^{-6})[1 + 0.02(12.7)]} = 0.201mS \quad | \quad R_{in} = 51k\Omega \left\| \frac{1}{g_m} \right\| = 4.53k\Omega$$

$$r_o = \frac{50 + 12.7}{32.2 \times 10^{-6}} = 1.95 M\Omega \quad R_{IS} = R_I + R_{in} = 5.53k\Omega \quad R_{2S} \cong R_D + R_3 = 30k\Omega$$

$$f_L \cong \frac{1}{2\pi} \left[\frac{1}{2.2\mu F(5.53k\Omega)} + \frac{1}{47\mu F(30k\Omega)} \right] = 13.2 Hz \quad \text{SPICE result : } f_L = 12.8 Hz$$

14.121 The power supply should be +16 V.

Assume Active Region operation. Since there is no negative feedback ($R_s = 0$), we should include the effect of channel - length modulation. $V_{GS} = 0$

$$I_D = \frac{4x10^{-4}}{2} (-5)^2 (1 + 0.02V_{DS}) \text{ and } V_{DS} = 16 - 1800I_D \rightarrow I_D = 5.59 \text{ mA}$$

$V_{DS} = 16 - 1800I_D = 5.93 \text{ V} > 5 \text{ V}$ - Active region is correct.

$$r_o = \frac{50 + 5.93}{5.59x10^{-3}} = 10.0k\Omega \quad R_{in} = 10.0 M\Omega \quad | \quad R_{out} = R_D \parallel r_o = 1.52 k\Omega$$

$$R_{1S} = R_i + R_{in} = 10.0 M\Omega \quad R_{2S} = R_{out} + R_3 = 37.5k\Omega$$

$$f_L \approx \frac{1}{2\pi} \left[\frac{1}{2.2\mu F(10.0 M\Omega)} + \frac{1}{10\mu F(37.5k\Omega)} \right] = 0.497 \text{ Hz} \quad \text{SPICE result : } f_L = 0.427 \text{ Hz}$$

14.122 Use $C_1 = C_2 = C_3 = 1 \mu\text{F}$

$$\text{M1: Assume saturation: } I_D = \frac{0.05}{2} (V_{GS} + 2)^2 \text{ and } V_{GS} = -1800I_D$$

$$V_{GS} = -1800 \frac{0.05}{2} (V_{GS} + 2)^2 \text{ or } 45V_{GS}^2 + 181V_{GS} + 180 = 0$$

$$V_{GS} = -2.22V, -1.80V \quad | \quad V_{GS} = -1.80 \text{ V and } I_D = 1 \text{ mA}$$

$$V_{DS} = 20 - 15000(0.001) - 1800(0.001) = 3.2 \text{ V} > V_{GS} - V_{TN}$$

$$\text{M2: Assume saturation: } I_D = \frac{0.05}{2} (V_{GS} + 2)^2 \text{ and } V_{GS} = -2500I_D$$

$$V_{GS} = -2500 \frac{0.05}{2} (V_{GS} + 2)^2 \text{ or } 62.5V_{GS}^2 + 251V_{GS} + 250 = 0$$

$$V_{GS} = -1.83 \text{ V and } I_D = 0.723 \text{ mA}$$

$$V_{DS} = 20 - 2500(0.723mA) = 18.2 \text{ V} > V_{GS} - V_{TN}$$

$$g_{m1} = \sqrt{2(0.05)(0.001)} = 10.0mS \quad | \quad g_{m2} = \sqrt{2(0.05)(7.23x10^{-4})} = 8.50mS$$

$$R_{1S} = R_{in} = 1800 \parallel \frac{1}{g_{m1}} = 1800 \parallel 100 = 94.7\Omega \quad | \quad R_{2S} = 15k\Omega + 1M\Omega = 1.02M\Omega$$

$$R_{out} = 2500 \parallel \frac{1}{g_{m2}} = 2500 \parallel 118 = 113\Omega \quad | \quad R_{3S} = 10k\Omega + R_{out} = 10.1k\Omega$$

$$f_L \approx \frac{1}{2\pi} \left[\frac{1}{1\mu F(113\Omega)} + \frac{1}{1\mu F(1.02M\Omega)} + \frac{1}{1\mu F(10.1k\Omega)} \right] = 1.42 \text{ kHz} \quad \text{SPICE result : } f_L = 1.68 \text{ kHz}$$

CHAPTER 15

15.1

$$(a) I_C = \alpha_F I_E = \frac{1}{2} \frac{\beta_F}{\beta_F + 1} \frac{12 - V_{BE}}{R_{EE}} = \frac{1}{2} \left(\frac{100}{101} \right) \left(\frac{12 - 0.7}{2.7 \times 10^5} \right) = 20.7 \mu A \quad | \quad V_C = 12 - 3.3 \times 10^5 I_C = 5.17 V$$

$$V_{CE} = V_C - (-0.7V) = 5.87V \quad | \quad Q\text{-Point} = (20.7 \mu A, 5.87V)$$

$$(b) A_{dd} = -g_m R_C = -40(20.7 \mu A)(330 k\Omega) = -273$$

$$R_{id} = 2r_\pi = 2 \frac{\beta_o V_T}{I_C} = 2 \frac{100(0.025V)}{20.7 \mu A} = 243 k\Omega \quad | \quad R_{od} = 2R_C = 660 k\Omega$$

$$(c) A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)2R_{EE}} = -\frac{100(330 k\Omega)}{122 k\Omega + 2(101)270 k\Omega} = -0.604$$

$$A_{dd} = -\frac{g_m R_C}{2} = -137 \quad | \quad A_{cd} = A_{cc} \quad | \quad CMRR = \left| \frac{-137}{-0.604} \right| = 227 \text{ or } 47.1 \text{ dB (very low)}$$

$$R_{ic} = \frac{r_\pi + (\beta_o + 1)2R_{EE}}{2} = \frac{122 k\Omega + 2(101)270 k\Omega}{2} = 27.3 M\Omega$$

15.2

$$(a) I_E = \frac{1}{2} \left(\frac{1.5 - 0.7}{75 \times 10^3} \right) V = 5.33 \mu A \quad | \quad I_C = \alpha_F I_E = \frac{60}{61} I_E = 5.25 \mu A$$

$$V_{CE} = 1.5 - 10^5 I_C - (-0.7) = 1.68 V \quad | \quad Q\text{-Pt: } (5.25 \mu A, 1.68 V)$$

$$(b) g_m = 40 I_C = 0.210 mS \quad | \quad r_\pi = \frac{60}{g_m} = 286 k\Omega \quad | \quad A_{dd} = -g_m R_C = -0.210 mS (100 k\Omega) = -21.0$$

$$A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)2R_{EE}} = -\frac{60(100 k\Omega)}{286 k\Omega + 61(150 k\Omega)} = -0.636$$

$$\text{For differential output: CMRR} = \left| \frac{-21.0}{0} \right| = \infty$$

$$\text{For single-ended output: CMRR} = \left| \frac{-21.0}{\frac{2}{-0.636}} \right| = 16.5, \text{ a paltry } 24.4 \text{ dB!}$$

$$R_{id} = 2r_\pi = 572 k\Omega \quad | \quad R_{ic} = \frac{r_\pi + (\beta_o + 1)2R_{EE}}{2} = \frac{286 + 61(150)}{2} k\Omega = 4.72 M\Omega$$

$$R_{od} = 2R_C = 200 k\Omega \quad | \quad R_{oc} = \frac{R_C}{2} = 50 k\Omega$$

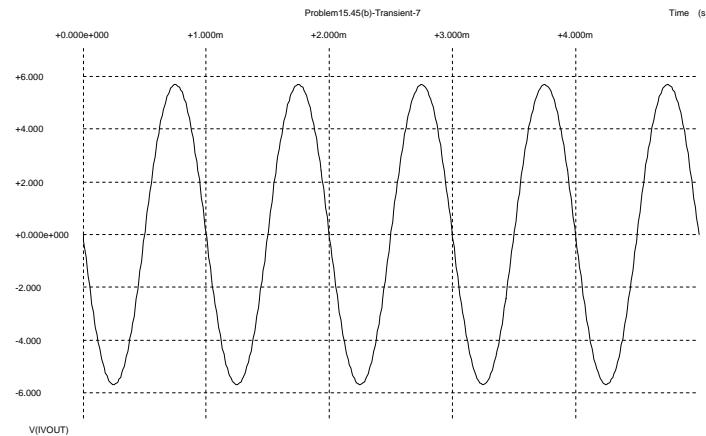
15.3

```

*Problem 15.3
VCC 2 0 DC 12
VEE 1 0 DC -12
VIC 8 0 DC 0
VID1 4 8 AC 0.5
VID2 6 8 AC -0.5
RC1 2 3 330K
RC2 2 7 330K
Q1 3 4 5 NBJT
Q2 7 6 5 NBJT
REE 5 1 270K
.MODEL NBJT NPN BF=100 VA=60 IS=1FA
.OP
.AC LIN 1 1KHZ 1KHZ
.PRINT AC IM(VID1) IP(VID1) VM(3,7) VP(3,7)
.TF V(7) VIC
.END

```

Results: $A_{dd} = VM(3,7) = -241$ | $R_{id} = \frac{1}{IM(VID1)} = 269 \text{ k}\Omega$ | $A_{cc} = -0.602$ | $R_{ic} = 23.2 \text{ M}\Omega$



Simulation results from B²SPICE.

Problem 15.3(b)-Fourier-Table

FREQ	mag	phase	norm_mag	norm_phase
+0.000	+49.786n	+0.000	+0.00	+0.000
+1.000k	+5.766	+180.000	+1.000	+0.000
+2.000k	+99.572n	+93.600	+17.268n	-86.400
+3.000k	+80.305m	-180.000	+13.927m	-360.000
+4.000k	+99.572n	+97.200	+17.268n	-82.800
+5.000k	+1.161m	+179.993	+201.326u	-7.528m
+6.000k	+99.572n	+100.800	+17.268n	-79.200
+7.000k	+13.351u	-179.005	+2.315u	-359.005
+8.000k	+99.572n	+104.400	+17.268n	-75.600

Using the Fourier analysis capability of SPICE, THD = 1.39%

15.4

$$(a) I_E = \frac{18V - 0.7V}{2(4.7 \times 10^4 \Omega)} = 184 \mu A \quad | \quad I_C = \alpha_F I_E = \frac{100}{101} I_E = 182 \mu A$$

$$V_{CE} = 18 - 10^5 I_C - (-0.7) = 0.92 V \quad | \quad Q\text{-point: } (182 \mu A, 0.92 V)$$

Note that R_C is quite large and the common-mode input range is poor.

More realistic choices might be 47 k Ω or 51 k Ω

$$(b) g_m = 40 I_C = 7.28 mS \quad | \quad r_\pi = \frac{100}{g_m} = 13.7 k\Omega \quad | \quad A_{dd} = -g_m R_C = -7.28 mS (100 k\Omega) = -728$$

$$A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1) 2R_{EE}} = -\frac{100(100 k\Omega)}{13.7 k\Omega + 101(94 k\Omega)} = -1.05$$

$$\text{For differential output: CMRR} = \left| \frac{-33.7}{0} \right| = \infty$$

$$\text{For single-ended output: CMRR} = \left| \frac{-728}{\frac{2}{-1.05}} \right| = 346, \text{ a paltry } 50.8 \text{ dB!}$$

$$R_{id} = 2r_\pi = 27.4 k\Omega \quad | \quad R_{ic} = \frac{r_\pi + (\beta_o + 1) 2R_{EE}}{2} = \frac{13.7 + 101(94)}{2} k\Omega = 4.75 M\Omega$$

$$R_{od} = 2R_C = 200 k\Omega \quad | \quad R_{oc} = \frac{R_C}{2} = 50 k\Omega$$

15.5

$$(a) I_C = \alpha_F I_E = \frac{1}{2} \left(\frac{\beta_F}{\beta_F + 1} \right) \left(\frac{12 - V_{BE}}{R_{EE}} \right) = \frac{1}{2} \left(\frac{100}{101} \right) \left(\frac{12 - 0.7}{2.7 \times 10^5} \right) = 20.7 \mu A$$

$$V_{C1} = V_{C2} = 12 - 2.4 \times 10^5 I_C = 7.03 V \quad | \quad V_{CE} = V_C - (-0.7 V) = 7.73 V$$

$$\text{Q-Point} = (20.7 \mu A, 7.73 V) \quad | \quad r_\pi = \frac{100(0.025 V)}{20.7 \mu A} = 121 k\Omega$$

$$A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1) R_{EE}} = \frac{100(240 k\Omega)}{121 k\Omega + (101)540 k\Omega} = -0.439 \quad | \quad v_{ic} = \frac{5.000 + 5.000}{2} = 5.00 V$$

$$v_{ic} = 5 V, \quad v_{C1} = v_{C2} = 7.03 + A_{cc} v_{ic} = 7.03 - 0.439(5) = 4.84 V$$

Note that the BJT's are just beyond the edge of saturation!

$$(b) I_C = \alpha_F I_E = \frac{1}{2} \frac{\beta_F}{\beta_F + 1} \left(\frac{5V - V_{BE} - (-12V)}{R_{EE}} \right) = \frac{1}{2} \left(\frac{100}{101} \right) \left(\frac{17V - 0.7V}{2.7 \times 10^5} \right) = 29.9 \mu A$$

$$V_{C1} = V_{C2} = 12 - 2.4 \times 10^5 I_C = 4.82 V \quad | \quad \text{Part (a) has a small error of 0.02 mV}$$

(c) The common - mode signal voltage applied to the base - emitter junction is

$$v_{be} = v_{ic} \frac{r_\pi}{r_\pi + (\beta_o + 1) R_{EE}} = 5 \frac{121 k\Omega}{121 k\Omega + (101)540 k\Omega} = 11.1 mV > 5 mV.$$

A common - mode input voltage of 5 volts exceeds the small - signal limit.

15.6

We should first check the feasibility of the design using the Rule- of - Thumb estimates similar to those developed in Chapter 13 (Eq. (13.55)). The required $A_{dd} = 794$ (58 db)

(This sounds fairly large - a significant fraction of the BJT amplification factor μ_f .)

Even assuming we choose to drop all of the positive power supply voltage across R_C

(which provides no common - mode input range): $A_{dd} = g_m R_C = 40 I_C R_L \leq 40 V_{CC} = 40(9) = 360$.

Thus, a gain of 794 is not feasible with this topology!

15.7

We should first check the feasibility of the design using the Rule-of-Thumb estimates similar to those developed in Chapter 13 (Eq. (13.55)). The required $A_{dd} = 200$ (46 db)

For symmetric supplies, $A_{dd} \approx 10(V_{CC} + V_{EE}) = 240$. Thus, a gain of 200 appears feasible.

$$R_{id} = 2r_\pi = 1M\Omega \rightarrow r_\pi = 500k\Omega \quad | \quad I_C = \frac{\beta_o V_T}{r_\pi} = \frac{100(0.025V)}{500k\Omega} = 5.00 \mu A$$

$$I_E = \frac{I_C}{\alpha_F} = \frac{101}{100} I_C = 5.05 \mu A \quad | \quad R_{EE} = \frac{V_{EE} - V_{BE}}{2I_E} = \frac{(12 - 0.7)V}{2(5.05 \mu A)} = 1.12 M\Omega$$

$$A_{dd} = -g_m R_C = -200 \text{ (46dB)} \quad | \quad R_C = \frac{200}{g_m} = \frac{200}{40(5 \times 10^{-6})} = 1.00 M\Omega$$

Checking the collector voltage: $V_C = 12 - (990k\Omega)(5\mu A) = 7V$ | Picking the closest 5% values from the table in the Appendix: $R_{EE} = 1.1 M\Omega$ and $R_C = 1 M\Omega$ are the final design values. These values give $I_C = 5.09 \mu A$ and $A_{dd} = -204$ (46.2dB)

15.8

$$(a) I_C = \alpha_F I_E = \alpha_F \frac{I_{EE}}{2} = \frac{100}{101} \left(\frac{400\mu A}{2} \right) = 198\mu A \quad | \quad V_{CE} = 12 - 3.9 \times 10^4 I_C - (-0.7) = 4.98V$$

Q-point: $(198\mu A, 4.98V)$

$$(b) g_m = 40I_C = 7.92mS \quad | \quad r_\pi = \frac{100}{g_m} = 12.6k\Omega \quad | \quad A_{dd} = -g_m R_C = -7.92mS(39k\Omega) = -309$$

$$A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)2R_{EE}} = -\frac{100(39k\Omega)}{12.6k\Omega + 101(400k\Omega)} = -0.0965$$

$$\text{For a differential output: CMRR} = \left| \frac{-309}{0} \right| = \infty$$

$$\text{For a single-ended output: CMRR} = \left| \frac{-309}{\frac{2}{-0.0965}} \right| = 1600 \text{ or } 64.1 \text{ dB}$$

$$R_{id} = 2r_\pi = 25.2 k\Omega \quad | \quad R_{ic} = \frac{r_\pi + (\beta_o + 1)2R_{EE}}{2} = \frac{12.6k\Omega + 101(400k\Omega)}{2} k\Omega = 20.2 M\Omega$$

(Note that this value is approaching the $\beta_o r_o$ limit and hence is not really correct.)

$$R_{od} = 2R_C = 78.0 k\Omega \quad | \quad R_{oc} = \frac{R_C}{2} = 19.5 k\Omega$$

$$(c) r_o = \frac{50 + 4.98}{198 \times 10^{-6}} = 278k\Omega$$

$$A_{dd} = -g_m (R_C \| r_o) = -7.92mS(39k\Omega \| 278k\Omega) = -271$$

$$A_{cc} \approx -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)2R_{EE}} = -\frac{100(39k\Omega)}{12.6k\Omega + 101(400k\Omega)} = -0.0965$$

$$\text{For differential output: CMRR} = \left| \frac{-271}{0} \right| = \infty$$

$$\text{For single-ended output: CMRR} = \left| \frac{-271}{\frac{2}{-0.0965}} \right| = 1400 \text{ or } 62.9 \text{ dB}$$

$$R_{id} = 2r_\pi = 25.2 k\Omega \quad | \quad R_{ic} = \frac{r_\pi + (\beta_o + 1)(2R_{EE} \| r_o)}{2} = \frac{12.6k\Omega + 101(164k\Omega)}{2} k\Omega = 8.29 M\Omega$$

$$R_{od} = 2(R_C \| r_o) = 68.4 k\Omega \quad | \quad R_{oc} = \frac{(R_C \| R_{out}^{CB})}{2} \approx \frac{R_C}{2} = 19.5 k\Omega \quad \text{since} \quad R_{out}^{CB} \approx \mu_f (2R_{EE} \| r_\pi) = 24.4 M\Omega$$

15.9

$$I_C = \alpha_F I_E = \alpha_F \frac{I_{EE}}{2} = \frac{75}{76} \frac{400\mu A}{2} = 197\mu A \quad | \quad V_{C1} = V_{C2} = 12 - 3.9 \times 10^4 I_C = 4.32V$$

$$V_{CE} = 4.32 - (-0.7) = 5.02V \quad | \quad \text{Q-point: } (197\mu A, 5.02V)$$

$$g_m = 40I_C = 7.88mS \quad | \quad r_\pi = \frac{75}{g_m} = 9.52k\Omega \quad | \quad A_{dd} = -g_m R_C = -7.88mS(39k\Omega) = -307$$

$$A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)2R_{EE}} = -\frac{75(39k\Omega)}{9.52k\Omega + 76(400k\Omega)} = -0.0962$$

$$v_{id} = 2.005 - 1.995 = 0.01V \quad | \quad v_{ic} = \frac{2.005 + 1.995}{2} = 2.00V$$

$$v_{C1} = V_{C1} + A_{dd} \frac{v_{id}}{2} + A_{cc} v_{ic} = 4.32V - 307 \frac{0.01V}{2} - 0.0962(2V) = 2.593 V$$

$$v_{C2} = V_{C2} - A_{dd} \frac{v_{id}}{2} + A_{cc} v_{ic} = 4.32V + 307 \frac{0.01V}{2} - 0.0962(2V) = 5.663 V$$

$$v_{OD} = 2.593 - 5.663 = -3.07 V$$

$$V_{CB} = V_{C1} + A_{cc} V_{IC} - V_{IC} \geq 0 \quad | \quad V_{IC} \leq \frac{4.32}{1 + 0.0962} = 3.94 V$$

15.10

$$R_{id} = 2r_\pi = \frac{2\beta_o V_T}{I_C} \rightarrow I_C \frac{2(100)(0.025V)}{5M\Omega} = 1.00\mu A \quad | \quad I_{EE} = 2 \frac{I_C}{\alpha_F} = 2 \frac{101}{100}(1\mu A) = 2.02 \mu A$$

$$CMRR = g_m R_{EE} = 10^5 \rightarrow R_{EE} = \frac{10^5}{40(1.00\mu A)} = 2.5 G\Omega !$$

15.11

$$(a) I_C = \alpha_F I_E = \alpha_F \frac{I_{EE}}{2} = \frac{100}{101} \left(\frac{20\mu A}{2} \right) = 9.90\mu A \quad | \quad V_{C2} = 10 - 9.1 \times 10^5 I_C = 0.991V$$

$$g_m = 40I_C = 0.396mS \quad | \quad A_{dd} = -g_m R_C = -0.396mS(910k\Omega) = -360 \quad | \quad R_{EE} = \infty \rightarrow A_{cc} \approx 0$$

$$v_{C2} = V_{C2} - A_{dd} \frac{v_{id}}{2} + A_{cc} v_{ic} \quad | \quad \text{For } v_s = 0: v_{C2} = V_{C2} = 0.991$$

$$\text{For } v_s = 2mV: v_{C2} = 0.991V + 360(0.001V) - 0(0.001V) = +1.35 V$$

$$(b) \text{For } v_{BC} \geq 0, v_s - (0.991 - 180v_s) \geq 0 \rightarrow v_s \leq \frac{0.991V}{181} = 5.48 mV$$

15.12

$$(a) I_C = \alpha_F I_E = \alpha_F \frac{I_{EE}}{2} = \frac{120}{121} \left(\frac{200\mu A}{2} \right) = 99.2\mu A \quad | \quad V_o = 12 - 1.10 \times 10^5 I_C = 1.09 V$$

$$g_m = 40I_C = 3.97mS \quad | \quad A_{dd} = -g_m R_C = -3.97mS (110k\Omega) = -437 \quad | \quad R_{EE} = \infty \rightarrow A_{cc} \equiv 0$$

$$\text{For } v_s = 0 : \quad V_o = 1.09 V \text{ and } v_o = -A_{dd} \frac{v_{id}}{2} = 0$$

$$\text{For } v_s = 1 mV : \quad V_o = 1.09 V \text{ and } v_o = -(-437) \frac{0.001V}{2} = 0.219 V$$

$$(b) \text{ For } v_{CB} \geq 0, v_s - \left(V_o - \frac{A_{dd}}{2} v_s \right) \geq 0 \rightarrow v_s \leq 4.96 mV$$

15.13

*Problem 15.13 - Figure P15.11

VCC 2 0 DC 12

VEE 1 0 DC -12

V1 3 7 AC 1

V2 5 7 AC 0

VIC 7 0 DC 0

RC 2 6 110K

Q1 2 3 4 NBJT

Q2 6 5 4 NBJT

IEE 4 1 DC 200U

.MODEL NBJT NPN VA=60V BF=120

.OP

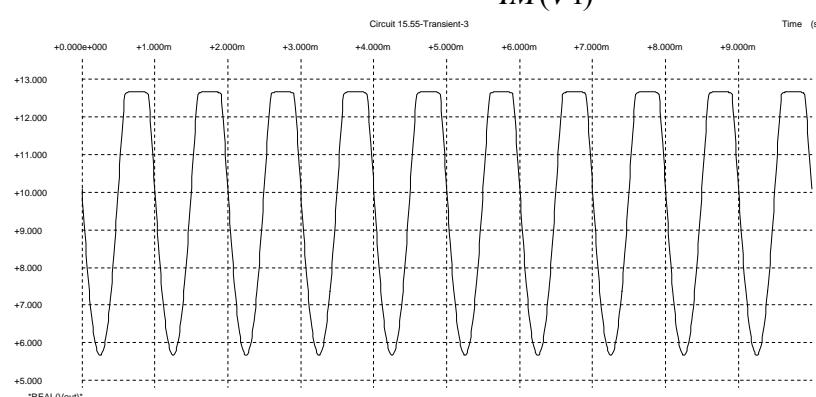
.AC LIN 1 1KHz 1KHZ

.PRINT AC IM(V1) IP(V1) VM(6) VP(6)

.TF V(6) VIC

.END

$$\text{Results: } A_{dd} = VM(6) = -193 \quad | \quad R_{id} = \frac{1}{IM(V1)} = 82.0 k\Omega \quad | \quad A_{cc} = +0.0123 \quad | \quad R_{ic} = 45.8 M\Omega$$



Simulation results from B²SPICE.

The amplifier is over driven causing the output to be distorted.

Using the Fourier analysis capability of SPICE, THD = 16.9%

15.14

$$I_C = \alpha_F I_E = \frac{150}{151} \left[\frac{15 - 0.7}{2(150k\Omega)} \right] = 47.4 \mu A \quad | \quad V_{EC} = 0.7 - (-15 + 2 \times 10^5 I_C) = 6.22V$$

$$\text{Q-points: } (47.4 \mu A, 6.22V) \quad | \quad g_m = 40I_C = 1.90mS \quad | \quad r_\pi = \frac{150}{g_m} = 79.0k\Omega$$

$$A_{dd} = -g_m R_C = -1.90mS(200k\Omega) = -380$$

$$A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)2R_{EE}} = -\frac{150(200k\Omega)}{79.0k\Omega + 151(300k\Omega)} = -0.661$$

$$R_{id} = 2r_\pi = 158k\Omega \quad | \quad R_{ic} = \frac{r_\pi + (\beta_o + 1)2R_{EE}}{2} = \frac{79.0k\Omega + 151(300k\Omega)}{2} = 22.7 M\Omega$$

$$\text{For a differential output: } A_{dm} = A_{dd} = -380 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$$

$$\text{For a single-ended output: } A_{dm} = \frac{A_{dd}}{2} = -190 \quad | \quad A_{cm} = A_{cc} = -0.661$$

$$CMRR = \left| \frac{-190}{-0.661} \right| = 287 \text{ or } 49.2dB$$

15.15

$$I_C = \alpha_F I_E = \frac{100}{101} \left[\frac{10 - 0.7}{2(430k\Omega)} \right] = 10.7 \mu A \quad | \quad V_{C1} = V_{C2} = -10 + 5.6 \times 10^5 I_C = -4.01V$$

$$V_{EC} = 0.7 - (-4.01) = 4.71V \quad | \quad g_m = 40I_C = 0.428mS \quad | \quad r_\pi = \frac{100}{g_m} = 234k\Omega$$

$$A_{dd} = -g_m R_C = -0.428mS(560k\Omega) = -240$$

$$A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)2R_{EE}} = -\frac{100(560k\Omega)}{234k\Omega + 101(860k\Omega)} = -0.643$$

$$v_{id} = 1 - 0.99 = 0.01V \quad | \quad v_{ic} = \frac{1 + 0.99}{2} = 0.995V$$

$$v_{C1} = V_{C1} + A_{dd} \frac{v_{id}}{2} + A_{cc} v_{ic} = -4.01V - 240 \frac{0.01V}{2} - 0.643(0.995V) = -5.850V$$

$$v_{C2} = V_{C2} - A_{dd} \frac{v_{id}}{2} + A_{cc} v_{ic} = -4.01V + 240 \frac{0.01V}{2} - 0.643(0.995V) = -3.450V$$

$$v_{OD} = -5.850 - (-3.450) = -2.40V \quad | \quad \text{Note: } A_{dd}v_{id} = -2.40V \text{ and } v_{OC} = \frac{-5.850 - 3.450}{2} = -4.65V$$

$$\text{Also note: } v_{OC} = V_C + A_{cc} v_{ic} = -4.01 - 0.643(0.995V) = -4.65V$$

15.16

*Problem 15.16 – Figure P15.14

VCC 2 0 DC 10

VEE 1 0 DC -10

V1 4 8 AC 1

V2 6 8 AC 0

VIC 8 0 DC 0

RC1 5 1 560K

RC2 7 1 560K

Q1 5 4 3 PBJT

Q2 7 6 3 PBJT

REE 2 3 430K

.MODEL PBJT PNP VA=60V BF=100

.OP

.AC LIN 1 5KHz 5KHZ

.PRINT AC IM(V1) IP(V1) VM(5,7) VP(5,7)

.TF V(7) VIC

.END

$$A_{dd} = VM(5,7) = -213 \quad | \quad R_{id} = \frac{1}{IM(V1)} = 511 \text{ k}\Omega$$

$$A_{cc} = -0.642 \quad | \quad R_{ic} = 37.5 \text{ M}\Omega \quad | \quad CMRR = \frac{213}{0.642} = 332 \rightarrow 50.4 \text{ dB}$$

15.17

$$I_C = \alpha_F \frac{I_{EE}}{2} = \frac{80}{81} \left(\frac{10\mu A}{2} \right) = 4.94\mu A \quad | \quad V_{EC} = 0.7 - (-3 + 3.9 \times 10^5 I_C) = 1.77V$$

$$\text{Q-points: } (4.94\mu A, 1.77V) \quad | \quad g_m = 40I_C = 0.198mS \quad | \quad r_\pi = \frac{80}{g_m} = 404k\Omega$$

$$A_{dd} = -g_m R_C = -0.198mS(390k\Omega) = -77.2$$

$$A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)2R_{EE}} = -\frac{80(390k\Omega)}{404k\Omega + 81(10M\Omega)} = -0.0385$$

$$R_{id} = 2r_\pi = 808k\Omega \quad | \quad R_{ic} = \frac{r_\pi + (\beta_o + 1)2R_{EE}}{2} = \frac{808k\Omega + 81(10M\Omega)}{2} = 405 M\Omega$$

Note that R_{ic} is similar to $\frac{\beta_o r_o}{2}$ so that $R_{ic} = 405 M\Omega$ will not be fully achieved.

$$\text{For example, if } V_A \text{ were } 80V, \frac{\beta_o r_o}{2} \approx \frac{80}{2} \left(\frac{80}{4.94\mu A} \right) = 648 M\Omega$$

For a differential output: $A_{dm} = A_{dd} = -77.2 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$

For a single-ended output: $A_{dm} = \frac{A_{dd}}{2} = -38.6 \quad | \quad A_{cm} = A_{cc} = -0.661$

$$CMRR = \left| \frac{-38.6}{-0.0385} \right| = 1000 \text{ or } 60.0dB \quad | \quad V_{BC} \geq 0 \text{ requires } V_{IC} \geq V_C = -1.07V \text{ and}$$

Without detailed knowledge of the circuit for I_{EE} , we can only estimate that V_{IC} should not exceed $V_{IC} + 0.7 \leq V_{CC} - 0.7V$ which allows 0.7V for biasing $I_{EE} \rightarrow -1.07V \leq V_{IC} \leq +1.6V$.

15.18

$$I_C = \alpha_F \frac{I_{EE}}{2} = \frac{120}{121} \left(\frac{1mA}{2} \right) = 496\mu A \quad | \quad V_{C1} = V_{C2} = -22 + 1.5 \times 10^4 I_C = -14.6V$$

$$\text{Checking } V_{EC} = 0.7 - (-14.6) = 15.3V \quad | \quad g_m = 40I_C = 19.8mS \quad | \quad r_\pi = \frac{120}{g_m} = 6.06k\Omega$$

$$A_{dd} = -g_m R_C = -19.8mS (15k\Omega) = -297$$

$$A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)2R_{EE}} = -\frac{120(15k\Omega)}{6.06k\Omega + 121(1M\Omega)} = -0.0149$$

$$v_{id} = 0.01 - 0 = 0.01V \quad | \quad v_{ic} = \frac{0.01 + 0}{2} = 0.005V$$

$$v_{C1} = V_{C1} + A_{dd} \frac{v_{id}}{2} + A_{cc} v_{ic} = -14.6V - 297 \frac{0.01V}{2} - 0.0149(0.005V) = -16.09V$$

$$v_{C2} = V_{C2} - A_{dd} \frac{v_{id}}{2} + A_{cc} v_{ic} = -14.6V + 297 \frac{0.01V}{2} - 0.0149(0.005V) = -13.12V$$

$$v_{OD} = -16.09 - (-13.12) = -2.97V \quad | \quad \text{Note: } A_{dd} v_{id} = -2.97V$$

$$\text{Also note: } v_{OC} = \frac{-16.09 - 13.12}{2} = -14.6 \text{ and}$$

$$v_{OC} = V_C + A_{cc} v_{ic} = -14.6V - 0.0149(0.005V) = -14.6V$$

15.19

$$I_C = \alpha_F I_E = \frac{100}{101} \left| \frac{15V - 0.7V}{2(100k\Omega)} \right| = 70.8\mu A \quad | \quad g_m = 40I_C = 2.83mS \quad | \quad r_\pi = \frac{100}{g_m} = 35.3k\Omega$$

$$A_{dd} = \frac{v_{od}}{v_{id}} \quad | \quad v_{od} = v_{c1} - v_{c2} = i_{c1} \left(R + \frac{\Delta R}{2} \right) - i_{c2} \left(R - \frac{\Delta R}{2} \right)$$

$$v_{od} = -gm \frac{v_{id}}{2} \left(R + \frac{\Delta R}{2} \right) - \left(-gm \frac{v_{id}}{2} \right) \left(R - \frac{\Delta R}{2} \right) = -g_m R v_{id} \quad | \quad A_{dd} = -g_m R = -283$$

$$A_{cd} = \frac{v_{od}}{v_{ic}} \quad | \quad v_{od} = v_{c1} - v_{c2} = i_{c1} \left(R + \frac{\Delta R}{2} \right) - i_{c2} \left(R - \frac{\Delta R}{2} \right)$$

$$\text{For a common-mode input, } i_{c1} = i_{c2} = \frac{\beta_o}{r_\pi + (\beta_o + 1)2R_{EE}} v_{ic}$$

$$v_{od} = -\frac{\beta_o}{r_\pi + (\beta_o + 1)2R_{EE}} v_{ic} \left[\left(R + \frac{\Delta R}{2} \right) - \left(R - \frac{\Delta R}{2} \right) \right] = v_{od} = -\frac{\beta_o \Delta R}{r_\pi + (\beta_o + 1)2R_{EE}} v_{ic}$$

$$A_{cd} = -\frac{\Delta R}{R} \frac{\beta_o R}{r_\pi + (\beta_o + 1)2R_{EE}} = -0.01 \frac{100(100k\Omega)}{35.3k\Omega + (101)200k\Omega} = -.00494$$

$$CMRR = \left| \frac{-283}{-0.00494} \right| = 57300 \text{ or } 95.2 dB$$

15.20

*Problem 15.20 – Figure P15.19

VCC 2 0 DC 15

VEE 1 0 DC -15

V1 4 8 AC 0.5

V2 6 8 AC -0.5

VIC 8 0 DC 0

RC1 2 5 100.5K

RC2 2 7 99.5K

Q1 5 4 3 NBJT

Q2 7 6 3 NBJT

REE 3 1 100K

.MODEL NBJT NPN BF=100

.OP

.AC LIN 1 100 100

.PRINT AC IM(V1) IP(V1) VM(5,7) VP(5,7)

.TF V(5,7) VIC

.END

Results: $A_{dd} = VM(5,7) = -274$ | $A_{cd} = -0.00494$ | CMRR = 55500 or 94.9 dB

15.21

For a differential - mode input :

$$v_{od} = -\left(\frac{v_{id}}{2} - v_e\right) \left(g_m + \frac{\Delta g_m}{2}\right) R + \left(-\frac{v_{id}}{2} - v_e\right) \left(g_m - \frac{\Delta g_m}{2}\right) R = -g_m R v_{id} + \Delta g_m R v_e$$

$$v_{od} = -g_m R \left(v_{id} + \frac{\Delta g_m}{g_m} v_e\right) \quad | \quad \text{At the emitter node :}$$

$$\left(\frac{v_{id}}{2} - v_e\right) \left(g_m + \frac{\Delta g_m}{2} + g_\pi\right) + \left(-\frac{v_{id}}{2} - v_e\right) \left(g_m - \frac{\Delta g_m}{2} + g_\pi\right) - G_{EE} v_e = 0$$

$$v_e = \frac{1}{2} \frac{\Delta g_m}{g_m} \frac{\beta_o R_{EE}}{r_\pi + (\beta_o + 1)2R_{EE}} v_{id} \cong \frac{1}{4} \frac{\Delta g_m}{g_m} v_{id} \ll v_{id} \quad | \quad v_{od} \cong -g_m R v_{id} \quad | \quad A_{dd} \cong -g_m R = -300$$

For a common - mode input :

$$v_{od} = -(v_{ic} - v_e) \left(g_m + \frac{\Delta g_m}{2}\right) R + (v_{ic} - v_e) \left(g_m - \frac{\Delta g_m}{2}\right) R = -\Delta g_m R (v_{ic} - v_e) = -\frac{\Delta g_m}{g_m} g_m R (v_{ic} - v_e)$$

$$\text{At the emitter node : } (v_{ic} - v_e) \left(g_m + \frac{\Delta g_m}{2} + g_\pi + g_m - \frac{\Delta g_m}{2} + g_\pi\right) - G_{EE} v_e = 0$$

$$v_e = \frac{(\beta_o + 1)2R_{EE}}{r_\pi + (\beta_o + 1)2R_{EE}} v_{ic} \quad | \quad v_{ic} - v_e = \frac{r_\pi}{r_\pi + (\beta_o + 1)2R_{EE}} v_{ic}$$

$$A_{cd} = \frac{v_{od}}{v_{ic}} = -\frac{\Delta g_m}{g_m} \frac{\beta_o R}{r_\pi + (\beta_o + 1)2R_{EE}} \cong -\frac{\Delta g_m}{g_m} \frac{g_m R}{1 + 2g_m R_{EE}} = -\frac{\Delta g_m}{g_m} \frac{g_m R}{1 + 2g_m R_{EE}} = -0.00499$$

$$CMRR \cong 2g_m R_{EE} \left[\frac{\Delta g_m}{g_m} \right]^{-1} = 60000 \text{ or } 95.6 \text{ dB}$$

Note for Problems 15.22 - 15.37

The MATLAB m-file listed below 'FET Bias' can be used to help find the drain currents in the FET circuits in Problems 15.22 - 15.37. Use fzero('FET Bias',0) to find I_D

```
function f=bias(id)
kn=4e-4; vto=1; gamma=0.0;
rss=62e3; vss=15;
vsb=2*id*rss;
vtn=vto+gamma*(sqrt(vsb+0.6)-sqrt(0.6));
f=vss-vtn-sqrt(2*id/kn)-vsb;
```

15.22

This solution made use of the m-file above. The solution to Problem 15.23 gives an example of direct hand calculation.

$$2I_s = \frac{12 - V_{GS}}{220k\Omega} \Rightarrow 2 \frac{K_n}{2} (V_{GS} - V_{TN})^2 = \frac{12 - V_{GS}}{220k\Omega} \text{ and for } K_n = 400 \frac{\mu A}{V^2} \text{ and } V_{TN} = 1V$$

$$12 - V_{GS} = 88(V_{GS}^2 - 2V_{GS} + 1) \text{ or } 88V_{GS}^2 - 175V_{GS} + 76 = 0 \text{ and } V_{GS} = 1.348V$$

$$I_D = I_s = \frac{1}{2} \left(\frac{12 - 1.35}{220k\Omega} \right) = 24.2 \mu A. \quad V_D = 12 - 3.3 \times 10^5 (I_D) = 4.01V$$

$$V_{DS} = 4.01 - (-V_{GS}) = 5.36V \quad (> V_{GS} - V_{TN}) \quad Q\text{-Point} = (24.2 \mu A, 5.36V)$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(24.2 \times 10^{-6})}{0.348} = 1.39mS \quad | \quad A_{dd} = -g_m R_D = -1.39ms(330k\Omega) = -45.9$$

$$A_{cc} = -\frac{g_m R_D}{1 + 2g_m R_{SS}} = \frac{1.39ms(330k\Omega)}{1 + 2(1.39ms)(220k\Omega)} = -0.738$$

For a differential output : $A_{dn} = A_{dd} = -45.9 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$

For a single - ended output : $A_{dm} = \frac{A_{dd}}{2} = -23.0 \quad | \quad A_{cm} = A_{cc} = -0.738$

$$CMRR = \frac{23.0}{0.738} = 31.2 \quad | \quad CMRR_{db} = 29.8 dB \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$$

15.23

$$V_{SS} - V_{GS} = 2I_D R_{SS} \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} \quad | \quad V_{SS} = 2I_D R_{SS} + V_{TN} + \sqrt{\frac{2I_D}{K_n}}$$

$$15 = 2I_{SS}(62 \times 10^3) + 1 + \sqrt{\frac{2I_D}{4 \times 10^{-4}}} \rightarrow I_D = 107 \mu A \quad | \quad V_{GS} - V_{TN} = 0.731V$$

$$V_{DS} = 15 - (62k\Omega)I_D - (-V_{GS}) = 10.1V > 0.731V - \text{Active} \quad | \quad Q\text{-pt: } (107 \mu A, 10.1V)$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(107 \mu A)}{0.731V} = 0.293mS \quad | \quad A_{dd} = -g_m R_D = -(0.293mS)(62k\Omega) = -18.2$$

$$A_{cc} = -\frac{g_m R_D}{1 + 2g_m R_{SS}} = -\frac{(0.293mS)(62k\Omega)}{1 + 2(0.293mS)(62k\Omega)} = -0.487$$

For a differential output : $A_{dn} = A_{dd} = -18.2 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$

For a single - ended output : $A_{dm} = \frac{A_{dd}}{2} = -9.10 \quad | \quad A_{cm} = A_{cc} = -0.487$

$$CMRR = \frac{9.10}{0.487} = 18.7 \quad | \quad CMRR_{db} = 25.4 dB \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$$

15.24

*Problem 15.24 - Figure P15.22

VCC 2 0 DC 12

VEE 1 0 DC -12

VIC 8 0 DC 0

VID1 4 8 AC 0.5

VID2 6 8 AC -0.5

RD1 2 3 330K

RD2 2 7 330K

M1 3 4 5 5 NFET

M2 7 6 5 5 NFET

REE 5 1 220K

.MODEL NFET NMOS KP=400U VTO=1

.OP

.AC LIN 1 1KHZ 1KHZ

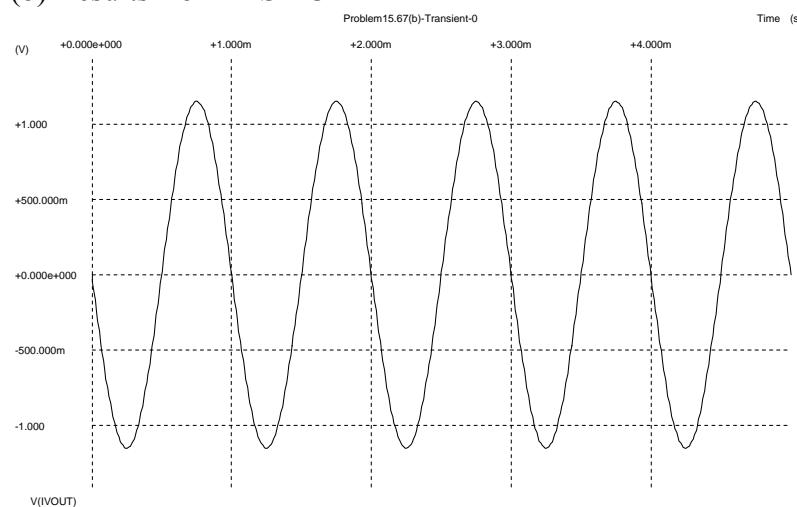
.PRINT AC IM(VID1) IP(VID1) VM(3,7) VP(3,7)

.TF V(7) VIC

.END

Results : $A_{dd} = VM(3,7) = -45.9$ | $A_{cc} = -0.738$ | $CMRR = 31.2$ | $R_{id} = \infty$ | $R_{ic} = \infty$

(b) Results from B²SPICE



Problem 15.24(b)-Fourier-Table

FREQ	mag	phase	norm_mag	norm_phase
+0.000	-4.011	+0.000	+0.000	+0.000
+1.000k	+586.074m	+180.000	+1.000	+0.000e+000
+2.000k	+82.747u	-90.000	+141.188u	-270.000
+3.000k	+90.858u	+179.996	+155.029u	-3.577m
+4.000k	+14.251n	+93.958	+24.316n	-86.042
+5.000k	+9.695n	+53.059	+16.541n	-126.941

THD = 0.021% is very low due to the Level-1 square law model used in the simulation

15.25

First, we should check our rule - of - thumb. Since we have symmetric power supplies, $A_{dd} \cong V_{DD} + V_{SS} = 10$ or 20 dB. We should be ok.

$$R_{od} = 2R_D = 5k\Omega \rightarrow R_D = 2.5k\Omega \quad | \quad \text{Selecting closest 5% value: } R_D = 2.4k\Omega$$

$$A_{dd} = -g_m R_D = 10^{\frac{20}{20}} = 10 \quad | \quad g_m = \frac{10}{2400} = 4.17mS = \sqrt{2K_n I_D}$$

$$I_D = \frac{(4.17 \times 10^{-3})^2}{2(25 \times 10^{-3})} = 348 \mu A \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = 1.16V$$

$$R_{ss} = \frac{V_{ss} - V_{GS}}{2I_D} = \frac{5 - 1.16}{2(348 \mu A)} = 5.52k\Omega \quad | \quad \text{Selecting closest 5% value: } R_{ss} = 5.6k\Omega$$

15.26

(a) This solution made use of the m - file listed above Prob. 15.22.

$$V_{ss} - V_{GS} = 2I_S R_{ss} = 2I_D R_{ss} \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} \quad | \quad V_{ss} = 2I_D R_{ss} + V_{TN} + \sqrt{\frac{2I_D}{K_n}}$$

$$V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB} + 0.6} - \sqrt{0.6}) = V_{TO} + \gamma(\sqrt{2I_D R_{ss} + 0.6} - \sqrt{0.6})$$

Solving iteratively with $R_{ss} = 62k\Omega$ | $K_n = 400 \frac{\mu A}{V^2}$ | $V_{TO} = 1V$ | $\gamma = 0.75\sqrt{V}$ yields

$$I_D = 91.3 \mu A \quad | \quad V_{GS} - V_{TN} = 0.676V \quad | \quad V_{TN} = 3.01V \quad | \quad V_{GS} = 3.69V$$

$$V_{DS} = 15 - (62k\Omega)I_D - (-V_{GS}) = 12.9V > 0.676V - \text{Saturated} \quad | \quad \text{Q-pt: } (91.3 \mu A, 12.9V)$$

$$(b) g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(91.3 \mu A)}{0.676V} = 0.270mS \quad | \quad A_{dd} = -g_m R_D = -(0.270mS)(62k\Omega) = -16.7$$

$$A_{cc} = -\frac{g_m R_D}{1 + 2g_m(1 + \eta)R_{ss}} = -\frac{(0.270mS)(62k\Omega)}{1 + 2(0.270mS)(62k\Omega)} = -0.486 \quad \text{assuming } \eta = 0$$

For a differential output: $A_{dm} = A_{dd} = -16.7$ | $A_{cm} = 0$ | $CMRR = \infty$

For a single - ended output: $A_{dm} = \frac{A_{dd}}{2} = -8.35$ | $A_{cm} = A_{cc} = -0.486$

$$CMRR = \frac{8.35}{0.486} = 17.2 \quad | \quad CMRR_{db} = 24.7 \text{ dB} \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$$

$$(c) \text{For } \gamma = 0, V_{TN} = V_{TO} \quad | \quad V_{ss} = 2I_D R_{ss} + V_{TO} + \sqrt{\frac{2I_D}{K_n}} \quad | \quad 15 = 124000I_D + 1 + \sqrt{\frac{2I_D}{4 \times 10^{-4}}}$$

$$I_D = 107 \mu A \quad V_{DS} = 30 - 62000I_D - 128000I_S = 10.1V \quad \text{Saturated} \quad | \quad \text{Q-pt: } (107 \mu A, 10.1V)$$

15.27

*Problem 15.27 - Figure P15.26

VCC 2 0 DC 15

VEE 1 0 DC -15

VIC 8 0 DC 0

VID1 4 8 AC 0.5

VID2 6 8 AC -0.5

RD1 2 3 62K

RD2 2 7 62K

M1 3 4 5 1 NFET

M2 7 6 5 1 NFET

REE 5 1 62K

.MODEL NFET NMOS KP=400U VTO=1 PHI=0.6 GAMMA=0.75

.OP

.AC LIN 1 1KHZ 1KHZ

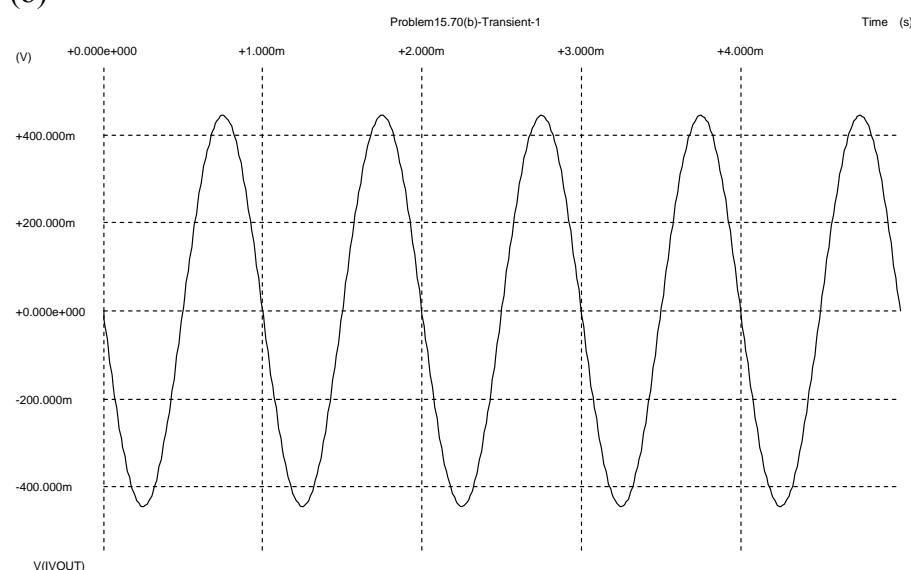
.PRINT AC IM(VID1) IP(VID1) VM(3,7) VP(3,7)

.TF V(7) VIC

.END

Results: $A_{dd} = VM(3,7) = -16.8$ | $A_{cc} = -0.439$ | $CMRR_{dB} = 25.6 \text{ dB}$ | $R_{id} = \infty$ | $R_{ic} = \infty$

(b)



Problem15.27(b)-Fourier-Table

THD = 0.0034%

FREQ	mag	phase	norm_mag	norm_phase
+0.000	-345.019n	+0.000	+0.000	+0.000
+1.000k	+444.350m	+180.0	+1.000	+0.000
+2.000k	+35.476n	-30.192	+79.838n	-210.192
+3.000k	+15.056u	-179.929	+33.884u	-359.929
+4.000k	+23.789n	-50.644	+53.536n	-230.643
+5.000k	+22.342n	-57.083	+50.280n	-237.083

15.28

This solution made use of the m - file listed above Prob. 15.22.

$$(a) V_{SS} - V_{GS} = 2I_S R_{SS} = 2I_D R_{SS} \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} \quad | \quad V_{SS} = 2I_D R_{SS} + V_{TN} + \sqrt{\frac{2I_D}{K_n}}$$

$$V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB} + 0.6} - \sqrt{0.6}) = V_{TO} + \gamma(\sqrt{2I_D R_{SS} + 0.6} - \sqrt{0.6})$$

Solving iteratively with $R_{SS} = 220k\Omega$ | $K_n = 400 \frac{\mu A}{V^2}$ | $V_{TO} = 1V$ | $\gamma = 0.75\sqrt{V}$ yields

$$I_D = 20.3\mu A \quad | \quad V_{GS} - V_{TN} = 0.319V \quad | \quad V_{TN} = 2.74V \quad | \quad V_{GS} = 3.05V$$

$$V_{DS} = 12 - (330k\Omega)I_D - (-V_{GS}) = 8.35V > 0.319V - \text{Active region} \quad | \quad \text{Q-pt: } (20.3\mu A, 8.35V)$$

$$(b) g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(20.3\mu A)}{0.319V} = 0.127mS \quad | \quad A_{dd} = -g_m R_D = -(0.127mS)(330k\Omega) = -41.9$$

$$A_{cc} = -\frac{g_m R_D}{1 + 2g_m(1 + \eta)R_{SS}} = -\frac{(0.127mS)(330k\Omega)}{1 + 2(0.127mS)(220k\Omega)} = -0.737 \quad \text{assuming } \eta = 0$$

For a differential output : $A_{dm} = A_{dd} = -41.9 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$

For a single - ended output : $A_{dm} = \frac{A_{dd}}{2} = -21.0 \quad | \quad A_{cm} = A_{cc} = -0.737$

$$CMRR = \frac{21.0}{0.737} = 28.4 \quad | \quad CMRR_{db} = 29.1 dB \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$$

$$(c) \text{For } \gamma = 0, V_{TN} = V_{TO} \quad | \quad V_{SS} = 2I_D R_{SS} + V_{TO} + \sqrt{\frac{2I_D}{K_n}} \quad | \quad 12 = 440000I_D + 1 + \sqrt{\frac{2I_D}{4 \times 10^{-4}}}$$

$$I_D = 24.2 \mu A \quad V_{DS} = 24 - 330000I_D - 440000I_S = 5.37 V \quad \text{Saturated} \quad | \quad \text{Q-pt: } (25.2 \mu A, 5.37 V)$$

15.29

$$(a) I_D = \frac{I_{SS}}{2} = 20\mu A \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = 1 + \sqrt{\frac{2(2 \times 10^{-5})}{4 \times 10^{-4}}} = 1.316V \quad | \quad V_{GS} - V_{TN} = 0.316V$$

$$V_{DS} = 9 - (300k\Omega)I_D - (-V_{GS}) = 4.32V > 0.316V - \text{Active region} \quad | \quad \text{Q-pt: } (20\mu A, 4.32V)$$

$$(b) g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(20\mu A)}{0.316V} = 0.127mS \quad | \quad A_{dd} = -g_m R_D = -(0.127mS)(300k\Omega) = -38.0$$

$$A_{cc} = -\frac{g_m R_D}{1 + 2g_m R_{SS}} = -\frac{(0.127mS)(300k\Omega)}{1 + 2(0.127mS)(1.25M\Omega)} = -0.120$$

For a differential output : $A_{dm} = A_{dd} = -38.0 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$

For a single - ended output : $A_{dm} = \frac{A_{dd}}{2} = -19.0 \quad | \quad A_{cm} = A_{cc} = -0.120$

$$CMRR = \frac{19.0}{0.120} = 158 \quad | \quad CMRR_{db} = 44.0 dB \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$$

15.30

$$(a) I_D = \frac{I_{SS}}{2} = 150\mu A \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = 1 + \sqrt{\frac{2(1.5 \times 10^{-4})}{4 \times 10^{-4}}} = 1.866V \quad | \quad V_{GS} - V_{TN} = 0.866V$$

$$V_{DS} = 15 - (75k\Omega)I_D - (-V_{GS}) = 5.62V > 0.866V \text{ - Active region} \quad | \quad \text{Q-pt: } (150\mu A, 5.62V)$$

$$(b) g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(150\mu A)}{0.866V} = 0.346mS \quad | \quad A_{dd} = -g_m R_D = -(0.346mS)(75k\Omega) = -26.0$$

$$A_{cc} = -\frac{g_m R_D}{1 + 2g_m R_{SS}} = -\frac{(0.346mS)(75k\Omega)}{1 + 2(0.346mS)(160k\Omega)} = -0.232$$

For a differential output : $A_{dm} = A_{dd} = -26.0 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$

For a single-ended output : $A_{dm} = \frac{A_{dd}}{2} = -13.0 \quad | \quad A_{cm} = A_{cc} = -0.232$

$$CMRR = \frac{13.0}{0.232} = 56.0 \quad | \quad CMRR_{db} = 35.0 \text{ dB} \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$$

15.31

$$(a) I_D = \frac{I_{SS}}{2} = 20\mu A \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = V_{TN} + \sqrt{\frac{2(2 \times 10^{-5})}{4 \times 10^{-4}}} = V_{TN} + 0.316V$$

$$V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB} + 0.6} - \sqrt{0.6}) = 1 + 0.75(\sqrt{9 - V_{GS} + 0.6} - \sqrt{0.6})$$

$$V_{GS} - 0.316 = 1 + 0.75(\sqrt{9 - V_{GS} + 0.6} - \sqrt{0.6}) \rightarrow V_{GS} = 2.71V \quad | \quad V_{TN} = 2.39V$$

$$V_{DS} = 9 - (300k\Omega)I_{DS} - (-V_{GS}) = 5.71V > 0.316V \text{ - Active region} \quad | \quad \text{Q-pt: } (20\mu A, 5.71V)$$

$$(b) g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(20\mu A)}{0.316V} = 0.127mS \quad | \quad A_{dd} = -g_m R_D = -(0.127mS)(300k\Omega) = -38.1$$

$$A_{cc} = -\frac{g_m R_D}{1 + 2g_m(1 + \eta)R_{SS}} = -\frac{(0.127mS)(300k\Omega)}{1 + 2(0.127mS)(1.25M\Omega)} = -0.120 \text{ assuming } \eta = 0$$

For a differential output : $A_{dm} = A_{dd} = -38.1 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$

For a single-ended output : $A_{dm} = \frac{A_{dd}}{2} = -19.0 \quad | \quad A_{cm} = A_{cc} = -0.120$

$$CMRR = \frac{19.0}{0.120} = 158 \quad | \quad CMRR_{db} = 44.0 \text{ dB} \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$$

15.32

$$(a) I_D = \frac{I_{SS}}{2} = 150\mu A \quad | \quad V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = V_{TN} + \sqrt{\frac{2(1.5 \times 10^{-4})}{4 \times 10^{-4}}} = V_{TN} + 0.866V$$

$$V_{TN} = V_{TO} + \gamma(\sqrt{V_{SB} + 0.6} - \sqrt{0.6}) = V_{TO} + \gamma(\sqrt{15 - V_{GS} + 0.6} - \sqrt{0.6})$$

$$V_{GS} - 0.866 = 1 + 0.75(\sqrt{15 - V_{GS} + 0.6} - \sqrt{0.6}) \rightarrow V_{GS} = 3.86V \quad | \quad V_{TN} = 2.99V$$

$$V_{DS} = 15 - (75k\Omega)I_{DS} - (-V_{GS}) = 7.61V > 0.866V \text{ - Active region} \quad | \quad Q\text{-pt: } (150\mu A, 7.61V)$$

$$(b) g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(150\mu A)}{0.866V} = 0.346mS \quad | \quad A_{dd} = -g_m R_D = -(0.346mS)(75k\Omega) = -26.0$$

$$A_{cc} = -\frac{g_m R_D}{1 + 2g_m(1 + \eta)R_{SS}} = -\frac{(0.346mS)(75k\Omega)}{1 + 2(0.346mS)(160k\Omega)} = -0.233 \text{ assuming } \eta = 0$$

For a differential output: $A_{dm} = A_{dd} = -26.0 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$

For a single-ended output: $A_{dm} = \frac{A_{dd}}{2} = -13.0 \quad | \quad A_{cm} = A_{cc} = -0.233$

$$CMRR = \frac{13.0}{0.233} = 55.8 \quad | \quad CMRR_{db} = 34.9 dB \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$$

15.33

$$A_{dd} = -g_m R_D = 10^{\frac{30}{20}} = 31.6 \quad | \quad \text{First, we should check our rule-of-thumb.}$$

Since we have symmetric power supplies, $A_{dd} \approx (V_{DD} + V_{SS}) = 15$, within a factor of about 2.

We should be ok if we reduce the value of $V_{GS} - V_{TN}$. (Remember, our rule-of-thumb

$$\text{used } V_{GS} - V_{TN} = 1V. \quad | \quad g_m R_D = 31.6 = \frac{2I_D R_D}{V_{GS} - V_{TN}}$$

Maximum common-mode range requires minimum $I_D R_D \Rightarrow$ minimum $V_{GS} - V_{TN}$

Choosing $V_{GS} - V_{TN} = 0.25V$ to insure strong inversion operation,

$$I_D R_D = \frac{0.25(31.6)}{2} = 3.95V \quad | \quad 0.25V = \sqrt{\frac{2I_D}{K_n}} \rightarrow I_D = \frac{(0.25)^2(0.005)}{2} = 156\mu A$$

$$I_{SS} = 2I_D = 312 \mu A \quad | \quad R_D = \frac{3.95V}{156\mu A} = 25.3k\Omega \rightarrow 27k\Omega, \text{ the nearest 5% value.}$$

15.34

$$(a) I_D = \frac{1}{2} \left(\frac{18 - V_{GS}}{56k\Omega} \right) \Rightarrow \frac{K_p}{2} (V_{GS} - V_{TP})^2 = \frac{18 + V_{GS}}{112k\Omega} \text{ and for } K_p = 200 \frac{\mu A}{V^2} \text{ and } V_{TP} = -1V$$

$$18 + V_{GS} = 11.2(V_{GS} + 1)^2 \rightarrow V_{GS} = -2.19V \quad | \quad V_{GS} - V_{TP} = -1.19V \quad | \quad I_D = 142\mu A$$

$$V_{DS} = -\left\{ V_{GS} - [91k\Omega]I_D - 18 \right\} = -7.27V \leq -1.19V \quad - \text{ Active region} \quad | \quad \text{Q-Point} = (142\mu A, 7.27V)$$

$$(b) g_m = \sqrt{2(2 \times 10^{-4})(1.42 \times 10^{-4})} = 0.238mS \quad | \quad A_{dd} = -g_m R_D = -0.238mS(91k\Omega) = -21.7$$

$$A_{cc} = -\frac{g_m R_D}{1 + 2g_m R_{SS}} = \frac{0.238mS(91k\Omega)}{1 + 2(0.238mS)(56k\Omega)} = -0.785$$

For a differential output: $A_{dm} = A_{dd} = -21.7 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$

For a single-ended output: $A_{dm} = \frac{A_{dd}}{2} = -10.9 \quad | \quad A_{cm} = A_{cc} = -0.785$

$$CMRR = \frac{10.9}{0.785} = 13.9 \quad | \quad CMRR_{db} = 22.9 \text{ dB} \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$$

15.35

*Problem 15.35 – Figure P15.34

VCC 2 0 DC 18

VEE 1 0 DC -18

VIC 8 0 DC 0

V1 4 8 AC 0.5

V2 6 8 AC -0.5

RD1 5 1 91K

RD2 7 1 91K

M1 5 4 3 3 PFET

M2 7 6 3 3 PFET

REE 2 3 56K

.MODEL PFET PMOS KP=200U VTO=-1

.OP

.AC LIN 1 3KHZ 3KHZ

.PRINT AC IM(V1) IP(V1) VM(5,7) VP(5,7)

.TF V(7) VIC

.END

Results: $A_{dd} = VM(5,7) = -21.6 \quad | \quad A_{cc} = -0.783 \quad | \quad CMRR = 13.8 \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$

15.36

$$(a) I_D = \frac{I_{ss}}{2} = 20\mu A \quad | \quad V_{GS} = V_{TP} - \sqrt{\frac{2I_D}{K_p}} = V_{TP} - \sqrt{\frac{2(2 \times 10^{-5})}{2 \times 10^{-4}}} = V_{TP} - 0.447V$$

$$V_{TP} = -\left\{ V_{TO} - \gamma \left(\sqrt{V_{BS} + 0.6} - \sqrt{0.6} \right) \right\} = -1 - 0.6 \left(\sqrt{10 + V_{GS} + 0.6} - \sqrt{0.6} \right)$$

$$V_{GS} = -0.447 - \left\{ + 0.6 \left(\sqrt{10.6 + V_{GS}} - \sqrt{0.6} \right) \right\} \rightarrow V_{GS} = -2.67V \quad | \quad V_{TP} = -2.23V$$

$$V_{DS} = V_{GS} + [-10 + (300k\Omega)I_D] = -6.67V \leq -0.447V \text{ - Active region} \quad | \quad \text{Q-pt: } (20\mu A, -6.67V)$$

$$(b) g_m = \sqrt{2(2 \times 10^{-5})(2 \times 10^{-4})} = 89.4\mu S \quad | \quad A_{dd} = -g_m R_D = -(89.4\mu S)(300k\Omega) = -26.8$$

$$A_{cc} = -\frac{g_m R_D}{1 + 2g_m(1 + \eta)R_{SS}} = -\frac{(89.4\mu S)(300k\Omega)}{1 + 2(89.4\mu S)(1.25M\Omega)} = -0.119 \text{ assuming } \eta = 0$$

For a differential output: $A_{dm} = A_{dd} = -26.8 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$

For a single-ended output: $A_{dm} = \frac{A_{dd}}{2} = -13.4 \quad | \quad A_{cm} = A_{cc} = -0.119$

$$CMRR = \frac{13.4}{0.119} = 113 \quad | \quad CMRR_{db} = 41.0 \text{ dB} \quad | \quad R_{id} = \infty \quad | \quad R_{ic} = \infty$$

15.37

$$(a) I_D = \frac{I_{ss}}{2} = 10\mu A \quad | \quad V_o = -12 + (820k\Omega)V_I = -3.80V \quad | \quad \text{For } v_I = 0, v_o = V_o = -3.80 \text{ V}$$

$$V_{GS} = V_{TP} + \sqrt{\frac{2I_D}{K_p}} = 1 - \sqrt{\frac{2(10^{-5})}{10^{-3}}} = 0.86 \text{ V} \quad | \quad V_{GS} - V_p = -0.14V$$

$V_{DS} \leq -0.14V$ for pinchoff. So $V_D \leq -1 \text{ V}$ for pinchoff.

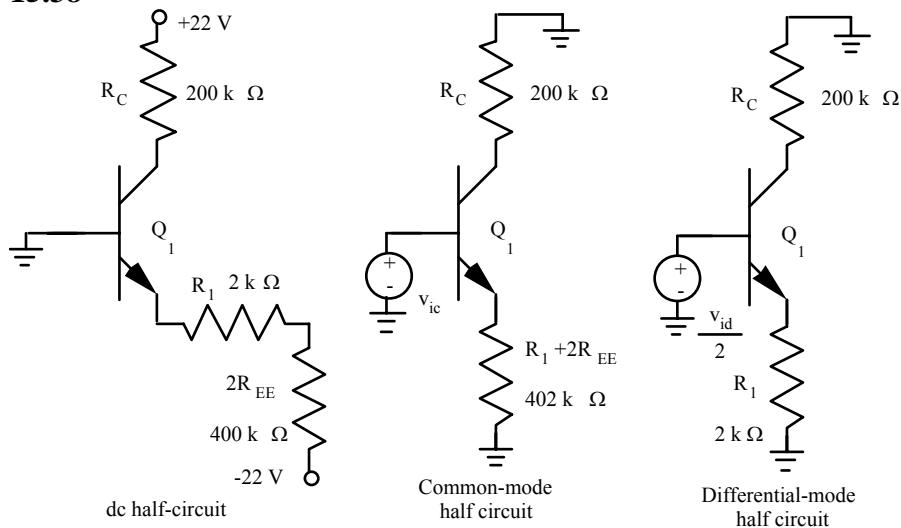
$$g_m = \sqrt{2(1mA)(10\mu A)} = 141\mu S \quad | \quad A_{dd} = -g_m R_D = -(141\mu S)(820k\Omega) = -116$$

$$A_{cc} = 0 \text{ for } R_{SS} \text{ and } r_o = \infty \quad | \quad v_o = V_o - \frac{A_{dd}}{2}v_1 = -3.80 + \frac{116.0}{2}(0.02) = -2.64V$$

$$(b) \frac{v_1}{2} \leq 0.2|V_{GS} - V_p| = 0.2(0.14) = 28.0mV \quad | \quad v_1 \leq 56 \text{ mV based upon the small-signal limit}$$

$$\text{Also } v_o \leq -1 \text{ V for pinchoff. } -1 \leq -3.80 + \frac{116.0}{2}v_1 \rightarrow v_1 = 48.3 \text{ mV} \quad | \quad \text{So, } v_1 \leq 48.3 \text{ mV}$$

15.38



(a)

$$(b) I_C = \alpha_F I_E = \frac{150}{151} \frac{22 - 0.7}{402k\Omega} = 52.6 \mu A \quad | \quad V_{CE} = 22 - (200k\Omega)I_C - (-0.7) = 12.2 V$$

$$Q-Point = (52.6\mu A, 12.2V) \text{ for both transistors} \quad | \quad r_\pi = \frac{150(0.025V)}{52.6\mu A} = 71.3k\Omega$$

$$A_{cc} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)(R_I + 2R_{EE})} = -\frac{150(200k\Omega)}{71.3k\Omega + (151)402k\Omega} = -0.494$$

$$A_{dd} = -\frac{\beta_o R_C}{r_\pi + (\beta_o + 1)R_I} = -\frac{150(200k\Omega)}{71.3k\Omega + (151)2k\Omega} = -80.4$$

$$R_{id} = 2[r_\pi + (\beta_o + 1)R_I] = 2[71.3k\Omega + (151)2k\Omega] = 747 k\Omega$$

$$\text{Note also: } R_{ic} = 0.5[r_\pi + (\beta_o + 1)(R_I + 2R_{EE})] = 0.5[71.3k\Omega + (151)(402k\Omega)] = 30 M\Omega$$

$$\text{and single-ended CMRR} = \frac{40.2}{0.494} = 81.4, \text{ a paltry } 38.2 \text{ dB}$$

15.39

*Problem 15.39 – Figure P15.38

VCC 2 0 DC 22

VEE 1 0 DC -22

VIC 10 0 DC 0

V1 4 10 AC 0.5

V2 8 10 AC -0.5

RC1 2 5 200K

RC2 2 9 200K

Q1 5 4 3 NBJT

Q2 9 8 7 NBJT

RE1 3 6 2K

RE2 7 6 2K

REE 6 1 200K

.MODEL NBJT NPN BF=150

.OP

.AC LIN 1 1KHZ 1KHZ

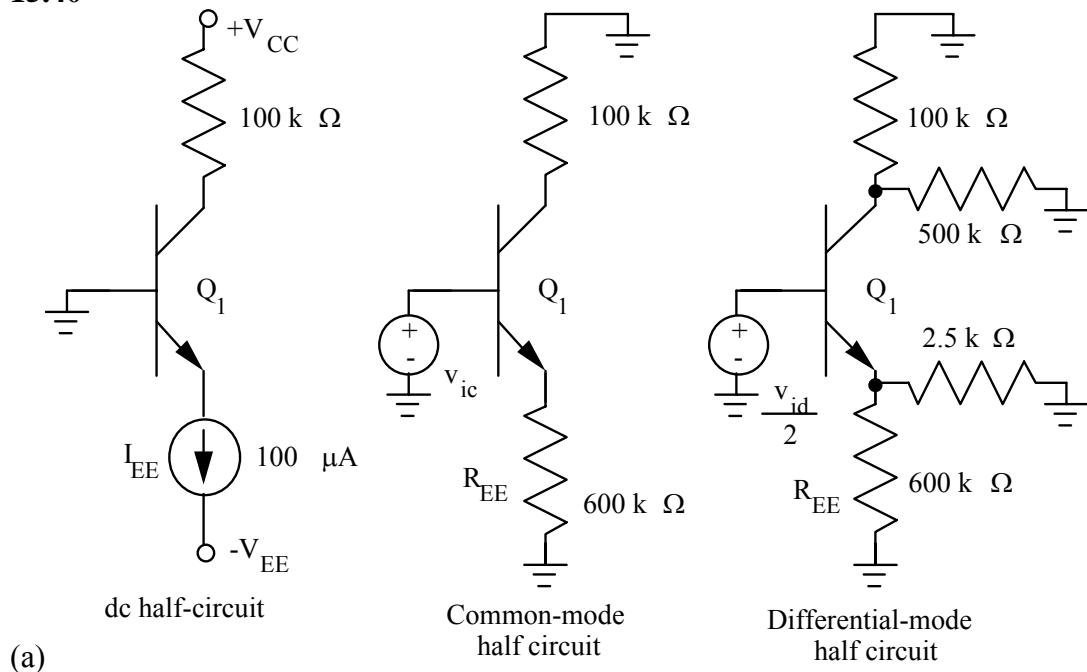
.PRINT AC IM(V1) IP(V1) VM(5,9) VP(5,9)

.TF V(9) VIC

.END

$$\text{Results: } A_{dd} = VM(5,9) = -79.9 \quad | \quad A_{cc} = -0.494 \quad | \quad R_{id} = \frac{1}{IM(V1)} = 751 \text{ k}\Omega$$

15.40



(a)

$$(b) I_C = \alpha_F I_E = \frac{100}{101} (100 \mu\text{A}) = 99.0 \mu\text{A} \quad V_{CE} = 20 - 10^5 I_C - (-0.7) = 10.8 \text{ V}$$

$$Q-\text{Point} = (99.0 \mu\text{A}, 10.8 \text{ V}) \text{ for both transistors} \quad | \quad r_\pi = \frac{100(0.025\text{V})}{99.0 \mu\text{A}} = 25.3 \text{ k}\Omega$$

$$A_{cc} = -\frac{\beta_o R_L'}{r_\pi + (\beta_o + 1)R_{EE}} = -\frac{100k\Omega}{25.3k\Omega + 101(600k\Omega)} = -0.165$$

$$A_{dd} = -\frac{\beta_o R_L}{r_\pi + (\beta_o + 1)R_S} \quad | \quad R_L = 100k\Omega \parallel 500k\Omega = 83.3k\Omega \quad | \quad R_S = 600k\Omega \parallel 2.5k\Omega = 2.49k\Omega$$

$$A_{dd} = -\frac{100(83.3k\Omega)}{25.3k\Omega + 101(2.49k\Omega)} = -30.1 \quad | \quad R_{id} = 2[r_\pi + (\beta_o + 1)R_S] = 2[25.3k\Omega + 101(2.49k\Omega)] = 554k\Omega$$

Note: Single-ended CMRR = $0.5 \left(\frac{30.1}{0.165} \right) = 91.2$ and

$$R_{ic} = 0.5[r_\pi + (\beta_o + 1)R_S] = 0.5[25.3k\Omega + 101(600k\Omega)] = 30.3 M\Omega$$

15.41

*Problem 15.41 – Figure P15.40

VCC 2 0 DC 20

VEE 1 0 DC -20

VIC 9 0 DC 0

V1 4 9 AC 0.5

V2 7 9 AC -0.5

RC1 2 5 100K

RC2 2 8 100K

RL 5 8 1MEG

Q1 5 4 3 NBJT

Q2 8 7 6 NBJT

REE 3 6 5K

IEE1 3 1 67.8U

RE1 3 1 600K

IEE2 6 1 67.8U

RE2 6 1 600K

.MODEL NBJT NPN BF=100

.OP

.AC LIN 1 1KHZ 1KHZ

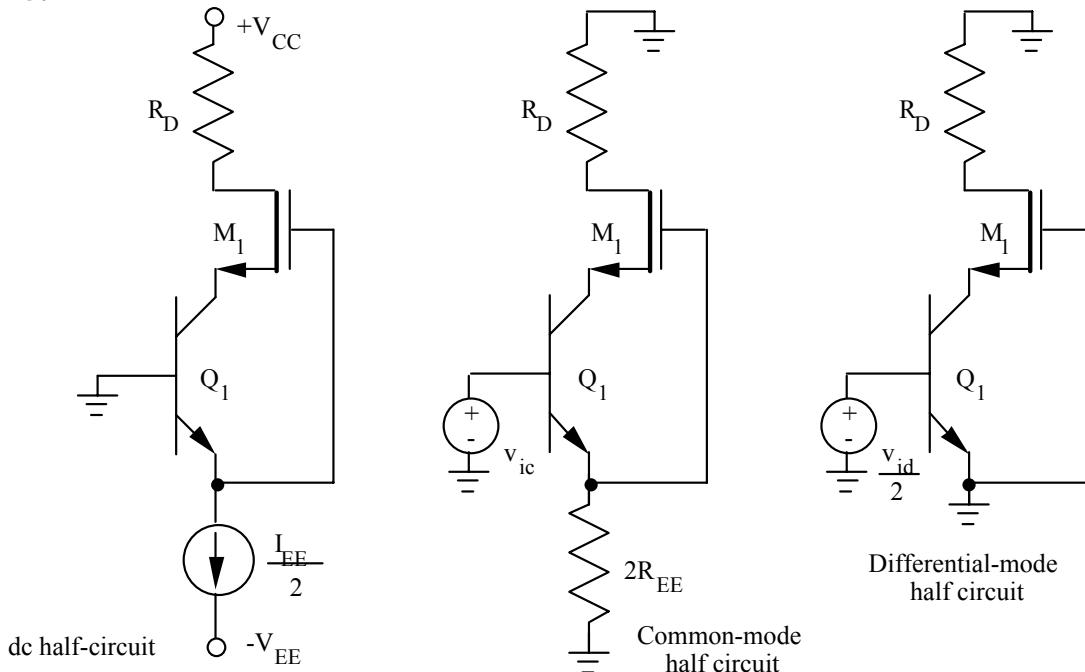
.PRINT AC IM(V1) IP(V1) VM(5,8) VP(5,8)

.TF V(8) VIC

.END

$$\text{Results: } A_{dd} = VM(5,8) = -30.0 \quad | \quad A_{cc} = -0.165 \quad | \quad R_{id} = \frac{1}{IM(V1)} = 555 \text{ k}\Omega$$

15.42



$$(b) I_C = \alpha_F \frac{I_{EE}}{2} = \frac{100}{101} \left(\frac{100\mu A}{2} \right) = 49.5 \mu A \quad | \quad 49.5\mu A = \frac{2 \times 10^{-4}}{2} [V_{GS} - (-4)] \rightarrow V_{GS} = -3.29V$$

$$V_{CE} = -V_{GS} = 3.29V \quad | \quad V_{DS} = 15 - 7.5 \times 10^4 I_C - V_{CE} - (-0.7) = 8.70V$$

BJT Q-Points = (49.5 μ A, 3.29V) | JFET Q-Points = (49.5 μ A, 8.70V)

$$r_\pi = \frac{100(0.025V)}{49.5 \mu A} = 50.5k\Omega \quad | \quad A_{cc} = -\frac{\beta_o R_L}{r_\pi + (\beta_o + 1)(2R_{EE})} = -\frac{100(75k\Omega)}{50.5k\Omega + 101(1.2M\Omega)} = -0.0619$$

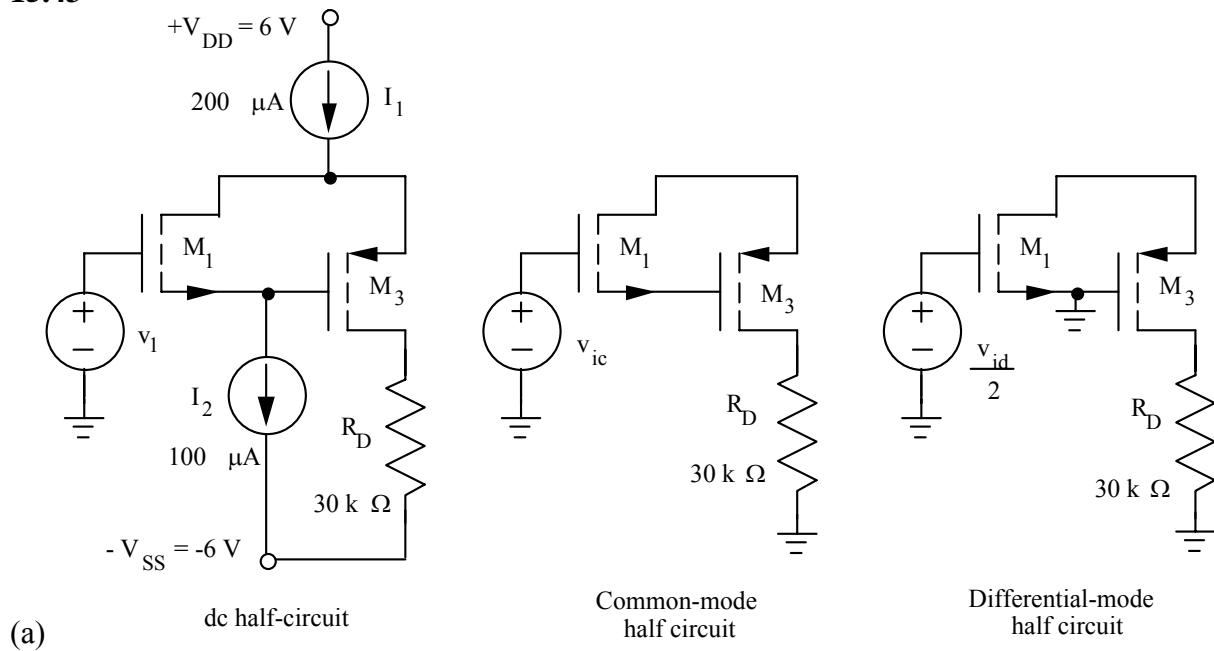
$$A_{dd} = -g_m R_D = -40(49.5\mu A)(75k\Omega) = -149 \quad | \quad R_{id} = 2r_\pi = 101k\Omega$$

Note: Single-ended CMRR = $0.5 \left(\frac{149}{0.0619} \right) = 1200$ or 61.6 dB and

$$R_{ic} = 0.5 [r_\pi + (\beta_o + 1)2R_{EE}] = 0.5 [50.5k\Omega + 101(1.2M\Omega)] = 60.6 M\Omega$$

(c) From (a) $V_{CE} = -V_{GS} = 3.29V \quad | \quad V_{BE} = 0.7V \quad | \quad V_{CE} \geq V_{BE} \rightarrow$ Active-region operation

15.43



(a)

dc half-circuit

Common-mode
half circuit

Differential-mode
half circuit

$$(b) I_{D1} = I_2 = 100 \mu\text{A} \quad | \quad V_{GS1} = V_{TN} + \sqrt{\frac{2I_{D1}}{K_n}} = 1 + \sqrt{2 \frac{10^{-4}}{10^{-3}}} = 1.447 \text{ V} \quad | \quad V_{GS1} - V_{TN} = 0.447 \text{ V}$$

$$I_{D3} = I_1 - I_{D1} = 200 \mu\text{A} - 100 \mu\text{A} = 100 \mu\text{A} \quad | \quad V_{DS1} = -V_{GS3} = 1 + \sqrt{2 \frac{10^{-4}}{5 \times 10^{-4}}} = 1.632 \text{ V}$$

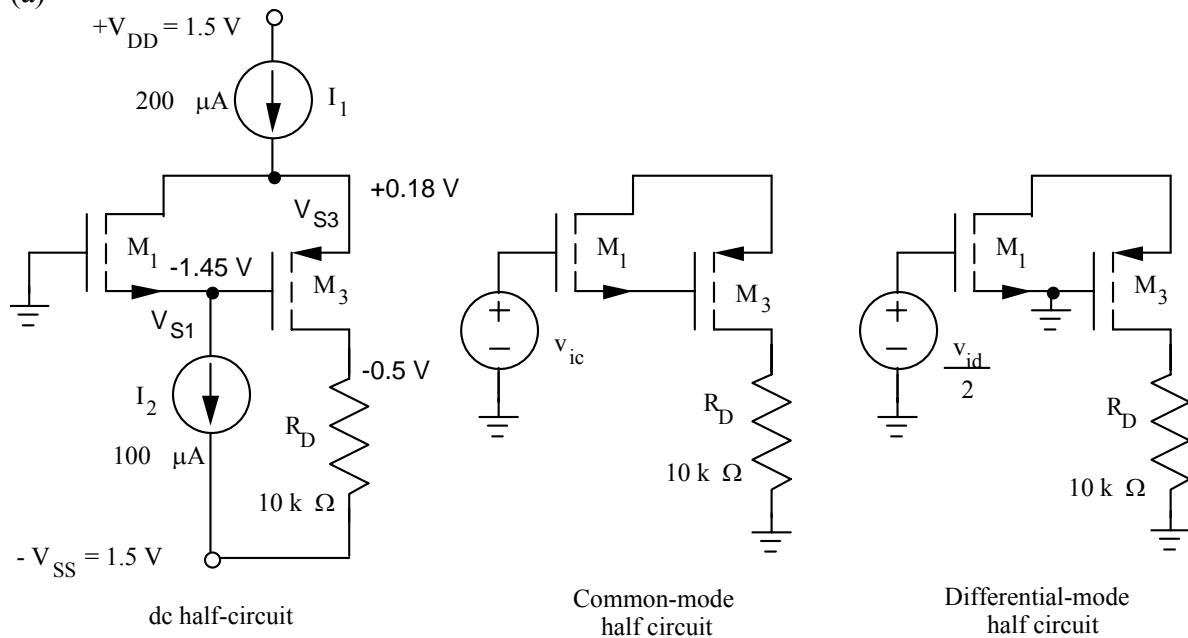
$$V_{GS3} - V_{TP} = -0.632 \text{ V} \quad | \quad V_{DS3} = -[V_{S1} - V_{GS3} - [-6 + (30 \text{ k}\Omega) I_{D3}]] = -(-1.45 + 1.63 + 6 - 3) = -3.18 \text{ V}$$

Both M_1 and M_3 are saturated. Q-points: $M_1 : (100 \mu\text{A}, 1.63 \text{ V})$ $M_3 : (100 \mu\text{A}, -3.18 \text{ V})$

$$A_{dd} = -g_m R_D = -\sqrt{2(10^{-4})(10^{-3})}(30 \text{ k}\Omega) = -13.4 \quad | \quad \text{For } r_o = \infty, A_{cc} = 0 \quad | \quad R_{id} = \infty$$

15.44

(a)



$$(b) I_{D1} = I_2 = 100 \mu\text{A} \quad | \quad V_{GS1} = V_{TN} + \sqrt{\frac{2I_{D1}}{K_n}} = 1 + \sqrt{2 \frac{10^{-4}}{10^{-3}}} = 1.447 \text{ V} \quad | \quad V_{GS1} - V_{TN} = 0.447 \text{ V}$$

$$I_{D3} = I_1 - I_{D1} = 200 \mu\text{A} - 100 \mu\text{A} = 100 \mu\text{A} \quad | \quad V_{DS1} = -V_{GS3} = 1 + \sqrt{2 \frac{10^{-4}}{5 \times 10^{-4}}} = 1.632 \text{ V}$$

$$V_{GS3} - V_{TP} = -0.632 \text{ V} \quad | \quad V_{DS3} = -\left\{ V_{S1} - V_{GS3} - \left[-1.5 + (30 \text{ k}\Omega) I_{D3} \right] \right\} = -(-1.45 + 1.63 + 1.5 - 3) = -1.32 \text{ V}$$

These voltages can barely be supported by the 1.5-V negative power supply.

$V_{S1} = -V_{GS1} = -1.45 \text{ V}$ which is more negative than the -1.5-V supply. Also,

$$V_{S2} = V_{S1} - V_{GS3} = -1.45 \text{ V} + 1.63 = +0.18 \text{ V}, \text{ but for } I_{D3} = 100 \mu\text{A}, V_{D3} = -1.5 + 10^{-4}(10 \text{ k}\Omega) = -0.5 \text{ V}.$$

M_3 is just beyond pinchoff, and current source I_2 has a very small voltage across it.

15.45

$$(a) I_{C1} = \alpha_F \frac{I_1}{2} = \frac{100}{101} \left(\frac{50\mu A}{2} \right) = 24.8 \mu A \quad | \quad V_{CE2} = 12 - V_{EB3} - (-V_{BE2}) = 12 V$$

$$\text{For } V_o = 0 \rightarrow V_{EC3} = 12 V \quad | \quad I_{C3} = \frac{12V}{24k\Omega} = 500 \mu A$$

Q-points: $(24.8 \mu A, 12V)$ $(24.8 \mu A, 12V)$ $(500 \mu A, 12V)$

$$(b) R_{C1} = \frac{0.7V}{24.8\mu A} = 28.2k\Omega \quad | \quad R_{C2} = \frac{V_{EB3}}{I_{C2} - I_{B3}} = \frac{0.7V}{24.8\mu A - 5\mu A} = 35.4k\Omega$$

$$r_{\pi 2} = \frac{100(0.025V)}{24.8\mu A} = 101k\Omega \quad | \quad r_{o2} = \frac{60+12}{24.8\mu A} = 2.90 M\Omega$$

$$r_{\pi 3} = \frac{100(0.025V)}{500\mu A} = 5k\Omega \quad | \quad r_{o3} = \frac{60+12}{500\mu A} = 144k\Omega$$

$$A_{dm} = \frac{g_{m2}}{2} (r_{o2} \| R_{C2} \| r_{\pi 3}) g_{m3} (r_{o3} \| R)$$

$$A_{dm} = \frac{40(24.8\mu A)}{2} (2.90 M\Omega \| 35.4k\Omega \| 5k\Omega) (40) (500\mu A) (144k\Omega \| 24k\Omega) = 893$$

$$R_{id} = 2r_{\pi 2} = 202 k\Omega \quad | \quad (c) R_{out} = r_{o3} \| R = 20.6 k\Omega$$

$$(d) R_{ic} \cong \frac{(\beta_o + 1)r_{o2}}{2} = \frac{(101)2.90 M\Omega}{2} = 147 M\Omega \quad | \quad (e) v_2 \text{ is the non-inverting input}$$

15.46

$$v_{ic} \geq -V_{EE} + 0.75V + V_{BE1} = -12 + 0.7 + 0.75 = -10.6V$$

$$v_{ic} \leq V_{CC} - V_{EB3} = 12 - 0.7 = 11.3V \quad | \quad -10.6 V \leq v_{ic} \leq 11.3 V$$

15.47

Note that the parameters of the transistors and values of R_C have been carefully adjusted to permit open-loop operation and achieve $V_O = 0$.

*Problem 15.47 - Two Stage Amplifier – Figure P15.45

VCC 1 0 DC 12

VEE 2 0 DC -12

RC1 1 5 28.2K

RC2 1 7 33.9K

Q1 5 4 3 NBJT

Q2 7 6 3 NBJT

I1 3 2 DC 50U

Q3 8 7 1 PBJT

R 8 2 24K

V1 4 10 AC 0.5

V2 6 10 AC -0.5

VIC 10 0 DC 0

.MODEL NBJT NPN BF=100 VA=60

.MODEL PBJT PNP BF=100 VA=60 IS=0.288F

.OPTIONS TNOM=17.2

.OP

.AC LIN 1 1KHZ 1KHZ

.TF V(8) VIC

.PRINT AC VM(8) VP(8) IM(V1) IP(V1)

.END

$$A_{dm} = VM(8) = 1030 \quad | \quad A_{cm} = -6.07 \times 10^{-3} \quad | \quad CMRR_{dB} = 105 \text{ dB}$$

Results: $R_{id} = \frac{1}{IM(V1)} = 239 \text{ k}\Omega \quad | \quad R_{out} = 20.6 \text{ k}\Omega$

15.48

$$I_{C1} = \beta_{F1} I_{B1} = \beta_{F1} I_B \quad I_{C2} = \beta_{F2} I_{B2} = \beta_{F2} [(\beta_{F1} + 1) I_B] \cong \beta_{F1} \beta_{F2} I_B$$

$$I_C = I_{C1} + I_{C2} = \beta_{F1} I_{B1} + \beta_{F2} [(\beta_{F1} + 1) I_B] \cong \beta_{F1} \beta_{F2} I_B$$

Assume $\beta_{o2} = \beta_{ol} = \beta_{F2} = \beta_{F1}$

$$g_{ml} = 40 I_{C1} = \beta_{F1} I_B \quad g_{m2} = 40 I_{C2} \cong \beta_{F2} \beta_{F1} I_B \quad g_{m2} = \beta_{o2} g_{ml} = \beta_{ol} g_{ml}$$

$$r_{\pi1} = \frac{\beta_{ol}}{g_{ml}} \quad r_{\pi2} = \frac{\beta_{o2}}{g_{m2}} = \frac{\beta_{ol}}{\beta_{ol} g_{ml}} = \frac{1}{g_{ml}} \quad r_{\pi1} = \beta_{ol} r_{\pi2}$$

$$r_{ol} \cong \frac{V_A}{I_{C1}} = \frac{V_A}{\beta_{F1} I_B} \quad r_{o2} \cong \frac{V_A}{I_{C2}} \cong \frac{V_A}{\beta_{F1} \beta_{F2} I_B} \quad r_{ol} \cong \beta_{o2} r_{o2} = \beta_{ol} r_{o2}$$

$$v_{bel} = v_{be} \frac{r_{\pi1}}{r_{\pi1} + (\beta_{ol} + 1) r_{\pi2}} \cong v_{be} \frac{\beta_{ol} r_{\pi2}}{\beta_{ol} r_{\pi2} + (\beta_{ol} + 1) r_{\pi2}} \cong \frac{v_{be}}{2} \rightarrow v_{be2} \cong \frac{v_{be}}{2}$$

$$G_m v_{be} = g_{ml} v_{bel} + g_{m2} v_{be2} \cong \frac{g_{m2}}{2} v_{be} \rightarrow G_m \cong \frac{g_{m2}}{2}$$

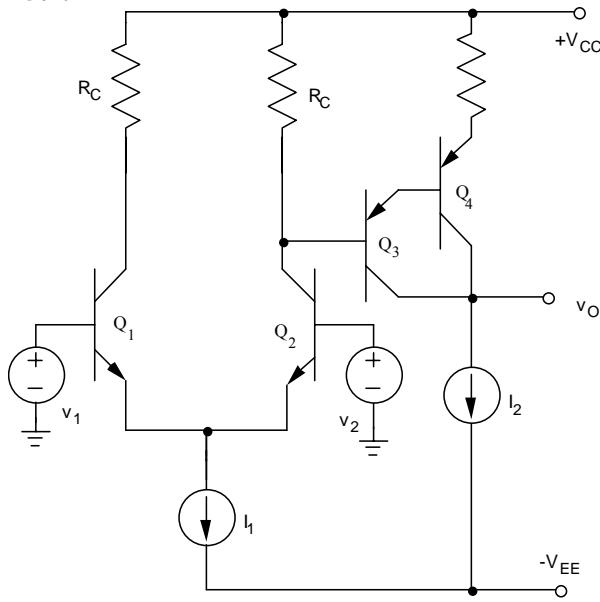
$$R_{iB} = r_{\pi1} + (\beta_{ol} + 1) r_{\pi2} = \beta_{ol} r_{\pi2} + (\beta_{ol} + 1) r_{\pi2} \cong 2 \beta_{ol} r_{\pi2}$$

$$i_c = v_{ce2} \left[\frac{1}{r_{o2}} + \frac{(\beta_{o2} + 1)}{r_{ol} (1 + g_{ml}(r_{\pi2} \| r_{\pi1}))} \right] \cong v_{ce2} \left[\frac{1}{r_{o2}} + \frac{\beta_{o2}}{r_{ol} [1 + g_{ml}(r_{\pi2} \| r_{\pi1})]} \right]$$

$$R_{ic} \cong r_{o2} \left\| \frac{r_{ol} [1 + g_{ml}(r_{\pi2} \| r_{\pi1})]}{\beta_{o2}} \right\| \cong r_{o2} \left\| \frac{r_{ol} [1 + g_{ml}(r_{\pi2})]}{\beta_{o2}} \right\| = r_{o2} \left\| 2 \frac{r_{ol}}{\beta_{o2}} \right\| = r_{o2} \left\| 2 r_{o2} \right\| = \frac{2}{3} r_{o2}$$

Note that $\beta_o = G_m R_{iB} = \beta_{ol} \beta_{o2} \cong \beta_o^2 \quad \mu_f = G_m R_{ic} = \frac{\mu_{f2}}{3}$

15.49



$$(a) I_{C1} = \alpha_F \frac{I_1}{2} = \frac{100}{101} \left(\frac{50\mu A}{2} \right) = 24.8 \mu A \quad | \quad V_{CE2} = V_{CC} - V_{EB3} - V_{EB4} - (-V_{BE2}) = 12 - 0.7 = 11.3 V$$

For $V_O = 0 \rightarrow V_{EC4} = 12 V$ and $V_{EC3} = 12 - 0.7 = 11.3 V$ | For balance, $V_{CE1} = V_{CE2} = 11.3 V$

$$I_{C4} + I_{C3} = I_{C4} + \alpha_{F3} I_{B4} = I_{C4} + \alpha_{F3} \frac{I_{C4}}{\beta_F} = I_{C4} \left(1 + \frac{1}{\beta_F + 1} \right) = \frac{12V}{24k\Omega} \quad | \quad I_{C4} = 495 \mu A \quad | \quad I_{C3} = 4.95 \mu A$$

Q-points : $(24.8 \mu A, 11.3V)$ $(24.8 \mu A, 11.3V)$ $(4.95 \mu A, -11.3V)$ $(495 \mu A, 12V)$

$145 M\Omega$ | (e) v_2 is the non-inverting input

$$(b) R_{C2} = \frac{V_{EB3} + V_{EB4}}{I_{C2} - I_{B3}} = \frac{1.4V}{24.8\mu A - 0.0495\mu A} = 56.6k\Omega \quad | \quad R_{C1} = \frac{1.4V}{24.8\mu A} = 56.5k\Omega$$

$$r_{\pi 2} = \frac{100(0.025V)}{24.8\mu A} = 101k\Omega \quad | \quad r_{o2} = \frac{60 + 11.3}{24.8\mu A} = 2.88 M\Omega \quad | \quad r_{\pi 3} = \frac{100(0.025V)}{4.95\mu A} = 505k\Omega$$

$$r_{o3} = \frac{60 + 11.3}{4.95\mu A} = 14.4 M\Omega \quad | \quad r_{\pi 4} = \frac{100(0.025V)}{495\mu A} = 5.05k\Omega \quad | \quad r_{o4} = \frac{60 + 11.3}{495\mu A} = 144k\Omega$$

$$A_{dm} = \frac{g_{m2}}{2} \left(r_{o2} \parallel R_{C2} \parallel R_{in}^{Darlington} \right) g_m^{Darlington} \left(R_{out}^{Darlington} \parallel R \right) = \frac{g_{m2}}{2} \left(r_{o2} \parallel R_{C2} \parallel 2\beta_o r_{\pi 4} \right) \left(\frac{g_{m4}}{2} \right) \left(\frac{2r_{o4}}{3} \parallel R \right)$$

$$A_{dm} = \frac{40(24.8\mu A)}{2} \left(2.88 M\Omega \parallel 56.6k\Omega \parallel 101k\Omega \right) \frac{(40)(495\mu A)}{2} \left(96k\Omega \parallel 24k\Omega \right) = 9180$$

$$R_{id} = 2r_{\pi 2} = 202 k\Omega \quad | \quad (c) R_{out} = \frac{2r_{o4}}{3} \parallel R = 19.2 k\Omega$$

$$(d) R_{ic} \equiv \frac{(\beta_o + 1)r_{o2}}{2} = \frac{(101)2.88 M\Omega}{2} = 145 M\Omega \quad | \quad (e) v_2 \text{ is the non-inverting input}$$

15.50

$$(a) \text{For } V_o = 0, I_{C3} = \frac{15V}{50k\Omega} = 300\mu A \quad | \quad V_{C2} = 15 - 2400I_{E3} - V_{EB3} = 15 - 0.729 - 0.7 = 13.6V$$

$$I_{C1} = I_{C2} = \alpha_F \left(\frac{200\mu A}{2} \right) = \frac{80}{81} \left(\frac{200\mu A}{2} \right) = 98.8\mu A \quad | \quad I_{B3} = \frac{I_{C3}}{\beta_{F3}} = \frac{300\mu A}{80} = 3.75\mu A$$

$$V_{CE1} = V_{CE2} = 13.6 - (-0.7) = 14.3V \quad | \quad V_{EC3} = 15 - 2400I_{E3} - V_o = 14.3V$$

Q - points : $(98.8\mu A, 14.3V)$ $(98.8\mu A, 14.3V)$ $(300\mu A, 14.3V)$

$$R_C = \frac{15 - 13.6}{(98.8 - 3.75)\mu A} \frac{V}{\mu A} = 15.1k\Omega \quad | \quad r_{\pi 3} = \frac{80(0.025V)}{0.3mA} = 6.67k\Omega$$

$$(b) A_{v1} = \frac{v_{c2}}{v_{id}} = -\left(\frac{g_{ml}}{2} \right) \left[R_C \left[r_{\pi 3} + (\beta_{o3} + 1)R_E \right] \right]$$

$$A_{v1} = -\left(\frac{40(98.8\mu A)}{2} \right) \left[15.1k\Omega \left[(6.67k\Omega + 81(2.4k\Omega)) \right] \right] = -27.7$$

$$A_{v2} = \frac{v_o}{v_{c2}} = -\frac{\beta_{o3}R_L}{r_{\pi 3} + (\beta_{o3} + 1)R_E} = -\frac{80(50k\Omega)}{6.67k\Omega + 81(2.4k\Omega)} = -19.9$$

$$A_v = \frac{v_{c2}}{v_{id}} \frac{v_o}{v_{c2}} = -27.7(-19.9) = 551$$

$$R_{id} = 2r_{\pi 1} = 2 \frac{\beta_{ol}V_T}{I_{C1}} = 2 \frac{80(0.025V)}{98.8\mu A} = 40.5k\Omega \quad | \quad r_{o3} = \frac{70 + 14.3}{0.3mA} = 281k\Omega$$

$$(c) R_{out} = 50k\Omega \left[r_{o3} \left(1 + \frac{\beta_o R_E}{R_C + r_{\pi 3} + R_E} \right) \right] = 50k\Omega \left[281k\Omega \left[1 + \frac{80(2.4k\Omega)}{15.1k\Omega + 6.67k\Omega + 2.4k\Omega} \right] \right] = 49.0k\Omega$$

$$(d) R_{ic} = \frac{(\beta_{ol} + 1)r_{ol}}{2} = \frac{81}{2} \left(\frac{70 + 14.3}{98.8\mu A} \right) = 34.6M\Omega \quad | \quad (e) v_2 \text{ is the non - inverting (+) input.}$$

15.51

$$v_{ic} \geq -V_{EE} + 0.75V + V_{BE1} = -15 + 0.7 + 0.75 = -13.6V \quad | \quad v_{ic} \leq V_{CC} - I_{E3}R_E - V_{EB3}$$

$$\text{From Prob. 15.92, } I_{E3}R_E = \left(\frac{81}{80} \right) \left(\frac{15V}{50k\Omega} \right) (2.4k\Omega) = 0.729V$$

$$v_{ic} \leq 15 - 0.729 - 0.7 = 13.6V \quad | \quad -13.6V \leq v_{ic} \leq 13.6V$$

15.52

$$(a) \text{ For } V_o = 0, I_{C3} = \frac{15V}{50k\Omega} = 300\mu A \quad V_{EC3} = 15 - V_o = 15 - 0 = 15V$$

$$I_{C1} = I_{C2} = \alpha_F \left(\frac{200\mu A}{2} \right) = \frac{80}{81} \left(\frac{200\mu A}{2} \right) = 98.8\mu A \quad I_{B3} = \frac{I_{C3}}{\beta_{F3}} = \frac{300\mu A}{80} = 3.75\mu A$$

$$V_{CE1} = V_{CE2} = 15 - V_{EB3} - (-V_{BE1}) = 15.0V$$

Q-points: $(98.8\mu A, 15.0V)$ $(98.8\mu A, 15.0V)$ $(300\mu A, 15.0V)$

$$R_{C2} = \frac{0.7}{(98.8 - 3.75)} \frac{V}{\mu A} = 7.37k\Omega \quad | \quad \text{For balance, } R_{C1} = \frac{0.7}{98.8} \frac{V}{\mu A} = 7.09k\Omega$$

$$r_{\pi 2} = \frac{80(0.025V)}{98.8\mu A} = 20.2k\Omega \quad | \quad r_{o2} = \frac{70V + 15V}{98.8\mu A} = 860k\Omega$$

$$r_{\pi 3} = \frac{80(0.025V)}{0.3mA} = 6.67k\Omega \quad | \quad r_{o3} = \frac{70V + 15V}{0.3mA} = 283k\Omega$$

15.53

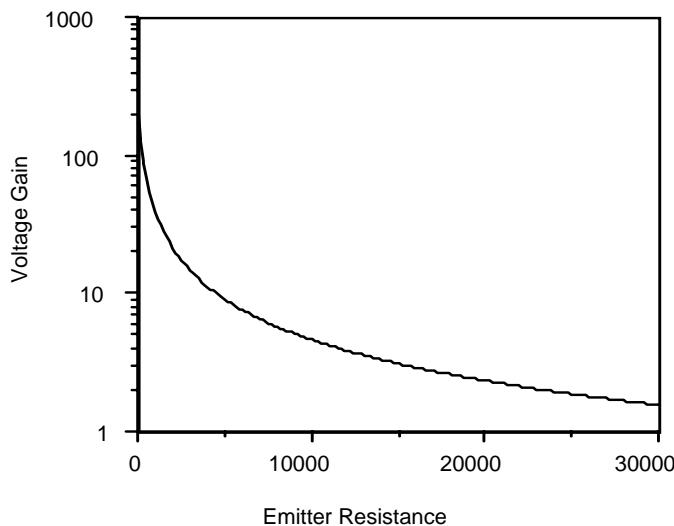
$$\text{For } V_o = 0, I_{C3} = \frac{15V}{50k\Omega} = 300\mu A \quad | \quad I_{B3} = \frac{I_{C3}}{\beta_{F3}} = \frac{300\mu A}{80} = 3.75\mu A \quad | \quad I_{E3} = \frac{81}{80} I_{C3} = 304\mu A$$

$$I_{C1} = I_{C2} = \alpha_F \left(\frac{200\mu A}{2} \right) = \frac{80}{81} \left(\frac{200\mu A}{2} \right) = 98.8\mu A \quad | \quad R_C = \frac{0.7V + I_{E3}R_E}{I_{C1} - I_{B3}} = \frac{0.7V + (304\mu A)R_E}{98.8\mu A - 3.75\mu A}$$

$$V_{C2} = 15 - 2400I_{E3} - V_{EB3} = 15 - 0.729 - 0.7 = 13.6V$$

$$A_{vt1} = -\frac{g_m l}{2} (R_C \| R_{in3}) = -20(98.8\mu A)(R_C \| R_{in3}) = -1.976 \times 10^{-3} (R_C \| R_{in3}) \quad | \quad R_{in3} = r_{\pi 3} + (\beta_o + 1)R_E$$

$$A_{vt2} = -\frac{\beta_o R_L}{r_{\pi 3} + (\beta_o + 1)R_E} \quad | \quad R_L = R \left\| r_{o3} \left(1 + \frac{\beta_o R_E}{R_{th} + r_{\pi 3} + R_E} \right) \right\| \quad | \quad A_v = A_{vt1} A_{vt2}$$



15.54

First, use our gain estimates to check feasibility of the design: $A_v \approx [10(V_{CC} + V_{EE})]^2 = 32,400$

There is plenty of margin available.

$$R_{out} = R \| r_{o3} \quad | \quad \frac{1}{R_{out}} = \frac{1}{R} + \frac{1}{r_{o3}} = \frac{1}{R} + \frac{I_{C3}}{V_A + V_{EC3}} = \frac{1}{R} + \frac{1}{R} \left(\frac{I_{C3} R}{V_A + V_{EC3}} \right) \quad | \quad V_o = 0V$$

$$10^{-3} = \frac{1}{R} \left(1 + \frac{9}{70+9} \right) \rightarrow R = 1.11 \text{ k}\Omega \quad | \quad I_{C3} = \frac{9}{R} = 8.11 \text{ mA} \quad | \quad r_{\pi3} = \frac{100(0.025V)}{8.11 \text{ mA}} = 308 \Omega$$

$$A_{vt2} = -g_m R_{out} = -40(8.11 \text{ mA})(1 \text{ k}\Omega) = -324 \quad | \quad A_{vt1} = \frac{A_v}{A_{vt2}} = \frac{2000}{-324} = -6.165$$

$$A_{vt1} = -\frac{g_m^2}{2} (R_C \| r_{\pi3}) = -20 \frac{I_{C2} R_C r_{\pi3}}{R_C + r_{\pi3}} = -20 \frac{I_{C2} R_C}{\frac{R_C}{r_{\pi3}} + 1} \approx -20 \frac{0.7}{\frac{R_C}{r_{\pi3}} + 1} \quad \text{neglecting } I_{B3}$$

$$-20 \frac{0.7}{\frac{R_C}{308} + 1} = -6.165 \rightarrow R_C = 391 \Omega \quad | \quad I_{C1} = \frac{0.7V}{391 \Omega} + I_{B3} = \frac{0.7V}{391 \Omega} + \frac{8.11 \text{ mA}}{100} = 1.87 \text{ mA}$$

Selecting the closest 5% values: $R = 1.1 \text{ k}\Omega$, $R_C = 390 \Omega$, $I_1 = 3.74 \text{ mA}$

15.55

(a) For $V_o = 0$, $I_{C3} = I_2 = 300\mu A$ $V_{C2} = 15 - 2400I_{E3} - V_{EB3} = 15 - 0.729 - 0.7 = 13.6V$

$$I_{C1} = I_{C2} = \alpha_F \left(\frac{200\mu A}{2} \right) = \frac{80}{81} \left(\frac{200\mu A}{2} \right) = 98.8\mu A \quad | \quad I_{B3} = \frac{I_{C3}}{\beta_{F3}} = \frac{300\mu A}{80} = 3.75\mu A$$

$$V_{CE1} = V_{CE2} = 13.6 - (-0.7) = 14.3V \quad | \quad V_{EC3} = 15 - 2400I_{E3} - V_o = 14.3V$$

Q-points: $(98.8\mu A, 14.3V)$ $(98.8\mu A, 14.3V)$ $(300\mu A, 14.3V)$

$$R_{C2} = \frac{15 - 13.6}{(98.8 - 3.75)\mu A} \frac{V}{\mu A} = 14.7k\Omega \quad | \quad \text{For balance, } R_{C1} = \frac{15 - 13.6}{98.8} \frac{V}{\mu A} = 14.2k\Omega$$

$$r_{\pi^3} = \frac{80(0.025V)}{0.3mA} = 6.67k\Omega \quad | \quad r_{o2} = \frac{80V}{98.8\mu A} = 810k\Omega$$

$$(b) A_{vt1} = \frac{v_{c2}}{v_{id}} = -\left(\frac{g_m}{2}\right) \left\{ R_C \left[2r_{o2} \left[r_{\pi^3} + (\beta_{o3} + 1)R_E \right] \right] \right\}$$

$$A_{vt1} = -\left(\frac{40(98.8\mu A)}{2}\right) \left[15.1k\Omega \left[1.62M\Omega \left[(6.67k\Omega + 81(2.4k\Omega)) \right] \right] \right] = -27.5$$

$$A_{vt2} = \frac{v_o}{v_{c2}} = -\frac{\beta_{o3}R_L}{r_{\pi^3} + (\beta_{o3} + 1)R_E} \quad | \quad R_L = r_{o3} \left(1 + \frac{\beta_o R_E}{R_C [2r_{o2} + r_{\pi^3} + R_E]} \right) \quad | \quad r_{o3} = \frac{70 + 14.3}{300\mu A} = 281k\Omega$$

$$R_L = 281k\Omega \left(1 + \frac{80(2.4k\Omega)}{14.8k\Omega + 6.67k\Omega + 2.4k\Omega} \right) = 2.53M\Omega \quad | \quad A_{vt2} = -\frac{80(2.53M\Omega)}{6.67k\Omega + 81(2.4k\Omega)} = -1010$$

$$A_v = A_{vt1}A_{vt2} = -27.5(-1010) = 27800 \quad | \quad R_{id} = 2r_{\pi^1} = 2 \frac{\beta_o V_T}{I_{C1}} = 2 \frac{80(0.025V)}{98.8\mu A} = 40.5k\Omega$$

$$R_{out} = R_L = 2.51M\Omega$$

15.56

The amplifier has an offset voltage of approximately 3.92 mV. Use this value to force the output to nearly zero. A transfer function analysis then yields

$$A_v = +28,627 \quad R_{out} = 2.868M\Omega \quad R_{in} = +50.051k\Omega$$

These values are similar to the hand calculations in Prob. 15.55. R_{in} and R_{out} are larger because the hand calculations did not adjust the value of current gain based upon the Early voltage.

15.57

$$I_{C1} = I_{C2} = \alpha_F \left(\frac{200\mu A}{2} \right) = \frac{100}{101} \left(\frac{200\mu A}{2} \right) = 99.0\mu A \quad | \quad V_{CE1} = V_{CE2} = 15 - V_{EB3} - (-V_{BE1}) = 15V$$

$$\text{For } V_o = 0, I_{C3} = I_2 = 300\mu A \quad | \quad V_{EC3} = 15 - V_o = 15V$$

Q-points: $(99.0\mu A, 15.0V)$ $(99.0\mu A, 15.0V)$ $(300\mu A, 15.0V)$

15.58

$$A_v = A_{vt1}A_{vt2} \quad | \quad A_{vt1} = -\frac{g_{ml}}{2} \left\{ R_C \left[2r_{o2} \left[r_{\pi3} + (\beta_o + 1)R_E \right] \right] \right\}$$

$$A_{vt2} = -\frac{\beta_o R_{out}}{r_{\pi3} + (\beta_o + 1)R_E} = -\frac{\beta_o}{r_{\pi3} + (\beta_o + 1)R_E} r_{o3} \left[1 + \frac{\beta_o R_E}{(R_C \left[2r_{o2} \right]) + r_{\pi3} + R_E} \right]$$

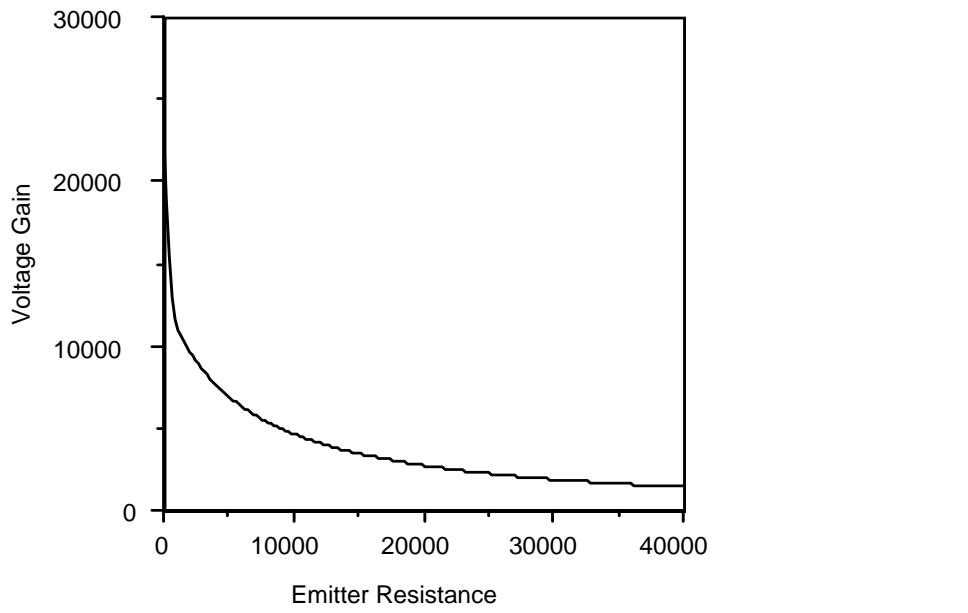
$$I_{C1} = I_{C2} = \alpha_F \frac{I_1}{2} = \frac{80}{81} \frac{200\mu A}{2} = 98.8\mu A \quad | \quad \text{For } V_O = 0, I_{C3} = I_2 = 300\mu A$$

$$I_{B3} = \frac{I_{C3}}{\beta_{F3}} = \frac{300\mu A}{80} = 3.75\mu A \quad | \quad I_{E3} = \frac{81}{80} I_{C3} = 303.8\mu A \quad | \quad V_{EC3} = 15 - I_{E3} R_E$$

$$R_{C2} = \frac{0.7V + I_{E3} R_E}{I_{C1} - I_{B3}} = \frac{0.7V + (303.8\mu A)R_E}{98.8\mu A - 3.75\mu A}$$

$$r_{\pi3} = \frac{80(0.025V)}{300\mu A} = 6.67k\Omega \quad | \quad r_{o3} = \frac{70 + 15 - (303.8\mu A)R_E}{300\mu A}$$

$$g_{ml} = 40(98.8\mu A) = 3.95mS \quad | \quad r_{o2} = \frac{70 + 14.3 - (303.8\mu A)R_E}{98.8\mu A}$$



15.59

$$(a) I_{D2} = \frac{500\mu A}{2} = 250\mu A \quad | \quad V_S = V_{SG} = -V_{TP} + \sqrt{\frac{2I_{D2}}{K_p}} = 1 + \sqrt{\frac{2(2.5 \times 10^{-4})}{5 \times 10^{-3}}} = 1.32V$$

$$V_D = -15 + 0.7 = -14.3V \quad | \quad V_{DS} = V_D - V_S = -14.3 - 1.32 = -15.6V \quad | \quad Q\text{-pt : } (250\mu A, -15.6V)$$

$$I_{C3} = 500\mu A \quad | \quad V_{CE3} = V_{C3} - V_{E3} = 0 - (-15) = 15V \quad | \quad Q\text{-pt : } (500\mu A, 15V)$$

$$R_D = \frac{V_{BE}}{I_{D2} - I_{B3}} = \frac{0.7V}{250\mu A - \frac{500\mu A}{80}} = 2.87k\Omega$$

$$(b) g_{m2} = \sqrt{2(0.005)(0.00025)} = 1.58 \times 10^{-3} S \quad | \quad r_{\pi3} = \frac{80(0.025V)}{0.5mA} = 4k\Omega$$

$$A_v = \frac{v_{d2}}{v_{id}} \frac{v_o}{v_{d2}} = A_{vt1} A_{vt2} \quad | \quad A_{vt1} = -\frac{g_{m2}}{2} (R_D \| r_{\pi3}) = -\frac{1.58mS}{2} (2.87k\Omega \| 4k\Omega) = -1.30$$

$$A_{vt2} = -g_{m3} (r_{o3} \| R_2) = -40(0.5mA) \left(\frac{75V + 15V}{0.5mA} \| 2M\Omega \right) = -0.02(180k\Omega \| 2M\Omega) = -3300$$

$$A_v = -1.30(-3300) = 4300 \quad | \quad R_{in} = \infty \quad | \quad R_{out} = r_{o3} \| R_2 = 180k\Omega \| 2M\Omega = 165k\Omega$$

(c) v_2 is the non-inverting (+) input (d) v_1 is the inverting (-) input

15.60

Note that the parameters of the transistors and values of R_D have been carefully adjusted to permit open-loop operation and achieve $V_O = 0$.

*Problem 15.60 – Figure P15.59

```
VCC 7 0 DC 15
VEE 8 0 DC -15
V1 1 9 AC 0.5
V2 3 9 AC -0.5
VIC 9 0 DC 0
I1 7 2 DC 493.2U
R1 7 2 2MEG
M1 4 1 2 2 PFET
M2 5 3 2 2 PFET
RD1 4 8 2.863K
RD2 5 8 2.863K
Q3 6 5 8 NBJT
I2 7 6 DC 492.5U
R2 7 6 2MEG
.MODEL PFET PMOS KP=5M VTO=-1
.MODEL NBJT NPN BF=80 VA=75 IS=0.2881FA
.OP
.AC LIN 1 1000 1000
.TF V(6) VIC
.PRINT AC IM(V1) IP(V1) VM(6) VP(6)
.OPTIONS TNOM=17.2
.END
```

$$A_{dm} = VM(6) = 4630 \quad | \quad A_{cm} = -1.46 \quad | \quad CMRR_{dB} = 70.0 \text{ dB}$$

Results: $R_{id} = \frac{1}{IM(V1)} = \infty \quad | \quad R_{out} = 164 \text{ k}\Omega$

15.61

$$A_v = \frac{v_{d2} - v_o}{v_{id} - v_{d2}} = A_{vt1} A_{vt2} \quad | \quad A_{vt1} = -\frac{g_{m2}}{2} (R_D \| r_{\pi3}) \quad | \quad I_{C3} = 100 \mu A \quad | \quad r_{\pi3} = \frac{80(0.025V)}{100 \mu A} = 20 \text{ k}\Omega$$

$$I_{D2} = \frac{500 \mu A}{2} = 250 \mu A \quad | \quad g_{m2} = \sqrt{2(0.005)(0.00025)} = 1.58 \times 10^{-3} \text{ S}$$

$$R_D = \frac{V_{BE}}{I_{D2} - I_{B3}} = \frac{0.7V}{250 \mu A - \frac{100 \mu A}{80}} = 2.81 \text{ k}\Omega \quad | \quad A_{vt1} = -\frac{1.58 mS}{2} (2.81 \text{ k}\Omega \| 20 \text{ k}\Omega) = -1.95$$

$$A_{vt2} = -g_{m3} (r_{o3} \| R_2) = -40 (100 \mu A) \left(\frac{75V + 5V}{100 \mu A} \| 10 M\Omega \right) = -0.02 (800 \text{ k}\Omega \| 10 M\Omega) = -2960$$

$$A_v = -1.95 (-2960) = 5770$$

15.62

$$V_{GS2} = V_{TP} - \sqrt{\frac{2I_D}{K_p}} = -1 - \sqrt{\frac{5 \times 10^4}{5 \times 10^3}} = -1.316V$$

For PMOS active region : $V_{DS2} \leq V_{GS2} - V_{TP} = -0.316V$

$$v_{ic} \geq -V_{EE} + V_{BE3} - V_{DS2} + V_{GS2} = -15 + 0.7 + 0.316 - 1.316 = -15.3V$$

$$v_{ic} \leq V_{CC} - 0.75 + V_{GS2} = 15 - 0.75 - 1.316 = 12.9V \quad | \quad -15.3V \leq v_{ic} \leq 12.9V$$

15.63

$$(a) I_{D2} = \frac{500\mu A}{2} = 250\mu A \quad | \quad V_S = -V_{GS} = -V_{TP} + \sqrt{\frac{2I_{D2}}{K_p}} = -1 + \sqrt{\frac{2(2.5 \times 10^{-4})}{5 \times 10^{-3}}} = 1.32V$$

$$V_D = -5 + 0.7 + 0.7 = -3.6V \quad | \quad V_{DS} = V_D - V_S = -3.6 - 1.32 = -4.92V \quad | \quad Q\text{-}pt : (250\mu A, -4.92V)$$

$$I_{C3} + I_{C4} = 500\mu A \quad | \quad I_{C3} + \beta_F I_{E3} = (\beta_F + 2)I_{C3} = 500\mu A \rightarrow I_{C3} = 6.10\mu A \quad | \quad I_{C4} = 494\mu A$$

$$\text{For } V_O = 0, V_{CE4} = 5V \text{ and } V_{CE3} = 5 - 0.7 = 4.30V$$

$$\text{Q-pts} : (250\mu A, -4.92V) (250\mu A, -4.92V) (6.10\mu A, 4.30V) (494\mu A, 5.00V)$$

$$R_D = \frac{V_{BE3} + V_{BE4}}{I_{D2} - I_{B3}} = \frac{1.4V}{250\mu A - \frac{6.10\mu A}{80}} = 5.60k\Omega \quad | \quad \text{Based upon results for the Darlington}$$

$$\text{circuit in Prob. 15.48} : A_{vt1} = \frac{g_{m1}}{2} (R_D \| 2r_{\pi3}) \quad | \quad r_{\pi3} = \frac{80(0.025V)}{6.10\mu A} = 328k\Omega$$

$$g_{m1} = \sqrt{2(0.005)(0.00025)} = 1.58mS \quad | \quad A_{vt1} = -\frac{1.58mS}{2} (5.60k\Omega \| 656k\Omega) = -4.39$$

$$A_{vt2} = -\frac{g_{m4}}{2} \left(\frac{2}{3} r_{o4} \| R_2 \right) = -\frac{40(494\mu A)}{2} \left[\frac{2}{3} \left(\frac{75V + 5V}{494\mu A} \right) \| 1M\Omega \right] = -9.88mS (108k\Omega \| 1M\Omega) = -963$$

$$A_v = -4.39(-963) = 4230 \quad | \quad R_{id} = \infty \quad | \quad R_{out} = \left(\frac{2}{3} r_{o4} \right) \| R_2 = 108k\Omega \| 1M\Omega = 97.5 k\Omega$$

15.64

*Problem 15.64 – Figure P15.63

*Vos (the dc value of V2) has been carefully adjusted to set $V_o \approx 0$

VCC 8 0 DC 5

VEE 9 0 DC -5

V1 1 10 AC 0.5

V2 3 10 DC 1.21M AC -0.5

VIC 10 0 DC 0

I1 8 2 DC 496.3U

R1 8 2 1MEG

M1 4 1 2 2 PFET

M2 5 3 2 2 PFET

RD1 4 9 5.6K

RD2 5 9 5.6K

```

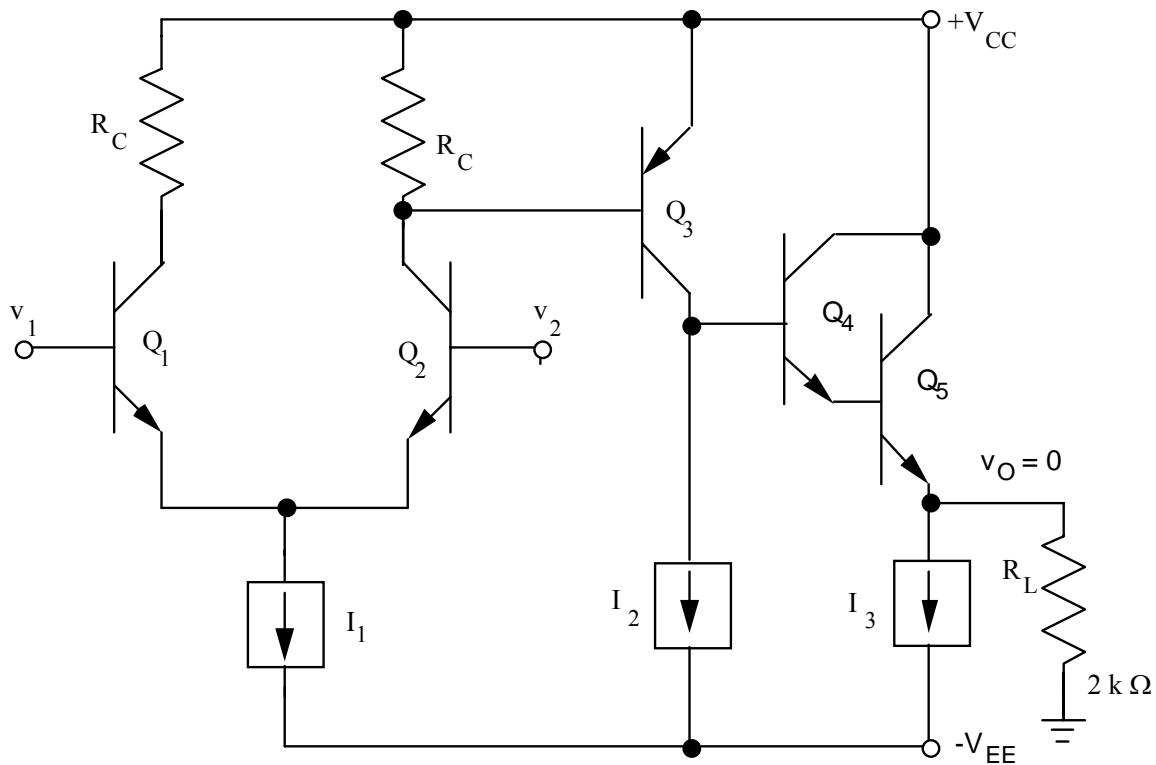
Q3 7 5 6 NBJT
Q4 7 6 9 NBJT
I2 8 7 DC 495U
R2 8 7 1MEG
.OP
.MODEL PFET PMOS KP=5M VTO=-1
.MODEL NBJT NPN BF=80 VA=75
.AC LIN 1 1000 1000
.TF V(7) VIC
.PRINT AC IM(V1) IP(V1) VM(7) VP(7)
.END

```

$$A_{dm} = VM(7) = 4080 \quad | \quad A_{cm} = -2.58 \quad | \quad CMRR_{dB} = 64.0 \text{ dB}$$

Results: $R_{id} = \frac{1}{IM(V1)} = \infty \quad | \quad R_{out} = 96.2 \text{ k}\Omega$

15.65



The new output stage can be treated as an improved single transistor using the results from Prob. 15.48. Using the results from Ex. 15.5:

$$R_{in4-5} = 2\beta_o r_{\pi 4} + \beta_o^2 R_L = 2(100)(505\Omega) + 100^2(2k\Omega) = 20.1M\Omega \quad | \quad A_{v2} \text{ becomes}$$

$$A_{v2} = -g_{m3}(r_{o3} \| R_{in4-5}) = -22mS(161k\Omega \| 20.1M\Omega) = -3510 \quad | \quad \text{The gain of the}$$

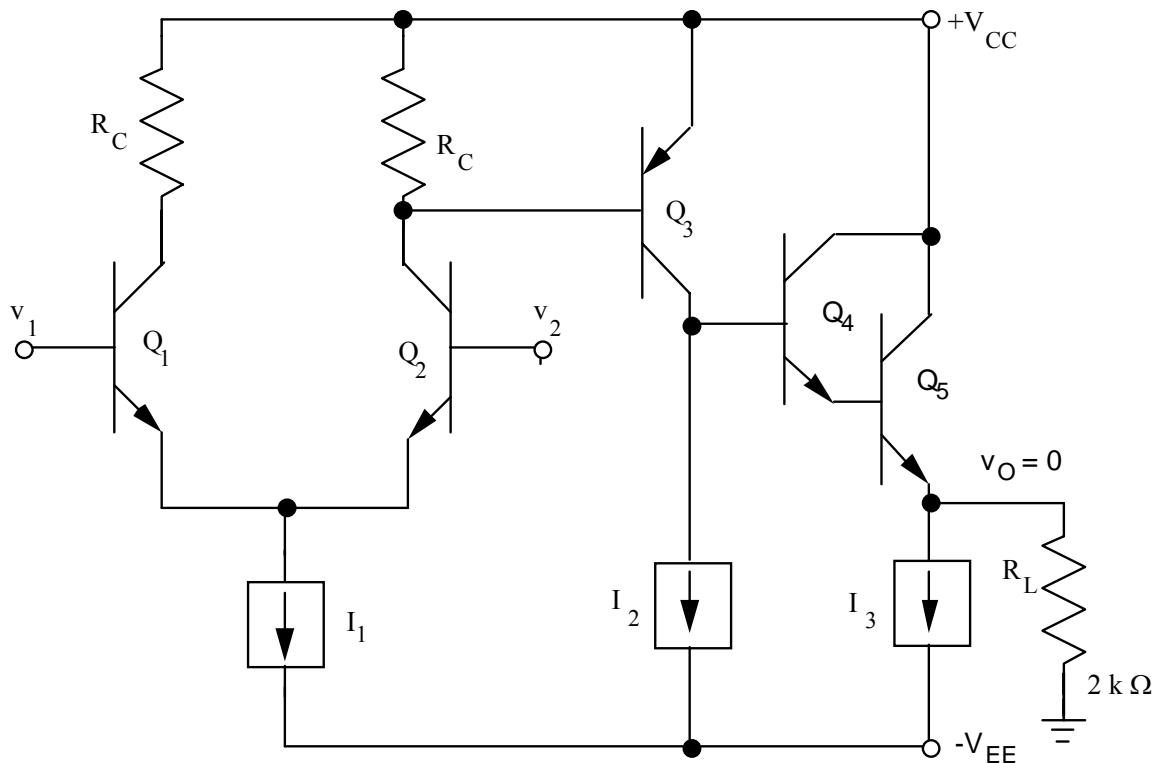
$$\text{emitter follower becomes } A_{v3} \approx \frac{\frac{g_{m4}R_L}{2}}{1 + \frac{g_{m4}R_L}{2}} = \frac{g_{m4}R_L}{2 + g_{m4}R_L} = \frac{40(4.95 \times 10^{-3})(2k\Omega)}{2 + 40(4.95 \times 10^{-3})(2k\Omega)} = 0.995$$

$$A_v = -3.50(-3510)(0.995) = 12200.$$

CMRR and R_{id} do not change: CMRR = 63.5 dB and $R_{id} = 101 k\Omega$

$$R_{out} = \frac{2}{g_{m4}} + \frac{r_{o3}}{\beta_o^2} = \frac{2}{40(4.95 \times 10^{-3})} + \frac{161k\Omega}{10^4} = 26.2 \Omega$$

15.66



The new output stage can be treated as an improved single transistor using the equation set from prob. 15.48 and the results from Ex. 15.4

$$R_{in4-5} = 2\beta_o r_{\pi 4} + \beta_o^2 R_L = 2(100)(505\Omega) + 100^2(2k\Omega) = 20.1M\Omega \quad | \quad A_{v2} \text{ becomes}$$

$$A_{v2} = -g_{m3}(r_{o3} \| R_{in4-5}) = -22mS(161k\Omega \| 20.1M\Omega) = -3510 \quad | \quad \text{The gain of the}$$

$$\text{emitter follower becomes } A_{v3} \approx \frac{\frac{g_{m4}R_L}{2}}{1 + \frac{g_{m4}R_L}{2}} = \frac{g_{m4}R_L}{2 + g_{m4}R_L} = \frac{40(4.95 \times 10^{-3})(2k\Omega)}{2 + 40(4.95 \times 10^{-3})(2k\Omega)} = 0.995$$

$$A_v = -3.50(-3510)(0.995) = 12200.$$

CMRR and R_{id} do not change: CMRR = 63.5 dB and $R_{id} = 101 k\Omega$

$$R_{out} = \frac{2}{g_{m4}} + \frac{r_{o3}}{\beta_o^2} = \frac{2}{40(4.95 \times 10^{-3})} + \frac{161k\Omega}{10^4} = 26.2 \Omega$$

15.67

$$(a) I_{C1} = I_{C2} = \alpha_F \frac{I_1}{2} = \frac{100}{101} \left(\frac{100\mu A}{2} \right) = 49.5\mu A \quad | \quad V_{EC2} = +0.7V - (-15V + 0.7V) = 15.0V$$

$$\text{For } V_O = 0, I_{C4} = \alpha_F I_3 = \left(\frac{100}{101} \right) 1.00mA = 990\mu A \quad | \quad V_{EC4} = 0 - (-15V) = 15.0V$$

$$I_{C3} = I_2 + I_{B4} = 350\mu A + \frac{1mA}{101} = 360\mu A \quad | \quad V_{CE3} = V_O - 0.7V - (-15) = 14.3$$

Q-pts: $(49.5\mu A, 15.0V)$ $(49.5\mu A, 15.0V)$ $(360\mu A, 14.3V)$ $(990\mu A, 15.0V)$

$$(b) R_C = \frac{0.7V}{I_{C2} - I_{B3}} = \frac{0.7V}{(49.5 - 3.60)\mu A} = 15.3k\Omega$$

$$r_{o2} = \frac{50V}{49.5\mu A} = 1.01M\Omega \quad | \quad r_{\pi 3} = \frac{100(0.025V)}{360\mu A} = 6.94k\Omega$$

$$r_{o3} = \frac{50 + 14.3}{360\mu A} = 179k\Omega \quad | \quad A_v = A_{vt1} A_{vt2} A_{vt3} = \frac{g_{ml}}{2} (R_C \| 2r_{o2} \| r_{\pi 3}) (g_{m3} r_{o3}) (1) = \frac{g_{ml}}{2} (R_C \| 2r_{o2} \| r_{\pi 3}) \mu_{f3}$$

$$A_v = \frac{40(49.5\mu A)}{2} (15.3k\Omega \| 2.02M\Omega \| 6.94k\Omega) (40) (64.3) = 12100$$

$$R_{id} = 2r_{\pi 1} = 2 \frac{100(0.025V)}{49.5\mu A} = 101 k\Omega$$

$$(c) R_{out} = \frac{r_{o3} + r_{\pi 4}}{\beta_{o4} + 1} \quad | \quad r_{\pi 4} = \frac{100(0.025V)}{990\mu A} = 2.53k\Omega \quad | \quad R_{out} = \frac{179k\Omega + 2.53k\Omega}{101} = 1.80 k\Omega$$

$$(d) R_{ic} = \frac{(\beta_{o1} + 1)r_{o1}}{2} \quad | \quad r_{o1} = \frac{50V + 15V}{49.5\mu A} = 1.31M\Omega \quad | \quad R_{ic} = \frac{101(1.31M\Omega)}{2} = 66.3 M\Omega \quad (e) v_2$$

15.68

*Problem 15.68 – Figure P15.67

*RC and Vos (see V2) have been carefully adjusted to set $V_o \approx 0$

VCC 7 0 DC 15

VEE 8 0 DC -15

V1 1 9 DC 0.117M AC 0.5

V2 3 9 AC -0.5

VIC 9 0 DC 0

I1 7 2 DC 100U

Q1 4 1 2 PBJT

Q2 5 3 2 PBJT

RC1 4 8 15.8K

RC2 5 8 15.8K

Q3 6 5 8 NBJT

I2 7 6 DC 350U

Q4 8 6 10 PBJT

I3 7 10 DC 1M

.MODEL PBJT PNP BF=100 VA=50

.MODEL NBJT NPN BF=100 VA=50

.NODESET V(10)=0

.OP

.AC LIN 1 1000 1000

.TF V(10) VIC

.PRINT AC IM(V1) IP(V1) VM(10) VP(10)

.END

$$A_{dm} = VM(10) = 13800 \quad | \quad A_{cm} = -0.0804 \quad | \quad CMRR_{dB} = 105 \text{ dB}$$

Results: $R_{id} = \frac{1}{IM(V1)} = 133 \text{ k}\Omega \quad | \quad R_{out} = 1.37 \text{ k}\Omega$

15.69

(a) Working backwards from the output : $V_{DS4} = V_{DD} - V_O = 12 - 0 = 12.0V \mid I_{D4} = I_3 = 5.00mA$

$$V_{GS4} = V_{TN} + \sqrt{\frac{2I_{D4}}{K_n}} = 0.75 + \sqrt{\frac{2(0.005)}{0.005}} = 2.16V \mid V_{DS3} = -(V_{DD} - V_{GS4}) = -(12 - 2.16) = -9.84V$$

$$I_{D3} = I_2 = 2.00mA \mid V_{GS3} = V_{TP} - \sqrt{\frac{2I_{D4}}{K_n}} = -0.75V - \sqrt{\frac{2(0.002)}{0.002}} = -2.16V$$

$$V_{D2} = V_{DD} + V_{GS3} = 12V - 2.16V = 9.84V \mid I_{D1} = I_{D2} = \frac{I_1}{2} = 250\mu A$$

$$V_{GS2} = 0.75V + \sqrt{\frac{2(2.5 \times 10^{-4})}{5 \times 10^{-3}}} = 1.07V \mid V_{DS1} = V_{DS2} = 9.84V - (-1.07V) = 10.9V$$

Q-pts : $(250\mu A, 10.9V)$ $(250\mu A, 10.9V)$ $(2.00mA, -9.84V)$ $(5.00mA, 12.0V)$

$$(b) A_{dm} = \frac{g_{m1}}{2} R_D (g_{m3} r_{o3}) \frac{g_{m4} r_{o4}}{1 + g_{m4} r_{o4}} = \frac{g_{m1}}{2} R_D \mu_{f3} \frac{\mu_{f4}}{1 + \mu_{f4}} \mid R_D = \frac{2.16V}{0.25mA} = 8.64k\Omega$$

$$g_{m1} = \sqrt{2(5 \times 10^{-3})(2.5 \times 10^{-4})[1 + 0.02(10.9)]} = 1.75mS \mid r_{o3} = \frac{0.015}{2mA} = 38.3k\Omega$$

$$g_{m3} = \sqrt{2(2 \times 10^{-3})(2 \times 10^{-3})[1 + 0.015(9.84)]} = 3.03mS \mid r_{o4} = \frac{0.02}{5mA} = 12.4k\Omega$$

$$g_{m4} = \sqrt{2(5 \times 10^{-3})(5 \times 10^{-3})[1 + 0.02(12)]} = 7.87mS \mid \mu_{f3} = g_{m3} r_{o3} = 116 \mid \mu_{f4} = 97.6$$

$$A_{dm} = \frac{1.75ms}{2} (8.64k\Omega)(116) \frac{97.6}{1 + 97.6} = 868 \mid R_{id} = \infty \mid R_{out} = \frac{1}{g_{m4}} = 127\Omega$$

15.70

*Problem 15.70 – Figure P15.69

*The values of RD have been adjusted to bring the offset voltage to ≈ 0

VCC 8 0 DC 12

VEE 9 0 DC -12

V1 1 10 AC 1

V2 3 10 AC 1

VIC 10 0 DC 0

I1 2 9 DC 500U

M1 4 1 2 2 NFET

M2 5 3 2 2 NFET

RD1 8 4 8.28K

RD2 8 5 8.28K

M3 6 5 8 8 PFET

M4 8 6 7 7 NFET

I2 6 9 DC 2M

I3 7 9 DC 5M

.MODEL PFET PMOS KP=2M VTO=-0.75 LAMBDA=0.015

.MODEL NFET NMOS KP=5M VTO=0.75 LAMBDA=0.02

.OP

.AC LIN 1 1000 1000

.TF V(7) VIC

.PRINT AC VM(7) VP(7) IM(V1) IP(V1)

.END

$$A_{dm} = VM(7) = 802 \quad | \quad A_{cm} = -4.74 \times 10^{-7} \cong 0 \quad | \quad CMRR_{dB} = \infty$$

Results: $R_{id} = \frac{1}{IM(V1)} = 10^{30} \cong \infty \quad | \quad R_{out} = 126 \Omega$

15.71

(a) Working backwards from the output : $V_{DS4} = -(V_o - V_{SS}) = 0 + (-5) = -5.00V$

$$I_{D4} = I_3 = 2.00mA \quad | \quad V_{GS4} = V_{TP} - \sqrt{\frac{2I_{D4}}{K_p}} = -0.7 - \sqrt{\frac{2(0.002)}{0.002}} = -2.11V$$

$$V_{DS3} = V_o + V_{GS4} - (-V_{SS}) = 0 - 2.11 + 5 = 2.89V$$

$$I_{D3} = I_2 = 500\mu A \quad | \quad V_{GS3} = V_{TN} + \sqrt{\frac{2I_{D4}}{K_n}} = 0.75V + \sqrt{\frac{2(5 \times 10^{-4})}{5 \times 10^{-3}}} = 1.15V$$

$$V_{D2} = -V_{SS} + V_{GS3} = -5 + 1.15V = -3.85V \quad | \quad I_{D1} = I_{D2} = \frac{I_1}{2} = 300\mu A$$

$$V_{GS1} = V_{GS2} = -0.7V - \sqrt{\frac{2(3 \times 10^{-4})}{2 \times 10^{-3}}} = -1.25V \quad | \quad V_{DS2} = V_{DS1} = -[1.25 - (3.85)] = -5.10V$$

Q-pts : $(300\mu A, -5.10V)$ $(300\mu A, -5.10V)$ $(500\mu A, 2.89V)$ $(2.00mA, 5.00V)$

$$(b) A_{dm} = \frac{g_{ml}}{2} R_D \left(g_{m3} r_{o3} \right) \frac{g_{m4} r_{o4}}{1 + g_{m4} r_{o4}} = \frac{g_{ml}}{2} R_D \mu_{f3} \frac{\mu_{f4}}{1 + \mu_{f4}} \quad | \quad R_D = \frac{1.15V}{0.3mA} = 3.83k\Omega$$

$$g_{ml} = \sqrt{2(2 \times 10^{-3})(3 \times 10^{-4})[1 + 0.015(5.10)]} = 1.14mS \quad | \quad r_{o3} = \frac{1}{0.02} = 50k\Omega \quad | \quad r_{o4} = \frac{1}{0.5mA} = 106k\Omega$$

$$g_{m3} = \sqrt{2(5 \times 10^{-3})(5 \times 10^{-4})[1 + 0.02(2.89)]} = 2.30mS \quad | \quad \mu_{f3} = \frac{0.015}{2mA} = 35.8k\Omega$$

$$g_{m4} = \sqrt{2(2 \times 10^{-3})(2 \times 10^{-3})[1 + 0.015(15)]} = 2.93mS \quad | \quad \mu_{f4} = g_{m3} r_{o3} = 244 \quad | \quad \mu_{f4} = 105$$

$$A_{dm} = \frac{1.14ms}{2} (3.83k\Omega)(244) \frac{105}{1 + 105} = 528 \quad | \quad R_{id} = \infty \quad | \quad R_{out} = \frac{1}{g_{m4}} = 341\Omega$$

15.72

The amplifier has an offset voltage of approximately -6.69 mV. This value is used to force the output to nearly zero. A transfer function analysis then yields

$$A_v = +517 \quad R_{out} = 339 \Omega \quad R_{in} = +1.00 \times 10^{20} \Omega$$

These values are similar to the hand calculations in Prob. 15.71.

15.73

(a) Working backwards from the output : $V_{DS4} = -(V_o - V_{SS}) = 0 + (-5) = -5.00V$

$$I_{D4} = I_3 = 2.00mA \quad | \quad V_{GS4} = V_{TP} - \sqrt{\frac{2I_{D4}}{K_p}} = -0.7 - \sqrt{\frac{2(0.002)}{0.002}} = -2.11V$$

$$V_{CE3} = V_o + V_{GS4} - (-V_{SS}) = 0 - 2.11 + 5 = 2.89V$$

$$I_{C3} = I_2 = 500\mu A \quad | \quad V_{D2} = -V_{SS} + V_{BE3} = -5 + 0.7V = -4.30V \quad | \quad I_{D1} = I_{D2} = \frac{I_1}{2} = 300\mu A$$

$$V_{GS1} = V_{GS2} = -0.7V - \sqrt{\frac{2(3 \times 10^{-4})}{2 \times 10^{-3}}} = -1.25V \quad | \quad V_{DS1} = V_{DS2} = -[1.25 - (-4.30)] = -5.55V$$

Q-pts : $(300\mu A, -5.55V)$ $(300\mu A, -5.55V)$ $(500\mu A, 2.89V)$ $(2.00mA, 5.00V)$

$$(b) A_{dm} = \frac{g_{m1}}{2} \left(R_D \| r_{\pi 3} \right) g_{m3} r_{o3} \left(\frac{g_{m4} r_{o4}}{1 + g_{m4} r_{o4}} \right) = \frac{g_{m1}}{2} \left(R_D \| r_{\pi 3} \right) \mu_{f3} \frac{\mu_{f4}}{1 + \mu_{f4}}$$

$$R_D = \frac{0.7V}{0.3mA} = 2.33k\Omega \quad | \quad r_{\pi 3} = \frac{150(0.025V)}{500\mu A} = 7.53k\Omega$$

$$g_{m1} = \sqrt{2(2 \times 10^{-3})(3 \times 10^{-4})[1 + 0.015(5.10)]} = 1.14mS \quad | \quad r_{o3} = \frac{\frac{1}{0.02} + 2.89}{0.5mA} = 106k\Omega$$

$$g_{m4} = \sqrt{2(2 \times 10^{-3})(2 \times 10^{-3})[1 + 0.015(15)]} = 2.93mS \quad | \quad r_{o4} = \frac{\frac{1}{0.015} + 5.00}{2mA} = 35.8k\Omega$$

$$\mu_{f3} = g_{m3} r_{o3} = 40(70) = 2800 \quad | \quad \mu_{f4} = 105$$

$$A_{dm} = \frac{1.14ms}{2} (2.33k\Omega \| 7.53k\Omega) (2800) \frac{105}{1+105} = 2810 \quad | \quad R_{id} = \infty \quad | \quad R_{out} = \frac{1}{g_{m4}} = 341\Omega$$

15.74

The amplifier has an offset voltage of approximately 48.69 mV. This value is used to force the output to nearly zero. A transfer function analysis then yields

$$A_v = +2810 \quad R_{out} = 339 \Omega \quad R_{in} = +1.00 \times 10^{20} \Omega$$

These values are similar to the hand calculations in Prob. 15.73

15.75

(a) Working backwards from the output with $V_o = 0$: $V_{DS4} = V_{CC} - V_o = 5 - 0 = 5V$

$$I_{D4} = I_3 = 2mA \quad | \quad V_{GS4} = V_{TN} + \sqrt{\frac{2I_{D4}}{K_n}} = 0.7 + \sqrt{\frac{2(0.002)}{0.005}} = 1.59V \quad | \quad I_{C3} = I_2 = 500\mu A$$

$$V_{EC3} = 5 - V_{GS4} = 5 - 1.59 = 3.41V \quad | \quad V_{CE2} = 5 - V_{EB3} - (-V_{BE2}) = 5 - 0.7 + 0.7 = 5.00V$$

$$I_{C1} = I_{C2} = \alpha_F \frac{I_1}{2} = \frac{100}{101} \frac{200\mu A}{2} = 99.0\mu A \quad | \quad R_C = \frac{V_{EB3}}{I_{C2} - I_{B3}} = \frac{0.7V}{(99.0 - 5.00)\mu A} = 7.45k\Omega$$

$$V_{CE1} = 5 - I_{C1}R_C - (-V_{BE2}) = 5 - 99.0\mu A(7.45k\Omega) + 0.7 = 4.96V$$

$$Q = pts: (99.0\mu A, 4.96V) (99.0\mu A, 5.00V) (500\mu A, 3.41V) (2.00mA, 5.00V)$$

(b) Using current division at the collector of Q₂:

$$A_{dm} = \frac{g_{m1}}{2} \left(\frac{R_C}{R_C + r_{\pi3}} \right) \beta_{o3} r_{o3} \left(\frac{g_{m4} R_L}{1 + g_{m4} R_L} \right) = \frac{g_{m1}}{2} (R_C \| r_{\pi3}) \mu_{f3} \frac{g_{m4} R_L}{1 + g_{m4} R_L}$$

$$r_{\pi3} = \frac{100(0.025V)}{500\mu A} = 5.00k\Omega \quad | \quad g_{m4} = \sqrt{2(0.005)(0.002)} = 4.47mS$$

$$A_{dm} = \frac{40(99.0\mu A)}{2} (7.45k\Omega \| 5.00k\Omega) (40)(50 + 3.41) \frac{4.47mS(2k\Omega)}{1 + 4.47mS(2k\Omega)} = 11400$$

$$R_{id} = 2r_{\pi1} = 2 \frac{100(0.025V)}{99.0\mu A} = 50.5 k\Omega \quad | \quad R_{out} = \frac{1}{g_{m4}} = 224 \Omega$$

(c)

*Problem 15.75 – Figure P15.75

*The values of RC have been adjusted to set Vo ≈ 0.

VCC 8 0 DC 5

VEE 9 0 DC -5

VIC 10 0 DC 0

V1 1 10 AC 0.5

V2 3 10 AC -0.5

I1 2 9 DC 200U

Q1 4 1 2 NBJT

Q2 5 3 2 NBJT

RC1 8 4 8.00K

RC2 8 5 8.00K

Q3 6 5 8 PBJT

I2 6 9 DC 500U

M4 8 6 7 7 NFET

I3 7 9 DC 2M

RL 7 0 2K

.MODEL NBJT NPN BF=100 VA=50

.MODEL PBJT PNP BF=100 VA=50

.MODEL NFET NMOS KP=5M VTO=0.70

.OP

.AC LIN 1 2KHZ 2KHZ

.PRINT AC VM(7) VP(7) IM(V1) IP(V1)

.TF V(7) VIC

.END

$$A_{dm} = VM(7) = 11200 \quad | \quad A_{cm} = -0.0957 \quad | \quad CMRR_{dB} = 101 \text{ dB}$$

Results: $R_{id} = \frac{1}{IM(V1)} = 56.4 \text{ k}\Omega \approx \infty \quad | \quad R_{out} = 201 \text{ }\Omega$

15.76

$$(a) I_{C1} = I_{C2} = \alpha_F \frac{I_1}{2} = \frac{100}{101} \frac{10\mu A}{2} = 4.95 \mu A \quad | \quad I_{C3} = I_{C4} = \alpha_F \frac{I_2}{2} = \frac{50}{51} \frac{50\mu A}{2} = 24.5 \mu A$$

$$V_{CE2} = V_{CC} - (I_{C2} - I_{B3})R_C - (-V_{BE2}) = 3V - \left(4.95\mu A - \frac{24.5 \mu A}{50}\right)300k\Omega - (-0.7) = 2.36V$$

$$\text{For } V_o = 0: I_{C5} = \alpha_F I_3 \frac{50}{51} (250\mu A) = 245\mu A \quad | \quad V_{EC5} = 3.00 \text{ V} \quad | \quad V_{C4} = -0.7V$$

$$V_{C1} = 3 - \left(4.95\mu A - \frac{24.5 \mu A}{50}\right)300k\Omega = 1.66V \quad | \quad V_{EC3} = V_{EC4} = 1.66 + 0.7 - (-0.7) = 3.06V$$

Q- pts: $(4.95\mu A, 2.36V) (4.95\mu A, 2.36V) (24.5\mu A, 3.06V) (24.5\mu A, 3.06V) (245\mu A, 3.00V)$

$$(b) A_{dm} = g_{m1} \left(R_{C1} \| r_{\pi3} \| r_{o1} \right) \frac{g_{m3}}{2} \left(R_{C2} \| 2r_{o4} \| [r_{\pi5} + (\beta_{o5} + 1)R_L] \right) \frac{(\beta_{o5} + 1)R_L}{r_{\pi5} + (\beta_{o5} + 1)R_L}$$

$$r_{\pi3} = \frac{50(0.025V)}{24.5\mu A} = 51.0k\Omega \quad | \quad r_{o4} = \frac{70}{24.5\mu A} = 2.86M\Omega \quad | \quad r_{\pi5} = \frac{50(0.025V)}{245\mu A} = 5.10k\Omega$$

$$r_{o1} = \frac{50}{4.95\mu A} = 10.1M\Omega \quad | \quad \frac{(\beta_{o5} + 1)R_L}{r_{\pi5} + (\beta_{o5} + 1)R_L} = \frac{51(5k\Omega)}{5.10k\Omega + 51(5k\Omega)} = 0.980$$

$$A_{dm} = 40(4.95\mu A)(300k\Omega \| 51.0k\Omega \| 10.1M\Omega)$$

$$\frac{(40)(24.5\mu A)}{2} \left(78k\Omega \| 5.72M\Omega \| [5.10k\Omega + 51(5k\Omega)] \right) 0.980 = 235$$

$$R_{id} = 2r_{\pi1} = 2 \frac{100(0.025V)}{4.95\mu A} = 1.01 M\Omega \quad | \quad R_{out} = \frac{R_{C2} + r_{\pi5}}{\beta_{o5} + 1} = \frac{78k\Omega \| 5.72M\Omega + 5.10k\Omega}{51} = 1.59 k\Omega$$

(c) v_A is the non-inverting input - v_B is the inverting input

(d) $A_v = (10V_{CC})(10V_{CC}) = 30^2 = 900 \quad | \quad r_{\pi3} \ll R_C$ is substantially reducing the gain

Also, the input resistance of the emitter follower is low, $R_{in5} = 107k\Omega \approx R_{C2}$, and is reducing the gain by an additional factor of almost 2.

15.77

$$(a) I_{C1} = I_{C2} = \alpha_F \frac{I_1}{2} = \frac{100}{101} \left(\frac{100\mu A}{2} \right) = 49.5 \mu A \quad | \quad I_{C3} = I_{C4} = \alpha_F \frac{I_2}{2} = \frac{50}{51} \left(\frac{200\mu A}{2} \right) = 98.0 \mu A$$

$$V_{CE2} = V_{CC} - (I_{C2} - I_{B3})R_C - (-V_{BE2}) = 18V - \left(49.5\mu A - \frac{98.0\mu A}{50} \right) 120k\Omega - (-0.7) = 13.0V$$

$$\text{For } V_O = 0 : I_{C5} = \alpha_F I_3 \frac{50}{51} (750\mu A) = 735\mu A \quad | \quad V_{EC4} = 18 V \quad | \quad V_{C4} = -0.7V$$

$$V_{C1} = 18 - \left(49.5\mu A - \frac{98.0\mu A}{50} \right) 120k\Omega = 12.3V \quad | \quad V_{EC3} = V_{EC4} = 12.3 + 0.7 - (-0.7) = 13.7V$$

Q - pts : (49.5μA, 13.0V) (49.5μA, 13.0V) (98.0μA, 13.7V) (98.0μA, 13.7V) (735μA, 18.0V)

$$(b) A_{dm} = g_{m1} \left(R_{C1} \| r_{\pi3} \| r_{o2} \right) \frac{g_{m3}}{2} \left(R_{C2} \| 2r_{o4} \| [r_{\pi5} + (\beta_{o5} + 1)R_L] \right) \frac{(\beta_{o5} + 1)R_L}{r_{\pi5} + (\beta_{o5} + 1)R_L}$$

$$r_{\pi3} = \frac{50(0.025V)}{98.0\mu A} = 12.8k\Omega \quad | \quad r_{o4} = \frac{70V}{98.0\mu A} = 714k\Omega \quad | \quad r_{\pi5} = \frac{50(0.025V)}{735\mu A} = 1.70k\Omega$$

$$r_{o2} = \frac{50V}{49.5\mu A} = 1.01M\Omega \quad | \quad \frac{(\beta_{o5} + 1)R_L}{r_{\pi5} + (\beta_{o5} + 1)R_L} = \frac{51(2k\Omega)}{1.70k\Omega + 51(2k\Omega)} = 0.984$$

$$A_{dm} = 40(49.5\mu A) (120k\Omega \| 12.8k\Omega \| 1.01M\Omega) \bullet$$

$$\frac{(40)(98.0\mu A)}{2} (170k\Omega \| 1.43M\Omega \| [1.70k\Omega + 51(2k\Omega)]) 0.984 = 2700$$

$$R_{id} = 2r_{\pi1} = 2 \frac{100(0.025V)}{49.5\mu A} = 101 k\Omega \quad | \quad R_{out} = \frac{R_{C2} + r_{\pi5}}{\beta_{o5} + 1} = \frac{170 + 1.70}{51} k\Omega = 3.37 k\Omega$$

(c) For positive v_{IC} , $v_{IC} \leq V_{C1} = 12.3V$ | For negative v_{IC} , the characteristics of I_l will determine v_{IC} . For the ideal current source, the negative limit of v_{IC} is not defined.

(d) The actual voltage at the collector of Q₄ would be

$$V_{C4} = -18V + (I_{C4} + I_{B5})R_{C2} = -18V + \left(98.0\mu A + \frac{735\mu A}{50} \right) 170k\Omega = 1.16V \text{ and } V_o = +1.86V$$

should be - 0.7V. The value of offset voltage required to bring the output back to zero is

$$V_{os} = \frac{\Delta V_o}{A_{dm}} = \frac{1.86V}{2700} = 0.689 mV.$$

15.78

$$(a) I_{C1} = I_{C2} = \alpha_F \frac{I_1}{2} = \frac{100}{101} \left(\frac{200\mu A}{2} \right) = 99.0\mu A \quad | \quad \text{For } V_o = 0 : I_{C3} = \alpha_F I_{E3} = \frac{100}{101} \left(\frac{12V}{12k\Omega} \right) = 990\mu A$$

$$V_{CE3} = 12V - 0V = 12.0V \quad | \quad V_{CE2} = +0.7 - (-0.7) = 1.4V$$

$$R_C = \frac{12V - 0.7V}{I_{C2} + I_{B3}} = \frac{0.7V}{(99.0 + 9.90)\mu A} = 104 k\Omega \quad | \quad V_{CE1} = 12 - 99.0\mu A(104k\Omega) - (-0.7) = 2.40V$$

Q-points: $(99.0\mu A, 2.40V)$ $(99.0\mu A, 1.40V)$ $(990\mu A, 12V)$

$$(b) A_{dm} = \frac{g_m 2}{2} \left(R_C \left\| 2r_{o2} \right\| \left[r_{\pi3} + (\beta_{o3} + 1)R \right] \right) \frac{(\beta_{o3} + 1)R}{r_{\pi3} + (\beta_{o3} + 1)R}$$

$$r_{o2} = \frac{70V}{99.0\mu A} = 707k\Omega \quad | \quad r_{\pi3} = \frac{100(0.025V)}{990\mu A} = 2.53k\Omega$$

$$A_{dm} = \frac{40(99.0\mu A)}{2} \left(104k\Omega \left\| 1.41M\Omega \right\| [2.53k\Omega + (101)12k\Omega] \right) \frac{(101)12k\Omega}{2.53k\Omega + (101)12k\Omega} = 177$$

$$R_{id} = 2r_{\pi1} = 2 \frac{100(0.025V)}{99.0\mu A} = 50.5 k\Omega \quad | \quad R_{out} = \frac{R_C \left\| 2r_{o2} + r_{\pi3} \right\|}{\beta_{o3} + 1} = \frac{96.9k\Omega + 2.53k\Omega}{101} = 984 \Omega$$

15.79

$$300k\Omega = 2r_{\pi1} \rightarrow I_{C1} = 2 \frac{100(0.025V)}{300k\Omega} = 16.7\mu A. \quad \text{For } V_o = 0, V_{C1} = 0.7V$$

$$R_C = \frac{12 - 0.7}{I_{C1} + I_{B3}} \cong \frac{11.3V}{I_{C1}} = \frac{11.3V}{16.7\mu A} = 677k\Omega \quad | \quad R_{out} \cong \frac{R_C + r_{\pi3}}{\beta_{o3} + 1} \geq \frac{677k\Omega}{101} = 6.7k\Omega$$

The R_{out} specification cannot be met if the R_{id} specification is met and vice-versa.

Either R_{id} must be reduced or R_{out} must be increased, or both must be changed.

15.80

$$1M\Omega = 2r_{\pi1} \rightarrow I_{C1} = 2 \frac{100(0.025V)}{1M\Omega} = 5.00\mu A \quad | \quad \text{For } V_o = 0, V_{C1} = 0.7V$$

$$R_C = \frac{9 - 0.7}{I_{C1} + I_{B3}} \cong \frac{8.3V}{I_{C1}} = \frac{8.3V}{5.00\mu A} = 1.66M\Omega \quad | \quad R_{out} \cong \frac{R_C + r_{\pi3}}{\beta_{o3} + 1} \geq \frac{1.66M\Omega}{101} = 16.4k\Omega$$

The R_{out} specification cannot be met if the R_{id} specification is met and vice-versa.

Either R_{id} must be reduced or R_{out} must be increased, or both must be changed.

15.81

$$(a) \text{For } V_o = 0, I_{C6} = \alpha_F I_{E6} = \alpha_F I_3 = \frac{100}{101} (5mA) = 4.95mA$$

$$I_{C5} = \alpha_F I_{E5} = \alpha_F \frac{I_{C6}}{\beta_{F6}} = \frac{4.95mA}{101} = 49.0\mu A \quad | \quad I_{C4} + I_{C3} = I_2 + I_{B5} = 500\mu A + \frac{49.0\mu A}{100} = 500\mu A$$

$$\beta_{F4} \frac{I_{C3}}{\alpha_{F3}} + I_{C3} = (\beta_{F3} + 2) I_{C3} = 500\mu A \rightarrow I_{C3} = 9.62\mu A \quad | \quad I_{C4} = 500\mu A - I_{C3} = 490\mu A$$

$$I_{C1} = I_{C2} = \alpha_F \frac{I_1}{2} = \frac{100}{101} \left(\frac{50\mu A}{2} \right) = 24.8\mu A \quad | \quad V_{CE6} = 18 - 0 = 18V \quad | \quad V_{CE5} = V_{CE6} - V_{BE6} = 17.3V$$

$$V_{EC4} = 18 - V_{BE5} - V_{BE6} = 16.6V \quad | \quad V_{EC3} = V_{EC4} - V_{EB4} = 15.9V$$

$$V_{CE1} = V_{CE2} = 18 - V_{EB4} - V_{EB3} - (-V_{EB2}) = 17.3V$$

Q-pts: $(24.8\mu A, 17.3V)$ $(24.8\mu A, 17.3V)$ $(9.62\mu A, 15.9V)$ $(490\mu A, 16.6V)$

$$(49.0\mu A, 17.3V) (4.95mA, 18.0V) \quad | \quad R_C = \frac{1.4V}{I_{C2} - I_{B3}} = \frac{1.4V}{\left(24.8 + \frac{9.62}{50} \right) \mu A} = 56.9k\Omega$$

(b) Using the properties of the Darlington configuration from Prob. 15.48:

$$A_{dm} = \frac{g_{m2}}{2} (R_C \| R_{in3}) \frac{g_{m4}}{2} \left(\frac{2}{3} r_{o4} \| R_{in5} \right) \frac{\beta_{o5} \beta_{o6} R_L}{2r_{\pi5} + \beta_{o5} \beta_{o6} R_L}$$

$$R_{in3} \cong 2\beta_{o3} r_{\pi4} = 2(50) \frac{50(0.025V)}{490\mu A} = 255k\Omega$$

$$R_{in5} \cong 2\beta_{o5} r_{\pi6} + \beta_{o5} \beta_{o6} R_L = 2(100) \frac{100(0.025V)}{4.95mA} + 100(100)(2k\Omega) = 20.1M\Omega$$

$$R_{in5} >> r_{o4} = \frac{70V + 16.6V}{490\mu A} = 177k\Omega \quad | \quad A_{dm} = \frac{40(24.8\mu A)}{2} (56.9k\Omega \| 255k\Omega) \frac{\mu_{f4}}{3} \left(\frac{20M\Omega}{20.1M\Omega} \right)$$

$$\frac{\mu_{f4}}{3} = \frac{40(70 + 11.6)}{3} = 1155 \quad | \quad A_{dm} = 26500 \text{ or } (88.5dB) \quad | \quad R_{id} = 2r_{\pi1} = 2 \frac{100(0.025V)}{24.8\mu A} = 202 k\Omega$$

$$R_{out} = \frac{R_{th5} + 2r_{\pi5}}{\beta_{o5} \beta_{o6}} = \frac{\frac{2}{3} r_{o4} + 2r_{\pi5}}{\beta_{o5} \beta_{o6}} = \frac{\frac{2}{3} 118k\Omega + 2 \frac{100(0.025V)}{49.0\mu A}}{100(100)} = 18.1 \Omega$$

15.82

$$(a) \text{For } V_o = 0, I_{C6} = \alpha_F I_{E6} = \alpha_F I_3 = \frac{100}{101} (5mA) = 4.95mA$$

$$I_{C5} = \alpha_F I_{E5} = \alpha_F \frac{I_{C6}}{\beta_{F6}} = \frac{4.95mA}{101} = 49.0\mu A \quad | \quad I_{C4} + I_{C3} = I_2 + I_{B5} = 500\mu A + \frac{49.0\mu A}{100} = 500\mu A$$

$$\beta_{F4} \frac{I_{C3}}{\alpha_{F3}} + I_{C3} = (\beta_{F3} + 2) I_{C3} = 500\mu A \rightarrow I_{C3} = 9.62\mu A \quad | \quad I_{C4} = 500\mu A - I_{C3} = 490\mu A$$

$$I_{C1} = I_{C2} = \alpha_F \frac{I_1}{2} = \frac{100}{101} \left(\frac{50\mu A}{2} \right) = 24.8\mu A \quad | \quad V_{CE6} = 22 - 0 = 22V \quad | \quad V_{CE5} = V_{CE6} - V_{BE6} = 21.3V$$

$$V_{EC4} = 22 - V_{BE5} - V_{BE6} = 20.6V \quad | \quad V_{EC3} = V_{EC4} - V_{EB4} = 19.9V$$

$$V_{CE1} = V_{CE2} = 22 - V_{EB4} - V_{EB3} - (-V_{EB2}) = 21.3V$$

Q-pts: $(24.8\mu A, 21.3V)$ $(24.8\mu A, 21.3V)$ $(9.62\mu A, 19.9V)$ $(490\mu A, 20.6V)$

$$(49.0\mu A, 21.3V) (4.95mA, 22.0V) \quad | \quad R_C = \frac{1.4V}{I_{C2} - I_{B3}} = \frac{1.4V}{\left(24.8 + \frac{9.62}{50} \right) \mu A} = 56.9k\Omega$$

(b) Using the properties of the Darlington configuration from Prob. 15.48:

$$A_{dm} = A_{V1} A_{V2} A_{V3} = \left[\frac{g_{m2}}{2} (R_C \| R_{in3}) \right] \left[\frac{g_{m4}}{2} \left(\frac{2}{3} r_{o4} \| R_{in5} \right) \right] \left[\frac{\beta_{o5} \beta_{o6} R_L}{2r_{\pi5} + \beta_{o5} \beta_{o6} R_L} \right]$$

$$R_{in3} \cong 2\beta_{o3} r_{\pi4} = 2(50) \frac{50(0.025V)}{490\mu A} = 255k\Omega$$

$$R_{in5} \cong 2\beta_{o5} r_{\pi6} + \beta_{o5} \beta_{o6} R_L = 2(100) \frac{100(0.025V)}{4.95mA} + 100(100)(2k\Omega) = 20.1M\Omega$$

$$R_{in5} > r_{o4} = \frac{70V + 20.6V}{490\mu A} = 185k\Omega \quad | \quad A_{dm} = \frac{40(24.8\mu A)}{2} (56.9k\Omega \| 255k\Omega) \frac{\mu_{f4}}{3} \left(\frac{20M\Omega}{20.1M\Omega} \right)$$

$$\frac{\mu_{f4}}{3} = \frac{40(70 + 20.6)}{3} = 1208 \quad | \quad A_{dm} = 27700 (88.9dB) \quad | \quad R_{id} = 2r_{\pi1} = 2 \frac{100(0.025V)}{24.8\mu A} = 202 k\Omega$$

$$R_{out} = \frac{R_{th5} + 2r_{\pi5}}{\beta_{o5} \beta_{o6}} = \frac{\frac{2}{3} r_{o4} + 2r_{\pi5}}{\beta_{o5} \beta_{o6}} = \frac{\frac{2}{3} 185k\Omega + 2 \frac{100(0.025V)}{49.0\mu A}}{100(100)} = 22.5 \Omega$$

15.83

Since the transistor parameters are the same, $V_{GS1} = -V_{GS2} = \frac{2.2V}{2} = 1.1V$

$$I_{D2} = I_{D1} = \frac{6 \times 10^{-4}}{2} (1.1 - 0.75)^2 = 36.8 \mu A$$

15.84

$$2.2V = V_{GS1} - V_{GS2} = V_{TN} + \sqrt{\frac{2I_{D1}}{K_n}} - \left(V_{TP} - \sqrt{\frac{2I_{D2}}{K_p}} \right) \text{ where } I_{D2} = I_{D1}$$

$$2.2 = 0.7 + 0.8 + \sqrt{I_{D1}} \left(\sqrt{\frac{2}{6 \times 10^{-4}}} + \sqrt{\frac{2}{4 \times 10^{-4}}} \right) \mid \sqrt{I_{D1}} = \frac{0.7}{128.5} \rightarrow I_{D2} = I_{D1} = 29.7 \mu A$$

15.85

Since the values of I_S and I_E are the same, $V_{BE1} = V_{EB2}$

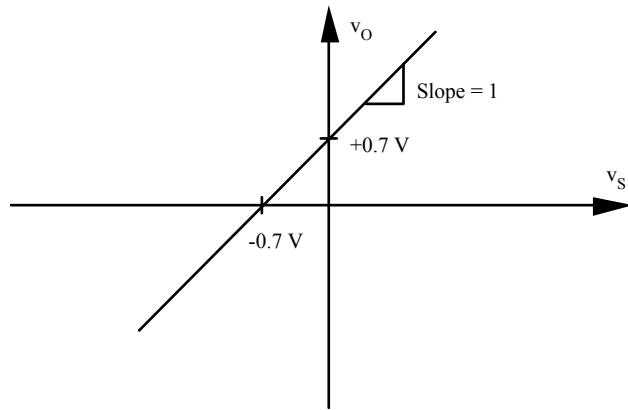
$$1.30 = V_{BE1} + V_{EB2} = 2V_T \ln \frac{I_C}{I_S} \mid I_C = 10^{-15} \exp \frac{1.30}{2(0.025V)} = 196 \mu A$$

15.86

$$1.30 = V_{BE1} + V_{EB2} = V_T \ln \frac{I_C}{I_{S1}} + V_T \ln \frac{I_C}{I_{S2}} = V_T \ln \frac{I_C^2}{I_{S1} I_{S2}}$$

$$I_C = \sqrt{(4 \times 10^{-15})(10^{-15}) \exp \frac{1.30}{0.025}} = 391 \mu A$$

15.87



15.88

*Problem 15.88 – Figure P15.87

VCC 3 0 DC 10

VEE 5 0 DC -10

VBB 2 1 DC 1.3

VS 1 0 DC 0

Q1 3 2 4 NBJT

Q2 5 1 4 PBJT

RL 4 0 1K

.MODEL NBJT NPN IS=5FA BF=60

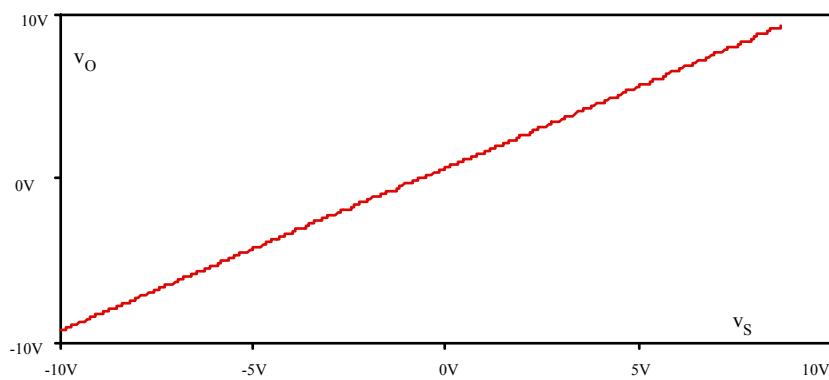
.MODEL PBJT PNP IS=1FA BF=50

.OP

.DC VS -10 +8.7 0.01

.PROBE

.END



15.89

Since the base currents are zero ($\beta_F = \infty$), $V_{BE1} + V_{EB2} = (250\mu A)(5k\Omega) = 1.25V$

$$1.25V = V_T \ln \frac{I_C}{I_{S1}} + V_T \ln \frac{I_C}{I_{S2}} = V_T \ln \frac{I_C^2}{I_{S1} I_{S2}} \quad | \quad I_C = \sqrt{(10^{-15})(10^{-16}) \exp \frac{1.25}{0.025}} = 22.8 \mu A$$

15.90

$$V_{GS1} + V_{GS2} = (0.5mA)(4k\Omega) = 2.00V \quad | \quad 2.00V = V_{TN} + \sqrt{\frac{2I_{D1}}{K_n}} - \left(V_{TP} - \sqrt{\frac{2I_{D2}}{K_p}} \right) \quad | \quad I_{D2} = I_{D1}$$

$$2.00 = 0.75 + 0.75 + \sqrt{I_{D1}} \left(\sqrt{\frac{2}{5 \times 10^{-4}}} + \sqrt{\frac{2}{2 \times 10^{-4}}} \right) \quad | \quad \sqrt{I_{D1}} = \frac{0.5}{163.3} \rightarrow I_{D2} = I_{D1} = 9.38 \mu A$$

15.91

$$I_{ss} \geq \frac{5V}{R_L} = \frac{5V}{1k\Omega} = 5.00mA \quad | \quad i_s = I_{ss} + i_L$$

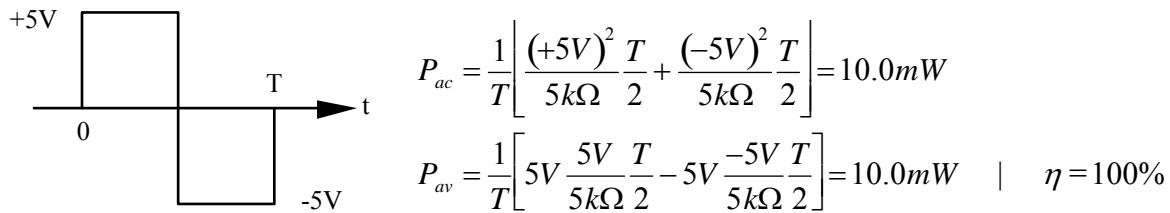
$$i_s^{\max} = I_{ss} + \frac{5V}{1k\Omega} = I_{ss} + 5.00mA \quad | \quad i_s^{\min} = I_{ss} - \frac{5V}{1k\Omega} = I_{ss} - 5.00mA$$

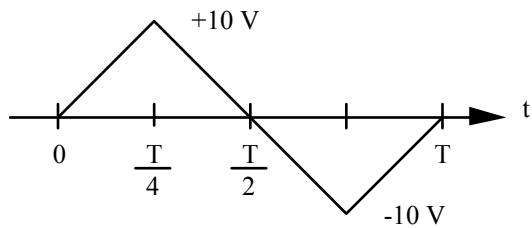
$$\text{For } I_{ss} = 5.00mA, \quad i_s^{\max} = 10.0mA \quad | \quad i_s^{\min} = 0 \quad | \quad i_d = 0.005(1 + \sin 2000\pi t)A$$

$$\text{Power delivered from the supplies: } P(t) = 10V(i_d) + 10V(I_{ss}) = 0.05(2 + \sin 2000\pi t)W$$

$$P_{av} = \frac{1}{T} \int_0^T 0.05(2 + \sin 2000\pi t) dt = 100mW$$

$$\text{Signal power developed in } R_L: \quad P_{ac} = \left(\frac{5}{\sqrt{2}} \right)^2 \frac{1}{1k\Omega} = 12.5mW \quad | \quad \eta = 100\% \frac{12.5mW}{100mW} = 12.5\%$$

15.92

15.93

$$P_{ac} = \frac{1}{T} \int_0^T \frac{v^2(t)}{R} dt = \frac{4}{T} \int_0^{\frac{T}{4}} \frac{\left(\frac{40t}{T}\right)^2}{R} dt = \frac{6400}{T^3 R} \int_0^{\frac{T}{4}} t^2 dt = \frac{100}{3R}$$

$$P_{av} = \frac{1}{T} \int_0^T 10i(t)dt = \frac{20}{T} \int_0^{\frac{T}{2}} i(t)dt = \frac{40}{T} \int_0^{\frac{T}{2}} \frac{40t}{TR} dt = \frac{1600}{T^2 R} \int_0^{\frac{T}{2}} t dt = \frac{50}{R} \quad | \quad \eta = 100\% \frac{\frac{100}{3R}}{\frac{50}{R}} = 66.7\%$$

15.94

*Problem 15.94(a) VBB = 0 V

VCC 3 0 DC 10

VEE 5 0 DC -10

VBB 2 1 DC 0

VS 1 0 DC 0 SIN(0 4 2000)

Q1 3 2 4 NBJT

Q2 5 1 4 PBJT

RL 4 0 2K

.MODEL NBJT NPN IS=5FA BF=60

.MODEL PBJT PNP IS=1FA BF=50

.OP

.TRAN 1U 2M

.FOUR 2000 V(4)

.PROBE

.END

*Problem 15.94(b) VBB = 1.3 V

VCC 3 0 DC 10

VEE 5 0 DC -10

VBB 2 1 DC 1.3

VS 1 0 DC 0 SIN(0 4 2000)

Q1 3 2 4 NBJT

Q2 5 1 4 PBJT

RL 4 0 2K

.MODEL NBJT NPN IS=5FA BF=60

.MODEL PBJT PNP IS=1FA BF=50

.OP

.TRAN 1U 2M

.FOUR 2000 V(4)

.PROBE

.END

(a)

HARMONIC FREQUENCY NORMALIZED		FOURIER	NORMALIZED	PHASE
NO	(HZ)	COMPONENT	COMPONENT	(DEG)
1	2.000E+03	3.056E+00	1.000E+00	-4.347E-01
2	4.000E+03	2.693E-02	8.811E-03	-1.300E+02
3	6.000E+03	2.112E-01	6.910E-02	-1.744E+02
4	8.000E+03	3.473E-02	1.136E-02	-1.550E+02
5	1.000E+04	7.718E-02	2.525E-02	-1.678E+02
6	1.200E+04	4.064E-02	1.330E-02	-1.679E+02
7	1.400E+04	3.179E-02	1.040E-02	-1.580E+02
8	1.600E+04	4.109E-02	1.345E-02	-1.736E+02
9	1.800E+04	2.127E-02	6.960E-03	-1.568E+02

TOTAL HARMONIC DISTORTION = 7.831458E+00 PERCENT with VBB = 0

(b)

HARMONIC FREQUENCY NORMALIZED		FOURIER	NORMALIZED	PHASE
NO	(HZ)	COMPONENT	COMPONENT	(DEG)
1	2.000E+03	3.853E+00	1.000E+00	2.544E-01
2	4.000E+03	1.221E-02	3.169E-03	6.765E+01
3	6.000E+03	1.537E-02	3.990E-03	9.046E+01
4	8.000E+03	1.504E-02	3.903E-03	5.520E+01
5	1.000E+04	1.501E-02	3.897E-03	5.500E+01
6	1.200E+04	1.531E-02	3.973E-03	4.231E+01
7	1.400E+04	1.435E-02	3.726E-03	3.680E+01
8	1.600E+04	1.467E-02	3.807E-03	2.823E+01
9	1.800E+04	1.382E-02	3.587E-03	2.087E+01

TOTAL HARMONIC DISTORTION = 1.064939E+00 PERCENT with VBB = 1.3 V

15.95

The current begins to limit at $i_E = \frac{V_{BE2}}{R} = \frac{0.7V}{10\Omega} = 70.0 \text{ mA}$.

$$v_S = 1000i_B + V_{BE1} + V_{BE2} + 250i_E = 1000 \frac{0.07}{101} + 0.7 + 0.7 + 250(0.07) = 19.6 \text{ V}$$

15.96

*Problem 15.96 – Figure 15.38

VCC 3 0 DC 50

VS 1 0 DC 1

R1 1 2 1K

Q1 3 2 4 NBJT

Q2 2 4 5 NBJT

R 4 5 10

RL 5 0 250

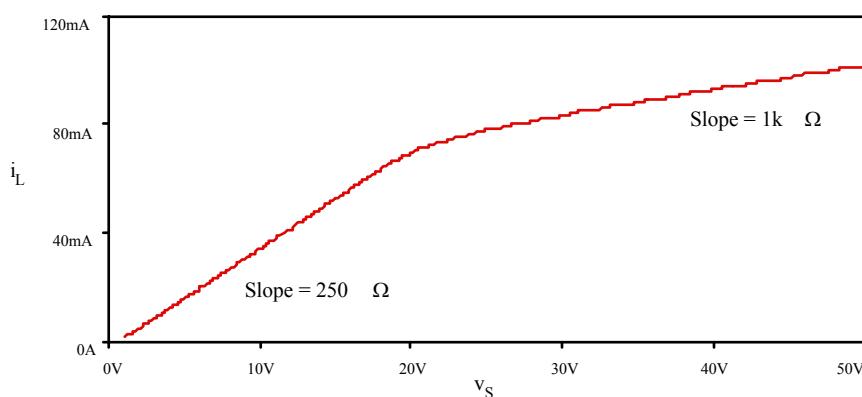
.MODEL NBJT NPN IS=1FA BF=100

.OP

.DC VS 1 50 .05

.PROBE

.END



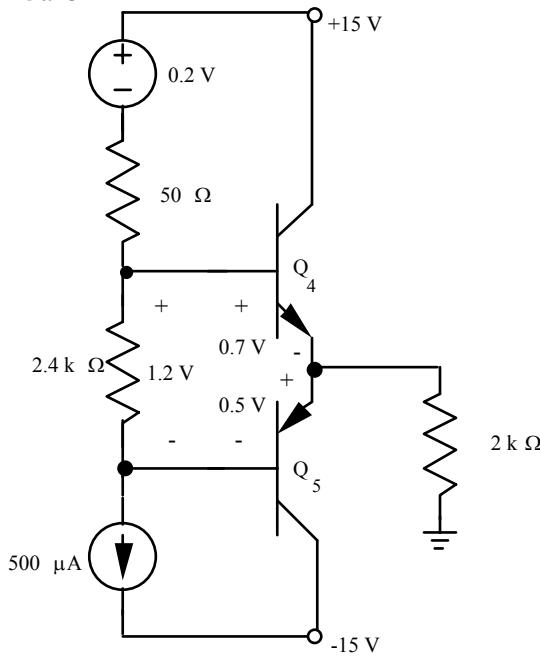
The results agree well with hand calculations.

15.97

$$I_2 R_G = V_{GS4} - V_{GS5} \quad | \quad (0.25 \text{ mA})(7k\Omega) = V_{TN4} + \sqrt{\frac{2I_{D4}}{0.005}} - \left(V_{TP5} - \sqrt{\frac{2I_{D5}}{0.002}} \right) \quad | \quad I_{D5} = I_{D4}$$

$$1.75 - 0.75 - 0.75 = \sqrt{I_{D4}} \left(\sqrt{\frac{2}{0.005}} + \sqrt{\frac{2}{0.002}} \right) \rightarrow I_{D5} = I_{D4} = 23.5 \mu\text{A}$$

15.98



For $V_{BE4} = 0.7V$, $V_{EB5} = I_2 R_B - V_{BE4}$
 $V_{EB5} = 1.2 - 0.7 = 0.5V$ and Q_5 is off.
 $V_{EQ} = 15 - 0.2 - 500\mu A(50\Omega) = 14.8V$
 $R_{EQ} = 50\Omega$

$$I_{C4} = 100 \frac{(14.8 - 0.7)V}{50\Omega + 101(2k\Omega)} = 6.98 mA$$

15.99

$$R_{out} = \frac{1}{n^2} \left(\frac{r_\pi}{\beta_o + 1} \right) = \frac{1}{100} \left(\frac{\beta_o}{\beta_o + 1} \right) \left(\frac{V_T}{I_C} \right) = \frac{1}{100} \left(\frac{V_T}{I_E} \right) = \frac{1}{100} \left(\frac{0.025V}{10mA} \right) = 25.0 m\Omega$$

15.100

$$I_C = 100I_B = 100 \frac{9 - 0.7}{200k\Omega + 101(82k\Omega)} \frac{V}{\Omega} = 97.9 \mu A \quad | \text{ Looking back into the}$$

transformer: $R_{th} = \frac{1}{n^2} \left(\frac{r_\pi}{\beta_o + 1} \right) \quad | \quad \frac{r_\pi}{\beta_o + 1} = \frac{1}{101} \frac{100(0.025V)}{97.9 \mu A} = 253\Omega$

Desire to match the Thevenin equivalent resistance to R_L : $\frac{1}{n^2} 253\Omega = 10\Omega \rightarrow n = 5.03$

$$v_{th} = \frac{(\beta_o + 1)n^2 R_L}{r_\pi + (\beta_o + 1)n^2 R_L} v_s = \frac{(101)253}{25.6k\Omega + (101)253} v_s = 0.500v_s \quad | \text{ Using the ideal transformer}$$

relationships: $v_{th} = i_1 R_{th} + n v_o \quad | \quad i_1 = \frac{1}{n} i_2 = \frac{1}{n} \frac{v_o}{R_L} \quad | \quad v_{th} = \frac{1}{n} \frac{v_o}{R_L} R_{th} + n v_o$

$$v_o = \frac{v_{th}}{n + \frac{R_{th}}{n R_L}} \quad | \quad v_o = \frac{0.500v_s}{5.03 + \frac{253\Omega}{5.03(10\Omega)}} = 0.0497v_s \quad | \quad v_o = 0.0497 \sin 2000\pi t$$

$$P_o = \left(\frac{0.0497}{\sqrt{2}} \right)^2 \frac{1}{10} = 0.124 mW$$

15.101

$$(a) V_{EQ} = -12V \frac{2M\Omega}{2M\Omega + 2M\Omega} = -6V \quad | \quad R_{EQ} = 2M\Omega \parallel 2M\Omega = 1M\Omega$$

$$I_o = 100I_B = 100 \frac{-6 - 0.7 - (-12)}{1M\Omega + 101(220k\Omega)} \frac{V}{\Omega} = 22.8 \mu A \quad | \quad r_\pi = \frac{100(0.025V)}{22.8\mu A} = 110k\Omega$$

$$V_{CE} = 12 - I_E(220k\Omega) = 12 - \frac{101}{100}(22.8\mu A)(220k\Omega) = 6.98V \quad | \quad r_o = \frac{(50 + 6.98)V}{22.8\mu A} = 2.50M\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 2.50M\Omega \left(1 + \frac{100(220k\Omega)}{1M\Omega + 110k\Omega + 220k\Omega} \right) = 43.9M\Omega$$

(b) Using the CVD model for the diode,

$$V_{EQ} = -12 + (12V - 0.7V) \frac{2M\Omega}{2M\Omega + 2M\Omega} + 0.7 = -5.65V \quad | \quad R_{EQ} = 2M\Omega \parallel 2M\Omega = 1M\Omega$$

$$I_o = 100I_B = 100 \frac{-5.65 - 0.7 - (-12)}{1M\Omega + 101(220k\Omega)} \frac{V}{\Omega} = 24.3 \mu A \quad | \quad r_\pi = \frac{100(0.025V)}{24.3\mu A} = 103k\Omega$$

$$V_{CE} = 12 - I_E(220k\Omega) = 12 - \frac{101}{100}(24.3\mu A)(220k\Omega) = 6.60V \quad | \quad r_o = \frac{(50 + 6.60)V}{24.3\mu A} = 2.33M\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 2.33M\Omega \left(1 + \frac{100(220k\Omega)}{1M\Omega + 103k\Omega + 220k\Omega} \right) = 41.1M\Omega$$

15.102

The dc analysis is the same as Problem 15.101. However, the bypass capacitor provides as ac ground at the base of the transistor so that $R_{th} = 0$.

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{r_\pi + R_E} \right) = 2.50M\Omega \left(1 + \frac{100(220k\Omega)}{110k\Omega + 220k\Omega} \right) = 169M\Omega$$

15.103

$$(a) V_{EQ} = -9V \frac{430k\Omega}{270k\Omega + 430k\Omega} = -5.53V \quad | \quad R_{EQ} = 270k\Omega \parallel 430k\Omega = 166k\Omega$$

$$I_o = 100I_B = 150 \frac{-5.53 - 0.7 - (-9)}{166k\Omega + 151(18k\Omega)} V = 144 \mu A \quad | \quad r_\pi = \frac{150(0.025V)}{144\mu A} = 26.0k\Omega$$

$$V_{CE} = 9 - I_E(18k\Omega) = 9 - \frac{151}{150}(144\mu A)(18k\Omega) = 6.39V \quad | \quad r_o = \frac{(75 + 6.39)V}{144\mu A} = 565k\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 565k\Omega \left(1 + \frac{150(18k\Omega)}{166k\Omega + 26.0k\Omega + 18k\Omega} \right) = 7.83 M\Omega$$

(b) Using the CVD model for the diode,

$$V_{EQ} = -9 + (9V - 0.7V) \left(\frac{270k\Omega}{270k\Omega + 430k\Omega} \right) + 0.7 = -5.10V \quad | \quad R_{EQ} = 270k\Omega \parallel 430k\Omega = 166k\Omega$$

$$I_o = 100I_B = 150 \frac{-5.10 - 0.7 - (-9)}{166k\Omega + 151(18k\Omega)} V = 166 \mu A \quad | \quad r_\pi = \frac{150(0.025V)}{166\mu A} = 22.6k\Omega$$

$$V_{CE} = 9 - I_E(18k\Omega) = 9 - \frac{151}{150}(166\mu A)(18k\Omega) = 5.99V \quad | \quad r_o = \frac{(75 + 5.99)V}{166\mu A} = 488k\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 488k\Omega \left(1 + \frac{150(18k\Omega)}{166k\Omega + 22.6k\Omega + 18k\Omega} \right) = 6.87 M\Omega$$

$$(c) V_{EQ} = -5V \frac{200k\Omega}{100k\Omega + 200k\Omega} = -3.33V \quad | \quad R_{EQ} = 100k\Omega \parallel 200k\Omega = 66.7k\Omega$$

$$I_o = 100I_B = 100 \frac{-3.33 - 0.7 - (-5)}{66.7k\Omega + 101(15k\Omega)} V = 61.3 \mu A \quad | \quad r_\pi = \frac{100(0.025V)}{61.3\mu A} = 40.8k\Omega$$

$$V_{CE} = 5 - I_E(15k\Omega) = 5 - \frac{101}{100}(61.3\mu A)(15k\Omega) = 4.07V \quad | \quad r_o = \frac{(75 + 4.07)V}{61.3\mu A} = 1.29 M\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 1.29 M\Omega \left(1 + \frac{100(15k\Omega)}{66.7k\Omega + 40.8k\Omega + 15k\Omega} \right) = 17.1 M\Omega$$

(d) Using the CVD model for the diode,

$$V_{EQ} = -5 + (5V - 0.7V) \left(\frac{100k\Omega}{100k\Omega + 200k\Omega} \right) + 0.7 = -2.87V \quad | \quad R_{EQ} = 100k\Omega \parallel 200k\Omega = 66.7k\Omega$$

$$I_o = 100I_B = 100 \frac{-2.87 - 0.7 - (-5)}{66.7k\Omega + 101(15k\Omega)} V = 90.4 \mu A \quad | \quad r_\pi = \frac{100(0.025V)}{90.4\mu A} = 27.7k\Omega$$

$$V_{CE} = 5 - I_E(15k\Omega) = 5 - \frac{101}{100}(90.4\mu A)(15k\Omega) = 3.63V \quad | \quad r_o = \frac{(75 + 3.63)V}{90.4\mu A} = 870k\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 870k\Omega \left(1 + \frac{100(15k\Omega)}{66.7k\Omega + 27.7k\Omega + 15k\Omega} \right) = 12.8 M\Omega$$

15.104

$$(a) V_{EQ} = -12V \frac{2M\Omega}{2M\Omega + 2M\Omega} = -6V \quad | \quad R_{EQ} = 2M\Omega \parallel 2M\Omega = 1M\Omega$$

$$I_O = 100I_B = 100 \frac{-6 - 0.7 - (-12)}{1M\Omega + 101(220k\Omega)} \frac{V}{\Omega} = 22.8 \mu A \quad | \quad r_\pi = \frac{100(0.025V)}{22.8\mu A} = 110k\Omega$$

$$V_{CE} = 12 - I_E(220k\Omega) = 12 - \frac{101}{100}(22.8\mu A)(220k\Omega) = 6.98V \quad | \quad r_o = \frac{(50 + 6.98)V}{22.8\mu A} = 2.50M\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 2.50M\Omega \left(1 + \frac{100(220k\Omega)}{1M\Omega + 110k\Omega + 220k\Omega} \right) = 43.9 M\Omega$$

(b) Using the CVD model for the diode (diode-connected transistor),

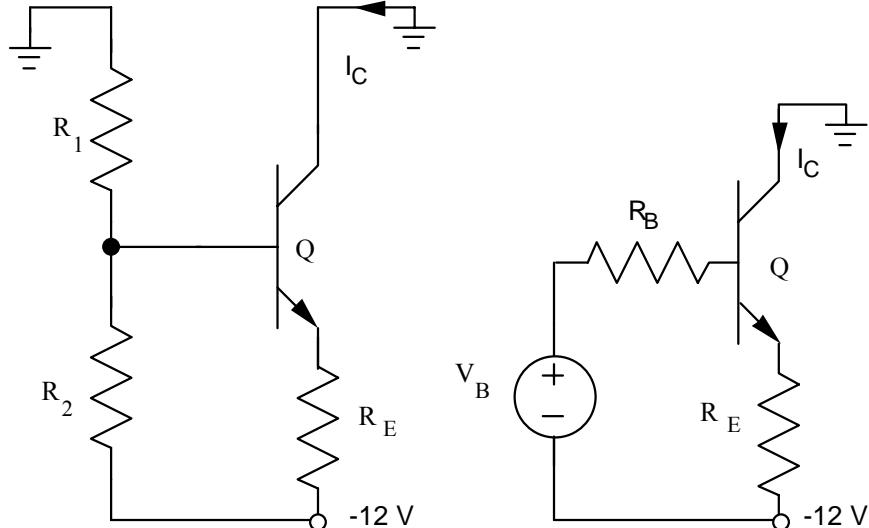
$$V_{EQ} = -12 + (12V - 0.7V) \frac{2M\Omega}{2M\Omega + 2M\Omega} + 0.7 = -5.65V \quad | \quad R_{EQ} = 2M\Omega \parallel 2M\Omega = 1M\Omega$$

$$I_O = 100I_B = 100 \frac{-5.65 - 0.7 - (-12)}{1M\Omega + 101(220k\Omega)} \frac{V}{\Omega} = 24.3 \mu A \quad | \quad r_\pi = \frac{100(0.025V)}{24.3\mu A} = 103k\Omega$$

$$V_{CE} = 12 - I_E(220k\Omega) = 12 - \frac{101}{100}(24.3\mu A)(220k\Omega) = 6.60V \quad | \quad r_o = \frac{(50 + 6.60)V}{24.3\mu A} = 2.33M\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 2.33M\Omega \left(1 + \frac{100(220k\Omega)}{1M\Omega + 103k\Omega + 220k\Omega} \right) = 41.1 M\Omega$$

15.105



A spread sheet will be used to assist in this design using $\beta_F = \beta_o = 100$ & $V_A = 70V$. The maximum current in the two bias resistors is 0.2mA. To allow some room for tolerances, choose $I_1 \approx 0.15mA$. Neglecting the transistor base current,

$$R_1 + R_2 = \frac{12V}{0.15mA} = 80k\Omega \quad | \quad R_2 = \frac{V_B}{12}(R_1 + R_2) = \frac{V_B}{12}80k\Omega \quad | \quad R_B = R_1 \parallel R_2$$

$$I_C = 100 \frac{(V_B - 0.7)}{R_B + 101R_E} \quad \text{or} \quad R_E = \frac{1}{101} \left(\frac{100(V_B - 0.7)}{I_C} - R_B \right) \quad | \quad V_{CE} = 12 - I_E R_E$$

$$r_o = \frac{70 + V_{CE}}{I_C} \quad | \quad R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_B + r_\pi + R_E} \right)$$

Now, a spreadsheet MATLAB, MATHCAD, etc. can be used to explore the design space with V_B as the primary design variable.

V_B	R_2	R_1	R_B	R_E	r_o	R_{out}	I_O
0.500	3.33E+03	7.67E+04	3.19E+03	-2.30E+02	-1.74E+05	5.57E+05	
0.600	4.00E+03	7.60E+04	3.80E+03	-1.37E+02	-8.00E+04	9.73E+04	
0.700	4.67E+03	7.53E+04	4.39E+03	-4.35E+01	1.41E+04	5.13E+03	
0.800	5.33E+03	7.47E+04	4.98E+03	4.97E+01	1.08E+05	1.80E+05	
0.900	6.00E+03	7.40E+04	5.55E+03	1.43E+02	2.03E+05	5.56E+05	
1.000	6.67E+03	7.33E+04	6.11E+03	2.37E+02	2.97E+05	1.09E+06	
1.100	7.33E+03	7.27E+04	6.66E+03	3.30E+02	3.91E+05	1.75E+06	
1.200	8.00E+03	7.20E+04	7.20E+03	4.24E+02	4.86E+05	2.52E+06	
1.300	8.67E+03	7.13E+04	7.73E+03	5.18E+02	5.81E+05	3.38E+06	
1.400	9.33E+03	7.07E+04	8.24E+03	6.11E+02	6.76E+05	4.31E+06	
1.500	1.00E+04	7.00E+04	8.75E+03	7.05E+02	7.71E+05	5.32E+06	
1.600	1.07E+04	6.93E+04	9.24E+03	8.00E+02	8.66E+05	6.38E+06	
1.700	1.13E+04	6.87E+04	9.73E+03	8.94E+02	9.61E+05	7.50E+06	
1.800	1.20E+04	6.80E+04	1.02E+04	9.88E+02	1.06E+06	8.68E+06	
1.900	1.27E+04	6.73E+04	1.07E+04	1.08E+03	1.15E+06	9.90E+06	
2.000	1.33E+04	6.67E+04	1.11E+04	1.18E+03	1.25E+06	1.12E+07	
Two possible solutions							
0.916	6.20E+03	7.50E+04	5.73E+03	1.50E+02	2.10E+05	5.85E+05	1.04E-03
1.800	1.20E+04	6.80E+04	1.02E+04	1.00E+03	1.07E+06	8.86E+06	9.89E-04

The first solution is the lowest value of V_B that was found to meet the output specification using the nearest 5% values. The second is one in which the values were found to be very close to existing standard 5% resistor values, but it uses twice the value of V_B and has a smaller output voltage compliance range.

15.106

$$V_{EQ} = \frac{330k\Omega}{330k\Omega + 680k\Omega} 10V = 3.27V \quad | \quad R_{EQ} = 330k\Omega \| 680k\Omega = 222k\Omega$$

Assume active region operation: $I_D = \left(\frac{5x10^{-4}}{2} \right) (V_{GS} - 1)^2$

$$V_{GS} = 3.27 - (33k\Omega)I_D = 3.27 - 33x10^3 \left(\frac{5x10^{-4}}{2} \right) (V_{GS} - 1)^2 \Rightarrow V_{GS} = 1.467V \quad | \quad I_o = I_D = 54.5 \mu A$$

$$V_{DS} = 10 - (33k\Omega)I_D = 8.20V \quad | \quad \text{Active region operation is correct.}$$

$$r_o = \frac{100 + 8.20}{54.5} \frac{V}{\mu A} = 1.99 M\Omega \quad | \quad g_m = \sqrt{2(5x10^{-4})(54.5x10^{-6})[1 + (0.01)8.20]} = 0.243 mS$$

$$R_{out} = r_o [1 + g_m (33x10^3)] = 1.99 M\Omega [1 + 0.243mS(33k\Omega)] = 17.9 M\Omega$$

15.107

$$V_{EQ} = \frac{68k\Omega}{68k\Omega + 200k\Omega} 3V = 0.760V \quad | \quad R_{EQ} = 68k\Omega \| 200k\Omega = 50.8k\Omega$$

$V_{EQ} < V_{TN}$, ($0.76V < 1V$) so the transistor is off, and $I_o = I_D = 0$.

The circuit designer made an error and failed to check the final design.

15.108

$$V_{EQ} = \frac{100k\Omega}{100k\Omega + 200k\Omega} 6V = 2V \quad | \quad R_{EQ} = 100k\Omega \| 200k\Omega = 66.7k\Omega$$

Assume active region operation: $2 = V_{GS} + (16k\Omega)I_D \quad | \quad I_D = \left(\frac{5x10^{-4}}{2} \right) (V_{GS} - 1)^2$

$$4V_{GS}^2 - 7V_{GS} + 2 = 0 \Rightarrow V_{GS} = 1.390V \quad | \quad I_o = I_D = 38.1 \mu A$$

$$V_{DS} = V_o - (16k\Omega)I_D = 6 - (16k\Omega)(38.1 \mu A) = 5.39V \quad | \quad \text{Active region is correct.}$$

$$r_o = \frac{100 + 5.39}{38.1} \frac{V}{\mu A} = 2.77 M\Omega \quad | \quad g_m = \sqrt{2(5x10^{-4})(38.1x10^{-6})[1 + 0.01(5.39)]} = 0.200 mS$$

$$R_{out} = r_o [1 + g_m (16x10^3)] = 2.77 M\Omega [1 + 0.200mS(16k\Omega)] = 11.6 M\Omega$$

15.109

$$V_{EQ} = 15V \frac{200k\Omega}{200k\Omega + 100k\Omega} = 10V \quad | \quad R_{EQ} = 200k\Omega \parallel 100k\Omega = 66.7k\Omega$$

$$I_o = 75I_B = 75 \frac{(15 - 0.7 - 10)V}{66.7k\Omega + 76(47k\Omega)} = 88.6 \mu A \quad | \quad r_\pi = \frac{75(0.025V)}{88.6\mu A} = 21.2k\Omega$$

$$V_{EC} = 15 - I_E R_E = 15 - \frac{76}{75}(88.6 \mu A)(47k\Omega) = 10.7V \quad | \quad r_o = \frac{(50 + 10.7)V}{88.6\mu A} = 685k\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 685k\Omega \left(1 + \frac{75(47k\Omega)}{66.7k\Omega + 21.2k\Omega + 47k\Omega} \right) = 18.6 M\Omega$$

15.110

$$V_{EQ} = 5V \frac{33k\Omega}{33k\Omega + 10k\Omega} = 3.84V \quad | \quad R_{EQ} = 33k\Omega \parallel 10k\Omega = 7.67k\Omega$$

$$I_o = 75I_B = 75 \frac{5 - 0.7 - 3.84}{7.67k\Omega + 76(1.5k\Omega)} V = 284 \mu A \quad | \quad r_\pi = \frac{75(0.025V)}{284\mu A} = 6.60k\Omega$$

$$V_{EC} = 5 - I_E R_E = 5 - \frac{76}{75}(284\mu A)(1.5k\Omega) = 4.57V \quad | \quad r_o = \frac{(60 + 4.57)V}{284\mu A} = 227k\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 227k\Omega \left(1 + \frac{75(1.5k\Omega)}{7.67k\Omega + 6.60k\Omega + 1.5k\Omega} \right) = 1.85 M\Omega$$

15.111

$$V_{EQ} = 10V \frac{300k\Omega}{300k\Omega + 100k\Omega} = 7.50V \quad | \quad R_{EQ} = 300k\Omega \parallel 100k\Omega = 75.0k\Omega$$

$$I_o = 90I_B = 90 \frac{10 - 0.7 - 7.50}{75.0k\Omega + 91(18k\Omega)} V = 94.6 \mu A \quad | \quad r_\pi = \frac{90(0.025V)}{94.6\mu A} = 23.4k\Omega$$

$$V_{EC} = 10 - I_E R_E = 10 - \frac{91}{90}(94.6\mu A)(18k\Omega) = 8.28V \quad | \quad r_o = \frac{(75 + 8.28)V}{94.6\mu A} = 880k\Omega$$

$$R_{out} = r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = 880k\Omega \left(1 + \frac{90(18k\Omega)}{75.0k\Omega + 23.4k\Omega + 18k\Omega} \right) = 13.1 M\Omega$$

15.112

$$V_{EQ} = \frac{200k\Omega}{200k\Omega + 100k\Omega} 6V = 4V \quad | \quad R_{EQ} = 200k\Omega \parallel 100k\Omega = 66.7k\Omega \quad | \quad 6 - 16x10^3 I_D + V_{GS} = 4$$

Assume active region operation: $I_D = \frac{7.5x10^{-4}}{2} (V_{GS} + 0.75)^2$

$$2 - 16x10^3 I_D + V_{GS} = 0 \Rightarrow V_{GS} = -1.13V \quad | \quad I_o = I_D = 54.3 \mu A$$

$$V_{DS} = -(6 - 16x10^3 I_D) = -5.13V \quad | \quad \text{Active region is correct.}$$

$$r_o = \frac{100 + 5.13}{54.3} \frac{V}{\mu A} = 1.94 M\Omega \quad | \quad g_m = \sqrt{2(7.5x10^{-4})(54.3x10^{-6})[1 + 0.01(5.13)]} = 0.292 mS$$

$$R_{out} = r_o (1 + g_m R_s) = 1.94 M\Omega [1 + 0.292 mS (16k\Omega)] = 11.0 M\Omega$$

15.113

$$V_{EQ} = 9V \frac{2M\Omega}{2M\Omega + 1M\Omega} = 6V \quad | \quad R_{EQ} = 2M\Omega \parallel 1M\Omega = 667k\Omega \quad | \quad 9 - 10^5 I_D + V_{GS} = 6$$

Assume active region operation: $V_{GS} = V_{TP} - \sqrt{\frac{2I_D}{K_p}}$

$$1.2x10^5 I_D = 3 + \left(-0.75 - \sqrt{\frac{2I_D}{7.5x10^{-4}}} \right) \Rightarrow I_o = I_D = 17.0 \mu A$$

$$V_{DS} = -(9 - 1.2x10^5 I_D) = -6.96V \quad | \quad \text{Active region is correct.}$$

$$r_o = \frac{100 + 6.96}{17.0} \frac{V}{\mu A} = 6.29 M\Omega \quad | \quad g_m = \sqrt{2(7.5x10^{-4})(17.0x10^{-6})[1 + 0.01(6.96)]} = 0.165 mS$$

$$R_{out} = r_o (1 + g_m R_s) = 6.29 M\Omega [1 + 0.165 mS (1.2x10^5)] = 131 M\Omega$$

15.114

$$V_{EQ} = \frac{200k\Omega}{200k\Omega + 62k\Omega} 4V = 3.05V \quad | \quad R_{EQ} = 200k\Omega \parallel 62k\Omega = 47.3k\Omega$$

Assume active region operation: $4 - 43x10^3 I_D + V_{GS} = 3.05 \quad | \quad I_D = \frac{7.5x10^{-4}}{2} (V_{GS} + 0.75)^2$

$$0.95 - 43x10^3 I_D + V_{GS} = 0 \Rightarrow V_{GS} = -0.6034V \quad | \quad I_o = I_D = 8.06 \mu A$$

$$V_{DS} = -(4 - 43x10^3 I_D) = -3.65V \quad | \quad \text{Active region is correct.}$$

$$r_o = \frac{100 + 3.65}{8.06} \frac{V}{\mu A} = 12.9 M\Omega \quad | \quad g_m = \sqrt{2(7.5x10^{-4})(8.06x10^{-6})[1 + 0.01(3.65)]} = 112 \mu S$$

$$R_{out} = r_o (1 + g_m R_s) = 12.9 M\Omega [1 + 112 \mu S (43k\Omega)] = 75.0 M\Omega$$

15.115

$$\text{Estimating } R_{out} \cong r_o(1 + g_m R_s) \cong \frac{50V}{1.75 \times 10^{-4}} \left(1 + \sqrt{2(2 \times 10^{-4})(1.75 \times 10^{-4})} R_s \right)$$

Note that including λ in the g_m expression will increase R_{out} above this estimate.

Hence neglecting λ represents a conservative simplification.

$$286k\Omega(1 + 2.65 \times 10^{-4} R_s) \geq 2.5M\Omega \Rightarrow R_s \geq 29.2k\Omega \quad | \quad \text{Choose } R_s = 33k\Omega$$

$$V_G = V_{DD} - I_D R_s + V_{GS} = 12 - 1.75 \times 10^{-4} (3.3 \times 10^4) + \left(-1 - \sqrt{\frac{2(1.75 \times 10^{-4})}{2 \times 10^{-4}}} \right) = 3.90V$$

$$\frac{R_4}{R_3 + R_4} 12 = 3.90 \quad | \quad I_2 \leq 25\mu A \quad | \quad \text{Assign } I_2 = 20\mu A \quad | \quad R_3 + R_4 = \frac{12V}{20\mu A} = 600k\Omega$$

$$R_4 = \frac{3.90}{12} (R_3 + R_4) = 195k\Omega \Rightarrow R_4 = 200k\Omega \quad | \quad R_3 = 430k\Omega$$

15.116

$$(a) V_{EQ} = -12V \frac{68k\Omega}{68k\Omega + 33k\Omega} = -8.08V \quad | \quad R_{EQ} = 68k\Omega \parallel 33k\Omega = 22.2k\Omega \quad | \quad V_B = -8.08 - (I_{B1} + I_{B2})R_{TH}$$

$$V_B = -8.08 - \left(\frac{V_B - 0.7 - (-12)}{126(20k\Omega)} + \frac{V_B - 0.7 - (-12)}{126(100k\Omega)} \right) 22.2k\Omega \rightarrow V_B = -8.11V$$

$$I_{C1} = \alpha_F I_{E1} = \frac{125}{126} \left(\frac{V_B - 0.7 - (-12)}{20k\Omega} \right) = 158 \mu A \quad | \quad I_{C2} = \alpha_F I_{E2} = \frac{125}{126} \left(\frac{V_B - 0.7 - (-12)}{100k\Omega} \right) = 31.7 \mu A$$

$$V_{CE} = 0 - (-8.11 - 0.7) = 8.87V \quad | \quad r_{o1} = \frac{(50 + 8.11)V}{158\mu A} = 368k\Omega \quad | \quad R_{th1} = R_{EQ} \parallel [r_{\pi2} + (\beta_o + 1)(100k\Omega)]$$

$$r_{\pi1} = \frac{125(0.025V)}{158 \mu A} = 19.8k\Omega \quad | \quad r_{\pi2} = \frac{125(0.025V)}{31.7 \mu A} = 98.6k\Omega$$

$$R_{th1} = 22.2k\Omega \parallel [98.6k\Omega + (126)(100k\Omega)] = 22.2k\Omega$$

$$R_{out1} = r_{o1} \left(1 + \frac{\beta_o R_E}{R_{th} + r_{\pi1} + R_E} \right) = 368k\Omega \left(1 + \frac{125(20k\Omega)}{22.2k\Omega + 19.8k\Omega + 20k\Omega} \right) = 15.2 M\Omega$$

$$r_{o2} = \frac{(50 + 8.11)V}{31.7 \mu A} = 1.83M\Omega \quad | \quad R_{th2} = R_{TH} \parallel [r_{\pi1} + (\beta_o + 1)(20k\Omega)]$$

$$R_{th2} = 22.2k\Omega \parallel [19.8k\Omega + (126)(20k\Omega)] = 22.0k\Omega$$

$$R_{out2} = r_{o2} \left(1 + \frac{\beta_o R_E}{R_{th} + r_{\pi2} + R_E} \right) = 1.83M\Omega \left(1 + \frac{125(100k\Omega)}{22.0k\Omega + 98.6k\Omega + 100k\Omega} \right) = 106 M\Omega$$

15.116 cont.

(b) Using the CVD model for diode Q₃ for dc calculations,

$$V_{EQ} = \frac{(12V - 0.7)}{68k\Omega + 33k\Omega} 68k\Omega = -7.61V \quad | \quad R_{EQ} = 68k\Omega \quad | \quad (33k\Omega) = 22.2k\Omega \quad | \quad V_B = -8.08 - (I_{B1} + I_{B2})R_{EQ}$$

$$V_B = -7.61 - \left(\frac{V_B - 0.7 - (-12)}{126(20k\Omega)} + \frac{V_B - 0.7 - (-12)}{126(100k\Omega)} \right) 22.2k\Omega \rightarrow V_B = -7.65V$$

$$I_{C1} = \alpha_F I_{E1} = \frac{125}{126} \left(\frac{V_B - 0.7 - (-12)}{20k\Omega} \right) = 181 \mu A \quad | \quad I_{C2} = \alpha_F I_{E2} = \frac{125}{126} \left(\frac{V_B - 0.7 - (-12)}{100k\Omega} \right) = 36.2 \mu A$$

$$V_{CE} = 0 - (-7.65 - 0.7) = 8.35V \quad | \quad r_{o1} = \frac{(50 + 8.35)V}{181\mu A} = 322k\Omega \quad | \quad R_{th1} = R_{EQ} \left[r_{\pi2} + (\beta_o + 1)(100k\Omega) \right]$$

$$r_{\pi1} = \frac{125(0.025V)}{181 \mu A} = 17.3k\Omega \quad | \quad r_{\pi2} = \frac{125(0.025V)}{36.2\mu A} = 86.3k\Omega$$

$$R_{th1} = 22.2k\Omega \left[86.3k\Omega + (126)(100k\Omega) \right] = 22.2k\Omega$$

$$R_{out1} = r_{o1} \left(1 + \frac{\beta_o R_E}{R_{th} + r_{\pi1} + R_E} \right) = 322k\Omega \left(1 + \frac{125(20k\Omega)}{22.2k\Omega + 17.3k\Omega + 20k\Omega} \right) = 13.9 M\Omega$$

$$r_{o2} = \frac{(50 + 8.35)V}{36.2\mu A} = 1.61M\Omega \quad | \quad R_{th2} = R_{TH} \left[r_{\pi1} + (\beta_o + 1)(20k\Omega) \right]$$

$$R_{th2} = 22.2k\Omega \left[17.3k\Omega + (126)(20k\Omega) \right] = 22.0k\Omega$$

$$R_{out2} = r_{o2} \left(1 + \frac{\beta_o R_E}{R_{th} + r_{\pi2} + R_E} \right) = 1.61M\Omega \left(1 + \frac{125(100k\Omega)}{22.0k\Omega + 86.3k\Omega + 100k\Omega} \right) = 98.2 M\Omega$$

15.117

$$V_{EQ} = -12V \frac{20k\Omega}{20k\Omega + 39k\Omega} = -4.07V \quad | \quad R_{EQ} = 20k\Omega \parallel 39k\Omega = 13.2k\Omega$$

$$I_B = -\left(\frac{1}{76} \frac{V_B + 0.7}{33k\Omega} + \frac{1}{76} \frac{V_B + 0.7}{16k\Omega} + \frac{1}{76} \frac{V_B + 0.7}{8.2k\Omega} \right) \quad | \quad V_B = -4.07V + 13200I_B \rightarrow V_B = -3.95V$$

$$I_{C1} = \frac{75}{76} \left(\frac{0 - 0.7V - (-3.95V)}{33k\Omega} \right) = 97.2\mu A \quad | \quad R_{out1} = r_{o1} \left(1 + \frac{\beta_o(33k\Omega)}{R_{th1} + r_{\pi1} + 33k\Omega} \right)$$

$$R_{th1} = 13.2k\Omega \parallel [r_{\pi2} + (\beta_{o2} + 1)16k\Omega] [r_{\pi3} + (\beta_{o3} + 1)8.2k\Omega] \cong 13.2k\Omega$$

$$R_{out1} = \frac{60 + 8.75}{97.2\mu A} \left(1 + \frac{75(33k\Omega)}{13.2k\Omega + 19.3k\Omega + 33k\Omega} \right) = 27.4 M\Omega$$

$$I_{C2} = \frac{75}{76} \left(\frac{0 - 0.7V - (-3.95V)}{16k\Omega} \right) = 201\mu A \quad | \quad R_{out2} = r_{o2} \left(1 + \frac{\beta_o(16k\Omega)}{R_{th2} + r_{\pi2} + 16k\Omega} \right)$$

$$R_{th2} = 13.2k\Omega \parallel [r_{\pi1} + (\beta_{o1} + 1)33k\Omega] [r_{\pi3} + (\beta_{o3} + 1)8.2k\Omega] \cong 13.2k\Omega$$

$$R_{out2} = \frac{60 + 8.75}{201\mu A} \left(1 + \frac{75(16k\Omega)}{13.2k\Omega + 9.33k\Omega + 16k\Omega} \right) = 11.0 M\Omega$$

$$I_{C3} = \frac{75}{76} \left(\frac{0 - 0.7V - (-3.95V)}{8.2k\Omega} \right) = 391\mu A \quad | \quad R_{out3} = r_{o3} \left(1 + \frac{\beta_o(8.2k\Omega)}{R_{th3} + r_{\pi2} + 8.2k\Omega} \right)$$

$$R_{th3} = 13.2k\Omega \parallel [r_{\pi1} + (\beta_{o1} + 1)33k\Omega] [r_{\pi2} + (\beta_{o2} + 1)16k\Omega] \cong 13.2k\Omega$$

$$R_{out3} = \frac{60 + 8.75}{391\mu A} \left(1 + \frac{75(8.2k\Omega)}{13.2k\Omega + 4.80k\Omega + 8.2k\Omega} \right) = 4.30 M\Omega$$

15.118

$$V_{EQ} = 12V \frac{2M\Omega}{2M\Omega + 2M\Omega} = 6.00V \quad | \quad R_{EQ} = 2M\Omega \parallel 2M\Omega = 1.00M\Omega$$

Assume saturation: $12 - 10^5 I_{D1} + V_{GS1} = 6 \quad | \quad V_{GS1} = -1 - \sqrt{\frac{2I_{D1}}{2.5 \times 10^{-4}}}$

$$I_{D1} = 44.1 \mu A, \quad V_{GS1} = -1.59V, \quad V_{DS1} = -(6 - V_{GS1}) = -7.59V$$

$$R_{out1} = r_{o1}(1 + g_{m1}R_i) = \frac{50V + 7.59V}{44.1 \mu A} \left(1 + 100k\Omega \sqrt{2(250\mu A)(44.1\mu A)[1 + 0.02(7.69)]} \right) = 22.2 M\Omega$$

$$12 - 4.7 \times 10^5 I_{D2} + V_{GS2} = 6 \quad | \quad V_{GS2} = -1 - \sqrt{\frac{2I_{D2}}{2.5 \times 10^{-4}}}$$

$$I_{D2} = 10.0 \mu A, \quad V_{GS2} = -1.28V, \quad V_{DS2} = -(6 - V_{GS2}) = -7.28V$$

$$R_{out2} = r_{o2}(1 + g_{m2}R_2) = \frac{50V + 7.28V}{10.0 \mu A} \left(1 + 470k\Omega \sqrt{2(250\mu A)(10.0\mu A)[1 + 0.02(7.28)]} \right) = 210 M\Omega$$

15.119

*Problem 15.119 – Figure P15.118

VCC 1 0 DC 12

R1 1 2 100K

R4 1 3 2MEG

R3 3 0 2MEG

R2 1 4 470K

M1 5 3 2 2 PFET

M2 6 3 4 4 PFET

VD1 5 0 DC 0

VD2 6 0 DC 0

.MODEL PFET PMOS VTO=-1 KP=250U LAMBDA=0.02

.OP

*.TF I(VD1) VD1

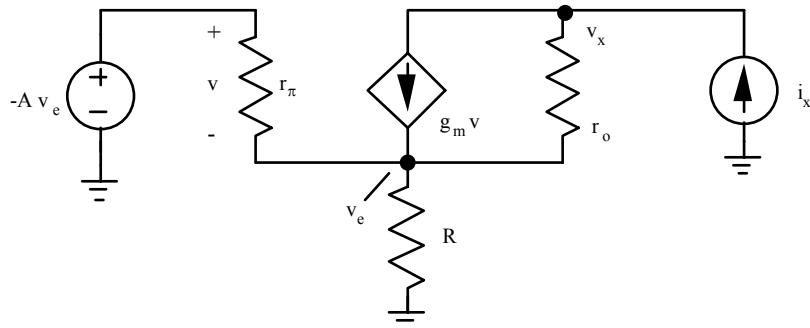
.TF I(VD2) VD2

.END

Results: $I_{O1} = 44.4 \mu A, R_{OUT1} = 22.1 M\Omega, I_{O1} = 10.1 \mu A, R_{OUT1} = 209 M\Omega$

15.120

For large A, $I_o \approx \alpha_F \frac{V_{REF}}{R} = \frac{120}{121} \frac{5V}{50k\Omega} = 99.2 \mu A$



For the small - signal model above,

$$v_x = v_e + (i_x - g_m v) r_o \quad | \quad v = (-Av_e) - v_e = -v_e(1+A) \quad | \quad i_x = Gv_e + g_\pi(1+A)v_e \quad | \quad \text{Combining:}$$

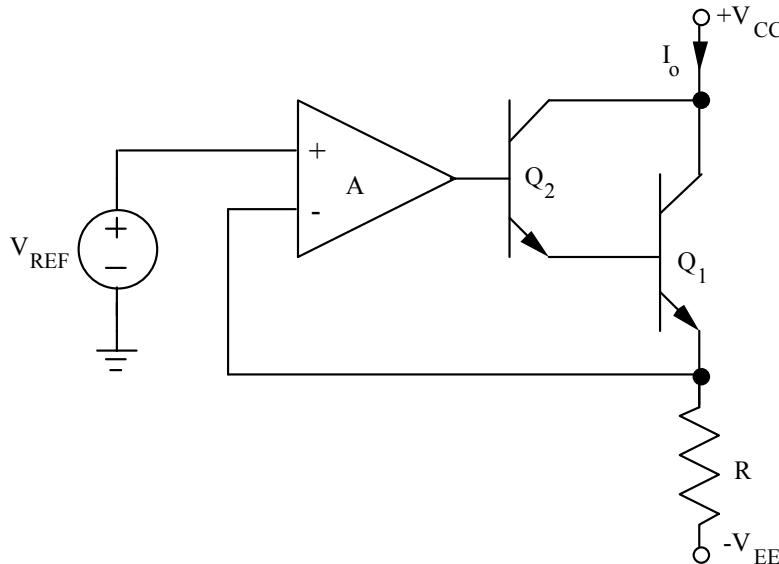
$$R_{out} = \frac{v_x}{i_x} = \frac{1 + \mu_f(1+A)}{G + g_\pi(1+A)} + \frac{1}{g_o} \approx r_o(1 + \beta_o) \text{ for } g_\pi(1+A) \gg G \text{ and } \mu_f(1+A) \gg 1$$

$$r_o = \frac{50V + 10V}{99.2 \mu A} = 605k\Omega \quad | \quad R_{out} = 605k\Omega(121) = 73.2 M\Omega$$

R_{out} cannot exceed $\beta_o r_o$ because of the loss of base current through r_π .

15.121

R_{OUT} is limited to $\beta_0 r_0$ of the BJT. We need to increase the effective current gain of the transistor which can be done by replacing Q_1 with a Darlington configuration of two transistors.

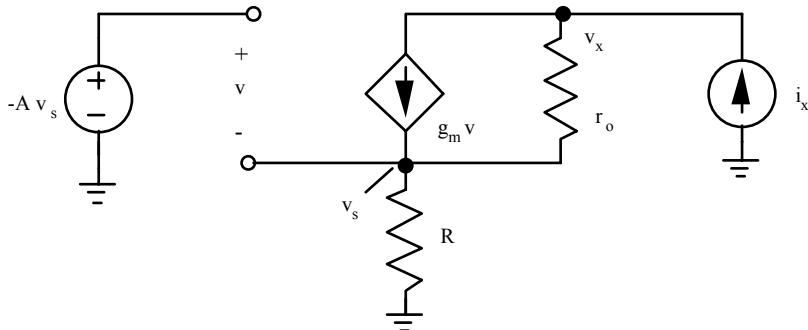


Now R_{OUT} can approach the $\beta_0 r_0$ product of the Darlington which is $R_{out} \approx \frac{2}{3} \beta_o^2 r_{o2}$. See Prob.

15.48

15.122

For large A, $I_o \cong \frac{V_{REF}}{R} = \frac{5V}{50k\Omega} = 100\mu A$



For the small-signal model above,

$$v_x = v_s + (i_x - g_m v) r_o \quad | \quad v = (-A v_s) - v_s = -v_s(1+A) \quad | \quad v_s = i_x R \quad | \quad \text{Combining :}$$

$$R_{out} = \frac{v_x}{i_x} = R + r_o [1 + g_m R (1+A)] \quad | \quad r_o = \frac{50V + 10V}{100\mu A} = 600k\Omega$$

$$g_m = \sqrt{2(8 \times 10^{-4})(10^{-4})[1 + 0.02(10)]} = 0.438mS$$

$$R_{out} = 50k\Omega + 600k\Omega [1 + 0.438mS(50k\Omega)(1 + 5 \times 10^4)] = 6.57 \times 10^{11}\Omega !!$$

15.123

$$(a) V_{EQ} = 12V \frac{91k\Omega}{91k\Omega + 30k\Omega} = 9.03V \quad | \quad R_{EQ} = 91k\Omega || 30k\Omega = 22.6k\Omega$$

$$I_{C3} = 85I_{B3} = 85 \frac{12 - 0.7 - 9.03}{22.6k\Omega + 86(240k\Omega)} \frac{V}{\Omega} = 9.34 \mu A$$

$$V_{EC3} = 12 - I_E R_E - 0.7 = 12 - \frac{86}{85}(9.34\mu A)(240k\Omega) - 0.7 = 9.03V$$

$$I_{C1} = I_{C2} = \alpha_F \frac{I_{C3}}{2} = \frac{85}{86} \left(\frac{9.34\mu A}{2} \right) = 4.62\mu A \quad | \quad V_{EC1} = V_{EC2} = 0.7 - [-12 + 1.2M\Omega(4.62\mu A)] = 7.16V$$

$$Q - \text{points : } (4.62\mu A, 7.16V), (4.62\mu A, 7.62V), (9.34\mu A, 9.03V)$$

$$(b) r_{\pi 3} = \frac{85(0.025V)}{9.34\mu A} = 228k\Omega \quad | \quad r_{o3} = \frac{(70 + 9.03)V}{9.34\mu A} = 8.46M\Omega$$

$$R_{out3} = r_{o3} \left(1 + \frac{\beta_o R_E}{R_{th} + r_{\pi 3} + R_E} \right) = 8.46M\Omega \left(1 + \frac{85(240k\Omega)}{22.6k\Omega + 228k\Omega + 240k\Omega} \right) = 360M\Omega$$

$$\text{For a single-ended output, } A_v = \frac{g_m R_C}{2} = 20(4.62\mu A)(1.2M\Omega) = +111 \quad (40.9dB)$$

$$CMRR = g_m R_{out3} = 40(4.62\mu A)(360M\Omega) = 6.65 \times 10^4 \quad (96.5dB)$$

(c) The answers are the same as parts (a) and (b).

15.124

$$(a) V_{EQ} = -15V \frac{100k\Omega}{100k\Omega + 51k\Omega} = -9.93V \quad | \quad R_{EQ} = 100k\Omega \parallel 51k\Omega = 33.8k\Omega \quad | \quad \text{Assume saturation :}$$

$$-9.93 = -15 + 7500I_{D3} + V_{GS3} \quad | \quad V_{GS3} = 1 + \sqrt{\frac{2I_{D3}}{4 \times 10^{-4}}} \quad | \quad I_{D3} = 363 \mu A, V_{GS3} = 2.35V$$

$$I_{D1} = I_{D2} = \frac{I_{D3}}{2} = 182 \mu A \quad | \quad V_{GS1} = 1 + \sqrt{\frac{2(363 \mu A)}{2(400 \mu A)}} = 1.95V$$

$$V_{DS3} = -V_{GS1} - 7500I_{D3} - (-15) = 10.3V$$

$$V_{DS1} = V_{DS2} = V_{D1} - V_{S1} = 15 - 36000I_{D1} - (-V_{GS1}) = 10.4V$$

$$(182 \mu A, 10.4V) \quad (182 \mu A, 10.4V) \quad (363 \mu A, 10.3V)$$

$$(b) r_{o3} = \frac{50V + 10.3V}{363 \mu A} = 166k\Omega$$

$$R_{out3} = r_{o3} \left(1 + g_{m3} R_s \right) = 166k\Omega \left(1 + \sqrt{2(4 \times 10^{-4})(3.63 \times 10^{-4})[1 + 0.02(10.3)]}(7.5k\Omega) \right) = 903 k\Omega$$

$$A_{dd} = -g_m (R_D \| r_{o2}) = -\sqrt{2(4 \times 10^{-4})(1.82 \times 10^{-4})[1 + 0.02(10.4)]}(36k\Omega \| 332k\Omega) = 0.419mS(325k\Omega) = -13.6$$

$$\text{For a single-ended output, } A_{cd} \cong -\frac{R_D}{2R_{out3}} = -\frac{36k\Omega}{2(903k\Omega)} = -0.199$$

$$CMRR = \left| \frac{13.6/2}{0.0199} \right| = 342 \text{ or } 50.7 \text{ dB}$$

The approximate CMRR estimate is $CMRR \cong g_{m1} R_{out3} = 0.419mS(903k\Omega) = 378 \text{ (51.6 dB)}$

15.125

Assuming all devices are identical, $R_{out} = \beta_{o1} \frac{r_{o1}}{2}$ since the collector current of the

current source is twice that of the input transistors. For a single-ended output,

$$A_{dd} = -\frac{g_{m1} R_C}{2} \quad | \quad A_{cc} = -\frac{R_C}{2 \left(\beta_{o1} \frac{r_{o1}}{2} \right)} = -\frac{R_C}{\beta_{o1} r_{o1}} \quad | \quad CMRR = \frac{g_{m1} \beta_{o1} r_{o1}}{2} = \frac{\beta_{o1} \mu_f}{2}$$

Using our default parameters: $CMRR \cong 20\beta_{o1}V_{A1} = 20(100)(70) = 140,000 \text{ (103dB)}$

(Note that this analysis neglects the contribution of the output resistance r_o of the input pair. If this resistance is included, a theoretical cancellation occurs and $A_{cc} = 0$! Of course the output resistance expression $R_{out} = \frac{\beta_o r_o}{2}$ is not precise, but an improvement over the CMRR expression above is possible.)

15.126

$$R_{out} = r_o(1 + g_m R_s) \cong \mu_F R_s = g_m r_o R_s \cong \sqrt{2K_n I_D} \frac{1}{\lambda I_D} R_s$$

$$V_{R_s} = I_D R_s = \frac{\lambda(I_D^{1.5}) R_{out}}{\sqrt{2K_n}} = \frac{0.02(10^{-4})^{1.5}(5 \times 10^6)}{\sqrt{2(5 \times 10^{-4})}} = 3.16 \text{ V}$$

15.127

*Problem 15.127 - Fig. 15.49(a) - BJT Current Source Monte Carlo Analysis

*Generate a Voltage Source with 5% Tolerances

```
IEE 0 5 DC 1
REE 5 0 RTOL 15
EEE 1 0 5 0 -1
*
VO 4 0 AC 1
RE 1 2 RTOL 18.4K
R1 1 3 RTOL 113K
R2 3 0 RTOL 263K
Q1 4 3 2 NBJT
.OP
.DC VO 0 0 .01
.AC LIN 1 1000 1000
.PRINT AC IM(VO) IP(VO)
.MODEL NBJT NPN BF=150 VA=75
.MODEL RTOL RES (R=1 DEV 5%)
.MC 1000 DC I(VO) YMAX
*.MC 1000 AC IM(VO) YMAX
.END
```

Results - 3σ limits: $I_O = 199 \mu A \pm 32.5 \mu A$, $R_{OUT} = 11.8 M\Omega \pm 2.6 M\Omega$

*Problem 15.127 - Fig. 15.49(b) - MOSFET Current Source

*Generate a Voltage Source with 5% Tolerance

```
IEE 0 5 DC 1
REE 5 0 RTOL 15
EEE 1 0 5 0 -1
*
VO 4 0 AC 1
RS 1 2 RTOL 18K
R3 1 3 RTOL 240K
R4 3 0 RTOL 510K
M1 4 3 2 2 NFET
.OP
.DC VO 0 0 .01
.AC LIN 1 1000 1000
.PRINT AC IM(VO) IP(VO)
.MODEL NFET NMOS KP=9.95M VTO=1 LAMBDA=0.01
.MODEL RTOL RES (R=1 DEV 5%)
.MC 1000 DC I(VO) YMAX
*.MC 1000 AC IM(VO) YMAX
.END
```

Results - 3σ limits: $I_O = 201 \mu A \pm 34.7 \mu A$, $R_{OUT} = 21.7 M\Omega \pm 3.6 M\Omega$

15.128

$$4.02k\Omega(1+0.15)(1-0.03) \leq R \leq 4.02k\Omega(1+0.15)(1+0.03) \quad | \quad 4.48k\Omega \leq R \leq 4.76k\Omega$$

15.129

$$I_{C1} = I_{S1} \exp\left(\frac{V_{BE1}}{V_T}\right) \quad | \quad I_{C2} = I_{S2} \exp\left(\frac{V_{BE2}}{V_T}\right) \quad | \quad \frac{I_{C2}}{I_{C1}} = \frac{I_{S2}}{I_{S1}} \exp\left(\frac{V_{BE2}-V_{BE1}}{V_T}\right) \quad | \quad \Delta V_{BE} = V_{BE2} - V_{BE1}$$

$$\Delta I_S = I_{S1} - I_{S2} \quad | \quad I_S = \frac{I_{S1} + I_{S2}}{2} \quad | \quad I_{S1} = I_S \left(1 + \frac{\Delta I_S}{2I_S}\right) \quad | \quad I_{S2} = I_S \left(1 - \frac{\Delta I_S}{2I_S}\right)$$

$$(a) I_{C2} = I_{C1} : \quad \Delta V_{BE} = V_T \ln\left(\frac{I_{C2}}{I_{C1}} \frac{I_{S1}}{I_{S2}}\right) = 0.025 \ln\left[\left(1 + \frac{\Delta I_S}{2I_S}\right)\left(1 - \frac{\Delta I_S}{2I_S}\right)^{-1}\right] = 0.025 \ln\left[\frac{(1.05)}{(0.95)}\right] = 2.50 \text{ mV}$$

$$(b) \Delta V_{BE} = 0.025 \ln\left[\frac{(1.10)}{(0.90)}\right] = 5.02 \text{ mV}$$

$$(c) \frac{I_{S1}}{I_{S2}} = \frac{\left(1 + \frac{\Delta I_S}{I_S}\right)}{\left(1 - \frac{\Delta I_S}{I_S}\right)} = \exp\left(\frac{V_{BE2}-V_{BE1}}{V_T}\right) = \exp\left(\frac{0.001}{0.025}\right) = 1.04 \rightarrow \frac{\Delta I_S}{I_S} = 0.02 \text{ or } 2\%$$

15.130

(a) For $v_1 = 0 = v_2$, $V_{BE1} = V_{BE2}$ and the collector currents are the same.

So, $V_{OS} = 0$. Only the base currents will be mismatched.

$$(b) I_{C1} = I_s \left(1 - 0.025\right) \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE}}{V_A}\right) \quad | \quad I_{C2} = I_s \left(1 + 0.025\right) \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE}}{V_A}\right)$$

$$\Delta I_C = I_{C2} - I_{C1} = 0.05 I_s \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE}}{V_A}\right) \quad | \quad I_C = \frac{I_{C1} + I_{C2}}{2} = I_s \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE}}{V_A}\right)$$

$$V_{OS} = \frac{\Delta I_C}{g_m} = V_T \frac{\Delta I_C}{I_C} = 0.025V(0.05) = 1.25 \text{ mV}$$

$$(c) I_{C1} = I_s \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE}}{V_A(1+0.025)}\right) \quad | \quad I_{C2} = I_s \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE}}{V_A(1-0.025)}\right)$$

$$\Delta I_C = I_{C2} - I_{C1} \cong I_s \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 - 1.025 \frac{V_{CE}}{V_A} - 1 + 0.975 \frac{V_{CE}}{V_A}\right) = I_s \exp\left(\frac{V_{BE}}{V_T}\right) \left(0.05 \frac{V_{CE}}{V_A}\right)$$

$$I_C = \frac{I_{C1} + I_{C2}}{2} = I_s \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE}}{V_A}\right) \quad | \quad V_{OS} = \frac{\Delta I_C}{g_m} = V_T \frac{\Delta I_C}{I_C} = 0.025V(0.05) \left(\frac{\frac{V_{CE}}{V_A}}{1 + \frac{V_{CE}}{V_A}}\right)$$

For $\frac{V_{CE}}{V_A} = 0.1$, $V_{OS} = 114 \mu V$

$$(d) V_{OD} = I_C \left[(R_C + 0.025R_C) - (R_C - 0.025R_C) \right] = 0.05I_C R_C$$

$$V_{OS} = \frac{V_{OD}}{g_m R_C} = V_T \frac{V_{OD}}{I_C R_C} = 0.025V(0.05) = 1.25 \text{ mV}$$

15.131

$$I_{S1} \exp\left(\frac{V_{BE1}}{V_T}\right) = I_{S2} \exp\left(\frac{V_{BE1} + 0.002}{V_T}\right) \quad | \quad \frac{I_{S1}}{I_{S2}} = \exp\left(\frac{0.002}{0.025}\right) = 1.08 \quad | \quad I_{S1} = 1.08 I_{S2}$$

$$\Delta I_S = I_{S1} - I_{S2} = 0.08 I_{S2} \quad | \quad I_S = \frac{I_{S1} + I_{S2}}{2} = 1.04 I_{S2} \quad | \quad \frac{\Delta I_S}{I_S} = \frac{0.08}{1.04} = 7.7\%$$

$$\beta_{F1} = 100 \left(1 + 0.025 \left(1 + \frac{10V}{50V}\right)\right) = 123 \quad | \quad \beta_{F2} = 100 \left(1 - 0.025 \left(1 + \frac{10V}{50V}\right)\right) = 117$$

$$I_{B1} = \frac{100 \mu A}{123} = 0.813 \mu A \quad | \quad I_{B2} = \frac{100 \mu A}{117} = 0.855 \mu A$$

Note: $I_{OS} = -42.0 \text{ nA}$.

15.132

$$(a) I_D = \frac{(250)(1 \pm 0.05)}{2} \frac{\mu A}{V^2} [2 - (1 \pm 0.025)]^2 \quad | \quad I_D^{\max} = \frac{(250)(1 + 0.05)}{2} \frac{\mu A}{V^2} [1 + 0.025]^2 = 138 \mu A$$

$$I_D^{\min} = \frac{(250)(1 - 0.05)}{2} \frac{\mu A}{V^2} [1 - 0.025]^2 = 113 \mu A$$

$$I_D = \frac{138 \mu A + 113 \mu A}{2} = 125.5 \mu A \quad | \quad \Delta I_D = 138 \mu A - 113 \mu A = 25 \mu A \quad | \quad \frac{\Delta I_D}{I_D} = 19.8\%$$

$$(b) I_D^{\max} = \frac{(250)(1 + 0.05)}{2} \frac{\mu A}{V^2} [3 + 0.025]^2 = 1.20 mA$$

$$I_D^{\min} = \frac{(250)(1 - 0.05)}{2} \frac{\mu A}{V^2} [3 - 0.025]^2 = 1.05 mA$$

$$I_D = \frac{1.20 mA + 1.05 mA}{2} = 1.125 mA \quad | \quad \Delta I_D = 1.20 mA - 1.05 mA = 0.150 mA \quad | \quad \frac{\Delta I_D}{I_D} = 13.3\%$$

15.133

$$V_{GS1} = V_{TN} + \sqrt{\frac{2I_{DS1}}{K_n' \left(\frac{W}{L}\right)_1}} = V_{TN} + \sqrt{\frac{2I_{DS1}}{K_n' \left(\frac{W}{L}\right)}} \sqrt{\frac{1}{1 + \frac{\Delta(W/L)}{2(W/L)}}} \approx V_{TN} + \sqrt{\frac{2I_{DS1}}{K_n' \left(\frac{W}{L}\right)}} \left(1 - \frac{\Delta(W/L)}{4(W/L)}\right)$$

$$V_{GS2} = V_{TN} + \sqrt{\frac{2I_{DS2}}{K_n' \left(\frac{W}{L}\right)_2}} = V_{TN} + \sqrt{\frac{2I_{DS2}}{K_n' \left(\frac{W}{L}\right)}} \sqrt{\frac{1}{1 - \frac{\Delta(W/L)}{2(W/L)}}} \approx V_{TN} + \sqrt{\frac{2I_{DS2}}{K_n' \left(\frac{W}{L}\right)}} \left(1 + \frac{\Delta(W/L)}{4(W/L)}\right)$$

$$I_{DS2} = I_{DS1} : V_{GS2} - V_{GS1} = \sqrt{\frac{2I_{DS2}}{K_n' \left(\frac{W}{L}\right)}} \left(\frac{\Delta(W/L)}{2(W/L)} \right) = (V_{GS} - V_{TN}) \left(\frac{\Delta(W/L)}{2(W/L)} \right)$$

$$(a) \Delta V_{GS} = (V_{GS} - V_{TN}) \left(\frac{\Delta(W/L)}{2(W/L)} \right) = (0.5) \left(\frac{0.10}{2} \right) = 25 mV$$

$$(b) \frac{\Delta(W/L)}{(W/L)} = 2 \frac{\Delta V_{GS}}{(V_{GS} - V_{TN})} = 2 \frac{0.003}{0.5} = 1.2 \% \quad | \quad (c) \frac{\Delta(W/L)}{(W/L)} = 2 \frac{\Delta V_{GS}}{(V_{GS} - V_{TN})} = 2 \frac{0.001}{0.5} = 0.4 \%$$

15.134

(a) Assume active region operation: $\Delta I_D = I_{D2} - I_{D1} = \left[\left(\frac{W}{L} \right)_2 - \left(\frac{W}{L} \right)_1 \right] \frac{K_n'}{2} (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS})$

$$\Delta I_D = 0.05 I_D \quad | \quad V_{OS} = \frac{\Delta I_D}{g_m} = (V_{GS} - V_{TN}) \frac{\Delta I_D}{2I_D} = 0.75V \left(\frac{0.05}{2} \right) = 18.8 \text{ mV}$$

(b) $\Delta I_D = I_{D2} - I_{D1} = \frac{K_n'}{2} (1 + \lambda V_{DS}) [(V_{GS} - V_{TN} + 0.025V_{TN})^2 - (V_{GS} - V_{TN} - 0.025V_{TN})^2]$

$$\Delta I_D = \frac{K_n'}{2} (1 + \lambda V_{DS}) (0.1V_{TN}) (V_{GS} - V_{TN}) = (0.1V_{TN}) \frac{I_D}{(V_{GS} - V_{TN})}$$

$$V_{OS} = \frac{\Delta I_D}{g_m} = (V_{GS} - V_{TN}) \frac{\Delta I_D}{2I_D} = 0.05 V_{TN} \quad | \quad \text{If } V_{TN} = 1V, V_{OS} = 50 \text{ mV}$$

(c) $\Delta I_D = I_{D2} - I_{D1} = \frac{K_n'}{2} (V_{GS} - V_{TN})^2 [(1 + \lambda V_{DS} + 0.025\lambda V_{DS}) - (1 + \lambda V_{DS} - 0.025\lambda V_{DS})]$

$$\Delta I_D = I_{D2} - I_{D1} = I_D \frac{0.05\lambda V_{DS}}{1 + \lambda V_{DS}} \quad | \quad V_{OS} = \frac{\Delta I_D}{g_m} = (V_{GS} - V_{TN}) \frac{\Delta I_D}{2I_D} = 0.75V \left(\frac{0.05}{2} \right) \left(\frac{\lambda V_{DS}}{1 + \lambda V_{DS}} \right)$$

If $\lambda V_{DS} = 0.1$, $V_{OS} = 1.71 \text{ mV}$

(d) $V_{OD} = I_D [(R_D + 0.025R_D) - (R_D - 0.025R_D)] = 0.05I_D R_D$

$$V_{OS} = \frac{V_{OD}}{A_{vt}} = \frac{V_{OD}}{g_m R_D} = \frac{0.05I_D}{2I_D} (V_{GS} - V_{TN}) = 0.025(0.75V) = 18.8 \text{ mV}$$

15.135

(a) $I_{ox} = \left(\frac{W}{L} \right)_X I_{REF} \frac{1 + \lambda V_{DSX}}{1 + \lambda V_{DS1}} \quad | \quad R_{outX} = \frac{1}{\lambda} + V_{DSX}$

$$V_{DS1} = V_{GS1} = V_{TN} + \sqrt{\frac{2I_{D1}}{K_n}} = 0.75 + \sqrt{\frac{2(30 \times 10^{-6})}{4(25 \times 10^{-6})}} = 1.52V$$

$$I_{o2} = \frac{10}{4} (30\mu A) \frac{1 + 0.015(10)}{1 + 0.015(1.52)} = 84.3\mu A \quad | \quad R_{out2} = \frac{1}{0.015} + 10 = 909k\Omega$$

$$I_{o3} = \frac{20}{4} (30\mu A) \frac{1 + 0.015(8)}{1 + 0.015(1.52)} = 164\mu A \quad | \quad R_{out3} = \frac{1}{0.015} + 8 = 455k\Omega$$

$$I_{o4} = \frac{40}{4} (30\mu A) \frac{1 + 0.015(12)}{1 + 0.015(1.52)} = 346\mu A \quad | \quad R_{out4} = \frac{1}{0.015} + 12 = 227k\Omega$$

15.135 cont.

$$(b) I_{ox} = \frac{\left(\frac{W}{L}\right)_X}{\left(\frac{W}{L}\right)_1} I_{REF} \frac{1 + \lambda V_{DSX}}{1 + \lambda V_{DS1}} \quad | \quad R_{outX} = \frac{\frac{1}{\lambda} + V_{DSX}}{I_{ox}}$$

$$V_{DS1} = V_{GS1} = V_{TN} + \sqrt{\frac{2I_{D1}}{K_n}} = 0.75 + \sqrt{\frac{2(50 \times 10^{-6})}{4(25 \times 10^{-6})}} = 1.75V$$

$$I_{o2} = \frac{10}{4} (50 \mu A) \frac{1 + 0.015(10)}{1 + 0.015(1.75)} = 140 \mu A \quad | \quad R_{out2} = \frac{\frac{1}{0.015} + 10}{140 \mu A} = 548 k\Omega$$

$$I_{o3} = \frac{20}{4} (50 \mu A) \frac{1 + 0.015(8)}{1 + 0.015(1.75)} = 273 \mu A \quad | \quad R_{out3} = \frac{\frac{1}{0.015} + 8}{273 \mu A} = 274 k\Omega$$

$$I_{o4} = \frac{40}{4} (50 \mu A) \frac{1 + 0.015(12)}{1 + 0.015(1.75)} = 575 \mu A \quad | \quad R_{out4} = \frac{\frac{1}{0.015} + 12}{575 \mu A} = 137 k\Omega$$

$$(c) I_{o2} = \frac{10}{4} (30 \mu A) = 75 \mu A \quad | \quad R_{out2} = \infty \quad | \quad I_{o3} = \frac{20}{4} (30 \mu A) = 150 \mu A \quad | \quad R_{out3} = \infty$$

$$I_{o4} = \frac{40}{4} (30 \mu A) = 300 \mu A \quad | \quad R_{out4} = \infty$$

15.136

$$(a) I_{ox} = \frac{\left(\frac{W}{L}\right)_X}{\left(\frac{W}{L}\right)_1} I_{REF} \frac{1 + \lambda V_{DSX}}{1 + \lambda V_{DS1}} \quad | \quad V_{DS1} = V_{GS1} = V_{TN} + \sqrt{\frac{2I_{D1}}{K_n}} = 0.75 + \sqrt{\frac{2(30 \times 10^{-6})}{2.5(25 \times 10^{-6})}} = 1.73V$$

$$I_{o2} = \frac{10}{2.5} (30 \mu A) \frac{1 + 0.015(10)}{1 + 0.015(1.73)} = 135 \mu A \quad | \quad I_{o3} = \frac{20}{2.5} (30 \mu A) \frac{1 + 0.015(8)}{1 + 0.015(1.73)} = 262 \mu A$$

$$I_{o4} = \frac{40}{2.5} (30 \mu A) \frac{1 + 0.015(12)}{1 + 0.015(1.73)} = 552 \mu A$$

$$(b) V_{DS1} = 0.75 + \sqrt{\frac{2(20 \times 10^{-6})}{6(25 \times 10^{-6})}} = 1.27V \quad | \quad I_{o2} = \frac{10}{6} (20 \mu A) \frac{1 + 0.015(10)}{1 + 0.015(1.27)} = 37.6 \mu A$$

$$I_{o3} = \frac{20}{6} (20 \mu A) \frac{1 + 0.015(8)}{1 + 0.015(1.27)} = 73.3 \mu A \quad | \quad I_{o4} = \frac{40}{6} (20 \mu A) \frac{1 + 0.015(12)}{1 + 0.015(1.27)} = 154 \mu A$$

15.137

$$(a) \text{For } \lambda = 0, I_{o2} = 30\mu A \left(\frac{10}{4} \right) = 75\mu A, I_{o3} = 30\mu A \left(\frac{20}{4} \right) = 150\mu A, I_{o4} = 30\mu A \left(\frac{40}{4} \right) = 300\mu A$$

(b) From Prob. 16.8, $I_{o2} = 84.3\mu A$, $I_{o3} = 164\mu A$, $I_{o4} = 346\mu A$

$$\frac{\Delta I_{o2}}{I_{o2}} = \frac{84.3 - 75}{75} = 0.124 \text{ LSB}, \quad \frac{\Delta I_{o3}}{I_{o2}} = \frac{164 - 150}{75} = 0.187 \text{ LSB}, \quad \frac{\Delta I_{o4}}{I_{o2}} = \frac{346 - 300}{75} = 0.613 \text{ LSB}$$

15.138

*Problem 15.135(a) - NMOS Current Source Array

IREF 0 1 DC 30U

VD2 2 0 DC 10 AC 1

VD3 3 0 DC 8 AC 1

VD4 4 0 DC 12 AC 1

M1 1 1 0 0 NFET W=4U L=1U

M2 2 1 0 0 NFET W=10U L=1U

M3 3 1 0 0 NFET W=20U L=1U

M4 4 1 0 0 NFET W=40U L=1U

.MODEL NFET NMOS KP=25U VTO=0.75 LAMBDA=0.015

.OP

.AC LIN 1 1000 1000

.PRINT AC IM(VD2) IM(VD3) IM(VD4) IP(VD2) IP(VD3) IP(VD4)

.END

The results are identical to the hand calculations.

15.139

$$I_{D1} = \frac{5 + V_{GS1}}{R} + \frac{15 \times 10^{-6}}{2} \left(\frac{2}{1} \right) (V_{GS1} + 0.9)^2 (1 - 0.01V_{GS1}) = \frac{5 + V_{GS1}}{3 \times 10^4} \rightarrow V_{GS1} = -2.985V$$

$$I_{REF} = \frac{5 - 2.985}{3 \times 10^4} = 67.2\mu A$$

$$I_{o2} = \frac{15 \times 10^{-6}}{2} \left(\frac{8}{1} \right) (-2.985 + 0.9)^2 [1 - 0.01(-5)] = 274\mu A \quad | \quad R_{out2} = \frac{\frac{1}{\lambda} + |V_{DS2}|}{I_{o2}} = \frac{100 + 5}{274\mu A} = 383k\Omega$$

$$I_{o3} = \frac{15 \times 10^{-6}}{2} \left(\frac{16}{1} \right) (-2.985 + 0.9)^2 [1 - 0.01(-10)] = 574\mu A \quad | \quad R_{out3} = \frac{100 + 10}{574\mu A} = 192k\Omega$$

15.140

$$(a) I_{D1} = \frac{5 + V_{GS1}}{R} + \frac{15 \times 10^{-6}}{2} \left(\frac{3.3}{1} \right) (V_{GS1} + 0.9)^2 (1 - 0.01 V_{GS1}) = \frac{5 + V_{GS1}}{3 \times 10^4} \rightarrow V_{GS1} = -2.655V$$

$$I_{REF} = \frac{5 - 2.655}{3 \times 10^4} = 78.2 \mu A \quad | \quad I_{O2} = \frac{15 \times 10^{-6}}{2} \left(\frac{8}{1} \right) (-2.655 + 0.9)^2 [1 - 0.01(-5)] = 194 \mu A$$

$$I_{O3} = \frac{15 \times 10^{-6}}{2} \left(\frac{16}{1} \right) (-2.655 + 0.9)^2 [1 - 0.01(-10)] = 407 \mu A$$

$$(b) I_{D1} = \frac{5 + V_{GS1}}{R} + \frac{15 \times 10^{-6}}{2} \left(\frac{4}{1} \right) (V_{GS1} + 0.9)^2 (1 - 0.01 V_{GS1}) = \frac{5 + V_{GS1}}{5 \times 10^4} \rightarrow V_{GS1} = -2.241V$$

$$I_{REF} = \frac{5 - 2.241}{3 \times 10^4} = 55.2 \mu A \quad | \quad I_{O2} = \frac{15 \times 10^{-6}}{2} \left(\frac{8}{1} \right) (-2.241 + 0.9)^2 [1 - 0.01(-5)] = 113 \mu A$$

$$I_{O3} = \frac{15 \times 10^{-6}}{2} \left(\frac{16}{1} \right) (-2.241 + 0.9)^2 [1 - 0.01(-10)] = 237 \mu A$$

15.141

*Problem 15.141 - PMOS Current Source Array
 RREF 0 1 30K
 VSS 4 0 DC 5
 VD2 2 0 DC 0 AC 1
 VD3 3 0 DC -5 AC 1
 M1 1 1 4 4 PFET W=2U L=1U
 M2 2 1 4 4 PFET W=8U L=1U
 M3 3 1 4 4 PFET W=16U L=1U
 .MODEL PFET PMOS KP=15U VTO=-0.9 LAMBDA=0.01
 .OP
 .AC LIN 1 1000 1000
 .PRINT AC IM(VD2) IM(VD3) IP(VD2) IP(VD3)
 .END

The results are identical to the hand calculations.

15.142

$$I_{D2} = \frac{K_p'}{2} \left(\frac{W}{L} \right) (V_{GS2} - V_{TP})^2 [1 + \lambda |V_{DS2}|] \quad | \quad 55 \times 10^{-6} = \frac{15 \times 10^{-6}}{2} \left(\frac{8}{1} \right) (V_{GS1} + 0.9)^2 [1 + 0.01(-5)]$$

$$V_{GS1} = -1.834V \quad | \quad \frac{I_{D2}}{I_{REF}} = \frac{\left(\frac{W}{L} \right)_2 [1 + \lambda |V_{DS2}|]}{\left(\frac{W}{L} \right)_1 [1 + \lambda |V_{DS1}|]} \quad | \quad \frac{55 \mu A}{I_{REF}} = \frac{\left(\frac{8}{1} \right)_2 [1 + 0.01(5)]}{\left(\frac{2}{1} \right)_1 [1 + 0.01(1.834)]} \rightarrow I_{REF} = 13.3 \mu A$$

$$I_{REF} = \frac{5 + V_{GS1}}{R} \quad | \quad R = \frac{5 - 1.834}{13.3 \mu A} = 238 k\Omega$$

15.143

$$(a) I_{REF} = \frac{12 - 0.7}{7.5 \times 10^4} = 151 \mu A \quad | \quad I_{REF} = I_{C1} + (1 + 5 + 8.3)I_B \quad | \quad I_{REF} = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}\right)$$

$$I_{O2} = 5I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE2}}{V_A}\right) = 5I_{REF} \frac{\frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}}}{1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}} \quad | \quad I_{O2} = 5(151 \mu A) \frac{\frac{1 + \frac{5}{60}}{1 + \frac{14.3}{50} + \frac{0.7}{60}}}{1 + \frac{14.3}{50} + \frac{0.7}{60}} = 631 \mu A$$

$$R_{out2} = r_{o2} = \frac{V_A + V_{CE2}}{I_{C2}} = \frac{60 + 5}{6.31 \times 10^{-4}} = 103 k\Omega$$

$$I_{O3} = 8.3I_{REF} \frac{\frac{1 + \frac{V_{CE3}}{V_A}}{1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}}}{1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}} = 8.3(151 \mu A) \frac{\frac{1 + \frac{3}{60}}{1 + \frac{14.3}{50} + \frac{0.7}{60}}}{1 + \frac{14.3}{50} + \frac{0.7}{60}} = 1.02 mA$$

$$R_{out3} = r_{o3} = \frac{V_A + V_{CE3}}{I_{C3}} = \frac{60 + 3}{1.02 \times 10^{-3}} = 61.8 k\Omega$$

(b) Since all areas are scaled equally, the current ratios stay the same, and there is no change from part (a). This ignores the slight change in V_{BE} of Q_1 due to its area change.

$$(c) I_{REF} = \frac{12 - 0.7 - 0.7}{7.5 \times 10^4} = 141 \mu A \quad | \quad I_{REF} = I_{C1} + (1 + 5 + 8.3) \frac{I_B}{\beta_{FO} + 1}$$

$$I_{REF} = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{14.3}{\beta_{FO}(\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}\right)$$

$$I_{O2} = 5I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE2}}{V_A}\right) = 5I_{REF} \frac{\frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{14.3}{\beta_{FO}(\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}}}{1 + \frac{14.3}{\beta_{FO}(\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}}$$

$$I_{O2} = 5(141 \mu A) \frac{\frac{1 + \frac{5}{60}}{1 + \frac{14.3}{50(51)} + \frac{1.4}{60}}}{1 + \frac{14.3}{50(51)} + \frac{1.4}{60}} = 745 \mu A \quad | \quad R_{out2} = r_{o2} = \frac{V_A + V_{CE2}}{I_{C2}} = \frac{60V + 5V}{745 \mu A} = 87.2 k\Omega$$

$$I_{O3} = 8.3I_{REF} \frac{\frac{1 + \frac{V_{CE3}}{V_A}}{1 + \frac{14.3}{\beta_{FO}(\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}}}{1 + \frac{14.3}{\beta_{FO}(\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}} = 8.3(141 \mu A) \frac{\frac{1 + \frac{3}{60}}{1 + \frac{14.3}{50(51)} + \frac{1.4}{60}}}{1 + \frac{14.3}{50(51)} + \frac{1.4}{60}} = 1.20 mA$$

$$R_{out3} = r_{o3} = \frac{V_A + V_{CE3}}{I_{C3}} = \frac{60V + 3V}{1.20mA} = 52.5 k\Omega$$

15.144

*Problem 15.144 – Figure P15.143(a) - NPN Current Source Array

```
RREF 2 1 75K  
VCC 2 0 DC 12  
VC2 3 0 DC 5 AC 1  
VC3 4 0 DC 3 AC 1  
Q1 1 1 0 NBJT 1  
Q2 3 1 0 NBJT 5  
Q3 4 1 0 NBJT 8.3  
.MODEL NBJT NPN BF=50 VA=60
```

```
.OP  
.AC LIN 1 1000 1000  
.PRINT AC IM(VC2) IM(VC3) IP(VC2) IP(VC3)  
.END
```

*Problem 15.144 – Figure 15.143(b) - Buffered NPN Current Source Array

```
RREF 2 5 75K  
VCC 2 0 DC 12  
VC2 3 0 DC 5 AC 1  
VC3 4 0 DC 3 AC 1  
Q1 5 1 0 NBJT 1  
Q2 3 1 0 NBJT 5  
Q3 4 1 0 NBJT 8.3  
Q4 2 5 1 NBJT 1  
.MODEL NBJT NPN BF=50 VA=60
```

```
.OP  
.AC LIN 1 1000 1000  
.PRINT AC IM(VC2) IM(VC3) IP(VC2) IP(VC3)  
.END
```

The results are almost identical to the hand calculations.

15.145

$$(a) I_{REF} = I_{C1} + (1 + 5 + 8.3)I_B = I_{C1} + 14.3I_B = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}\right)$$

$$I_{REF} \cong I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{14.3}{50} + \frac{0.7}{60}\right) = 1.298 I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$I_{O3} = 8.3 I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE3}}{V_A}\right) = 8.3 I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1.298} \quad | \quad I_{REF} = \frac{150 \mu A (1.298)}{8.3 \left(1 + \frac{3}{60}\right)} = 22.3 \mu A$$

$$I_{REF} = \frac{12 - 0.7}{R} \quad | \quad R = \frac{12 - 0.7}{22.3 \mu A} = 507 \text{ k}\Omega \quad | \quad I_{O2} = 5 I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1.298} = 5 (22.3 \mu A) \frac{1 + \frac{5}{60}}{1.298} = 93.1 \mu A$$

$$(b) I_{REF} = I_{C1} + (1 + 5 + 8.3) \frac{I_B}{\beta_{FO} + 1} = I_{C1} + \frac{14.3 I_B}{\beta_{FO} + 1} = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{14.3}{\beta_{FO} (\beta_{FO} + 1)} + \frac{2 V_{BE}}{V_A}\right)$$

$$I_{REF} \cong I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{14.3}{50(51)} + \frac{1.4}{60}\right) = 1.029 I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$I_{O3} = 8.3 I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE3}}{V_A}\right) = 8.3 I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1.029} \quad | \quad I_{REF} = \frac{150 \mu A (1.029)}{8.3 \left(1 + \frac{3}{60}\right)} = 17.7 \mu A$$

$$I_{REF} = \frac{12 - 0.7 - 0.7}{R} \quad | \quad R = \frac{12 - 1.4}{17.7 \mu A} = 599 \text{ k}\Omega \quad | \quad I_{O2} = 5 I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1.029} = 5 (17.7 \mu A) \frac{1 + \frac{5}{60}}{1.029} = 93.2 \mu A$$

15.146

$$(a) I_{REF} = \frac{12 - 0.7}{75 \times 10^3} = 151 \mu A \quad | \quad I_{REF} = I_{C1} + \left(1 + \frac{5}{2} + \frac{8.3}{2}\right) I_B \quad | \quad I_{REF} = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{7.65}{\beta_{FO}} + \frac{V_{BE}}{V_A}\right)$$

$$I_{O2} = \frac{5}{2} I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE2}}{V_A}\right) = 2.5 I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{7.65}{\beta_{FO}} + \frac{V_{BE}}{V_A}} \quad | \quad I_{O2} = 2.5(151 \mu A) \frac{1 + \frac{5}{75}}{1 + \frac{7.65}{125} + \frac{0.7}{75}} = 376 \mu A$$

$$I_{O3} = \frac{8.3}{2} I_{REF} \frac{1 + \frac{V_{CE3}}{V_A}}{1 + \frac{7.65}{\beta_{FO}} + \frac{V_{BE}}{V_A}} = 4.15(151 \mu A) \frac{1 + \frac{3}{75}}{1 + \frac{7.65}{125} + \frac{0.7}{75}} = 609 \mu A$$

$$(b) I_{REF} = \frac{12 - 0.7 - 0.7}{75 \times 10^4} = 141 \mu A \quad | \quad I_{REF} = I_{C1} + \left(1 + \frac{5}{2} + \frac{8.3}{2}\right) \frac{I_B}{\beta_{FO} + 1}$$

$$I_{REF} = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{7.65}{\beta_{FO}(\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}\right)$$

$$I_{O2} = \frac{5}{2} I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE2}}{V_A}\right) = 2.5 I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{7.65}{\beta_{FO}(\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}}$$

$$I_{O2} = 2.5(141 \mu A) \frac{1 + \frac{5}{75}}{1 + \frac{7.65}{125(126)} + \frac{1.4}{75}} = 370 \mu A$$

$$I_{O3} = \frac{8.3}{2} I_{REF} \frac{1 + \frac{V_{CE3}}{V_A}}{1 + \frac{7.65}{\beta_{FO}(\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}} = 4.15(141 \mu A) \frac{1 + \frac{3}{75}}{1 + \frac{6.65}{125(126)} + \frac{1.4}{75}} = 596 \mu A$$

15.147

$$I_{REF} = \frac{12 - 0.7 - 0.7}{100 \times 10^3} = 106 \mu A \quad | \quad I_{REF} = I_{C1} + \left(1 + \frac{5}{3} + \frac{8.3}{3} \right) \frac{I_B}{\beta_{FO} + 1}$$

$$I_{REF} = I_S \exp \left(\frac{V_{BE}}{V_T} \right) \left(1 + \frac{5.43}{\beta_{FO} (\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A} \right)$$

$$I_{O2} = \frac{5}{3} I_S \exp \left(\frac{V_{BE}}{V_T} \right) \left(1 + \frac{V_{CE2}}{V_A} \right) = \frac{5}{3} I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{5.43}{\beta_{FO} (\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}}$$

$$I_{O2} = \frac{5}{3} (106 \mu A) \frac{1 + \frac{5}{75}}{1 + \frac{5.43}{100(101)} + \frac{1.4}{75}} = 185 \mu A$$

$$I_{O3} = \frac{8.3}{3} I_{REF} \frac{1 + \frac{V_{CE3}}{V_A}}{1 + \frac{5.43}{\beta_{FO} (\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}} = \frac{8.3}{3} (106 \mu A) \frac{1 + \frac{3}{75}}{1 + \frac{5.43}{100(101)} + \frac{1.4}{75}} = 299 \mu A$$

15.148

$$(a) I_{REF} = \frac{12 - 0.7}{1.4 \times 10^5} = 80.7 \mu A \quad | \quad I_{REF} = I_{C1} + (1 + 5 + 8.3)I_B \quad | \quad I_{REF} = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}\right)$$

$$I_{O2} = 5I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE2}}{V_A}\right) = 5I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}} \quad | \quad I_{O2} = 5(80.7 \mu A) \frac{1 + \frac{5}{75}}{1 + \frac{14.3}{125} + \frac{0.7}{75}} = 383 \mu A$$

$$I_{O3} = 8.3I_{REF} \frac{1 + \frac{V_{CE3}}{V_A}}{1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}} = 8.3(80.7 \mu A) \frac{1 + \frac{3}{75}}{1 + \frac{14.3}{125} + \frac{0.7}{75}} = 620 \mu A$$

$$(b) I_{REF} = I_{C1} + (1 + 5 + 8.3) \frac{I_B}{\beta_{FO} + 1} = I_{C1} + \frac{14.3 I_B}{\beta_{FO} + 1} = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{14.3}{\beta_{FO}(\beta_{FO} + 1)} + \frac{2V_{BE}}{V_A}\right)$$

$$I_{REF} = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{14.3}{125(126)} + \frac{1.4}{75}\right) = 1.029 I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$I_{O3} = 8.3I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE3}}{V_A}\right) = 8.3I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1.02} \quad | \quad I_{REF} = \frac{620 \mu A (1.02)}{8.3 \left(1 + \frac{3}{75}\right)} = 73.3 \mu A$$

$$I_{REF} = \frac{12 - 0.7 - 0.7}{R} \quad | \quad R = \frac{12 - 1.4}{73.3 \mu A} = 145 k\Omega$$

$$\text{Checking: } I_{O2} = 5I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1.02} = 5(73.3 \mu A) \frac{1 + \frac{5}{75}}{1.02} = 383 \mu A \text{ - Correct.}$$

15.149

Use $\beta_{FO} = 50$ and $V_A = 60$ V.

$$(a) I_{REF} = \frac{12 - 0.7}{10^5} = 113 \mu A \quad | \quad I_{REF} = I_{C1} + (1 + 5 + 8.3)I_B \quad | \quad I_{REF} = I_s \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}\right)$$

$$I_{O2} = 5I_s \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CE2}}{V_A}\right) = 5I_{REF} \frac{\frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}}}{1 + \frac{14.3}{50} + \frac{0.7}{60}} \quad | \quad I_{O2} = 5(113 \mu A) \frac{1 + \frac{5}{60}}{1 + \frac{14.3}{50} + \frac{0.7}{60}} = 472 \mu A$$

$$I_{O3} = 8.3I_{REF} \frac{\frac{1 + \frac{V_{CE3}}{V_A}}{1 + \frac{14.3}{\beta_{FO}} + \frac{V_{BE}}{V_A}}}{1 + \frac{14.3}{50} + \frac{0.7}{60}} = 8.3(113 \mu A) \frac{1 + \frac{3}{60}}{1 + \frac{14.3}{50} + \frac{0.7}{60}} = 759 \mu A$$

$$(b) I_{O2} = 5(113 \mu A) \frac{1 + \frac{6}{60}}{1 + \frac{14.3}{50} + \frac{0.7}{60}} = 479 \mu A \quad | \quad \text{No change in } I_{O3}.$$

$$(c) I_{REF} = \frac{11 - 0.7}{10^5} = 103 \mu A \quad | \quad I_{O2} \text{ and } I_{O3} \text{ are proportional to } I_{REF}$$

$$I_{O2} = 472 \mu A \frac{103 \mu A}{113 \mu A} = 430 \mu A \quad | \quad I_{O3} = 472 \mu A \frac{103 \mu A}{113 \mu A} = 430 \mu A$$

$$I_{O3} \propto I_{REF} \quad | \quad I_{O2} = 759 \mu A \frac{103 \mu A}{113 \mu A} = 692 \mu A$$

$$(d) R_{out2} = r_{o2} = \frac{V_A + V_{CE2}}{I_{C2}} = \frac{60 + 5}{472 \mu A} = 138 k\Omega \quad | \quad \Delta I_{O2} = \frac{\Delta V}{r_{o2}} = \frac{1V}{138 k\Omega} = 7.25 \mu A$$

$I_{O2-6V} - I_{O2-5V} = 479 \mu A - 472 \mu A = 7 \mu A$ - Agrees within the calculation precision.

15.150

$$I_{REF} = \frac{15 - 0.7}{6 \times 10^4} = 238 \mu A \quad | \quad I_{REF} = 2I_{C1} + (2 + 1 + 6 + 9)I_B = 2\beta_{FO} \left(1 + \frac{V_{EC1}}{V_A}\right) I_B + 18I_B$$

$$I_B = \frac{238 \mu A}{18 + 2(50) \left(1 + \frac{0.7}{60}\right)} = 2.00 \mu A$$

$$I_{O2} = \beta_{FO} \left(1 + \frac{V_{EC2}}{V_A}\right) I_B = 50 \left(1 + \frac{15}{60}\right) (2.00 \mu A) = 125 \mu A \quad | \quad R_{out2} = r_{o2} = \frac{60 + 15}{1.25 \times 10^{-4}} = 600 k\Omega$$

$$I_{O3} = 6\beta_{FO} \left(1 + \frac{V_{EC3}}{V_A}\right) I_B = 300 \left(1 + \frac{9}{60}\right) (2.00 \mu A) = 690 \mu A \quad | \quad R_{out3} = r_{o3} = \frac{60 + 9}{6.90 \times 10^{-4}} = 100 k\Omega$$

$$I_{O4} = 9\beta_{FO} \left(1 + \frac{V_{EC4}}{V_A}\right) I_B = 450 \left(1 + \frac{27}{60}\right) (2.00 \mu A) = 1.31 mA \quad | \quad R_{out4} = r_{o4} = \frac{60 + 27}{1.31 \times 10^{-3}} = 66.4 k\Omega$$

15.151

$$I_{REF} = \frac{15 - 0.7}{R} = 238\mu A \quad | \quad I_{REF} = 2I_{C1} + (2 + 1 + 6 + 9)I_B = 2\beta_{FO} \left(1 + \frac{V_{EC1}}{V_A} \right) I_B + 18I_B$$

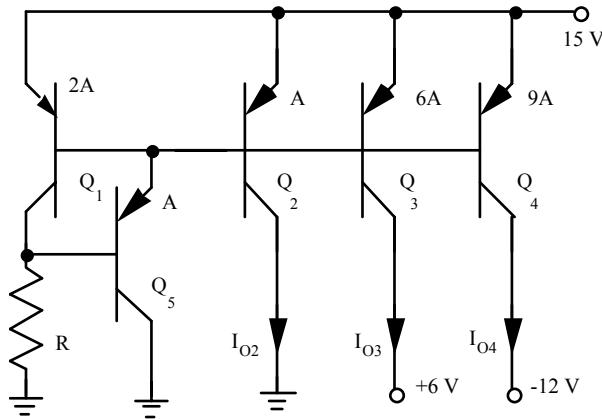
$$I_{REF} = I_B \left[18 + 2 \left(50 \left(1 + \frac{0.7}{60} \right) \right) \right] = 119I_B \quad | \quad I_{O3} = 6\beta_{FO} \left(1 + \frac{V_{EC3}}{V_A} \right) I_B \quad | \quad I_B = \frac{65\mu A}{300 \left(1 + \frac{9}{60} \right)} = 0.189\mu A$$

$$I_{REF} = 119I_B = 22.4\mu A \quad | \quad R = \frac{15 - 0.7}{22.4\mu A} = 63.8 k\Omega$$

$$I_{O2} = \beta_{FO} \left(1 + \frac{V_{EC2}}{V_A} \right) I_B = 50 \left(1 + \frac{15}{60} \right) (0.189\mu A) = 11.8 \mu A$$

$$I_{O4} = 9\beta_{FO} \left(1 + \frac{V_{EC4}}{V_A} \right) I_B = 450 \left(1 + \frac{27}{60} \right) (0.189\mu A) = 123 \mu A$$

15.152



$$R = \frac{15V - 0.7V - 0.7V}{25\mu A} = 544k\Omega \quad | \quad I_{REF} = I_{C1} + \frac{(2 + 1 + 6 + 9)I_B}{\beta_{FO} + 1}$$

$$I_{REF} = 2\beta_{FO} \left(1 + \frac{V_{EC1}}{V_A} \right) I_B + \frac{18I_B}{\beta_{FO} + 1} \quad | \quad I_B = \frac{25\mu A}{2(50 \left(1 + \frac{1.4}{60} \right) + \frac{18}{51})} = 0.2435\mu A$$

$$I_{O2} = \beta_{FO} \left(1 + \frac{V_{EC2}}{V_A} \right) I_B = 50 \left(1 + \frac{15}{60} \right) I_B = 15.2 \mu A$$

$$I_{O3} = 6\beta_{FO} \left(1 + \frac{V_{EC3}}{V_A} \right) I_B = 300 \left(1 + \frac{9}{60} \right) I_B = 84.0 \mu A$$

$$I_{O4} = 9\beta_{FO} \left(1 + \frac{V_{EC4}}{V_A} \right) I_B = 450 \left(1 + \frac{27}{60} \right) I_B = 159 \mu A \quad | \quad I_{C5} = \alpha_F I_{E5} = \frac{50}{51} 18I_B = 4.30 \mu A$$

15.153

$$V_{BE2} + I_{E2}R_2 = V_{BE3} + I_{E3}R_3 \rightarrow I_{E3} = \frac{R_2}{R_3}I_{E2} + \frac{V_{BE2} - V_{BE3}}{R_3}$$

In order to have equal base - emitter voltages, the two transistors must operate at the

$$\text{equal collector - current densities : } \frac{I_{E2}}{2A} = \frac{I_{E3}}{nA} = \frac{5I_{E2}}{nA} \rightarrow n = 10$$

15.154

$$I_{REF} = I_{C1} + 7I_B \quad | \quad I_{C1} \cong \frac{I_{REF}}{1 + \frac{7}{75}} = \frac{I_{REF}}{1.093} \quad | \quad I_{E1} = \frac{I_{C1}}{\alpha_F} = \frac{76}{75} \left(\frac{I_{REF}}{1.093} \right) = \frac{I_{REF}}{1.079}$$

$$12 = I_{REF}(10k\Omega) + 0.7V + \frac{I_{REF}}{1.079}(10k\Omega) \quad | \quad I_{REF} = \frac{12V - 0.7V}{10k\Omega(1.927)} = 586\mu A \quad | \quad I_{E1} = 543\mu A$$

$$I_{E2} = 2I_{E1} \quad | \quad I_{O2} = \alpha_F(2I_{E1}) = 2 \frac{75}{76} (543\mu A) = 1.07mA \quad | \quad V_{E1} = 543\mu A(10k\Omega) = 5.43V$$

$$I_{E3} = 4I_{E1} \quad | \quad I_{O3} = \alpha_F(4I_{E1}) = 4 \frac{75}{76} (543\mu A) = 2.14mA \quad | \quad \frac{1}{g_{m1}} = \frac{1}{40(536\mu A)} = 46.6\Omega$$

$$R_{th} = R \left(\frac{1}{g_{m1}} + R_i \right) = 10k\Omega \left[(46.6\Omega + 10k\Omega) \right] = 5.01k\Omega \quad | \quad R_{th2} = R_{th} \left[r_{\pi3} + (\beta_{o3} + 1)(2.5k\Omega) \right]$$

$$r_{\pi2} = \frac{75(0.025V)}{1.07mA} = 1.75k\Omega \quad | \quad r_{\pi3} = \frac{75(0.025V)}{2.14mA} = 0.876k\Omega \quad | \quad r_{o2} = \frac{60 + (10 - 5.43)}{1.07mA} = 60.4k\Omega$$

$$R_{th2} = 5.01k\Omega \left[[0.876k\Omega + (76)(2.5k\Omega)] \right] = 4.88k\Omega$$

$$R_{out2} = r_{o2} \left(1 + \frac{\beta_o R_2}{R_{th2} + r_{\pi2} + R_2} \right) = 60.4k\Omega \left(1 + \frac{75(5k\Omega)}{4.88k\Omega + 1.75k\Omega + 5k\Omega} \right) = 2.01 M\Omega$$

$$r_{o3} = \frac{(60 + 10 - 5.43)V}{2.14mA} = 30.2k\Omega \quad | \quad R_{th2} = R_{th} \left[r_{\pi2} + (\beta_o + 1)(5k\Omega) \right]$$

$$R_{th3} = 5.01k\Omega \left[[1.75k\Omega + (76)(5k\Omega)] \right] = 4.95k\Omega$$

$$R_{out3} = r_{o3} \left(1 + \frac{\beta_o R_3}{R_{th} + r_{\pi3} + R_3} \right) = 30.2k\Omega \left(1 + \frac{75(2.5k\Omega)}{4.95k\Omega + 0.876k\Omega + 2.5k\Omega} \right) = 710 k\Omega$$

15.155

$$\text{For } V_{BE2} = V_{BE3}, I_{O3}R_3 = I_{O2}R_2 \quad | \quad R_3 = \frac{I_{O2}}{I_{O3}}R_2 = 3(5k\Omega) = 15 k\Omega \quad | \quad \frac{I_{O2}}{2A} = \frac{I_{O3}}{nA} \quad | \quad n = \frac{2}{3}$$

15.156

$$I_{REF} = I_{C1} + 13I_B \quad | \quad I_{C1} \cong \frac{I_{REF}}{1 + \frac{13}{75}} = \frac{I_{REF}}{1.173} \quad | \quad I_{E1} = \frac{I_{C1}}{\alpha_F} = \frac{76}{75} \left(\frac{I_{REF}}{1.173} \right) = \frac{I_{REF}}{1.158}$$

$$12 = I_{REF} (10k\Omega) + 0.7V + \frac{I_{REF}}{1.079} (20k\Omega) \quad | \quad I_{REF} = \frac{12V - 0.7V}{10k\Omega(2.73)} = 414\mu A \quad | \quad I_{E1} = 357\mu A$$

$$I_{E2} = 4I_{E1} \quad | \quad I_{O2} = \alpha_F (4I_{E1}) = 4 \frac{75}{76} (357\mu A) = 1.41 mA \quad | \quad V_{E1} = 357\mu A (20k\Omega) = 7.14V$$

$$I_{E3} = 8I_{E1} \quad | \quad I_{O3} = \alpha_F (8I_{E1}) = 8 \frac{75}{76} (357\mu A) = 2.82 mA \quad | \quad \frac{1}{g_m} = \frac{1}{40(352\mu A)} = 71.0\Omega$$

$$R_{th} = R \left(\frac{1}{g_m} + R_l \right) = 10k\Omega \left((71.0\Omega + 20k\Omega) \right) = 6.68k\Omega \quad | \quad R_{th2} = R_{th} \left[r_{\pi 3} + (\beta_o + 1)(2.5k\Omega) \right]$$

$$r_{\pi 2} = \frac{75(0.025V)}{1.41mA} = 1.33k\Omega \quad | \quad r_{\pi 3} = \frac{75(0.025V)}{2.82mA} = 0.665k\Omega \quad | \quad r_{o2} = \frac{60 + (10 - 7.14)}{1.41mA} = 44.6k\Omega$$

$$R_{th2} = 6.68k\Omega \left[0.665k\Omega + (76)(2.5k\Omega) \right] = 6.45k\Omega$$

$$R_{out2} = r_{o2} \left(1 + \frac{\beta_o R_2}{R_{th2} + r_{\pi 2} + R_2} \right) = 44.2k\Omega \left(1 + \frac{75(5k\Omega)}{6.45k\Omega + 1.33k\Omega + 5k\Omega} \right) = 1.35 M\Omega$$

$$r_{o3} = \frac{(60 + 10 - 7.14)V}{2.82mA} = 22.3k\Omega \quad | \quad R_{th2} = R_{th} \left[r_{\pi 2} + (\beta_o + 1)(5k\Omega) \right]$$

$$R_{th3} = 6.68k\Omega \left[1.33k\Omega + (76)(5k\Omega) \right] = 6.57k\Omega$$

$$R_{out3} = r_{o3} \left(1 + \frac{\beta_o R_3}{R_{th} + r_{\pi 3} + R_3} \right) = 22.3k\Omega \left(1 + \frac{75(2.5k\Omega)}{6.57k\Omega + 0.665k\Omega + 2.5k\Omega} \right) = 452 k\Omega$$

15.157

$$I_{C1} = I_{REF} = 15\mu A \quad | \quad I_B = \frac{I_{C1}}{\beta_{FO} \left(1 + \frac{V_{CE1}}{V_A} \right)} \quad | \quad V_{CE1} = V_{BE1} + V_{GS3} = 0.7 + V_{TN} + \sqrt{\frac{2I_D}{K_n}}$$

$$I_B = \frac{15\mu A}{100 \left(1 + \frac{V_{CE1}}{V_A} \right)} \quad | \quad V_{CE1} = 1.45 + \sqrt{\frac{4I_B}{50 \times 10^{-6}}} \quad | \quad \text{Solving iteratively yields } I_B = 0.147\mu A$$

$$I_{O2} = \beta_{FO} \left(1 + \frac{V_{CE2}}{V_A} \right) I_B = 100 \left(1 + \frac{5}{75} \right) (0.147\mu A) = 15.7 \mu A \quad | \quad R_{out} = r_{o2} = \frac{(75 + 5)V}{15.7\mu A} = 5.10 M\Omega$$

Note : If one assumes $I_B \cong \frac{I_{C1}}{\beta_{FO}} = 0.15\mu A$, then $I_{O2} = 100 \left(1 + \frac{5}{75} \right) (0.15\mu A) = 16.0 \mu A$, a very similar result and a valid approximation, since $V_{CE1} \ll V_A$.

15.158

Results from SPICE were $I_{C1} = 15.0 \mu\text{A}$, $I_0 = 15.7 \mu\text{A}$ and $R_{out} = 5.06 \text{ M}\Omega$.

ELTOL VNTOL an These results are very close to our hand calculations. Remember, SPICE uses

$$r_{o3} = \frac{V_A + V_{CB}}{I_C} \approx \frac{(75 + 4.3)V}{15.7\mu A} = 5.05 M\Omega .$$

15.159

$$v_{bel} = v_{ref} \left[\frac{g_{m3}(r_{\pi 1} \| r_{\pi 2})}{1 + g_{m3}(r_{\pi 1} \| r_{\pi 2})} \right] \cong v_{ref} \left(\frac{g_{m3} \frac{r_{\pi 1}}{2}}{1 + g_{m3} \frac{r_{\pi 1}}{2}} \right) = v_{ref} \left(\frac{g_{m3} r_{\pi 1}}{2 + g_{m3} r_{\pi 1}} \right)$$

$$R_{in} = \frac{r_{ol}}{1 + \mu_{f1} \left(\frac{g_{m3} r_{\pi 1}}{2 + g_{m3} r_{\pi 1}} \right)} \cong \frac{1}{g_{ml}} \left(\frac{1}{\frac{g_{m3} r_{\pi 1}}{2 + g_{m3} r_{\pi 1}}} \right) = \frac{1}{g_{ml}} \left(\frac{g_{m3} r_{\pi 1}}{2 + g_{m3} r_{\pi 1}} \right)^{-1}$$

From Prob. 15.157, $I_D = 0.294\mu A$, and $g_{m3} = \sqrt{2(50x10^{-6})(0.294x10^{-6})} = 5.42x10^{-6} S$

$$g_{m1} = 40(15\mu A) = 0.600 mS \quad r_{\pi 1} = \frac{100}{0.600 mS} = 167 k\Omega \quad g_{m3}r_{\pi 1} = 0.905$$

$$R_{in} \cong \frac{1}{0.600mS} \left[\frac{2.905}{0.905} \right] = 5.35 \text{ } k\Omega \quad (\text{b) SPICE yields } R_{in} = 5.35 \text{ } k\Omega$$

15.160

$$I_{REF} = \frac{10V - 0.7V - 0.7V}{10k\Omega} = 860\mu A \cong I_{C1} \quad | \quad I_{O2}R_2 = V_T \ln \left(\frac{I_{C1}}{I_{O2}} \frac{I_{S2}}{I_{S1}} \right)$$

$$10^4 I_{O2} = 0.025 \ln \left(\frac{860 \mu A}{I_{O2}} \frac{2}{1} \right) \rightarrow I_{O2} = 12.4 \mu A \quad | \quad V_{E2} \cong 12.4 \mu A (10k\Omega) = 0.124V$$

$$r_{o2} = \frac{60 + 5 - 0.124}{12.4\mu A} = 5.23 M\Omega \quad | \quad R_{th} \text{ is small and the voltage across } R_2 \text{ is also small.}$$

$$R_{out2} \cong r_{o2} \left(1 + g_{m2} R_2 \right) = 5.23 M\Omega \left[1 + 40 \left(12.4 \mu A \right) \left(10 k\Omega \right) \right] = 31.2 M\Omega$$

$$5 \times 10^3 I_{O3} = 0.025 \ln \left(\frac{860 \mu A}{I_{O2}} \frac{12}{1} \right) \rightarrow I_{O3} = 29.3 \mu A \quad | \quad V_{E3} \cong 29.3 \mu A (5k\Omega) = 0.147V$$

$$r_{o3} = \frac{60 + 5 - 0.147}{29.3\mu A} = 2.21 M\Omega \quad | \quad R_{out3} \equiv r_{o3}(1 + g_{m3}R_3) = 2.21M\Omega [1 + 40(0.147)] = 15.2 M\Omega$$

15.161

$$R = \frac{(10 - 0.7 - 0.7)V}{75\mu A} = 115 k\Omega \quad | \quad R_2 = \frac{V_T}{I_{o2}} \ln \left(\frac{I_{REF}}{I_{o2}} \frac{I_{S2}}{I_{S1}} \right) = \frac{0.025V}{5\mu A} \ln \left(\frac{75\mu A}{5\mu A} \frac{2}{1} \right) = 17.0 k\Omega$$

$$I_{o3}R_3 = V_T \ln \left(\frac{I_{REF}}{I_{o3}} \frac{I_{S3}}{I_{S1}} \right) \quad | \quad (10\mu A)(2k\Omega) = 0.025V \ln \left(\frac{75\mu A}{10\mu A} \frac{n}{1} \right) \rightarrow n = 0.297$$

15.162

*Problem 15.162 - Buffered NPN Widlar Current Source Array

RREF 1 3 115K

VCC 1 0 DC 10

VC2 2 0 DC 5 AC 1

Q1 3 4 0 NBJT 1

Q2 2 4 5 NBJT 2

R2 5 0 17K

Q3 2 4 6 NBJT 0.297

R3 6 0 2K

Q4 1 3 4 NBJT 1

.MODEL NBJT NPN BF=100 VA=60

.OP

.AC LIN 1 1000 1000

.PRINT AC IC(Q2) IC(Q3)

.END

Results: $I_{C1} = 75.7 \mu A$, $I_{O2} = 5.18 \mu A$, $I_{O3} = 10.5 \mu A$, $R_{OUT2} = 53.4 M\Omega$, $R_{OUT3} = 11.1 M\Omega$

15.163

$$I_{REF} = \frac{5V - 0.7V - 0.7V - (-5V)}{40k\Omega} = 215\mu A \cong I_{C1} \quad | \quad I_{o2} = \frac{V_T}{R_2} \ln \left(\frac{I_{C1}}{I_{o2}} \frac{I_{S2}}{I_{S1}} \right)$$

$$I_{o2} = \frac{0.025V}{5k\Omega} \ln \left(\frac{215\mu A}{I_{o2}} \frac{10}{1} \right) \rightarrow I_{o2} = 22.7 \mu A \quad | \quad V_{E2} \cong 22.7\mu A (5k\Omega) = 0.114V$$

$$r_{o2} = \frac{70 + 5 - 0.114}{22.7\mu A} = 3.30 M\Omega \quad | \quad R_{th} \text{ is small and the voltage across } R_2 \text{ is also small.}$$

$$R_{out2} \cong r_{o2}(1 + g_{m2}R_2) = r_{o2}(1 + 40I_{C2}R_2) = 3.30 M\Omega [1 + 40(0.114)] = 18.3 M\Omega$$

$$I_{o3} = \frac{0.025V}{2.5k\Omega} \ln \left(\frac{215\mu A}{I_{o3}} \frac{20}{1} \right) \rightarrow I_{o3} = 45.5 \mu A \quad | \quad V_{E3} \cong 45.5\mu A (2.5k\Omega) = 0.114V$$

$$r_{o3} = \frac{70 + 5 - 0.114}{45.5\mu A} = 1.65 M\Omega \quad | \quad R_{out3} \cong r_{o3}(1 + g_{m3}R_3) = 1.65 M\Omega [1 + 40(0.114)] = 9.17 M\Omega$$

15.164

$$R = \frac{[5 - 0.7 - 0.7 - (-5)]V}{50\mu A} = 172 \text{ k}\Omega$$

$$R_2 = \frac{V_T}{I_{o2}} \ln \left(\frac{I_{REF}}{I_{O2}} \frac{I_{S2}}{I_{S1}} \right) = \frac{0.025V}{10\mu A} \ln \left(\frac{50\mu A}{10\mu A} \frac{10}{1} \right) = 9.78 \text{ k}\Omega$$

$$I_{o3}R_3 = V_T \ln \left(\frac{I_{REF}}{I_{O3}} \frac{I_{S3}}{I_{S1}} \right) \quad | \quad (10\mu A)(2\text{k}\Omega) = 0.025V \ln \left(\frac{50\mu A}{10\mu A} \frac{n}{1} \right) \rightarrow n = 0.445$$

15.165

For the current mirror at the bottom: $I_{C2} = \beta_F I_{B2}$ | $I_{E3} = I_{C1} + I_{B1} + I_{B2} = n\beta_F I_{B2} + nI_{B2} + I_{B2}$

$$I_{C2} = \frac{\beta_F}{1+n(\beta_F+1)} I_{E3} \quad | \quad I_O = \alpha_F I_{E3} = \frac{\beta_F}{\beta_F+1} \frac{1+n(\beta_F+1)}{\beta_F} I_{C2} \quad | \quad I_{C2} = I_{REF} - I_{B3} = I_{REF} - \frac{I_O}{\beta_F}$$

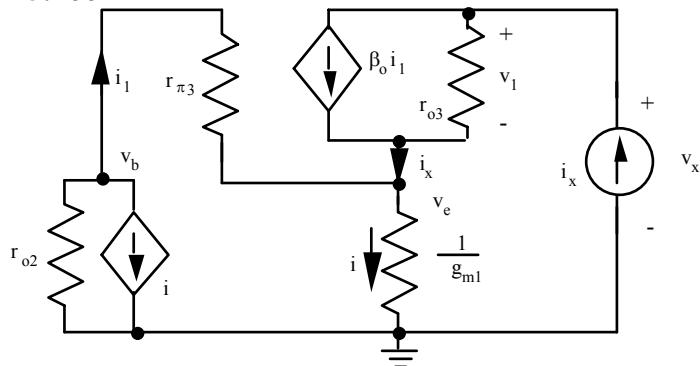
$$I_O = \frac{1+n(\beta_F+1)}{\beta_F+1} \left(I_{REF} - \frac{I_O}{\beta_F} \right) \rightarrow I_O = \frac{n + \frac{1}{\beta_F(\beta_F+1)}}{1 + \frac{n}{\beta_F} + \frac{1}{\beta_F(\beta_F+1)}} I_{REF} \cong \frac{n}{1 + \frac{n}{\beta_F}} I_{REF} \cong nI_{REF} \text{ for } \beta_F \gg n$$

$$(a) I_O \cong \frac{1}{1 + \frac{1}{125}} 50\mu A = 49.6 \mu A \quad | \quad R_{out} \cong \frac{\beta_o r_o}{2} = \frac{125}{2} \frac{40 - 0.7 - (-5)}{49.6} \frac{V}{\mu A} = 55.8 M\Omega$$

$$(b) I_O \cong \frac{3}{1 + \frac{3}{125}} 50\mu A = 146 \mu A \quad | \quad R_{out} \cong \frac{\beta_o r_o}{2} = \frac{125}{2} \frac{44.3}{146} \frac{V}{\mu A} = 19.0 M\Omega$$

$$(c) V_{CS} = I_O R_{out} = 146\mu A (19.0 M\Omega) = 2770V \quad (d) V_{CB3} = V_{EE} - 0.7V - 0.7V \geq 0 \rightarrow V_{EE} \geq 1.40V$$

15.166



$$R_{out} = \frac{v_x}{i_x} \quad | \quad \begin{bmatrix} i_x \\ 0 \end{bmatrix} = \begin{bmatrix} g_{m1} + g_{\pi3} & -g_{\pi3} \\ g_{m1} - g_{\pi3} & g_{\pi3} + g_{o2} \end{bmatrix} \begin{bmatrix} v_e \\ v_b \end{bmatrix}$$

$I_{C1} \cong I_{C2} \cong I_{C3}$ so the small-signal parameters are matched

$$\Delta = 2g_{m1}g_{\pi3} + g_{m1}g_{o2} + g_{\pi3}g_{o2} = g_{m1}g_{\pi3} \left(2 + \frac{\beta_o}{\mu_f} + \frac{1}{\mu_f} \right) \cong 2g_{m1}g_{\pi3} \quad \text{for } \mu_f \gg \beta_o \gg 1$$

$$v_e = i_x \frac{g_{\pi3} + g_{o2}}{\Delta} = \frac{i_x}{2g_{m1}} \left(1 + \frac{\beta_o}{\mu_f} \right) \cong \frac{i_x}{2g_{m1}} \quad | \quad v_b = -i_x \frac{g_{m1} - g_{\pi3}}{\Delta}$$

$$v_b - v_e = -i_x \frac{g_{m1} + g_{o2}}{\Delta} = -\frac{i_x}{2g_{\pi3}} \left(1 + \frac{1}{\mu_f} \right) \cong \frac{i_x}{2} r_{\pi3} \quad | \quad i_1 = g_{\pi3}(v_b - v_e) = \frac{i_x}{2}$$

$$v_x = v_e + (i_x - \beta_o i_1) r_{o3} = \frac{i_x}{2g_{m1}} + i_x r_{o3} + \beta_o r_{o3} \frac{i_x}{2} \quad | \quad R_{out} = \frac{v_x}{i_x} = \frac{1}{2g_{m1}} + r_{o3} + \frac{\beta_o r_{o3}}{2} \cong \frac{\beta_o r_{o3}}{2}$$

15.167

$$R_{out} \cong \frac{\beta_o r_o}{2} \cong \frac{\beta_o V_A}{2I_O} = \frac{\beta_o V_A}{2nI_{REF}} \quad | \quad \text{For Prob. 15.165, } R_{out} \cong \frac{125(40)}{2n(50\mu A)} = \frac{50}{n} M\Omega$$

15.168

$$V_{CB3} = V_{C3} - V_{BE3} - V_{BE2} - (-V_{EE}) \geq 0 \rightarrow V_{C3} \geq -V_{EE} + V_{BE3} + V_{BE2}$$

$$V_{BE3} + V_{BE1} = V_T \ln \frac{I_{C3}}{I_{S3}} + V_T \ln \frac{I_{C1}}{I_{S1}} \quad | \quad I_{C1} + \frac{I_{C1}}{\beta_F} + \frac{I_{C1}}{n\beta_F} = \frac{I_{C3}}{\alpha_F} \cong \frac{\beta_F + 1}{\beta_F} I_{C3} \quad | \quad \text{From Prob.}$$

$$15.165: I_{C3} \cong \frac{n}{1 + \frac{n}{\beta_F}} I_{REF} = \frac{5}{1 + \frac{5}{125}} 15\mu A = 72.1\mu A \quad | \quad I_{C1} = \frac{1}{1 + \frac{1}{\beta_F} + \frac{1}{n\beta_F}} \frac{\beta_F + 1}{\beta_F} I_{C3} = 72.0\mu A$$

$$V_{BE3} + V_{BE2} = 0.025V \left(\ln \frac{72.1\mu A}{3fA} + \ln \frac{72.0\mu A}{15fA} \right) = 1.16V \quad | \quad V_{C3} \geq -V_{EE} + 1.16 V$$

15.169

(a) Assuming balanced drain voltages, $I_{D3} = I_{D1} = I_{REF}$

$$\left(\frac{W}{L} \right)_1 = \frac{I_{REF}}{4} \quad | \quad I_{REF} = \frac{5 - V_{GS1} - V_{GS3}}{30k\Omega}$$

$$V_{GS1} = V_{TN} + \sqrt{\frac{2I_{D1}}{K_n l}} = 0.75 + \sqrt{\frac{2I_{REF}}{4(5K_n)}} \quad | \quad V_{GS3} = 0.75 + \sqrt{\frac{2I_{REF}}{4(20K_n)}}$$

$$I_{REF} = \frac{5 - 0.75 - \sqrt{\frac{2I_{REF}}{4(5K_n)}} - 0.75 - \sqrt{\frac{2I_{REF}}{4(20K_n)}}}{30k\Omega} \quad | \quad (30k\Omega)I_{REF} = 3.5 - 1.5\sqrt{\frac{I_{REF}}{10K_n}}$$

Using $K_n' = 25 \times 10^{-6}$ and rearranging: $9 \times 10^8 I_{REF}^2 - 2.19 \times 10^5 I_{REF} + 12.25 = 0$

$I_{REF} = 87.2 \mu A$ and $I_O = \frac{I_{REF}}{4} = 21.8 \mu A$. Drain voltage balance on M_1 and M_2

requires $V_{GS4} = V_{GS3}$ | $V_{TN} + \sqrt{\left(\frac{W}{L}\right)_4 K_n'} = V_{TN} + \sqrt{\frac{2I_{REF}}{4(20K_n')}} \quad | \quad \left(\frac{W}{L}\right)_4 = \frac{80}{1}$

(b) This part requires an iterative solution or the use of a computer solver.

Assuming V_{DS} balance between M_1 and M_2 , $\lambda \neq 0$ will not affect the current mirror ratio, but it will change V_{GS} and hence I_{REF} slightly.

One iterative approach :

Guess V_{GS1} | Then $I_{D1} = \frac{5K_n'}{2} (V_{GS1} - V_{TN})^2 (1 + \lambda V_{GS1})$

Since $I_{D3} = I_{D1}$, $V_{GS3} = V_{TN} + \sqrt{\frac{2I_{D1}}{20K_n' [1 + \lambda(5 - V_{GS1})]}}$

$I_{REF} = \frac{5 - V_{GS1} - V_{GS3}}{30k\Omega}$ and $I_{D1} = \frac{I_{REF}}{4}$.

If the second value of I_{D1} does not agree with the first, then try a new V_{GS1} .

A spreadsheet yields: $V_{GS1} = 1.336V$, $V_{GS3} = 1.381V$, $I_{REF} = 87.5\mu A$, $I_O = 21.7\mu A$.

Note: There is essentially no change from the first answer!

15.169 cont.

(c)

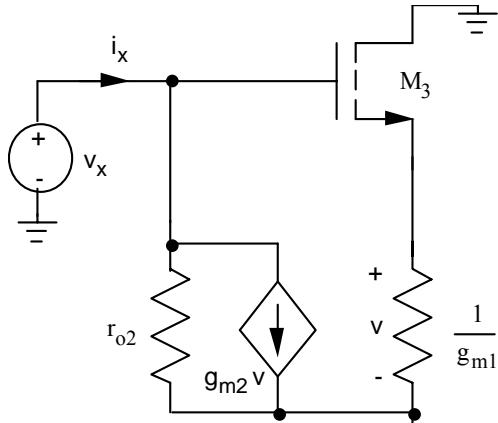
*Problem 15.169 - NMOS Wilson Source
 RREF 1 0 30K
 VSS 4 0 DC -5
 M1 3 3 4 4 NFET W=5U L=1U
 M2 2 3 4 4 NFET W=20U L=1U
 M3 0 1 3 3 NFET W=20U L=1U
 M4 1 1 2 2 NFET W=80U L=1U
 .MODEL NFET NMOS KP=25U VTO=0.75 LAMBDA=0.015
 .OP
 .END

15.170

$$I_o = I_{REF} \frac{\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_2} \quad | \quad R_{out} = \mu_{f2} r_{o3} = \mu_{f2} \frac{1}{\lambda_3 I_o} = \frac{1}{\lambda_2} \sqrt{\frac{2K_n}{I_{D2}}} \frac{1}{\lambda_3 I_o}$$

$$R_{out} = \frac{1}{\lambda_2} \sqrt{\frac{2\left(\frac{W}{L}\right)_2 K_n}{I_{REF}}} \frac{1}{\lambda_3 I_{REF}} \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1} = \frac{1}{\lambda_2 \lambda_3} \left[\frac{\left(\frac{W}{L}\right)_2}{I_{REF}} \right]^{\frac{3}{2}} \frac{\sqrt{2K_n}}{\left(\frac{W}{L}\right)_1}$$

15.171



$$i_x = g_{o2}v_x + g_{m2}v_1 \quad | \quad v_1 = v_x \frac{g_{m3} \left(\frac{1}{g_{m1}} \right)}{1 + g_{m3} \left(\frac{1}{g_{m1}} \right)} = \frac{v_x}{2} \quad | \quad g_{m1} = g_{m3} \quad | \quad v_1 = \frac{v_x}{2}$$

$$i_x = g_{o2}v_x + g_{m2} \frac{v_x}{2} \quad | \quad R_{in} = \frac{v_x}{i_x} = r_o \parallel \frac{2}{g_{m2}} \approx \frac{2}{g_{m2}}$$

15.172

$$\text{Since } \lambda = 0, \quad I_{D3} = I_{D1} = I_{REF} \frac{\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_2} = \frac{150\mu A}{4} = 37.5\mu A$$

$$V_{DS3} \geq V_{GS3} - V_{TN3} \quad | \quad V_{D3} - (-10 + V_{GS1}) \geq V_{GS3} - V_{TN3} \quad | \quad V_{D3} \geq -10 + V_{GS1} + V_{GS3} - V_{TN3}$$

$$V_{D3} \geq -10 + V_{TN1} + \sqrt{\frac{2I_{D1}}{K_{n1}}} + V_{TN3} + \sqrt{\frac{2I_{D3}}{K_{n3}}} - V_{TN3}$$

$$V_{D3} \geq -10V + 0.75V + \sqrt{\frac{2(37.5\mu A)V^2}{5(25\mu A)}} + \sqrt{\frac{2(37.5\mu A)V^2}{20(25\mu A)}} = -8.09 V$$

15.173

$$R_{out} \approx \mu_{f2} r_{o3} \quad | \quad \left(\frac{W}{L}\right)_2 = \left(\frac{W}{L}\right)_1 \Rightarrow I_o = I_{REF} = 50\mu A \quad | \quad r_{o3} \approx \frac{1}{\lambda I_{D3}} = \frac{1}{0.0125(50\mu A)} = 1.60M\Omega$$

$$\mu_{f2} = \frac{R_{out}}{r_{o3}} = \frac{250M\Omega}{1.60M\Omega} = 156 \quad | \quad \text{Using Eq. 13.71, } \mu_{f2} = \frac{1}{\lambda} \sqrt{\frac{2K_n}{I_{D2}}}$$

$$\left(\frac{W}{L}\right)_2 = (\lambda \mu_{f2})^2 \frac{I_{D2}}{2K_n} = [0.0125(156)]^2 \frac{5 \times 10^{-5}}{2(2.5 \times 10^{-5})} = \frac{3.80}{1}$$

15.174

The circuit is the same as Fig. 16.20 with the addition of R_{REF} in parallel with r_{o2} . We require $R_{REF} \gg r_{o2}$ in order not to reduce the gain of the feedback loop. A current source with a source resistor which achieves $R_{OUT} = r_o(1+g_m R_s)$ should be sufficient. A cascode or Wilson source will also work.

15.175

M_1 and M_2 are voltage balanced.

$$(a) R_{out} = \mu_{f4} r_{o2} \quad | \quad \text{All } K_n \text{ are the same: } I_O = I_{REF} = 17.5\mu A$$

$$V_{GS1} = 0.75 + \sqrt{\frac{2(17.5 \times 10^{-6})}{75 \times 10^{-6}}} = 1.43 V \quad | \quad \Delta V_3 = V_{GS3} - V_{TN3} = 1.43 V - 0.75 V = 0.680$$

$$r_{o2} = \frac{\frac{1}{0.0125} + 1.43}{17.5 \mu A} = 4.65 M\Omega \quad | \quad r_{o4} = \frac{\frac{1}{0.0125} + (5 - 1.43)}{17.5 \mu A} = 4.78 M\Omega$$

$$g_{m4} = \sqrt{2(75 \times 10^{-6})(17.5 \times 10^{-6})(1 + 0.0125(5 - 1.43))} = 5.24 \times 10^{-5} S$$

$$\mu_{f4} = 5.24 \times 10^{-5} S (4.78 M\Omega) = 250 \quad | \quad R_{out} = 1.16 G\Omega$$

$$(b) V_{CS} = I_O R_{out} = 20.3 kV! \quad (c) V_{DD}^{\min} = V_{GS1} + \Delta V_4 = 1.43 + 0.680 = 2.11V$$

15.176

*Problem 15.176 - NMOS Cascode Source

IREF 0 1 DC 17.5U

VDD 2 0 DC 5

M1 3 3 0 0 NFET W=3U L=1U

M2 4 3 0 0 NFET W=3U L=1U

M3 1 1 3 3 NFET W=3U L=1U

M4 2 1 4 4 NFET W=3U L=1U

.MODEL NFET NMOS KP=25U VTO=0.75 LAMBDA=0.0125

.OP

.TF I(VDD) VDD

.END

Results: $I_O = 17.5 \mu A$ $R_{OUT} = 1.17 G\Omega$ The same as the hand analysis.

15.177

(a) M_1 and M_2 are voltage balanced, so $I_o = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1} I_{REF} = 1.05 I_{REF} = 18.4 \mu A$, a 5% error.

(b) To first order, I_o does not depend upon W/L of M_3 and M_4 . The mismatch will create a small V_{DS} mismatch between M_1 and M_2 , but this error will be negligible.

An estimate of this effect is $\Delta I_o = g_{o2} \Delta V_{DS}$ where

$$\Delta V_{DS} = V_{GS3} - V_{GS4} = \left(V_{TN} + \sqrt{\frac{2I_{D3}}{K_{n3}}} \right) - \left(V_{TN} + \sqrt{\frac{2I_{D4}}{K_{n4}}} \right) = \sqrt{\frac{2I_D}{K_{n3}}} - \sqrt{\frac{2I_D}{0.95K_{n3}}} = 0.026 \sqrt{\frac{2I_D}{K_{n3}}}$$

$$\Delta V_{DS} = 0.026 \sqrt{\frac{2(17.5)}{50}} = 0.0218 V \quad | \quad \Delta I_o = 0.0125(17.5 \times 10^{-6})(0.0218) = 3.89 nA$$

15.178

$$R_{out} = \mu_{f4} r_{o2} \quad | \quad \left(\frac{W}{L}\right)_2 = \left(\frac{W}{L}\right)_1 \Rightarrow I_o = I_{REF} = 50 \mu A \quad | \quad r_{o2} \approx \frac{1}{\lambda I_{D2}} = \frac{1}{0.0125(50 \mu A)} = 1.60 M\Omega$$

$$\mu_{f4} = \frac{R_{out}}{r_{o2}} = \frac{250 M\Omega}{1.60 M\Omega} = 156 \quad | \quad \text{Using Eq. 13.71, } \mu_{f4} = \frac{1}{\lambda} \sqrt{\frac{2K_{n4}}{I_{D4}}}$$

$$\left(\frac{W}{L}\right)_4 = (\lambda \mu_{f4})^2 \frac{I_{DS4}}{2K_n} = [0.0125(156)]^2 \frac{5 \times 10^{-5}}{2(2.5 \times 10^{-5})} = \frac{3.80}{1}$$

15.179

(a - a) $R_{out} = \mu_{f4} r_{o2}$ | All K_n are the same : $I_O = I_{REF} = 25\mu A$

$$V_{GS1} = 0.75 + \sqrt{\frac{2(25 \times 10^{-6})}{75 \times 10^{-6}}} = 1.57V \quad | \quad \Delta V_3 = V_{GS3} - V_{TN3} = 1.57V - 0.75V = 0.817V$$

$$r_{o2} = \frac{\frac{1}{0.0125} + 1.57}{25\mu A} = 3.26M\Omega \quad | \quad r_{o4} = \frac{\frac{1}{0.0125} + (5 - 1.57)}{25\mu A} = 3.38M\Omega$$

$$g_{m4} = \sqrt{2(75 \times 10^{-6})(25 \times 10^{-6})(1 + 0.0125(5 - 1.57))} = 6.25 \times 10^{-5} S$$

$$\mu_{f4} = 6.25 \times 10^{-5} S (3.38 M\Omega) = 211 \quad | \quad R_{out} = 689 M\Omega$$

$$(a - b) V_{CS} = I_O R_{out} = 17.2 kV! \quad (a - c) V_{DD}^{\min} = V_{GS1} + \Delta V_4 = 1.57 + 0.817 = 2.39 V$$

(b - a) $R_{out} = \mu_{f4} r_{o2}$ | All K_n are the same : $I_O = I_{REF} = 25\mu A$

$$V_{GS1} = 0.75 + \sqrt{\frac{2(50 \times 10^{-6})}{75 \times 10^{-6}}} = 1.91V \quad | \quad \Delta V_3 = V_{GS3} - V_{TN3} = 1.91V - 0.75V = 1.16V$$

$$r_{o2} = \frac{\frac{1}{0.0125} + 1.91}{50\mu A} = 1.64M\Omega \quad | \quad r_{o4} = \frac{\frac{1}{0.0125} + (5 - 1.91)}{50\mu A} = 1.66M\Omega$$

$$g_{m4} = \sqrt{2(75 \times 10^{-6})(50 \times 10^{-6})(1 + 0.0125(5 - 1.91))} = 8.83 \times 10^{-5} S$$

$$\mu_{f4} = 8.83 \times 10^{-5} S (1.66 M\Omega) = 147 \quad | \quad R_{out} = 240 M\Omega$$

$$(b - b) V_{CS} = I_O R_{out} = 12.0 kV! \quad (b - c) V_{DD}^{\min} = V_{GS1} + \Delta V_4 = 1.91 + 1.16 = 3.07 V$$

15.180

$$R = \frac{1}{g_{m3}} + \frac{1}{g_{m1}} = \frac{2}{g_{m1}} = \frac{2}{\sqrt{2(75 \times 10^{-6})(17.5 \times 10^{-6})}} = 39.0 k\Omega$$

15.181

$$\begin{aligned} \text{(a)} I_{REF} &= I_{C3} + I_{B3} + I_{B4} = I_{E3} + I_{B4} = I_{C1} + \frac{2I_{C1}}{\beta_F} + \frac{I_{C2}}{\beta_F + 1} = I_{C1} + \frac{2I_{C1}}{\beta_F} + \frac{I_{C1}}{\beta_F + 1} \\ I_{C1} &= \frac{I_{REF}}{1 + \frac{2}{\beta_F} + \frac{1}{\beta_F + 1}} \quad | \quad I_o = I_{C4} = \alpha_F I_{C2} = \alpha_F I_{C1} = \frac{\beta_F}{\beta_F + 1} \frac{I_{REF}}{1 + \frac{2}{\beta_F} + \frac{1}{\beta_F + 1}} \\ I_o &= \frac{110}{111} \left(\frac{17.5\mu A}{1 + \frac{2}{110} + \frac{1}{111}} \right) = 16.9 \mu A \quad | \quad R_{out} = \frac{\beta_o r_o}{2} \cong \frac{110(50)}{2(16.9\mu A)} = 163 M\Omega \\ \text{(b)} V_{CS} &= I_o R_{out} = 16.9\mu A (163 M\Omega) = 2750 V \quad \text{(c)} V_{CC} \geq 2V_{BE} = 1.40 V \end{aligned}$$

15.182

*Figure 15.182 - NPN Cascode Current Source

IREF 0 1 17.5U

VCC 2 0 DC 5

Q1 3 3 0 NBJT 1

Q2 4 3 0 NBJT 1

Q3 1 1 3 NBJT 1

Q4 2 1 4 NBJT 1

.MODEL NBJT NPN BF=110 VA=50

.OP

.TF I(VCC) VCC

.END

Results: $I_O = 16.9 \mu A$ $R_{out} = 164 M\Omega$, the same as the hand analysis

15.183

$$R = \left(\frac{1}{g_{m3}} + \frac{1}{g_{m1}} \parallel r_{\pi 2} \right) \parallel \left[r_{\pi 4} + (\beta_{o4} + 1) r_{o2} \right] \cong \frac{1}{g_{m3}} + \frac{1}{g_{m1}} \cong \frac{2}{g_{m1}} = \frac{2}{40(17.5\mu A)} = 2.86 k\Omega$$

15.184

(a) Assuming $\beta_o = 80$ and $V_A = 60V$:

$$I_o = \frac{V_T}{R_2} \left(\ln \frac{I_{REF}}{I_o} \frac{A_{E2}}{A_{E1}} \right) = \frac{0.025V}{500\Omega} \left(\ln \frac{80\mu A}{I_o} 20 \right) \rightarrow I_o = 127 \mu A$$

$$r_{o2} = \frac{60V + 10 - 0.0635}{0.127mA} = 551k\Omega \quad | \quad r_{\pi 2} = \frac{100(0.025)}{0.127mA} = 19.7k\Omega \quad | \quad g_{ml} = 40(80\mu A) = 3.2mS$$

$$R_{out} = r_{o2} \left(1 + \frac{\beta_o R_2}{\frac{1}{g_{ml}} + r_{\pi 2} + R_2} \right) = 551k\Omega \left(1 + \frac{100(0.5k\Omega)}{0.313k\Omega + 19.7k\Omega + 0.5k\Omega} \right) = 1.89 M\Omega$$

$$(b) I_o = \frac{0.025V}{500\Omega} \left(\ln \frac{80\mu A}{I_o} 20(1.05) \right) \rightarrow I_o = 129 \mu A$$

$$(c) I_o = \frac{V_T}{R_2} \left(\ln \frac{I_{REF}}{I_o} \frac{A_{E2}}{A_{E1}} \right) = \frac{0.025V}{500\Omega} \left(\ln \frac{80\mu A}{I_o} 14 \right) \rightarrow I_o = 114 \mu A$$

$$r_{o2} = \frac{60V + 10 - 0.057}{0.114mA} = 614k\Omega \quad | \quad r_{\pi 2} = \frac{100(0.025)}{0.114mA} = 21.9k\Omega \quad | \quad g_{ml} = 40(80\mu A) = 3.2mS$$

$$R_{out} = 614k\Omega \left(1 + \frac{100(0.5k\Omega)}{0.313k\Omega + 21.9k\Omega + 0.5k\Omega} \right) = 1.97 M\Omega$$

15.185

Assuming $\beta_o = 80$ and $V_A = 60V$:

$$(a) I_o = \frac{V_T}{R_2} \left(\ln \frac{I_{REF}}{I_o} \frac{A_{E2}}{A_{E1}} \right) = \frac{0.025V}{935\Omega} \left(\ln \frac{35\mu A}{I_o} 20 \right) \rightarrow I_o = 64 \mu A$$

$$r_{o2} = \frac{60V + 10 - 0.0598}{0.064mA} = 1.09 M\Omega \quad | \quad r_{\pi 2} = \frac{100(0.025)}{0.064mA} = 39.1k\Omega \quad | \quad g_{ml} = 40(35\mu A) = 1.40mS$$

$$R_{out} = r_{o2} \left(1 + \frac{\beta_o R_2}{\frac{1}{g_{ml}} + r_{\pi 2} + R_2} \right) = 1.09 M\Omega \left(1 + \frac{100(0.935k\Omega)}{0.714k\Omega + 39.1k\Omega + 0.935k\Omega} \right) = 3.59 M\Omega$$

$$(b) I_o = \frac{V_T}{R_2} \left(\ln \frac{I_{REF}}{I_o} \frac{A_{E2}}{A_{E1}} \right) = \frac{0.025V}{935\Omega} \left(\ln \frac{35\mu A}{I_o} 10 \right) \rightarrow I_o = 51.3 \mu A$$

$$r_{o2} = \frac{60V + 10 - 0.0480}{51.3\mu A} = 1.36 M\Omega \quad | \quad r_{\pi 2} = \frac{100(0.025)}{51.3\mu A} = 48.7k\Omega \quad | \quad g_{ml} = 40(35\mu A) = 1.40mS$$

$$R_{out} = r_{o2} \left(1 + \frac{\beta_o R_2}{\frac{1}{g_{ml}} + r_{\pi 2} + R_2} \right) = 1.36 M\Omega \left(1 + \frac{100(0.935k\Omega)}{0.714k\Omega + 48.7k\Omega + 0.935k\Omega} \right) = 3.89 M\Omega$$

15.186

$$(a) R_2 = \frac{V_T}{I_O} \left(\ln \frac{I_{REF}}{I_O} \frac{A_{E2}}{A_{E1}} \right) = \frac{0.025V}{22\mu A} \left(\ln \frac{73\mu A}{22\mu A} 20 \right) = 4.77 k\Omega$$

$$(b) R_2 = \frac{V_T}{I_O} \left(\ln \frac{I_{REF}}{I_O} \frac{A_{E2}}{A_{E1}} \right) = \frac{0.025V}{5.7\mu A} \left(\ln \frac{73\mu A}{5.7\mu A} 20 \right) = 24.3 k\Omega$$

$$(c) R_2 = \frac{V_T}{I_O} \left(\ln \frac{I_{REF}}{I_O} \frac{A_{E2}}{A_{E1}} \right) = \frac{0.025V}{5.7\mu A} \left(\ln \frac{73\mu A}{5.7\mu A} 10 \right) = 21.3 k\Omega$$

15.187

$$(a) R_2 = \frac{V_T}{I_O} \left(\ln \frac{I_{REF}}{I_O} \frac{A_{E2}}{A_{E1}} \right) = \frac{0.025V}{12\mu A} \left(\ln \frac{62\mu A}{12\mu A} 10 \right) = 8.22 k\Omega$$

$$(b) R_2 = \frac{V_T}{I_O} \left(\ln \frac{I_{REF}}{I_O} \frac{A_{E2}}{A_{E1}} \right) = \frac{0.025V}{512\mu A} \left(\ln \frac{62\mu A}{512\mu A} 10 \right) = 8.22 k\Omega$$

15.188

*Problem 15.188 - NPN Widlar Current Source

IREF 2 1 50U

VCC 2 0 DC 10

Q1 1 1 0 NBJT 1

Q2 2 1 3 NBJT 20

R2 3 0 4K

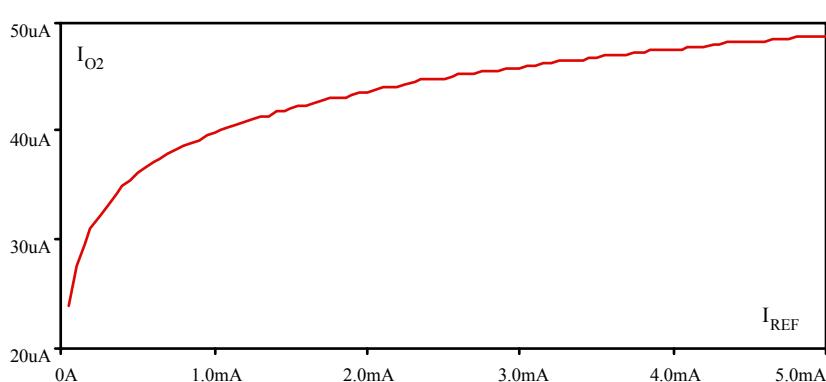
.MODEL NBJT NPN BF=110

.OP

.DC IREF 50U 5M 50U

.PROBE IC(Q2)

.END



15.189

$$I_O = \alpha_F I_{E2} = \alpha_F \left(\frac{V_{BE1}}{R_2} + I_{B1} \right) \cong \frac{V_{BE1}}{R_2} = \frac{V_T}{R_2} \ln \frac{I_{C1}}{I_{S1}}$$

$$I_{C1} = \frac{V_{EE} - V_{BE2} - V_{BE1}}{R_1} - I_{B2} \cong \frac{V_{EE} - V_{BE2} - V_{BE1}}{R_1}$$

$$(a) I_{C2} \cong \frac{0.025V}{2.2k\Omega} \ln \frac{15-1.4}{10^4(10^{-15})} = 318 \mu A \quad | \quad \text{Note: } \frac{V_{BE1}}{R_2} \cong \frac{0.7V}{2.2k\Omega} = 318 \mu A$$

$$(b) I_{C2} \cong \frac{0.025V}{2.2k\Omega} \ln \frac{3.3-1.4}{10^4(10^{-15})} = 295 \mu A \quad | \quad \text{Note: } \frac{V_{BE1}}{R_2} \cong \frac{0.7V}{2.2k\Omega} = 318 \mu A$$

$$(c) I_{C2} \cong \frac{V_T}{R_2} \ln \frac{V_{CC} - V_{EB1} - V_{EB2}}{I_{S1}R_1} = \frac{0.025V}{10k\Omega} \ln \frac{5-1.4}{10^4(10^{-15})} = 66.5 \mu A \quad | \quad \frac{0.7V}{10k\Omega} = 70 \mu A$$

15.190

$$(a) \text{Choose } I_{C1} = 0.2I_O \quad | \quad R_1 = \frac{V_{EE} - V_{BE2} - V_{BE1}}{I_{C1}} - I_{B2} \cong \frac{3.3-1.4}{6\mu A} = 317k\Omega$$

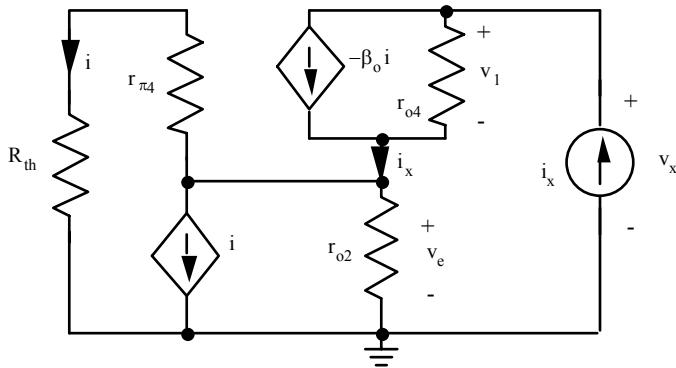
$$I_O = \alpha_F I_{E2} = \alpha_F \left(\frac{V_{BE1}}{R_2} + I_{B1} \right) \quad | \quad R_2 = \frac{V_T \ln \frac{I_{C1}}{I_{S1}}}{\frac{I_O}{\alpha_F} - I_{B1}} = \frac{0.0258V \left(\ln \frac{6\mu A}{0.1fA} \right)}{\frac{131}{130}(30\mu A) - \frac{6\mu A}{130}} = 21.2k\Omega$$

(b) This is the same circuit implemented with pnp transistors.

$$\text{Choose } I_{C1} = 0.2I_O \quad | \quad R_1 = \frac{V_{CC} - V_{EB2} - V_{EB1}}{I_{C1}} - I_{B2} \cong \frac{3.3-1.4}{6\mu A} = 317k\Omega$$

$$I_O = \alpha_F I_{E2} = \alpha_F \left(\frac{V_{EB1}}{R_2} + I_{B1} \right) \quad | \quad R_2 = \frac{V_T \ln \frac{I_{C1}}{I_{S1}}}{\frac{I_O}{\alpha_F} - I_{B1}} = \frac{0.0258V \left(\ln \frac{6\mu A}{0.1fA} \right)}{\frac{131}{130}(30\mu A) - \frac{6\mu A}{130}} = 21.2k\Omega$$

15.191



$$v_x = v_1 + v_e = (i_x - \beta_o i_1) r_{o4} + (i_x - 2i) r_{o2} \quad | \quad i_1 = -i \quad | \quad v_x = (i_x + \beta_o i) r_{o4} + (i_x - 2i) r_{o2}$$

$$i = \frac{(i_x - 2i) r_{o2}}{r_{\pi 4} + R_{th}} \text{ where } R_{th} = \frac{1}{g_{m3}} + \frac{1}{g_{m2}} \ll r_{\pi 4} \quad | \quad i \cong \frac{(i_x - 2i) r_{o2}}{r_{\pi 4}} \quad | \quad i = i_x \frac{r_{o2}}{r_{\pi 4} + 2r_{o2}}$$

$$i = i_x \frac{\mu_{f2}}{\beta_{o4} + 2\mu_{f2}} \cong \frac{i_x}{2} \text{ for } 2\mu_{f2} \gg \beta_o \quad | \quad v_x = i_x \left(r_{o2} + r_{o4} + \frac{\beta_o r_{o4}}{2} - r_{o2} \right)$$

$$R_{out} \cong r_{o4} \left(\frac{\beta_o}{2} + 1 \right) \cong \frac{\beta_o r_{o4}}{2} \quad \text{for } R_{th} \ll r_{\pi 4} \text{ and } 2\mu_{f2} \gg \beta_o$$

15.192

An iterative solution is required :

$$1. \text{ Choose } V_{GS2}. \text{ Then } I_{D2} = \frac{K_{n2}}{2} (V_{GS2} - V_{TN2})^2 [1 + \lambda(V_{DD} - I_{D2}R_l)]$$

$$\text{or } I_{D2} = \frac{\frac{K_{n2}}{2} (V_{GS2} - V_{TN2})^2 (1 + \lambda V_{DD})}{1 + \frac{K_{n2}}{2} (V_{GS2} - V_{TN2})^2 (\lambda R_l)} \quad \text{and} \quad I_{D1} = \frac{V_{GS2}}{R_2}$$

$$2. V_{GS1} = V_{TN1} + \sqrt{\frac{2I_{D1}}{K_{n1}[1 + \lambda(V_{DD} - I_{D1}R_2)]}}$$

$$3. I_{D2} = \frac{V_{DD} - V_{GS1} - V_{GS2}}{R_l} \quad \text{Compare to } I_{D2} \text{ in step 1 and choose new } V_{GS2}$$

$$I_{D2} = \frac{\frac{2.5 \times 10^{-4}}{2} (V_{GS2} - 0.75)^2 (1.17)}{1 + \frac{2.5 \times 10^{-4}}{2} (V_{GS2} - 0.75)^2 (0.017 * 10000)} \quad | \quad I_{D1} = \frac{V_{GS2}}{15k\Omega}$$

$$V_{GS1} = 0.75 + \sqrt{\frac{2I_{D1}}{2.5 \times 10^{-4} [1 + 0.017(10 - 15000I_{D1})]}} \quad | \quad I_{D2} = \frac{10 - V_{GS1} - V_{GS2}}{10k\Omega}$$

Iteration yields $V_{GS2} = 2.744V$, $I_O = I_{D2} = 536 \mu A$, and $I_{D1} = 183 \mu A$.

15.193

Choose $I_{D2} = 0.2I_o = 15\mu A$ | The effect of λ_l can be ignored because of the presence of

resistor R_2 : $V_{GS1} = V_{TN1} + \sqrt{\frac{2I_{D1}}{K_{n1}}} = 0.75 + \sqrt{\frac{2(75 \times 10^{-6})}{250 \times 10^{-6}}} = 1.53V$ | Then,

$$I_{D2} = \frac{K_{n2}}{2} (V_{GS2} - V_{TN2})^2 [1 + \lambda(V_{GS2} + V_{GS1})] \quad | \quad 15\mu A = \frac{250\mu A}{2} (V_{GS2} - 0.75)^2 [1 + \lambda(V_{GS2} + 1.53)]$$

An iterative solution gives $V_{GS2} = 1.089V$ | $R_2 = \frac{V_{GS2}}{I_o} = \frac{1.09V}{75\mu A} = 14.5 k\Omega$

$$R_l = \frac{V_{DD} - V_{GS1} - V_{GS2}}{I_{D2}} = \frac{6 - 1.53 - 1.09}{15\mu A} = 225 k\Omega$$

15.194

An iterative solution is required :

1. Choose V_{GS1} . Then $I_{D1} = \frac{K_{p1}}{2} (V_{GS1} - V_{TP1})^2 [1 + \lambda(V_{DD} - I_{D1}R_l)]$

or $I_{D2} = \frac{\frac{K_{p1}}{2} (V_{GS1} - V_{TP1})^2 (1 + \lambda V_{DD})}{1 + \frac{K_{p1}}{2} (V_{GS1} - V_{TP1})^2 (\lambda R_l)}$ and $I_{D2} = \frac{V_{SG1}}{R_2}$

2. $V_{GS2} = V_{TP2} - \sqrt{\frac{2I_{D2}}{K_{p2} [1 + \lambda(V_{DD} - I_{D2}R_2)]}}$

3. $I_{D1} = \frac{V_{DD} - V_{SG1} - V_{SG2}}{R_l}$ Compare to I_{D2} in step 1 and choose new V_{GS1}

$$I_{D1} = \frac{\frac{10^{-4}}{2} (V_{GS1} + 0.75)^2 (1.10)}{1 + \frac{10^{-4}}{2} (V_{GS1} + 0.75)^2 (0.02 * 10000)} \quad | \quad I_{D2} = \frac{V_{GS1}}{18k\Omega}$$

$$V_{GS2} = -0.75 - \sqrt{\frac{2I_{D2}}{10^{-4} [1 + 0.02(5 - 18000I_{D2})]}} \quad | \quad I_{D1} = \frac{5 - V_{SG1} - V_{SG2}}{10k\Omega}$$

Iteration yields $V_{GS1} = -1.984V$, $I_o = I_{D2} = 110 \mu A$, and $I_{D1} = 82.4 \mu A$.

15.195

Choose $I_{D1} = 0.2I_o = 25\mu A$ | The effect of λ_2 can be ignored because of the presence of

$$\text{resistor } R_2 : V_{GS2} = V_{TP2} - \sqrt{\frac{2I_{D2}}{K_{P2}}} = -0.75 - \sqrt{\frac{2(125 \times 10^{-6})}{100 \times 10^{-6}}} = -2.33V \quad | \text{ Then,}$$

$$I_{D1} = \frac{K_{p1}}{2} (V_{GS1} - V_{TP1})^2 [1 + \lambda(|V_{GS1}| + |V_{GS2}|)] \quad | \quad 25\mu A = \frac{100\mu A}{2} (V_{GS1} + 0.75)^2 [1 + \lambda(|V_{GS1}| + 2.33)]$$

$$\text{An iterative solution gives } V_{GS1} = -1.432V \quad | \quad R_2 = -\frac{V_{GS}}{I_o} = \frac{1.43V}{125\mu A} = 11.4 k\Omega$$

$$R_1 = \frac{V_{DD} + V_{GS1} + V_{GS2}}{I_{D1}} = \frac{9 - 1.43 - 2.33}{25\mu A} = 210 k\Omega$$

15.196

$$I_{C1} = I_{C3} = 3I_{C4} \quad | \quad I_{C4} = I_{C2} = \frac{V_{BE1} - V_{BE2}}{R} = \frac{V_T}{R} \left(\ln \frac{I_{C1}}{I_{S1}} - \ln \frac{I_{C2}}{I_{S2}} \right) = \frac{V_T}{R} \left(\ln \frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}} \right)$$

$$I_{C2} = \frac{0.025V}{2.2k\Omega} \left(\ln \frac{3I_{C2}}{I_{C2}} \frac{20A}{A} \right) = 46.5 \mu A \quad | \quad I_{C1} = 3I_{C2} = 140 \mu A$$

15.197

*Problem 15.197 - BJT reference current cell P15.196

VCC 1 0 DC 1.5 AC 1

VEE 5 0 DC -1.5

Q4 2 2 1 PBJT 1

Q3 3 2 1 PBJT 3

Q1 3 3 5 NBJT 1

Q2 2 3 4 NBJT 20

R 4 5 2.2K

.MODEL NBJT NPN BF=100 VA=50

.MODEL PBJT PNP BF=100 VA=50

.OP

.AC LIN 1 1000 1000

.PRINT AC IC(Q1) IC(Q2)

.END

Results: $I_{C1} = 140 \mu A$ $I_{C2} = 47.8 \mu A$ $S_{V_{CC}}^{I_{C1}} = 2.92 \times 10^{-2}$ $S_{V_{CC}}^{I_{C2}} = 9.92 \times 10^{-3}$

15.198

$$I_{C1} = I_{C3} = 3I_{C4} \quad | \quad I_{C4} = I_{C2} = \frac{V_{BE1} - V_{BE2}}{R} = \frac{V_T}{R} \left(\ln \frac{I_{C1}}{I_{S1}} - \ln \frac{I_{C2}}{I_{S2}} \right) = \frac{V_T}{R} \left(\ln \frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}} \right)$$

$$I_{C4} = I_{C2} = \frac{0.025V}{4k\Omega} \left(\ln \frac{3I_{C2}}{I_{C2}} \frac{8A}{A} \right) = 19.9 \mu A \quad | \quad I_{C1} = 3I_{C2} = 59.6 \mu A \quad | \quad I_{C3} = I_{C1} = 59.6 \mu A$$

15.199

$V_{BE1} - V_{BE2}$ must be greater than 0. | $V_{BE1} - V_{BE2} = V_T() > 0$

$$\ln \frac{I_{C1} I_{S2}}{I_{C2} I_{S1}} > 0 \text{ or } 3 \frac{nA}{A} > 1 \text{ | } n > \frac{1}{3}$$

15.200

$$(a) I_{C1} = I_{C3} = 3I_{C4} \text{ | } I_{C4} = I_{C2} = \frac{V_{BE1} - V_{BE2}}{R} = \frac{V_T}{R} \left(\ln \frac{I_{C1}}{I_{S1}} - \ln \frac{I_{C2}}{I_{S2}} \right) = \frac{V_T}{R} \ln \left(\frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}} \right)$$

$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23} (323)}{1.6 \times 10^{-19}} = 0.0279V \text{ | } R = \frac{V_T}{I_{C2}} \ln \left(\frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}} \right) = \frac{27.9mV}{35\mu A} \ln(3 \cdot 5) = 2.16 k\Omega$$

$$(b) V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23} (273)}{1.6 \times 10^{-19}} = 0.0236V \text{ | } R = \frac{V_T}{I_{C2}} \ln \left(\frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}} \right) = \frac{23.6mV}{35\mu A} \ln(3 \cdot 10) = 2.29 k\Omega$$

15.201

The M₃ - M₄ current mirror forces $I_{D1} = I_{D2}$.

$$V_{GS1} - V_{GS2} = I_{D2}R \text{ | } I_{D2}R = V_{TN} + \sqrt{\frac{2I_{D1}}{10K_n}} - V_{TN} - \sqrt{\frac{2I_{D2}}{20K_n}} \text{ | } I_{D2}R = \sqrt{\frac{2I_{D2}}{10K_n}} \left(1 - \frac{1}{\sqrt{2}} \right)$$

$$\sqrt{I_{D2}} = \frac{0.293}{R} \sqrt{\frac{1}{5K_n}} = \frac{0.293}{5100} \sqrt{\frac{1}{5(25 \times 10^{-6})}} \Rightarrow I_{D2} = 26.4 \mu A$$

15.202

(a) The M₃ - M₄ current mirror forces $I_{D1} = I_{D2}$.

$$V_{GS1} - V_{GS2} = I_{D2}R \text{ | } I_{D2}R = V_{TN1} + \sqrt{\frac{2I_{D1}}{10K_n}} - V_{TN2} - \sqrt{\frac{2I_{D2}}{20K_n}} \text{ | } I_{D2}R = \sqrt{\frac{2I_{D2}}{10K_n}} \left(1 - \frac{1}{\sqrt{2}} \right)$$

$$\sqrt{I_{D2}} = \frac{0.293}{R} \sqrt{\frac{1}{5K_n}} = \frac{0.293}{10^4} \sqrt{\frac{1}{5(25 \times 10^{-6})}} \Rightarrow I_{D2} = 6.86 \mu A$$

$$(b) V_{TN1} = V_{TO} \text{ | } V_{TN2} = V_{TO} + \gamma \left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F} \right) = V_{TO} + 0.5 \left(\sqrt{0.6 + I_{D2}R} - \sqrt{0.6} \right)$$

$$I_{D2}R = V_{TO} + \sqrt{\frac{2I_{D1}}{10K_n}} - V_{TO} - 0.5 \left(\sqrt{0.6 + I_{D2}R} - \sqrt{0.6} \right) - \sqrt{\frac{2I_{D2}}{20K_n}}$$

$$I_{D2} = \frac{0.293}{10^4} \sqrt{\frac{2I_{DS2}}{10K_n}} - \frac{0.5}{10^4} \left(\sqrt{0.6 + 10^4 I_{D2}} - \sqrt{0.6} \right) \rightarrow I_{D2} = 3.96 \mu A$$

15.203 This problem should refer to Prob. 15.202 (a) and (b)

*Problem 15.203(a) - MOS reference current cell

VDD 1 0 DC 5 AC 1

VSS 5 0 DC -5

M1 3 3 5 5 NFET W=10U L=1U

M2 2 3 4 5 NFET W=20U L=1U

M3 3 2 1 1 PFET W=10U L=1U

M4 2 2 1 1 PFET W=10U L=1U

R 4 5 10K

.MODEL NFET NMOS KP=25U VTO=0.75 PHI=0.6 GAMMA=0 LAMBDA=0.017

.MODEL PFET PMOS KP=10U VTO=-0.75 PHI=0.6 GAMMA=0 LAMBDA=0.017

*.MODEL NFET NMOS KP=25U VTO=0.75 PHI=0.6 GAMMA=0 LAMBDA=0

*.MODEL PFET PMOS KP=10U VTO=-0.75 PHI=0.6 GAMMA=0 LAMBDA=0

*Problem 15.203(b) - MOS reference current cell

*.MODEL NFET NMOS KP=25U VTO=0.75 PHI=0.6 GAMMA=0.5 LAMBDA=0.017

*.MODEL PFET PMOS KP=10U VTO=-0.75 PHI=0.6 GAMMA=0.75 LAMBDA=0.017

.OP

.AC LIN 1 1000 1000

.PRINT AC ID(M1) ID(M2)

.END

Results: (a) $I_{D2} = 13.9 \mu A$ $I_{D2} = 12.3 \mu A$ $S_{V_{DD}}^{I_{D1}} = 7.64 \times 10^{-2}$ $S_{V_{DD}}^{I_{D2}} = 6.23 \times 10^{-2}$

The currents differ considerably from the hand calculations.

Results: (b) $I_{D1} = 8.19 \mu A$ $I_{D2} = 7.24 \mu A$ $S_{V_{DD}}^{I_{D1}} = 7.75 \times 10^{-2}$ $S_{V_{DD}}^{I_{D2}} = 6.31 \times 10^{-2}$

The currents differ considerably from the hand calculations. The currents are quite sensitive to the value of λ . The hand calculations used $\lambda = 0$. If the simulations are run with $\lambda = 0$, then the results are identical to the hand calculations.

15.204

$$I_{C2} = \frac{V_T}{R} \ln\left(\frac{I_{C1}}{A} \frac{5A}{I_{C2}}\right) \quad | \quad I_{C1} = I_{C3} = 2I_{C4} = 2I_{C2} \quad | \quad I_{C2} = \frac{0.025V}{11k\Omega} \ln\left(\frac{2I_{C2}}{A} \frac{5A}{I_{C2}}\right) = 5.23 \mu A$$

$$I_{C7} = 5I_{C4} = 5(5.23 \mu A) = 26.2 \mu A \quad | \quad I_{C8} = \frac{V_T}{R_8} \ln\left(\frac{I_{C4}}{A} \frac{3A}{I_{C8}}\right) = \frac{0.025V}{4k\Omega} \ln\left(\frac{15.7 \mu A}{I_{C8}}\right) \rightarrow I_{C8} = 6.00 \mu A$$

$$I_{C5} = 2.5I_{C1} = 5I_{C2} = 26.2 \mu A \quad | \quad I_{C6} = \frac{V_T}{R_6} \ln\left(\frac{I_{C1}}{A} \frac{A}{I_{C6}}\right) = \frac{0.025V}{3k\Omega} \ln\left(\frac{10.4 \mu A}{I_{C6}}\right) \rightarrow I_{C6} = 5.42 \mu A$$

15.205

$$I_{C2} = \frac{V_T}{R} \ln\left(\frac{I_{C1}}{A} \frac{10A}{I_{C2}}\right) \quad | \quad I_{C1} = I_{C3} = I_{C4} = I_{C2} \quad | \quad I_{C2} = \frac{0.025V}{11k\Omega} \ln\left(\frac{I_{C2}}{A} \frac{10A}{I_{C2}}\right) = 5.23 \mu A$$

$$I_{C7} = 5I_{C4} = 5(5.23 \mu A) = 26.2 \mu A \quad | \quad I_{C8} = \frac{V_T}{R_8} \ln\left(\frac{I_{C4}}{A} \frac{3A}{I_{C8}}\right) = \frac{0.025V}{4k\Omega} \ln\left(\frac{15.7 \mu A}{I_{C8}}\right) \rightarrow I_{C8} = 6.00 \mu A$$

$$I_{C5} = 2.5I_{C1} = 13.1 \mu A \quad | \quad I_{C6} = \frac{V_T}{R_6} \ln\left(\frac{I_{C1}}{A} \frac{A}{I_{C6}}\right) = \frac{0.025V}{3k\Omega} \ln\left(\frac{5.23 \mu A}{I_{C6}}\right) \rightarrow I_{C6} = 3.45 \mu A$$

15.206

$$(a) I_{C1} = 2I_{C2} \text{ set by } Q_4 \text{ and } Q_3 \quad | \quad I_{C2} = \frac{V_T}{R} \left(\ln \frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}} \right) = \frac{0.025V}{4.3k\Omega} \left(\ln \frac{2I_{C2}}{I_{C2}} \frac{7I_{S1}}{I_{S1}} \right) = 15.3 \mu A$$

$$I_{C1} = 2I_{C2} = 30.6 \mu A \quad | \quad I_{C4} = I_{C5} = I_{C6} = I_{C1} = 30.6 \mu A \quad | \quad I_{C3} = I_{C7} = I_{C2} = 15.3 \mu A$$

(b) No change. The currents are independent of the areas of Q_5 , Q_6 , and Q_7 .

15.207

*Problem 15.207 - NPN Cascode Current Source

VCC 1 0 DC 5 AC 1

Q4 2 2 1 PBJT 2

Q3 3 2 1 PBJT 1

Q5 4 3 2 PBJT 1

Q1 6 6 0 NBJT 1

Q2 5 6 7 NBJT 7

Q6 4 4 6 NBJT 1

Q7 3 4 5 NBJT 1

R 7 0 4.3K

.MODEL NBJT NPN BF=100 VA=50

.MODEL PBJT PNP BF=50 VA=50

.OP

.AC LIN 1 1000 1000

.PRINT AC IC(Q7) IC(Q5)

.END

Results: $I_{C2} = 15.2 \mu A$ $I_{C1} = 28.5 \mu A$ - Similar to hand calculations.

$$S_{V_{CC}}^{I_{C1}} = 1.81 \times 10^{-3} \quad S_{V_{CC}}^{I_{C2}} = 7.07 \times 10^{-4}$$

15.208

$$(a) I_{C1} = I_{C2} \text{ set by } Q_4 \text{ and } Q_3 \quad | \quad I_{C2} = \frac{V_T}{R} \left(\ln \frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}} \right) = \frac{0.025V}{4.3k\Omega} \left(\ln \frac{I_{C2}}{I_{C2}} \frac{7I_{S1}}{I_{S1}} \right) = 11.3 \mu A$$

$$I_{C1} = I_{C2} = 11.3 \mu A \quad | \quad I_{C4} = I_{C5} = I_{C6} = I_{C1} = 11.3 \mu A \quad | \quad I_{C3} = I_{C7} = I_{C2} = 11.3 \mu A$$

(b) No change. The currents are independent of the areas of Q_5 , Q_6 , and Q_7 .

15.209

(a) The M₃ - M₄ current mirror forces I_{D1} = 1.5I_{D2}.

$$V_{GS1} - V_{GS2} = I_{D2}R \quad | \quad I_{D2}R = V_{TN} + \sqrt{\frac{2I_{D1}}{10K_n}} - V_{TN} - \sqrt{\frac{2I_{D2}}{30K_n}}$$
$$I_{D2} = \frac{1}{R} \left(\sqrt{\frac{3I_{D2}}{10K_n}} - \sqrt{\frac{2I_{D2}}{30K_n}} \right) = \frac{1}{3300} \left(\sqrt{\frac{3I_{D2}}{10(25 \times 10^{-6})}} - \sqrt{\frac{2I_{D2}}{30(25 \times 10^{-6})}} \right)$$

$$\sqrt{I_{D2}} = \frac{57.9}{3300} \Rightarrow I_{D2} = 308 \mu A \quad I_{D1} = 462 \mu A$$

$$I_{D4} = I_{D5} = I_{D6} = I_{D1} = 462 \mu A \quad | \quad I_{D3} = I_{D7} = I_{D2} = 308 \mu A$$

(b) With $\lambda = 0$, the currents do not depend upon the W/L ratios of M₅, M₆ or M₇ as long as all transistors remain in the active region. For $\lambda \neq 0$, there will be a weak dependence, since the drain - source voltages of M₂ and M₃ will change slightly.

15.210

*Problem 15.210 - MOS reference current cell

VDD 1 0 DC 15 AC 1

M3 3 2 1 1 PFET W=10U L=1U

M4 2 2 1 1 PFET W=15U L=1U

M5 4 3 2 2 PFET W=10U L=1U

M6 4 4 6 6 NFET W=10U L=1U

M7 3 4 5 5 NFET W=10U L=1U

M1 6 6 0 0 NFET W=10U L=1U

M2 5 6 7 7 NFET W=30U L=1U

R 7 0 3.3K

*.MODEL NFET NMOS KP=25U VTO=0.75 LAMBDA=0

*.MODEL PFET PMOS KP=10U VTO=-0.75 LAMBDA=0

.MODEL NFET NMOS KP=25U VTO=0.75 LAMBDA=0.017

.MODEL PFET PMOS KP=10U VTO=-0.75 LAMBDA=0.017

.OP

.AC LIN 1 1000 1000

.PRINT AC ID(M1) ID(M2)

.END

Results: I_{D2} = 265 μA I_{D1} = 377 μA These differ from the hand calculations due to the non-zero value of λ . Simulation with $\lambda = 0$ gives results very close to the hand calculations.

$$S_{V_{DD}}^{I_{D2}} = 9.82 \times 10^{-4} \quad S_{V_{DD}}^{I_{D1}} = 6.99 \times 10^{-4}$$

15.211

The $M_3 - M_4$ current mirror forces $I_{D1} = I_{D2}$.

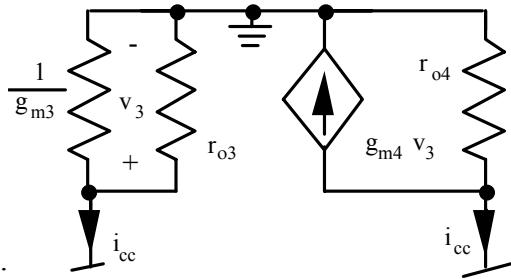
$$V_{GS1} - V_{GS2} = I_{D2}R \quad | \quad I_{D2}R = \left(V_{TN} + \sqrt{\frac{2I_{D1}}{10K_n}} \right) - \left(V_{TN} + \sqrt{\frac{2I_{D2}}{30K_n}} \right)$$

$$I_{D2} = \frac{1}{R} \left(\sqrt{\frac{2I_{D2}}{10K_n}} - \sqrt{\frac{2I_{D2}}{30K_n}} \right) = \frac{1}{3300} \left(\sqrt{\frac{I_{D2}}{5(25 \times 10^{-6})}} - \sqrt{\frac{I_{D2}}{15(25 \times 10^{-6})}} \right)$$

$$\sqrt{I_{D2}} = \frac{34.1}{3300} \Rightarrow I_{D2} = 107 \mu A \quad I_{D1} = 107 \mu A$$

$$I_{D4} = I_{D5} = I_{D6} = I_{D1} = 107 \mu A \quad | \quad I_{D3} = I_{D7} = I_{D2} = 107 \mu A$$

15.212



Current mirror model:

Assuming $V_{DS} \ll \frac{1}{\lambda}$ since it is unknown:

$$A_{dd} = g_{m1}(r_{o2} \| r_{o4}) \approx g_{m1} \frac{r_{o4}}{2} \approx \sqrt{2(5 \times 10^{-4})(10^{-4})} \left(\frac{50}{10^{-4}} \middle\| \frac{50}{10^{-4}} \right) = 0.316 mS (250 k\Omega) = 79.1$$

A_{cd} is determined by the mirror ratio error:

$$i_{cc} + g_{m4}v_3 = i_{cc} - g_{m4} \frac{i_{cc}}{g_{m3} + g_{o3}} = i_{cc} \frac{g_{m3} - g_{m4} + g_{o3}}{g_{m3} + g_{o3}} = i_{cc} \frac{1}{\mu_{f3} + 1} \quad \text{for } g_{m3} = g_{m4}$$

This error current goes through r_{o4} to produce the output voltage since the

common-mode output resistance at the drain of M_2 is very large: $v_{od} = i_{cc} \frac{r_{o4}}{\mu_{f3} + 1}$

$$i_{cc} = v_{ic} \frac{g_{m1}}{1 + 2g_{m1}R_{SS}} \approx v_{ic} \frac{1}{2R_{SS}} \quad | \quad A_{cd} = \frac{1}{\mu_{f3} + 1} \left(\frac{r_{o4}}{2R_{SS}} \right) = \left[\frac{1}{2(79.1) + 1} \right] \frac{500 k\Omega}{50 M\Omega} = 6.28 \times 10^{-5}$$

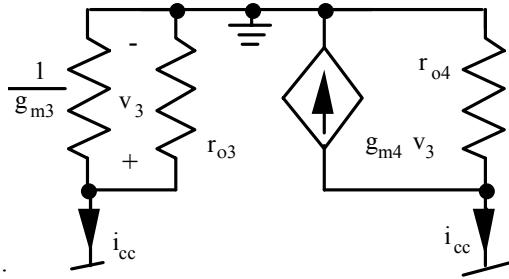
$$CMRR = \frac{79.1}{6.28 \times 10^{-5}} = 1.26 \times 10^6 \quad (122 \text{ dB})$$

15.213

*Problem 15.213 - MOS Amplifier with Active Load
VDD 1 0 DC 10
VSS 5 0 DC -10
V1 6 8 DC 0 AC 0.5
V2 7 8 DC 0 AC -0.5
VIC 8 0 DC 0
M3 2 2 1 1 PFET W=50U L=1U
M4 3 2 1 1 PFET W=50U L=1U
M1 2 6 4 4 NFET W=20U L=1U
M2 3 7 4 4 NFET W=20U L=1U
ISS 4 5 DC 199.5U
RSS 4 5 25MEG
.MODEL NFET NMOS KP=25U VTO=1 LAMBDA=0.02
.MODEL PFET PMOS KP=10U VTO=-1 LAMBDA=0.02
.OP
.AC LIN 1 1000 1000
.PRINT AC VM(3) VP(3)
.TF V(3) VIC
.END

Results: $A_{dm} = 98.8$ $A_{cd} = 6.16 \times 10^{-5}$. The results are similar to hand calculations. The discrepancies result from not including V_{DS} in the hand calculations for both g_m and r_o .

15.214



Current mirror model:

Assuming $V_{DS} \ll \frac{1}{\lambda}$ since it is unknown:

$$A_{dd} = g_{m1}(r_{o2} \| r_{o4}) \approx g_{m1} \frac{r_{o4}}{2} \approx \sqrt{2(5 \times 10^{-4})(5 \times 10^{-4})} \left(\frac{66.7}{5 \times 10^{-4}} \parallel \frac{66.7}{5 \times 10^{-4}} \right) = 0.707 mS (66.7 k\Omega) = 47.2$$

A_{cd} is determined by the mirror ratio error:

$$i_{cc} + g_{m4}v_3 = i_{cc} - g_{m4} \frac{i_{cc}}{g_{m3} + g_{o3}} = i_{cc} \frac{g_{m3} - g_{m4} + g_{o3}}{g_{m3} + g_{o3}} = i_{cc} \frac{1}{\mu_{f3} + 1} \quad \text{for } g_{m3} = g_{m4}$$

This error current goes through r_{o4} to produce the output voltage since the

common-mode output resistance at the drain of M₂ is very large: $v_{od} = i_{cc} \frac{r_{o4}}{\mu_{f3} + 1}$

$$i_{cc} = v_{ic} \frac{g_{m1}}{1 + 2g_{m1}R_{SS}} \approx v_{ic} \frac{1}{2R_{SS}} \quad | \quad A_{cd} = \frac{1}{\mu_{f3} + 1} \left(\frac{r_{o4}}{2R_{SS}} \right) = \left[\frac{1}{2(47.2) + 1} \right] \frac{133 k\Omega}{20 M\Omega} = 6.97 \times 10^{-5}$$

$$CMRR = \frac{47.2}{6.97 \times 10^{-5}} = 6.77 \times 10^5 \quad (117 \text{ dB})$$

15.215

*Problem 15.214 - MOS Amplifier with Active Load
VDD 1 0 DC 12
VSS 5 0 DC -12
V1 6 8 DC 0 AC 0.5
V2 7 8 DC 0 AC -0.5
VIC 8 0 DC 0
M3 2 2 1 1 PFET W=50U L=1U
M4 3 2 1 1 PFET W=50U L=1U
M1 2 6 4 4 NFET W=20U L=1U
M2 3 7 4 4 NFET W=20U L=1U
ISS 4 5 DC 1M
RSS 4 5 10MEG
.MODEL NFET NMOS KP=25U VTO=1 LAMBDA=0.02
.MODEL PFET PMOS KP=10U VTO=-1 LAMBDA=0.02
.OP
.AC LIN 1 1000 1000
.PRINT AC VM(3) VP(3)
.TF V(3) VIC
.END

Results: $A_{dm} = 56.2$ $A_{cd} = 6.82 \times 10^{-5}$. The results are similar to hand calculations. The discrepancies result from not including V_{DS} in the hand calculations for g_m and r_o .

15.216

Assuming $V_{CE} \ll V_A$ since it is unknown :

$$A_{dd} = g_{m2} \left(r_{o2} \| r_{o4} \right) \approx g_{m2} \frac{r_{o4}}{2} \approx 40 \left(10^{-4} \right) \left(\frac{60}{10^{-4}} \right) \left(\frac{60}{10^{-4}} \right) = 4.00 mS (300 k\Omega) = 1200$$

A_{cd} : This circuit is often the input stage of a feedback amplifier and the feedback applies an offset voltage V_{os} that forces $v_{C1} = v_{C2}$. In this case, the induced collector current imbalance exactly matches the current mirror imbalance and $A_{cd} = 0$.

The case for $V_{C1} \neq V_{C2}$ is a more difficult problem!

The mirror ratio causes a mismatch in the collector currents and therefore

a mismatch in g_m : $g_{m1} = g_m + \frac{\Delta g_m}{2}$ $g_{m2} = g_m - \frac{\Delta g_m}{2}$ | The common - mode voltage that is developed across $r_{\pi 1}$ and $r_{\pi 2}$ (v_{π}^{cm}) is multiplied by g_{m1} and g_{m2} . The common $g_m v_{\pi}^{cm}$ term is canceled out by the current mirror, but the mismatch terms add at the output of the current mirror. The output voltage is given approximately by

$$v_o = \Delta g_{m2} v_{\pi}^{cm} \left(r_{o4} \| r_{o2} \right) = \Delta g_{m2} v_{\pi}^{cm} \frac{r_{o2}}{2} = \frac{\Delta g_{m2}}{g_{m2}} v_{\pi}^{cm} \frac{\mu_{f2}}{2}$$

$$v_{\pi}^{cm} = v_{ic} \frac{r_{\pi 2}}{r_{\pi 2} + (\beta_o + 1)(2R_l \| r_{o2})} \approx v_{ic} \frac{1}{g_{m2}(2R_l \| r_{o2})} \approx \frac{v_{ic}}{g_{m2} r_{o2}} = \frac{v_{ic}}{\mu_{f2}} \text{ for } 2R_l \gg r_{o2}$$

$$A_{cd} = \frac{v_o}{v_{ic}} \approx \frac{1}{2} \frac{\Delta g_{m2}}{g_{m2}}$$

The collector current imbalance can be found as follows: Assume that $V_{EC4} = V_{EC3} + \Delta V$

$$\text{and equal Early voltages: } I_{C4} = I_{C2} \Rightarrow I_{C1} \frac{\frac{V_A}{2 + \frac{0.7}{\beta_F}}}{\frac{V_A}{1 + \frac{0.7}{\beta_F}}} = I_{C1} \left(1 - \frac{\Delta V}{V_A} \right) | \Delta V \approx \frac{V_A}{\beta_F} = \frac{60V}{125} = 0.48V$$

$$\Delta I_C = I_{C1} - I_{C2} = I_{C0} \left(1 + \frac{V_{C1}}{V_A} \right) - I_{C0} \left(1 + \frac{V_{C1} - \Delta V}{V_A} \right) = I_{C0} \frac{\Delta V}{V_A} | I_{C0} = I_S \exp \frac{V_{BE}}{V_T} \approx I_C$$

$$\Delta I_C = I_{C0} \frac{\Delta V}{V_A} \approx I_C \frac{\Delta V}{V_A} | \frac{\Delta I_C}{I_C} \approx \frac{\Delta V}{V_A} = \frac{1}{\beta_F} | \frac{\Delta g_{m2}}{g_{m2}} = \frac{\Delta I_C}{I_C} = \frac{1}{\beta_F} | A_{cd} = \frac{1}{2\beta_F}$$

$$A_{cd} = \frac{1}{2(125)} = 4 \times 10^{-3} | CMRR = \frac{1200}{4 \times 10^{-3}} = 3 \times 10^5 \text{ (110 dB)}$$

$$\text{Note that } V_{os} \approx \frac{\Delta V}{A_{dd}} | \Delta V \approx \frac{60}{125} = 0.48V | V_{os} \approx \frac{0.48}{1200} = 0.400 mV$$

15.216 cont.

For V_{IC} : $V_{CB1} = V_{CC} - V_{EB3} - V_{IC} \geq 0$ | $V_{CC} \geq V_{IC} + V_{EB3} = 1.5 + 0.7 = 2.2$ V

Assume that the current source needs $V_{CS} = 0.7$ V across it to operate properly.

$$V_{IC} - V_{BE} - (-V_{EE}) \geq V_{CS} \quad | \quad V_{EE} \geq V_{CS} + V_{BE} - V_{IC} = 0.7 + 0.7 - (-1.5) = 2.9\text{V}$$

We need ± 2.9 - V supplies or approximately ± 3 V.

These results can be easily checked with SPICE - See Problem 15.217

15.217

*Figure 15.83 - BJT Differential Amplifier with Active Load

VCC 1 0 DC 5

VEE 5 0 DC -5

Q4 3 2 1 PBJT 1

Q3 2 2 1 PBJT 1

Q1 2 6 4 NBJT 1

Q2 3 7 4 NBJT 1

*Apply offset voltage to balance collector voltages

V1 6 8 DC 0.4107M AC 0.5

*V1 6 8 DC 0 AC 0.5

V2 7 8 DC 0 AC -0.5

VIC 8 0 DC 0

I1 4 5 199.8U

R1 4 5 25MEG

.MODEL NBJT NPN BF=125 VA=60

.MODEL PBJT PNP BF=125 VA=60

.OP

.AC LIN 1 1000 1000

.PRINT AC VM(3) VP(3) VM(4) VP(4)

.TF V(3) VIC

.END

Results: $A_{dm} = 1200$ $A_{cd} = 5.11 \times 10^{-6}$. CMRR = 167 dB. The results are similar to hand calculations. Note that a very high CMRR is achieved when the circuit is brought back to balance, as is the case in operational amplifier input stages with feedback applied. For the case with no offset voltage applied, $A_{cd} = 3.73 \times 10^{-3}$, and $\Delta V = 0.49$ V. These agree well with the analysis in Prob. 15.216. The value of the required offset voltage is also very similar to the hand calculations.

15.218

(a) Assuming $V_{CE} \ll V_A$ since it is unknown :

$$A_{dd} = g_{m2}(r_{o2}\|r_{o4}) \approx g_{m2} \frac{r_{o4}}{2} \approx 40(5 \times 10^{-5}) \left(\frac{75}{5 \times 10^{-5}} \right) \left(\frac{75}{5 \times 10^{-5}} \right) = 2.00 mS (750 k\Omega) = 1500$$

A_{cd} : This circuit is often the input stage of a feedback amplifier and the feedback applies an offset voltage V_{os} that forces $v_{C1} = v_{C2}$. In this case, the induced collector current imbalance exactly matches the current mirror imbalance and $A_{cd} = 0$.

The case for $V_{C1} \neq V_{C2}$ is a more difficult problem!

The mirror ratio causes a mismatch in the collector currents and therefore

a mismatch in g_m : $g_{m1} = g_m + \frac{\Delta g_m}{2}$ $g_{m2} = g_m - \frac{\Delta g_m}{2}$ | The common - mode voltage that is

developed across $r_{\pi 1}$ and $r_{\pi 2}$ (v_{π}^{cm}) is multiplied by g_{m1} and g_{m2} . The common $g_m v_{\pi}^{cm}$ term is canceled out by the current mirror, but the mismatch terms add at the output of the current mirror. The output voltage is given approximately by

$$v_o = \Delta g_{m2} v_{\pi}^{cm} (r_{o4}\|r_{o2}) = \Delta g_{m2} v_{\pi}^{cm} \frac{r_{o2}}{2} = \frac{\Delta g_{m2}}{g_{m2}} v_{\pi}^{cm} \frac{\mu_{f2}}{2}$$

$$v_{\pi}^{cm} = v_{ic} \frac{r_{\pi 2}}{r_{\pi 2} + (\beta_o + 1)(2R_l\|r_{o2})} \approx v_{ic} \frac{1}{g_{m2}(2R_l\|r_{o2})} \approx \frac{v_{ic}}{g_{m2} r_{o2}} = \frac{v_{ic}}{\mu_{f2}} \text{ for } 2R_l \gg r_{o2}$$

$$A_{cd} = \frac{v_o}{v_{ic}} \approx \frac{1}{2} \frac{\Delta g_{m2}}{g_{m2}}$$

The collector current imbalance can be found as follows: Assume that $V_{EC4} = V_{EC3} + \Delta V$

$$\text{and equal Early voltages: } I_{C4} = I_{C2} \Rightarrow I_{C1} \frac{V_A}{1 + \frac{2}{\beta_F} + \frac{0.7}{V_A}} = I_{C1} \left(1 - \frac{\Delta V}{V_A} \right) \mid \Delta V \approx \frac{V_A}{\beta_F} = \frac{75V}{125} = 0.60V$$

$$\Delta I_C = I_{C1} - I_{C2} = I_{C0} \left(1 + \frac{V_{C1}}{V_A} \right) - I_{C0} \left(1 + \frac{V_{C1} - \Delta V}{V_A} \right) = I_{C0} \frac{\Delta V}{V_A} \mid I_{C0} = I_S \exp \frac{V_{BE}}{V_T} \approx I_C$$

$$\Delta I_C = I_{C0} \frac{\Delta V}{V_A} \approx I_C \frac{\Delta V}{V_A} \mid \frac{\Delta I_C}{I_C} \approx \frac{\Delta V}{V_A} = \frac{1}{\beta_F} \mid \frac{\Delta g_{m2}}{g_{m2}} = \frac{\Delta I_C}{I_C} = \frac{1}{\beta_F} \mid A_{cd} = \frac{1}{2\beta_F}$$

$$A_{cd} = \frac{1}{2(125)} = 4 \times 10^{-3} \mid CMRR = \frac{1500}{4 \times 10^{-3}} = 3.75 \times 10^5 \text{ (112 dB)}$$

15.218 continued on next page

15.218 cont.

Note that $V_{os} \approx \frac{\Delta V}{A_{dd}} \quad | \quad \Delta V \approx \frac{75}{125} = 0.60V \quad | \quad V_{os} \approx \frac{0.60}{1500} = 0.400 mV$

For V_{IC} : $V_{CB1} = V_{CC} - V_{EB3} - V_{IC} \geq 0 \quad | \quad V_{CC} \geq V_{IC} + V_{EB3} = 1.5 + 0.7 = 2.2 V$

Assume that the current source needs $V_{CS} = 0.7 V$ across it to operate properly.

$$V_{IC} - V_{BE} - (-V_{EE}) \geq V_{CS} \quad | \quad V_{EE} \geq V_{CS} + V_{BE} - V_{IC} = 0.7 + 0.7 - (-1.5) = 2.9V$$

We need ± 2.9 - V supplies or approximately $\pm 3V$.

$$(b) A_{dd} = g_{m2} (r_{o2} \| r_{o4}) \approx g_{m2} \frac{r_{o4}}{2} \approx 40 (5 \times 10^{-5}) \left(\frac{100}{5 \times 10^{-5}} \right) \left(\frac{100}{5 \times 10^{-5}} \right) = 2.00 mS (1.00 M\Omega) = 2000$$

$$A_{cd} = \frac{v_o}{v_{ic}} \approx \frac{1}{2} \frac{\Delta g_{m2}}{g_{m2}} \quad | \quad I_{C4} = I_{C2} \Rightarrow I_{C1} \frac{V_A}{1 + \frac{2}{\beta_F} + \frac{0.7}{V_A}} = I_{C1} \left(1 - \frac{\Delta V}{V_A} \right) \quad | \quad \Delta V \approx \frac{V_A}{\beta_F} = \frac{100V}{125} = 0.80V$$

$$\Delta I_C = I_{C1} - I_{C2} = I_{C0} \left(1 + \frac{V_{C1}}{V_A} \right) - I_{C0} \left(1 + \frac{V_{C1} - \Delta V}{V_A} \right) = I_{C0} \frac{\Delta V}{V_A} \quad | \quad I_{C0} = I_S \exp \frac{V_{BE}}{V_T} \approx I_C$$

$$\Delta I_C = I_{C0} \frac{\Delta V}{V_A} \approx I_C \frac{\Delta V}{V_A} \quad | \quad \frac{\Delta I_C}{I_C} \approx \frac{\Delta V}{V_A} = \frac{1}{\beta_F} \quad | \quad \frac{\Delta g_{m2}}{g_{m2}} = \frac{\Delta I_C}{I_C} = \frac{1}{\beta_F} \quad | \quad A_{cd} = \frac{1}{2\beta_F}$$

$$A_{cd} = \frac{1}{2(125)} = 4 \times 10^{-3} \quad | \quad CMRR = \frac{2000}{4 \times 10^{-3}} = 5.00 \times 10^5 \text{ (114 dB)}$$

For V_{IC} : $V_{CB1} = V_{CC} - V_{EB3} - V_{IC} \geq 0 \quad | \quad V_{CC} \geq V_{IC} + V_{EB3} = 1.5 + 0.7 = 2.2 V$

Assume that the current source needs $V_{CS} = 0.7 V$ across it to operate properly.

$$V_{IC} - V_{BE} - (-V_{EE}) \geq V_{CS} \quad | \quad V_{EE} \geq V_{CS} + V_{BE} - V_{IC} = 0.7 + 0.7 - (-1.5) = 2.9V$$

We need ± 2.9 - V supplies or approximately $\pm 3V$.

15.219

Results: For $V_A = 75 V$, $A_{dm} = 1470$ and $A_{cd} = 6.92 \times 10^{-3}$. $CMRR = 106$ dB. The results are similar to hand calculations. Note that a very high CMRR is achieved when the circuit is brought back to balance (with $V_{OS} = 0.728$ mV), as is the case in operational amplifier input stages with feedback applied. For the case with the offset voltage applied, $A_{cd} = 2.71 \times 10^{-7}$.

15.220

$$(a) I_{D5} = I_{D4} = I_{D3} = I_{D2} = I_{D1} = \frac{I_{SS}}{2} = 100 \mu A$$

$$V_{GS2} = V_{GS1} = V_{TN} + \sqrt{\frac{2I_{D1}}{K_{n1}}} = 0.75 + \sqrt{\frac{2(10^{-4})}{40(2.5 \times 10^{-5})}} = 1.20V$$

$$V_{GS5} = V_{GS4} = V_{GS3} = V_{TP} - \sqrt{\frac{2I_{D4}}{K_{p4}}} = -0.75 - \sqrt{\frac{2(10^{-4})}{80(10^{-5})}} = -1.25V \quad | \quad V_{DS3} = V_{DS4} + V_{GS5} = -2.50V$$

$$V_{DS1} = V_{DS2} = 10 + V_{GS4} + V_{GS5} - (-V_{GS1}) = 8.70V \quad | \quad V_{DS5} = V_{DS4} = V_{GS4} = -1.25V$$

$Q-Pts : (100\mu A, 8.70V) (100\mu A, 8.70V) (100\mu A, -2.50V) (100\mu A, -1.25V) (100\mu A, -1.25V)$

$$(b) A_{dd} = g_{m2} \left(r_{o2} \parallel \frac{2}{3} \mu_f r_{o5} \right) \cong g_{m2} r_{o2}$$

$$A_{dd} = \sqrt{2(40)(2.5 \times 10^{-5})(10^{-4})} \left[1 + 0.017(8.7) \right] \left(\frac{1}{10^{-4}} + 8.7 \right) = 0.479 mS (675 k\Omega) = 323$$

(Note that the loop-gain of the Wilson source is reduced by the presence of $R_{out1} \cong 2r_{o1}$.)

$$(c) A_{dd} = g_{m1} (r_{o1} \parallel r_{o3}) \quad | \quad r_{o3} = \left(\frac{1}{10^{-4}} + 1.25 \right) = 601 k\Omega$$

$$A_{dd} = 0.479 mS (675 k\Omega \parallel 601 k\Omega) = 152 \quad - \text{The Wilson source yields a 2X improvement.}$$

15.221

M	1	2	3	4	5
I _D (μA)	101	99.0	101	99.0	99.0
V _{DS} (V)	8.69	7.33	-2.48	-1.24	-2.60

Results: A_{dm} = 313. The gain and Q-points are similar to hand calculations.

15.222

$$I_{D2} = I_{D1} = \frac{I_1}{2} = 125 \mu A \quad | \quad I_{D3} = I_{D4} = I_{D5} = I_{D6} = I_{D7} = I_2 - \frac{I_1}{2} = 125 \mu A$$

$$\text{For the NMOS transistors } V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = 0.75 + \sqrt{\frac{2(1.25 \times 10^{-4})}{40(2.5 \times 10^{-5})}} = 1.25V$$

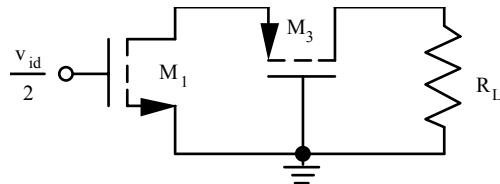
$$\text{For the PMOS transistors } V_{GS} = V_{TP} - \sqrt{\frac{2I_D}{K_p}} = -0.75 - \sqrt{\frac{2(1.25 \times 10^{-4})}{40(10^{-5})}} = -1.54V$$

$$V_{DS1} = V_{DS2} = -V_{GS3} = 1.54V \quad | \quad V_{DS7} = V_{DS6} = V_{GS6} = 1.25V \quad | \quad V_{DS5} = V_{GS6} + V_{GS7} = 2.50V$$

$$V_{DS4} = V_{DS3} = (-5 + V_{DS5}) - (-V_{GS1} - V_{GS3}) = -5 + 2.50 - (-1.25 + 1.54) = -2.79V$$

Q-Pts: $(125\mu A, 1.54V)$ $(125\mu A, 1.54V)$ $(125\mu A, -2.79V)$ $(125\mu A, -2.79V)$

$(125\mu A, 2.50V)$ $(125\mu A, 1.25V)$ $(125\mu A, 1.25V)$



$$(b) A_{dd} = g_{m2} (\mu_{f4} r_{o2} \| \mu_{f5} r_{o7}) \cong \frac{\mu_{f2} \mu_{f4}}{2}$$

$$g_{m2} = \sqrt{2(40)(2.5 \times 10^{-5})(1.25 \times 10^{-4})[1 + 0.017(1.54)]} = 0.507 mS \quad | \quad r_{o3} = \left(\frac{1}{0.017} + 1.54 \right) = 483 k\Omega$$

$$g_{m4} = \sqrt{2(40)(10^{-5})(1.25 \times 10^{-4})[1 + 0.017(2.79)]} = 0.324 mS \quad | \quad r_{o4} = \left(\frac{1}{0.017} + 2.79 \right) = 493 k\Omega$$

$$A_{dd} \cong \frac{\mu_{f2} \mu_{f4}}{2} = \frac{(0.507 mS)(483 k\Omega)(0.324 mS)(493 k\Omega)}{2} = 19600$$

15.223

*Figure P15.222 - CMOS Folded Cascode Amplifier with Active Load

VDD 1 0 DC 5

VSS 10 0 DC -5

*An offset voltage must be applied to bring output to -2.5V

V1 4 11 DC -5.085M AC 0.5

V2 5 11 DC 0 AC -0.5

VIC 11 0 DC 0

M1 2 4 6 6 NFET W=40U L=1U

M2 3 5 6 6 NFET W=40U L=1U

M3 8 6 2 2 PFET W=40U L=1U

M4 7 6 3 3 PFET W=40U L=1U

M5 8 9 10 10 NFET W=40U L=1U

M6 9 9 10 10 NFET W=40U L=1U

M7 7 8 9 9 NFET W=40U L=1U

I2A 1 2 DC 250U

I2B 1 3 DC 250U

I1 6 10 DC 250U

.MODEL NFET NMOS KP=25U VTO=0.75 LAMBDA=0.017

.MODEL PFET PMOS KP=10U VTO=-0.75 LAMBDA=0.017

.OP

.AC LIN 1 1000 1000

.PRINT AC VM(7) VP(7) VM(6) VP(6) VM(8) VP(8)

.TF V(7) VIC

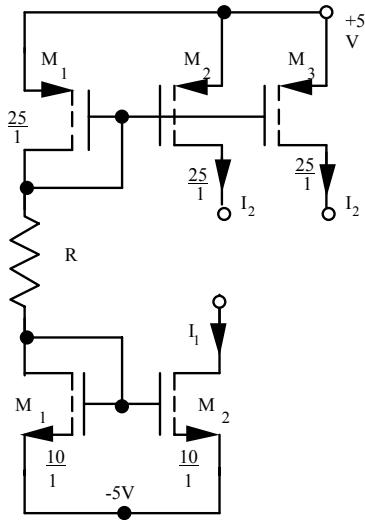
.END

Results: $A_{dd} = 23700$, $A_{cd} = 1.81 \times 10^{-4}$. $R_{out} = 47.7 \text{ M}\Omega$, $\text{CMRR} = 1.31 \times 10^8$. The values of A_{dd} and R_{out} are similar to hand calculations. A_{cd} and the CMRR are limited by the small residual mismatches in device parameters.

From Problem 15.222, $g_{m2} = 0.507 \text{ mS}$ | $r_{o3} = 483 \text{ k}\Omega$ | $g_{m4} = 0.324 \text{ mS}$ | $r_{o4} = 493 \text{ k}\Omega$

$$R_{out} = \mu_f r_{o2} \parallel \mu_f r_{o7} \approx \frac{\mu_f r_{o2}}{2} = \frac{0.324 \text{ mS} (493 \text{ k}\Omega) (493 \text{ k}\Omega)}{2} = 39.4 \text{ M}\Omega$$

15.224



Using a reference current of $250\mu\text{A}$ and 1:1 current mirrors with $-V_{GSP} = V_{GSN}$:

$$-V_{GSP} = V_{GSN} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = 0.75 + \sqrt{\frac{2(2.5 \times 10^{-4})}{10(25 \times 10^{-6})}} = 2.16V \quad | \quad R = \frac{10 - 2.16 - 2.16}{2.5 \times 10^{-4}} \frac{V}{A} = 22.7k\Omega$$

15.225

$$\text{For } \beta_F = \infty, I_B = 0. \quad | \quad V_{BE3} + V_{EB4} = V_{BE2} + \frac{V_{BE2}}{R_1} R_2 = V_{BE2} \left(1 + \frac{R_2}{R_1}\right)$$

$$V_{BE2} = 0.025 \ln \left(\frac{200\mu\text{A} - I_1}{10f\text{A}} \right) \quad | \quad I_1 = \frac{V_{BE2}}{R_1} \quad | \quad V_{BE2} = 0.025 \ln \left(\frac{200\mu\text{A} - \frac{V_{BE2}}{R_1}}{10f\text{A}} \right)$$

$$V_{BE2} = 0.025 \ln \left(\frac{200\mu\text{A} - \frac{V_{BE2}}{20k\Omega}}{10f\text{A}} \right) \rightarrow V_{BE2} = 0.589V \quad | \quad I_{C2} = 200\mu\text{A} - \frac{0.589}{20k\Omega} = 171\mu\text{A}$$

Since $I_{S4} = I_{S3}$, $V_{BE3} = V_{EB4} = \frac{1}{2}(0.589) \left(1 + \frac{20k\Omega}{20k\Omega}\right) = 0.589V$ and $I_{C4} = I_{C3} = 171\mu\text{A}$.

15.226

$$(a) \beta_F = \infty : V_{BE3} + V_{EB4} = V_{BE1} + V_{EB2}$$

$$V_T \ln \frac{I_o}{I_{SON} \frac{A_{E3}}{A_{EO}}} + V_T \ln \frac{I_o}{I_{SOP} \frac{A_{E4}}{A_{EO}}} - V_T \ln \frac{I_2}{I_{SON} \frac{A_{E1}}{A_{EO}}} - V_T \ln \frac{I_2}{I_{SOP} \frac{A_{E2}}{A_{EO}}} = 0$$

$$V_T \ln \left[\frac{I_o^2 A_{EO}^2}{I_{SON} I_{SOP} A_{E3} A_{E4}} \frac{I_{SON} I_{SOP} A_{E1} A_{E2}}{I_2^2 A_{EO}^2} \right] = 0 \rightarrow \frac{I_o^2 A_{E1} A_{E2}}{I_2^2 A_{E3} A_{E4}} = 1 \quad | \quad I_o = I_2 \sqrt{\frac{A_{E3} A_{E4}}{A_{E1} A_{E2}}}$$

$$(b) I_o = 300 \mu A \sqrt{\frac{A_{E3} A_{E4}}{3A_{E3} 3A_{E4}}} = 100 \mu A$$

15.227

$$(a) I_{D8} = I_{REF} = 250 \mu A \quad | \quad I_{D10} = I_{D9} = 2I_{D8} = 500 \mu A$$

$$I_{D1} = I_{D2} = I_{D3} = I_{D4} = \frac{I_{D9}}{2} = 250 \mu A \quad | \quad V_{DS8} = V_{GS8} = 0.75 + \sqrt{\frac{2(250 \mu A)}{10(25 \times 10^{-6})}} = 2.16 V$$

$$I_{D5} = I_{D11} = I_{D10} = 500 \mu A \quad | \quad V_{GS11} = 0.75 + \sqrt{\frac{2(500 \mu A)}{5(25 \times 10^{-6})}} = 3.58 V$$

$$V_{GS6} = -V_{GS7} = \frac{V_{GS11}}{2} = 1.789 V \quad | \quad I_{D7} = I_{D6} = \frac{10(25 \times 10^{-6})}{2} (1.789 - 0.75)^2 = 135 \mu A$$

$$-V_{DS4} = -V_{DS3} = -V_{GS3} = V_{GS2} = V_{TN} + \sqrt{\frac{2I_{D2}}{K_{n2}}} = 0.75 + \sqrt{\frac{2(250 \mu A)}{20(25 \times 10^{-6})}} = 1.75 V$$

$$V_{DS1} = V_{DS2} = 5 - V_{SD4} - (-V_{GS2}) = 5.00 V \quad | \quad V_{DS10} = -V_{DS5} = 5 - \frac{V_{GS11}}{2} = 3.21 V$$

$$V_{DS6} = -V_{DS7} = 5.00 V \quad | \quad V_{DS9} = 5 - V_{GS2} = 5 - 1.75 = 3.25 V$$

	1	2	3	4	5	6	7	8	9	10	11
I _D (μA)	250	250	250	250	500	135	135	250	500	500	500
V _{DS} (V)	5.00	5.00	-1.75	-1.75	-3.21	5.00	-5.00	2.16	3.25	3.21	3.58
SPICE											
I _D (μA)	255	255	255	255	509	139	139	250	509	509	509
V _{DS} (V)	4.97	4.99	-1.74	-1.73	-3.24	5.01	-5.00	2.14	3.28	3.23	3.52

$$(b) A_{dm} = A_{vt1}A_{vt2}A_{vt3} = [g_{m2}(r_{o2}\|r_{o4})][g_{m5}(r_{o5}\|r_{o12})][1]$$

$$g_{m2} = \sqrt{2(20)(25 \times 10^{-6})(2.50 \times 10^{-4})[1 + 0.017(5.00)]} = 0.521 mS$$

$$\frac{1}{\lambda} = \frac{1}{0.017} = 58.8V \quad | \quad r_{o2} = \frac{58.8 + 5.00}{2.5 \times 10^{-4}} \frac{V}{A} = 255 k\Omega \quad | \quad r_{o4} = \frac{58.8 + 1.75}{2.5 \times 10^{-4}} \frac{V}{A} = 242 k\Omega \quad | \quad A_{v1} = 64.7$$

$$g_{m5} = \sqrt{2(100)(10^{-5})(5.00 \times 10^{-4})[1 + 0.017(3.21)]} = 1.03 mS \quad | \quad r_{o12} = r_{o5} = \frac{58.8 + 3.21}{5.00 \times 10^{-4}} \frac{V}{A} = 124 k\Omega$$

$$A_{vt2} = 63.9 \quad | \quad A_{dm} = A_{vt1}A_{vt2}A_{vt3} = [64.7][63.9][1] = 4130$$

(c) The amplification factor is inversely proportional to the square root of current. Thus,

$$A_{dm} = A_{vt1}A_{vt2}A_{vt3} \approx \left[\frac{64.7}{\sqrt{2}} \right] \left[\frac{63.9}{\sqrt{2}} \right] [1] = 2065$$

SPICE Results: $A_{dm} = 4000$, $A_{cm} = 0.509$, $R_{out} = 1.81 \text{ k}\Omega$.

15.228

$$A_{dm} \approx \frac{\mu_{f2}\mu_{f5}}{4} \quad | \quad \text{For the MOSFET, } \mu_{f2} \propto \frac{1}{\sqrt{I_D}} \quad \therefore A_{dm} \propto \frac{1}{\sqrt{I_{D2}}} \frac{1}{\sqrt{I_{D5}}}$$

$$\text{But, } I_{D2} \propto I_{REF} \text{ and } I_{D5} \propto I_{REF} \rightarrow A_{dm} \propto \frac{1}{I_{REF}}$$

$$(a) A_{dm} = 16000 \frac{100 \mu A}{250 \mu A} = 6400 \quad (b) A_{dm} = 16000 \frac{100 \mu A}{20 \mu A} = 80000$$

15.229

$$A_{dm} = A_{v1}A_{v2}A_{v3} = [g_{m2}(r_{o2}\|r_{o4})][g_{m5}(r_{o5}\|r_{o12})][1]$$

$$I_{D10} = I_{REF} = 100 \mu A \quad | \quad I_{D12} = I_{D11} = 2I_{D10} = 200 \mu A \quad | \quad I_{D1} = I_{D2} = I_{D3} = I_{D4} = \frac{I_{D11}}{2} = 100 \mu A$$

$$I_{D5} = I_{D12} = 200 \mu A \quad | \quad V_{DS4} = V_{GS3} = -V_{GS2} = -V_{TN} - \sqrt{\frac{2I_{DS2}}{K_{n2}}} = -0.75 - \sqrt{\frac{2(100 \mu A)}{20(25 \times 10^{-6})}} = -1.38 V$$

$$V_{DS2} = 10 + V_{DS4} - (-V_{GS2}) = 10.0 V \quad | \quad g_{m2} = \sqrt{2(20)(25 \times 10^{-6})(100 \mu A)[1 + 0.017(10)]} = 0.342 mS$$

$$\frac{1}{\lambda} = \frac{1}{0.017} = 58.8V \quad | \quad r_{o2} = \frac{58.8 + 10}{10^{-4}} \frac{V}{A} = 688 k\Omega \quad | \quad r_{o4} = \frac{58.8 + 1.38}{10^{-4}} \frac{V}{A} = 602 k\Omega \quad | \quad A_{v1} = 110$$

$$V_{DS12} = -V_{DS5} = 10 - \frac{V_{GS2}}{2} \quad | \quad V_{GS2} = 0.75 + \sqrt{\frac{2(200 \mu A)}{5(25 \times 10^{-6})}} = 2.54 V \quad | \quad V_{DS12} = -V_{DS5} = 8.73 V$$

$$g_{m5} = \sqrt{2(100)(10^{-5})(2 \times 10^{-4})[1 + 0.017(8.73)]} = 0.678 mS \quad | \quad r_{o12} = r_{o5} = \frac{58.8 + 8.73}{2 \times 10^{-4}} \frac{V}{A} = 338 k\Omega$$

$$A_{v2} = 115 \quad | \quad A_{dm} = A_{v1}A_{v2}A_{v3} = [110][115][1] = 12600$$

$A_{dm} = 10900$ if $(1 + \lambda V_{DS})$ is neglected in the g_m calculation.

15.230

*Figure P15.229 - CMOS Amplifier with Active Load

VDD 8 0 DC 10

VSS 14 0 DC -10

*An offset voltage is used to set Vo to approximately zero volts.

V2 1 15 DC 0.3506M AC 0.5

V1 2 15 DC 0 AC -0.5

VIC 15 0 DC 0

M1 3 1 5 14 NFET W=20U L=1U

M2 4 2 5 14 NFET W=20U L=1U

M3 3 3 8 8 PFET W=50U L=1U

M4 4 3 8 8 PFET W=50U L=1U

M5 6 4 8 8 PFET W=100U L=1U

*The offset can be adjusted to zero by correcting the value of W/L

*M5 6 4 8 8 PFET W=89.5U L=1U

M6 8 6 13 14 NFET W=10U L=1U

M7 14 7 13 8 PFET W=25U L=1U

MGG 6 6 7 14 NFET W=5U L=1U

M10 9 9 14 14 NFET W=10U L=1U

M11 5 9 14 14 NFET W=20U L=1U

M12 7 9 14 14 NFET W=20U L=1U

IREF 0 9 DC 100U

.MODEL NFET NMOS KP=25U VTO=0.75 LAMBDA=0.017

.MODEL PFET PMOS KP=10U VTO=-0.75 LAMBDA=0.017

*.MODEL NFET NMOS KP=25U VTO=0.75 GAMMA=0.6 LAMBDA=0.017

*.MODEL PFET PMOS KP=10U VTO=-0.75 GAMMA=0.75 LAMBDA=0.017

.OP

.AC LIN 1 1000 1000

.PRINT AC VM(13) VP(13) VM(4) VP(4)

.TF V(13) VIC

.END

Results: $A_{dm} = 11200$, $A_{cm} = 0.604$, $R_{out} = 3.10 \text{ k}\Omega$.

(a)	1	2	3	4	5	6	7	GG	10	11	12
I_{DS} (μA)	112	112	112	112	223	44.2	44.2	223	100	223	223
V_{DS} (V)	9.96	9.99	-1.41	-1.37	-8.70	10.0	-10.0	-2.60	1.63	8.63	8.70
(b)											
I_{DS} (μA)	110	110	110	110	219	0	0	219	100	219	219
V_{DS} (V)	11.2	11.2	-1.40	-1.37	-8.85	10.0	-9.97	-3.79	1.63	7.41	7.35

Note that the body effect has increased the threshold voltages of M_6 and M_7 to the point that they are no longer conducting. $V_{TN6} = 2.24 \text{ V}$ and $V_{TP7} = -2.61 \text{ V}$. The W/L ratio of M_{GG} needs to be redesigned to solve this problem.

15.231

$$I_{D10} = I_{REF} = 250\mu A \quad | \quad I_{D11} = 2I_{D10} = 500\mu A \quad | \quad I_{D12} = 4I_{D10} = 1000\mu A$$

$$I_{D1} = I_{D2} = I_{D3} = I_{D4} = \frac{I_{D11}}{2} = 250\mu A \quad | \quad V_{DS10} = V_{GS10} = 0.75 + \sqrt{\frac{2(250\mu A)}{10(25 \times 10^{-6})}} = 2.16V$$

$$I_{D5} = I_{DGG} = I_{D12} = 1000\mu A \quad | \quad V_{GS GG} = 0.75 + \sqrt{\frac{2(1000\mu A)}{5(25 \times 10^{-6})}} = 4.75V$$

$$V_{GS6} = -V_{GS7} = \frac{V_{GS GG}}{2} = 2.375V \quad | \quad I_{D7} = I_{D6} = \frac{10(25 \times 10^{-6})}{2} (2.375 - 0.75)^2 = 330\mu A$$

$$V_{DS4} = V_{DS3} = V_{GS3} = -V_{GS2} = -V_{TN} - \sqrt{\frac{2I_{D2}}{K_{n2}}} = -0.75 - \sqrt{\frac{2(250\mu A)}{20(25 \times 10^{-6})}} = -1.75V$$

$$V_{DS1} = V_{DS2} = 7.5 + V_{DS4} - (-V_{GS2}) = 7.50V \quad | \quad V_{DS12} = -V_{DS5} = 7.5 + \frac{V_{GS GG}}{2} = 5.13V$$

$$V_{DS6} = -V_{DS7} = 7.5V \quad | \quad V_{DS11} = 7.5 - V_{GS2} = 7.5 - 1.75 = 5.75V$$

M	1	2	3	4	5	6	7	GG	10	11	12
I _{DS} (μA)	250	250	250	250	1000	330	330	1000	250	500	1000
V _{DS} (V)	7.50	7.50	-1.75	-1.75	-5.13	7.50	-7.50	4.75	2.16	5.75	5.13
SPICE											
I _{DS} (μA)	264	266	-264	-266	1050	359	-359	1050	250	530	1050
V _{DS} (V)	7.46	7.09	-1.76	-2.14	-5.20	7.54	-7.46	4.69	2.14	5.78	5.11

$$A_{dm} = A_{v1}A_{v2}A_{v3} = [g_{m2}(r_{o2}\|r_{o4})][g_{m5}(r_{o5}\|r_{o12})][1]$$

$$g_{m2} = \sqrt{2(20)(25 \times 10^{-6})(250\mu A)[1 + 0.017(7.50)]} = 0.531mS$$

$$\frac{1}{\lambda} = \frac{1}{0.017} = 58.8V \quad | \quad r_{o2} = \frac{58.8 + 7.50}{2.5 \times 10^{-4}} \frac{V}{A} = 265k\Omega \quad | \quad r_{o4} = \frac{58.8 + 1.75}{2.5 \times 10^{-4}} \frac{V}{A} = 242k\Omega \quad | \quad A_{v1} = 67.2$$

$$g_{m5} = \sqrt{2(100)(10^{-5})(10^{-3})[1 + 0.017(5.13)]} = 1.48mS \quad | \quad r_{o12} = r_{o5} = \frac{58.8 + 5.13}{10^{-3}} \frac{V}{A} = 63.9k\Omega$$

$$A_{v2} = 47.3 \quad | \quad A_{dm} = A_{v1}A_{v2}A_{v3} = [67.2][47.3][1] = 3180$$

SPICE Results: A_{dm} = 2950, A_{cm} = 0.03, R_{out} = 1.10 kΩ.

15.232

(a) For saturation of M_{11} :

$$V_{DS11} = 0 - V_{GS2} - (-V_{SS}) = V_{SS} - V_{GS2} \geq \sqrt{\frac{2I_{DS11}}{K_{n11}}} = \sqrt{\frac{2(200\mu A)}{20(25 \times 10^{-6})}} = 0.894$$

$$V_{GS2} = V_{TN} + \sqrt{\frac{2I_{DS2}}{K_{n2}}} = 0.75 + \sqrt{\frac{2(100\mu A)}{20(25 \times 10^{-6})}} = 1.38V \quad | \quad V_{SS} - 1.38 \geq 0.894 \rightarrow V_{SS} \geq 2.27V$$

For saturation of M_{12} :

$$V_{DS12} = 0 - \frac{V_{GSGG}}{2} - (-V_{SS}) = V_{SS} - \frac{V_{GSGG}}{2} \geq \sqrt{\frac{2I_{D12}}{K_{n12}}} = \sqrt{\frac{2(200\mu A)}{20(25 \times 10^{-6})}} = 0.894$$

$$V_{GSGG} = 0.75 + \sqrt{\frac{2(200\mu A)}{5(25 \times 10^{-6})}} = 2.54V \quad | \quad V_{SS} - \frac{2.54}{2} \geq 0.894 \rightarrow V_{SS} \geq 2.16V$$

For saturation of M_1 and M_2 :

$$V_{DS1} = V_{DD} + V_{GS3} - (-V_{GS1}) = V_{DD} + V_{GS3} + V_{GS1} \geq \sqrt{\frac{2I_{D1}}{K_{n1}}} = \sqrt{\frac{2(100\mu A)}{20(25 \times 10^{-6})}} = 0.633$$

$$V_{GS3} = -V_{GS1} : V_{DD} \geq 0.633V$$

For saturation of M_5 :

$$-V_{DS5} = V_{DD} - \frac{2.54}{2} \geq \sqrt{\frac{2I_{D5}}{K_{p5}}} = \sqrt{\frac{2(200\mu A)}{100(10 \times 10^{-6})}} = 0.633V \rightarrow V_{DD} \geq 1.90V$$

M_6 and M_7 are always saturated: e.g. $V_{DS6} \geq V_{GS6}$

The minimum supply voltages are: $V_{DD} \geq 1.90V$ $V_{SS} \geq 2.27V$

For the symmetrical supply case, $V_{DD} = V_{SS} \geq 2.27V$

(b) The values of V_{DD} and V_{SS} in part (a) do not provide any significant common-mode input voltage range. For saturation of M_{11} with $V_{IC} = -5V$,

$$V_{DS11} = V_{IC} - V_{GS2} - (-V_{SS}) = V_{SS} - 1.38 - 5 \geq 0.894 \rightarrow V_{SS} \geq 7.27V$$

For saturation of M_1 and M_2 :

$$V_{DS1} = V_{DD} - V_{GS3} - (V_{IC} - V_{GS1}) = V_{DD} - 5 - 1.38 + 1.38 \geq 0.633 \rightarrow V_{DD} \geq 5.63V$$

For an output range of 5V, saturation of M_{12} requires

$$V_{DS12} = -5 - \frac{V_{GSGG}}{2} - (-V_{SS}) = V_{SS} - 5 - \frac{2.54}{2} \geq 0.894 \rightarrow V_{SS} \geq 7.25V$$

For Saturation of M_5 :

$$V_{DS5} = V_{DD} - \frac{2.54}{2} - 5 \geq 0.633V \rightarrow V_{DD} \geq 6.90V$$

The minimum supply voltages are: $V_{DD} \geq 6.90V$ $V_{SS} \geq 7.25V$

For the symmetrical supply case, $V_{DD} = V_{SS} \geq 7.25V$

15.233

$$I_{D9} = I_{D10} = I_{D12} = I_{D11} = I_{REF} = 250\mu A \quad | \quad I_{D6} = I_{D7} = I_{D8} = 3I_{D12} = 750\mu A$$

$$I_{D1} = I_{D2} = I_{D13} = I_{D5} = I_{D3} = I_{D4} = \frac{I_{D9}}{2} = 125\mu A$$

$$V_{DS10} = V_{DS12} = V_{DS11} = V_{GS12} = V_{TN} + \sqrt{\frac{2I_{D12}}{K_{n12}}} = 0.75 + \sqrt{\frac{2(250\mu A)}{5(25 \times 10^{-6})}} = 2.75V$$

$$V_{GS1} = 0.75 + \sqrt{\frac{2(125\mu A)}{40(25 \times 10^{-6})}} = 1.25V \quad | \quad V_{DS9} = -V_{GS1} - (-10 + V_{GS12}) = 6V$$

$$V_{DS7} = V_O - (-10 + V_{GS12} + V_{GS11} - V_{GS7}) = 0 + 10 - 2.75 - 2.75 + 0.75 + \sqrt{\frac{2(750\mu A)}{15(25 \times 10^{-6})}} = 7.25V$$

$$V_{DS8} = 10 - V_{DS7} = 2.75V$$

$$V_{DS6} = -(10 - V_O) = -10V + 0 = -10V \quad | \quad V_{DS5} = V_{DS13} = V_{DS3} = V_{DS4} = -0.75 - \sqrt{\frac{2(125\mu A)}{80(10 \times 10^{-6})}} = -1.31V$$

M	1	2	3	4	5	6	7	8	9	10	11	12	13
ID (μA)	125	125	125	125	125	750	750	750	250	250	250	250	125
VDS (V)	8.63	8.63	-1.31	-1.31	-1.31	-10	7.25	2.75	6.00	2.75	2.75	2.75	-1.31

$$(b) \frac{K_n}{2} \left(\frac{W}{L} \right)_6 (V_{GS6} - V_{TP})^2 = \frac{10^{-5}}{2} \left(\frac{W}{L} \right)_6 (-V_{DS4} - V_{DS5} + 0.75)^2 = 750\mu A$$

$$\frac{10^{-5}}{2} \left(\frac{W}{L} \right)_6 (-2.62 + 0.75)^2 = 750\mu A \rightarrow \left(\frac{W}{L} \right)_6 = 42.9$$

$$A_{dd} = A_{v1}A_{v2} = (g_{m2}r_{o2})(g_{m6}r_{o6}) = \mu_{f2}\mu_{f6} \quad | \quad \mu_{f2} \cong \frac{1}{\lambda_n} \sqrt{\frac{2K_{n2}}{I_{D2}}} = \frac{1}{0.017} \sqrt{\frac{2(40)(25 \times 10^{-6})}{125 \times 10^{-6}}} = 235$$

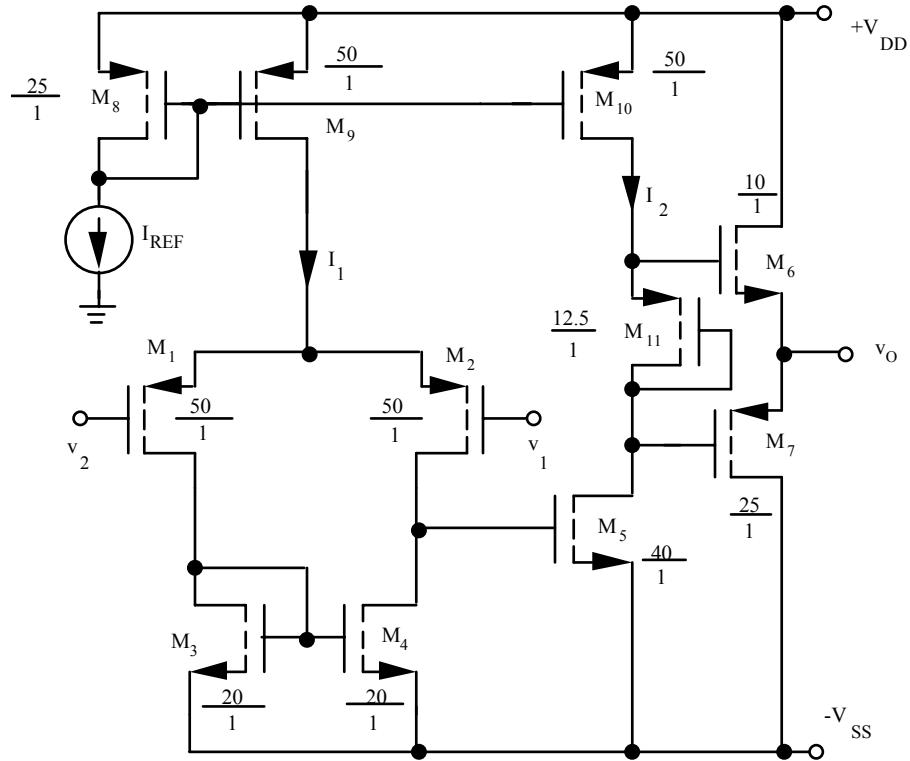
$$\mu_{f6} \cong \frac{1}{\lambda_p} \sqrt{\frac{2K_{p6}}{I_{D6}}} = \frac{1}{0.017} \sqrt{\frac{2(42.9)(10 \times 10^{-6})}{750 \times 10^{-6}}} = 62.9 \quad | \quad A_{dd} = 235(62.9) = 14800$$

15.234

*Figure P15.233 - CMOS Amplifier with Active Load
VDD 8 0 DC 10
VSS 14 0 DC -10
*Connect feedback to determine Vos
*V1 1 13 DC 0
*The offset voltage must be used to set Vo to approximately zero voltages.
V1 1 15 DC 0.4423M AC 0.5
V2 2 15 DC 0 AC -0.5
VIC 15 0 DC 0
M1 3 1 5 5 NFET W=40U L=1U
M2 4 2 5 5 NFET W=40U L=1U
M3 6 7 8 8 PFET W=80U L=1U
M4 7 7 8 8 PFET W=80U L=1U
M5 4 3 7 7 PFET W=80U L=1U
M6 13 4 8 8 PFET W=42.9U L=1U
*The offset can be adjusted to zero by correcting the value of W/L
*M6 13 4 8 8 PFET W=37.25U L=1U
M7 13 9 12 12 NFET W=15U L=1U
M8 12 10 14 14 NFET W=15U L=1U
M9 5 9 11 11 NFET W=5U L=1U
M10 11 10 14 14 NFET W=5U L=1U
M11 9 9 10 10 NFET W=5U L=1U
M12 10 10 14 14 NFET W=5U L=1U
M13 3 3 6 6 PFET W=80U L=1U
IREF 0 9 DC 250U
.MODEL NFET NMOS KP=25U VTO=0.75 LAMBDA=0.017
.MODEL PFET PMOS KP=10U VTO=-0.75 LAMBDA=0.017
.OP
.AC LIN 1 1000 1000
.PRINT AC VM(13) VP(13) VM(4) VP(4)
.TF V(13) VIC
.END

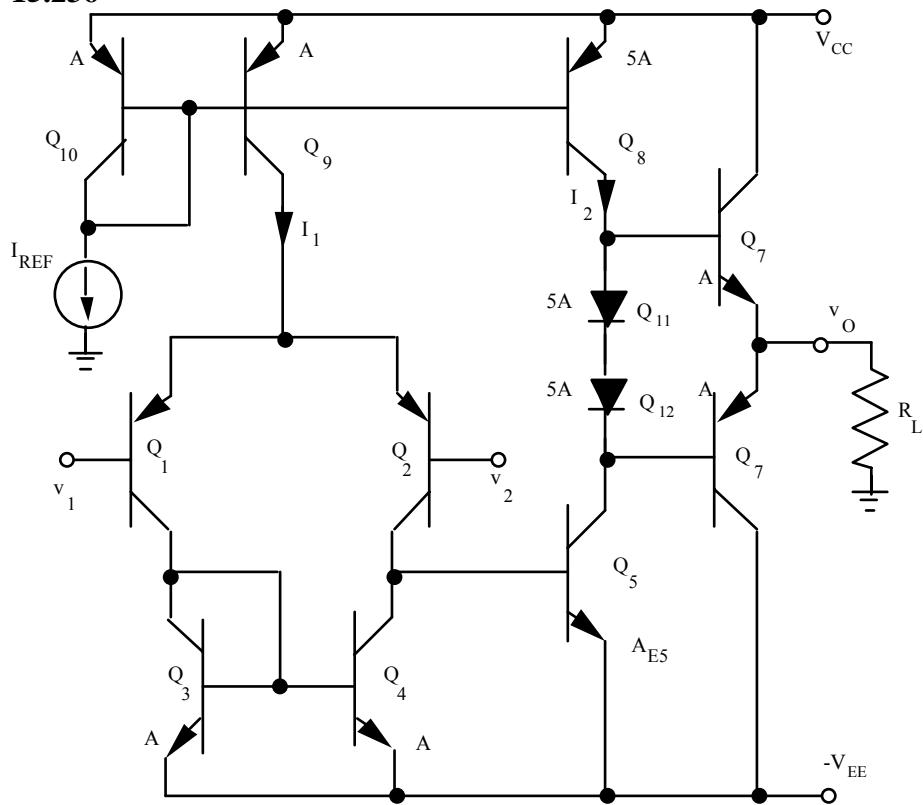
Results: $V_{os} = 0.4423$ mV, $A_{dm} = 22500$, $A_{cm} = 0.2305$, CMRR = 99.9 dB, $R_{out} = 90.3$ M Ω . The values of A_{dd} and R_{out} are similar to hand calculations. A_{cd} and the CMRR are limited by the offset induced mismatches in the devices. With the W/L of M_6 corrected, $V_{os} \approx 0$, $A_{dm} = 20800$, $A_{cm} = 9.28 \times 10^{-3}$. $R_{out} = 90.3$ M Ω , CMRR = 127 dB.

15.235



The W/L ratios have been scaled to keep the Q-points and gain the same. Note that the output stage should remain a source follower pair and is not mirrored.

15.236



Note that the output stage should remain complementary emitter-followers.

The gain of the first stage is approximately $A_{v1} = g_m r_{\pi 5} = \frac{I_{C1}}{I_{C5}} \beta_{o5}$, the mirror

image amplifier with an npn transistor for Q_5 will have the highest gain. The voltage gain of the rest of the amplifier is the same.

15.237

$$V_{EB7} + V_{EB8} = V_{EB6} + V_{EB4} = 2V_T \ln \frac{I_{C4}}{I_{S4}} = 2V_T \ln \frac{I_{C14}}{2I_{S4}} = 0.05 \ln \left[\frac{250\mu A}{2(15fA)} \right] = 1.142V$$

$$V_{EB7} + V_{EB8} = V_T \ln \frac{I_{C7}}{I_{S7}} + V_T \ln \frac{I_{C8}}{I_{S8}} \quad I_{C7} = \alpha_F I_{B8} = \alpha_F \frac{I_{C8}}{\beta_F} = \frac{60}{61} \frac{I_{C8}}{60} = \frac{I_{C8}}{61}$$

$$V_{EB7} + V_{EB8} = V_T \ln \frac{I_{C8}}{61(15fA)} + V_T \ln \frac{I_{C8}}{4(15fA)} \rightarrow 0.025 \ln \frac{I_{C8}^2}{61(15fA)(4)(15fA)} = 1.142$$

$$I_{C8} = 1.946 \text{ mA} \quad | \quad I_{C16} \cong I_{C8} \quad | \quad A_{E16} = \frac{I_{C16}}{I_{C12}} A_{E12} = \frac{1946\mu A}{250\mu A}(1) = 7.78$$

$$V_{BE6} = V_{EB10} = 0.025 \ln \left(\frac{75\mu A}{15fA} \right) = 0.558V \quad | \quad R_{BB} = \frac{2(0.5583V)}{1.946 \text{ mA}} = 574 \Omega$$

$$A_{dm} = A_{v1} A_{v2} A_{v3} \cong \left[g_{m2} \left\{ r_{o2} \left\| \left[r_{\pi7} + (\beta_o + 1)r_{\pi8} \right] \right\} \right] \left[\frac{(\beta_o + 1)r_{\pi8}}{r_{\pi7} + (\beta_o + 1)r_{\pi8}} g_{m8} (r_{o8} \left\| r_{o16} \right\|) \right] [1]$$

$$A_{dm} = A_{v1} A_{v2} A_{v3} \cong \left[g_{m2} (r_{o2} \left\| r_{\pi7} + (\beta_o + 1)r_{\pi8} \right\|) \right] \left[\frac{(\beta_o + 1)r_{\pi8}}{r_{\pi7} + (\beta_o + 1)r_{\pi8}} \left(\frac{\mu_{f8}}{2} \right) \right] [1]$$

$$A_{dm} \cong \left[g_{m2} (r_{o2} \left\| 2r_{\pi7} \right\|) \right] \frac{\mu_{f8}}{4} \cong \frac{I_{C2}}{I_{C7}} \beta_{o7} \frac{\mu_{f8}}{2} = \frac{125\mu A}{31.8\mu A} 60 \frac{(40)(60 + 4.3)}{2} = 3.03 \times 10^5$$

$$R_{id} = 2r_{\pi1} = 2 \frac{150(0.025V)}{125\mu A} = 60 \text{ k}\Omega$$

15.238

*Figure P15.237 - Bipolar Op-Amp
VCC 1 0 DC 5
VEE 14 0 DC -5
V1 6 15 DC -74.17U AC 0.5
V2 7 15 DC 0 AC -0.5
VIC 15 0 DC 0
Q1 4 6 8 NBJT 1
Q2 5 7 8 NBJT 1
Q3 4 4 2 PBJT 1
Q4 5 4 3 PBJT 1
Q5 2 3 1 PBJT 1
Q6 3 3 1 PBJT 1
Q7 14 5 10 PBJT 1
Q8 11 10 1 PBJT 4
Q9 1 11 12 NBJT 1
Q10 14 13 12 PBJT 1
Q12 9 9 14 NBJT 1
Q14 8 9 14 NBJT 1
Q16 13 9 14 NBJT 7.78
IB 0 9 250U
RBB 11 13 574
.MODEL NBJT NPN BF=150 VA=60 IS=15F
.MODEL PBJT PNP BF=60 VA=60 IS=15F
.OP
.AC LIN 1 1000 1000
.PRINT AC VM(12) VP(12)
.TF V(12) VIC
.END

SPICE Results: $V_{OS} = -74.17\mu V$, $A_{dm} = 2.83 \times 10^5$, $A_{cm} = 0.507$, CMRR = 115 dB,

$$R_{id} = 81.6 \text{ k}\Omega, R_{out} = 523 \Omega.$$

15.239

(a) We require forward - active region operation of all transistors.

$$\text{For } Q_{14} : V_{CB14} = 0 - V_{BE1} - (-V_{EE} + V_{BE14}) \geq 0 \rightarrow V_{EE} \geq 1.4V$$

$$\text{For } Q_1 : V_{CB1} = V_{CC} - V_{EB6} - V_{EB4} \geq 0 \rightarrow V_{CC} \geq 1.4V$$

$$\text{For } Q_{16} : V_{CB16} = 0 - V_{EB10} - (-V_{EE} + V_{BE14}) \geq 0 \rightarrow V_{EE} \geq 1.4V$$

$$\text{For } Q_8 : V_{BC8} = V_{CC} - V_{EB8} - V_{BE6} \geq 0 \rightarrow V_{CC} \geq 1.4V$$

So $V_{CC} \geq 1.4V$ and $V_{EE} \geq 1.4V$

(b) We require forward - active region operation of all transistors with V_{IC} present.

$$\text{For } Q_{14} : V_{CB14} = V_{IC} - V_{BE1} - (-V_{EE} + V_{BE14}) = -1 - 0.7 - (-V_{EE} + 0.7) \geq 0 \rightarrow V_{EE} \geq 2.4V$$

$$\text{For } Q_1 : V_{CB1} = V_{CC} - V_{EB6} - V_{EB4} - V_{IC} = V_{CC} - 0.7 - 0.7 - 1 \geq 0 \rightarrow V_{CC} \geq 2.4V$$

For an output range of $\pm 1V$,

$$\text{For } Q_{16} : V_{CB16} = V_O - V_{EB10} - (-V_{EE} + V_{BE14}) = -1 \geq 0 \rightarrow V_{EE} \geq 1.4V$$

$$\text{For } Q_8 : V_{BC8} = V_{CC} - V_{EB8} - (V_O + V_{BE6}) = V_{CC} - 0.7 - (1 + 0.7) \geq 0 \rightarrow V_{CC} \geq 2.4V$$

So $V_{CC} \geq 2.4V$ and $V_{EE} \geq 2.4V$

15.240

$$(a) I_{C22} = I_{C20} = \frac{V_{CC} - V_{EB22} - V_{BE20} - (-V_{EE})}{R_l} = \frac{3V - 0.7 - 0.7 - (-3V)}{100k\Omega} = 46.0\mu A$$

$$I_{C23} = 3I_{C22} = 138 \mu A \quad | \quad I_{C24} = I_{C22} = 46.0 \mu A \quad |$$

$$I_1 = \frac{V_T}{R} \ln\left(\frac{I_{C20}}{I_1}\right) = \frac{0.025V}{4k\Omega} \ln\left(\frac{46.0\mu A}{I_1}\right) = 6.25\mu A \ln\left(\frac{46.0\mu A}{I_1}\right) \rightarrow I_1 = 9.72\mu A$$

$$(b) I_{C22} = I_{C20} = \frac{22V - 0.7 - 0.7 - (-22V)}{100k\Omega} = 426\mu A$$

$$I_{C23} = 3I_{C22} = 128 \mu A \quad | \quad I_{C24} = I_{C22} = 426 \mu A$$

$$I_1 = \frac{V_T}{R} \ln\left(\frac{I_{C20}}{I_1}\right) = 6.25\mu A \ln\left(\frac{426\mu A}{I_1}\right) \rightarrow I_1 = 19.3\mu A$$

(c) The input bias current and input resistance of the amplifier are directly dependent upon I_1 , whereas the gain of the interior amplifier stages is approximately independent of bias current.

15.241

$$I_2 = 3I_{REF} \rightarrow I_{REF} = \frac{250\mu A}{3} = 83.3 \mu A \quad | \quad I_3 = I_{REF} = 83.3 \mu A$$

$$I_{REF} = \frac{V_{CC} - V_{EB22} - V_{BE20} - (-V_{EE})}{R_1} \quad | \quad R_1 = \frac{12 - 0.7V - 0.7 - (-12)}{83.3} \frac{V}{\mu A} = 271 k\Omega$$

$$R_2 = \frac{V_T}{I_1} \ln\left(\frac{I_{REF}}{I_1}\right) = \frac{0.025V}{50\mu A} \ln\left(\frac{83.3\mu A}{50\mu A}\right) = 255 \Omega$$

15.242

$$I_{REF} = I_3 = 300 \mu A \quad | \quad I_2 = 3I_{REF} = 900 \mu A$$

$$I_{REF} = \frac{V_{CC} - V_{EB22} - V_{BE20} - (-V_{EE})}{R_1} \quad | \quad R_1 = \frac{15 - 0.7V - 0.7 - (-15)}{300} \frac{V}{\mu A} = 95.3 k\Omega$$

$$R_2 = \frac{V_T}{I_1} \ln\left(\frac{I_{REF}}{I_1}\right) = \frac{0.025V}{75\mu A} \ln\left(\frac{300\mu A}{75\mu A}\right) = 462 \Omega$$

15.243

For forward - active region operation of Q_3 , $V_{BC3} \geq 0$

$$V_{EE} \geq V_{IC} + V_{BE1} + V_{BE3} + V_{BE7} + V_{BE5} + V_{R_1}$$

For forward - active region operation of Q_1 , $V_{CB1} \geq 0$

$$V_{CC} - V_{EB9} \geq V_{IC}$$

For the output stage, $V_{CC} \geq V_{BE15} + V_{I3} = 0.7 + 0.7 = 1.4 V$

$$-V_{EB16} - V_{EB12} \geq V_{BE11} + V_{R_5} - (-V_{EE}) \rightarrow V_{EE} \geq 3V_{BE} + V_{R_1} \cong 2.1V$$

$$(a) V_{IC} = 0, V_{EE} \geq 4V_{BE} + V_{R_1} \cong 2.8V \quad | \quad V_{CC} - V_{EB9} \geq 0 \rightarrow V_{CC} \geq 0.7V$$

Combining these results yields: $V_{CC} \geq 1.4V$ and $V_{EE} \geq 2.8V$

$$(b) V_{IC} = \pm 1, V_{EE} \geq 1 + 4V_{BE} + V_{R_1} \cong 3.8V \quad | \quad V_{CC} - V_{EB9} \geq 1 \rightarrow V_{CC} \geq 1.7V$$

If also account for the output stage, $V_{CC} \geq V_O + V_{BE15} + V_{I3} = 1 + 0.7 + 0.7 = 2.4 V$

Combining these results yields: $V_{CC} \geq 2.4V$ and $V_{EE} \geq 3.8V$

15.244

The input stage current is proportional to I_1 : $I_{C2} = \frac{50\mu A}{18\mu A}(7.32\mu A) = 20.3\mu A$

Using Eq. 16.139: $i_o = -20(20.3\mu A)v_{id} = (-0.406 mS)v_{id}$ | $I_{C4} = \frac{50\mu A}{18\mu A}(7.25\mu A) = 20.1\mu A$

$$R_{out6} \approx r_{o6} \left(1 + \frac{20.3\mu A(1k\Omega)}{0.025V} \right) = 1.81r_{o6} \quad | \quad R_{th} = 1.81r_{o6} \| 2r_{o4} = 0.952r_{o4} = 0.95 \frac{60V}{20.1\mu A} = 2.84 M\Omega$$

$$i_o = (-4.06 \times 10^{-4})v_{id} \quad | \quad R_{th} = 2.84 M\Omega$$

As a check, we know that $g_m \propto I_C$ and $r_o \propto \frac{1}{I_C}$. Using the results from Fig. 16.60,

$$i_o = 1.46 \times 10^{-4} v_{id} \left(\frac{50\mu A}{18\mu A} \right) = -4.06 \times 10^{-4} v_{id} \quad \text{and} \quad R_{th} = 6.54 M\Omega \left(\frac{18\mu A}{50\mu A} \right) = 2.35 M\Omega$$

which underestimates R_{th} .

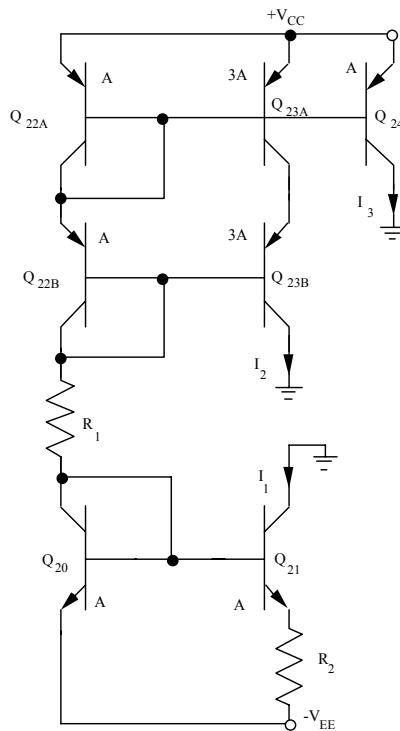
15.245

$$(a) R_2 = \frac{\beta_{o2}r_{o2}}{2} = \frac{50}{2} \frac{60 + 15.7}{0.666mA} = 2.84 M\Omega \quad | \quad \text{The cascode source uses up an extra } V_{EB}.$$

$$(b) [y_{22}]^{-1} = R_{out11} \| R_2 = 407 k\Omega \| 2.84 M\Omega = 356 k\Omega \quad | \quad \text{The other y - parameters are unchanged.}$$

$$(c) A_{dm} = 256(6.70 mS)(356 k\Omega) = 6.11 \times 10^5$$

15.246



15.247

$$g_{m10} = 40(19.8\mu A) = 0.792 mS \quad | \quad r_{\pi10} = \frac{150(0.025V)}{19.8\mu A} = 189 k\Omega \quad | \quad r_{o10} = \frac{60V}{19.8\mu A} = 3.03 M\Omega$$

$$g_{m11} = 40(0.666mA) = 26.6 mS \quad | \quad r_{\pi11} = \frac{150(0.025V)}{0.666mA} = 5.63 k\Omega \quad | \quad r_{o11} = \frac{60V}{0.666mA} = 90.1 k\Omega$$

*Problem 15.247 - Small Signal Parameters.

V1 1 0 DC 0

V2 4 0 AC 1

RPI10 1 2 189K

RO10 2 0 3.03MEG

GM10 0 2 1 2 0.792M

RE10 2 0 50K

RPI11 2 3 5.63K

RO11 4 3 90.1K

GM11 4 3 2 3 26.6M

RE11 3 0 100

R2 4 0 115K

.TF I(V2) V1

.AC LIN 1 1000 1000

.PRINT AC IM(V2) IP(V2) IM(V1) IP(V1)

.END

Results: $y_{11}^{-1} = 2.38 M\Omega$ | $y_{12} = 3.27 \times 10^{-10} S \cong 0$ | $y_{21} = 6.66 mS$ | $y_{22}^{-1} = 81.9 k\Omega$

15.248

(a) Assume large β_F : $I_{C11} = I_{REF} = 100\mu A$ | $I_{C4} = I_{C5} = \frac{I_{C11}}{2} = 50\mu A$ | $I_{C3} = I_{C6} = I_{C4} = 50\mu A$

$$I_{C1} = I_{C3} = I_{C7} = 50\mu A \quad | \quad I_{C2} = I_{C6} = I_{C8} = 50\mu A \quad | \quad I_{C9} = 2 \frac{I_{C8}}{\beta_F}$$

$$V_{CE1} = V_{CE2} = 15 - (-0.7) = 15.7V \quad | \quad V_{EC4} = V_{EC5} = 0.7V$$

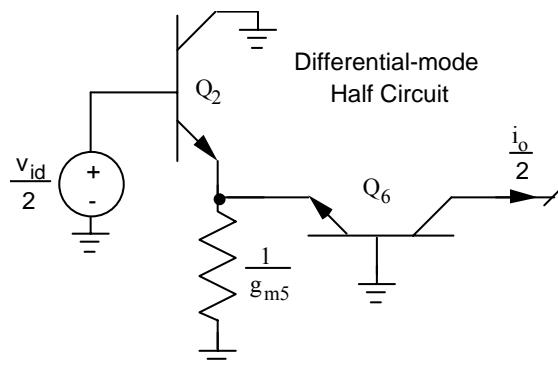
$$V_{CE7} = V_{CE8} = 0.7 + 0.7 = 1.4V \quad | \quad V_{CE9} = 15 - (-15 + 0.7) = 29.3V \quad | \quad V_{CE10} = 0.7V$$

$$V_{EC3} = V_{EC2} = (0 - 0.7) - (-15 + 1.4) = 12.9 \quad | \quad V_{CE11} = 0 - 0.7 - 0.7 - (-15) = 13.6V$$

Q	1	2	3	4	5	6	7	8	9	10	11
$I_C (\mu A)$	100	100	-50	-50	-50	-50	50	50	---	100	100
$V_{CE} (V)$	15.7	15.7	-12.9	-0.7	-0.7	-12.9	1.4	1.4	29.3	0.7	13.6

(b) Transistor Q_{11} replicates the reference current. This current divides in two and controls two matched current mirrors formed of Q_4 - Q_3 and Q_5 - Q_6 . The currents of Q_1 and Q_7 , and Q_2 and Q_8 are equal to the output current of Q_3 and Q_4 .

(c) v_1 is the inverting input; v_2 is the non-inverting input.



$$g_{m5} = g_{m6} \quad | \quad g_{m2} = 2g_{m6} \quad | \quad r_{o8} = r_{o6} \quad | \quad i_o = g_{m6}v_{e6}$$

$$v_{e6} = v_{id} \frac{g_{m2}}{1 + g_{m2} \left(\frac{1}{g_{m5}} \parallel \frac{1}{g_{m6}} \right)} = \frac{1}{2}v_{id} \quad | \quad i_o = g_{m6} \frac{1}{2}v_{id}$$

$$G_m = \frac{1}{2}g_{m6} = \frac{1}{4}g_{m2} = \frac{1}{4}(40)(100\mu A) = 1.00 mS$$

$$R_{out} = r_{o8} \parallel R_{out}^6 = r_{o8} \left| \left[r_{o6} \left[1 + g_{m6} \left(\frac{1}{g_{m5} + g_{m2}} \right) \right] \right] \right|$$

$$R_{out} = r_{o8} \left| \left[1.33r_{o6} \left(\frac{61.4V}{50\mu A} \right) \right] \right| \left[1.33 \left(\frac{72.9V}{50\mu A} \right) \right] = 752 k\Omega$$

15.249

(a) Assume large β_F : $I_{C8} = I_{REF} = 100\mu A$ | $I_{C10} = I_{C9} = I_{B8} = \frac{I_{C8}}{\beta_F}$

$$I_{C3} = I_{C4} = \beta_F \frac{I_{C10}}{2} = \frac{I_{C8}}{2} = 50\mu A$$

$$I_{C1} = I_{C3} = I_{C5} = 50\mu A$$

$$I_{C2} = I_{C4} = I_{C6} = 50\mu A$$

$$I_{C7} = 2 \frac{I_{C5}}{\beta_F}$$

$$V_{CE1} = V_{CE2} = 15 - (-0.7) = 15.7V$$

$$V_{EC3} = V_{EC4} = 0 - 0.7 - (-15 + 1.4) = 12.9V$$

$$V_{EC8} = 0.7 + 0.7 = 1.4V$$

$$V_{CE9} = 0.7V$$

$$V_{CE10} = 0 - 0.7 - 0.7 - (-15) = 13.6V$$

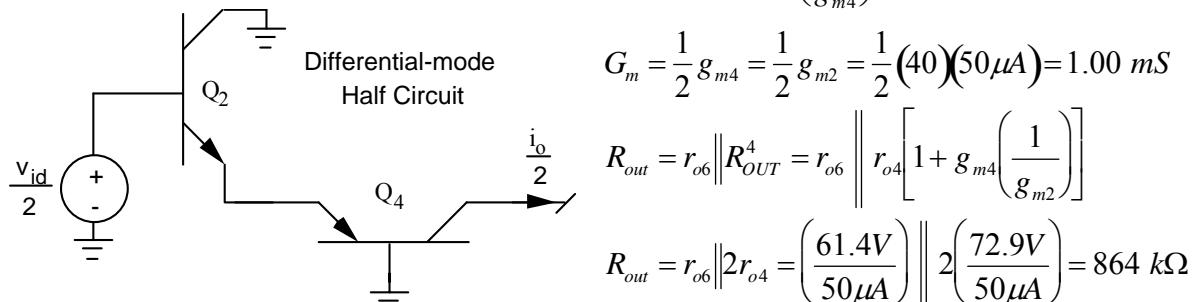
Q	1	2	3	4	5	6	7	8	9	10
$I_C (\mu A)$	50	50	-50	-50	50	50	---	-100	---	---
$V_{CE} (V)$	15.7	15.7	-12.9	-12.9	1.4	1.4	29.3	1.4	0.7	13.6

(b) Transistors Q_9 and Q_{10} form a current mirror that replicates the base current of transistor Q_8 . The output current divides in two and forms the base currents of Q_3 and Q_4 . Since Q_3 and Q_4 match Q_8 , the collector currents of Q_1 - Q_6 will all be equal to $I_{REF}/2$.

(c) v_1 is the inverting input; v_2 is the non-inverting input.

$$g_{m2} = g_{m4} \mid r_{o6} = r_{o4} \mid \frac{i_o}{2} = g_{m4} v_{e4} \mid i_o = 2g_{m4} v_{e4}$$

$$v_{e4} = \frac{v_{id}}{2} \frac{g_{m2}}{1 + g_{m2} \left(\frac{1}{g_{m4}} \right)} = \frac{1}{4} v_{id} \mid i_o = g_{m4} \frac{v_{id}}{2}$$



CHAPTER 16

16.1

$$A_v(s) = 50 \frac{s^2}{(s+2)(s+30)} \quad | \quad A_{mid} = 50 \quad | \quad F_L(s) = \frac{s^2}{(s+2)(s+30)} \quad | \quad \text{Poles: } -2, -30 \quad | \quad \text{Zeros: } 0, 0$$

$$\text{Yes, } s = -30 \quad | \quad A_v(s) \approx 50 \frac{s}{(s+30)} \quad | \quad \omega_L \approx 30 \frac{\text{rad}}{s} \quad | \quad f_L = \frac{\omega_L}{2\pi} \approx \frac{30}{2\pi} = 4.77 \text{ Hz}$$

$$f_L = \frac{1}{2\pi} \sqrt{30^2 + 2^2 - 2(0)^2 - 2(0)^2} = 4.79 \text{ Hz}$$

$$|A_v(j\omega)| = \frac{50\omega^2}{\sqrt{\omega^2 + 2^2} \sqrt{\omega^2 + 30^2}} \quad | \quad \text{MATLAB: } f_L = -4.80 \text{ Hz}$$

16.2

$$A_v(s) = \frac{400s^2}{2s^2 + 1400s + 100,000} = 200 \frac{s^2}{(s+619)(s+80.8)} \quad | \quad A_{mid} = 200 \quad | \quad F_L(s) = \frac{s^2}{(s+619)(s+80.8)}$$

Poles: -619, -80.8 $\frac{\text{rad}}{\text{s}}$ | Zeros: 0, 0 | Yes, a 5:1 split is sufficient | $s = -619$

$$A_v(s) \approx 200 \frac{s}{(s+619)} \quad | \quad \omega_L \approx 619 \frac{\text{rad}}{s} \quad | \quad f_L \approx \frac{619}{2\pi} = 98.5 \text{ Hz}$$

$$f_L \approx \frac{1}{2\pi} \sqrt{80.8^2 + 619^2 - 2(0)^2 - 2(0)^2} = 99.4 \text{ Hz}$$

$$|A_v(j\omega)| = \frac{200\omega^2}{\sqrt{\omega^2 + 80.8^2} \sqrt{\omega^2 + 619^2}} \quad | \quad \text{MATLAB: } 100 \text{ Hz}$$

16.3

$$A_v(s) = -150 \frac{s(s+15)}{(s+12)(s+20)} \quad | \quad A_{mid} = -150 \quad | \quad F_L(s) = \frac{s(s+15)}{(s+12)(s+20)}$$

Poles: -12, -20 $\frac{\text{rad}}{\text{s}}$ | Zeros: 0, -15 $\frac{\text{rad}}{\text{s}}$ | No, the poles and zeros are closely spaced.

$$f_L \approx \frac{1}{2\pi} \sqrt{12^2 + 20^2 - 2(0)^2 - 2(15)^2} = 1.54 \text{ Hz}$$

$$|A_v(j\omega)| = \frac{150\omega\sqrt{\omega^2 + 15^2}}{\sqrt{\omega^2 + 12^2} \sqrt{\omega^2 + 20^2}} \quad | \quad \text{MATLAB: } f_L = 2.72 \text{ Hz} \quad | \quad \omega_L = 17.1 \frac{\text{rad}}{\text{s}}$$

Note that $\omega_L = 16.1 \text{ rad/s}$ does not satisfy the assumption used to obtain Eq. (16.15), and the estimate using Eq. (16.15) is rather poor.

16.4

$$A_v(s) = \frac{9x10^{11}}{3s^2 + 3.3x10^5 s + 3x10^9} = \frac{(3x10^{11})(10^{-4})(10^{-5})}{\left(\frac{s}{10^4} + 1\right)\left(\frac{s}{10^5} + 1\right)} = \frac{300}{\left(\frac{s}{10^4} + 1\right)\left(\frac{s}{10^5} + 1\right)}$$

$$A_{mid} = 300 \quad | \quad F_H(s) = \frac{1}{\left(\frac{s}{10^4} + 1\right)\left(\frac{s}{10^5} + 1\right)}$$

Poles: $-10^4, -10^5 \frac{rad}{s}$ | Yes: $A_v(s) \approx \frac{300}{\frac{s}{10^4} + 1} \quad | \quad \omega_H \cong 10^4 \frac{rad}{s} \quad | \quad f_H \cong \frac{10^4}{2\pi} = 1.59 kHz$

$$f_H \cong \frac{1}{2\pi} \sqrt{\left(\frac{1}{10^4}\right)^2 + \left(\frac{1}{10^5}\right)^2 - 2\left(\frac{1}{\infty}\right)^2 - 2\left(\frac{1}{\infty}\right)^2}^{-1} = 1.58 kHz$$

$$|A_v(j\omega)| = \frac{3x10^{11}}{\sqrt{\omega^2 + (10^4)^2} \sqrt{\omega^2 + (10^5)^2}} \quad | \quad \text{MATLAB: } f_H = 1.58 kHz$$

16.5

$$A_v(s) = \frac{(3x10^9)\left(1 + \frac{s}{3x10^9}\right)}{10^7\left(1 + \frac{s}{10^7}\right)\left(1 + \frac{s}{10^9}\right)} = 300 \frac{\left(1 + \frac{s}{2x10^9}\right)}{\left(1 + \frac{s}{10^7}\right)\left(1 + \frac{s}{10^9}\right)}$$

$$A_{mid} = 300 \quad | \quad F_H(s) = \frac{\left(1 + \frac{s}{3x10^9}\right)}{\left(1 + \frac{s}{10^7}\right)\left(1 + \frac{s}{10^9}\right)} \quad | \quad \text{Poles: } -10^7, -10^9 \quad \text{Zeros: } -3x10^9, \infty$$

Yes: $A_v(s) \approx \frac{300}{\left(1 + \frac{s}{10^7}\right)} \quad | \quad \omega_H \cong 10^7 \frac{rad}{s} \quad | \quad f_H \cong \frac{10^4}{2\pi} = 1.59 MHz$

$$f_H = \frac{1}{2\pi} \sqrt{\left(\frac{1}{10^7}\right)^2 + \left(\frac{1}{10^9}\right)^2 - 2\left(\frac{1}{3x10^9}\right)^2 - 2\left(\frac{1}{\infty}\right)^2}^{-1} = 1.59 MHz$$

$$|A_v(j\omega)| = \frac{2x10^9 \sqrt{\omega^2 + (3x10^9)^2}}{\sqrt{\omega^2 + (10^7)^2} \sqrt{\omega^2 + (10^9)^2}} \quad | \quad \text{MATLAB: } f_H = 1.59 MHz$$

16.6

$$A_v(s) = \frac{(2 \times 10^9)(5 \times 10^5) \left(1 + \frac{s}{5 \times 10^5}\right)}{(1.5 \times 10^5)(2 \times 10^6) \left(1 + \frac{s}{1.3 \times 10^5}\right) \left(1 + \frac{s}{2 \times 10^6}\right)} = 3333 \frac{\left(1 + \frac{s}{5 \times 10^5}\right)}{\left(1 + \frac{s}{1.5 \times 10^5}\right) \left(1 + \frac{s}{2 \times 10^6}\right)}$$

$$A_{mid} = 3333 \quad | \quad F_H(s) = \frac{\left(1 + \frac{s}{5 \times 10^5}\right)}{\left(1 + \frac{s}{1.5 \times 10^5}\right) \left(1 + \frac{s}{2 \times 10^6}\right)} \quad | \quad \text{Poles: } -1.5 \times 10^5, -2 \times 10^6 \frac{\text{rad}}{\text{s}}$$

Zeros: $-5 \times 10^5 \frac{\text{rad}}{\text{s}}, \infty$ | No, the poles and zeros are closely spaced and will interact.

$$f_H \equiv \frac{1}{2\pi} \sqrt{\left(\frac{1}{1.5 \times 10^5}\right)^2 + \left(\frac{1}{2 \times 10^6}\right)^2 - 2\left(\frac{1}{5 \times 10^5}\right)^2 - 2\left(\frac{1}{\infty}\right)^2}^{-1} = 26.3 \text{ kHz}$$

$$|A_v(j\omega)| = \frac{2 \times 10^9 \sqrt{\omega^2 + (5 \times 10^5)^2}}{\sqrt{\omega^2 + (1.3 \times 10^5)^2} \sqrt{\omega^2 + (2 \times 10^6)^2}} \quad | \quad \text{MATLAB: } 26.3 \text{ kHz}$$

16.7

$$A_v(s) = \frac{6 \times 10^8}{1000(2000)} \frac{s^2}{(s+1)(s+2)} \frac{1}{\left(1 + \frac{s}{1000}\right) \left(1 + \frac{s}{2000}\right)}$$

$$A_v(s) = 300 \left[\frac{s^2}{(s+1)(s+2)} \right] \left[\frac{1}{\left(1 + \frac{s}{500}\right) \left(1 + \frac{s}{1000}\right)} \right] = 200 F_L(s) F_H(s)$$

Poles: $-1, -2, -1000, -2000 \frac{\text{rad}}{\text{s}}$ | Zeros: $0, 0, \infty, \infty$ | No. | No.

$$|A_v(j\omega)| = \frac{6 \times 10^8 \omega^2}{\sqrt{1^2 + \omega^2} \sqrt{2^2 + \omega^2} \sqrt{1000^2 + \omega^2} \sqrt{2000^2 + \omega^2}}$$

$$f_L = \frac{1}{2\pi} \sqrt{(1)^2 + (2)^2 - 2(0)^2 - 2(0)^2} = 0.356 \text{ Hz} \quad | \quad \text{MATLAB: } 0.380 \text{ Hz}$$

$$f_H = \frac{1}{2\pi} \sqrt{\left(\frac{1}{1000}\right)^2 + \left(\frac{1}{2000}\right)^2 - 2\left(\frac{1}{\infty}\right)^2 - 2\left(\frac{1}{\infty}\right)^2} = 142 \text{ Hz} \quad | \quad \text{MATLAB: } 133 \text{ Hz}$$

16.8

$$A_v(s) = \frac{10^{10}(200)}{(100)^2(300)(s+3)(s+5)(s+7)} \frac{\left(1 + \frac{s}{200}\right)}{\left(1 + \frac{s}{100}\right)^2 \left(1 + \frac{s}{300}\right)}$$

$$A_v(s) = 6.67 \times 10^5 \left[\frac{s^2(s+1)}{(s+3)(s+5)(s+7)} \frac{\left(1 + \frac{s}{200}\right)}{\left(1 + \frac{s}{100}\right)^2 \left(1 + \frac{s}{300}\right)} \right] = 6.67 \times 10^5 F_L(s) F_H(s)$$

No dominant pole at either low or high frequencies.

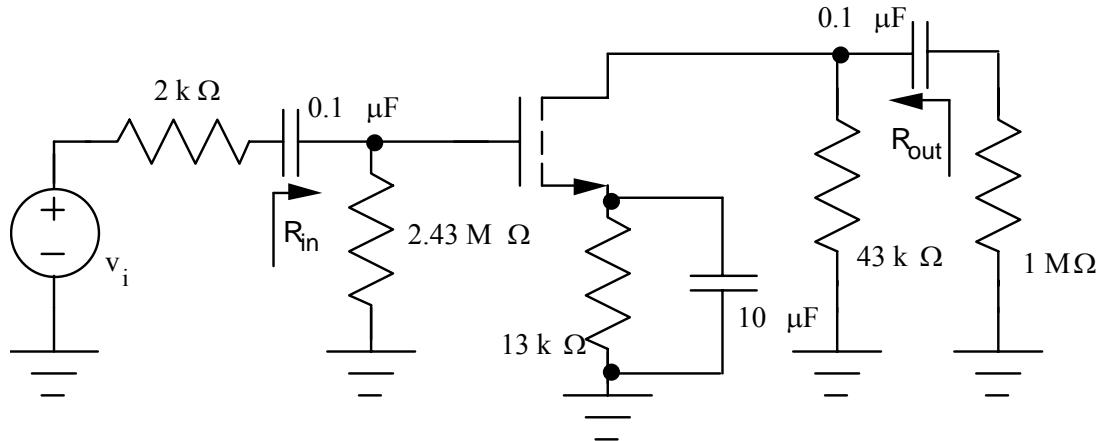
$$|A_v(j\omega)| = \frac{10^{10} \omega^2 \sqrt{\omega^2 + 1^2} \sqrt{\omega^2 + 200^2}}{\sqrt{\omega^2 + 3^2} \sqrt{\omega^2 + 5^2} \sqrt{\omega^2 + 7^2} (\omega^2 + 100^2) \sqrt{\omega^2 + 300^2}}$$

$$f_L = \frac{1}{2\pi} \sqrt{(3)^2 + (5)^2 + (7)^2 - 2(1)^2 - 2(0)^2} = 1.43 \text{ Hz} \quad | \quad \text{MATLAB: } 1.62 \text{ Hz}$$

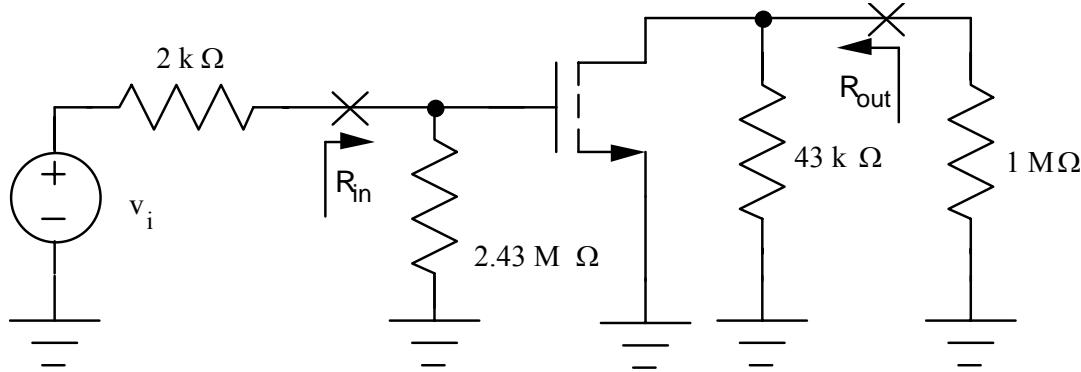
$$f_H = \frac{1}{2\pi} \left(\sqrt{\left(\frac{1}{100}\right)^2 + \left(\frac{1}{100}\right)^2 + \left(\frac{1}{300}\right)^2} - 2\left(\frac{1}{200}\right)^2 - 2\left(\frac{1}{\infty}\right)^2 \right)^{-1} = 12.5 \text{ Hz} \quad | \quad \text{MATLAB: } 10.6 \text{ Hz}$$

16.9

Low frequency:



Mid-band:



$$(b) A_{vt} = \frac{v_d}{v_g} = -g_m R_L = -g_m (R_{out} \| R_3) \quad | \quad A_{mid} = \frac{R_{in}}{R_I + R_{in}} A_{vt} \quad | \quad g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(0.2mA)}{1V} = 0.400mS$$

$R_{in} = 2.43 M\Omega$ | $R_{out} = R_D \| r_o \equiv R_D = 43k\Omega$ assuming $\lambda = 0$ since it is not specified.

$$A_{mid} = -\left(\frac{2.43 M\Omega}{2k\Omega + 2.43 M\Omega}\right)(0.400mS)(43k\Omega \| 1M\Omega) = -16.5$$

$$\omega_1 = \frac{1}{(10^{-7}F)(2.43 M\Omega + 2k\Omega)} = 4.11 \frac{rad}{s} \quad | \quad \omega_2 = \frac{1}{(10^{-7}F)(43k\Omega + 1M\Omega)} = 9.59 \frac{rad}{s}$$

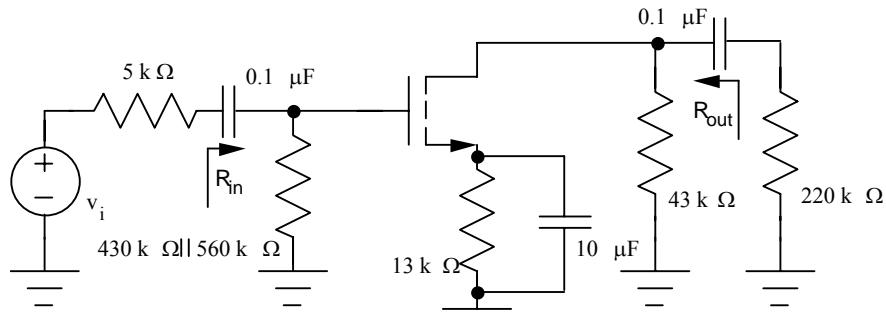
$$\omega_3 = \frac{1}{(10^{-5}F)(13k\Omega \| \frac{1}{g_m})} = \frac{1}{(10^{-5}F)(13k\Omega \| 2.5k\Omega)} = 47.7 \frac{rad}{s} \quad | \quad \omega_z = \frac{1}{(10^{-5}F)(13k\Omega)} = 7.69 \frac{rad}{s}$$

$$\omega_3 \text{ is dominant: } f_L \equiv \frac{\omega_3}{2\pi} = 7.59 \text{ Hz}$$

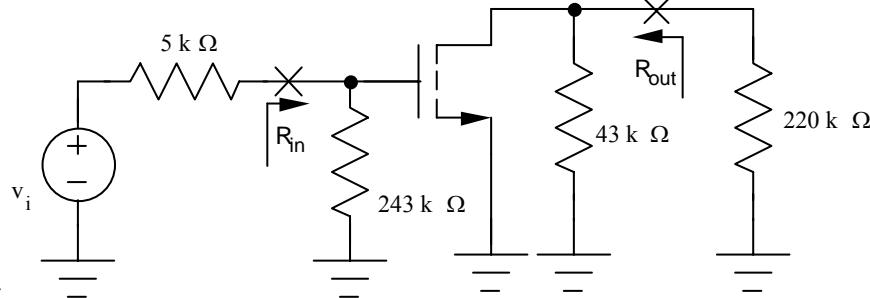
$$\text{Using Eq. (16.15) yields: } f_L \equiv \frac{1}{2\pi} \sqrt{(4.11)^2 + (9.59)^2 + (47.7)^2 - 2(7.69)^2} = 7.58 \text{ Hz}$$

$$(c) V_{DD} = I_D(R_D + R_s) + V_{DS} = 0.2mA(56k\Omega) + 5V = 16.2 \text{ V}$$

16.10



Low frequency:



Mid-band:

$$A_{vt} = \frac{v_d}{v_g} = -g_m R_L = -g_m (R_{out} \| R_3) \quad | \quad A_{mid} = \frac{R_{in}}{R_I + R_{in}} A_{vt} \quad | \quad g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(0.2mA)}{1V} = 0.400mS$$

$R_{in} = 243k\Omega$ | $R_{out} = R_D \| r_o \approx R_D = 43k\Omega$ assuming $\lambda = 0$ since it is not specified.

$$A_{mid} = -\left(\frac{243k\Omega}{5k\Omega + 243k\Omega}\right)(0.400mS)(43k\Omega \| 220k\Omega) = -14.1$$

$$\omega_1 = \frac{1}{(10^{-7}F)(243k\Omega + 5k\Omega)} = 40.3 \frac{rad}{s} \quad | \quad \omega_2 = \frac{1}{(10^{-7}F)(43k\Omega + 220k\Omega)} = 38.0 \frac{rad}{s}$$

$$\omega_3 = \frac{1}{(10^{-5}F)(13k\Omega \| \frac{1}{g_m})} = \frac{1}{(10^{-5}F)(13k\Omega \| 2.5k\Omega)} = 47.7 \frac{rad}{s} \quad | \quad \omega_z = \frac{1}{(10^{-5}F)(13k\Omega)} = 7.69 \frac{rad}{s}$$

Using Eq. (17.16): $f_L \approx \frac{1}{2\pi} \sqrt{(40.3)^2 + (38.0)^2 + (47.7)^2 - 2(7.69)^2} = 11.5 \text{ Hz}$

16.11

(a) Assume that ω_3 is dominant : $f_L \approx \omega_3 = 2\pi(50) = 314 \frac{rad}{s}$

$$C_3 = \frac{1}{\omega_3 \left(R_S \left\| \frac{1}{g_m} \right\| \right)} = \frac{1}{314(13k\Omega \| 2.5k\Omega)} = 1.52 \mu F \quad \text{where} \quad g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{0.4mA}{1V} = 0.4mS$$

(b) Choose $C_3 = 1.5 \mu F$ | $\omega_3 = \frac{1}{1.5 \mu F (13k\Omega \| 2.5k\Omega)} = 318 \frac{rad}{s}$ | $\omega_z = \frac{1}{(1.5\mu F)(13k\Omega)} = 51.3 \frac{rad}{s}$

$$\omega_1 = \frac{1}{(10^{-7}F)(2.43M\Omega + 2k\Omega)} = 4.11 \frac{rad}{s} \quad | \quad \omega_2 = \frac{1}{(10^{-7}F)(43k\Omega + 1M\Omega)} = 9.59 \frac{rad}{s}$$

Using Eq. (17.16) yields : $f_L \approx \frac{1}{2\pi} \sqrt{(4.11)^2 + (9.59)^2 + (318)^2 - 2(51.3)^2} = 49.3 \text{ Hz}$

(c) Assume that ω_3 is dominant : $f_L \approx \omega_3 = 2\pi(50) = 314 \frac{rad}{s}$

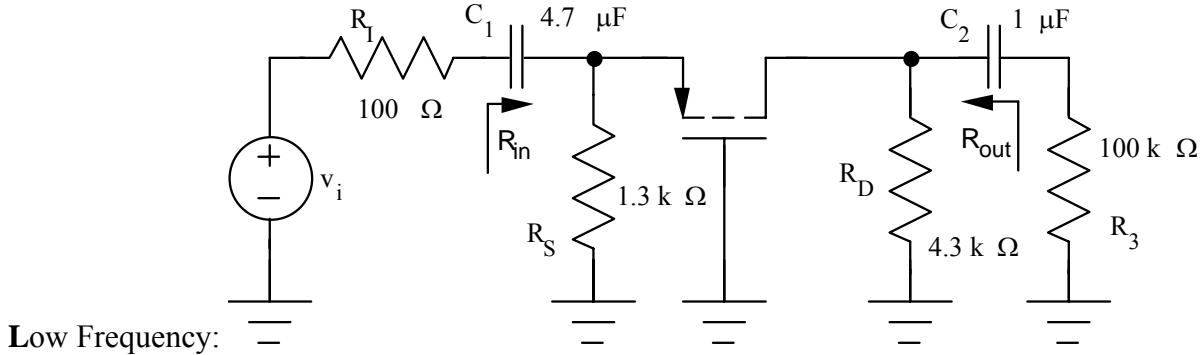
$$C_3 = \frac{1}{\omega_3 \left(R_S \left\| \frac{1}{g_m} \right\| \right)} = \frac{1}{314(13k\Omega \| 2.5k\Omega)} = 1.52 \mu F \quad \text{where} \quad g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{0.4mA}{1V} = 0.4mS$$

Choose $C_3 = 1.5 \mu F$ | $\omega_3 = \frac{1}{1.5 \mu F (13k\Omega \| 2.5k\Omega)} = 318 \frac{rad}{s}$ | $\omega_z = \frac{1}{(1.5\mu F)(13k\Omega)} = 51.3 \frac{rad}{s}$

$$\omega_1 = \frac{1}{(10^{-7}F)(243k\Omega + 5k\Omega)} = 40.3 \frac{rad}{s} \quad | \quad \omega_2 = \frac{1}{(10^{-7}F)(43k\Omega + 220k\Omega)} = 38.0 \frac{rad}{s}$$

Using Eq. (16.15) yields : $f_L \approx \frac{1}{2\pi} \sqrt{(40.3)^2 + (38.0)^2 + (318)^2 - 2(51.3)^2} = 50.1 \text{ Hz}$

16.12



$$(b) A_v(s) = A_{mid} \frac{s^2}{(s + \omega_1)(s + \omega_2)} \quad | \quad \omega_1 = \frac{1}{C_1(R_I + R_S \parallel \frac{1}{g_m})} \quad | \quad \omega_2 = \frac{1}{C_2(R_D + R_3)} \quad | \quad 2 \text{ zeros at } \omega = 0$$

$$(c) A_{mid} = \left(\frac{R_{in}}{R_I + R_{in}} \right) A_{vt} = \left(\frac{R_{in}}{R_I + R_{in}} \right) g_m R_L = \left(\frac{R_{in}}{R_I + R_{in}} \right) g_m (R_{out} \parallel R_3) \quad | \quad g_m = 5mS$$

$$R_{in} = R_S \parallel \frac{1}{g_m} = 173\Omega \quad | \quad R_L = R_{out} \parallel R_3 \quad | \quad R_{out} = R_D \parallel r_o = R_D = 4.3k\Omega \quad (\text{assuming } r_o = \infty)$$

$$A_{mid} = \left(\frac{173\Omega}{100\Omega + 173\Omega} \right) (0.005)(4.3k\Omega \parallel 100k\Omega) = +13.1 \rightarrow 22.3 \text{ dB}$$

$$\omega_1 = \frac{1}{4.7 \times 10^{-6} (100 + 173)} = 779 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_2 = \frac{1}{10^{-6} (4.3k\Omega + 100k\Omega)} = 9.59 \frac{\text{rad}}{\text{s}}$$

$$\omega_1 \text{ is dominant : } f_L \cong \frac{\omega_1}{2\pi} = 124 \text{ Hz}$$

16.13

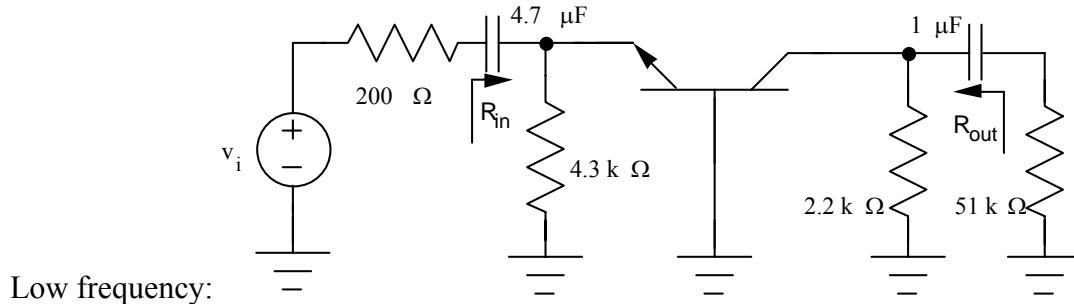
$$(a) \text{ Assume } \omega_1 \text{ is dominant : } \omega_L \cong \omega_1 = 2\pi(1000\text{Hz}) = 6280 \frac{\text{rad}}{\text{s}} \quad | \quad C_1 = \frac{1}{\omega_1(R_I + R_{in})}$$

$$R_{in} = R_S \parallel \frac{1}{g_m} = 1300\Omega \parallel 200\Omega = 173\Omega \quad | \quad C_1 = \frac{1}{6.28 \times 10^3 (100 + 173)} = 0.583 \mu F$$

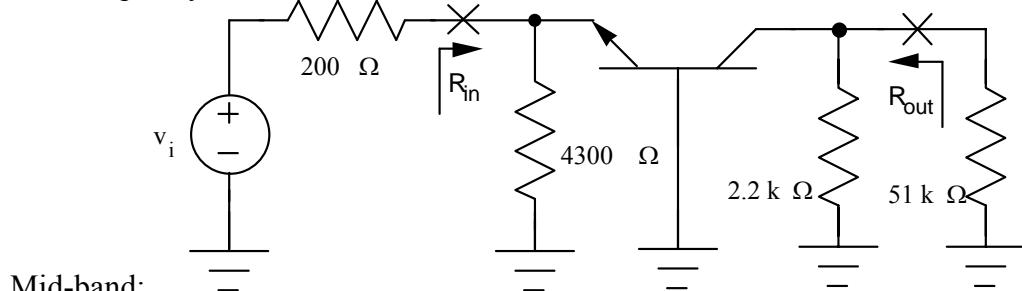
$$(b) \text{ Choose } C_1 = 0.56 \mu F \quad | \quad \omega_1 = \frac{1}{0.56 \times 10^{-6} (100 + 173)} = 6540 \frac{\text{rad}}{\text{s}}$$

$$\omega_2 = \frac{1}{10^{-6} (22k\Omega + 75k\Omega)} = 10.3 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_1 \text{ is dominant : } f_L \cong \frac{\omega_1}{2\pi} = 1040 \text{ Hz}$$

16.14



Low frequency:



Mid-band:

$$(b) A_v(s) = A_{mid} \frac{s^2}{(s + \omega_1)(s + \omega_2)} \quad | \quad \omega_1 = \frac{1}{C_1 (R_S + R_E) \left\| \frac{1}{g_m} \right\|} \quad | \quad \omega_2 = \frac{1}{C_2 (R_C + R_3)} \quad | \quad 2 \text{ zeros at } \omega = 0$$

$$(c) A_{mid} = \left(\frac{R_{in}}{R_I + R_{in}} \right) A_{vt} = \left(\frac{R_{in}}{R_I + R_{in}} \right) g_m R_L = \left(\frac{R_{in}}{R_I + R_{in}} \right) g_m (R_{out} \parallel R_3) \quad | \quad g_m = 40(1mA) = 0.04S$$

$$R_{in} = R_E \left\| \frac{1}{g_m} \right\| = 24.9 \Omega \quad | \quad R_L = R_{out} \parallel R_3 \quad | \quad R_{out} = R_C \parallel r_o = R_C = 2.2k\Omega$$

$$A_{mid} = \left(\frac{24.9 \Omega}{200\Omega + 24.9 \Omega} \right) (0.04) (2.2k\Omega \parallel 51k\Omega) = +9.34 \rightarrow 19.4 \text{ dB}$$

$$\omega_1 = \frac{1}{4.7 \times 10^{-6} (200 + 24.9)} = 946 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_2 = \frac{1}{10^{-6} (2.2k\Omega + 51k\Omega)} = 18.8 \frac{\text{rad}}{\text{s}}$$

$$\omega_1 \text{ is dominant : } f_L \equiv \frac{\omega_1}{2\pi} = 151 \text{ Hz}$$

$$(d) g_m = 40(10\mu A) = 0.0004S \quad | \quad R_{in} = 2.49k\Omega \quad | \quad R_{out} = R_C \parallel r_o = R_C = 220k\Omega$$

$$A_{mid} = \left(\frac{2.49k\Omega}{200\Omega + 2.49k\Omega} \right) (0.0004) (220k\Omega \parallel 510k\Omega) = +56.9 \rightarrow 35.1 \text{ dB}$$

$$\omega_1 = \frac{1}{4.7 \times 10^{-6} (200 + 2.49k\Omega)} = 79.1 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_2 = \frac{1}{10^{-6} (220k\Omega + 510k\Omega)} = 1.37 \frac{\text{rad}}{\text{s}}$$

$$\omega_1 \text{ is dominant : } f_L \equiv \frac{\omega_1}{2\pi} = 12.6 \text{ Hz}$$

16.15

(a) Assume ω_1 is dominant : $\omega_L \approx \omega_1 = 2\pi(500\text{Hz}) = 3140 \frac{\text{rad}}{\text{s}}$

$$C_1 = \frac{1}{\omega_1(R_I + R_{in})} \quad | \quad R_{in} = R_E \left| \frac{1}{g_m} \quad | \quad g_m = 40(1\text{mA}) = 0.04\text{S} \quad | \quad R_{in} = 4300\Omega \right| 25\Omega = 24.9\Omega$$

$$C_1 = \frac{1}{3.14 \times 10^3 (200 + 24.9)} = 1.42 \mu\text{F}$$

(b) Choose $C_1 = 1.5 \mu\text{F}$ | $\omega_1 = \frac{1}{1.5 \times 10^{-6} (200 + 24.9)} = 2960 \frac{\text{rad}}{\text{s}}$

$$\omega_2 = \frac{1}{10^{-6} (2.2k\Omega + 51k\Omega)} = 18.8 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_1 \text{ is dominant : } f_L \approx \frac{\omega_1}{2\pi} = 472 \text{ Hz}$$

(c) Assume ω_1 is dominant : $\omega_L \approx \omega_1 = 2\pi(500\text{Hz}) = 3140 \frac{\text{rad}}{\text{s}}$

$$C_1 = \frac{1}{\omega_1(R_I + R_{in})} \quad | \quad R_{in} = R_E \left| \frac{1}{g_m} \quad | \quad g_m = 40(10\mu\text{A}) = 0.0004\text{S} \quad | \quad R_{in} = 430k\Omega \right| 2500\Omega = 2.49k\Omega$$

$$C_1 = \frac{1}{3.14 \times 10^3 (200 + 2490)} = 0.118 \mu\text{F} \quad | \quad \text{Choose } C_1 = 0.12 \mu\text{F}$$

$$\omega_1 = \frac{1}{0.12 \times 10^{-6} (200 + 2490)} = 2100 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_2 = \frac{1}{10^{-6} (2.2k\Omega + 51k\Omega)} = 18.8 \frac{\text{rad}}{\text{s}}$$

$$\omega_1 \text{ is dominant : } f_L \approx \frac{\omega_1}{2\pi} = 493 \text{ Hz}$$

16.16

$$(a) g_m = 40I_C = 40(0.175mA) = 7.00mS \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{100}{7.00mS} = 14.3k\Omega \quad | \quad r_o = \infty \text{ (V_A not given)}$$

$$R_{in} = R_1 \| R_2 \| r_\pi = 100k\Omega \| 300k\Omega \| 14.3k\Omega = 12.0k\Omega \quad | \quad R_L = R_C \| R_3 = 43k\Omega \| 100k\Omega = 30.1k\Omega$$

$$A_{mid} = \frac{R_{in}}{R_I + R_{in}} g_m R_L = \frac{12.0k\Omega}{1k\Omega + 12.0k\Omega} (7.00mS)(30.1k\Omega) = -194$$

$$\text{SCTC: } R_{1S} = R_I + R_{in} = 1k\Omega + 12.0k\Omega = 13.0k\Omega \quad | \quad R_{th} = R_1 \| R_2 \| R_I = 100k\Omega \| 300k\Omega \| 1k\Omega = 987\Omega$$

$$R_{2S} = R_E \left| \frac{R_{th} + r_\pi}{\beta_o + 1} \right| = 15k\Omega \left| \frac{987\Omega + 14.3k\Omega}{101} \right| = 150\Omega \quad | \quad R_{3S} = R_C + R_3 = 43k\Omega + 100k\Omega = 143k\Omega$$

$$f_L \cong \frac{1}{2\pi} \left[\frac{1}{2 \times 10^{-6}(13.0k\Omega)} + \frac{1}{10 \times 10^{-6}(150\Omega)} + \frac{1}{1 \times 10^{-7}(143k\Omega)} \right] = \frac{(38.5 + 667 + 69.9)}{2\pi} = 123 \text{ Hz}$$

(b) Note that the Q-point assumed in part (a) is not quite correct.

SPICE yields: (144 μA, 3.67 V), A_{mid} = 43.9 dB, f_L = 91 Hz

$$(c) V_{EQ} = V_{CC} \frac{R_1}{R_1 + R_2} = 12 \frac{100k\Omega}{100k\Omega + 300k\Omega} = 3V \quad | \quad R_{EQ} = R_1 \| R_2 = 100k\Omega \| 300k\Omega = 75.0k\Omega$$

$$I_C = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} = 100 \frac{3 - 0.7}{75k\Omega + (101)15k\Omega} = 145\mu A$$

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E = 12 - (0.145mA)(43k\Omega) - \frac{101}{100}(0.145mA)(15k\Omega) = 3.57 \text{ V}$$

These values agree with the SPICE results listed above in part (b).

16.17

(a) Use the values from Section 16.3.1, and assume ω₃ is dominant.

$$\omega_L = 2\pi(2500\text{Hz}) = 15700 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_3 = \omega_L - \omega_1 - \omega_2 = 15700 - 225 + 96.1 = 15390 \frac{\text{rad}}{\text{s}}$$

$$C_3 = \frac{1}{\omega_3 R_{3S}} = \frac{1}{15390(22.7\Omega)} = 2.86 \mu F$$

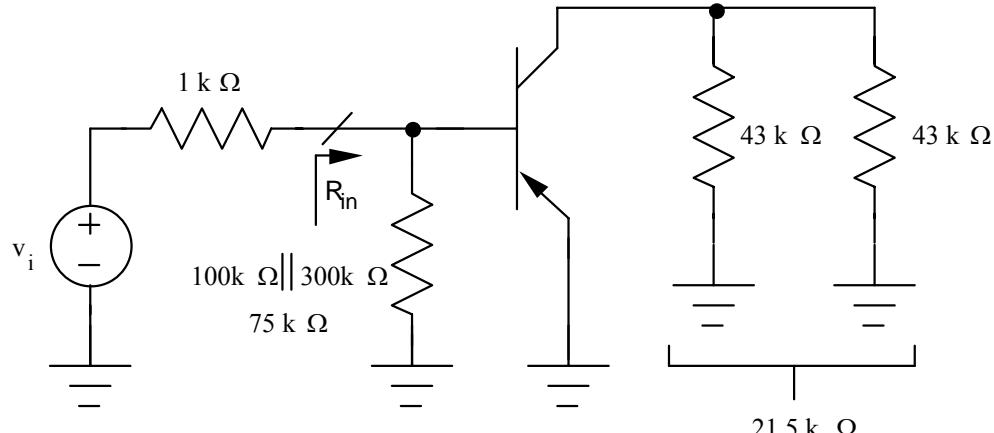
$$(b) \text{Choose } C_3 = 2.7 \mu F \quad | \quad \omega_3 = \frac{1}{2.7 \times 10^{-6}(22.7\Omega)} = 16320 \frac{\text{rad}}{\text{s}}$$

$$\omega_2 = 96.1 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_1 = 225 \frac{\text{rad}}{\text{s}} \quad | \quad f_L \cong \frac{225 + 96.1 + 16320}{2\pi} = 2650 \text{ Hz}$$

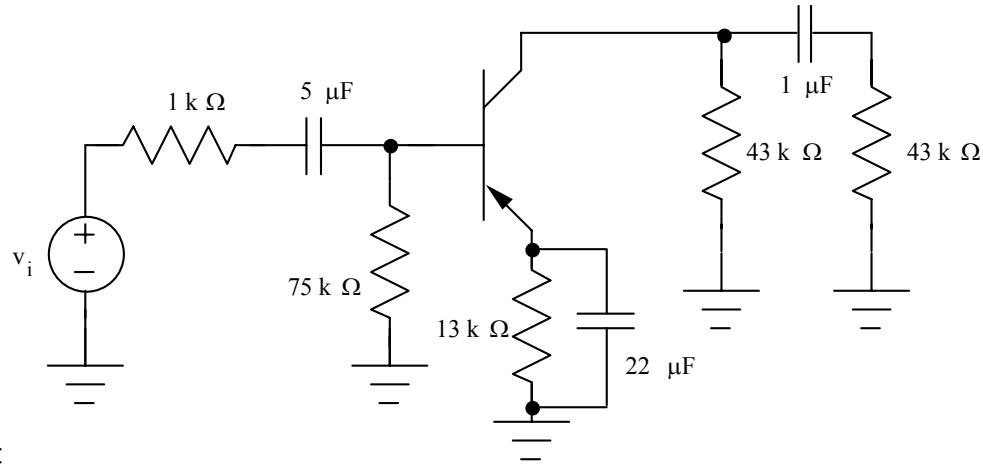
or if ω_L must be no more than 2500 Hz, choose C₃ = 3.3 μF

$$\omega_3 = \frac{1}{3.3 \times 10^{-6}(22.7\Omega)} = 13350 \frac{\text{rad}}{\text{s}} \quad | \quad f_L \cong \frac{225 + 96.1 + 13350}{2\pi} = 2180 \text{ Hz}$$

16.18



(a) Mid-band:



Low frequency:

$$(b) g_m = 40I_C = 40(0.164mA) = 6.56mS \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{100}{6.56mS} = 15.2k\Omega \quad | \quad r_o = \infty \quad (\text{V}_A \text{ not given})$$

$$R_{in} = R_i \parallel R_2 \parallel r_\pi = 100k\Omega \parallel 300k\Omega \parallel 15.2k\Omega = 12.6k\Omega \quad | \quad R_L = R_C \parallel R_3 = 43k\Omega \parallel 43k\Omega = 21.5k\Omega$$

$$A_{mid} = \frac{R_{in}}{R_i + R_{in}} g_m R_L = \frac{12.6k\Omega}{1k\Omega + 12.6k\Omega} (6.56mS)(21.5k\Omega) = -131$$

$$\text{SCTC: } R_{IS} = R_i + R_{in} = 1k\Omega + 12.6k\Omega = 13.6k\Omega \quad | \quad R_{th} = R_i \parallel R_2 \parallel R_l = 100k\Omega \parallel 300k\Omega \parallel 1k\Omega = 987\Omega$$

$$R_{2S} = R_E \left| \frac{R_{th} + r_\pi}{\beta_o + 1} \right| = 13k\Omega \left| \frac{987\Omega + 15.2k\Omega}{101} \right| = 158\Omega \quad | \quad R_{3S} = R_C + R_3 = 43k\Omega + 43k\Omega = 86k\Omega$$

$$f_L \equiv \frac{1}{2\pi} \left[\frac{1}{5 \times 10^{-6} (13.6k\Omega)} + \frac{1}{22 \times 10^{-6} (158\Omega)} + \frac{1}{1 \times 10^{-6} (86k\Omega)} \right] = \frac{(14.7 + 288 + 11.6)}{2\pi} = 50.0 \text{ Hz}$$

$$(c) V_{CC} = I_E R_E + V_{EC} + I_C R_C = 0.164mA \left(\frac{101}{100} \right) (13k\Omega) + 2.79V + 0.164mA (43k\Omega) = 12.0 \text{ V}$$

16.19

$$\text{SCTC: } R_{1S} = R_I + R_G = 1k\Omega + 1M\Omega = 1.00M\Omega \quad | \quad \omega_1 = \frac{1}{1.00M\Omega(0.1\mu F)} = 10.0 \frac{\text{rad}}{\text{s}}$$

$$R_{2S} = R_S \left| \frac{1}{g_m} = 6.8k\Omega \right| \left| \frac{1}{1.5mS} = 607\Omega \quad | \quad \omega_2 = \frac{1}{607\Omega(10\mu F)} = 165 \frac{\text{rad}}{\text{s}} \right.$$

$$R_{3S} = R_D + R_3 = 22k\Omega + 68k\Omega = 90k\Omega \quad | \quad \omega_3 = \frac{1}{90k\Omega(0.1\mu F)} = 111 \frac{\text{rad}}{\text{s}}$$

$$f_L \equiv \frac{(10.0 + 165 + 111)}{2\pi} = 45.5 \text{ Hz}$$

16.20

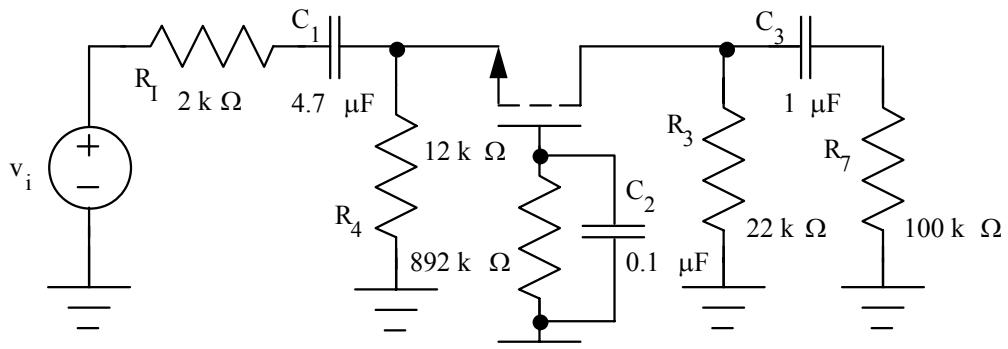
$$\text{SCTC: } R_{1S} = R_I + R_G = 1k\Omega + 500k\Omega = 501k\Omega \quad | \quad \omega_1 = \frac{1}{501k\Omega(0.1\mu F)} = 20.0 \frac{\text{rad}}{\text{s}}$$

$$R_{2S} = R_S \left| \frac{1}{g_m} = 10k\Omega \right| \left| \frac{1}{0.75mS} = 1.18k\Omega \quad | \quad \omega_2 = \frac{1}{1.18k\Omega(10\mu F)} = 84.8 \frac{\text{rad}}{\text{s}} \right.$$

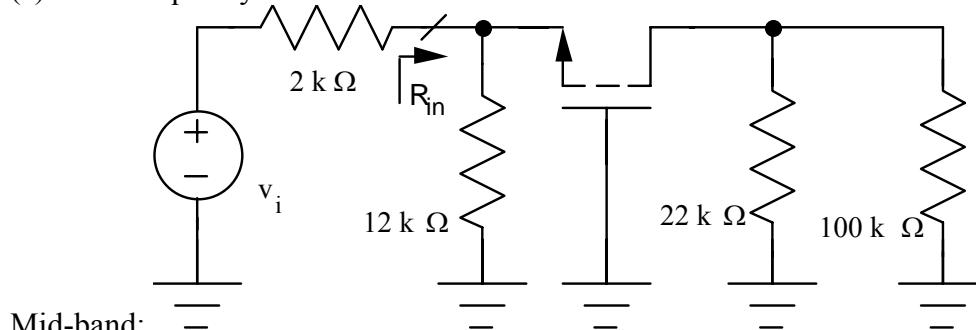
$$R_{3S} = R_D + R_3 = 43k\Omega + 10k\Omega = 53k\Omega \quad | \quad \omega_3 = \frac{1}{53k\Omega(0.1\mu F)} = 189 \frac{\text{rad}}{\text{s}}$$

$$f_L \equiv \frac{(20.0 + 84.8 + 189)}{2\pi} = 46.8 \text{ Hz}$$

16.21



(a) Low Frequency:



Mid-band:

$$g_m = \frac{2(0.1mA)}{1V} = 0.200mS \quad | \quad \frac{1}{g_m} = 5000\Omega$$

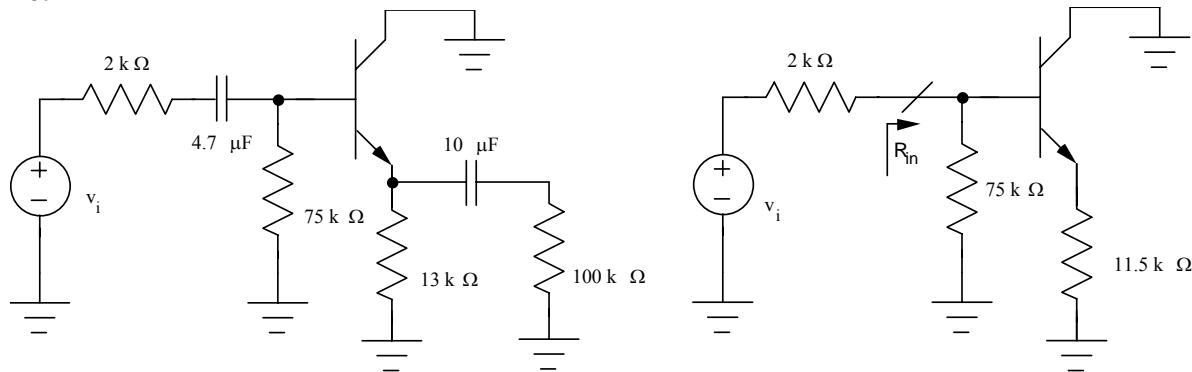
$$R_{in} = R_s \parallel \frac{1}{g_m} = 12k\Omega \parallel 5k\Omega = 3.53k\Omega \quad | \quad R_L = 22k\Omega \parallel 100k\Omega = 18.0k\Omega$$

$$A_{mid} = \frac{R_{in}}{R_I + R_{in}} g_m R_L = \frac{3.53k\Omega}{2k\Omega + 3.53k\Omega} (0.200mS)(18k\Omega) = 2.30 \text{ (7.24dB)}$$

$$\omega_1 = \frac{1}{C_1(R_I + R_{in})} = \frac{1}{4.7 \times 10^{-6} (2k\Omega + 3.53k\Omega)} = 38.5 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_2 = \text{doesn't matter since } i_g = 0!$$

$$\omega_3 = \frac{1}{C_3(R_3 + R_7)} = \frac{1}{10^{-7} (100k\Omega + 22k\Omega)} = 82.0 \frac{\text{rad}}{\text{s}} \quad | \quad f_L \approx \frac{1}{2\pi} (38.5 + 82.0) = 19.2 \text{Hz}$$

16.22



(a) Low frequency

Mid-band

$$(b) R_{in} = R_1 \parallel R_2 \parallel r_\pi + (\beta_o + 1) R_L \quad | \quad R_L = 13k\Omega \parallel 100k\Omega = 11.5k\Omega \quad | \quad r_\pi = \frac{100}{40(0.25mA)} = 10.0k\Omega$$

$$R_{in} = R_1 \parallel R_2 \parallel [r_\pi + (\beta_o + 1) R_L] = 100k\Omega \parallel 300k\Omega \parallel [10.0k\Omega + (101)11.5k\Omega] = 70.5k\Omega$$

$$A_{mid} = \frac{R_{in}}{R_I + R_{in}} \frac{(\beta_o + 1) R_L}{R_{in}} = 0.972 \frac{101(11.5k\Omega)}{[2 + 10.0 + 101(11.5)]k\Omega} = 0.963 \quad | \quad R_B = R_1 \parallel R_2 = 75k\Omega$$

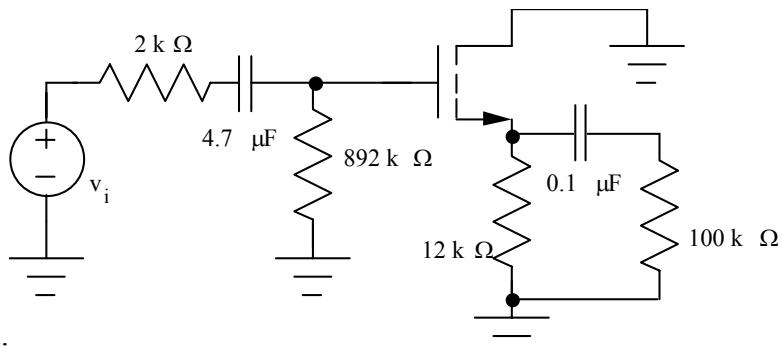
$$R_{IS} = R_I + R_B \parallel [r_\pi + (\beta_o + 1) R_L] = 2k\Omega + 75k\Omega \parallel [10.0k\Omega + (101)11.5k\Omega] = 72.5k\Omega$$

$$\omega_1 = \frac{1}{(72.5k\Omega)4.7 \times 10^{-6}} = 2.94 \frac{\text{rad}}{\text{s}}$$

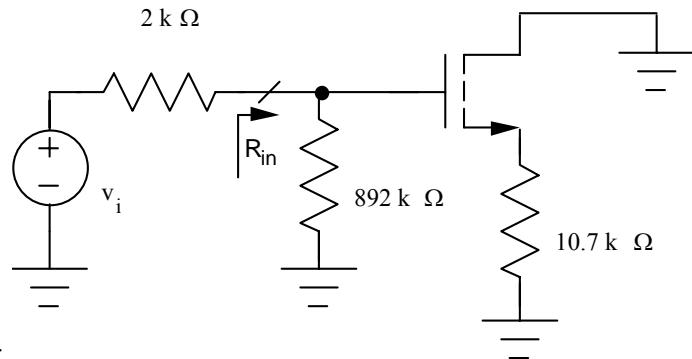
$$R_{3S} = R_7 + R_E \frac{R_B \parallel R_I + r_\pi}{(\beta_o + 1)} = 100k\Omega + 13k\Omega \parallel \frac{1.95k\Omega + 10.0k\Omega}{101} = 100k\Omega$$

$$\omega_3 = \frac{1}{10^{-5}(10^5)} = 1 \frac{\text{rad}}{\text{s}} \quad f_L \cong \frac{(2.94 + 1)}{2\pi} = 0.627 \text{Hz}$$

16.23



(a) Low Frequency:



Mid-band:

$$(b) g_m = \frac{2(0.1mA)}{0.75V} = 0.267mS \quad | \quad R_{in} = R_1 \parallel R_2 = 892\text{ k}\Omega \quad | \quad R_L = 12\text{ k}\Omega \parallel 100\text{ k}\Omega = 10.7\text{ k}\Omega$$

$$A_{mid} = \frac{R_{in}}{R_I + R_{in}} \frac{g_m R_L}{1 + g_m R_L} = 0.998 \frac{(0.267mS)(10.7\text{ k}\Omega)}{1 + (0.267mS)(10.7\text{ k}\Omega)} = +0.739 \quad (-2.62 \text{ dB})$$

$$\omega_I = \frac{1}{C_1(R_I + R_{in})} = \frac{1}{4.7 \times 10^{-6}(2\text{ k}\Omega + 892\text{ k}\Omega)} = 0.238 \frac{\text{rad}}{\text{s}}$$

$$\omega_3 = \frac{1}{C_3 \left[R_7 + \left(R_S \parallel \frac{1}{g_m} \right) \right]} = \frac{1}{10^{-7} \left[100\text{ k}\Omega + \left(12\text{ k}\Omega \parallel \frac{1}{0.267mS} \right) \right]} = 97.2 \frac{\text{rad}}{\text{s}}$$

$$f_L \cong \frac{1}{2\pi} (0.238 + 97.2) = 15.5 \text{ Hz}$$

$$(c) V_{DD} = V_{DS} + I_S R_S = 8.8V + 0.1mA(12\text{ k}\Omega) = 12.0 \text{ V}$$

16.24

$$\text{SCTC requires: } \omega_L \approx \sum_{i=1}^3 \frac{1}{R_{is} C_i} = 2\pi(500) = 3140 \frac{\text{rad}}{\text{s}}$$

$$\omega_1 = \frac{1}{(10^{-7} F)(2.43 M\Omega + 1 k\Omega)} = 4.11 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_2 = \frac{1}{(10^{-7} F)(43 k\Omega + 1 M\Omega)} = 9.59 \frac{\text{rad}}{\text{s}}$$

$\omega_1 + \omega_2 \ll \omega_L$ | ω_3 will be dominant $\rightarrow \omega_3 \approx \omega_L$

$$\omega_3 = \frac{1}{C_3 \left(R_S \left\| \frac{1}{g_m} \right. \right)} \quad | \quad g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(0.2 \text{mA})}{1 \text{V}} = 0.400 \text{mS} \quad | \quad \frac{1}{g_m} = 2.50 \text{k}\Omega$$

$$C_3 = \frac{1}{3140(13 k\Omega \| 2.5 k\Omega)} = 0.152 \mu\text{F} \rightarrow 0.15 \mu\text{F} \text{ from Appendix C}$$

16.25

$$\text{SCTC requires: } \omega_L \approx \sum_{i=1}^3 \frac{1}{R_{is} C_i} = 2\pi(100) = 628 \frac{\text{rad}}{\text{s}}$$

$$\omega_2 = \frac{1}{C_2(R_C + R_3)} = \frac{1}{(10^{-6} F)(2.2 k\Omega + 51 k\Omega)} = 18.8 \frac{\text{rad}}{\text{s}} \ll \omega_L \quad | \quad \omega_1 \text{ will be dominant} \rightarrow \omega_L \approx \omega_1$$

$$\omega_1 = \frac{1}{C_1 \left(R_I + R_E \left\| \frac{1}{g_m} \right. \right)} \quad | \quad \frac{1}{g_m} = \frac{1}{40(10^{-3})} = 25 \Omega$$

$$C_1 = \frac{1}{628(200 \Omega + 4.3 k\Omega \| 25 \Omega)} = 7.08 \mu\text{F} \rightarrow 6.8 \mu\text{F} \text{ nearest value in Appendix C}$$

Note: We might want to choose 8.2 μF to insure that $f_L \leq 100 \text{ Hz}$.

$$(b) \text{ SCTC requires: } \omega_L \approx \sum_{i=1}^3 \frac{1}{R_{is} C_i} = 2\pi(100) = 628 \frac{\text{rad}}{\text{s}}$$

$$\omega_2 = \frac{1}{(10^{-6} F)(220 k\Omega + 510 k\Omega)} = 1.37 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_1 \text{ will be dominant} \rightarrow \omega_L \approx \omega_1$$

$$\omega_1 = \frac{1}{C_1 \left(R_I + R_E \left\| \frac{1}{g_m} \right. \right)} \quad | \quad \frac{1}{g_m} = \frac{1}{40(10^{-5})} = 2.5 k\Omega$$

$$C_1 = \frac{1}{628(200 \Omega + 430 k\Omega \| 2.5 k\Omega)} = 0.592 \mu\text{F} \rightarrow 0.56 \mu\text{F} \text{ nearest value in Appendix C}$$

Note: We might want to use 0.68 μF to insure that $f_L \leq 100 \text{ Hz}$.

16.26

$$g_m = 40I_C = 40(0.164mA) = 6.56mS \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{100}{6.56mS} = 15.2k\Omega \quad | \quad r_o = \infty \text{ (V_A not given)}$$

SCTC requires: $\sum_{i=1}^3 \frac{1}{R_{is}C_i} = 2\pi(20) = 126 \frac{rad}{s}$

$$R_{1s} = R_I + (R_B \| r_\pi) = 1k\Omega + (75k\Omega \| 15.2k\Omega) = 13.6k\Omega \quad | \quad \omega_1 = \frac{1}{5 \times 10^{-6} (13.6k\Omega)} = 14.7$$

$$R_{3s} = R_C + R_3 = 43k\Omega + 43k\Omega = 86k\Omega \quad | \quad \omega_3 = \frac{1}{1 \times 10^{-6} (86k\Omega)} = 11.6$$

$$\omega_2 = 126 - 14.7 - 11.6 = 99.7 \frac{rad}{s} \quad | \quad R_{2s} = R_E \left\| \frac{(R_B \| R_I) + r_\pi}{\beta_o + 1} = 13k\Omega \right\| \frac{987\Omega + 15.2k\Omega}{101} = 158\Omega$$

$$C_2 \cong \frac{1}{99.7(158)} = 63.5 \mu F \rightarrow 68 \mu F \text{ from Appendix C}$$

16.27

SCTC requires: $\sum_{i=1}^3 \frac{1}{R_{is}C_i} = 2\pi(1) = 6.28 \frac{rad}{s}$

$$\text{However, } R_{3s} = R_3 + R_7 = 22k\Omega + 100k\Omega = 122k\Omega$$

$$\omega_3 = \frac{1}{1 \times 10^{-7} (122k\Omega)} = 82.0 \frac{rad}{s} > 6.28 \frac{rad}{s} \quad | \quad \text{The design goal cannot be met.}$$

It is not possible to force f_L below the limit set by C_3 .

16.28

SCTC requires: $\omega_L \cong \sum_{i=1}^3 \frac{1}{R_{is}C_i} = 2\pi(10) = 62.8 \frac{rad}{s} \quad | \quad R_G = R_1 \| R_2 = 892k\Omega$

$$\omega_1 = \frac{1}{C_1(R_I + R_G)} = \frac{1}{4.7 \times 10^{-6} (2k\Omega + 892k\Omega)} = 0.238 \frac{rad}{s} \quad | \quad \omega_L >> \omega_1 \rightarrow \omega_3 \text{ is dominant}$$

$$\omega_L \cong \omega_3 = \frac{1}{C_3 \left[R_7 + \left(R_S \left\| \frac{1}{g_m} \right\| \right) \right]} \quad | \quad \frac{1}{g_m} = \frac{0.75V}{2(0.1mA)} = 3.75k\Omega$$

$$C_3 = \frac{1}{62.8 [100k\Omega + (12k\Omega \| 3.75k\Omega)]} = 0.155 \frac{rad}{s} \rightarrow 0.15 \mu F \text{ using Appendix C}$$

16.29

SCTC requires: $\omega_L \approx \sum_{i=1}^3 \frac{1}{R_{is} C_i} = 2\pi(5) = 31.4 \frac{rad}{s}$

$$R_L = 13k\Omega \parallel 100k\Omega = 11.5k\Omega \quad | \quad r_\pi = \frac{100}{40(0.25mA)} = 10.0k\Omega$$

$$R_{ls} = R_I + R_B \left[r_\pi + (\beta_o + 1)R_L \right] = 2k\Omega + 75k\Omega \left[[0.0k\Omega + (101)11.5k\Omega] \right] = 72.5k\Omega$$

$$\omega_1 = \frac{1}{(72.5k\Omega)4.7 \times 10^{-6}} = 2.94 \frac{rad}{s} \quad | \quad \omega_3 = 31.4 - 2.94 = 28.5 \frac{rad}{s}$$

$$R_{3s} = R_7 + R_E \left[\frac{(R_B \parallel R_I) + r_\pi}{(\beta_o + 1)} \right] = 100k\Omega + 13k\Omega \left[\frac{1.95k\Omega + 10.0k\Omega}{101} \right] = 100k\Omega$$

$$C_3 = \frac{1}{28.5(100k\Omega)} = 0.351 \mu F \rightarrow 0.39 \mu F \text{ using the values from Appendix C.}$$

16.30

$$f_T = \frac{1}{2\pi} \left(\frac{g_m}{C_\pi + C_\mu} \right) \quad | \quad C_\pi = \frac{g_m}{2\pi f_T} - C_\mu \quad | \quad g_m = 40I_C$$

I_C	f_T	C_π	C_μ	$1/2\pi r_x C_\mu$
10 μA	50 MHz	0.773 pF	0.5 pF	1.59 GHz
100 μA	300 MHz	0.75 pF	1.37 pF	580 MHz
50 μA	1 GHz	2.93 pF	0.25 pF	3.19 GHz
10 mA	6.06 GHz	10 pF	0.500 pF	1.59 GHz
1 μA	3.18 MHz	1 pF	1 pF	795 MHz
1.18 mA	5 GHz	1 pF	0.5 pF	1.59 GHz

16.31

$$C_\pi = g_m \tau_F \quad | \quad C_\pi = \frac{g_m}{\omega_T} - C_\mu \quad | \quad V_{CB} = 5 - 0.7 = 4.3V \quad | \quad C_\mu = \frac{C_{\mu o}}{\sqrt{1 + \frac{V_{CB}}{\phi_{jc}}}} = \frac{2pF}{\sqrt{1 + \frac{4.3V}{0.9V}}} = 0.832pF$$

$$C_\pi = \frac{40(2 \times 10^{-3})}{2\pi(5 \times 10^8)} - 0.832pF = 24.6 pF \quad | \quad \tau_F = \frac{C_\pi}{g_m} = \frac{24.6 \times 10^{-12}}{40(2 \times 10^{-3})} = 0.308ns = 308 ps$$

16.32

$$f_T = \frac{1}{2\pi} \left(\frac{g_m}{C_{GS} + C_{GD}} \right) \quad | \quad g_m = \sqrt{2K_n I_D}$$

I _D	f _T	C _{GS}	C _{GD}
10 μA	15.9 MHz	1.5 pF	0.5 pF
250 μA	79.6 MHz	1.5 pF	0.5 pF
2.47 mA	250 MHz	1.5 pF	0.5 pF

16.33

$$(a) f_T = \frac{3 \mu_n (V_{GS} - V_{TN})}{2 L^2} = \frac{3}{2} \frac{600(0.25V)}{(10^{-4})^2} \frac{cm^2}{V-s} = 22.5 \text{ GHz}$$

$$(b) f_T = \frac{3 \mu_n (V_{GS} - V_{TN})}{2 L^2} = \frac{3}{2} \frac{250(0.25V)}{(10^{-4})^2} \frac{cm^2}{V-s} = 9.38 \text{ GHz}$$

$$(c) \text{ NMOS: } f_T = \frac{3 \mu_n (V_{GS} - V_{TN})}{2 L^2} = \frac{3}{2} \frac{600(0.25V)}{(10^{-5})^2} \frac{cm^2}{V-s} = 2.25 \text{ THz}$$

$$\text{PMOS: } f_T = \frac{3 \mu_n (V_{GS} - V_{TN})}{2 L^2} = \frac{3}{2} \frac{250(0.25V)}{(10^{-5})^2} \frac{cm^2}{V-s} = 938 \text{ GHz}$$

$$(d) \text{ NMOS: } f_T = \frac{3 \mu_n (V_{GS} - V_{TN})}{2 L^2} = \frac{3}{2} \frac{600(0.25V)}{(2.5 \times 10^{-6})^2} \frac{cm^2}{V-s} = 36.0 \text{ THz}$$

$$\text{PMOS: } f_T = \frac{3 \mu_n (V_{GS} - V_{TN})}{2 L^2} = \frac{3}{2} \frac{250(0.25V)}{(2.5 \times 10^{-6})^2} \frac{cm^2}{V-s} = 15.0 \text{ GHz}$$

16.34

$$(a) r_\pi = \frac{125(0.025V)}{1mA} = 3.13k\Omega \quad | \quad R_{in} = 7.5k\Omega \parallel (r_x + r_\pi) = 2.44k\Omega \quad | \quad R_L = 4.3k\Omega \parallel 100k\Omega = 4.12k\Omega$$

$$g_m = 40(10^{-3}) = 40mS \quad | \quad A_{mid} = -\frac{R_{in}}{R_I + R_{in}} g_m R_L = -\left(\frac{2.44k\Omega}{1k\Omega + 2.44k\Omega}\right)(40mS)(4.12k\Omega) = -117$$

$$(b) R_{in} = 7.5k\Omega \parallel r_\pi = 2.21k\Omega \quad | \quad A_{mid} = -\left(\frac{2.21k\Omega}{1k\Omega + 2.21k\Omega}\right)(40mS)(4.12k\Omega) = -113$$

16.35

$$r_\pi = \frac{125(0.025V)}{1mA} = 3.13k\Omega \quad | \quad g_m = 40(1mA) = 40mS \quad | \quad R_L = 3k\Omega \quad | \quad 47k\Omega = 2.82k\Omega$$

$$R_{in} = R_B \left[r_x + r_\pi + (\beta_o + 1)R_L \right] = 100k\Omega \left[0.35k\Omega + 3.13k\Omega + (126)2.82k\Omega \right] = 78.2k\Omega$$

$$(a) A_{mid} = A_{mid} = \frac{R_{in}}{R_I + R_{in}} \left[\frac{(\beta_o + 1)R_L}{r_x + r_\pi + (\beta_o + 1)R_L} \right] = \frac{78.2k\Omega}{1k\Omega + 78.2k\Omega} \left[\frac{126(2820)}{350 + 3130 + 126(2820)} \right] = 0.978$$

$$(b) R_{in} = R_B \left[r_\pi + (\beta_o + 1)R_L \right] = 100k\Omega \left[3.13k\Omega + (126)2.82k\Omega \right] = 78.2k\Omega$$

$$A_{mid} = \frac{78.2k\Omega}{1k\Omega + 78.2k\Omega} \left[\frac{126(2820)}{350 + 3130 + 126(2820)} \right] = 0.978$$

16.36

$$r_\pi = \frac{125(0.025V)}{0.1mA} = 31.25k\Omega \quad | \quad g_m = 40(0.1mA) = 4mS$$

$$R_{in} = R_E \left[\frac{r_x + r_\pi}{\beta_o + 1} \right] = 43k\Omega \left[\frac{200\Omega + 31.25k\Omega}{126} \right] = 248\Omega \quad | \quad R_L = 22k\Omega \quad | \quad 75k\Omega = 17.0k\Omega$$

$$(a) A_{mid} = \frac{R_{in}}{R_I + R_{in}} g_m R_L = \frac{248\Omega}{100\Omega + 248\Omega} (4mS)(17.0k\Omega) = 48.5$$

$$(b) R_{in} = R_E \left[\frac{r_\pi}{\beta_o + 1} \right] = 43k\Omega \left[\frac{31.25k\Omega}{126} \right] = 247\Omega \quad | \quad A_{mid} = \frac{247\Omega}{100\Omega + 247\Omega} (4mS)(17.0k\Omega) = 48.4$$

16.37

$$(a) s^2 + 5100s + 500000 \quad | \quad s_1 \cong -\frac{5100}{1} = -5100 \quad | \quad s_2 \cong -\frac{5 \times 10^5}{5100} = -98.0$$

$$s = \frac{-5100 \pm \sqrt{5100^2 - 4(5 \times 10^5)}}{2} = \frac{-5100 \pm 4900}{2} \rightarrow -100, -5000 \quad | \quad 2\% \text{ error}$$

$$(b) 2s^2 + 700s + 30000 = 2(s^2 + 350s + 15000)$$

$$s_1 \cong -\frac{350}{1} = -350 \quad | \quad s_2 \cong -\frac{15000}{350} = -42.9$$

$$s = \frac{-350 \pm \sqrt{350^2 - 4(15000)}}{2} = \frac{-350 \pm 250}{2} \rightarrow -50, -300 \quad | \quad 14\% \text{ error}$$

$$(c) 3s^2 + 3300s + 300000 \quad | \quad s_1 \cong -\frac{3300}{3} = -1100 \quad | \quad s_2 \cong -\frac{3 \times 10^5}{3300} = -90.9$$

$$s = \frac{-3300 \pm \sqrt{3300^2 - 4(3)(3 \times 10^5)}}{6} = \frac{-3300 \pm 2700}{6} \rightarrow -100, -1000 \quad | \quad 11\% \text{ error}$$

$$(d) 0.5s^2 + 300s + 40000 = 0.5(s^2 + 600s + 80000)$$

$$s_1 \cong -\frac{600}{1} = -600 \quad | \quad s_2 \cong -\frac{80000}{600} = -133$$

$$s = \frac{-600 \pm \sqrt{600^2 - 4(80000)}}{2} = \frac{-600 \pm 200}{2} \rightarrow -200, -400 \quad | \quad 34\%, 50\% \text{ error}$$

16.38

$$s^3 + 1110s^2 + 111000s + 1000000$$

$$s_1 \cong -\frac{1110}{1} = -1110 \quad | \quad s_2 \cong -\frac{111000}{1110} = -100 \quad | \quad s_3 \cong -\frac{1000000}{111000} = -9.01$$

Factoring the polynomial: $s^3 + 1110s^2 + 111000s + 1000000 = (s+10)(s+100)(s+1000)$

$s = -1000, -100, -10 \quad | \quad 11\% \text{ error in } s_1, 10\% \text{ error in } s_3$

In MATLAB: roots([1 1110 111000 1000000])

16.39

$$f(s) = s^6 + 142s^5 + 4757s^4 + 58230s^3 + 256950s^2 + 398000s + 300000$$

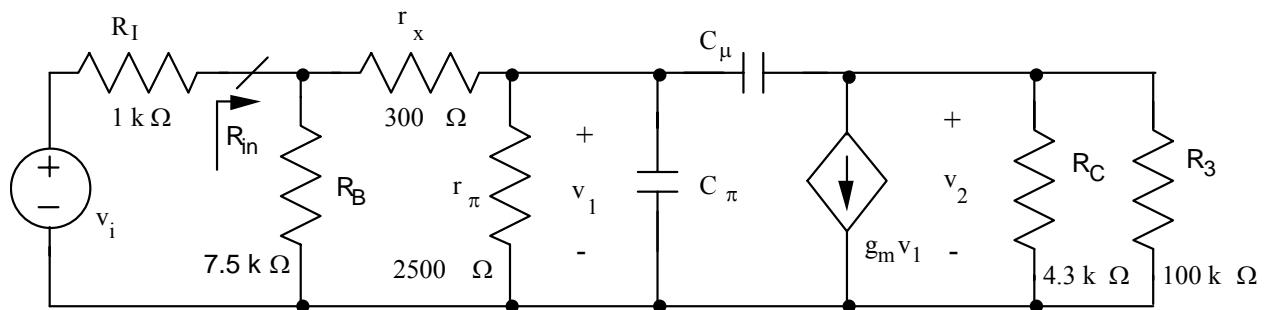
$$f'(s) = 6s^5 + 710s^4 + 19028s^3 + 174690s^2 + 513900s + 398000$$

$$s^{i+1} = s^i - \frac{f(s^i)}{f'(s^i)} \quad | \quad \text{Using a spreadsheet, four real roots are found: } -100, -20, -15, -5$$

Using MATLAB: roots([1 142 4757 58230 256950 398000 300000])

ans = -100, -20, -15, -5, -1+i, -1-i

16.40



$$(a) r_\pi = \frac{100(0.025)}{0.001} = 2500\Omega \quad | \quad C_\mu = 0.75 pF \quad | \quad C_\pi = \frac{40(10^{-3})}{2\pi(5 \times 10^8)} - 0.75 pF = 12.0 pF$$

$$R_{in} = 7.5k\Omega \parallel (r_x + r_\pi) = 2.03k\Omega \quad | \quad R_L = 4.3k\Omega \parallel 100k\Omega = 4.12k\Omega \quad | \quad g_m = 40(10^{-3}) = 40mS$$

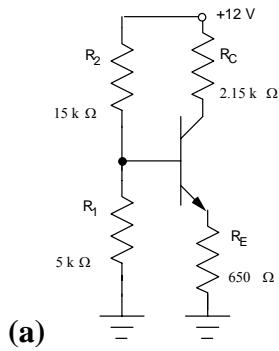
$$A_{mid} = -\left(\frac{R_{in}}{R_I + R_{in}}\right)\left(\frac{r_\pi}{r_x + r_\pi}\right)g_m R_L = -\left(\frac{2.03k\Omega}{1k\Omega + 2.03k\Omega}\right)\left(\frac{2500\Omega}{300\Omega + 2500\Omega}\right)(40mS)(4.12k\Omega) = -98.6$$

$$\omega_H = \frac{1}{r_{\pi o} C_T} \quad | \quad r_{\pi o} = r_\pi \parallel [r_x + (R_B \parallel R_I)] = 2500 \parallel [300 + (7500 \parallel 1000)] = 803 \Omega$$

$$C_T = 12.0 + 0.75 \left[1 + 40(10^{-3})(4120) + \frac{4120}{803} \right] = 140 pF \quad | \quad f_H = \frac{1}{2\pi(803)(1.4 \times 10^{-10})} = 1.42 MHz$$

$$(b) GBW = 98.6(1.42 MHz) = 140 MHz$$

16.41



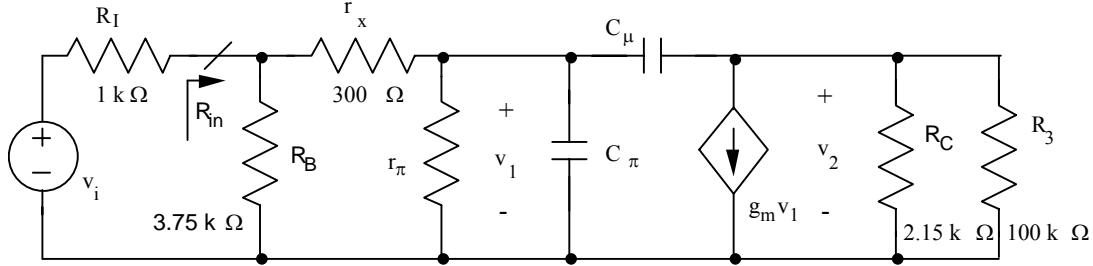
(a)

$$V_{EQ} = 12V \frac{5k\Omega}{5k\Omega + 15k\Omega} = 3V \quad | \quad R_{EQ} = 5k\Omega \parallel 15k\Omega = 3.75k\Omega$$

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} = 100 \frac{(3 - 0.7)V}{3.75k\Omega + (101)(0.65k\Omega)} = 3.31 \text{ mA}$$

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E = 12 - (3.31 \text{ mA}) \left(2.15k\Omega + \frac{101}{100} 0.65k\Omega \right) = 2.71 \text{ V} \quad | \quad \text{Q-Point: } (3.31 \text{ mA}, 2.71 \text{ V})$$

(b)



Note: As designers, we are free to change the amplifier design, but we typically cannot change the characteristics of the source and load resistances.

$$r_\pi = \frac{100(0.025)}{3.31 \text{ mA}} = 755 \Omega \quad | \quad C_\mu = 0.75 \text{ pF} \quad | \quad C_\pi = \frac{40(3.31 \times 10^{-3})}{2\pi(5 \times 10^8)} - 0.75 \text{ pF} = 41.4 \text{ pF}$$

$$R_{in} = 3.75k\Omega \parallel (r_x + r_\pi) = 823\Omega \quad | \quad R_L = 2.15k\Omega \parallel 100k\Omega = 2.11k\Omega$$

$$g_m = 40(3.31 \times 10^{-3}) = 132 \text{ mS}$$

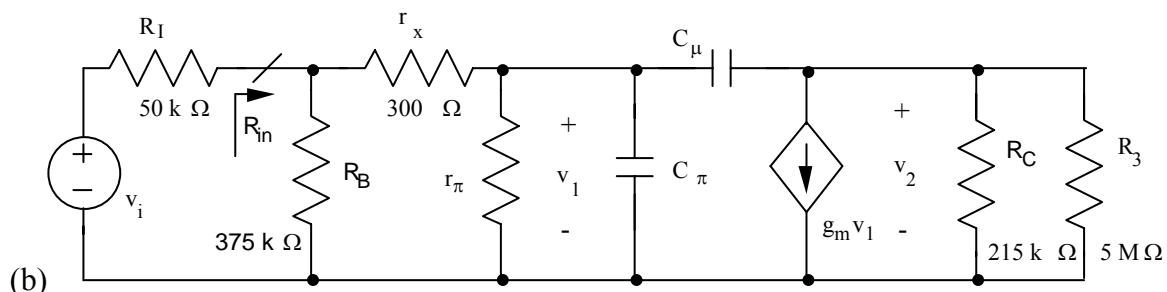
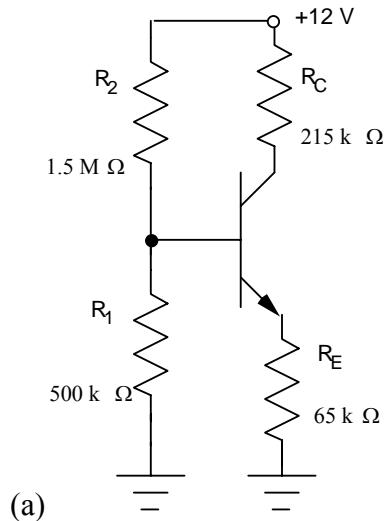
$$A_{mid} = -\frac{R_{in}}{R_I + R_{in}} \left(\frac{r_\pi}{r_x + r_\pi} \right) g_m R_L = -\left(\frac{823\Omega}{1000\Omega + 823\Omega} \right) \left(\frac{755\Omega}{300\Omega + 755\Omega} \right) (132 \text{ mS})(2.11k\Omega) = -90.0$$

$$\omega_H = \frac{1}{r_\pi C_T} \quad | \quad r_{\pi o} = r_\pi \parallel [r_x + (R_B \parallel R_I)] = 755\Omega \parallel [300 + (3.75k\Omega \parallel 1k\Omega)] = 260\Omega$$

$$C_T = 41.4 + 0.75 \left[1 + (132 \text{ mS})(2.11k\Omega) + \frac{2.11k\Omega}{0.260k\Omega} \right] = 312 \text{ pF} \quad | \quad f_H = \frac{1}{2\pi(260\Omega)(3.12 \times 10^{-10} \text{ F})} = 1.96 \text{ MHz}$$

$$(c) GBW = 90.0(1.96 \text{ MHz}) = 176 \text{ MHz} \quad | \quad GBW \leq \frac{1}{2\pi \left(\frac{1}{r_x C_\mu} \right)} = \frac{1}{2\pi(300\Omega)(0.75 \text{ pF})} = 707 \text{ MHz}$$

16.42



$$V_{EQ} = 12V \frac{500k\Omega}{500k\Omega + 1.5M\Omega} = 3V \quad | \quad R_{EQ} = 500k\Omega \parallel 1.5M\Omega = 3.75k\Omega$$

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} = 100 \frac{(3 - 0.7)V}{375k\Omega + (101)(65k\Omega)} = 33.1 \mu A$$

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E = 12 - (33.1 \mu A) \left(215k\Omega + \frac{101}{100} 65k\Omega \right) = 2.71 V \quad | \quad \text{Q-Point: } (33.1 \mu A, 2.71 V)$$

Note: As designers, we are free to change the amplifier design, but we typically cannot change the characteristics of the source and load resistances. However, the problem statement indicated changing all resistors.

$$r_\pi = \frac{100(0.025)}{33.1\mu A} = 75.5k\Omega \quad | \quad C_\mu = 0.75 pF \quad | \quad C_\pi = \frac{40(33.1 \times 10^{-6})}{2\pi(5 \times 10^8)} - 0.75 pF = -0.329 pF \text{ - not possible.}$$

The constant f_T model is breaking down at low currents. Set $C_\pi = 0$

$$R_{in} = 375k\Omega \parallel (r_x + r_\pi) = 63.1k\Omega \quad | \quad R_L = 215k\Omega \parallel 5M\Omega = 211k\Omega \quad | \quad g_m = 40(33.1 \times 10^{-6}) = 1.32mS$$

$$A_{mid} = -\frac{R_{in}}{R_I + R_{in}} \left(\frac{r_\pi}{r_x + r_\pi} \right) g_m R_L = -\left(\frac{63.1k\Omega}{50k\Omega + 63.1k\Omega} \right) \left(\frac{75.5k\Omega}{300\Omega + 75.5k\Omega} \right) (1.32mS)(211k\Omega) = -155.0$$

$$\omega_H = \frac{1}{r_{\pi o} C_T} \quad | \quad r_{\pi o} = r_\pi \parallel [r_x + (R_B \parallel R_I)] = 75.5k\Omega \parallel [300 + (375k\Omega \parallel 50k\Omega)] = 28.0k\Omega$$

$$C_T = 0 + 0.75 \left[1 + (1.32mS)(211k\Omega) + \frac{211k\Omega}{8.86k\Omega} \right] = 228pF \quad | \quad f_H = \frac{1}{2\pi(28.0k\Omega)(2.28 \times 10^{-10} F)} = 24.9 kHz$$

$$(c) GBW = 155(24.9kHz) = 3.86 MHz \quad | \quad GBW \leq \frac{1}{2\pi} \left(\frac{1}{r_x C_\mu} \right) = \frac{1}{2\pi(300\Omega)(0.75 pF)} = 707 MHz$$

16.43

$$R_{in} = R_1 \parallel R_2 = 4.3 M\Omega \parallel 5.6 M\Omega = 2.43 M\Omega \quad | \quad R_L = 43 k\Omega \parallel 470 k\Omega = 39.4 k\Omega$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(0.2mA)}{1} = 0.400mS \quad |$$

$$A_{mid} = -\frac{R_{in}}{R_I + R_{in}} g_m R_L = -\frac{2.43 M\Omega}{2k\Omega + 2.43 M\Omega} 0.400mS (39.4 k\Omega) = -15.7$$

$$f_H = \frac{1}{2\pi r_{ao} C_T} \quad | \quad r_{ao} = R_1 \parallel R_2 \parallel R_I = 2.00 k\Omega$$

$$C_T = 2.5 pF + 2.5 pF \left[1 + (0.400mS)(39.4 k\Omega) + \frac{39.4 k\Omega}{2k\Omega} \right] = 93.7 pF$$

$$f_H = \frac{1}{2\pi(2k\Omega)(93.7 \times 10^{-12} F)} = 849 \text{ kHz}$$

16.44

*Problem 16.44 - Common-Source Amplifier

VDD 7 0 DC 0

VS 1 0 AC 1

RS 1 2 2K

C1 2 3 0.1UF

R1 3 0 4.3MEG

R2 3 7 5.6MEG

RD 7 5 43K

R4 4 0 13K

C3 4 0 10UF

C2 5 6 0.1UF

R3 6 0 1MEG

*Small-Signal FET Model

GM 5 4 3 4 0.4MS

CGS 3 4 2.5PF

CGD 3 5 2.5PF

*

.AC DEC 20 1 10MEG

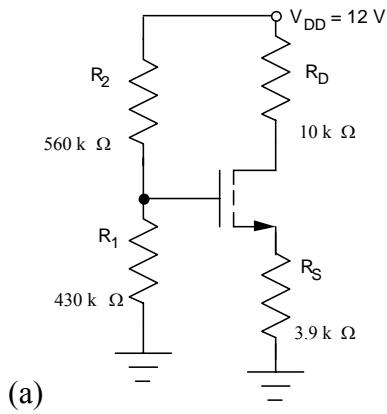
.PRINT AC VM(6)

.PROBE

.END

Results: $A_{mid} = -15.7$, $f_L = 8.52 \text{ Hz}$, $f_H = 866 \text{ MHz}$

16.45



(a)

$$V_{EQ} = 12V \frac{430k\Omega}{430k\Omega + 560k\Omega} = 5.21V \quad | \quad R_{EQ} = 430k\Omega \parallel 560k\Omega = 243k\Omega$$

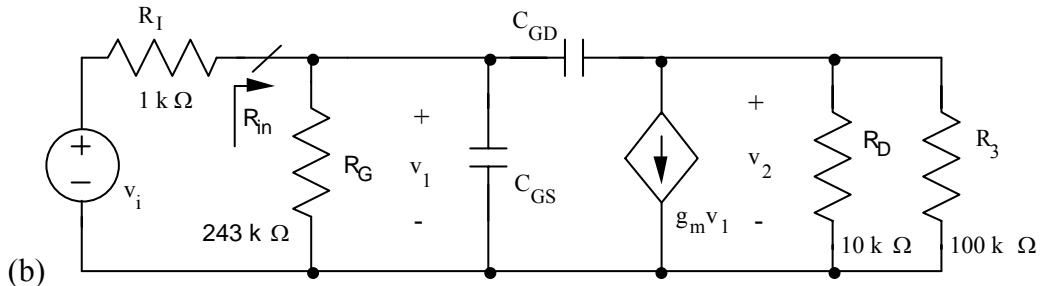
$$\text{Assume active region operation: } I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 \quad | \quad V_{EQ} = V_{GS} + I_D R_S$$

$$5.21 = V_{GS} + 3.9k\Omega \left(\frac{0.5mA}{2} \right) (V_{GS} - 1)^2 \rightarrow V_{GS} = 2.629V \text{ and } I_D = 663\mu A$$

$$V_{DS} = V_{DD} - I_D R_D - I_S R_S = 12 - (663\mu A)(13k\Omega + 3.9k\Omega) = 0.795 V$$

The transistor is not in pinch off! Reduce R_D to 10 kΩ.

$$V_{DS} = V_{DD} - I_D R_D - I_S R_S = 12 - (663\mu A)(10k\Omega + 3.9k\Omega) = 2.78 V \text{ - Active region is correct.}$$



(b)

$$R_{in} = R_I \parallel R_2 = 430k\Omega \parallel 560k\Omega = 243k\Omega \quad | \quad R_L = 10k\Omega \parallel 100k\Omega = 9.09k\Omega$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(0.663mA)}{1} = 1.33mS$$

$$A_{mid} = -\frac{R_{in}}{R_I + R_{in}} g_m R_L = -\frac{243k\Omega}{1k\Omega + 243k\Omega} (1.33mS)(9.09k\Omega) = -12.0$$

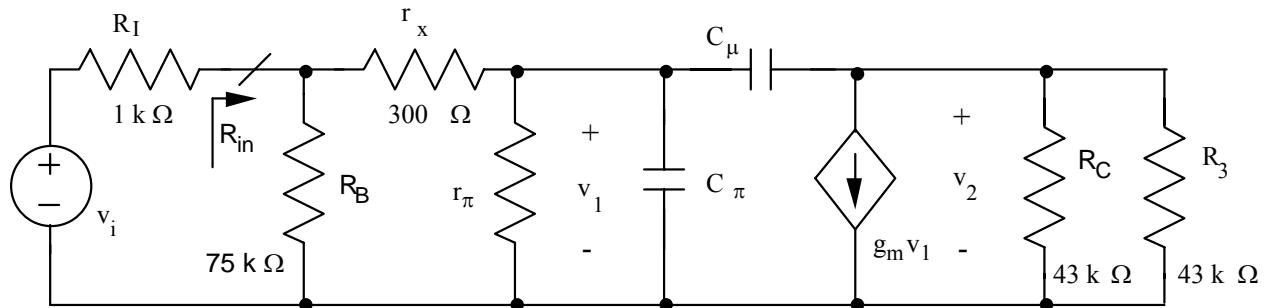
$$f_H = \frac{1}{2\pi r_{\pi o} C_T} \quad | \quad r_{\pi o} = R_I \parallel R_2 \parallel R_I = 243k\Omega \parallel 1k\Omega = 0.996k\Omega$$

$$C_T = 2.5pF + 2.5pF \left[1 + (1.33mS)(9.09k\Omega) + \frac{9.09k\Omega}{0.996k\Omega} \right] = 58.1pF$$

$$f_H = \frac{1}{2\pi(0.996k\Omega)(58.1 \times 10^{-11} F)} = 2.75 MHz$$

$$(c) GBW = 12.0(2.75 MHz) = 33 MHz$$

16.46



$$g_m = 40I_C = 40(0.164mA) = 6.56mS \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{100}{6.56mS} = 15.2k\Omega \quad | \quad r_o = \infty \quad (V_A \text{ not given})$$

$$R_{in} = R_I \| R_2 \| r_\pi = 100k\Omega \| 300k\Omega \| 15.2k\Omega = 12.6k\Omega \quad | \quad R_L = R_C \| R_3 = 43k\Omega \| 43k\Omega = 21.5k\Omega$$

$$A_{mid} = -\frac{R_{in}}{R_I + R_{in}} g_m R_L = -\frac{12.6k\Omega}{1k\Omega + 12.6k\Omega} (6.56mS)(21.5k\Omega) = -131$$

$$C_\pi = \frac{g_m}{\omega_T} - C_\mu = \frac{6.56mS}{2\pi(5 \times 10^8 Hz)} - 0.75 = 1.34 pF$$

$$\omega_H = \frac{1}{r_{\pi o} C_T} \quad | \quad r_{\pi o} = r_\pi \left(r_x + R_I \| R_2 \| R_I \right) = 15.2 k\Omega \left(300 + 987 \right) = 1.19 k\Omega$$

$$C_T = C_\pi + C_\mu \left(1 + g_m R_L + \frac{R_L}{r_{\pi o}} \right) = 1.34 pF + 0.75 pF \left[1 + 6.56mS(21.5k\Omega) + \frac{21.5k\Omega}{1.19k\Omega} \right] = 121 pF$$

$$f_H \equiv \frac{1}{2\pi(1.19k\Omega)(1.21 \times 10^{-10} F)} = 1.10 MHz$$

16.47

*Problem 16.47 - Common-Emitter Amplifier

VCC 7 0 DC 0

VS 1 0 AC 1

RS 1 2 1K

C1 2 3 5UF

R1 3 0 300K

R2 3 7 100K

RC 5 0 43K

R4 7 4 13K

C2 7 4 22UF

C3 5 6 1UF

R3 6 0 43K

*Small-signal Model for the BJT

GM 5 4 8 4 6.56MS

RX 3 8 0.3K

RPI 8 4 15.24K

CPI 8 4 1.34PF

CU 8 5 0.75PF

*

.AC DEC 100 1 10MEG

.PRINT AC VM(6)

.PROBE

.END

Results: $A_{\text{mid}} = -128$, $f_L = 47 \text{ Hz}$, $f_H = 1.10 \text{ MHz}$

16.48

(a) See Eqs. (16.88 - 16.96).

$$\begin{bmatrix} I_s(s) \\ 0 \end{bmatrix} = \begin{bmatrix} s(C_\pi + C_\mu) + g_{\pi o} & -sC_\mu \\ -(sC_\mu - g_m) & s(C_\mu + C_L) + g_L \end{bmatrix} \begin{bmatrix} V_1(s) \\ V_2(s) \end{bmatrix}$$

$$\Delta = s^2 [C_\pi(C_\mu + C_L) + C_\mu C_L] + s [C_\pi g_L + C_\mu(g_m + g_{\pi o} + g_L) + C_L g_{\pi o}] + g_L g_{\pi o}$$

$$(b) \omega_{p1} \equiv \frac{g_L g_{\pi o}}{C_\pi g_L + C_\mu(g_m + g_{\pi o} + g_L) + C_L g_{\pi o}} = \frac{1}{r_{\pi o} \left[C_\pi + C_\mu(1 + g_m R_L) + (C_\mu + C_L) \frac{R_L}{r_{\pi o}} \right]}$$

$$\omega_{p2} \equiv \frac{C_\pi g_L + C_\mu(g_m + g_{\pi o} + g_L) + C_L g_{\pi o}}{C_\pi(C_\mu + C_L) + C_\mu C_L} = \frac{g_m}{C_\pi \left(1 + \frac{C_L}{C_\mu} \right) + C_L}$$

(c) The three capacitors form a loop, and there are only two independent voltages among the three capacitors.

16.49

$$C_T = C_\pi + C_\mu(1 + g_m R_L) = 20 \text{ pF} + 1 \text{ pF} [1 + 40(1 \text{ mA})(1 \text{ k}\Omega)] = 61 \text{ pF}$$

$$f_T = \frac{1}{2\pi} \left(\frac{g_m}{C_\pi + C_\mu} \right) = \frac{1}{2\pi} \left[\frac{40(1 \text{ mA})}{20 \text{ pF} + 1 \text{ pF}} \right] = 303 \text{ MHz}$$

16.50

$$(a) Y_{in} = \frac{1+A}{Z(s)} = \frac{1+A}{\frac{1}{sC}} = sC(1+A) \quad | \quad C_{in} = C(1+A) = 10^{-10} F(1+10^5) = 10 \mu F$$

$$(b) Z_{in} = \frac{1}{Y_{in}} = \frac{Z(s)}{1+A(s)} = \frac{10^5}{1+\frac{10^6}{s+10}} = 10^5 \frac{s+10}{s+10+10^6} \cong 10^5 \frac{s+10}{s+10^6}$$

Using MATLAB: $Z_{in}(j2000\pi) = (4.95 + j6.28)\Omega$

$$Z_{in}(j10^5\pi) = (8.98 + j28.6)k\Omega \quad | \quad Z_{in}(j2\pi \times 10^6) = (97.5 + j15.5)k\Omega$$

16.51

$$(a) A_v(s) = \frac{\left(\frac{1}{RC}\right) \frac{A(s)}{1+A(s)}}{s + \frac{1}{RC[1+A(s)]}} \quad | \quad A(s) = \frac{10A_o}{s+10} \quad | \quad A_v(s) = \left(\frac{1}{RC}\right) \frac{\frac{10A_o}{s+10}}{s + \frac{1}{RC\left(1+\frac{10A_o}{s+10}\right)}}$$

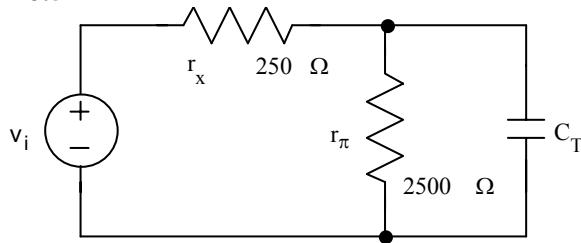
$$A_v(s) = \left(\frac{1}{RC}\right) \frac{10A_o}{s^2 + s(1+A_o)10 + \frac{s+10}{RC}} = \frac{\left(\frac{10A_o}{RC}\right)}{s^2 + s\left[\frac{1}{RC} + 10(1+A_o)\right] + \frac{10}{RC}}$$

$$A_v(s) = \frac{\left(\frac{10^6}{RC}\right)}{s^2 + s\left[\frac{1}{RC} + 10^6\right] + \frac{10}{RC}} \cong \frac{\left(\frac{10^6}{RC}\right)}{(s+10^6)\left(s + \frac{1}{10^5 RC}\right)}; \omega_L = \frac{1}{10^5 RC}$$

$$(b) A_v(s) = \frac{\left(\frac{10^7}{RC}\right)}{s^2 + s\left[\frac{1}{RC} + 10^7\right] + \frac{10}{RC}} \cong \frac{\left(\frac{10^6}{RC}\right)}{(s+10^7)\left(s + \frac{1}{10^6 RC}\right)}; \omega_L = \frac{1}{10^6 RC}$$

$$(c) \lim_{A_o \rightarrow \infty} A_v(s) = \frac{\left(\frac{10A_o}{RC}\right)}{10A_o s} = \frac{1}{sRC}$$

16.52



$$r_{\pi o} = 2500 \Omega \| 250 \Omega = 227 \Omega \quad | \quad C_T = 15 + 1 \left[1 + 0.04(2500) + \frac{2500}{227} \right] = 127 \text{ pF}$$

$$(a) \text{ At } 1 \text{ kHz, } Z_C = \frac{1}{j(2\pi)(10^3)(127 \text{ pF})} = -j(1.25 \times 10^6)$$

Using MATLAB: $Z = 250 + \frac{2500Z_C}{2500 + Z_C} = (2750 - j4.99) \Omega$ | SPICE: $(2750 - j4.56) \Omega$

$$(b) \text{ At } 50 \text{ kHz, } Z_C = \frac{1}{j(2\pi)(5 \times 10^4)(127 \text{ pF})} = -j2.51 \times 10^4 \Omega$$

Using MATLAB: $Z = 250 + \frac{2500Z_C}{2500 + Z_C} = (2730 - j247) \Omega$ | SPICE: $(2730 - j226) \Omega$

$$(c) \text{ At } 1 \text{ MHz, } Z_C = \frac{1}{j(2\pi)(10^6)(127 \text{ pF})} = -j(12.53)$$

Using MATLAB: $Z = 250 + \frac{2500Z_C}{2500 + Z_C} = (752 - j1000) \Omega$ | SPICE: $(836 - j1040) \Omega$

(d) *Problem 16.52 - Common-Emitter Amplifier

IS 0 1 AC 1

RX 1 2 0.25K

RPI 2 0 2.5K

CPI 2 0 15PF

CU 2 3 1PF

GM 3 0 2 0 40MS

RL 3 0 2.5K

.AC LIN 1 1KHZ 1KHZ

*.AC LIN 1 50KHZ 50KHZ

*.AC LIN 1 1MEG 1MEG

.PRINT AC VR(1) VI(1) VM(1) VP(1)

.END

Note that the C_T approximation does not provide as good an estimate of Z_{in} at high frequencies (note the discrepancy at 1 MHz).

16.53

$A_{mid} = 39.2 \text{ dB, } f_L = 0 \text{ Hz, } f_H = 5.53 \text{ MHz}$

16.54

$$(a) g_m = 40I_C = 40(1mA) = 40.0mS \mid r_\pi = \frac{\beta_o V_T}{I_C} = \frac{125(0.025)}{1mA} = 3.13k\Omega \mid r_o = \infty (V_A \text{ not given})$$

$$r_{\pi o} = r_\pi \left[R_x + (R_B \| R_I) \right] = 3.13k\Omega \left[(500 + (7.5k\Omega \| 1k\Omega)) \right] = 959\Omega \mid R_L = R_C \| R_3 = 4.3k\Omega \| 100k\Omega = 4.12k\Omega$$

$$C_\pi = \frac{g_m}{\omega_T} - C_\mu = \frac{40.0mS}{2\pi(5 \times 10^8 Hz)} - 0.75 pF = 12.0 pF \mid f_H \cong \frac{1}{2\pi r_{\pi o} C_T}$$

$$C_T = C_\pi + C_\mu \left(1 + g_m R_L + \frac{R_L}{r_{\pi o}} \right) = 12.0 pF + 0.75 pF \left[1 + 40.0mS(4.12k\Omega) + \frac{4.12k\Omega}{0.959k\Omega} \right] = 140 pF$$

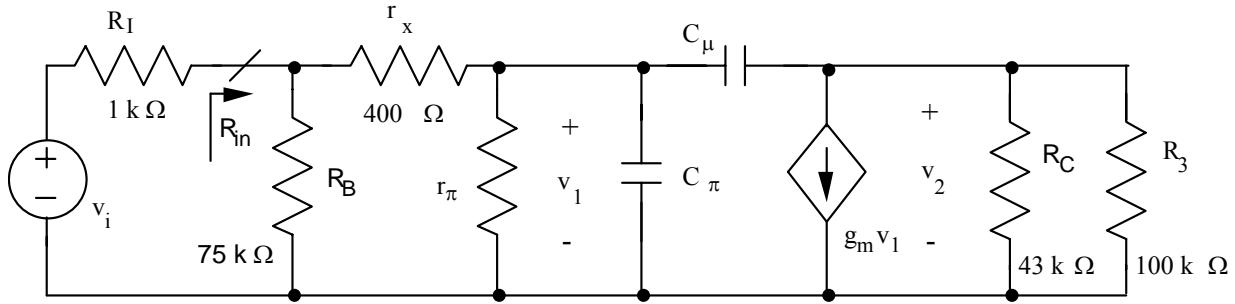
$$f_H \cong \frac{1}{2\pi(959\Omega)(1.40 \times 10^{-10} F)} = 1.19 MHz$$

$$(b) r_{\pi o} = r_\pi \left[R_x + (R_B \| R_I) \right] = 3.13k\Omega \left[(0 + (7.5k\Omega \| 1k\Omega)) \right] = 688\Omega$$

$$C_T = 12.0 pF + 0.75 pF \left[1 + 40.0mS(4.12k\Omega) + \frac{4.12k\Omega}{0.688k\Omega} \right] = 141 pF$$

$$f_H \cong \frac{1}{2\pi(688\Omega)(1.41 \times 10^{-10} F)} = 1.64 MHz$$

16.55



$$(a) g_m = 40I_C = 40(0.1mA) = 4.00mS \quad | \quad r_\pi = \frac{\beta_o V_T}{I_C} = \frac{100(0.025)}{0.1mA} = 25k\Omega \quad | \quad r_o = \infty \quad (V_A \text{ not given})$$

$$r_{\pi o} = r_\pi \left[r_x + (R_B \| R_I) \right] = 25k\Omega \left[(400 + (75k\Omega \| 1k\Omega)) \right] = 1.31k\Omega$$

$$R_{in} = R_I \| R_2 \left[(r_x + r_\pi) \right] = 100k\Omega \left[300k\Omega \parallel 25.4k\Omega \right] = 19.0k\Omega \quad | \quad R_L = R_C \| R_3 = 43k\Omega \parallel 100k\Omega = 30.1k\Omega$$

$$A_{mid} = -\frac{R_{in}}{R_I + R_{in}} g_m R_L = -\frac{19.0k\Omega}{1k\Omega + 19.0k\Omega} (4.00mS)(30.1k\Omega) = -114$$

$$C_\pi = \frac{g_m}{\omega_T} - C_\mu = \frac{4.00mS}{2\pi(5 \times 10^8 Hz)} - 0.75pF = 0.523pF \quad | \quad f_H \approx \frac{1}{2\pi r_{\pi o} C_T}$$

$$C_T = C_\pi + C_\mu \left(1 + g_m R_L + \frac{R_L}{r_{\pi o}} \right) = 0.523pF + 0.75pF \left[1 + 4.00mS(30.1k\Omega) + \frac{30.1k\Omega}{1.31k\Omega} \right] = 109pF$$

$$f_H \approx \frac{1}{2\pi(1.31k\Omega)(1.09 \times 10^{-10} F)} = 1.12 MHz$$

$$(b) GBW = 114(1.12 MHz) = 128 MHz \quad | \quad \frac{1}{2\pi r_x C_\mu} = \frac{1}{2\pi(400\Omega)(0.75pF)} = 531 MHz$$

16.56

$$R_{in} = R_I \| R_2 = 4.3M\Omega \parallel 5.6M\Omega = 2.43M\Omega \quad | \quad R_L = 43k\Omega \parallel 470k\Omega = 39.4k\Omega$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(0.2mA)}{1} = 0.400mS \quad |$$

$$A_{mid} = -\frac{R_{in}}{R_I + R_{in}} g_m R_L = -\frac{2.43M\Omega}{2k\Omega + 2.43M\Omega} 0.400mS(39.4k\Omega) = -15.7$$

$$f_H = \frac{1}{2\pi r_{\pi o} C_T} \quad | \quad r_{\pi o} = R_I \| R_2 \| R_I = 2.00k\Omega$$

$$C_T = 5pF + 2pF \left[1 + (0.400mS)(39.7k\Omega) + \frac{39.7k\Omega}{2k\Omega} \right] = 78.5pF$$

$$f_H = \frac{1}{2\pi(2k\Omega)(78.5 \times 10^{-12} F)} = 1.01 MHz \quad | \quad GBW = 15.7(1.01 MHz) = 15.9 MHz$$

16.57

Problem 16.57 should refer to Fig. 16.34, or Fig. 16.31.

$$f_H = \frac{1}{2\pi r_{\text{ao}} C_T} = \frac{1}{2\pi(656\Omega)C_T} \quad | \quad C_T = \frac{1}{2\pi(656\Omega)(5\text{MHz})} = 48.5\text{ pF}$$

$$C_T = C_\pi + C_\mu \left[1 + g_m R_L + \frac{R_L}{r_{\text{ao}}} \right] \quad | \quad R_L \left(g_m + \frac{1}{r_{\text{ao}}} \right) = \frac{C_T - C_\pi}{C_\mu} - 1 = \frac{48.5\text{ pF} - 19.9\text{ pF}}{0.5\text{ pF}} - 1 = 56.2$$

$$R_L = \frac{56.2}{0.064S + \frac{1}{656\Omega}} = 858\Omega \quad | \quad R_L = R_C \parallel 100k\Omega \rightarrow R_C = 865\Omega$$

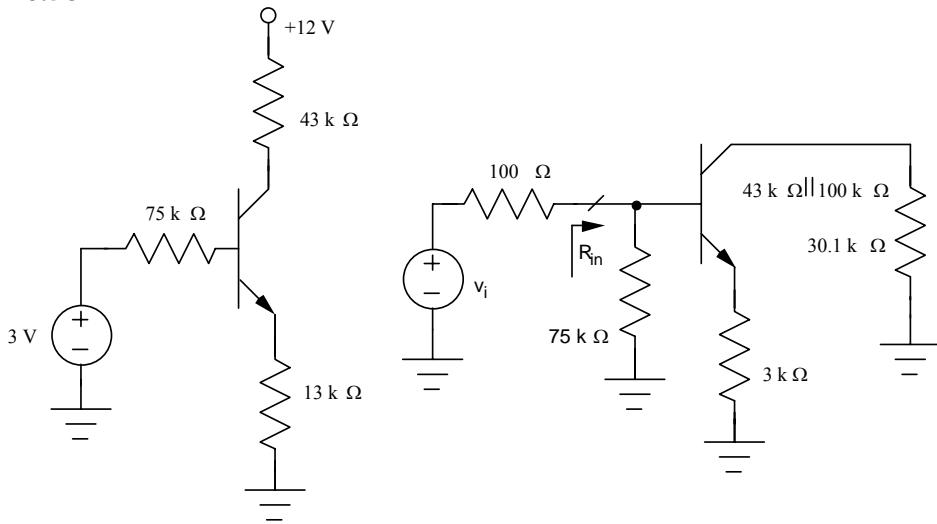
$$A_{\text{mid}} = -\frac{100(858\Omega)}{882\Omega + 250\Omega + 1560\Omega} = -31.9 \quad | \quad GBW = 31.9(5\text{MHz}) = 160\text{ MHz}$$

The nearest 5% value is $R_C = 820\Omega$ | $R_L = 820\Omega \parallel 100k\Omega = 813\Omega$

$$A_{\text{mid}} = -\frac{100(813\Omega)}{882\Omega + 250\Omega + 1560\Omega} = -30.2 \quad | \quad C_T = 19.9 + 0.5 \left[1 + 0.064(813) + \frac{813}{656} \right] = 47.0\text{ pF}$$

$$f_H = \frac{1}{2\pi r_{\text{ao}} C_T} = \frac{1}{2\pi(656\Omega)(47.0\text{ pF})} = 5.16\text{ MHz} \quad | \quad GBW = 156\text{ MHz}$$

16.58



$$I_C = 100 \frac{3 - 0.7}{75k\Omega + 101(13k\Omega)} = 0.166mA \quad | \quad V_{CE} = 12 - 43k\Omega I_C - 13k\Omega I_E = 2.70 V$$

$$g_m = 40(0.166mA) = 6.64mS \quad r_{\pi 0} = \frac{100}{6.64mS} = 15.1k\Omega \quad C_{\pi} = \frac{g_m}{\omega_T} - C_{\mu} = 3.02pF$$

Short-Circuit Time Constants

$$R_{1s} = 100\Omega + 75k\Omega \left[300\Omega + 15.1k\Omega + 101(3k\Omega) \right] = 60.8k\Omega$$

$$R_{2s} = 10k\Omega \left[3k\Omega + \frac{15.1k\Omega + 99.9\Omega}{101} \right] = 2.40k\Omega$$

$$R_{3s} = 43k\Omega + 100k\Omega = 143k\Omega$$

$$f_L \approx \frac{1}{2\pi} \left[\frac{1}{(60.8k\Omega)(1\mu F)} + \frac{1}{(2.40k\Omega)(2.2\mu F)} + \frac{1}{(143k\Omega)(0.1\mu F)} \right] = 43.9Hz$$

Open-Circuit Time Constants

$$\text{Using the results from Table 16.2 on page 1037: } r_{\pi 0} = 15.1k\Omega \left[300 + (100 \parallel 75k\Omega) \right] = 390 \Omega$$

$$C_{TB} = \frac{3.02pF}{1 + (6.64mS)(3k\Omega)} + 0.5pF \left[1 + \frac{(6.64mS)(30.1k\Omega)}{1 + (6.64mS)(3k\Omega)} + \frac{30.1k\Omega}{390\Omega} \right]$$

$$C_{TB} = 44.0pF \quad | \quad f_H = \frac{1}{2\pi(390\Omega)(44.0pF)} = 9.27MHz$$

$$(b) A_{mid} = - \left(\frac{60.7k\Omega}{60.8k\Omega} \right) \frac{(6.64mS)(30.1k\Omega)}{1 + (6.64mS)(3k\Omega)} = -9.54 \quad GBW = 9.54(9.27MHz - 43.9Hz) = 88.0MHz$$

16.59

Using the results from Table 16.2 on page 1037 and Prob. 16.58

$$r_{\pi 0} = 15.1k\Omega \left[300 + (100 \parallel 75k\Omega) \right] = 390 \Omega \quad C_{TB} = \frac{1}{2\pi(7.5MHz)(390\Omega)} = 54.4$$

$$C_{TB} = \frac{3.02 pF}{1 + (6.64mS)R_E} + 0.5pF \left[1 + \frac{(6.64mS)(30.1k\Omega)}{1 + (6.64mS)R_E} + \frac{30.1k\Omega}{390\Omega} \right] = 54.4 pF$$

Using MATLAB : $R_E = 862 \Omega$

$$A_{mid} = 0.999 \frac{-100(30.1k\Omega)}{99.9\Omega + 300\Omega + 15.1k\Omega + 101(862\Omega)} = -29.3 \quad | \quad GBW = 220 MHz$$

The closest 5% resistor values are $R_E = 820 \Omega$ and $R_6 = 12 k\Omega$

$$C_{TB} = \frac{3.02 pF}{1 + (6.64mS)0.82k\Omega} + 0.5pF \left[1 + \frac{(6.64mS)(30.1k\Omega)}{1 + (6.64mS)0.82k\Omega} + \frac{30.1k\Omega}{390\Omega} \right] = 55.1 pF$$

$$f_H = \frac{1}{2\pi(390\Omega)(55.1pF)} = 7.41 MHz$$

$$A_{mid} = 0.999 \frac{-100(30.1k\Omega)}{99.9\Omega + 300\Omega + 15.1k\Omega + 101(0.82k\Omega)} = -30.6 \quad | \quad GBW = 227 MHz$$

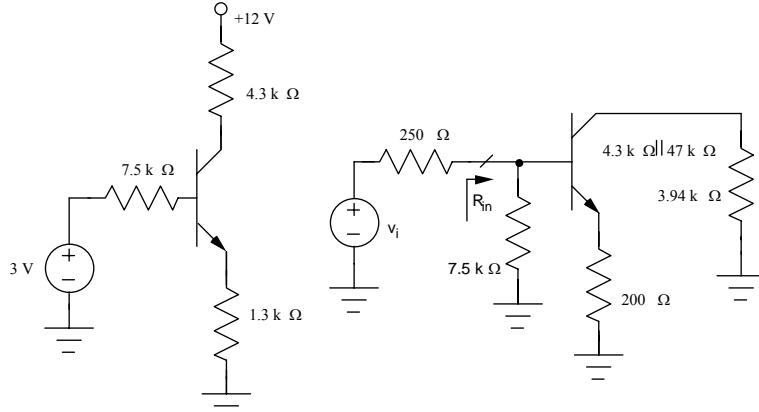
Note: The Q-point will actually change somewhat and this has been neglected.

16.60

$$(a) I_C = 100 \left| \frac{3 - 0.7}{7.5k\Omega + 101(1.3k\Omega)} \right| = 1.66mA \quad | \quad V_{CE} = 12 - 4.3k\Omega(I_C) - 1.3k\Omega \left(\frac{I_C}{\alpha_F} \right) = 2.69V$$

$2.69V \geq 0.7V$ Active region operation is correct. $| r_\pi = \frac{100(0.025)}{1.66 mA} = 1.51 k\Omega$

$$g_m = 40(1.66 mA) = 66.4mS \quad | \quad C_\pi = \frac{66.4mS}{2\pi(2 \times 10^8)} - 1 = 51.8 pF \quad | \quad r_x = 300\Omega \quad | \quad C_\mu = 1.0 pF$$



$$R_{in} = R_1 \| R_2 \| [r_x + r_\pi + (\beta_o + 1)R_{E1}] = 10k\Omega \| 30k\Omega \| [0.350k\Omega + 1.51k\Omega + (101)(200\Omega)] = 5.60 k\Omega$$

$$R_{th} = 7.5k\Omega \| 250\Omega = 242\Omega \quad | \quad R_L = 4.3k\Omega \| 47k\Omega = 3.94k\Omega$$

$$A_{mid} = -\frac{R_{in}}{R_I + R_{in}} \left[\frac{\beta_o R_L}{r_x + r_\pi + (\beta_o + 1)R_{E1}} \right] = -\frac{5.60k\Omega}{350\Omega + 5.60k\Omega} \left[\frac{100(3.94k\Omega)}{22.0k\Omega} \right] = -16.9$$

(b) Using the Short-Circuit Time Constants:

$$R_{1s} = 250\Omega + 7.5k\Omega \| [350\Omega + 1.51k\Omega + 101(200\Omega)] = 5.85k\Omega$$

$$R_{2s} = 4.3k\Omega + 43k\Omega = 47.3k\Omega$$

$$R_{3s} = 1.1k\Omega \left(200\Omega + \frac{1.51k\Omega + 350 + 242\Omega}{101} \right) = 184\Omega$$

$$f_L \approx \frac{1}{2\pi} \left[\frac{1}{(5.85k\Omega)(5\mu F)} + \frac{1}{(47.3k\Omega)(1\mu F)} + \frac{1}{(184\Omega)(4.7\mu F)} \right] = 193Hz$$

(c) Using the Open-Circuit Time Constants:

Using the results from Table 16.2 on page 1037: $r_{\pi 0} \approx R_{th} + r_x = 242\Omega + 350\Omega = 592\Omega$

$$C_{TB} = \frac{51.8 pF}{1 + (66.4mS)(200\Omega)} + 1pF \left[1 + \frac{(66.4mS)(3.94k\Omega)}{1 + (66.4mS)(200\Omega)} + \frac{3.94k\Omega}{592\Omega} \right] = 29.6 pF$$

$$C_{TB} = 29.6 pF \quad f_L = \frac{1}{2\pi(592\Omega)(29.6 pF)} = 9.08 MHz$$

16.61

Using the results in Table 16.2 on page 1037 and the values from Prob. 16.60:

$$r_{\pi 0} \equiv R_{th} + r_x = 242\Omega + 350\Omega = 592\Omega \quad | \quad C_{TB} = \frac{1}{2\pi(592\Omega)(12\text{MHz})} = 22.4 \text{ pF}$$

$$C_{TB} = \frac{51.8}{1 + (66.4mS)R_E} + 1\text{pF} \left[1 + \frac{(66.4mS)(3.94k\Omega)}{1 + (66.4mS)R_E} + \frac{3.94k\Omega}{592\Omega} \right] = 22.4 \text{ pF}$$

Using MATLAB: $R_E = 305 \Omega$

The closest 5% resistor values are $R_E = 300 \Omega$ and $R_6 = 1 k\Omega$

$$C_{TB} = \frac{51.8 \text{ pF}}{1 + (66.4mS)300\Omega} + 1\text{pF} \left[1 + \frac{(66.4mS)(3.94k\Omega)}{1 + (66.4mS)300\Omega} + \frac{3.94k\Omega}{592\Omega} \right] = 22.6 \text{ pF}$$

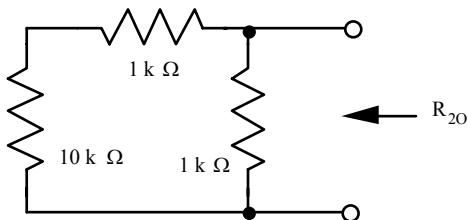
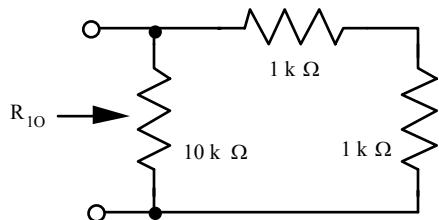
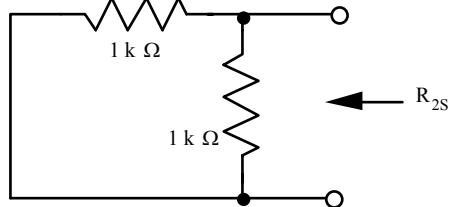
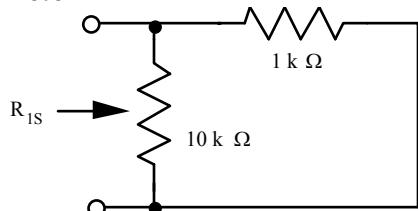
$$f_H = \frac{1}{2\pi(592\Omega)(22.6\text{pF})} = 11.9 \text{ MHz}$$

$$R_{in} = R_I \| R_2 \| [r_x + r_\pi + (\beta_o + 1)R_{E1}] = 10k\Omega \| 30k\Omega \| [0.300k\Omega + 1.51k\Omega + (101)300\Omega] = 6.08 k\Omega$$

$$R_{th} = 7.5k\Omega \| 250\Omega = 242\Omega \quad | \quad R_L = 4.3k\Omega \| 47k\Omega = 3.94k\Omega$$

$$A_{mid} = -\frac{R_{in}}{R_I + R_{in}} \left[\frac{\beta_o R_L}{r_x + r_\pi + (\beta_o + 1)R_{E1}} \right] = -\frac{6.08k\Omega}{250\Omega + 6.08k\Omega} \left[\frac{100(3.94k\Omega)}{32.1k\Omega} \right] = -11.8$$

16.62



(a) SCTC:

$$R_{IS} = 10k\Omega \parallel 1k\Omega = 909\Omega \quad | \quad R_{2S} = 1k\Omega \parallel 1k\Omega = 500\Omega \quad | \quad \omega_L = \frac{1}{909(10^{-6})} + \frac{1}{500(10^{-5})} = 1300 \frac{\text{rad}}{\text{s}}$$

(b) OCTC:

$$R_{IO} = 10k\Omega \parallel 2k\Omega = 1.67k\Omega \quad | \quad R_{2O} = 1k\Omega \parallel 1k\Omega = 917\Omega \quad | \quad \omega_H = \frac{1}{1670(10^{-6})} + \frac{1}{917(10^{-5})} = 92.3 \frac{\text{rad}}{\text{s}}$$

(c) There are two poles. The SCTC technique assumes both are at low frequency and yields the largest pole. The OCTC assumes both are at high frequency and yields the smallest pole.

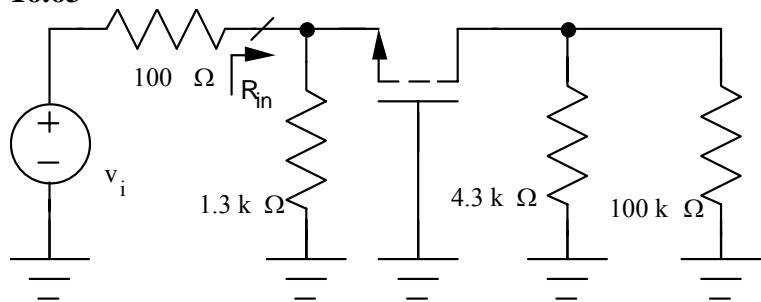
$$(d) \begin{vmatrix} (sC_1 + G_1 + G_2) & -G_2 \\ -G_2 & (sC_2 + G_2 + G_3) \end{vmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = 0$$

$$\Delta = s^2 C_1 C_2 + s [C_2 (G_1 + G_2) + C_1 (G_2 + G_3)] + G_1 G_2 + G_2 G_3 + G_1 G_3$$

$$\Delta = s^2 10^{-11} + s(1.30 \times 10^{-8}) + 1.20 \times 10^{-6}$$

$$\Delta = s^2 + 1300s + 1.20 \times 10^5 \rightarrow s = -1200, -100 \frac{\text{rad}}{\text{s}}$$

16.63



$$R_L = 4.3k\Omega \parallel 100k\Omega = 4.12k\Omega \quad | \quad C_{GS} = 3.0 \text{ pF} \quad | \quad C_{GD} = 0.6 \text{ pF}$$

$$R_{in} = R_s \parallel \frac{1}{g_m} = 1.3k\Omega \parallel \frac{1}{5mS} = 173\Omega$$

$$A_{mid} = \frac{R_{in}}{R_I + R_{in}} g_m R_L = \frac{173\Omega}{100\Omega + 173\Omega} (5ms)(4.12k\Omega) = +13.1$$

$$f_H \cong \frac{1}{2\pi} \left(\frac{1}{C_{GD} R_L} \right) = \frac{1}{2\pi} \left(\frac{1}{0.6 \text{ pF} (4.12k\Omega)} \right) = 64.4 \text{ MHz}$$

16.64

*Problem 16.12 - Common-Gate Amplifier - ac small-signal model

VI 1 0 AC 1

RI 1 2 100

C1 2 3 4.7UF

RS 3 0 1.3K

RD 4 0 4.3K

C2 4 5 1UF

R3 5 0 100K

G1 4 3 0 3 5mS

.OP

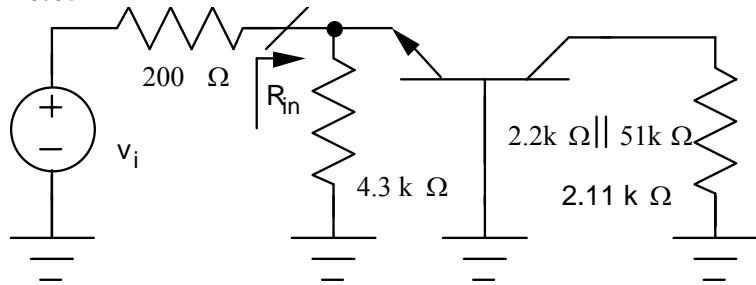
.AC DEC 100 0.01 100MEG

.PRINT AC VM(5) VP(5)

.END

Results: $A_{mid} = +13.3$, $f_L = 123 \text{ Hz}$, $f_H = 64.4 \text{ MHz}$

16.65



$$g_m = 40(1 \text{ mA}) = 0.04 \text{ S} \quad | \quad r_x = 300 \Omega \quad | \quad r_\pi = \frac{100(0.025)}{1 \text{ mA}} = 2.50 \text{ k}\Omega \quad | \quad C_\mu = 0.6 \text{ pF}$$

$$C_\pi = \frac{40(10^{-3})}{2\pi(5 \times 10^8)} - 0.6 = 12.1 \text{ pF} \quad | \quad R_{th} = 4.3 \text{ k}\Omega \parallel 200 \Omega = 191 \Omega \quad | \quad R_L = 2.2 \text{ k}\Omega \parallel 51 \text{ k}\Omega = 2.11 \text{ k}\Omega$$

$$R_{in} = R_E \parallel \frac{(r_x + r_\pi)}{\beta_o + 1} = 4.3 \text{ k}\Omega \parallel \frac{(0.3 \text{ k}\Omega + 2.50 \text{ k}\Omega)}{101} = 27.6 \Omega$$

$$A_{mid} = \frac{R_{in}}{R_I + R_{in}} \left(\frac{\beta_o R_L}{r_x + r_\pi} \right) = \frac{27.6 \Omega}{200 \Omega + 27.6 \Omega} \frac{100(2.11 \text{ k}\Omega)}{2.80 \text{ k}\Omega} = +9.14$$

$$\omega_H = \frac{1}{191 \frac{12.1 \text{ pF}}{1 + 0.04(191)} \left(1 + \frac{300}{191} \right) + 0.6 \text{ pF} (300 \Omega) \left[1 + \frac{0.04(2110)}{1 + 0.04(191)} \right] + 0.6 \text{ pF} (2110 \Omega)}$$

$$f_H = \frac{1}{2\pi} \left(\frac{1}{6.876 \times 10^{-10} + 1.938 \times 10^{-9} + 1.266 \times 10^{-9}} \right) = 40.9 \text{ MHz}$$

16.66

First, estimate the required SPICE parameters:

$$C_{\mu} = \frac{CJC}{\left(1 + \frac{V_{CB}}{PHIE}\right)^{ME}} \quad | \quad CJC = CJC = 0.6 \text{ pF} \left(1 + \frac{2.8}{0.75}\right)^{0.333} \cong 1.01 \text{ pF}$$

$$\tau_F = \frac{C_{\pi}}{g_m} = \frac{1}{\omega_T} - \frac{C_{\mu}}{g_m} = \frac{1}{10^9 \pi} - \frac{0.6 \text{ pF}}{40(1 \text{ mA})} = 303 \text{ ps}$$

*Figure P16.14 - Common-Base Amplifier

VCC 6 0 DC 5

VEE 7 0 DC -5

VI 1 0 AC 1

RI 1 2 200

C1 2 3 4.7UF

RE 3 7 4.3K

Q1 4 0 3 NBJT

RC 4 6 2.2K

C2 4 5 1UF

R3 5 0 51K

.MODEL NBJT NPN BF=100 RB=300 CJC=1.01PF TF=303PS

.OP

.AC DEC 50 1 50MEG

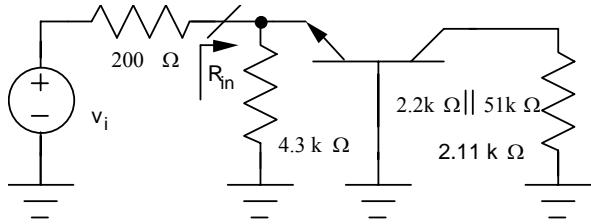
.PRINT AC VM(5)

.PROBE

.END

Results: $A_{\text{mid}} = 19.1 \text{ dB}$, $f_L = 149 \text{ Hz}$, $f_H = 43.8 \text{ MHz}$

16.67



$$I_c = \alpha_F I_E = \frac{100}{101} \left| \frac{-0.7 - (-10)}{4300} \right| = 2.14 \text{ mA} \quad | \quad V_{CE} = 10 - (2.14 \text{ mA})(2.2 \text{ k}\Omega) - (-0.7) = 5.99 \text{ V}$$

$$g_m = 40(2.14 \text{ mA}) = 85.6 \text{ mS} \quad | \quad r_x = 300 \Omega \quad | \quad r_\pi = \frac{100(0.025)}{2.14 \text{ mA}} = 1.17 \text{ k}\Omega \quad | \quad C_\mu = 0.6 \text{ pF}$$

$$C_\pi = \frac{85.6 \text{ mS}}{2\pi(5 \times 10^8)} - 0.6 = 26.7 \text{ pF} \quad | \quad R_{th} = 4.3 \text{ k}\Omega \parallel 200 \Omega = 191 \Omega \quad | \quad R_L = 2.2 \text{ k}\Omega \parallel 51 \text{ k}\Omega = 2.11 \text{ k}\Omega$$

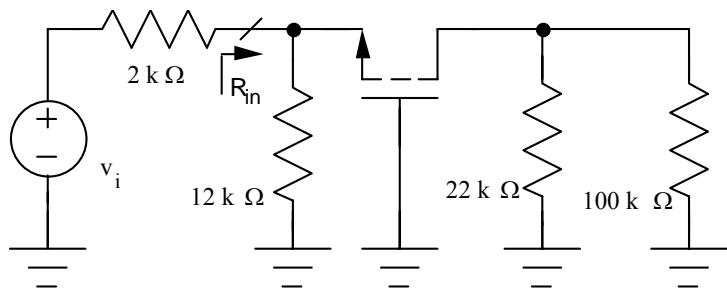
$$R_{in} = R_E \parallel \frac{(r_x + r_\pi)}{\beta_o + 1} = 4.3 \text{ k}\Omega \parallel \frac{(0.3 \text{ k}\Omega + 1.17 \text{ k}\Omega)}{101} = 14.5 \Omega$$

$$A_{mid} = \frac{R_{in}}{R_I + R_{in}} \left(\frac{\beta_o R_L}{r_x + r_\pi} \right) = \frac{14.5 \Omega}{200 \Omega + 14.5 \Omega} \frac{100(2.11 \text{ k}\Omega)}{1.47 \text{ k}\Omega} = +9.70$$

$$\omega_H = \frac{1}{191 \frac{26.7 \text{ pF}}{1 + 0.0856(191)} \left(1 + \frac{300}{191} \right) + 0.6 \text{ pF} (300 \Omega) \left[1 + \frac{0.0856(2110)}{1 + 0.0856(191)} \right] + 0.6 \text{ pF} (2110 \Omega)}$$

$$f_H = \frac{1}{2\pi} \left(\frac{1}{7.556 \times 10^{-10} + 2.054 \times 10^{-9} + 1.266 \times 10^{-9}} \right) = 39.1 \text{ MHz}$$

16.68



$$R_{th} = 12k\Omega \parallel 2k\Omega = 1.71k\Omega \quad | \quad R_L = 22k\Omega \parallel 100k\Omega = 18.0k\Omega \quad | \quad C_{GS} = 3.0 \text{ pF} \quad | \quad C_{GD} = 0.6 \text{ pF}$$

$$g_m = \frac{2(0.1mA)}{1V} = 0.200mS \quad | \quad R_{in} = 12k\Omega \parallel \frac{1}{g_m} = 12k\Omega \parallel \frac{1}{0.200mS} = 3.53k\Omega$$

$$A_{mid} = \frac{R_{in}}{R_I + R_{in}} g_m R_L = \frac{3.53k\Omega}{2k\Omega + 3.53k\Omega} (0.200ms)(18.0k\Omega) = +2.30$$

$$f_H = \frac{1}{2\pi} \left(\frac{1}{\frac{C_{GS}}{G_{th} + g_m} + C_{GD}R_L} \right) = \frac{1}{2\pi} \left(\frac{1}{\frac{3.0 \text{ pF}}{(0.5848 + 0.200)mS} + 0.6 \text{ pF}(18.0k\Omega)} \right) = 10.9 \text{ MHz}$$

16.69

(a) First find V_{TN} and K_n based upon Problem 16.21

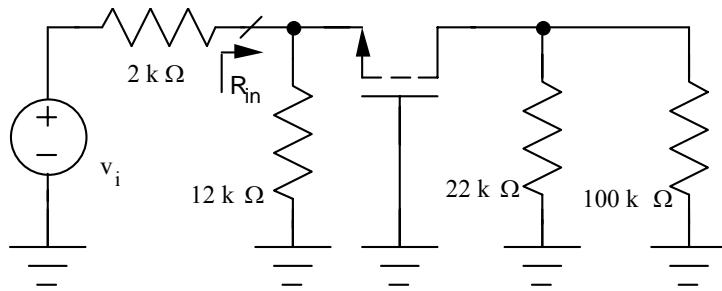
$$V_{GG} = \frac{1.5M\Omega}{1.5M\Omega + 2.2M\Omega} 12V = 4.87V \quad | \quad V_{GG} - V_{GS} = 0.1mA(12k\Omega) \rightarrow V_{GS} = 3.67V$$

$$V_{GS} - V_{TN} = 1V \rightarrow V_{TN} = 2.67V \quad | \quad K_n = \frac{2I_D}{(V_{GS} - V_{TN})^2} = \frac{2(0.1mA)}{1^2} = 0.2mS$$

Now, find the Q-point for $V_{DD} = 18V$: $V_{GG} = \frac{1.5M\Omega}{1.5M\Omega + 2.2M\Omega} 18V = 7.30V$

$$R_{GG} = 1.5M\Omega \parallel 2.2M\Omega = 892k\Omega \quad | \quad V_{GG} - V_{GS} = I_D R_S$$

$$7.30 - V_{GS} = (12k\Omega) \left(\frac{0.2mS}{2} \right) (V_{GS} - 2.67)^2 \rightarrow V_{GS} = 4.73V \quad | \quad I_D = 0.254 mA \quad | \quad V_{DS} = 9.37V \text{ ok}$$



$$R_{th} = 12k\Omega \parallel 2k\Omega = 1.71k\Omega \quad | \quad R_L = 22k\Omega \parallel 100k\Omega = 18.0k\Omega \quad | \quad C_{GS} = 3.0 pF \quad | \quad C_{GD} = 0.6 pF$$

$$g_m = \frac{2(0.254mA)}{(4.26 - 2.67)V} = 0.320mS \quad | \quad R_{in} = 12k\Omega \parallel \frac{1}{g_m} = 12k\Omega \parallel \frac{1}{0.320mS} = 2.48k\Omega$$

$$A_{mid} = \frac{R_{in}}{R_I + R_{in}} g_m R_L = \frac{2.48k\Omega}{2k\Omega + 2.48k\Omega} (0.320ms)(18.0k\Omega) = +3.19$$

$$f_H = \frac{1}{2\pi} \left(\frac{1}{\frac{C_{GS}}{G_{th} + g_m} + C_{GD} R_L} \right) = \frac{1}{2\pi} \left(\frac{1}{\frac{3.0 pF}{(0.5848 + 0.32)mS} + 0.6 pF(18.0k\Omega)} \right) = 11.3 MHz$$

Note that the contribution of the input pole cannot be neglected because of the low f_T of the MOSFET.

$$R_{1S} = R_I + R_{in} = 4.48k\Omega \quad | \quad R_{3S} = R_7 + R_{out} \cong 100k\Omega + 22k\Omega = 122k\Omega$$

$$f_L = \frac{1}{2\pi} \left(\frac{1}{R_{1S} C_1} + \frac{1}{R_{3S} C_3} \right) = 20.6 Hz$$

Note that there is no signal current in C_2 , so it does not contribute to f_L .

16.70

$$g_m = 40(0.25 \text{ mA}) = 10.0 \text{ mS} \quad | \quad r_x = 300\Omega \quad | \quad r_\pi = \frac{100(0.025)}{0.25 \text{ mA}} = 10.0 \text{ k}\Omega$$

$$C_\mu = 0.6 \text{ pF} \quad | \quad C_\pi = \frac{0.01}{2\pi(5 \times 10^8)} - 0.6 = 2.58 \text{ pF} \quad | \quad R_B = 100 \text{ k}\Omega \parallel 300 \text{ k}\Omega = 75.0 \text{ k}\Omega$$

$$R_L = 13 \text{ k}\Omega \parallel 100 \text{ k}\Omega = 11.5 \text{ k}\Omega \quad | \quad R_{th} = 75 \text{ k}\Omega \parallel 2 \text{ k}\Omega = 1.95 \text{ k}\Omega$$

$$R_{in} = R_B \parallel [r_x + r_\pi + (\beta_o + 1)R_L] = 75.0 \text{ k}\Omega \parallel [300\Omega + 10.0 \text{ k}\Omega + (101)1.5 \text{ k}\Omega] = 70.5 \text{ k}\Omega$$

$$A_{mid} = \left(\frac{R_{in}}{R_I + R_{in}} \right) \frac{(\beta_o + 1)R_L}{r_x + r_\pi + (\beta_o + 1)R_L} = 0.972 \frac{101(11.5 \text{ k}\Omega)}{[0.300 + 10.0 + 101(11.5)] \text{ k}\Omega} = 0.964$$

$$f_H \cong \frac{1}{2\pi} \frac{1}{(1950 + 300) \left[\frac{2.58 \text{ pF}}{1 + 10 \text{ mS}(11.5 \text{ k}\Omega)} + 0.6 \text{ pF} \right]} = \frac{1}{2\pi} \frac{1}{(2250)(0.622 \text{ pF})} = 114 \text{ MHz}$$

(b) Calculating the required SPICE parameters:

$$C_\mu = \frac{CJC}{\left(1 + \frac{V_{CB}}{PHIE}\right)^{ME}} \quad | \quad CJC = 0.6 \text{ pF} \left(1 + \frac{11.8}{0.75}\right)^{0.333} \cong 1.54 \text{ pF}$$

$$\tau_F = \frac{C_\pi}{g_m} = \frac{1}{\omega_T} - \frac{C_\mu}{g_m} = \frac{1}{10^9 \pi} - \frac{0.6 \text{ pF}}{40(0.25 \text{ mA})} = 260 \text{ ps} \quad | \quad TF = 260 \text{ ps}$$

*Problem 16.70 - Common-Collector Amplifier

VCC 6 0 DC 15

VS 1 0 AC 1

RS 1 2 2K

C1 2 3 4.7UF

R1 3 0 100K

R2 6 3 300K

Q1 6 3 4 NBJT

R4 4 0 13K

C3 4 5 10UF

R7 5 0 100K

.MODEL NBJT NPN BF=100 TF=260PS CJC=1.54PF RB=300

.OP

.AC DEC 100 0.1 200MEG

.PRINT AC VM(5) VP(5)

.END

Results: $A_{mid} = 0.962$, $f_L = 0.52 \text{ Hz}$, $f_H = 110 \text{ MHz}$

16.71

$$V_{BB} = 9V \frac{100k\Omega}{100k\Omega + 300k\Omega} = 2.25V \quad | \quad R_B = 100k\Omega \parallel 300k\Omega = 75.0k\Omega$$

$$I_C = 100 \frac{(2.25 - 0.7)V}{75.0k\Omega + 101(13k\Omega)} = 0.251mA$$

$$g_m = 40(0.251mA) = 10.0mS \quad | \quad r_x = 300\Omega \quad | \quad r_\pi = \frac{100(0.025)}{0.251mA} = 9.96k\Omega$$

$$C_\mu = 0.6pF \quad | \quad C_\pi = \frac{0.01}{2\pi(5 \times 10^8)} - 0.6 = 2.58 pF$$

$$R_L = 13k\Omega \parallel 100k\Omega = 11.5k\Omega \quad | \quad R_{th} = 75k\Omega \parallel 2k\Omega = 1.95k\Omega$$

$$R_{in} = R_B \parallel [r_x + r_\pi + (\beta_o + 1)R_L] = 75.0k\Omega \parallel [300\Omega + 9.96k\Omega + (101)11.5k\Omega] = 70.5k\Omega$$

$$A_{mid} = \left(\frac{R_{in}}{R_I + R_{in}} \right) \frac{(\beta_o + 1)R_L}{r_x + r_\pi + (\beta_o + 1)R_L} = 0.972 \frac{101(11.5k\Omega)}{[0.300 + 9.96 + 101(11.5)]k\Omega} = 0.964$$

$$f_H \cong \frac{1}{2\pi} \frac{1}{(1950 + 300) \left[\frac{2.58pF}{1 + 10mS(11.5k\Omega)} + 0.6pF \right]} = \frac{1}{2\pi} \frac{1}{(2250)(0.622pF)} = 114 MHz$$

16.72

First, find the value of K_n required for $I_D = 0.1 \text{ mA}$

$$V_{GG} = \frac{1.5M\Omega}{1.5M\Omega + 2.2M\Omega} 10V = 4.05V \quad | \quad V_{GG} - V_{GS} = 0.1mA(12k\Omega) \rightarrow V_{GS} = 2.85V$$

$$V_{GS} - V_{TN} = 0.75V \rightarrow V_{TN} = 2.10V \quad | \quad K_n = \frac{2I_D}{(V_{GS} - V_{TN})^2} = \frac{2(0.1mA)}{(0.75)^2} = 0.356 \frac{mA}{V^2}$$

$$g_m = \frac{2(0.1mA)}{0.75V} = 0.267mS \quad | \quad R_{in} = R_i \parallel R_2 = 892k\Omega \quad | \quad R_L = 12k\Omega \parallel 100k\Omega = 10.7k\Omega$$

$$A_{mid} = \frac{R_{in}}{R_i + R_{in}} \frac{g_m R_L}{1 + g_m R_L} = 0.998 \frac{(0.267mS)(10.7k\Omega)}{1 + (0.267mS)(10.7k\Omega)} = +0.739 \quad (-2.62 \text{ dB})$$

From Table 16.2 on page 1037: $f_H = \frac{1}{2\pi(2k\Omega \parallel 892k\Omega) \left[\frac{3pF}{1 + (0.267mS)(10.7k\Omega)} + 0.6pF \right]} = 57.9 \text{ MHz}$

$$f_{P1} = \frac{1}{2\pi(894k\Omega)(4.7\mu F)} = 0.379 \text{ Hz} \quad f_{P2} = \frac{1}{2\pi \left[100k\Omega + \left(12k\Omega \parallel \frac{1}{0.267mS} \right) (0.1\mu F) \right]} = 15.5 \text{ Hz}$$

$$f_L \approx 15.5 \text{ Hz}$$

Note that a low frequency RHP zero makes the calculation of f_H a very poor estimate for the FET case. See the analysis in Prob. 17.73 which shows $\omega_Z = g_m/C_{GS}$.

*Problem 16.72 - Common-Drain Amplifier

VDD 6 0 DC 10

VS 1 0 AC 1

RS 1 2 2K

C1 2 3 4.7UF

R1 3 0 1.5MEG

R2 6 3 2.2MEG

M1 6 3 4 4 NFET

R4 4 0 12K

C3 4 5 0.1UF

R7 5 0 100K

.MODEL NFET NMOS VTO=2.10 KP=0.356MA CGSO=30NF CGDO=6NF

.OP

.AC DEC 100 1 500MEG

.PRINT AC VM(5) VP(5)

.END

Results: $A_{mid} = 0.740$, $f_L = 15.5 \text{ Hz}$, $f_H = 195 \text{ MHz}$ - Note that there is peaking in the response.

16.73

First find V_{DD} , V_{TN} and K_n from Prob. 17.22: $V_{DD} = V_{DS} + I_D R_S = 10 \text{ V}$

$$V_{GG} = \frac{1.5M\Omega}{1.5M\Omega + 2.2M\Omega} 10V = 4.05V \quad | \quad V_{GG} - V_{GS} = 0.1mA(12k\Omega) \rightarrow V_{GS} = 2.85V$$

$$V_{GS} - V_{TN} = 0.75V \rightarrow V_{TN} = 2.10V \quad | \quad K_n = \frac{2I_D}{(V_{GS} - V_{TN})^2} = \frac{2(0.1mA)}{(0.75)^2} = 0.356 \frac{mA}{V^2}$$

Now find the new Q-point with $V_{DD} = 20 \text{ V}$.

$$V_{GG} = \frac{1.5M\Omega}{1.5M\Omega + 2.2M\Omega} 20V = 8.11V \quad | \quad R_{GG} = 1.5M\Omega \parallel 2.2M\Omega = 892k\Omega \quad | \quad V_{GG} - V_{GS} = I_D R_S$$

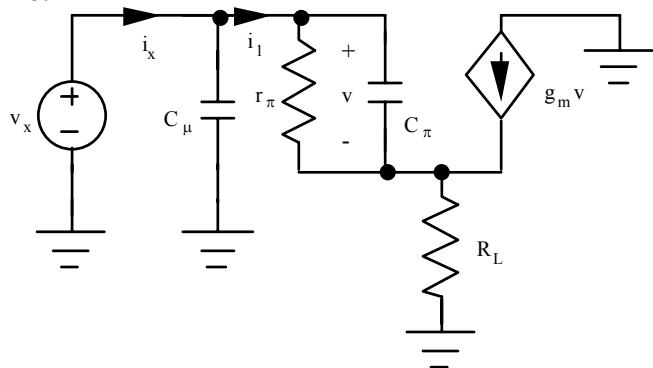
$$8.11 - V_{GS} = (12k\Omega) \left(\frac{0.356mA}{2V^2} \right) (V_{GS} - 2.10)^2 \rightarrow V_{GS} = 3.56V \quad | \quad I_D = 0.379 \text{ mA} \quad | \quad V_{DS} = 15.5 \text{ V} \text{ ok}$$

$$g_m = \frac{2(0.379mA)}{(3.56 - 2.10)V} = 0.519mS \quad | \quad R_{in} = R_i \parallel R_2 = 892k\Omega \quad | \quad R_L = 12k\Omega \parallel 100k\Omega = 10.7k\Omega$$

$$A_{mid} = \frac{R_{in}}{R_i + R_{in}} \frac{g_m R_L}{1 + g_m R_L} = 0.998 \frac{(0.519mS)(10.7k\Omega)}{1 + (0.519mS)(10.7k\Omega)} = +0.846 \quad (-1.46 \text{ dB})$$

From Table 16.2 on page 1037: $f_H = \frac{1}{2\pi(2k\Omega \parallel 892k\Omega) \left[\frac{3pF}{1 + (0.519mS)(10.7k\Omega)} + 0.6pF \right]} = 75.4 \text{ MHz}$

16.74



$$I_x = sC_\mu V_x + I_1 \quad | \quad V_x = \frac{I_1}{(sC_\pi + g_\pi)} + \left(I_1 + g_m \frac{I_1}{(sC_\pi + g_\pi)} \right) R_L$$

$$Z_1 = \frac{V_x}{I_1} = \frac{sC_\pi r_\pi R_L + R_L + r_\pi + \beta_o R_L}{sC_\pi r_\pi + 1} = \frac{sC_\pi r_\pi R_L + r_\pi + (\beta_o + 1)R_L}{sC_\pi r_\pi + 1}$$

$$Y_1 = \frac{1}{Z_1} = \frac{\frac{sC_\pi r_\pi}{r_\pi + (\beta_o + 1)R_L} + \frac{1}{r_\pi + (\beta_o + 1)R_L}}{s \frac{C_\pi r_\pi R_L}{r_\pi + (\beta_o + 1)R_L} + 1} \cong \frac{\frac{sC_\pi}{(1 + g_m R_L)} + \frac{1}{r_\pi + (\beta_o + 1)R_L}}{s \frac{C_\pi R_L}{(1 + g_m R_L)} + 1} \text{ for } \beta_o \gg 1$$

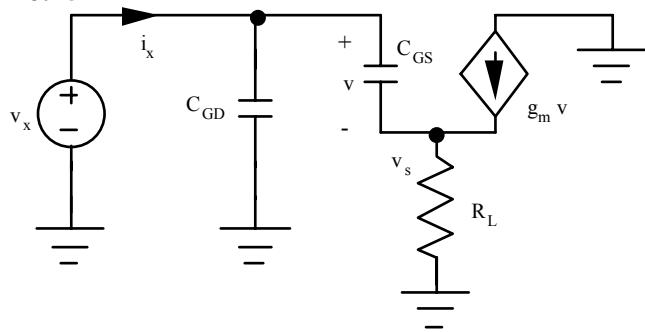
$$\omega \frac{C_\pi R_L}{(1 + g_m R_L)} \ll 1 \rightarrow \omega \ll \frac{1}{C_\pi} \left(\frac{1}{R_L} + g_m \right) \text{ but } \frac{1}{C_\pi} \left(\frac{1}{R_L} + g_m \right) > \omega_T$$

$$\text{So, for } \omega \ll \omega_T, Y_1 \cong s \frac{C_\pi}{(1 + g_m R_L)} + \frac{1}{r_\pi + (\beta_o + 1)R_L}$$

$$C_{in} = C_\mu + \frac{C_\pi}{(1 + g_m R_L)} \quad \text{and} \quad R_{in} = r_\pi + (\beta_o + 1)R_L$$

ω_H is determined by the input capacitance C_{in} and the source resistance $R_{th} + r_x$.

16.75



$$I_x = sC_{GD}V_x + sC_{GS}(V_x - V_s) \quad | \quad V_x = V + (sC_{GS}V + g_m V)R_L \quad | \quad V = \frac{V_x}{(1 + g_m R_L + sC_{GS}R_L)}$$

$$I_x = sC_{GD}V_x + sC_{GS} \frac{V_x}{(1 + g_m R_L + sC_{GS}R_L)} \quad | \quad \text{Note: } V_s = \frac{(sC_{GS} + g_m)R_L}{(1 + g_m R_L + sC_{GS}R_L)} V_x$$

$$\frac{I_x}{V_x} = s \left[C_{GD} + \frac{C_{GS}}{1 + g_m R_L} \frac{1}{1 + s \frac{C_{GS}R_L}{1 + g_m R_L}} \right] \quad | \quad \frac{C_{GS}R_L}{1 + g_m R_L} \approx \frac{C_{GS}R_L}{g_m R_L} = \frac{C_{GS}}{g_m} \quad \& \quad \frac{g_m}{C_{GS}} > \omega_T$$

Assuming $\omega \ll \omega_T$: $C_{IN} \approx C_{GD} + \frac{C_{GS}}{1 + g_m R_L}$ | Note the zero in V_s at $\omega_z = -\frac{g_m}{C_{GS}}$

16.76

$$A_v = -141 \text{ (43dB)} \quad | \quad f_H = 6 \times 10^6 \text{ Hz} \quad | \quad f_T \geq 2(141)(6 \times 10^6) = 1.69 \text{ GHz}$$

$$GBW \leq \frac{1}{r_x C_\mu} \quad | \quad r_x C_\mu \leq \frac{1}{2\pi(1.69 \times 10^9 \text{ Hz})} = 94.2 \text{ ps}$$

16.77

$$A_v = 100 \text{ (40dB)} \quad | \quad f_H = 40 \times 10^6 \text{ Hz} \quad | \quad f_T \geq 2(100)(4 \times 10^7) = 8.00 \text{ GHz}$$

$$GBW \leq \frac{1}{r_x C_\mu} \quad | \quad r_x C_\mu \leq \frac{1}{2\pi(8 \times 10^9 \text{ Hz})} = 19.9 \text{ ps}$$

16.78

$$A_{mid} = g_m R_L \quad | \quad g_m = \frac{100}{100k\Omega} = 1.00mS \quad | \quad r_\pi = \frac{\beta_o}{g_m} \cong \frac{100}{1.00mS} = 100k\Omega$$

Assume $r_\pi \gg r_x \quad | \quad r_{\pi o} = r_\pi \| r_x \cong r_x$

$$\omega_H = \frac{1}{r_x \left[C_\pi + C_\mu \left(1 + g_m R_L + \frac{R_L}{r_x} \right) \right]} \cong \frac{1}{r_x C_\mu \left(1 + g_m R_L + \frac{R_L}{r_x} \right)} = \frac{1}{r_x C_\mu (1 + g_m R_L) + R_L C_\mu}$$

$$r_x C_\mu (1 + g_m R_L) + R_L C_\mu = \frac{1}{\omega_H} \quad | \quad r_x C_\mu (1 + 100) + 10^5 C_\mu = \frac{1}{2\pi(1.8 \times 10^6)} = 8.84 \times 10^{-8}$$

$$C_\mu = \frac{0.884 \text{ pF}}{1 + 1.01 \times 10^{-3} r_x} \quad | \quad C_\mu \text{ cannot exceed } 0.884 \text{ pF for an ideal transistor with } r_x = 0.$$

Other more realistic possibilities (C_u, r_x) : $(0.75 \text{ pF}, 177\Omega)$ $(0.5 \text{ pF}, 760\Omega)$

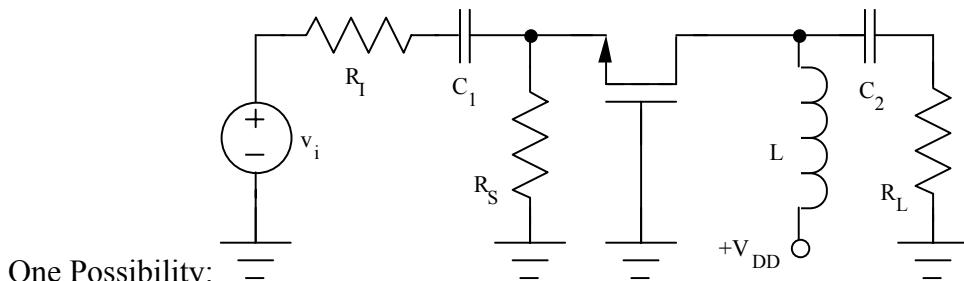
16.79

$$\omega_H \cong \frac{1}{R_L C_{GD}} \quad | \quad A_{mid} = \frac{R_{in}}{R_I + R_{in}} g_m R_L \cong \frac{g_m R_L}{1 + g_m R_I} \quad | \quad R_L = A_{mid} \left(\frac{1}{g_m} + R_I \right) = 20 \left(\frac{1}{g_m} + 100 \right)$$

$$2\pi(25 \times 10^6) = \frac{1}{20 \left(\frac{1}{g_m} + 100 \Omega \right) 3 \times 10^{-12} F} \rightarrow g_m = 164 mS$$

$$R_L = 20 \left(\frac{1}{0.164} + 100 \right) = 2.12 k\Omega \quad | \quad I_D = \frac{g_m^2}{2K_n} = \frac{(164 mS)^2}{2 \left(20 \frac{mS}{V} \right)} = 672 mA$$

Note that we cannot supply I_D through R_L since $I_D R_L = 1420V \gg V_{DD}$.



One Possibility:

This is really not a realistic design. The current and power are far too high. We need to find an FET with a much higher K_n .

16.80

$$\omega_H = \frac{1}{R_{th} C_{GS} + C_{GD} \left[1 + g_m R_L + \frac{R_L}{R_{th}} \right]} = \frac{1}{100 \left[12 pF + 5 pF \left[1 + g_m R_L + \frac{R_L}{100} \right] \right]}$$

$$2\pi(25 \times 10^6) = \frac{1}{100 \left[17 pF + 5 pF \left[g_m R_L + \frac{R_L}{100} \right] \right]} \quad | \quad g_m R_L + \frac{R_L}{100} = \left[\frac{1}{2\pi(25 \times 10^6)(100)10^{-12}} - 17 \right] \frac{1}{5}$$

$$g_m = \frac{9.33}{R_L} - 0.01 \rightarrow R_L \leq 933 \Omega \quad | \quad I_D = \frac{g_m^2}{2K_n} = \frac{g_m^2}{0.05} = 20g_m^2$$

For strong inversion (for the square-law model to be valid), we desire

$$(V_{GS} - V_{TN}) \geq 0.25V \rightarrow I_D \geq \frac{0.025}{2} (0.25)^2 = 781 \mu A.$$

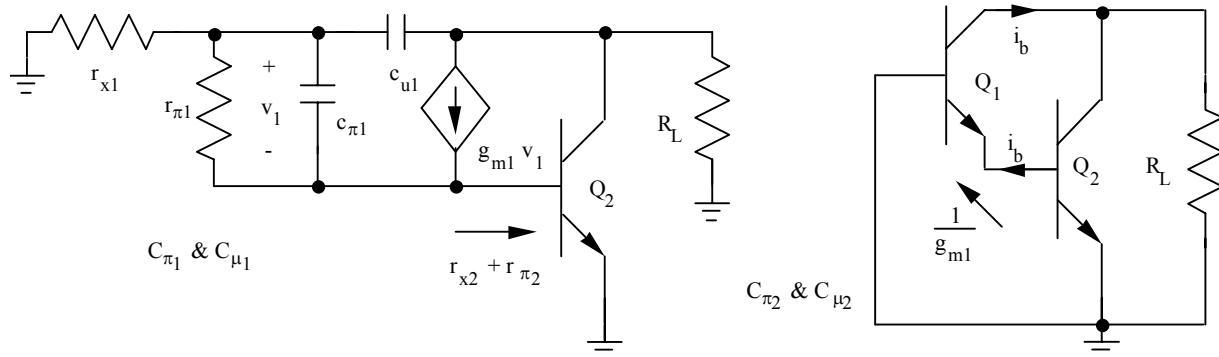
g_m must exceed 0.01S. Choose $g_m = 0.015S$. $I_D = \frac{(0.015)^2}{.05} = 4.5 mA$.

$$R_L = \frac{9.33}{g_m - .01} = 1.87 k\Omega \quad | \quad g_m R_L = 28.0$$

16.81

$$f_H \leq \frac{1}{2\pi R_L C_\mu} = \frac{1}{2\pi (12k\Omega \parallel 47k\Omega) (2 pF)} \rightarrow f_H \leq 8.33 MHz$$

16.82



Use the open-circuit time-constant approach:

$$(a) R_{\mu 1O} : v_x \cong i_x r_{x1} - i_x r_{x1} \left[\frac{(\beta_o + 1)(r_{x2} + r_{\pi 2})}{r_{\pi 1} + (\beta_o + 1)(r_{x2} + r_{\pi 2})} \right] \left[-\frac{\beta_o}{r_{x2} + r_{\pi 2}} R_L \right] - (-i_x R_L)$$

$$R_{\mu 1O} \cong i_x \left[R_L + r_{x1} \left(1 + \frac{\beta_o r_{\pi 2}}{r_{\pi 1} + \beta_o r_{\pi 2}} g_{m2} R_L \right) \right] \text{ assuming } r_{x2} \ll r_{\pi 2}.$$

$$r_{\pi 1} \cong 10r_{\pi 2} \quad | \quad \beta_o = 100 \quad | \quad g_{m1} \cong \frac{\beta_o}{r_{\pi 1}} = \frac{10}{r_{\pi 2}} \quad | \quad R_{\mu 1O} = \frac{v_x}{i_x} = R_L + r_{x1} \left(1 + \frac{10}{11} g_{m2} R_L \right)$$

$R_{\pi 1O}$: Split i_x and use superposition with $r_{x2} \ll r_{\pi 2}$:

$$v_x \cong i_x r_{x1} \left[1 - \frac{(\beta_o + 1)(r_{x2} + r_{\pi 2})}{r_{\pi 1} + (\beta_o + 1)(r_{x2} + r_{\pi 2})} \right] + \frac{i_x}{g_{\pi 2} + g_{m1}} \cong i_x r_{x1} \frac{r_{\pi 1}}{r_{\pi 1} + \beta_o r_{\pi 2}} + \frac{i_x}{g_{\pi 2} + 10g_{\pi 2}}$$

$$R_{\pi 1O} = \frac{v_x}{i_x} \cong \frac{10r_{x1} + r_{\pi 2}}{11}$$

$R_{\pi 2O}$: The circuit is the same as that used for the C_T calculation.

$$R_{\pi 2O} = r_{\pi 2} \left(r_{x2} + \frac{1}{g_{m1}} \right) = r_{\pi 2} \left(r_{x2} + \frac{r_{\pi 2}}{10} \right)$$

$R_{\mu 2O}$: The circuit is the same as that used for the C_T calculation except the additional $i_b = i_x/2$ is returned back to the output :

$$R_{\mu 2O} = R_{\pi 2O} + R_{\pi 2O} g_{m2} R_L + \frac{R_L}{2} = R_{\pi 2O} \left(1 + g_{m2} R_L + \frac{R_L}{2R_{\pi 2O}} \right)$$

$$\omega_H = \frac{1}{C_{\pi 1} \left(\frac{10r_{x1} + r_{\pi 2}}{11} \right) + C_{\mu 1} r_{x1} \left(1 + \frac{10}{11} g_{m2} R_L + \frac{R_L}{r_{x1}} \right) + R_{\pi 2O} \left[C_{\pi 2} + C_{\mu 2} \left(1 + g_{m2} R_L + \frac{R_L}{2R_{\pi 2O}} \right) \right]}$$

$$r_{\pi 2} = \frac{100(0.025V)}{1mA} = 2.50k\Omega \quad | \quad \text{Use } R_L = \frac{r_{o2}}{2} = \frac{50V}{2mA} = 25.0k\Omega$$

$$C_{\pi 1} = \frac{40(10^{-4})}{6 \times 10^8 \pi} - 0.5pF = 1.62pF \quad | \quad C_{\pi 2} = \frac{40(10^{-3})}{6 \times 10^8 \pi} - 0.5pF = 20.7pF$$

$$R_{\pi 2O} = r_{\pi 2} \left(r_{x2} + \frac{r_{\pi 2}}{10} \right) = 2.50k\Omega \left(300 + \frac{2.50k\Omega}{10} \right) = 451\Omega$$

$$f_H = \frac{1}{2\pi} \left\{ \begin{aligned} & 1.62pF \left(\frac{3k\Omega + 2.5k\Omega}{11} \right) + 0.5pF \left(300\Omega \left[1 + 40mS(25k\Omega) + \frac{25k\Omega}{300\Omega} \right] \right)^{-1} \\ & + 451\Omega \left[20.7pF + 0.5pF \left(1 + 40mS(25k\Omega) + \frac{25k\Omega}{902\Omega} \right) \right] \end{aligned} \right\} = 393 \text{ kHz}$$

(b) The circuit is almost the same except for two important changes: $C_{\mu 1}$ sees only r_{x1} , and the $i_b = i_x/2$ is not returned to the output for $C_{\mu 2}$.

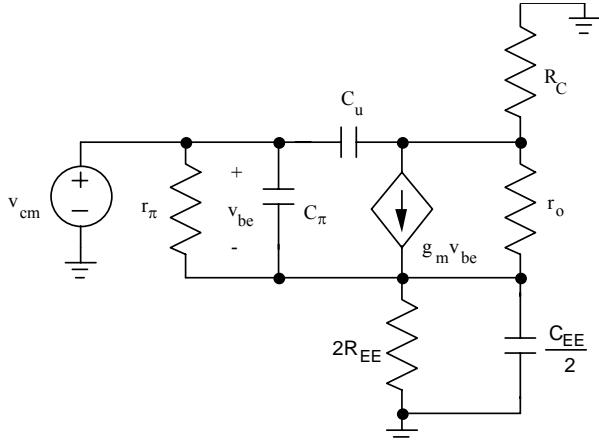
$$\omega_H = \frac{1}{C_{\pi 1} \frac{10r_{x1} + r_{\pi 2}}{11} + C_{\mu 1} r_{x1} + R_{\pi 2 O} \left[C_{\pi 2} + C_{\mu 2} \left(1 + g_{m 2} R_L + \frac{R_L}{R_{\pi 2 O}} \right) \right]}$$

$$f_H = \frac{1}{2\pi} \left\{ \begin{aligned} & 1.62 \text{ pF} \left(\frac{3k\Omega + 2.5k\Omega}{11} \right) + 0.5 \text{ pF} (300\Omega) \\ & + 451\Omega \left[20.7 \text{ pF} + 0.5 \text{ pF} \left(1 + 40mS(25k\Omega) + \frac{25k\Omega}{451\Omega} \right) \right] \end{aligned} \right\}^{-1} = 640 \text{ kHz}$$

(c) The C - C/C - E cascade offers significantly better bandwidth than the Darlington configuration because $C_{\mu 1}$ is not subject to Miller multiplication.

(d) Improved bandwidth is one reason for the use of the C - C/C - E cascade in the 741 op-amp.

16.83



Assume R_L represents a differential-mode load between the collectors. Degradation of the CMRR starts with the zero in the common-mode gain transfer function.

$$(sC_\pi + g_m + g_\pi)v_{cm} = \left[s\left(C_\pi + \frac{C_{EE}}{2}\right) + g_m + g_\pi + g_o + \frac{G_{EE}}{2} \right]v_e - g_o v_c$$

$$(sC_\mu - g_m)v_{cm} = -(g_m + g_o)v_e + (sC_\mu + g_o + G_C)v_{cm}$$

Keeping the dominant terms, the numerator polynomial is approximately

$$N \approx s^2 C_\mu \left(C_\pi + \frac{C_{EE}}{2} \right) + s \left[\left(C_\mu - \frac{C_{EE}}{2} \right) g_m + C_\pi g_o \right] + g_o g_\pi - g_m \frac{G_{EE}}{2}$$

Using dominant root factorization :

$$\omega_z \approx \left| \begin{array}{c} g_o g_\pi - g_m \frac{G_{EE}}{2} \\ \left(C_\mu - \frac{C_{EE}}{2} \right) g_m + C_\pi g_o \end{array} \right| = \left| \begin{array}{c} \left(\frac{1}{\beta_o r_o} - \frac{1}{2R_{EE}} \right) \\ \left(C_\mu - \frac{C_{EE}}{2} \right) + \frac{C_\pi}{\mu_f} \end{array} \right| \approx \left| \begin{array}{c} \left(\frac{1}{\beta_o r_o} - \frac{1}{2R_{EE}} \right) \\ \left(C_\mu - \frac{C_{EE}}{2} \right) \end{array} \right|$$

The dominant terms in the determinant are

$$\Delta = s^2 C_\mu \left(C_\pi + \frac{C_{EE}}{2} \right) + s C_\mu g_m + s \left(C_\pi + \frac{C_{EE}}{2} \right) G_C + g_m G_C = \left[s \left(C_\pi + \frac{C_{EE}}{2} \right) + g_m \right] \left[s C_\mu + G_C \right]$$

The high pole is in the vicinity of ω_T . The dominant pole is $\omega_{p_{cm}} = \frac{1}{R_C C_\mu}$.

At dc, the common - mode gain is approximately $A_{cm} = R_C \left(\frac{1}{\beta_o r_o} - \frac{1}{2R_{EE}} \right)$

For zero base resistance r_x , the dominant pole in the differential mode response is

$$\omega_{p_{dm}} = \left(\frac{1}{R_C \left\| \frac{R_L}{2} \right\| C_\mu} \right) \text{ and } A_{dm} = 0.5 g_m \left(R_C \left\| \frac{R_L}{2} \right\| \right) \quad \omega_{p_{dm}} \text{ and } \omega_{p_{cm}} \text{ approximately cancel.}$$

The CMRR reaches - 6 dB when C_μ shorts the base to the collector.

$$g_m = 40I_C = 4 \times 10^{-3} \quad r_o = \frac{50 + 10.1}{10^{-4}} = 611 k\Omega$$

$$A_{cm} = R_C \left(\frac{1}{\beta_o r_o} - \frac{1}{2R_{EE}} \right) = 6k\Omega \left[\frac{1}{100(611 k\Omega)} - \frac{1}{20 M\Omega} \right] = -2.02 \times 10^{-4} \quad (-73.9 dB)$$

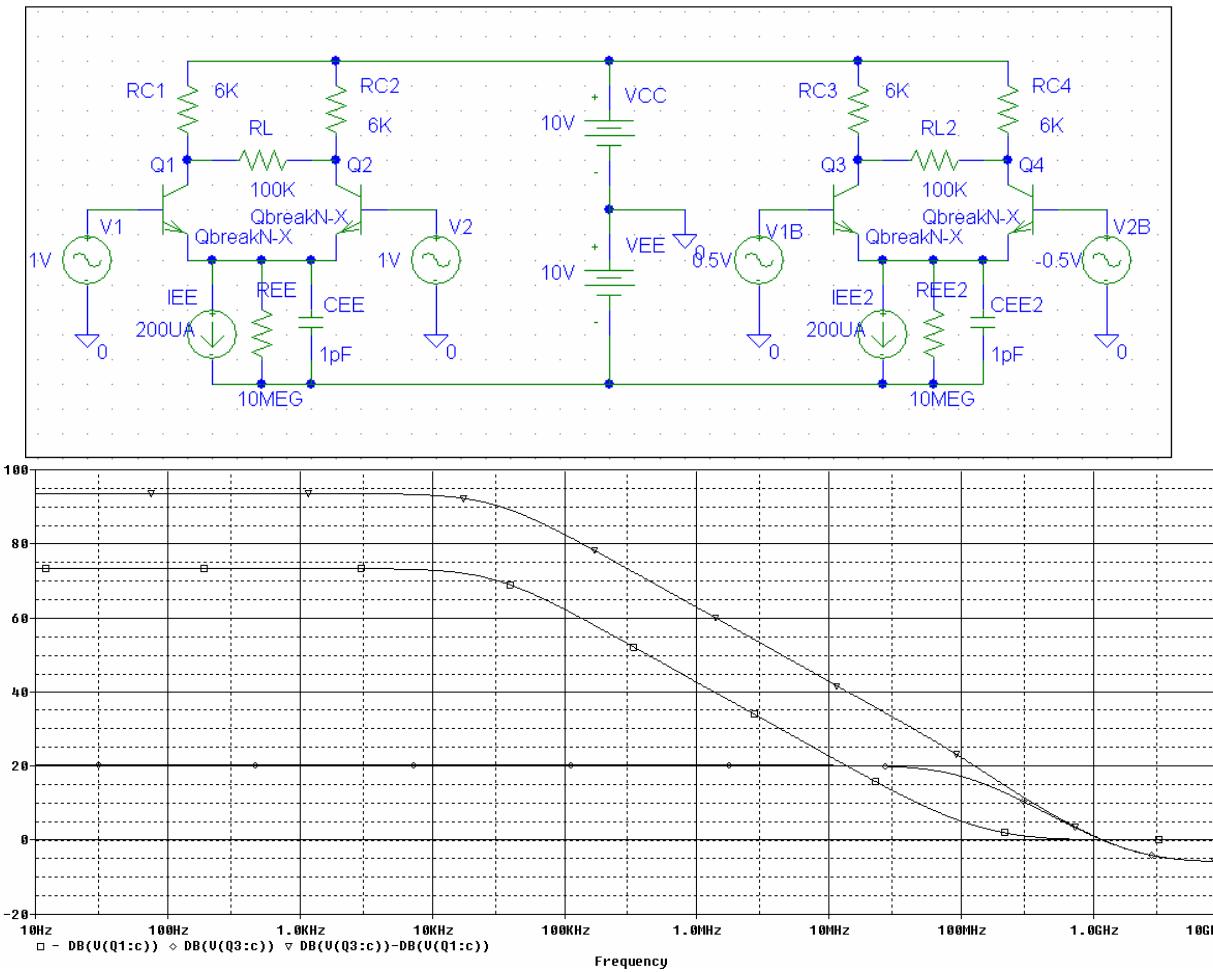
$$A_{dm} = -0.5 \left(4 \times 10^{-3} \right) \left(6k\Omega \left| \left| \frac{100k\Omega}{2} \right| \right. \right) = -10.7 \quad CMRR_{dB} = 94.5 dB$$

$$f_z \approx \frac{1}{2\pi} \left| \left(\frac{\frac{1}{\beta_o r_o} - \frac{1}{2R_{EE}}}{C_\mu - \frac{C_{EE}}{2}} \right) \right| = \frac{1}{2\pi} \left(\frac{-3.36 \times 10^{-8}}{-0.2 pF} \right) = 26.8 kHz$$

$$\omega_{Pdm} = \frac{1}{R_L C_\mu} = 88.4 MHz \quad \omega_{Pdm} = \frac{1}{\left(R_C \left| \left| \frac{R_L}{2} \right| \right. \right) C_\mu} = 99.0 MHz$$

See the PSPICE graph in Prob. 16.84 below.

16.84



The three curves from top to bottom are: CMRR, $-20\log(A_{cm})$, $20\log(A_{dm}/2)$. At high frequencies (near 100 MHz), the pole of A_{dm} approximately cancels the pole in A_{cm} .

16.85

$$\omega_H = \frac{g_{m1}}{C_{GS1} + C_{GS2} + C_{GD2}(1 + g_{m1}r_{o2} + g_{m2}r_{o2})}$$

$$g_{m1} = g_{m2} = \sqrt{2(25 \times 10^{-6}) \left(\frac{5}{1}\right) (10^{-4})} = 158 \mu S \quad | \quad r_{o2} \equiv \frac{50V}{0.1mA} = 500k\Omega$$

$$C_{GS1} = 3pF \quad | \quad C_{GS2} = 3pF \quad | \quad C_{GD1} = 0.5pF \quad | \quad C_{GD2} = 0.5pF$$

$$f_H = \frac{1}{2\pi} \frac{158\mu S}{3pF + 3pF + 0.5pF [1 + 2(0.158mS)500k\Omega]} = 294 kHz$$

16.86

$$\omega_H = \frac{g_{m1}}{C_{GS1} + C_{GS2} + C_{GD2}(1 + g_{m1}r_{o2} + g_{m2}r_{o2})} \quad | \quad I_{D2} = 5I_{D1} = 1.00mA \quad | \quad r_{o2} = \frac{50V}{1mA} = 50k\Omega$$

$$g_{m1} = \sqrt{2(25 \times 10^{-6}) \left(\frac{5}{1}\right) (2 \times 10^{-4})} = 224\mu S \quad | \quad g_{m2} = \sqrt{2(25 \times 10^{-6}) \left(\frac{25}{1}\right) (1 \times 10^{-3})} = 1.12mS$$

$$C_{GS} \text{ & } C_{GD} \propto W : C_{GS1} = 3pF \quad | \quad C_{GS2} = 15pF \quad | \quad C_{GD1} = 1pF \quad | \quad C_{GD2} = 5pF$$

$$f_H = \frac{1}{2\pi} \frac{0.224mS}{3pF + 15pF + 5pF [1 + (1.12mS + 0.224mS)50k\Omega]} = 99.3 \text{ kHz}$$

16.87

The most probable answer that will be produced is

$$\omega_H = \frac{g_{m1}}{C_{\pi1} + C_{\pi2} + C_{\mu2}[1 + (g_{m1} + g_{m2})r_{o2}]} \quad | \quad I_{C2} \cong 10I_{C1} = 1.00mA \quad | \quad r_{o2} = \frac{60V}{1.00mA} = 60k\Omega$$

$$C_{\pi1} = \frac{40(10^{-4})}{1.2 \times 10^9 \pi} - 0.5pF = 0.561pF \quad | \quad C_{\pi2} = \frac{40(10^{-3})}{1.2 \times 10^9 \pi} - 0.5pF = 10.1pF$$

$$f_H = \frac{1}{2\pi} \frac{40(10^{-4})}{0.561pF + 10.1pF + 0.5pF [1 + 40(1.1mA)60k\Omega]} = 478 \text{ kHz}$$

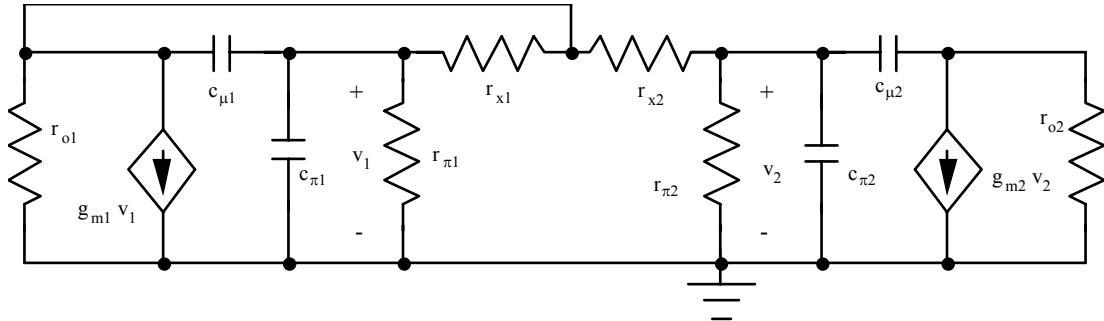
However, C_{\square} should be approximately proportional to emitter area:

$$C_{\mu2} = 10C_{\mu1} = 5.00pF \quad | \quad C_{\pi2} = \frac{40(10^{-3})}{1.2 \times 10^9 \pi} - 5.00pF = 5.10pF$$

$$f_H = \frac{1}{2\pi} \frac{40(10^{-4})}{0.561pF + 5.10pF + 5.00pF [1 + 40(1.1mA)60k\Omega]} = 48.2 \text{ kHz}$$

16.88

With the addition of r_x , we must re-evaluate the open-circuit time constants.



Assume: $r_x \ll r_o$

$$C_{\pi 2} \text{ & } C_{\mu 2} \text{ are part of a common - emitter stage with } r_{\pi o2} = r_{\pi 2} \left(r_{x2} + \frac{1}{g_{m1}} \right) \cong \frac{1 + g_{m1} r_{x2}}{g_{m1}}$$

$$C_{\pi 1}: R_{\pi 1o}^{-1} = g_{\pi 1} + g_{x1} \left(1 + \frac{g_{m1}}{g_{x1} + g_{o1} + \frac{1}{r_{x2} + r_{\pi 2}}} \right) \quad | \quad R_{\pi 1o} \cong \frac{r_{x1}}{1 + g_{m1} r_{x1}} \cong \frac{1}{g_{m1}}$$

$$C_{\mu 1}: R_{\mu 1o} = \frac{r_{x1}}{1 + \frac{1}{\beta_o} + \frac{1}{g_m R}} \quad \text{with} \quad R = r_{o1} \parallel (r_{x2} + r_{\pi 2}) \quad | \quad R_{\mu 1o} \cong r_{x1}$$

$$\omega_H = \left\{ C_{\pi 1} \frac{r_{x1}}{1 + g_{m1} r_{x1}} + C_{\mu 1} r_{x1} + \frac{1 + g_{m1} r_{x2}}{g_{m1}} [C_{\pi 2} + C_{\mu 2} (1 + g_{m2} r_{o2})] \right\}^{-1}$$

$$\text{The last term will be dominant: } \omega_H \cong \frac{1}{\frac{1 + g_{m1} r_{x2}}{g_{m1}} C_{\mu 2} (1 + g_{m2} r_{o2})}$$

The most probable answer that will be generated is

$$I_{C2} \cong 4I_{C1} = 1.00mA \quad | \quad r_{o2} = \frac{50V}{1.00mA} = 50k\Omega \quad | \quad g_{m2} = 40(0.001) = 40mS$$

$$C_{\pi 1} = \frac{40(2.5 \times 10^{-4})}{10^9 \pi} - 0.3pF = 2.88pF \quad | \quad C_{\pi 2} = \frac{40(10^{-3})}{10^9 \pi} - 0.3pF = 9.73pF$$

$$f_H \cong \frac{1}{2\pi} \frac{1}{\frac{1 + 0.01S(175\Omega)}{0.01S} 0.3pF [1 + 40mS(50k\Omega)]} = 964 \text{ kHz}$$

However, C_{\square} should be approximately proportional to emitter area:

$$C_{\mu 2} = 4C_{\mu 1} = 1.2pF \quad | \quad f_H \cong \frac{1}{2\pi} \frac{1}{\frac{1 + 0.01S(175\Omega)}{0.01S} 1.2pF [1 + 40mS(50k\Omega)]} = 241 \text{ kHz}$$

16.89

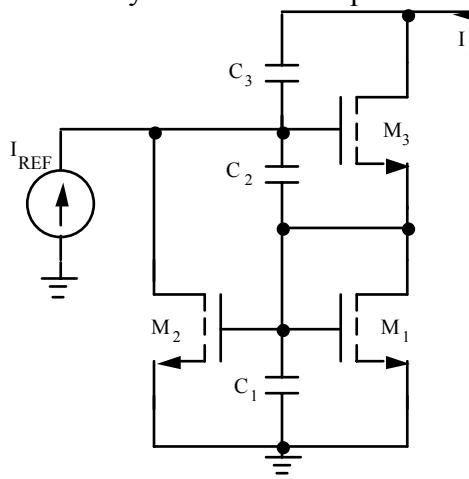
$$\omega_H = \frac{g_{m1}}{C_{\pi 1} + C_{\pi 2} + C_{\mu 2} [1 + (g_{m1} + g_{m2})r_{o2}]} \quad | \quad I_{C2} \equiv I_{C1} = 100 \mu A$$

$$r_{o2} = \frac{60V}{100 \mu A} = 600 k\Omega \quad | \quad C_{\pi 2} = C_{\pi 1} = \frac{40(10^{-4})}{10^8 \pi} - 2 pF = 10.7 pF$$

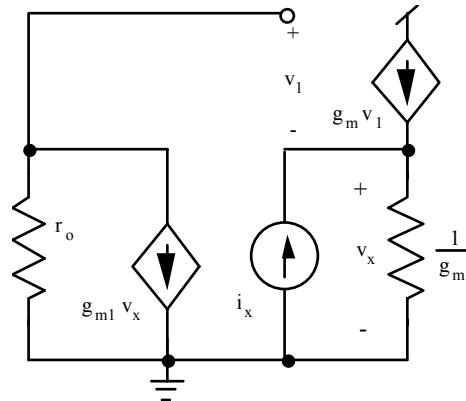
$$f_H = \frac{1}{2\pi} \left[\frac{40(10^{-4})}{10.7 pF + 10.7 pF + 2 pF(1 + 2(40)(0.100mA)600 k\Omega)} \right] = 66.2 \text{ kHz}$$

16.90

This analysis utilizes the open-circuit time-constant approach.

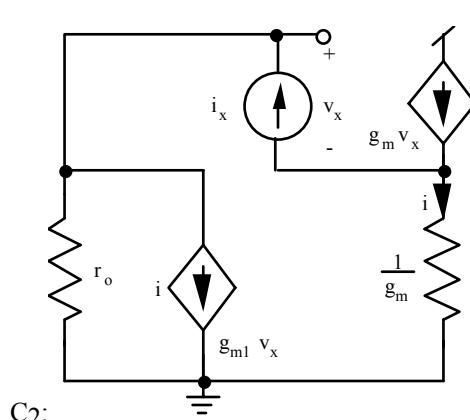


C1:

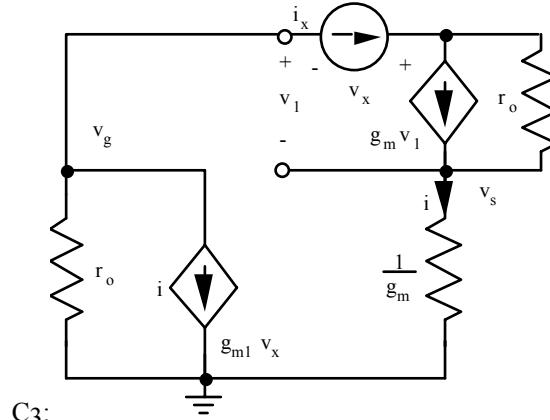


$$C_1 = C_{GS1} + C_{GS2} \quad | \quad C_2 = C_{GD2} + C_{GS3} \quad | \quad C_3 = C_{GD3}$$

$$R_{IO} : v_x = (i_x + g_m v_1) \frac{1}{g_m} \quad | \quad v_1 = -\mu_f v_x - v_x \quad | \quad R_{IO} = \frac{v_x}{i_x} = \frac{1}{g_m(\mu_f + 2)}$$



C2:



C3:

$$\begin{aligned}
R_{2O} : \quad v_x &= (i_x - i)r_o - (g_m v_x - i_x) \frac{1}{g_m} \quad | \quad i = g_m v_x - i_x \\
2v_x &= i_x \left(r_o + \frac{1}{g_m} \right) - r_o (g_m v_x - i_x) \quad | \quad R_{2O} = \frac{v_x}{i_x} = \frac{2r_o + \frac{1}{g_m}}{\mu_f + 2} \cong \frac{2}{g_m} \\
R_{3O} : \quad v_x &= (i_x - g_m v_1)r_o + \frac{i_x}{g_m} - (i_x + i)r_o \quad | \quad i = i_x \quad | \quad v_1 = -2i_x r_o - \frac{i_x}{g_m} \\
R_{3O} &= \frac{v_x}{i_x} = 2\mu_f r_o + 4r_o + \frac{1}{g_m} \cong 2(\mu_f + 2)r_o \cong 2\mu_f r_o \\
\omega_H &\cong \frac{1}{\frac{2C_{GS}}{g_m \mu_f} + 2 \frac{C_{GS} + C_{GD}}{g_m} + 2\mu_f r_o C_{GD}} \cong \frac{1}{2\mu_f r_o C_{GD}} = \frac{1}{2g_m r_o^2 C_{GD}}
\end{aligned}$$

$$f_H \cong \frac{1}{2\pi} \frac{1}{2\sqrt{2(2.5 \times 10^{-4})(2.5 \times 10^{-4}) \left(\frac{50}{2.5 \times 10^{-4}}\right)^2 (10^{-12})}} = 5.63 \text{ kHz}$$

Note: R_{3O} neglects any attached load resistance. If a load exists, essentially all of i_x will go through the load R_L , and the frequency response will significantly improve. For that case, $R_{3O} \approx R_L + r_o \approx r_o$.

16.91

$$\begin{aligned}
(a) \quad r_\pi &= \frac{100(0.025)}{15 \times 10^{-6}} = 167 \text{ k}\Omega \quad | \quad C_\mu = 0.5 \text{ pF} \quad | \quad C_\pi = \frac{40(15 \times 10^{-6})}{2\pi(75 \times 10^6)} - 0.5 \text{ pF} = 0.773 \text{ pF} \\
r_\pi &= r_\pi \| r_x = 167 \text{ k}\Omega \| 500 \Omega = 499 \Omega \quad | \quad g_m = 40(15 \times 10^{-6}) = 0.6 \text{ mS} \quad | \quad \omega_H = \frac{1}{r_\pi C_T} \quad | \\
C_T &= 0.773 + 0.5 \left[1 + 0.6 \text{ mS}(430 \text{ k}\Omega) + \frac{430 \text{ k}\Omega}{499 \Omega} \right] = 561 \text{ pF} \quad | \quad f_H = \frac{1}{2\pi(499)(5.61 \times 10^{-10})} = 568 \text{ kHz} \\
(b) \quad r_\pi &= \frac{100(0.025)}{5 \times 10^{-5}} = 50.0 \text{ k}\Omega \quad | \quad C_\mu = 0.5 \text{ pF} \quad | \quad C_\pi = \frac{40(5 \times 10^{-5})}{2\pi(75 \times 10^6)} - 0.5 \text{ pF} = 3.74 \text{ pF} \\
r_\pi &= r_\pi \| r_x = 50 \text{ k}\Omega \| 500 \Omega = 495 \Omega \quad | \quad g_m = 40(5 \times 10^{-5}) = 2.00 \text{ mS} \quad | \quad \omega_H = \frac{1}{r_\pi C_T} \quad | \\
C_T &= 3.74 + 0.5 \left[1 + 2.0 \text{ mS}(140 \text{ k}\Omega) + \frac{140 \text{ k}\Omega}{495 \Omega} \right] = 285 \text{ pF} \quad | \quad f_H = \frac{1}{2\pi(495)(2.85 \times 10^{-10})} = 1.13 \text{ MHz}
\end{aligned}$$

16.92

$$(a) C_{\mu} = 1 \text{ pF} \quad | \quad C_{\pi} = \frac{40(125 \times 10^{-6})}{2\pi(100 \times 10^6)} - 1 \text{ pF} = 6.96 \text{ pF} \quad | \quad r_x = 500\Omega \quad | \quad g_m = 40(125 \times 10^{-6}) = 5.00 \text{ mS}$$

$$C_T = 6.96 + 1.0 \left[2 + \frac{5.00 \text{ mS}(62 \text{ k}\Omega)}{2} + \frac{62 \text{ k}\Omega}{0.500 \text{ k}\Omega} \right] = 288 \text{ pF} \quad | \quad f_H = \frac{1}{2\pi(500)(2.88 \times 10^{-10})} = 1.11 \text{ MHz}$$

$$(b) C_{\pi} = \frac{40(1 \times 10^{-3})}{2\pi(100 \times 10^6)} - 1 \text{ pF} = 62.7 \text{ pF} \quad | \quad r_x = 500\Omega \quad | \quad g_m = 40(1 \times 10^{-3}) = 40.0 \text{ mS}$$

$$C_T = 62.7 + 1.0 \left[2 + \frac{40.0 \text{ mS}(7.5 \text{ k}\Omega)}{2} + \frac{7.5 \text{ k}\Omega}{0.500 \text{ k}\Omega} \right] = 230 \text{ pF} \quad | \quad f_H = \frac{1}{2\pi(500)(2.30 \times 10^{-10})} = 1.39 \text{ MHz}$$

16.93

$$(a) C_{\mu} = 1 \text{ pF} \quad | \quad C_{\pi} = \frac{40(100 \times 10^{-6})}{2\pi(100 \times 10^6)} - 1 \text{ pF} = 5.37 \text{ pF} \quad | \quad r_x = 500\Omega \quad | \quad g_m = 40(100 \times 10^{-6}) = 4.00 \text{ mS}$$

$$r_{\pi} = \frac{100(0.25)}{10^{-4}} = 25 \text{ k}\Omega \quad | \quad r_{\pi o} = 500\Omega \quad | \quad 25 \text{ k}\Omega = 490\Omega$$

$$f_H = \frac{1}{2\pi[(490\Omega)(5.37+2)\text{pF} + (500+75\text{k}\Omega)\text{l pF}]} = 2.01 \text{ MHz}$$

$$(b) C_{\mu} = 1 \text{ pF} \quad | \quad C_{\pi} = \frac{40(1 \times 10^{-3})}{2\pi(100 \times 10^6)} - 1 \text{ pF} = 62.7 \text{ pF} \quad | \quad r_x = 500\Omega \quad | \quad g_m = 40(1 \times 10^{-4}) = 40.0 \text{ mS}$$

$$r_{\pi} = \frac{100(0.25)}{10^{-3}} = 2.5 \text{ k}\Omega \quad | \quad r_{\pi o} = 500\Omega \quad | \quad 2.5 \text{ k}\Omega = 417\Omega$$

$$f_H = \frac{1}{2\pi[(417\Omega)(62.7+2)\text{pF} + (500+7.5\text{k}\Omega)\text{l pF}]} = 4.55 \text{ MHz}$$

16.94

For A_{mid} , refer to Section 14.8: $R_{B3} = \frac{51.8k\Omega}{2} = 25.9k\Omega$, $R_{E3} = 1.65k\Omega$, $r_{\pi3} = \frac{1k\Omega}{2} = 500\Omega$

$$A_{vt1} = \text{doesn't change} \quad | \quad R_{L2} = 4.7k\Omega \parallel 25.9k\Omega \parallel [500\Omega + 81(1.65k\Omega \parallel 250\Omega)] = 3.26k\Omega$$

$$A_{vt2} = -62.8mS(3.26k\Omega) = -205 \quad | \quad A_{vt3} = \frac{81(217)}{500 + 81(217)} = 0.972$$

$$A_v = \frac{1M\Omega}{1.01M\Omega} (-4.78)(-205)(0.972) = +943 \text{ or } 59.5 \text{ dB}$$

For f_L , refer to Section 16.10.5

$$R_{ss} = (4.7k\Omega \parallel 54.2k\Omega) + 25.9k\Omega \parallel [500\Omega + 81(1.65k\Omega \parallel 250\Omega)] = 15.0k\Omega$$

$$R_{th3} = 25.9k\Omega \parallel 4.7\Omega \parallel 54.2k\Omega = 3.71k\Omega \quad | \quad R_{6s} = 250 + 1.65k\Omega \parallel \frac{3.71k\Omega + 0.5k\Omega}{81} = 300\Omega$$

$$f_L = \frac{1}{2\pi} \left(99 + 319 + 372 + 2340 + \frac{1}{15.0k\Omega(1\mu F)} + \frac{1}{300\Omega(22\mu F)} \right) = 533 \text{ Hz}$$

For f_H , refer to Section 16.10.5

$$R_{L2} = 54.2k\Omega \parallel 4.7k\Omega \parallel 25.9k\Omega \parallel [500\Omega + 81(1.65k\Omega \parallel 250\Omega)] = 3.07k\Omega$$

$$R_{\pi2}C_{T2} = (610\Omega) \left[39pF + 1pF \left(1 + 67.8mS(3.07k\Omega) + \frac{3.07k\Omega}{0.610k\Omega} \right) \right] = 1.54 \times 10^{-7} \text{ s}$$

$$C_\pi + C_\mu = \frac{g_m}{\omega_r} \propto I_C \rightarrow C_{\pi3} = 2(51pF) - 1pF = 101pF \quad | \quad R_{th3} = 25.9k\Omega \parallel 4.7\Omega \parallel 54.2k\Omega = 3.71k\Omega$$

$$\frac{3.71k\Omega + 250\Omega}{1 + 159.4mS(0.217k\Omega)} 101pF + (3.71k\Omega + 250\Omega)pF = 1.52 \times 10^{-8} \text{ s}$$

$$f_H = \frac{1}{2\pi(1.07 \times 10^{-7} \text{ s} + 1.54 \times 10^{-7} \text{ s} + 1.52 \times 10^{-8} \text{ s})} = 576 \text{ kHz}$$

16.95

For A_{mid} , refer to Section 14.8 : $R_1 = 39k\Omega$, $R_2 = 11k\Omega$, $R_{E21} = 750\Omega$, $R_{C2} = 2.35k\Omega$

$$r_{\pi 2} = \frac{2.39k\Omega}{2} = 1.40k\Omega \quad | \quad R_{I1} = 620\Omega \parallel 39k\Omega \parallel 11k\Omega = 578\Omega \quad | \quad A_{vt1} = -10mS(578\Omega \parallel 1.20\Omega) = -3.91$$

$$R_{I2} = 2.35\Omega \parallel 51.8k\Omega = 2.25k\Omega \quad | \quad A_{vt2} = -62.8mS(2.25k\Omega \parallel 19.8k\Omega) = -127 \quad | \quad A_{vt3} \text{ doesn't change}$$

$$A_v = \frac{1M\Omega}{1.01M\Omega}(-3.91)(-127)(0.95) = +467 \text{ or } 53.4 \text{ dB}$$

For f_L , refer to Section 16.10.5

$$R_{3S} = (620\Omega \parallel 12.2k\Omega) + \left(\frac{17.2k\Omega}{2} \parallel \frac{2.39k\Omega}{2} \right) = 1.64k\Omega \quad | \quad R_{th} = \frac{17.2k\Omega}{2} \parallel 620\Omega \parallel 12.2k\Omega = 552\Omega$$

$$R_{4S} = 750 \parallel \frac{552 + 1195}{151} = 11.4\Omega \quad | \quad R_{5S} = \left(\frac{R_{C2}}{2} \parallel \frac{r_{o2}}{2} \right) + (R_{B3} \parallel R_{in3}) = 16.3k\Omega$$

$$R_{th3} = 51.8k\Omega \parallel 2.35\Omega \parallel 27.1k\Omega = 2.08k\Omega \quad | \quad R_{6S} = 250 + 3.3k\Omega \parallel \frac{2.08k\Omega + 1.00k\Omega}{81} = 288\Omega$$

$$f_L = \frac{1}{2\pi}(99 + 319 + 610 + 3987 + 61.4 + 158) = 833 \text{ Hz}$$

For f_H , refer to Section 16.10.5

$$R_{L1} = 598\Omega \parallel \frac{2.39k\Omega}{2} = 399\Omega \quad | \quad R_{th} C_{T1} = (9.9k\Omega) \left[5pF + 1pF \left(1 + 0.01S(399\Omega) + \frac{399\Omega}{9900\Omega} \right) \right] = 9.92 \times 10^{-8} s$$

$$R_{th2} = 598\Omega \parallel \frac{12.2k\Omega}{2} = 544\Omega \quad | \quad r_{\pi 2} = R_{4S} = \frac{2.39k\Omega}{2} \parallel (544\Omega + 250\Omega) = 596\Omega$$

$$R_{L2} = 51.8k\Omega \parallel \frac{4.7k\Omega}{2} \parallel R_{in2} = 2.25k\Omega \parallel 19.8k\Omega = 2.02k\Omega$$

$$C_{\pi} + C_{\mu} = \frac{g_m}{\omega_T} \propto I_C \rightarrow C_{\pi 2} = 2(40pF) - 1pF = 79pF$$

$$r_{\pi 2} C_{T2} = (544) \left[79pF + 1pF \left(1 + 136mS(2.02k\Omega) + \frac{2.02k\Omega}{0.544k\Omega} \right) \right] = 1.95 \times 10^{-7} s$$

$$R_{th3} = \frac{54.2k\Omega}{2} \parallel \frac{4.7k\Omega}{2} \parallel 51.8k\Omega = 2.08k\Omega$$

$$\frac{2.08k\Omega + 250\Omega}{1 + 79.6mS(0.232k)} 50pF + (2.08k\Omega + 250\Omega)pF = 8.31 \times 10^{-9} s$$

$$f_H = \frac{1}{2\pi(9.92 \times 10^{-8} s + 1.95 \times 10^{-7} s + 8.31 \times 10^{-9} s)} = 526 \text{ kHz}$$

16.96

$$f_o = \frac{1}{2\pi\sqrt{LC_{GD}}} = \frac{1}{2\pi\sqrt{10^{-5}(5 \times 10^{-12})}} = 22.5 \text{ MHz}$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{0.02}{2} = 0.01S \quad r_o = \frac{\frac{1}{0.0167} + 10}{0.01} = 6.99k\Omega$$

$$A_v = -g_m(r_o \| R_L) = -0.01S(6.99k\Omega \| 10k\Omega) = -41.1$$

$$BW = \frac{1}{2\pi R_p C_{GD}} = \frac{1}{2\pi(4.11k\Omega)(5pF)} = 7.75 \text{ MHz} \quad Q = \frac{22.5}{7.75} = 2.90$$

16.97

$$(a) f_o = \frac{1}{2\pi\sqrt{(C + C_\mu)L}} \rightarrow C = \frac{1}{(2\pi f_o)^2 L} - C_\mu = \frac{1}{[2\pi(10.7 \times 10^6 \text{ Hz})]^2 10^{-5} H} - 2pF = 20.1pF$$

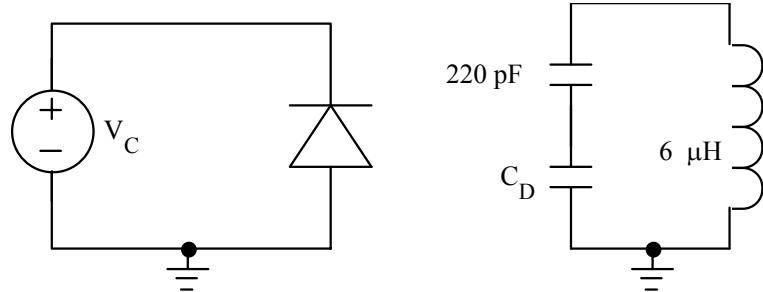
$$(b) r_o = \frac{75V + 10V}{10mA} = 8.50k\Omega \quad | \quad BW = \frac{1}{2\pi(8.5k\Omega)(22.1pF)} = 847\text{kHz} \quad | \quad Q = \frac{10.7}{0.847} = 12.6$$

$$(c) Q = 100 \quad | \quad BW = \frac{f_o}{Q} = 107\text{kHz} \quad | \quad r_o = \frac{1}{\omega_o(C + C_\mu)} = \frac{1}{2\pi(107\text{kHz})(22.1pF)} = 67.3k\Omega$$

$$n^2 = \frac{67.3k\Omega}{8.50k\Omega} = 7.918 \quad | \quad n = 2.81$$

$$(d) C_\mu = \frac{C_\mu}{n^2} = \frac{2pF}{7.918} = 0.253pF \quad | \quad C = 22.1 - 0.253 = 21.9pF$$

16.98



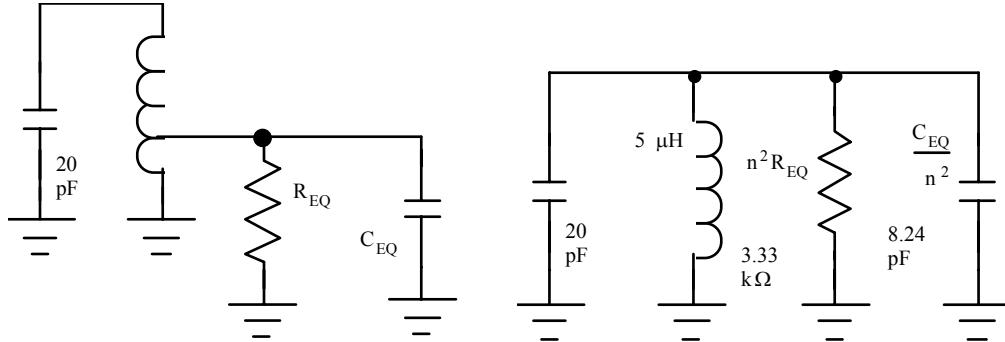
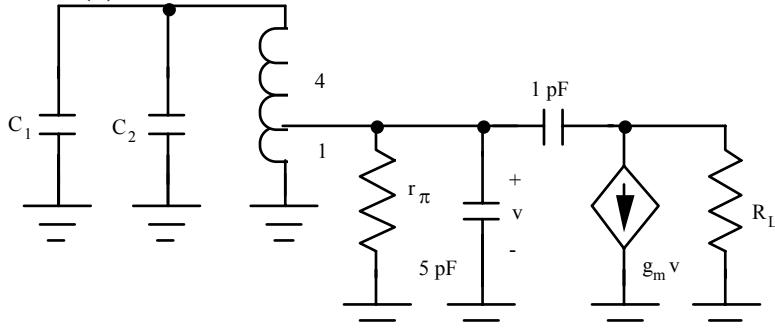
$$C_D = \frac{20 \text{ pF}}{\sqrt{1 + \frac{V_c}{0.9}}} \quad (a) C_D = \frac{20 \text{ pF}}{\sqrt{1 + \frac{0}{0.9}}} = 20 \text{ pF} \quad | \quad C = \frac{20(220)}{20 + 220} \text{ pF} = 18.3 \text{ pF}$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(6\mu\text{H})(18.3 \text{ pF})}} = 15.2 \text{ MHz}$$

$$(b) C_D = \frac{20 \text{ pF}}{\sqrt{1 + \frac{10}{0.9}}} = 5.75 \text{ pF} \quad | \quad C = \frac{5.75(220)}{5.75 + 220} \text{ pF} = 5.60 \text{ pF}$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(6\mu\text{H})(5.60 \text{ pF})}} = 27.5 \text{ MHz}$$

16.99(a)



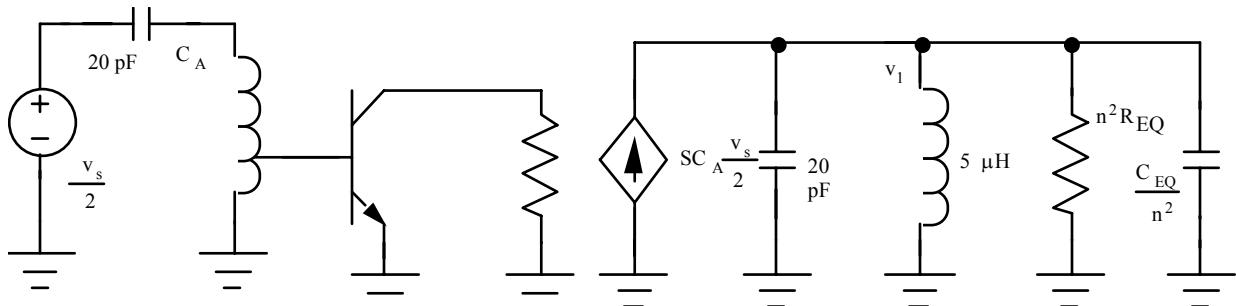
$$C_{EQ} = C_\pi + C_\mu [1 + g_m R_L] = 5 \text{ pF} + 1 \text{ pF} [1 + 40(1 \text{ mA})(5 \text{ k}\Omega)] = 206 \text{ pF}$$

$$C_P = 20 \text{ pF} + \frac{C_{EQ}}{n^2} = 20 \text{ pF} + \frac{206 \text{ pF}}{5^2} = 28.2 \text{ pF} \quad | \quad f_o = \frac{1}{2\pi\sqrt{(5 \mu\text{H})(28.2 \text{ pF})}} = 13.4 \text{ MHz}$$

$$R_{EQ} = r_\pi \left| \frac{R_L}{(1 + g_m R_L)(\omega R_L C_\mu)} \right|^2 = 2.5 \text{ k}\Omega \left| \frac{5000}{(1 + 200)[2\pi(13.4 \text{ MHz})(5 \text{ k}\Omega)(1 \text{ pF})]} \right|^2 = 2.5 \text{ k}\Omega || 140 \text{ }\Omega = 133 \text{ }\Omega$$

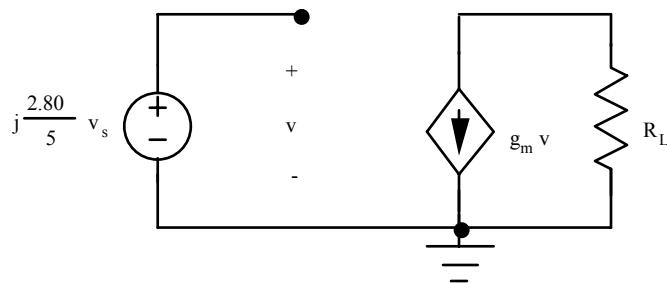
$$R_P = n^2 R_{EQ} = 25(133 \text{ }\Omega) = 3.33 \text{ k}\Omega \quad | \quad BW = \frac{1}{2\pi(3.33 \text{ k}\Omega)(28.2 \text{ pF})} = 1.70 \text{ MHz} \quad | \quad Q = \frac{13.4}{1.70} = 7.88$$

Note the huge error that would be caused by using only r_π as the input resistance term.

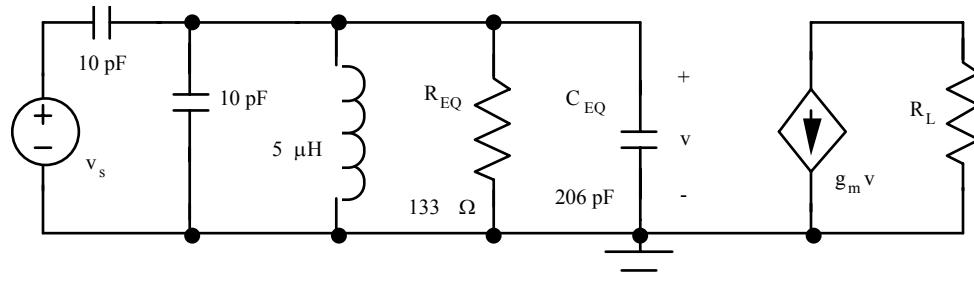


$$v_1 = j2\pi(13.4 \text{ MHz})(20 \text{ pF}) \left(\frac{1}{2} \right) (3.33 \text{ k}\Omega) v_i = j2.80 v_i$$

$$v_o = (-g_m R_L) \frac{j2.80 v_s}{5} = -40(10^{-3})(5 \text{ k}\Omega)j0.560 v_i \quad | \quad A_v = 112 \angle -90^\circ$$



16.99(b)



$$C_T = 5 \text{ pF} + 1 \text{ pF} [1 + 40(1 \text{ mA})(5 \text{ k}\Omega)] = 206 \text{ pF} \quad | \quad C_P = 20 \text{ pF} + 206 \text{ pF} = 226 \text{ pF}$$

$$f_o = \frac{1}{2\pi\sqrt{(5 \mu\text{H})(226 \text{ pF})}} = 4.74 \text{ MHz}$$

$$R_{EQ} = r_\pi \left| \frac{R_L}{(1 + g_m R_L)(\omega R_L C_\mu)^2} \right| = 2.5 \text{ k}\Omega \left| \frac{5000}{(1 + 200)[2\pi(4.74 \text{ MHz})(5 \text{ k}\Omega)(1 \text{ pF})]^2} \right|$$

$$R_{EQ} = 2.5 \text{ k}\Omega \parallel 1.12 \text{ k}\Omega = 774 \Omega \quad | \quad BW = \frac{1}{2\pi(774 \Omega)(226 \text{ pF})} = 910 \text{ kHz} \quad | \quad Q = \frac{4.74}{0.910} = 5.21$$

$$v_o = j2\pi(4.74 \text{ MHz})(10 \text{ pF})(774 \Omega)(-g_m R_L)v_i$$

$$v_o = j2\pi(4.74 \text{ MHz})(10 \text{ pF})(774 \Omega)[-0.04 \text{ mS}(5 \text{ k}\Omega)]v_i \quad | \quad A_v = 46.1 \angle -90^\circ$$

16.100 (a)

Referring to Eqns. (16.180-16.182) in *Jaeger and Blalock*,

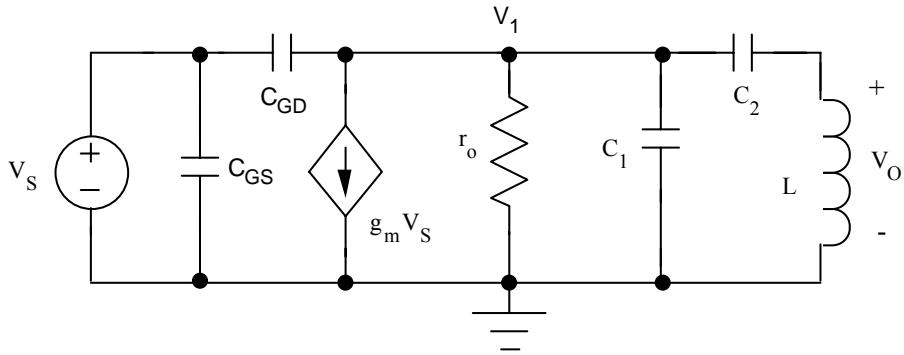
$$f_o = \frac{1}{2\pi\sqrt{L(C_{GD} + C)}} = \frac{1}{2\pi\sqrt{(10\mu H)(25\text{ pF})}} = 10.1 \text{ MHz}$$

$$r_o \approx \frac{1}{\lambda I_D} = \frac{1}{(0.02/V)(20mA)} = 2500\Omega \quad g_m \approx \sqrt{2K_n I_D} = \sqrt{2(0.005)(0.02)} = 14.1 \text{ mS}$$

$$BW = \frac{1}{2\pi(r_o)(C_{GD} + C)} = \frac{1}{2\pi(2.5k\Omega)(25\text{ pF})} = 2.55 \text{ MHz}$$

$$Q = \frac{10.1}{2.55} = 3.96 \quad | \quad A_{mid} = -g_m r_o = -\mu_f = -35.4$$

16.100(b)



$$\begin{bmatrix} (sC_{GD} - g_m)V_s \\ 0 \end{bmatrix} = \begin{bmatrix} s(C_1 + C_{GD} + C_2) + g_o & -sC_2 \\ -sC_2 & sC_2 + \frac{1}{sL} \end{bmatrix} \begin{bmatrix} V_1 \\ V_o \end{bmatrix} \quad | \quad A_V(j\omega) = \frac{V_o}{V_s} = \frac{j\omega C_2 (j\omega C_{GD} - g_m)}{\Delta}$$

Let $C_{EQ} = C_1 + C_{GD}$

$$\Delta(s) = C_{EQ} C_2 \left[s^2 + s \frac{g_o}{C_{EQ}} + \frac{g_o}{s C_{EQ} C_2 L} + \frac{C_{EQ} + C_2}{C_{EQ} C_2} \frac{1}{L} \right]$$

$$\Delta(j\omega) = C_{EQ} C_2 \left[\frac{C_{EQ} + C_2}{C_{EQ} C_2} \frac{1}{L} - \omega^2 + j\omega \frac{g_o}{C_{EQ}} + \frac{g_o}{j\omega C_{EQ} C_2 L} \right] \quad | \quad \omega_o^2 = \frac{C_{EQ} + C_2}{C_{EQ} C_2} \frac{1}{L}$$

$$A_v(j\omega_o) = -\frac{\omega_o \frac{g_m}{C_{EQ}} - j\omega_o^2 \frac{C_{GD}}{C_{EQ}}}{\omega_o \frac{g_o}{C_{EQ}} - \frac{g_o}{\omega_o C_{EQ} C_2 L}} = -\frac{g_m r_o}{1 - \frac{1}{\omega_o^2 L C_2}} \left(1 - j\omega_o \frac{C_{GD}}{g_m} \right)$$

$$A_v(j\omega_o) = -\frac{\mu_f}{1 - \frac{C_{EQ}}{C_{EQ} + C_2}} \left(1 - j \frac{\omega_o}{\omega_l} \right) = -\mu_f \left(1 + \frac{C_{EQ}}{C_2} \right) \left(1 - j \frac{\omega_o}{\omega_l} \right)$$

$$\text{But } \omega_l = \frac{g_m}{C_{GD}} > \omega_T. \text{ So, } A_v(j\omega_o) \approx -\mu_f \left(1 + \frac{C_{EQ}}{C_2} \right) \text{ for } \omega_l \ll \omega_T$$

Referring to Eqs. (17.192 - 17.193):

$$BW = \frac{\omega_o}{Q} = \frac{g_o}{C_{EQ}} - \frac{g_o}{\omega_o^2 C_{EQ} C_2 L} = \frac{1}{r_o C_{EQ}} \left(1 - \frac{1}{\omega_o^2 L C_2} \right) = \frac{1}{r_o C_{EQ} \left(1 + \frac{C_{EQ}}{C_2} \right)}$$

$$Q = \omega_o r_o C_{EQ} \left(1 + \frac{C_{EQ}}{C_2} \right)$$

$$\frac{C_2 C_{EQ}}{C_{EQ} + C_2} = \frac{45(40)}{45+40} pF = 21.2 pF \quad | \quad f_o = \frac{1}{2\pi\sqrt{(10\mu H)(21.2 pF)}} = 10.9 MHz$$

$$r_o \approx \frac{1}{0.02(20mA)} = 2.50 k\Omega \quad | \quad Q = 2\pi(10.9 MHz)(2.50 k\Omega)(45 pF) \left(1 + \frac{45}{40}\right) = 16.4$$

$$BW = \frac{10.9 MHz}{16.4} = 666 kHz$$

$$A_{mid} = -\mu_f \left(1 + \frac{C_{EQ}}{C_2}\right) = -\sqrt{2(0.005)(0.02)}(2500) \left(1 + \frac{45 pF}{40 pF}\right) = -75.1$$

Checking the approximation: $\left(\frac{1}{2\pi}\right) \frac{g_m}{C_{GD}} = \left(\frac{1}{2\pi}\right) \frac{\sqrt{2(0.005)(0.02)}}{5 pF} = 450 MHz \gg \omega_o$

16.101

$$C_{EQ} = \frac{(C_1 + 5 pF)C_2}{C_1 + 5 pF + C_2} = 25 pF \quad | \quad C_2 = 50 pF \quad | \quad C_1 = 45 pF$$

$$f_o = \frac{1}{2\pi\sqrt{(10\mu H)(25 pF)}} = 10.1 MHz \quad | \quad r_o = \frac{1}{0.02(20mA)} = 2.50 k\Omega$$

Using the results from Prob. 17.113: $BW = \frac{1}{2\pi(2.50 k\Omega)(50 pF) \left(1 + \frac{50 pF}{50 pF}\right)} = 635 kHz$

$$Q = \frac{10.1}{0.635} = 15.9 \quad | \quad A_{mid} = -\mu_f \left(1 + \frac{C_1}{C_2}\right) = -\sqrt{2(0.005)(0.02)}(2500) \left(1 + \frac{50 pF}{50 pF}\right) = -70.7$$

16.102

*Problem 16.102(a) - Fig. P16.100(a)

```
VS 1 0 AC 1
CGD 1 2 5PF
GM 2 0 1 0 14.1MS
RO 2 0 2.5K
C1 2 0 20PF
L1 2 0 10UH
.AC LIN 400 8MEG 12MEG
.PRINT AC VM(2) VP(2)
.PROBE V(2)
.END
```

Results: $A_{mid} = 35.3$, $f_o = 10.1$ MHz, $BW = 2.50$ MHz

*Problem 16.102(b) - Fig. P16.100(b)

```
VS 1 0 AC 1
CGD 1 2 5PF
GM 2 0 1 0 14.1MS
RO 2 0 2.5K
C1 2 0 40PF
C2 2 3 40PF
L1 3 0 10UH
.AC LIN 400 8MEG 12MEG
.PRINT AC VM(2) VP(2) VM(3) VP(3)
.PROBE V(2) V(3)
.END
```

Results: $A_{mid} = 75.1$, $f_o = 10.1$ MHz, $BW = 670$ kHz

*Problem 16.102(c) - Problem 16.101

```
VS 1 0 AC 1
CGD 1 2 5PF
GM 2 0 1 0 14.1MS
RO 2 0 2.5K
C1 2 0 45PF
C2 2 3 50PF
L1 3 0 10UH
.AC LIN 400 8MEG 12MEG
.PRINT AC VM(2) VP(2) VM(3) VP(3)
.PROBE V(2) V(3)
.END
```

Results: $A_{mid} = 70.7$, $f_o = 10.1$ MHz, $BW = 640$ kHz

16.103

$$(a) C_{EQ} \approx C_{GS1} + C_{GD1} \left(1 + g_{m1} R_L\right) = C_{GS1} + C_{GD1} \left(1 + \frac{g_{m1}}{g_{m2}}\right)$$

$$I_{D2} = I_{D1} = \frac{0.01}{2} \left[0 - (-1) \right]^2 = 5.00 \text{mA} \quad | \quad V_{GS2} = -4 + \sqrt{\frac{2(0.005)}{0.01}} = -3 \text{V}$$

$$V_{DS1} = V_{SG2} = +3 \text{V} > 1 \text{V} \rightarrow \text{Saturation region is ok.} \quad | \quad g_{m2} = g_{m1} = \sqrt{2(0.01)(0.005)} = 10.0 \text{mS}$$

$$C_{EQ} = 20 \text{pF} + 5 \text{pF} [1+1] = 30 \text{pF} \quad | \quad C_p = C_1 + C_3 + C_{EQ} = 20 \text{pF} + 20 \text{pF} + 30 \text{pF} = 70 \text{pF}$$

Require $C_2 + C_{GD} = C_p \rightarrow C_2 = 70 \text{pF} - 5 \text{pF} = 65 \text{pF}$

$$(b) f_o = \frac{1}{2\pi\sqrt{LC_p}} = \frac{1}{2\pi\sqrt{(10\mu\text{H})(70 \text{pF})}} = 6.02 \text{MHz} \quad | \quad R_{L1} = \frac{1}{g_{m2}}$$

$$R_p = R_G \left\| \frac{R_{L1}}{(1 + g_{m1} R_{L1})(\omega R_{L1} C_{GD1})^2} = 100 \text{k}\Omega \right\| \frac{100}{(1+1)[2\pi(6.02 \text{MHz})(100)(5 \text{pF})]^2}$$

$$R_p = 100 \text{k}\Omega \left\| 140 \text{k}\Omega = 58.3 \text{k}\Omega \quad | \quad BW_1 = \frac{1}{2\pi R_p C_p} = \frac{1}{2\pi(58.3 \text{k}\Omega)(70 \text{pF})} = 39.0 \text{kHz} \right.$$

$$BW_2 \cong BW_1 \sqrt{2^{\frac{1}{2}} - 1} = 25.1 \text{kHz} \quad | \quad \text{Note that this is an approximation since } R_p = 100 \text{k}\Omega$$

$$\text{at the output and } 58.3 \text{ k}\Omega \text{ at the input.} \quad | \quad Q = \frac{6.02 \text{ MHz}}{25.1 \text{ kHz}} = 240 \quad | \quad v_o = (\omega C_3 v_i)(R_p)(-g_m R_D)$$

$$A_{mid} = 2\pi(6.02 \text{MHz})(20 \text{pF})(58.3 \text{k}\Omega)(-10.0 \text{mS})(100 \text{k}\Omega) = 4.41 \times 10^4$$

16.104

*Problem 16.103 - Synchronously-Tuned Cascode Amplifier

VDD 5 0 DC 12

VS 1 0 AC 1

C3 1 2 20PF

L1 2 0 10UH

C1 2 0 20PF

RG 2 0 100K

M1 3 2 0 0 NFET1

CGS1 2 0 20PF

CGD1 2 3 5PF

M2 4 0 3 3 NFET2

CGS2 3 0 20PF

CGD2 4 3 5PF

L2 4 5 10UH

C2 4 5 65PF

RD 4 5 100K

.MODEL NFET1 NMOS VTO=-1 KP=10M

.MODEL NFET2 NMOS VTO=-4 KP=10M

.OP

.AC LIN 200 5.5MEG 6.5MEG

.PRINT AC VM(2) VP(2) VM(3) VP(3) VM(4) VP(4)

.PROBE

.END

Results: $A_{mid} = 279$, $f_o = 6.10 \text{ MHz}$, $Q = 24$

The amplifier is actually stagger-tuned. Note that the loop of capacitors around M_1 messes up the hand results based upon the C_{EQ} approximation. The C_{EQ} approximation itself may not be accurate enough for precise synchronous tuning. Plot a graph of $V(2)$ and $V(3)$ to show the problem. Evidence of the problem is also provided by the huge error in the mid-band gain.

16.105

From Prob. 16.103: $C_{P2} = \frac{1}{(2\pi f_o)^2 L} = \frac{1}{\left(2\pi \frac{1.02}{\sqrt{LC_{P1}}}\right)^2 L} = \frac{C_{P1}}{(1.02)^2} = \frac{70 \text{ pF}}{(1.02)^2} = 67.3 \text{ pF}$

$$C_2 = C_{P2} - C_{GD2} = 67.3 \text{ pF} - 5 \text{ pF} = 62.3 \text{ pF} \quad | \quad R_{p2} = 100k\Omega$$

$$BW_1 = \frac{1}{2\pi(58.3k\Omega)(70 \text{ pF})} = 39.0 \text{ kHz} \quad | \quad BW_2 = \frac{1}{2\pi(10^5 \Omega)(67.3 \text{ pF})} = 23.7 \text{ kHz}$$

$$BW \cong \frac{BW_1}{2} + 0.02f_{o1} + \frac{BW_2}{2} = \frac{39.0 \text{ kHz}}{2} + 0.02(6.02 \text{ MHz}) + \frac{23.7 \text{ kHz}}{2} = 152 \text{ kHz}$$

$$\text{The new } f_o \cong \frac{f_{o1} + 1.02f_o}{2} = 6.08 \text{ MHz} \quad | \quad Q = \frac{6.08 \text{ MHz}}{152 \text{ kHz}} = 40$$

16.106

*Problem 16.105 - Stagger-Tuned Cascode Amplifier

VDD 5 0 DC 12

VS 1 0 AC 1

C3 1 2 20PF

L1 2 0 10UH

C1 2 0 20PF

RG 2 0 100K

M1 3 2 0 0 NFET1

CGS1 2 0 20PF

CGD1 2 3 5PF

M2 4 0 3 3 NFET2

CGS2 3 0 20PF

CGD2 4 3 5PF

L2 4 5 10UH

C2 4 5 62.3PF

RD 4 5 100K

.MODEL NFET1 NMOS VTO=-1 KP=10M

.MODEL NFET2 NMOS VTO=-4 KP=10M

.OP

.AC LIN 200 5.5MEG 6.5MEG

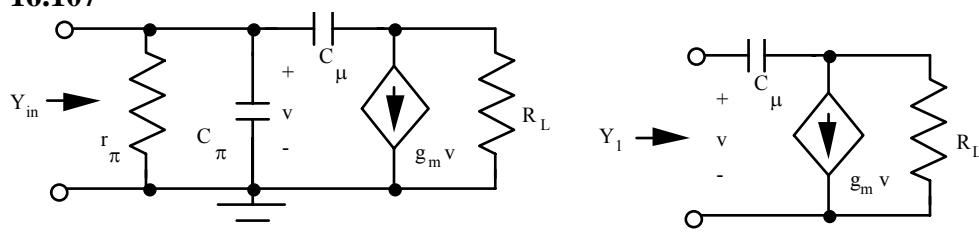
.PRINT AC VM(2) VP(2) VM(3) VP(3) VM(4) VP(4)

.PROBE

.END

Results: $A_{mid} = 512$, $f_o = 6.19$ MHz, $BW = 0.19$ MHz, $Q = 33$

16.107



$$Y_{in} = g_\pi + sC_\pi + Y_1 \quad | \quad (sC_\mu - g_m)V = (sC_\mu + G_L)V_o \quad | \quad V_o = \frac{(sC_\mu - g_m)}{(sC_\mu + G_L)}V$$

$$I = sC_\mu(V - V_o) = sC_\mu \frac{g_m + G_L}{(sC_\mu + G_L)}V \quad | \quad Y_1 = \frac{I}{V} = sC_\mu \frac{g_m + G_L}{(sC_\mu + G_L)} = sC_\mu \frac{1 + g_m R_L}{(sC_\mu R_L + 1)}$$

$$Y_1(j\omega) = j\omega C_\mu \frac{1 + g_m R_L}{(j\omega C_\mu R_L + 1)} = j\omega C_\mu (1 + g_m R_L) \frac{1 - j\omega C_\mu R_L}{(\omega C_\mu R_L)^2 + 1} \quad | \quad \text{For } (\omega C_\mu R_L)^2 \ll 1,$$

$$Y_1(j\omega) \approx j\omega C_\mu (1 + g_m R_L) + \frac{(1 + g_m R_L)}{R_L} (\omega C_\mu R_L)^2$$

From the results we see that the input capacitance is correctly modeled by the total Miller input capacitance, but the input resistance is not correctly modeled by just r_π :

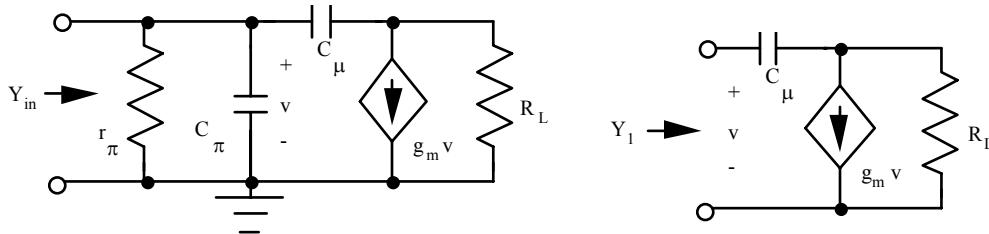
$$C_{in} = C_\pi + C_\mu(1 + g_m R_L) \quad | \quad R_{in} = r_\pi \left| \frac{R_L}{(1 + g_m R_L)(\omega C_\mu R_L)^2} \right.$$

$$(b) C_{in} = C_{GS} + C_{GD}(1 + g_m R_L) = 6 pF + 2 pF [1 + 5mS(10k\Omega)] = 108 pF$$

$$R_{in} = \frac{R_L}{(1 + g_m R_L)(\omega C_{GD} R_L)^2} = \frac{10k\Omega}{[1 + 5mS(10k\Omega)][2\pi(5 \times 10^6)(2pF)(10k\Omega)]^2} = 497\Omega !$$

Note also that $X_{C_{in}} = \frac{1}{2\pi(5 \times 10^6)(108 pF)} = 295 \Omega$ | Both values are far less than infinity.

Although the C_T approximation gives an excellent estimate for the dominant pole of the common-emitter amplifier, it does not do a good job of representing the input admittance at high frequencies. An improved estimate is needed for several of the problems to come.



$$Y_{in} = g_\pi + sC_\pi + Y_1 \quad | \quad (sC_\mu - g_m)V = (sC_\mu + G_L)V_o \quad | \quad V_o = \frac{(sC_\mu - g_m)}{(sC_\mu + G_L)}V$$

$$I = sC_\mu(V - V_o) = sC_\mu \frac{g_m + G_L}{(sC_\mu + G_L)}V \quad | \quad Y_1 = \frac{I}{V} = sC_\mu \frac{g_m + G_L}{(sC_\mu + G_L)} = sC_\mu \frac{1 + g_m R_L}{(sC_\mu R_L + 1)}$$

$$Y_1(j\omega) = j\omega C_\mu \frac{1 + g_m R_L}{(j\omega C_\mu R_L + 1)} = j\omega C_\mu (1 + g_m R_L) \frac{1 - j\omega C_\mu R_L}{(\omega C_\mu R_L)^2 + 1} \quad | \quad \text{For } (\omega C_\mu R_L)^2 \ll 1,$$

$$Y_1(j\omega) \approx j\omega C_\mu (1 + g_m R_L) + \frac{(1 + g_m R_L)}{R_L} (\omega C_\mu R_L)^2$$

From the results we see that the input capacitance is correctly modeled by the total Miller input capacitance, but the input resistance is not correctly modeled by just r_π :

$$C_{in} = C_\pi + C_\mu(1 + g_m R_L) \quad | \quad R_{in} = r_\pi \left| \frac{R_L}{(1 + g_m R_L)(\omega C_\mu R_L)^2} \right.$$

CHAPTER 17

17.1

$$(a) T = A\beta = \infty \quad | \quad A_v = \frac{1}{\beta} = 5 \quad | \quad FGE = 0$$

$$(b) A = 10^{\frac{80}{20}} = 10000 \quad | \quad T = 10000(0.2) = 2000$$

$$A_v = \frac{A}{1 + A\beta} = \frac{10000}{1 + 2000} = 5.00 \quad | \quad FGE = \frac{100\%}{1 + A\beta} = \frac{100\%}{2001} = 0.05\%$$

$$(c) T = 10(0.2) = 2 \quad | \quad A_v = \frac{A}{1 + A\beta} = \frac{10}{1 + 2} = 3.33 \quad | \quad FGE = \frac{100\%}{1 + 2} = 33.3\%$$

17.2

$$(a) \beta = \frac{R_1}{R_1 + R_2} = \frac{1k\Omega}{101k\Omega} = \frac{1}{101}$$

$$(b) T = A\beta = 10^{\frac{86}{20}} \left(\frac{1}{101} \right) = 198.6 \quad | \quad A_v = \frac{A}{1 + A\beta} = \frac{2 \times 10^4}{200} = 100$$

17.3

$$(a) \beta(s) = \frac{R_1}{R_1 + R_2} = \frac{1k\Omega}{101k\Omega} = \frac{1}{101} \quad | \quad T(s) = A\beta = 10^{\frac{80}{20}} \left(\frac{1}{101} \right) = 99.0$$

$$A_v = -\frac{R_2}{R_1} \frac{A\beta}{1 + A\beta} = -\left(\frac{100k\Omega}{1k\Omega} \right) \left(\frac{99}{100} \right) = -99$$

17.4

$$\beta(s) = \frac{Z_1(s)}{Z_1(s) + Z_2(s)} = \frac{R}{R + \frac{1}{sC}} = \frac{s}{s + \frac{1}{RC}} = \frac{s}{s + 5000} \quad | \quad A = 10^{\frac{80}{20}} = 10^4$$

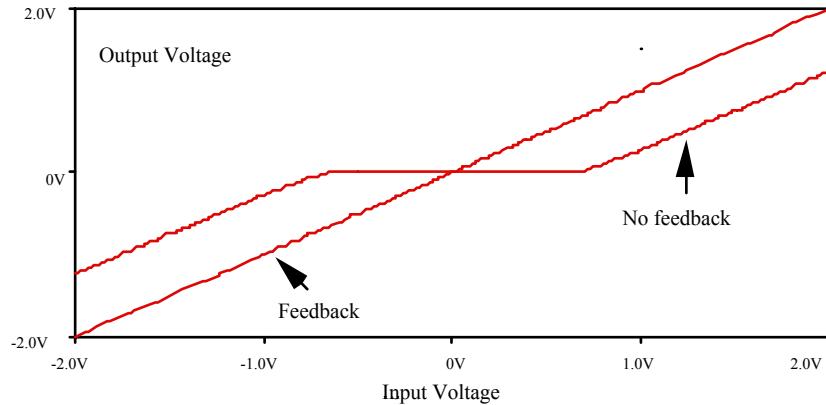
$$T(s) = A\beta = \frac{10^4 s}{s + 5000} \quad | \quad A_v = -\frac{Z_2}{Z_1} \frac{A\beta}{1 + A\beta} = -\left(\frac{1}{sRC} \right) \frac{\frac{10^4 s}{s + 5000}}{1 + \frac{10^4 s}{s + 5000}} = -\left(\frac{1}{RC} \right) \left(\frac{1}{s + 0.5} \right)$$

Instead of a pole at the origin, the integrator has a low-pass response with a pole at $\omega = 0.5$ rad/s.

17.5

$$A_v = \frac{A}{1+A\beta} = \frac{A}{1+A} \quad | \quad \text{From Chapter 12, } GE = \frac{1}{1+A\beta} = \frac{1}{1+A}$$

$$\frac{1}{1+A} \leq 10^{-4} \rightarrow A \geq 9999 \quad | \quad A \geq 80 \text{ dB}$$

17.6

*Problem 17.6 – Figure P17.6- Class-B Amplifiers

VCC 3 0 DC 10

VEE 4 0 DC -10

VI 1 0 DC 0

Q1 3 1 2 NBJT

Q2 4 1 2 PBJT

RL1 2 0 2K

RID 1 7 100K

E1 5 0 1 7 5000

RO 5 6 100

Q3 3 6 7 NBJT

Q4 4 6 7 PBJT

RL2 7 0 2K

.MODEL NBJT NPN

.MODEL PBJT PNP

.OP

.DC VS -10 10 .01

.PROBE V(1) V(2) V(7)

.END

17.7

$$A_v = \frac{A}{1+A\beta} \quad | \quad \text{From Chapter 12, } GE = \frac{1}{1+A\beta} \approx \frac{1}{A\beta}$$

$$\frac{1}{\beta} = 200 \quad | \quad GE \approx \frac{200}{A} \leq 0.002 \rightarrow A \geq \frac{200}{0.002} = 10^5 \quad | \quad A \geq 100 \text{ dB}$$

17.8

$$S_A^{A_v} = \frac{A}{A_v} \frac{\partial A_v}{\partial A} \quad A_v = \frac{A}{1 + A\beta}$$

$$\frac{\partial A_v}{\partial A} = \frac{(1 + A\beta)(1 - A\beta)}{(1 + A\beta)^2} = \frac{1}{(1 + A\beta)^2} \quad S_A^{A_v} = \frac{A}{\frac{A}{1 + A\beta}} \frac{1}{(1 + A\beta)^2} = \frac{1}{1 + A\beta} \approx \frac{1}{A\beta}$$

$$S_A^{A_v} = \frac{1}{1 + 10^5(0.01)} = \frac{1}{1001}$$

$$\frac{\partial A_v}{A_v} = S_A^{A_v} \frac{\partial A}{A} = \frac{1}{1001} 10\% = 9.99 \times 10^{-3}\%$$

17.9

- (a) Series-series feedback (b) Shunt-series feedback
 (c) Shunt-shunt feedback (d) Series-shunt feedback
-

17.10

- (a) Series-shunt feedback (b) Shunt-series feedback
 (c) Series-series feedback (d) Shunt-shunt feedback
-

17.11

- (a) Shunt-series and series-series feedback (b) Shunt-shunt and series-shunt feedback
-

17.12

- (a) Series-shunt and series-series feedback (b) Shunt-series and shunt-shunt and feedback
-

17.13

$$(a) A_v = 10^{\frac{86}{20}} = 20000 \quad | \quad A_i = \frac{i_o}{i_i} \quad | \quad i_o = i_i (40k\Omega) \frac{20000}{1k\Omega} \rightarrow A_i = 8.00 \times 10^5$$

With resistive feedback, the closed-loop gain cannot exceed the open-loop gain.

Therefore, $A_i \leq 8.00 \times 10^5$.

$$(b) A_{tr} = \frac{i_o}{v_i} = \frac{i_o}{i_i (40k\Omega)} = \frac{A_i}{(40k\Omega)} \quad | \quad A_{tr} \leq \frac{8 \times 10^5}{4 \times 10^4 \Omega} = 20 \text{ S}$$

17.14

$$A = 10^{\frac{90}{20}} = 31600$$

$$(a) R_{in} = R_{id}(1 + A\beta) \quad | \quad \text{For } \beta = 1, \quad R_{in} = 40k\Omega(1 + 31600) = 1.26 \text{ G}\Omega$$

$$(b) R_{in} = \frac{R_{id}}{(1 + A\beta)} \quad | \quad \text{For } \beta = 1, \quad R_{in} = \frac{40k\Omega}{(1 + 31600)} = 1.27 \Omega$$

$$(c) R_{out} = R_o(1 + A\beta) \quad | \quad \text{For } \beta = 1, \quad R_{out} = 1k\Omega(1 + 31600) = 31.6 M\Omega$$

$$(d) R_{out} = \frac{R_o}{(1 + A\beta)} \quad | \quad \text{For } \beta = 1, \quad R_{out} = \frac{1k\Omega}{(1 + 31600)} = 31.6 \text{ m}\Omega$$

17.15

The circuit topology is identical to Fig. 17.8.

$$h_{11}^F = 5k\Omega \parallel 45k\Omega = 4.50k\Omega \quad | \quad h_{22}^F = (45k\Omega + 5k\Omega)^{-1} = (50.0k\Omega)^{-1}$$

$$\beta = h_{12}^F = \left. \frac{v_1}{v_2} \right|_{i_2=0} = \frac{5k\Omega}{5k\Omega + 45k\Omega} = \frac{1}{10} \quad | \quad R_L \parallel \frac{1}{h_{22}^F} = 5k\Omega \parallel 50k\Omega = 4.55k\Omega$$

$$A = \frac{20k\Omega}{1k\Omega + 20k\Omega + 4.5k\Omega} (4000) \frac{4.55k\Omega}{1k\Omega + 4.55k\Omega} = 2570$$

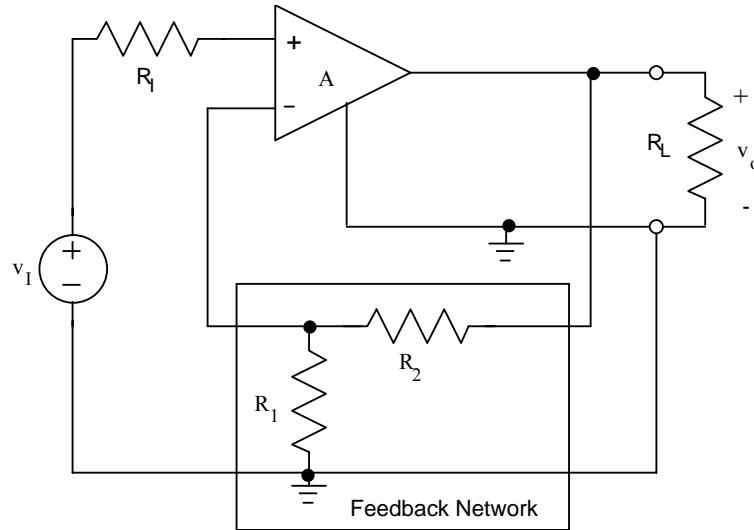
$$A_v = \frac{A}{1 + A\beta} = \frac{2570}{1 + 2570 \left(\frac{1}{10} \right)} = \frac{2570}{258} = 9.96$$

$$R_{in} = R_{in}^A(1 + A\beta) = (1k\Omega + 20k\Omega + 4.5k\Omega)(258) = 6.58 M\Omega$$

$$R_{out} = \frac{R_{out}^A}{1 + A\beta} = \frac{5k\Omega \parallel 50k\Omega \parallel 1k\Omega}{258} = 3.18 \Omega$$

17.16

(a)



$$(b) h_{11}^A = \frac{\mathbf{v}_1}{\mathbf{i}_1} \Big|_{\mathbf{v}_2=0} = 15k\Omega \quad | \quad h_{11}^F = 4.3k\Omega \parallel 39k\Omega = 3.87k\Omega \quad | \quad h_{11}^T = 18.9k\Omega$$

$$h_{22}^A = \frac{\mathbf{i}_2}{\mathbf{v}_2} \Big|_{\mathbf{i}_1=0} = (1k\Omega)^{-1} = (1k\Omega)^{-1} \quad | \quad h_{22}^F = (39k\Omega + 4.3k\Omega)^{-1} = (43.3k\Omega)^{-1} \quad | \quad h_{22}^T = +1.02mS$$

$$h_{21}^A = \frac{\mathbf{i}_2}{\mathbf{i}_1} \Big|_{\mathbf{v}_2=0} = -\frac{20k\Omega(4000)}{1k\Omega} = -80,000 \quad | \quad h_{21}^F = \frac{\mathbf{i}_2}{\mathbf{i}_1} \Big|_{\mathbf{v}_2=0} = -\frac{4.3k\Omega}{39k\Omega + 4.3k\Omega} = -0.0993$$

$$h_{12}^A = \frac{\mathbf{v}_1}{\mathbf{v}_2} \Big|_{\mathbf{i}_1=0} = 0 \quad | \quad h_{12}^F = \frac{\mathbf{v}_1}{\mathbf{v}_2} \Big|_{\mathbf{i}_2=0} = \frac{4.3k\Omega}{39k\Omega + 4.3k\Omega} = 0.0993$$

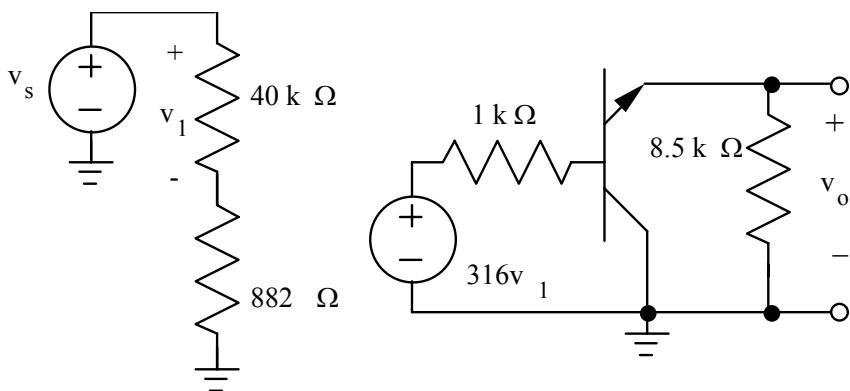
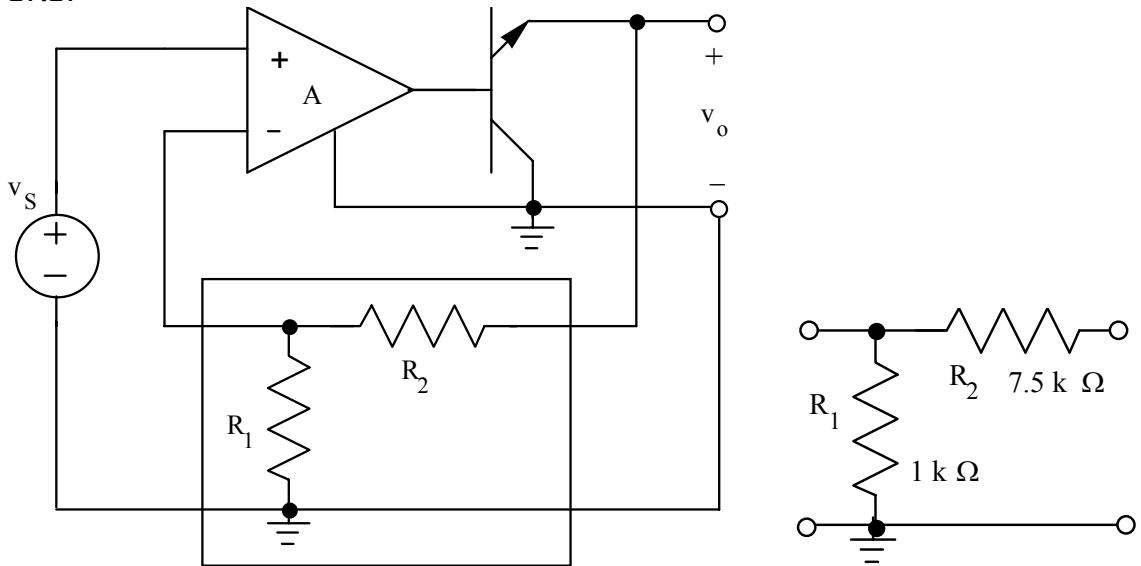
$$(c) A = \frac{-h_{21}^A}{(R_I + h_{11}^T)(h_{22}^T + G_L)} = \frac{-(-80000)}{(1k\Omega + 20k\Omega + 3.87k\Omega) \left(\frac{1}{5.6k\Omega} + \frac{1}{1k\Omega} + \frac{1}{43.3k\Omega} \right)} = 2680$$

$$\beta = 0.0993$$

$$(d) A_v = \frac{2680}{1 + 2680(0.0993)} = 10.0$$

$$(e) h_{21}^A \gg h_{21}^F \quad | \quad h_{12}^F \gg h_{12}^A \quad | \quad \text{Note: } (R_{in} = 6.64 M\Omega, R_{out} = 3.11 \Omega)$$

17.17



$$h_{11}^F = \left. \frac{v_1}{i_1} \right|_{v_2=0} = 1k\Omega \parallel 7.5k\Omega = 882\Omega \quad | \quad h_{22}^F = \left. \frac{i_2}{v_2} \right|_{i_1=0} = \frac{1}{1k\Omega + 7.5k\Omega} = \frac{1}{8.5k\Omega}$$

$$\beta = h_{12}^F = \left. \frac{v_1}{v_2} \right|_{i_1=0} = \frac{1k\Omega}{1k\Omega + 7.5k\Omega} = \frac{1}{8.5}$$

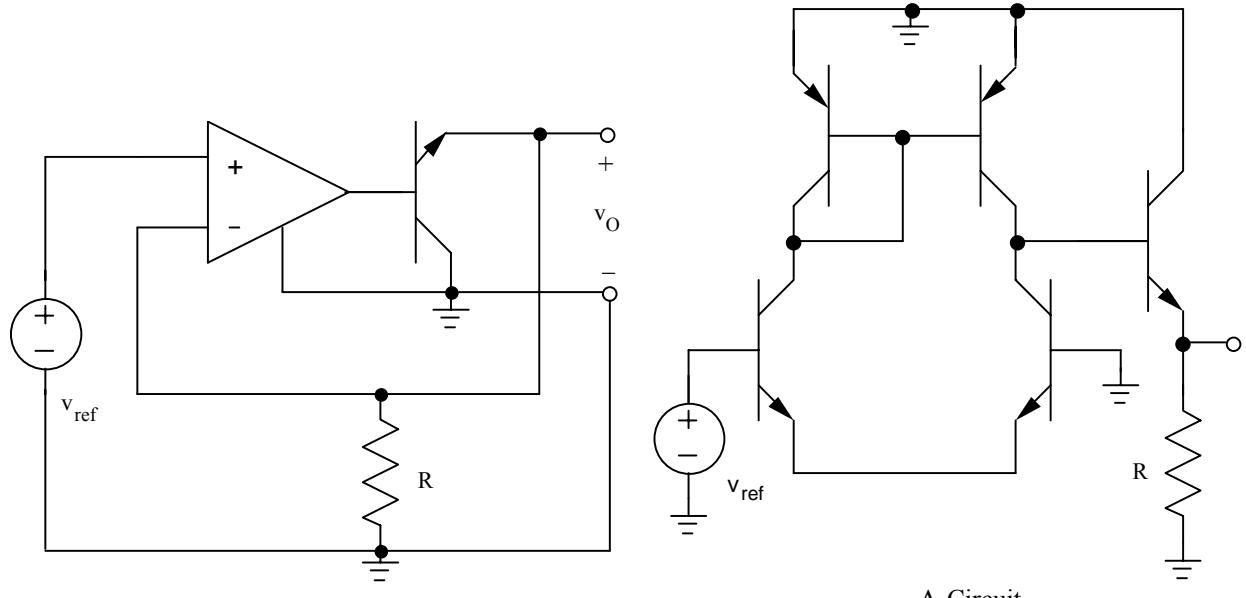
$$I_C = \alpha_F I_E = \frac{100}{101} (200\mu A) = 198\mu A \quad | \quad r_\pi = \frac{100(0.025V)}{198\mu A} = 12.6k\Omega$$

$$A = \frac{v_o}{v_s} = \frac{40k\Omega}{40k\Omega + 0.882k\Omega} (316) \frac{(\beta_o + 1)8.5k\Omega}{R_o + r_\pi + (\beta_o + 1)8.5k\Omega} = 309 \frac{(101)8.5k\Omega}{1k\Omega + 12.6k\Omega + (101)8.5k\Omega} = 304$$

$$A_v = \frac{A}{1+T} = \frac{304}{1+304\left(\frac{1}{8.5}\right)} = \frac{304}{36.8} = 8.27$$

$$R_{in} = R_{in}^A (1+T) = 40.9k\Omega (36.8) = 1.51M\Omega \quad | \quad R_{out} = \frac{R_{out}^A}{1+T} = \frac{8.5k\Omega \parallel \frac{12.6k\Omega + 1k\Omega}{101}}{36.8} = 3.60\Omega$$

17.18



A-Circuit

$$h_{11}^F = \left. \frac{v_1}{i_1} \right|_{v_2=0} = 0 \quad | \quad h_{22}^F = \left. \frac{i_2}{v_2} \right|_{i_1=0} = \frac{1}{R} \quad | \quad h_{12}^F = \left. \frac{v_1}{v_2} \right|_{i_2=0} = 1$$

$$A = g_{m1} \left(r_{o2} \| r_{o4} \parallel [r_{\pi 5} + (\beta_o + 1)R] \right) \frac{(\beta_o + 1)R}{r_{\pi 5} + (\beta_o + 1)R} = g_{m1} \frac{r_{o2} \| r_{o4}}{(r_{o2} \| r_{o4}) + r_{\pi 5} + (\beta_o + 1)R} (\beta_o + 1)R$$

$$r_{o2} = \frac{50 + 1.4}{10^{-4}} = 514 k\Omega \quad | \quad r_{o4} = \frac{50 + 11.3}{10^{-4}} = 613 k\Omega \quad | \quad r_{o2} \| r_{o4} = 280 k\Omega$$

$$I_{C5} \equiv I_{E5} \equiv \frac{12}{10^4} = 1.2 mA \quad | \quad r_{\pi 5} = \frac{100(0.025)}{1.2 mA} = 2.08 k\Omega$$

$$A = 40(10^{-4})(280 k\Omega) \frac{(101)10 k\Omega}{280 k\Omega + 2.08 k\Omega + (101)10 k\Omega} = 876$$

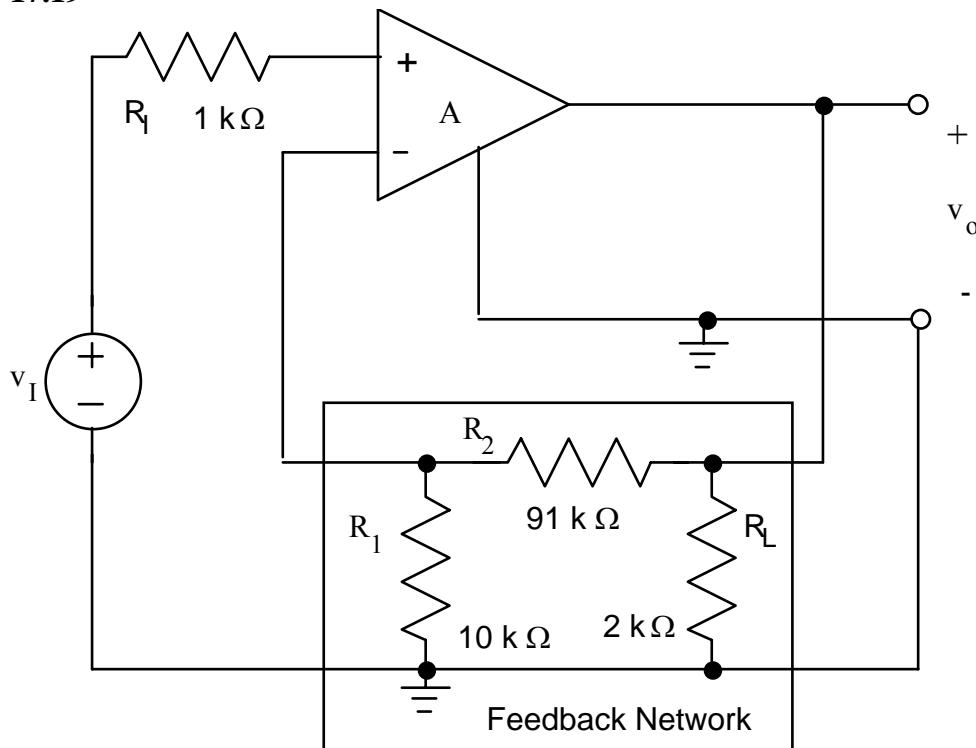
$$A_v = \frac{A}{1+T} = \frac{876}{1+876(1)} = \frac{109}{110} = 0.999$$

$$R_{in} = R_{id}(1+T) = 2r_{\pi 1}(1+T) = 2 \frac{100(0.025)}{10^{-4}} (877) = 43.9 M\Omega$$

$$R_{out} = \frac{R \left\| \frac{r_{\pi 5} + r_{o2} \| r_{o4}}{\beta_o + 1} \right\|}{1+T} = \frac{10 k\Omega \left\| \frac{2.08 k\Omega + 280 k\Omega}{101} \right\|}{877} = 2.49 \Omega$$

$$i_o = \alpha_o i_e = \alpha_o \frac{v_o}{R} \quad | \quad \frac{i_o}{v_{ref}} = \frac{\alpha_o}{R} \frac{v_o}{v_{ref}} = \frac{100}{101} \left(\frac{1}{10^4} \right) (0.999) = 98.9 \mu S$$

17.19



$$h_{11}^F = \left. \frac{v_1}{i_1} \right|_{v_2=0} = 10k\Omega \parallel 91k\Omega = 9.01k\Omega \quad | \quad h_{22}^F = \left. \frac{i_2}{v_2} \right|_{i_1=0} = \frac{1}{2k\Omega \parallel (1k\Omega + 7.5k\Omega)} = \frac{1}{1.96k\Omega}$$

$$\beta = h_{12}^F = \left. \frac{v_1}{v_2} \right|_{i_2=0} = \frac{10k\Omega}{10k\Omega + 91k\Omega} = \frac{1}{0.0990}$$

$$A = \frac{v_o}{v_i} = \frac{25k\Omega}{1k\Omega + 25k\Omega + 9.01k\Omega} (10^4) \frac{1.96k\Omega}{1k\Omega + 1.96k\Omega} = 4730$$

$$A_v = \frac{A}{1 + A\beta} = \frac{4730}{1 + 4730(0.990)} = 10.1 \quad | \quad R_{in} = R_{in}^A (1 + T) = 34.0k\Omega (469) = 16.0 M\Omega$$

$$R_{out} = \frac{R_{out}^A}{1 + T} = \frac{1.96k\Omega \parallel 1k\Omega}{469} = 1.41 \Omega$$

17.20

$$(a) S_A^{R_{in}} = \frac{A}{R_{in}} \frac{\partial R_{in}}{\partial A} \quad | \quad R_{in} = R_{in}^A (1 + A\beta) \quad | \quad S_A^{R_{in}} = \frac{A}{R_{in}^A (1 + A\beta)} R_{in}^A \beta = \frac{A\beta}{(1 + A\beta)} \approx 1$$

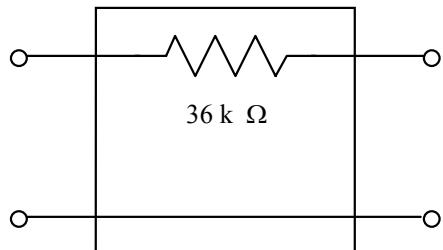
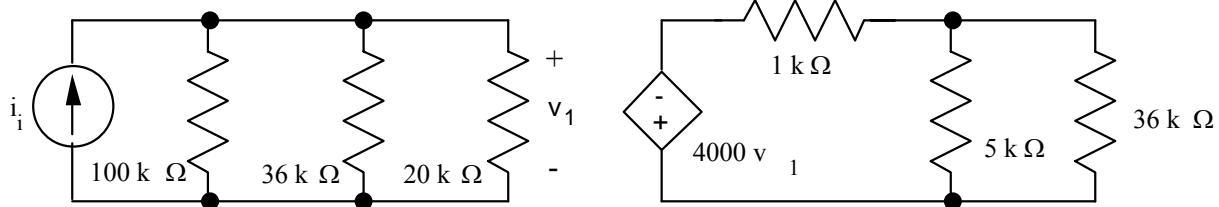
$$(b) \frac{\partial R_{in}}{R_{in}} = S_A^{R_{in}} \frac{\partial A}{A} = \frac{5 \times 10^4 (0.01)}{1 + 5 \times 10^4 (0.01)} 10\% = 9.98\%$$

$$(c) S_A^{R_{out}} = \frac{A}{R_{out}} \frac{\partial R_{out}}{\partial A} \quad | \quad R_{out} = \frac{R_{out}^A}{(1 + A\beta)} \quad | \quad \frac{\partial R_{out}}{\partial A} = -\frac{\beta R_{out}^A}{(1 + A\beta)^2}$$

$$S_A^{R_{out}} = -\frac{A(1 + A\beta)}{R_{out}^A} \frac{\beta R_{out}^A}{(1 + A\beta)^2} = -\frac{A\beta}{(1 + A\beta)} \approx -1$$

$$(d) \frac{\partial R_{out}}{R_{out}} = S_A^{R_{out}} \frac{\partial A}{A} = -\frac{10^5 (0.01)}{1 + 10^5 (0.01)} 10\% = -9.99\%$$

17.21



$$y_{11}^F = \left. \frac{i_1}{v_1} \right|_{v_2=0} = \frac{1}{36k\Omega} \quad | \quad y_{22}^F = \left. \frac{i_2}{v_2} \right|_{v_1=0} = \frac{1}{36k\Omega} \quad | \quad y_{12}^F = \left. \frac{i_1}{v_2} \right|_{v_1=0} = -\frac{1}{36k\Omega}$$

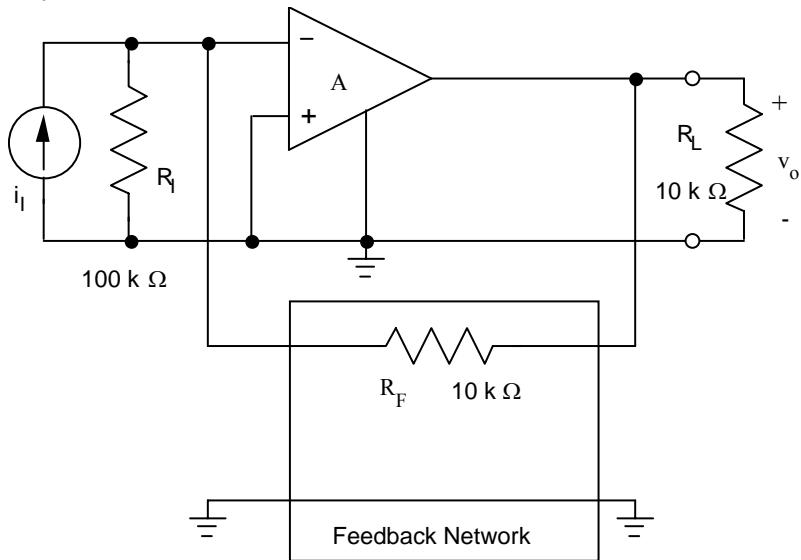
$$(20k\Omega \parallel 36k\Omega \parallel 100k\Omega) = 11.4k\Omega \quad | \quad (5k\Omega \parallel 36k\Omega) = 4.39k\Omega$$

$$A = \frac{v_o}{i_i} = -4000 \frac{4.39k\Omega}{1k\Omega + 4.39k\Omega} (11.4k\Omega) = -3.71 \times 10^7$$

$$A_r = \frac{A}{1 + A\beta} = \frac{-3.71 \times 10^7}{1 + (-3.71 \times 10^7) \left(-\frac{1}{36 \times 10^3} \right)} = -36.0 \text{ k}\Omega$$

$$R_{in} = \frac{(20k\Omega \parallel 36k\Omega \parallel 100k\Omega)}{1 + (-3.71 \times 10^7) \left(-\frac{1}{36 \times 10^3} \right)} = 11.1 \Omega \quad | \quad R_{out} = \frac{(36k\Omega \parallel 5k\Omega \parallel 1k\Omega)}{1 + (-3.71 \times 10^7) \left(-\frac{1}{36 \times 10^3} \right)} = 0.790 \Omega$$

17.22



$$y_{11}^A = \left. \frac{i_1}{v_1} \right|_{v_2=0} = \frac{1}{20k\Omega} \quad | \quad y_{22}^A = \left. \frac{i_2}{v_2} \right|_{v_1=0} = \frac{1}{1k\Omega} \quad | \quad y_{21}^A = \left. \frac{i_2}{v_1} \right|_{v_2=0} = -\frac{(-4000)}{1k\Omega} = 4S \quad | \quad y_{12}^A = \left. \frac{i_1}{v_2} \right|_{v_1=0} = 0$$

$$y_{11}^F = \left. \frac{i_1}{v_1} \right|_{v_2=0} = \frac{1}{10k\Omega} \quad | \quad y_{22}^F = \left. \frac{i_2}{v_2} \right|_{v_1=0} = \frac{1}{10k\Omega} \quad | \quad y_{12}^F = \left. \frac{i_1}{v_2} \right|_{v_1=0} = -\frac{1}{10k\Omega} \quad | \quad y_{21}^F = \left. \frac{i_2}{v_1} \right|_{v_2=0} = -\frac{1}{10k\Omega}$$

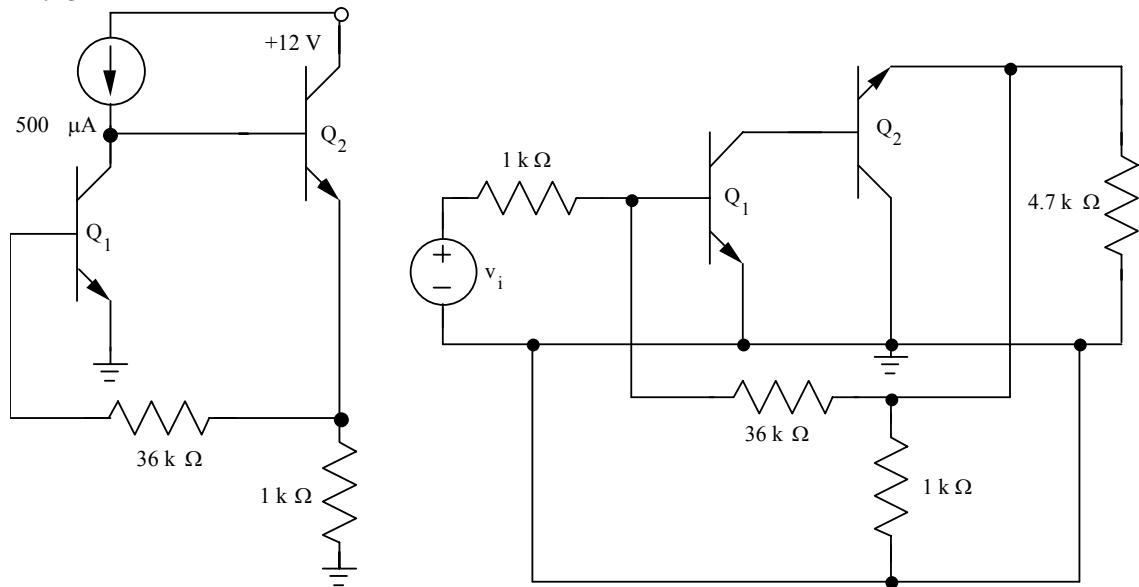
$$y_{11}^T = \frac{1}{20k\Omega} + \frac{1}{10k\Omega} = 0.150mS \quad | \quad y_{22}^T = \frac{1}{1k\Omega} + \frac{1}{10k\Omega} = 1.10mS$$

$$A = \frac{-y_{21}^A}{(G_I + y_{11}^T)(y_{22}^T + G_L)} = \frac{-4}{(10^{-5} + 0.150 \times 10^{-3})(1.1 \times 10^{-3} + 10^{-4})} = -2.08 \times 10^7 \Omega \quad | \quad \beta = y_{12}^F = -10^{-4}$$

$$A_{tr} = \frac{A}{1 + A\beta} = \frac{-2.08 \times 10^7 \Omega}{1 + (-2.08 \times 10^7 \Omega)(-10^{-4} S)} = -10.0 k\Omega \quad | \quad A\beta = 2080$$

$$\text{Note: } R_{in} = \frac{100k\Omega \parallel 10k\Omega \parallel 20k\Omega}{1 + 2080} = 1.92 \Omega \quad | \quad R_{out} = \frac{10k\Omega \parallel 1k\Omega \parallel 10k\Omega}{1 + 2080} = 0.400 \Omega$$

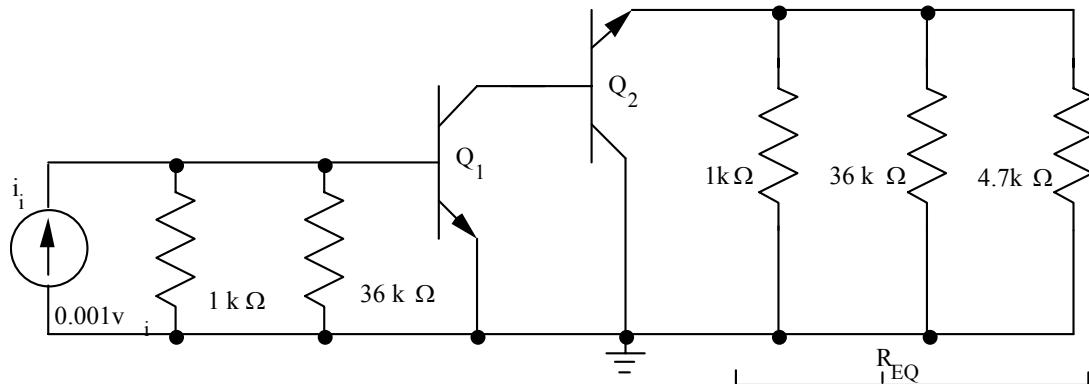
17.23



$$I_{C1} = 500\mu A - I_{B2} \quad | \quad I_{E2} = I_{B1} + \frac{36000I_{B1} + 0.7}{1000} = 37I_{B1} + 700\mu A \quad | \quad I_{B2} = \frac{I_{E2}}{101}$$

$$I_{C1} = 500\mu A - \frac{37I_{B1} + 700\mu A}{101} = 493\mu A - 0.366I_{B1} \rightarrow I_{C1} = 491.2\mu A$$

$$I_{E2} = 37 \frac{I_{C1}}{100} + 700\mu A = 881.7\mu A \quad | \quad I_{C2} = \frac{100}{101}I_{E2} = 873\mu A$$



$$y_{11}^F = \left. \frac{i_1}{v_1} \right|_{v_2=0} = \frac{1}{36k\Omega} \quad | \quad y_{22}^F = \left. \frac{i_2}{v_2} \right|_{v_1=0} = \frac{1}{36k\Omega \| 1k\Omega} \quad | \quad y_{12}^F = \left. \frac{i_1}{v_2} \right|_{v_1=0} = -\frac{1}{36k\Omega}$$

$$r_{\pi 1} = \frac{100(0.025)}{491\mu A} = 5.09k\Omega \quad | \quad r_{\pi 2} = \frac{100(0.025)}{873\mu A} = 2.86k\Omega \quad | \quad r_{o1} = \frac{50+1.6}{493 \times 10^{-6}} = 105k\Omega$$

$$R_E = (1k\Omega \| 36k\Omega \| 4.7k\Omega) = 807\Omega$$

$$A = \frac{v_o}{i_i} = (1k\Omega \| 36k\Omega \| r_{\pi 1}) g_{m1} [r_{o1} (r_{\pi 2} + (\beta_o + 1)R_E)] \frac{r_{\pi 2} + (\beta_o + 1)R_E}{r_{o1} + r_{\pi 2} + (\beta_o + 1)R_E}$$

$$A = \frac{v_o}{i_i} = -(1k\Omega \| 36k\Omega \| 5.09k\Omega) g_{m1} [r_{o1} (r_{\pi 2} + (\beta_o + 1)R_{EQ})] \frac{(\beta_o + 1)R_{EQ}}{r_{\pi 2} + (\beta_o + 1)R_{EQ}}$$

$$(1k\Omega \| 36k\Omega \| r_{\pi 1}) = (1k\Omega \| 36k\Omega \| 5.09k\Omega) = 817\Omega \quad | \quad g_m = 40(491\mu A) = 19.6mS$$

$$[r_{o1} (r_{\pi 2} + (\beta_o + 1)R_{EQ})] = [105k\Omega \| (2.86k\Omega + (101)806\Omega)] = 46.8k\Omega$$

$$R_{EQ} = 1k\Omega \| 36k\Omega \| 4.7k\Omega = 806\Omega \quad | \quad \frac{(\beta_o + 1)R_{EQ}}{r_{\pi 2} + (\beta_o + 1)R_{EQ}} = \frac{(101)806\Omega}{2.86k\Omega + (101)806\Omega} = 0.966$$

$$A = -(817\Omega)(19.6mS)(46.8k\Omega)(0.966) = -724 k\Omega \quad | \quad A\beta = -724 k\Omega \left(-\frac{1}{36k\Omega} \right) = 20.1$$

$$A_{tr} = \frac{A}{1 + A\beta} = \frac{-724k\Omega}{1 + 20.1} = -36.0 k\Omega$$

Note: $R_{in} = \frac{(1k\Omega \| 36k\Omega \| 5.09k\Omega)}{1 + 20.1} = 38.7\Omega \quad | \quad R_{in} = \left(R_{EQ} \left\| \frac{r_{\pi 2} + r_{o1}}{\beta_o + 1} \right. \right) \frac{1}{1 + A\beta} = 21.8\Omega$

$$R_{in} = \frac{(1k\Omega \| 36k\Omega \| 5.09k\Omega)}{1 + A\beta} = \frac{817\Omega}{9.94} = 82.2 \Omega$$

$$R_{out} = \frac{\left(1k\Omega \| 36k\Omega \| 4.7k\Omega \left\| \frac{r_{\pi 2} + r_{o1}}{101} \right. \right)}{1 + A\beta} = \frac{\left(806\Omega \left\| \frac{2.86k\Omega + 105k\Omega}{101} \right. \right)}{9.94} = 46.2 \Omega$$

$$i_i = 10^{-3} v_i \rightarrow A_v = \frac{v_o}{v_i} = \frac{v_o}{1000 i_i} = -32.4$$

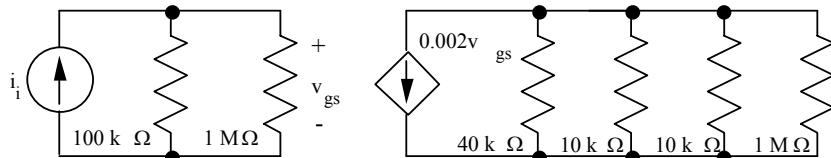
Note that this amplifier can be analyzed as a shunt-series feedback amplifier. This is good for student practice - see Problem 17.32.

17.24

*Problem 17.24 – Figure P17.23
 VCC 5 0 DC 12
 IDC 5 4 DC 500UA
 II 0 2 AC 1
 *IX 0 7 AC 1
 RS 2 0 1K
 C1 2 3 82UF
 Q1 4 3 0 NBJT
 Q2 5 4 6 NBJT
 RF 3 6 36K
 RE 6 0 1K
 C2 6 7 47UF
 RL 7 0 4.7K
 .MODEL NBJT NPN BF=100 VA=50 IS=1E-15
 .OP
 .AC DEC 100 1E2 1E7
 .PRINT AC VM(7) VP(7) VM(2) VP(2)
 .END

Results: $A_{tr} = -34.4 \text{ k}\Omega$, $R_{in} = 36.8 \Omega$, $R_{out} = 17.6 \Omega$ -- Note that these values are highly sensitive to the precise value of $r_{\pi 1}$.

17.25



$$y_{11}^F = \left. \frac{i_1}{v_1} \right|_{v_2=0} = 10^{-6} S \quad | \quad y_{22}^F = \left. \frac{i_2}{v_2} \right|_{v_1=0} = 10^{-6} S \quad | \quad y_{12}^F = \left. \frac{i_1}{v_2} \right|_{v_1=0} = -10^{-6} S$$

$$v_{gs} = i_i (100k\Omega \| 1M\Omega) = (90.9k\Omega) i_i \quad | \quad v_o = -(2 \times 10^{-3}) v_{gs} (40k\Omega \| 10k\Omega \| 10k\Omega \| 1M\Omega)$$

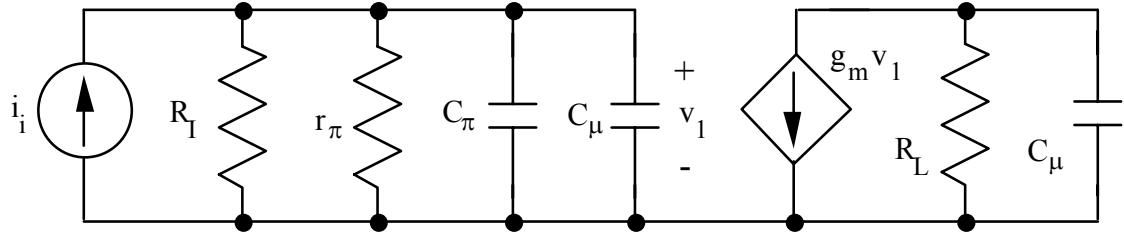
$$A = \frac{v_o}{i_i} = -(2mS)(4.44k\Omega)(90.9k\Omega) = -8.08 \times 10^5$$

$$A_r = \frac{A}{1 + A\beta} = \frac{-8.08 \times 10^5}{1 + (-8.08 \times 10^5)(-10^{-6})} = \frac{-8.08 \times 10^5}{1.81} = -446 \text{ k}\Omega$$

$$R_{in} = \frac{(100k\Omega \| 1M\Omega)}{(1 + A\beta)} = \frac{90.9k\Omega}{1.81} = 50.2 \text{ k}\Omega$$

$$R_{out} = \frac{(40k\Omega \| 10k\Omega \| 10k\Omega \| 1M\Omega)}{(1 + A\beta)} = \frac{4.44k\Omega}{1.81} = 2.45k\Omega$$

17.26



$$y_{12}^F = -sC_\mu \quad | \quad A = \frac{v_o}{i_i} = -\frac{r_{\pi o}}{s(C_\pi + C_\mu)r_{\pi o} + 1} (g_m) \frac{R_L}{sC_\mu R_L + 1} = -\frac{g_m r_{\pi o} R_L}{[s(C_\pi + C_\mu)r_{\pi o} + 1][sC_\mu R_L + 1]}$$

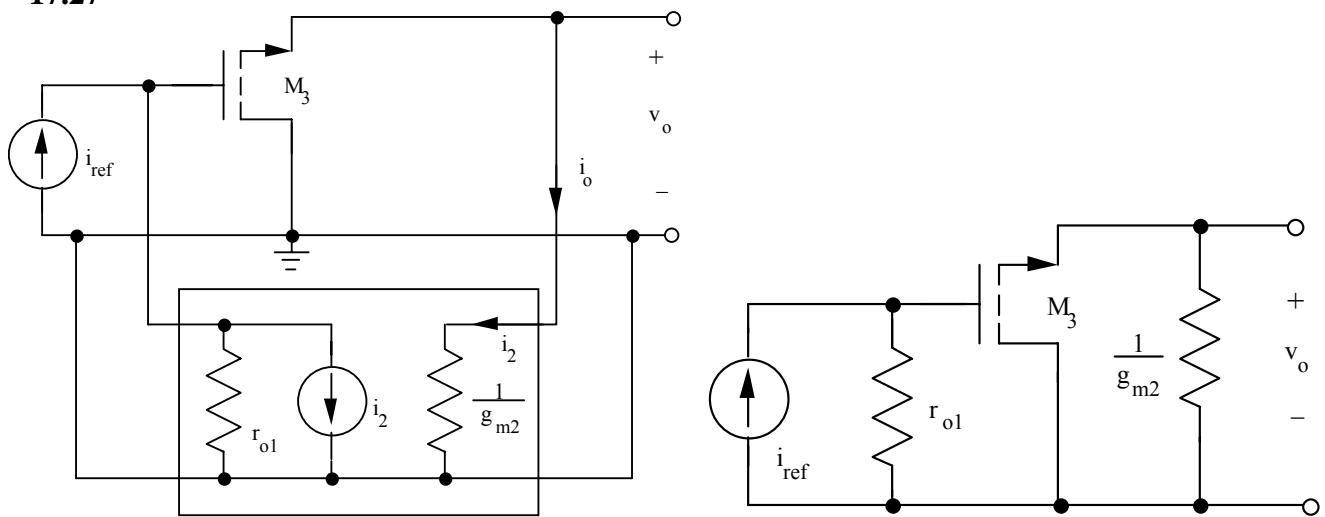
$$Z_{in}^A = \frac{r_{\pi o}}{s(C_\pi + C_\mu)r_{\pi o} + 1} \quad | \quad Z_{in} = \frac{Z_{in}^A}{1 + A\beta} = \frac{\frac{r_{\pi o}}{s(C_\pi + C_\mu)r_{\pi o} + 1}}{1 - \frac{g_m r_{\pi o} R_L}{[s(C_\pi + C_\mu)r_{\pi o} + 1][sC_\mu R_L + 1]}(-sC_\mu)}$$

$$\text{where } r_{\pi o} = r_\pi \| R_I \quad | \quad Z_{in} = \frac{r_{\pi o}(sC_\mu R_L + 1)}{[s(C_\pi + C_\mu)r_{\pi o} + 1][sC_\mu R_L + 1] + sC_\mu g_m r_{\pi o} R_L}$$

$$Z_{in} = \frac{r_{\pi o}(sC_\mu R_L + 1)}{s^2(C_\pi + C_\mu)C_\mu r_{\pi o} R_L + sr_{\pi o} \left[C_\pi + C_\mu(1 + g_m R_L) + \frac{R_L}{r_{\pi o}} \right] + 1} = \frac{r_{\pi o}(sC_\mu R_L + 1)}{s^2(C_\pi + C_\mu)C_\mu r_{\pi o} R_L + sr_{\pi o} C_T + 1}$$

$$Z_{in} \equiv \frac{r_{\pi o}(sC_\mu R_L + 1)}{sr_{\pi o} \left[C_\pi + C_\mu(1 + g_m R_L) + \frac{R_L}{r_{\pi o}} \right] + 1} = \frac{r_{\pi o}(sC_\mu R_L + 1)}{sr_{\pi o} C_T + 1} \text{ for } \omega \ll \omega_T$$

17.27



$$y_{11}^F = \frac{i_1}{v_1} \Big|_{v_2=0} = g_{o1} \quad | \quad y_{22}^F = \frac{i_2}{v_2} \Big|_{v_1=0} = g_{m2} \quad | \quad y_{12}^F = \frac{i_1}{v_2} \Big|_{v_1=0} = g_{m2}$$

$$A = \frac{v_o}{i_{ref}} = r_{o1} \frac{\frac{1}{g_{m3}} \frac{1}{g_{m2}}}{1 + \frac{1}{g_{m3}} \frac{1}{g_{m2}}} = \frac{r_{o1}}{2} \quad | \quad A_{tr} = \frac{A}{1 + A\beta} = \frac{\frac{r_{o1}}{2}}{1 + \frac{r_{o1}}{2} (g_{m2})} = \frac{r_{o1}}{2 + \mu_{f1}}$$

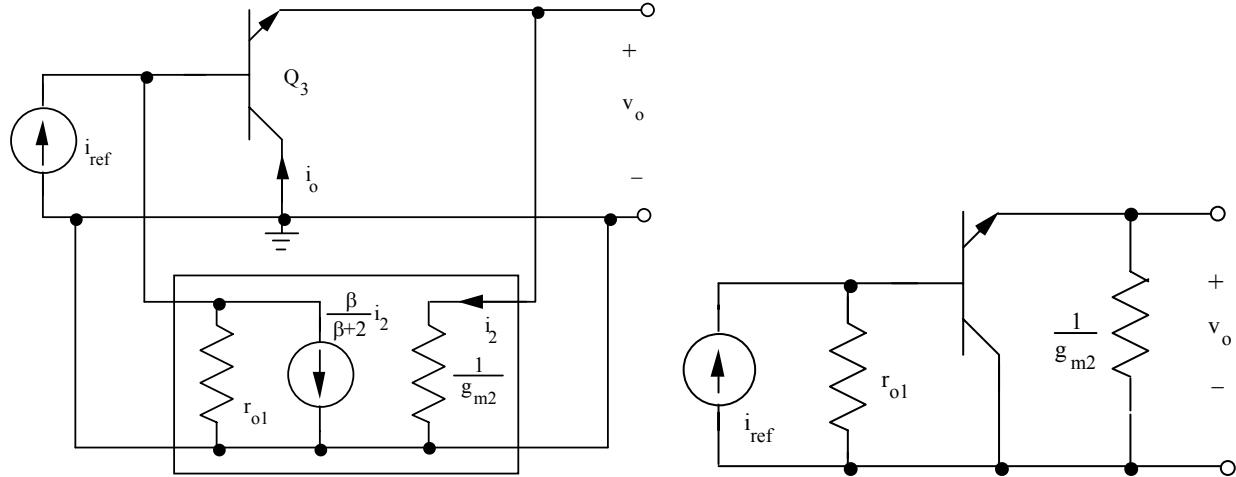
$$R_{in} = \frac{r_{o1}}{1 + A\beta} = \frac{r_{o1}}{1 + \frac{\mu_{f2}}{2}} = \frac{36k\Omega}{1 + \frac{72}{2}} = 973\Omega \quad | \quad \text{Note: } R_{in} \cong \frac{2}{g_m}$$

$$i_o = i_2 = g_{m2}v_o = g_{m2} \frac{r_{o1}}{\mu_{f1} + 2} i_{ref} \quad | \quad \frac{i_o}{i_{ref}} = \frac{\mu_{f1}}{\mu_{f1} + 2} = 0.973$$

17.28

$$y_{11}^F = \left. \frac{i_1}{v_1} \right|_{v_2=0} = g_{o1} \quad | \quad y_{22}^F = \left. \frac{i_2}{v_2} \right|_{v_1=0} = g_{m2} \quad | \quad y_{12}^F = \left. \frac{i_1}{v_2} \right|_{v_1=0} = \frac{\beta}{\beta+2} g_{m2} \cong g_{m2}$$

$$i_o = \alpha_o i_2 = \alpha_o g_{m2} v_o \quad | \quad A = \frac{v_o}{i_{ref}} = r_{o1} \frac{(\beta_o + 1) \frac{1}{g_{m2}}}{r_{o1} + r_{\pi3} + (\beta_o + 1) \frac{1}{g_{m2}}} \cong r_{o1} \frac{(\beta_o + 1)}{\mu_f + 2\beta_o + 1} \cong \frac{\beta_o}{\mu_f} r_{o1} = r_{\pi1}$$



$$A_{tr} = \frac{A}{1 + A\beta} = \frac{r_{o1} \frac{(\beta_o + 1)}{\mu_f + 2\beta_o + 1}}{1 + r_{o1} \frac{(\beta_o + 1)}{\mu_f + 2\beta_o + 1} (g_{m2})} \cong r_{o1} \frac{\beta_o + 1}{\mu_f \beta_o + 2\mu_f + 2\beta_o + 2} \cong \frac{r_{o1}}{\mu_f} = \frac{1}{g_{m1}}$$

$$A_{tr} = \frac{1}{50mS} = 20.0 \Omega \quad | \quad A_I = \frac{i_o}{i_{ref}} = \alpha_o g_{m2} \frac{v_o}{i_{ref}} = \alpha_o \frac{g_{m2}}{g_{m1}} \cong 1$$

$$R_{in}^A = r_{o1} \left[r_{\pi3} + (\beta_o + 1) \frac{1}{g_{m2}} \right] \cong r_{o1} \| 2r_{\pi3} \cong 2r_{\pi3}$$

$$R_{in} = \frac{R_{in}^A}{1 + A\beta} = \frac{r_{o1} \| 2r_{\pi3}}{1 + r_{o1} \frac{(\beta_o + 1)}{\mu_f + 2\beta_o + 1} (g_{m2})} \cong \frac{r_{o1} \| 2r_{\pi3}}{1 + \frac{\mu_f (\beta_o + 1)}{\mu_f + 2\beta_o + 1}} \cong \frac{r_{o1} \| 2r_{\pi3}}{\beta_o + 1} \cong \frac{2r_{\pi3}}{\beta_o + 1} \cong \frac{2}{g_{m3}}$$

$$R_{in} = \frac{r_{o1} \| 2r_{\pi3}}{\beta_o + 1} = \frac{40k\Omega \| 4k\Omega}{101} = 36.0 \Omega$$

17.29

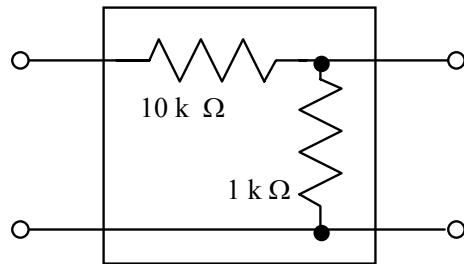
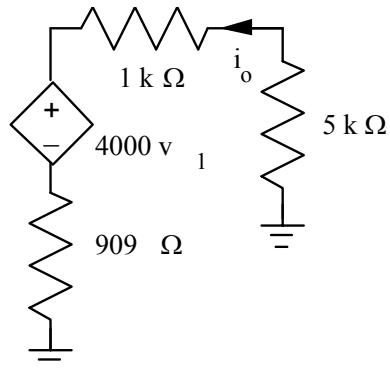
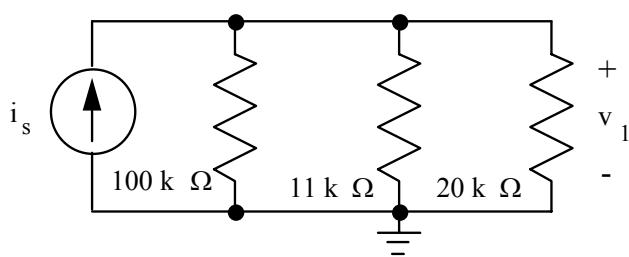
*Problem 17.29 - BJT Wilson Source
*Current gain = 100
VCC 0 3 DC -6
IREF 0 1 DC 100UA
Q1 1 2 0 NBJT
Q2 2 2 0 NBJT
Q3 3 1 2 NBJT
.MODEL NBJT NPN BF=100 VA=50 IS=1E-15
.OP
.TF I(VCC) IREF

$$\text{.END} \quad \frac{\beta_o r_{o3}}{2} = \frac{100(55.3V)}{2(100\mu A)} = 27.7 M\Omega \quad | \quad \text{SPICE : } 29.9 M\Omega$$

*Problem 17.29 - BJT Wilson Source
*Current gain = 10K
VCC 0 3 DC -6
IREF 0 1 DC 100UA
Q1 1 2 0 NBJT
Q2 2 2 0 NBJT
Q3 3 1 2 NBJT
.MODEL NBJT NPN BF=10K VA=50 IS=1E-15
.OP
.TF I(VCC) IREF
.END SPICE : 799 MΩ

*Problem 17.29 - BJT Wilson Source
*Current gain = 1MEG
VCC 0 3 DC -6
IREF 0 1 DC 100UA
Q1 1 2 0 NBJT
Q2 2 2 0 NBJT
Q3 3 1 2 NBJT
.MODEL NBJT NPN BF=1MEG VA=50 IS=1E-15
.OP
.TF I(VCC) IREF
.END $\mu_{f1} r_{o3} = 40(51.4) \frac{55.3V}{100\mu A} = 1.14 G\Omega \quad | \quad \text{SPICE : } 1.08 G\Omega$

17.30



$$g_{11}^F = \left. \frac{i_1}{v_1} \right|_{i_2=0} = \frac{1}{11k\Omega} \quad | \quad g_{22}^F = \left. \frac{v_2}{i_2} \right|_{v_1=0} = 1k\Omega \parallel 10k\Omega = 909\Omega \quad | \quad g_{12}^F = \left. \frac{i_1}{i_2} \right|_{v_1=0} = -\frac{1k\Omega}{10k\Omega + 1k\Omega} = -\frac{1}{11}$$

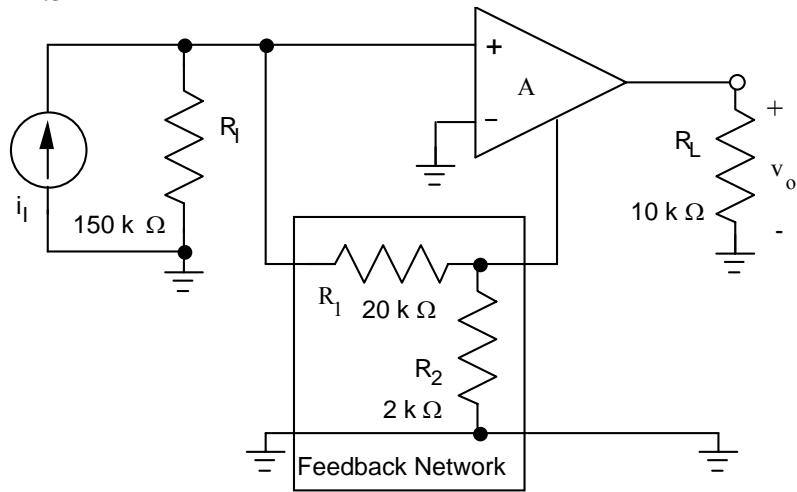
$$A = \frac{i_2}{i_i} = -\left(100k\Omega \parallel 11k\Omega \parallel 20k\Omega\right) \frac{4000}{(5+1+0.909)k\Omega} = -384.84 \times 10^3$$

$$A_i = \frac{A}{1 + A\beta} = \frac{-3.84 \times 10^3}{1 + (-3.84 \times 10^3) \left(-\frac{1}{11}\right)} = -10.97$$

$$R_{in} = \frac{(100k\Omega \parallel 11k\Omega \parallel 20k\Omega)}{(1 + A\beta)} = \frac{6.63k\Omega}{351} = 18.9 \Omega$$

$$R_{out} = (5k\Omega + 1k\Omega + 0.909k\Omega)(1 + A\beta) = (6.91k\Omega)(351) = 2.43M\Omega$$

17.31



$$g_{11}^F = \left. \frac{i_1}{v_1} \right|_{i_2=0} = \frac{1}{22k\Omega} \quad | \quad g_{22}^F = \left. \frac{v_2}{i_2} \right|_{v_1=0} = 2k\Omega \parallel 20k\Omega = 1.82k\Omega \quad | \quad g_{12}^F = \left. \frac{i_1}{i_2} \right|_{v_1=0} = -\frac{2k\Omega}{20k\Omega + 2k\Omega} = -\frac{1}{11}$$

$$g_{11}^T = \frac{1}{20k\Omega} + \frac{1}{22k\Omega} = \frac{1}{10.5k\Omega} \quad | \quad g_{22}^T = 1.82k\Omega + 1k\Omega = 2.82k\Omega \quad | \quad g_{21}^A = \left. \frac{v_2}{v_1} \right|_{i_2=0} = 4000$$

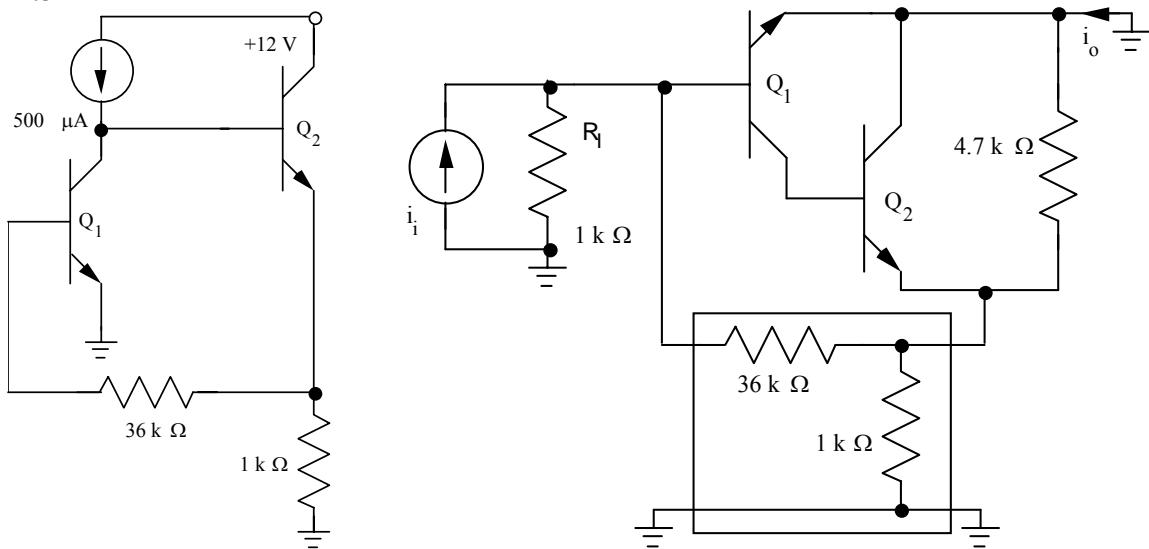
$$A = -\frac{g_{21}^A}{(G_I + g_{11}^T)(g_{22}^T + R_L)} = -\frac{4000}{\left(\frac{1}{150k\Omega} + \frac{1}{10.5k\Omega}\right)(2.82k\Omega + 10k\Omega)} = -3060 \quad | \quad \beta = g_{12}^F = -\frac{1}{11}$$

$$A_i = \frac{A}{1 + A\beta} = \frac{-3060}{1 + (-3060)\left(-\frac{1}{11}\right)} = -11.0 \quad | \quad A\beta = 278$$

$$R_{in} = \frac{(150k\Omega \parallel 10.5k\Omega)}{(1 + A\beta)} = \frac{9.81k\Omega}{1 + 278} = 35.2 \Omega$$

$$R_{out} = (10k\Omega + 2.82k\Omega)(1 + A\beta) = (12.8k\Omega)(279) = 3.57 M\Omega$$

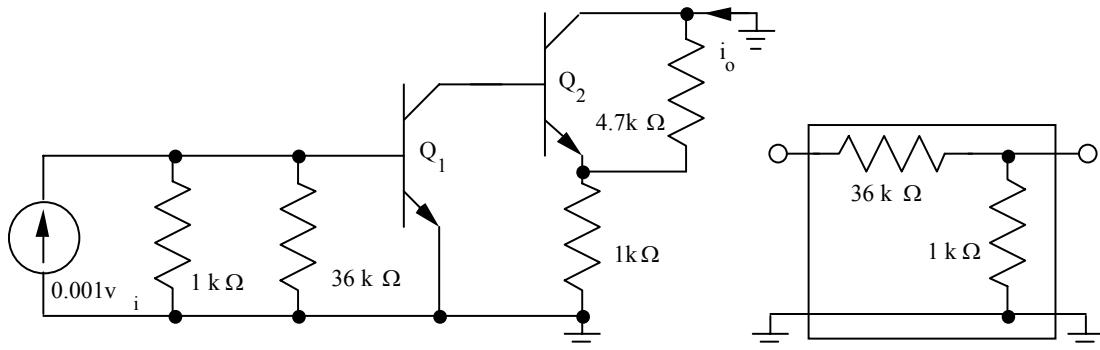
17.32



$$I_{C1} = 500\mu A - I_{B2} \quad | \quad I_{E2} = I_{B1} + \frac{36000I_{B1} + 0.7}{1000} = 37I_{B1} + 700\mu A \quad | \quad I_{B2} = \frac{I_{E2}}{101}$$

$$I_{C1} = 500\mu A - \frac{37I_{B1} + 700\mu A}{101} = 493\mu A - 0.366I_{B1} \rightarrow I_{C1} = 491.2\mu A$$

$$I_{E2} = 37 \frac{I_{C1}}{100} + 700\mu A = 881.7\mu A \quad | \quad I_{C2} = \frac{100}{101}I_{E2} = 873\mu A$$



$$g_{11}^F = \left. \frac{i_1}{v_1} \right|_{i_2=0} = \frac{1}{37 k\Omega} \quad | \quad g_{22}^F = \left. \frac{v_2}{i_2} \right|_{v_1=0} = 36k\Omega \parallel 1k\Omega = 973 \Omega \quad | \quad g_{12}^F = \left. \frac{i_1}{i_2} \right|_{v_1=0} = -\frac{1k\Omega}{1k\Omega + 36k\Omega} = -\frac{1}{37}$$

$$1k\Omega \parallel 37k\Omega = 974 \Omega \quad | \quad r_{\pi 1} = \frac{100(0.025)}{491\mu A} = 5.09 k\Omega \quad | \quad r_{\pi 2} = \frac{100(0.025)}{873\mu A} = 2.86 k\Omega$$

$$A = \frac{i_o}{i_i} = -\frac{974\Omega}{974\Omega + 5090\Omega} (-100)(101) \left(\frac{4700\Omega}{973\Omega + 4700\Omega} \right) = -1340$$

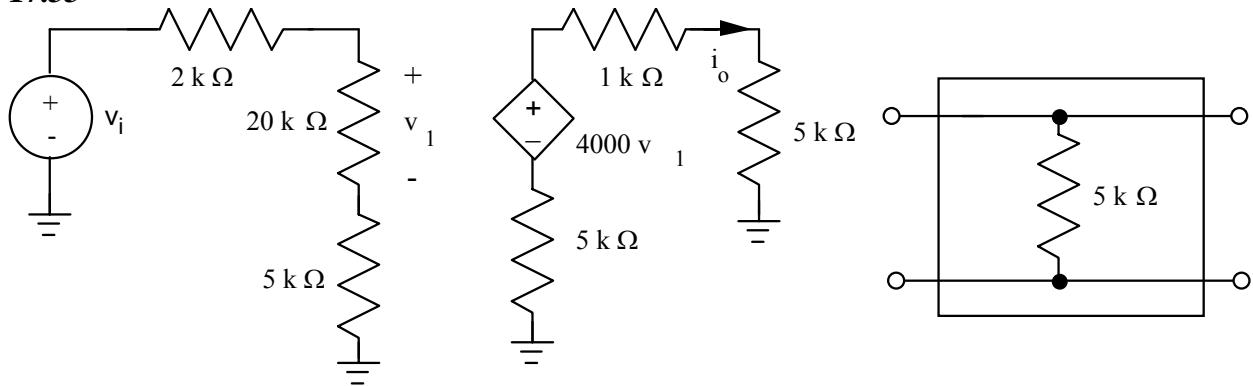
$$A_i = \frac{A}{1 + A\beta} = \frac{-1340}{1 + (-1340)\left(-\frac{1}{37}\right)} = \frac{-1340}{37.2} = -36.0 \quad | \quad 1 + A\beta = 37.2$$

$$A_v = \frac{v_o}{v_i} = \frac{973i_o}{1000i_i} = 0.973 \frac{i_o}{i_i} = -35.0$$

$$R_{in} = \frac{(1k\Omega \parallel 37k\Omega \parallel r_{\pi 1})}{1 + A\beta} = \frac{(1k\Omega \parallel 37k\Omega \parallel 5.09k\Omega)}{37.2} = 22.0 \Omega \quad | \quad r_{ol} = \frac{50 + 1.6}{493 \times 10^{-6}} = 105k\Omega$$

$$R_{out} = \frac{\left(1k\Omega \parallel 36k\Omega \parallel 4.7k\Omega \parallel \frac{r_{\pi 2} + r_{ol}}{101}\right)}{1 + A\beta} = \frac{\left(1k\Omega \parallel 36k\Omega \parallel 4.7k\Omega \parallel \frac{5.09k\Omega + 105k\Omega}{101}\right)}{37.2} = 12.5 \Omega$$

17.33



$$z_{11}^F = \left. \frac{v_1}{i_1} \right|_{i_2=0} = 5 \text{ k}\Omega \quad | \quad z_{22}^F = \left. \frac{v_2}{i_2} \right|_{i_1=0} = 5 \text{ k}\Omega \quad | \quad \beta = z_{12}^F = \left. \frac{v_1}{i_2} \right|_{i_1=0} = 5 \text{ k}\Omega$$

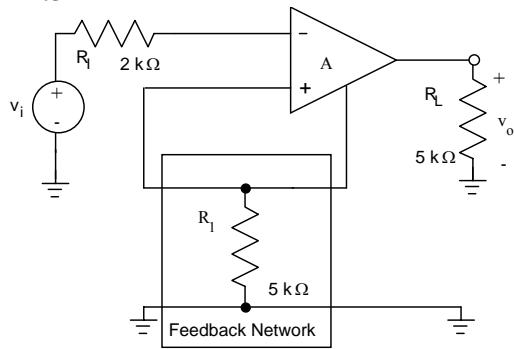
$$A = \frac{i_o}{v_s} = \frac{20k\Omega}{2k\Omega + 20k\Omega + 5k\Omega} \left(\frac{4000}{5k\Omega + 1k\Omega + 5k\Omega} \right) = 0.269$$

$$A_{tr} = \frac{i_o}{v_s} = \frac{A}{1 + A\beta} = \frac{0.269}{1 + 0.269(5000)} = 0.200 \text{ mS} \quad | \quad \frac{v_o}{v_s} = -5000 \frac{i_o}{v_s} = -1.00 \quad | \quad 1 + A\beta = 1350$$

$$R_{in} = (2k\Omega + 20k\Omega + 5k\Omega)(1 + A\beta) = (27k\Omega)(1350) = 36.5 M\Omega$$

$$R_{out} = (5k\Omega + 1k\Omega + 5k\Omega)(1 + A\beta) = (11k\Omega)(1350) = 14.9 M\Omega$$

17.34



$$z_{11}^F = \left. \frac{v_1}{i_1} \right|_{i_2=0} = 5 \text{ k}\Omega \quad | \quad z_{22}^F = \left. \frac{v_2}{i_2} \right|_{i_1=0} = 5 \text{ k}\Omega \quad | \quad \beta = z_{12}^F = \left. \frac{v_1}{i_2} \right|_{i_1=0} = 5 \text{ k}\Omega$$

$$z_{11}^T = 5\text{k}\Omega + 20\text{k}\Omega = 25 \text{ k}\Omega \quad | \quad z_{22}^T = 5\text{k}\Omega + 1\text{k}\Omega = 6 \text{ k}\Omega \quad | \quad z_{21}^A = \left. \frac{v_2}{i_1} \right|_{i_2=0} = 20\text{k}\Omega(4000) = 80 \text{ M}\Omega$$

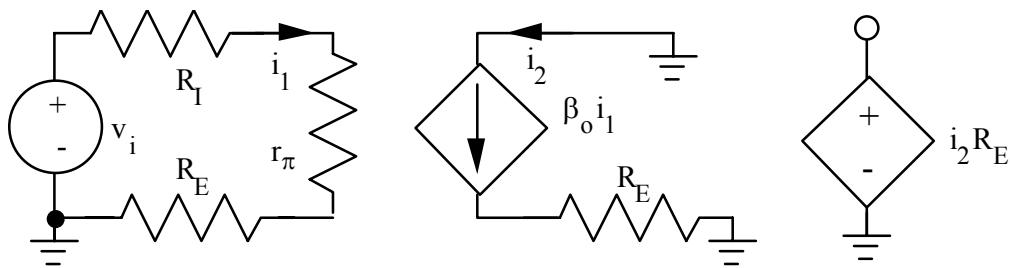
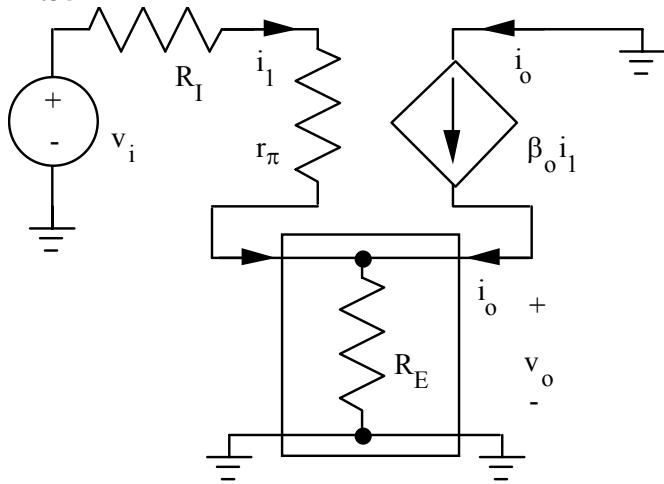
$$A = \frac{z_{21}^A}{(R_I + z_{11}^T)(z_{22}^T + R_L)} = \frac{80 \text{ M}\Omega}{(2\text{k}\Omega + 25\text{k}\Omega)(6\text{k}\Omega + 5\text{k}\Omega)} = 0.269 \text{ S}$$

$$A_{tc} = \frac{A}{1 + A\beta} = \frac{0.269}{1 + 0.269(5\text{k}\Omega)} = 2.00 \times 10^{-4} \text{ S} \quad | \quad A\beta = 1345$$

$$\text{Note: } R_{in} = (R_I + z_{11}^T)(1 + A\beta) = (27\text{k}\Omega)(1346) = 36.3 \text{ M}\Omega$$

$$R_{out} = (z_{22}^T + R_L)(1 + A\beta) = (11\text{k}\Omega)(1346) = 14.8 \text{ M}\Omega$$

17.35



By carefully drawing the circuit, it can be represented as a series-series feedback amplifier. In particular, r_π and the current generator are connected within the feedback network.

$$A = \frac{i_2}{v_s} = \frac{\beta_o}{R_S + r_\pi + R_E} \quad | \quad \beta = z_{12}^F = R_E$$

$$A_{tc} = \frac{i_o}{v_s} = \frac{A}{1 + A\beta} = \frac{\frac{\beta_o}{R_S + r_\pi + R_E}}{1 + \frac{\beta_o}{R_S + r_\pi + R_E} R_E} = \frac{\beta_o}{R_S + r_\pi + (\beta_o + 1)R_E}$$

$$A_v = \frac{v_o}{v_s} = \frac{i_o}{v_s} \frac{R_E}{\alpha_o} = \frac{\beta_o}{R_S + r_\pi + (\beta_o + 1)R_E} \frac{(\beta_o + 1)R_E}{\beta_o} = \frac{(\beta_o + 1)R_E}{R_S + r_\pi + (\beta_o + 1)R_E}$$

$$R_{in} = R_{in}^A(1 + A\beta) = (R_S + r_\pi + R_E) \left(1 + \frac{\beta_o}{R_S + r_\pi + R_E} R_E \right) = R_S + r_\pi + (\beta_o + 1)R_E$$

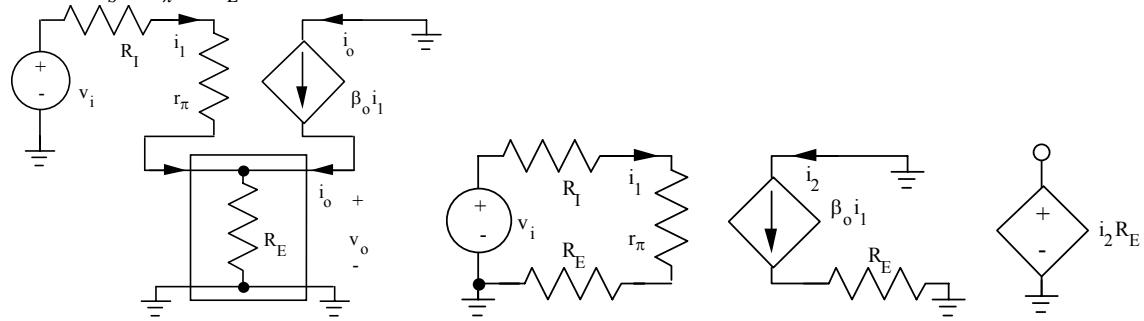
Both answers agree with our previous direct derivations.

17.36

$$A_v = \frac{\beta_o R_L}{R_S + r_\pi + (\beta_o + 1)R_E} = \frac{\beta_o R_L}{R_S + r_\pi + R_E + \beta_o R_E}$$

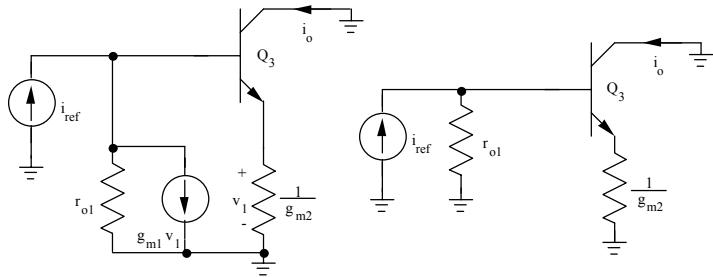
$$A_v = \frac{\frac{\beta_o}{R_S + r_\pi + R_E}}{1 + \frac{\beta_o}{R_S + r_\pi + R_E} R_E} R_L = \frac{A_{tc}}{1 + A_{tc}\beta} R_L$$

$$A_{tc} = \frac{\beta_o}{R_S + r_\pi + R_E} \quad | \quad \beta = R_E$$



By carefully drawing the circuit, it can be represented as a series-series feedback amplifier. In particular, r_π and the current generator are connected within the feedback network.

17.37



$$g_{11}^F = \frac{i_1}{v_1} \Big|_{i_2=0} = \frac{1}{r_{o1}} \quad | \quad g_{22}^F = \frac{v_2}{i_2} \Big|_{v_1=0} = \frac{1}{g_{m2}} \quad | \quad g_{12}^F = \frac{i_1}{i_2} \Big|_{v_1=0} = \frac{g_{m1}}{g_{m2}} \cong 1$$

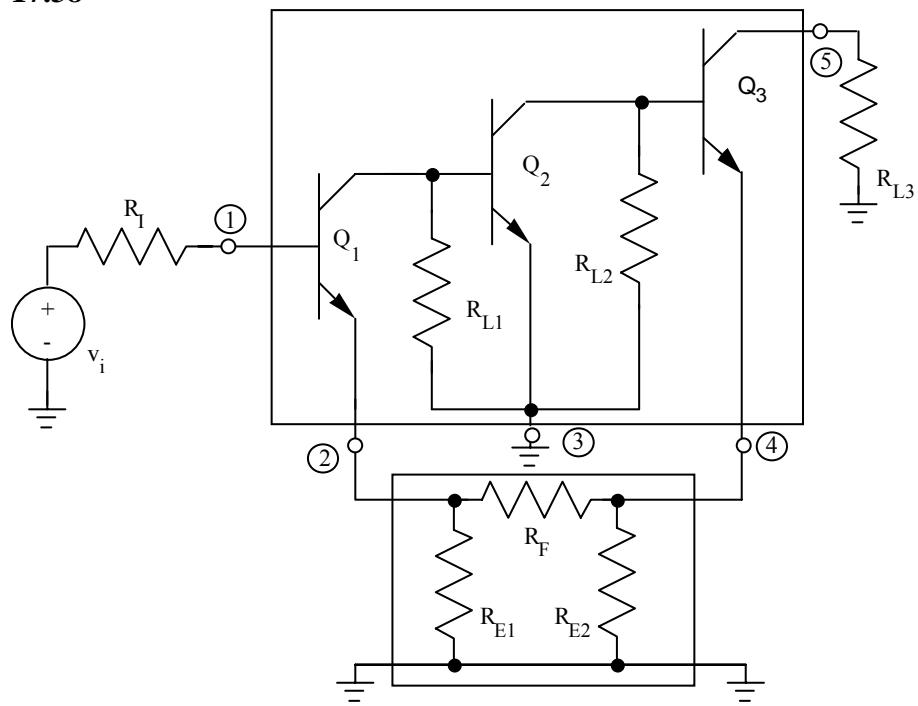
$$i_o = i_{ref} r_{o1} \frac{\beta_o}{r_{o1} + r_{\pi3} + (\beta_{o3} + 1) \frac{1}{g_{m2}}} \approx i_{ref} \frac{\beta_o r_{o1}}{r_{o1} + 2r_{\pi3} + \frac{1}{g_{m2}}} \quad | \quad A = \frac{i_o}{i_{ref}} = \frac{\beta_o \mu_f}{\mu_f + 2\beta_o + 1} \approx \beta_o$$

$$A_i = \frac{A}{1 + A\beta} = \frac{\beta_o}{1 + \beta_o(1)} = \alpha_o \approx 1 \text{ which is correct.}$$

$$R_{in} = \frac{r_{o1} \left(r_{\pi3} + (\beta_{o3} + 1) \frac{1}{g_{m2}} \right)}{1 + \beta_o} \approx \frac{2r_{\pi}}{\beta_o} = \frac{2}{g_m} \text{ which is correct.}$$

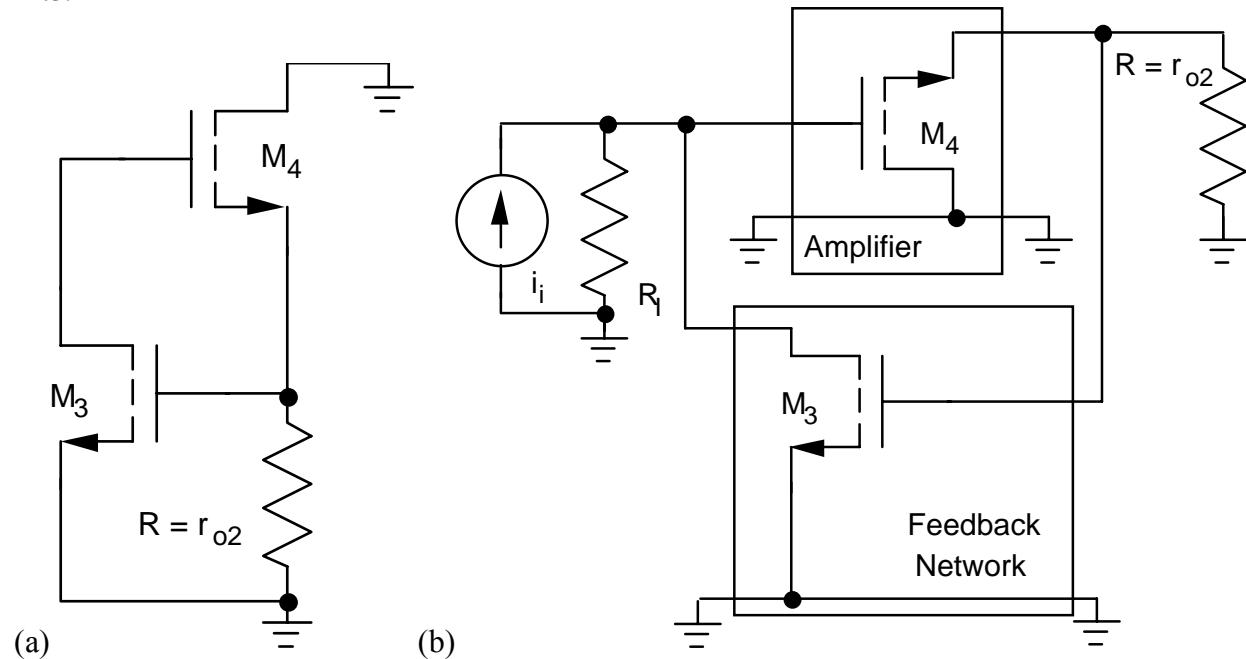
$$R_{out} = (1 + \beta_o) r_{o3} \left(1 + \frac{\beta_{o3} \frac{1}{g_{m2}}}{r_{o1} + r_{\pi3} + \frac{1}{g_{m2}}} \right) = (1 + \beta_o) r_o \left(1 + \frac{\beta_o}{\mu_f + \beta_o + 1} \right) \approx \beta_o r_o - \text{not correct!}$$

17.38



The amplifier is not a two-port. It has five separate terminals. It can be analyzed correctly as a series-shunt configuration with the output defined at terminal 4. In the series-shunt configuration, R_L is absorbed into the amplifier thereby making it a two-port.

17.39



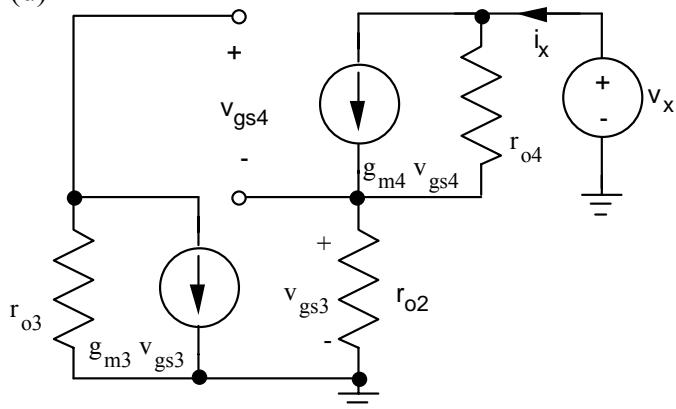
(c) Yes, see figure.

$$A_{(i)} = r_{o3} \frac{g_{m4} r_{o2}}{1 + g_{m4} r_{o2}} \frac{1}{r_{o2}} \cong \frac{r_{o3}}{r_{o2}} \quad | \quad \beta = g_{m3} r_{o2} \quad | \quad A\beta = g_{m3} r_{o3} = \mu_{f3}$$

$$R_{out}^A = \mu_{f4} r_{o2} \quad | \quad R_{out} = R_{out}^A (1 + A\beta) = \mu_{f4} (1 + \mu_{f3}) r_{o2}$$

$$\text{Also, } R_{in}^A = r_{o3} \quad | \quad R_{in} = \frac{R_{in}^A}{(1 + A\beta)} = \frac{r_{o3}}{1 + \mu_{f3}} \cong \frac{1}{g_{m3}}$$

(d)



$$v_x = (i_x - g_{m4} v_{gs4}) r_{o4} + i_x r_{o2} \quad | \quad v_{gs4} = (-\mu_{f3} v_{gs3} - v_{gs3}) = -i_x r_{o2} (\mu_{f3} + 1)$$

$$v_x = i_x r_{o4} + i_x r_{o2} + g_{m4} r_{o4} (1 + \mu_{f3}) i_x r_{o2} \quad | \quad R_{out} = \mu_{f4} (1 + \mu_{f3}) r_{o2}$$

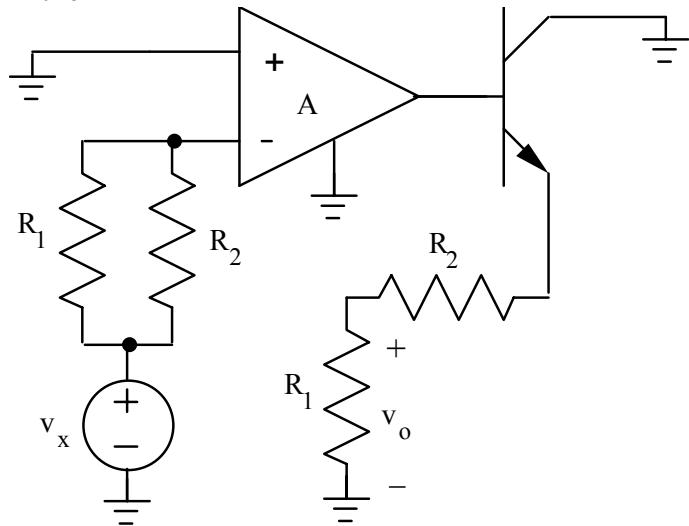
(e)

$$\mu_f = g_m r_o \approx \sqrt{2(0.75 \times 10^{-3})(10^{-4})} \left| \frac{50 + 8}{(10^{-4})} \right| = (0.387 mS)(580 k\Omega) = 194$$

$$R_{out} = \mu_{f4} (1 + \mu_{f3}) r_{o2} = 194 (195) (580 k\Omega) = 21.9 G\Omega$$

(f) SPICE yields 28.0 GΩ with the formula above using the parameter values from SPICE.

17.40



Note: The loading effects of the feedback network must be carefully included.

$$R_l \| R_2 = 1k\Omega \| 9.1k\Omega = 901\Omega \quad | \quad \text{For } v_s = 0, I_C = \alpha_F I = 198\mu A \quad | \quad r_\pi = \frac{100(0.025V)}{198\mu A} = 12.6k\Omega$$

$$T = \frac{v_o}{v_x} = \frac{R_{ID}}{R_{ID} + 901\Omega} (A) \frac{(\beta_o + 1)(R_l + R_2)}{R_o + r_\pi + (\beta_o + 1)(R_l + R_2)} \left(\frac{R_l}{R_l + R_2} \right)$$

$$T = \frac{v_o}{v_x} = \frac{40k\Omega}{40k\Omega + 901\Omega} (316) \frac{(101)(10.1k\Omega)}{1k\Omega + 12.6k\Omega + (101)(10.1k\Omega)} \left(\frac{1k\Omega}{1k\Omega + 9.1k\Omega} \right) = 30.2$$

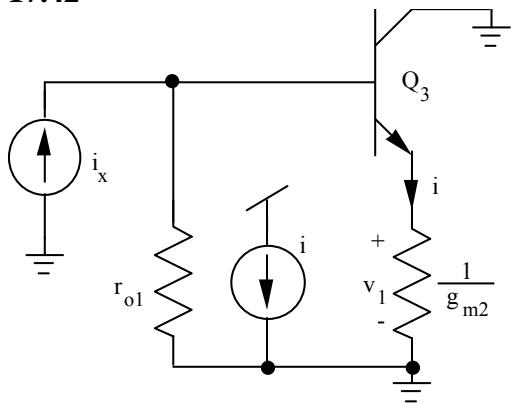
17.41

$$T = \frac{v_o}{v_x} = g_{m2} (r_{o2} \| r_{o4}) \frac{(\beta_o + 1)R}{(r_{o2} \| r_{o4}) + r_{\pi3} + (\beta_o + 1)R} \quad | \quad g_{m1} = 40(10^{-4}) = 4.00 mS$$

$$r_{o2} = \frac{50 + 1.4}{10^{-4}} = 514k\Omega \quad | \quad r_{o4} = \frac{50 + 11.3}{10^{-4}} = 613k\Omega \quad | \quad r_{\pi3} = \frac{100(0.025)}{(12V/10k\Omega)} = 2.08k\Omega$$

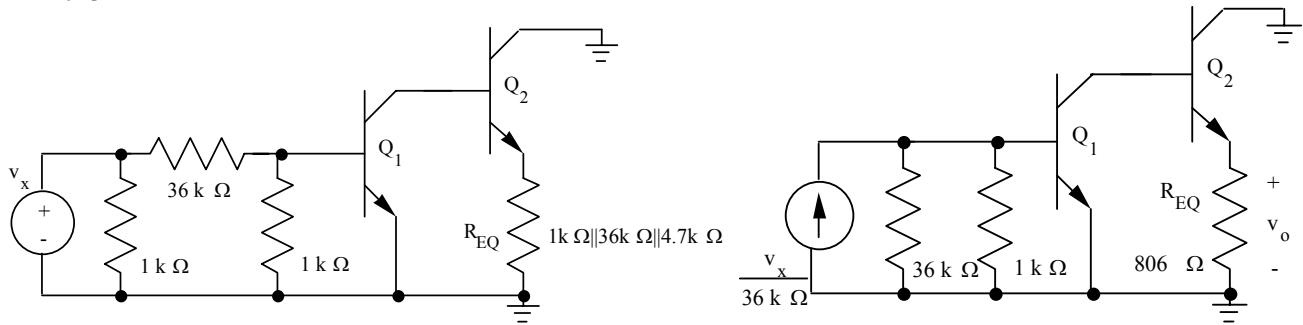
$$T = (4 \times 10^{-3})(280k\Omega) \frac{(101)10k\Omega}{280k\Omega + 2.08k\Omega + 101(10k\Omega)} = 876 \quad (58.9 \text{ dB})$$

17.42



$$T = \frac{i}{i_x} = (\beta_o + 1) \frac{r_o}{r_o + r_\pi + (\beta_o + 1) \frac{1}{g_m}} = \frac{(\beta_o + 1)\mu_f}{\mu_f + 2\beta_o + 1} = \frac{(101)(2000)}{2000 + 200 + 1} = 91.8$$

17.43



$$y_{11}^F = \left. \frac{i_1}{v_1} \right|_{v_2=0} = \frac{1}{36k\Omega} \quad | \quad y_{22}^F = \left. \frac{i_2}{v_2} \right|_{v_1=0} = \frac{1}{36k\Omega \| 1k\Omega } \quad | \quad y_{12}^F = \left. \frac{i_1}{v_2} \right|_{v_1=0} = -\frac{1}{36k\Omega}$$

$$r_{\pi 1} = \frac{100(0.025)}{491\mu A} = 5.09k\Omega \quad | \quad r_{\pi 2} = \frac{100(0.025)}{873\mu A} = 2.86k\Omega \quad | \quad r_{o1} = \frac{50 + 1.6}{493 \times 10^{-6}} = 105k\Omega$$

$$T = \frac{v_o}{v_s} = \frac{1}{36k\Omega} \left(1k\Omega \| 36k\Omega \| r_{\pi 1} \right) g_{m1} \left[r_{o1} \left(r_{\pi 2} + (\beta_o + 1)R_{EQ} \right) \right] \frac{r_{\pi 2} + (\beta_o + 1)R_{EQ}}{r_{o1} + r_{\pi 2} + (\beta_o + 1)R_{EQ}}$$

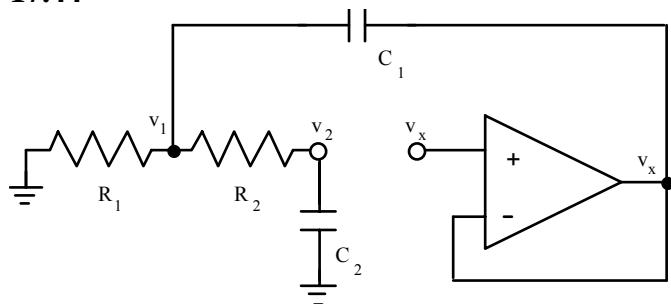
$$\frac{\left(1k\Omega \| 36k\Omega \| r_{\pi 1} \right)}{36k\Omega} = \frac{\left(1k\Omega \| 36k\Omega \| 5.09k\Omega \right)}{36k\Omega} = 0.0227 \quad | \quad g_m = 40(491\mu A) = 19.6mS$$

$$\left[r_{o1} \left(r_{\pi 2} + (\beta_o + 1)R_{EQ} \right) \right] = \left[105k\Omega \left(2.86k\Omega + (101)806\Omega \right) \right] = 46.8k\Omega$$

$$\frac{r_{\pi 2} + (\beta_o + 1)R_{EQ}}{r_{o1} + r_{\pi 2} + (\beta_o + 1)R_{EQ}} = \frac{2.86k\Omega + (101)806\Omega}{105k\Omega + 2.86k\Omega + (101)806\Omega} = 0.430$$

$$T = (0.0227)(19.6mS)(46.8k\Omega)(0.430) = 8.95$$

17.44

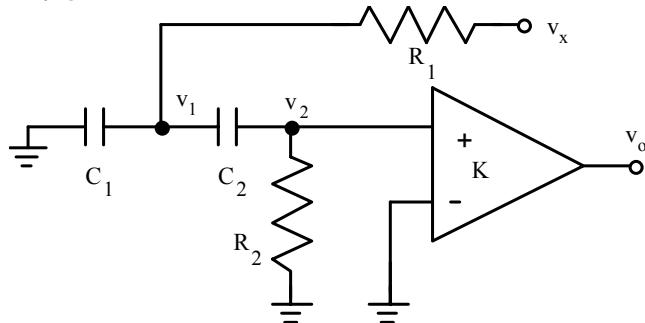


$$\begin{bmatrix} sC_1 V_x \\ 0 \end{bmatrix} = \begin{bmatrix} sC_1 + G_1 + G_2 & -G_2 \\ -G_2 & sC_2 + G_2 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad V_2 = \frac{sC_1 G_2}{\Delta} V_x$$

$$\Delta = s^2 C_1 C_2 + s[C_1 G_2 + C_2(G_1 + G_2)] + G_1 G_2$$

$$T = \frac{V_2}{V_x} = \frac{\frac{s}{R_2 C_2}}{s^2 + s \left[\frac{1}{R_2 C_2} + \frac{1}{(R_1 \| R_2) C_1} \right] + \frac{1}{R_1 R_2 C_1 C_2}}$$

17.45



$$\begin{bmatrix} G_1 V_x \\ 0 \end{bmatrix} = \begin{bmatrix} s(C_1 + C_2) + G_1 & -sC_2 \\ -sC_2 & sC_2 + G_2 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad V_o = KV_2$$

$$\Delta = s^2 C_1 C_2 + s[C_1 G_2 + C_2(G_1 + G_2)] + G_1 G_2$$

$$T = \frac{V_o}{V_x} = K \frac{\frac{1}{s R_1 C_1}}{s^2 + s \left[\frac{1}{R_2 C_2} + \frac{1}{(R_1 \| R_2) C_1} \right] + \frac{1}{R_1 R_2 C_1 C_2}}$$

17.46

*Problem 17.46 - Fig. P17.17

VCC 4 0 DC 10

IS 5 0 DC 200U

VS 1 0 DC 0

Q1 4 3 5 NBJT

RID 1 8 40K

RO 2 3 1K

E1 2 0 1 8 316.2

R2 6 5 7.5K

R1 8 0 1K

VB 7 8 DC 0

VX 7 6 AC 0

IX 0 7 AC 1

*VX 7 6 AC 1

*IX 0 7 AC 0

.MODEL NBJT NPN BF=100 VA=50 IS=1E-15

.OP

.AC LIN 1 10 10

.PRINT AC IM(VX) IP(VX) IM(VB) IP(VB) VM(7) VP(7) VM(6) VP(6)

.END

Results: I(VX) = 0.9759 A, I(VB) = 0.0241 A, V(7) = 3.078 mV, V(6) = -0.9969 V

$$T_v = -\frac{-0.9969V}{3.078mV} = 324 \quad | \quad T_i = \frac{0.9759A}{0.0241A} = 40.5 \times 10^4$$

$$T = \frac{T_v T_i - 1}{2 + T_v + T_i} = \frac{324(40.5) - 1}{2 + 324 + 40.5} = 35.8 \quad | \quad \frac{R_2}{R_1} = \frac{1 + T_v}{1 + T_i} = \frac{1 + 324}{1 + 40.5} = 7.83$$

17.47

*Problem 17.47 - Fig. P17.18 BJT Op-amp

VCC 8 0 DC 12

VEE 9 0 DC -12

IS 2 9 DC 200U

VS 1 0 DC 0

Q1 4 1 2 NBJT

Q2 5 3 2 NBJT

Q3 4 4 8 PBJT

Q4 5 4 8 PBJT

Q5 8 5 6 NBJT

R 6 9 10K

VB 7 3 DC 0

VX 7 6 AC 0

IX 0 7 AC 1

*VX 7 6 AC 1

*IX 0 7 AC 0

.MODEL NBJT NPN BF=100 VA=50 IS=1E-15

.MODEL PBJT PNP BF=100 VA=50 IS=1E-15

.OP

.AC LIN 1 10 10

.PRINT AC IM(VX) IP(VX) IM(VB) IP(VB) VM(7) VP(7) VM(6) VP(6)

Results: $I(VX) = 1.000 \text{ A}$, $I(VB) = 3.703 \times 10^{-5} \text{ A}$, $V(7) = 1.188 \text{ mV}$, $V(6) = -1.000 \text{ V}$

$$T_v = -\frac{-0.9988V}{1.188mV} = 841 \quad | \quad T_i = \frac{1.000A}{37.03\mu A} = 2.70 \times 10^4$$

$$T = \frac{T_v T_i - 1}{2 + T_v + T_i} = \frac{841(2.70 \times 10^4) - 1}{2 + 841 + 2.70 \times 10^4} = 816 \quad | \quad \frac{R_2}{R_1} = \frac{1 + T_v}{1 + T_i} = \frac{1 + 841}{2.70 \times 10^4} = 0.0312$$

17.48

The circuit description is the same as Problem 17.46 except for the change in the values of R_1 and R_2 .

R2 6 5 300K

R1 8 0 40K

Results: $I(VX) = 0.9548 \text{ A}$, $I(VB) = 45.19 \text{ mA}$, $V(7) = 3.011 \text{ mV}$, $V(6) = -0.9970 \text{ V}$

$$T_v = -\frac{-0.9970V}{3.011mV} = 331 \quad | \quad T_i = \frac{0.9548A}{45.19mA} = 21.1$$

$$T = \frac{T_v T_i - 1}{2 + T_v + T_i} = \frac{331(21.1) - 1}{2 + 331 + 21.1} = 19.7 \quad | \quad \frac{R_2}{R_1} = \frac{1 + T_v}{1 + T_i} = \frac{1 + 331}{1 + 21.1} = 15.0$$

17.49

*Problem 17.49 - Fig. 17.2(b)

IS 0 1 DC 0
RS 1 0 1K
RID 1 0 15K
RO 2 3 1K
E1 3 4 1 0 5000
RL 2 0 4.7K
R2 4 0 1K
R1 4 6 36K
VB 7 1 DC 0
VX 7 6 AC 0
IX 0 7 AC 1
*VX 7 6 AC 1
*IX 0 7 AC 0
.OP

.AC LIN 1 10 10

.PRINT AC IM(VX) IP(VX) IM(VB) IP(VB) VM(7) VP(7) VM(6) VP(6)

.END

Results: I(VX) = 0.9500 A, I(VB) = 49.97 mA, V(7) = 1.271 mV, V(6) = -0.9987 V

$$T_v = -\frac{-0.9987V}{1.271mV} = 786 \quad | \quad T_i = \frac{0.9500A}{49.97mA} = 19.0$$

$$T = \frac{T_v T_i - 1}{2 + T_v + T_i} = \frac{786(19.0) - 1}{2 + 786 + 19.0} = 18.5 \quad | \quad \frac{R_2}{R_1} = \frac{1 + T_v}{1 + T_i} = \frac{1 + 786}{1 + 19.0} = 39.4$$

17.50

*Problem 17.50

VCC 5 0 DC 6

IREF 0 1 DC 100UA

Q1 1 4 0 NBJT

Q2 4 4 0 NBJT

Q3 5 3 4 NBJT

IX 0 2 DC 0

VX1 2 1 DC 0

VX2 2 3 DC 0

.MODEL NBJT NPN BF=100 VA=50 IS=1E-15

.OP

.TF I(VX1) IX ---> 0.9910

*.TF I(VX2) IX ---> 9.043 x 10⁻³

.END

*Problem 17.50

VCC 5 0 DC 6

IREF 0 1 DC 100UA

Q1 1 4 0 NBJT

Q2 4 4 0 NBJT

Q3 5 3 4 NBJT

IX 0 2 DC 0

VX1 2 1 DC 0

VX2 2 3 DC 0

.MODEL NBJT NPN BF=100 VA=50 IS=1E-15

.OP

.TF V(1) VX1 ---> -0.9990

*.TF V(2) VX1 ---> 1.012 x 10⁻³

.END

$$T_v = -\frac{-0.9990}{1.012 \times 10^{-3}} = 987 \quad | \quad T_i = \frac{0.9910}{9.043 \times 10^{-3}} = 110$$

$$T = \frac{987(110) - 1}{2 + 987 + 110} = 98.8 \quad | \quad \frac{R_2}{R_1} = \frac{1 + 987}{1 + 110} = 8.90$$

17.51

Since the output resistance of the amplifier is zero ($R_2 = 0$), the simplified method can be used:

$$T = T_V.$$

*Problem 17.51

VS 1 0 DC 0

C1 1 2 0.005UF

C2 2 3 0.005UF

R1 2 7 2K

R2 3 0 2K

E1 4 0 3 0 1

R 4 5 31.83

C 5 0 1NF

E2 6 0 5 0 2

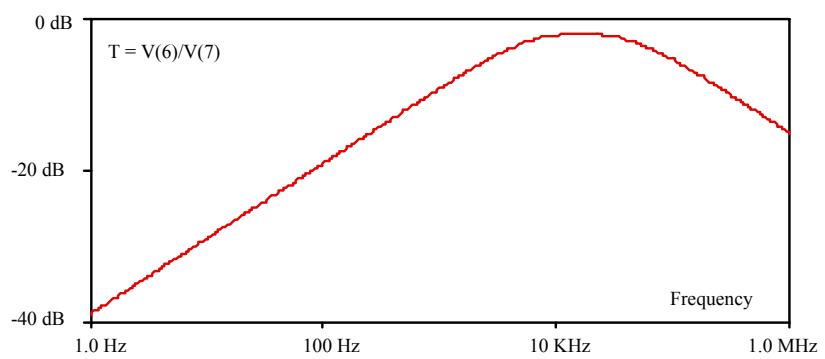
VX 7 6 AC 1

.OP

.AC DEC 100 1 1E6

.PROBE V(6) V(7)

.END



17.52

(a) With gain $A = 0$, $R_{inD} = R_I + R_{id} + R_1 \parallel [R_2 + R_o \parallel R_L]$

$$R_{inD} = 1k\Omega + 20k\Omega + 5k\Omega \parallel [45k\Omega + 1k\Omega \parallel 5k\Omega] = 25.5k\Omega$$

With the input open - circuited, the current in R_{id} is zero, and so $T_{OC} = 0$.

With the input set to zero, The Thevenin equivalent looking back into R_1 is

$$V_{th} = \left[4000 \left(\frac{5k\Omega}{5k\Omega + 1k\Omega} \right) \right] \frac{5k\Omega}{5k\Omega + 45k\Omega + (5k\Omega \parallel 1k\Omega)} = 328 \text{ and}$$

$$R_{th} = R_1 \parallel [R_2 + R_o \parallel R_L] = 5k\Omega \parallel [45k\Omega + 5k\Omega \parallel 1k\Omega] = 4.51k\Omega$$

$$T_{SC} = 328 \frac{20k\Omega}{4.51k\Omega + 20k\Omega + 1k\Omega} = 257 \quad | \quad R_{in} = 25.5k\Omega \left(\frac{1+257}{1+0} \right) = 6.58 M\Omega$$

With gain v_s and $A = 0$,

$$R_{outD} = R_L \parallel [R_o \parallel [R_2 + (R_1 \parallel (R_{id} + R_I))] = 5k\Omega \parallel 1k\Omega \parallel [45k\Omega + (5k\Omega \parallel (20k\Omega + 1k\Omega))] = 819\Omega$$

With the output shorted, $T_{SC} = 0$. With the output open - circuited, $T_{OC} = 257$

$$R_{out} = 819\Omega \left(\frac{1+0}{1+257} \right) = 3.17 \Omega \quad | \quad R_{in} \text{ and } R_{out} \text{ agree with both Prob. 17.15 and SPICE.}$$

(b) With gain $A = 0$,

$$R_{inD} = R_I \parallel R_{id} \parallel [R_1 + R_2 \parallel (R_o + R_L)] = 100k\Omega \parallel 20k\Omega \parallel [10k\Omega + 1k\Omega \parallel (1k\Omega + 5k\Omega)] = 6.57k\Omega$$

With the input short - circuited, $T_{SC} = 0$.

With the input open - circuited, $T_{OC} = \frac{4000}{R_L + R_o + R_2 \parallel [R_1 + (R_I \parallel R_{id})]} \frac{R_2}{R_2 + R_1 + (R_I \parallel R_{id})} (R_I \parallel R_{id})$

$$T_{OC} = -\frac{4000}{5k\Omega + 1k\Omega + 1k\Omega \parallel [10k\Omega + (100k\Omega \parallel 20k\Omega)]} \left[\frac{1k\Omega}{1k\Omega + 10k\Omega + (100k\Omega \parallel 20k\Omega)} \right] (100k\Omega \parallel 20k\Omega) = -346$$

$$R_{in} = 6.57k\Omega \left(\frac{1+0}{1+346} \right) = 18.9 \Omega \quad | \quad \text{Since the circuit is series feedback at the output,}$$

we look into the circuit between ground and the bottom of R_L . With gain $A = 0$,

$$R_{outD} = R_L + R_o + R_2 \parallel [R_1 + (R_I \parallel R_{id})] = 5k\Omega + 1k\Omega + 1k\Omega \parallel [10k\Omega + (100k\Omega \parallel 20k\Omega)] = 6.96k\Omega$$

With the output open, $i_o = 0$, and $T_{OC} = 0$. With the output short - circuited, T_{SC} is

$$T_{SC} = -\frac{4000}{R_L + R_o + R_2 \parallel [R_1 + (R_I \parallel R_{id})]} \frac{R_2}{R_2 + R_1 + (R_I \parallel R_{id})} (R_I \parallel R_{id}) = -346$$

$$R_{out} = 6.96k\Omega \left(\frac{1+346}{1+0} \right) = 2.42 M\Omega \quad | \quad R_{in} \text{ and } R_{out} \text{ agree with both Prob. 17.30 and SPICE.}$$

(b) cont.

We can instead choose to look at the shunt output. With gain $A = 0$,

$$R_{outD} = R_L \parallel \{R_o + R_2 \parallel [R_l + (R_I \parallel R_{id})]\} = 5k\Omega \parallel \{k\Omega + 1k\Omega \parallel [10k\Omega + (100k\Omega \parallel 20k\Omega)]\} = 1.40k\Omega$$

$$\text{With the output shorted, } T_{SC} = -\frac{4000}{R_o + R_2 \parallel [R_l + (R_I \parallel R_{id})]} \frac{R_2}{R_2 + R_l + (R_I \parallel R_{id})} (R_I \parallel R_{id}) = -1227$$

With the output open - circuited,

$$T_{OC} = -\frac{4000}{R_L + R_o + R_2 \parallel [R_l + (R_I \parallel R_{id})]} \frac{R_2}{R_2 + R_l + (R_I \parallel R_{id})} (R_I \parallel R_{id}) = -346$$

$$R_{out} = 1.40k\Omega \left(\frac{1+1227}{1+346} \right) = 4.954 \text{ k}\Omega \text{ and removing the } 5\text{k}\Omega \text{ resistor yields } R_{out} = 544 \text{ k}\Omega.$$

The error is due to loss of significance in the calculations.

If we remove R_L from across the output, $R_{outD} = 1.94k\Omega$, $T_{SC} = -1227$, and $T_{OC} = 0$.

$$R_{out} = 1.94k\Omega \left(\frac{1+1227}{1+0} \right) = 2.38 \text{ M}\Omega \quad | \quad R_{out} \text{ again agrees with both Prob. 17.30 and SPICE.}$$

(c) With gain $A = 0$,

$$R_{inD} = R_I + R_{id} + R_l \parallel (R_o + R_L) = 2k\Omega + 20k\Omega + 5k\Omega \parallel (1k\Omega + 5k\Omega) = 24.7k\Omega$$

When the input is open - circuited, zero current exists in R_{id} and $T_{OC} = 0$.

With the input short - circuited,

$$\begin{aligned} |T_{SC}| &= \frac{4000}{R_L + R_o + [R_l \parallel (R_{id} + R_I)]} \left(\frac{R_l}{R_l + R_{id} + R_I} \right) R_{id} \\ |T_{SC}| &= \frac{4000}{5k\Omega + 1k\Omega + [5k\Omega \parallel (20k\Omega + 2k\Omega)]} \left(\frac{5k\Omega}{5k\Omega + 20k\Omega + 2k\Omega} \right) 20k\Omega = 1471 \\ R_{in} &= 24.7k\Omega \left(\frac{1+1471}{1+0} \right) = 36.3 \text{ M}\Omega \end{aligned}$$

With gain $A = 0$, (remember, this is series feedback and we look into the bottom of R_L)

$$R_{outD} = R_L + R_o + [R_l \parallel (R_{id} + R_I)] = 5k\Omega + 1k\Omega + [5k\Omega \parallel (20k\Omega + 2k\Omega)] = 10.1k\Omega$$

With the output open - circuited, $T_{OC} = 0$. With the output shorted,

$$|T_{SC}| = 1730, \text{ the same as above, and } R_{out} = 10.1k\Omega \left(\frac{1+1471}{1+0} \right) = 14.9 \text{ M}\Omega$$

R_{in} and R_{out} agree with both Prob. 17.33 and SPICE.

(d) With gain $A = 0$,

$$R_{inD} = R_I \| R_{id} \| [R_F + (R_L \| R_o)] = 100k\Omega \| 20k\Omega \| [36k\Omega + (5k\Omega \| 1k\Omega)] = 11.5k\Omega$$

With the input short - circuited, $T_{SC} = 0$.

When the input is open - circuited and using a Norton equivalent,

$$|T_{oc}| = \left(\frac{4000}{R_o} \right) \frac{(R_L \| R_o)}{(R_L \| R_o) + R_F + (R_I \| R_{id})} (R_I \| R_{id})$$

$$|T_{oc}| = \left(\frac{4000}{1k\Omega} \right) \frac{(5k\Omega \| 1k\Omega)}{(5k\Omega \| 1k\Omega) + 36k\Omega + (100k\Omega \| 20k\Omega)} (100k\Omega \| 20k\Omega) = 1040$$

$$R_{in} = 11.5k\Omega \left(\frac{1+0}{1+1040} \right) = 11.0 \Omega$$

With gain $A = 0$,

$$R_{outD} = R_L \| R_o \| [R_F + (R_I \| R_{id})] = 5k\Omega \| 1k\Omega \| [36k\Omega + (100k\Omega \| 20k\Omega)] = 820\Omega$$

With the output short - circuited, $T_{SC} = 0$. With the output open,

$$|T_{oc}| = 1040, \text{ the same as above, and } R_{out} = 820\Omega \left(\frac{1+0}{1+1040} \right) = 0.788 \Omega$$

R_{in} and R_{out} agree with both Prob. 17.21 and SPICE.

17.53

$$I_{C1} = 500\mu A - I_{B2} \quad | \quad I_{E2} = I_{B1} + \frac{36000I_{B1} + 0.7}{1000} = 37I_{B1} + 700\mu A \quad | \quad I_{B2} = \frac{I_{E2}}{101}$$

$$I_{C1} = 500\mu A - \frac{37I_{B1} + 700\mu A}{101} = 493\mu A - 0.366I_{B1} \rightarrow I_{C1} = 491.2\mu A$$

$$I_{E2} = 37 \frac{I_{C1}}{100} + 700\mu A = 881.7\mu A \quad | \quad I_{C2} = \frac{100}{101} I_{E2} = 873\mu A \quad | \quad g_{m1} = 40(491.2\mu A) = 19.6mS$$

$$r_{\pi 1} = \frac{100(0.025)}{491\mu A} = 5.09k\Omega \quad | \quad r_{\pi 2} = \frac{100(0.025)}{873\mu A} = 2.86k\Omega \quad | \quad r_{o1} = \frac{50+1.6}{493 \times 10^{-6}} = 105k\Omega$$

After replacing v_i and R_I with their Norton equivalent, and with $g_{m1} = 0$,

$$R_{inD} = R_I \| r_{\pi 1} \left[R_F + R_E \| R_L \left(\frac{r_{\pi 2} + r_{o1}}{\beta_{o2} + 1} \right) \right]$$

$$R_{inD} = 1k\Omega \| 5.09k\Omega \left[36k\Omega + 1k\Omega \| 4.7k\Omega \left(\frac{2.86k\Omega + 105k\Omega}{101} \right) \right] = 817\Omega$$

With the input shorted, $T_{SC} = 0$. With the input open and starting at the output of Q_1 ,

$$T_{OC} = (-g_{m1} r_{o1}) \left\{ \frac{(\beta_{o2} + 1) [R_E \| R_L \| (R_F + R_I \| r_{\pi 1})]}{r_{o1} + r_{\pi 2} + (\beta_{o2} + 1) [R_E \| R_L \| (R_F + R_I \| r_{\pi 1})]} \right\} \left[\frac{(R_I \| r_{\pi 1})}{R_F + (R_I \| r_{\pi 1})} \right]$$

$$T_{OC} = (-2062) \left\{ \frac{(101) [1k\Omega \| 4.7k\Omega \| (36k\Omega + 1k\Omega \| 5.09k\Omega)]}{105k\Omega + 2.86k\Omega + (101) [1k\Omega \| 4.7k\Omega \| (36k\Omega + 1k\Omega \| 5.09k\Omega)]} \right\} \left[\frac{1k\Omega \| 5.09k\Omega}{36k\Omega + (1k\Omega \| 5.09k\Omega)} \right]$$

$$T_{OC} = (-2062)(0.403)(0.0227) = -18.9$$

$$R_{in} = 817\Omega \left(\frac{1+0}{1+18.9} \right) = 41.2\Omega$$

$$R_{outD} = R_E \| R_L \| (R_F + R_I \| r_{\pi 1}) \left| \frac{r_{\pi 2} + r_{o1}}{(\beta_{o2} + 1)} \right. = 1k\Omega \| 4.7k\Omega \| (36k\Omega + 1k\Omega \| 5.09k\Omega) \left| \frac{2.86k\Omega + 105k\Omega}{(101)} \right. = 460\Omega$$

$$T_{SC} = 0, T_{OC} = 18.9, R_{out} = 460\Omega \left(\frac{1+0}{1+18.9} \right) = 23.1\Omega \quad | \text{ The results agree with SPICE.}$$

17.54

With gain $A = 0$, $R_{inD} = R_{id} + R_1 \left[R_2 + \frac{r_\pi + R_o}{\beta_o + 1} \right]$ | $r_\pi = \frac{100(0.025V)}{200\mu A} = 12.5k\Omega$

$$R_{inD} = 40k\Omega + 1k\Omega \left[7.5k\Omega + \frac{12.5k\Omega + 1k\Omega}{101} \right] = 40.9k\Omega$$

With the input open - circuited, the current in R_{id} is zero, and so $T_{OC} = 0$.

With the input set to zero, the load on the emitter follower is

$$R_{LEQ} = R_2 + (R_1 \| R_{id}) = 7.5k\Omega + (1k\Omega \| 40k\Omega) = 8.48k\Omega$$

$$T_{SC} = A \frac{(\beta_o + 1)R_{LEQ}}{R_o + r_\pi + (\beta_o + 1)R_{LEQ}} \frac{(R_1 \| R_{id})}{R_2 + (R_1 \| R_{id})} = 316 \frac{101(8.48k\Omega)}{1k\Omega + 12.5k\Omega + 101(8.48k\Omega)} \left(\frac{0.976k\Omega}{8.48k\Omega} \right) = 35.8$$

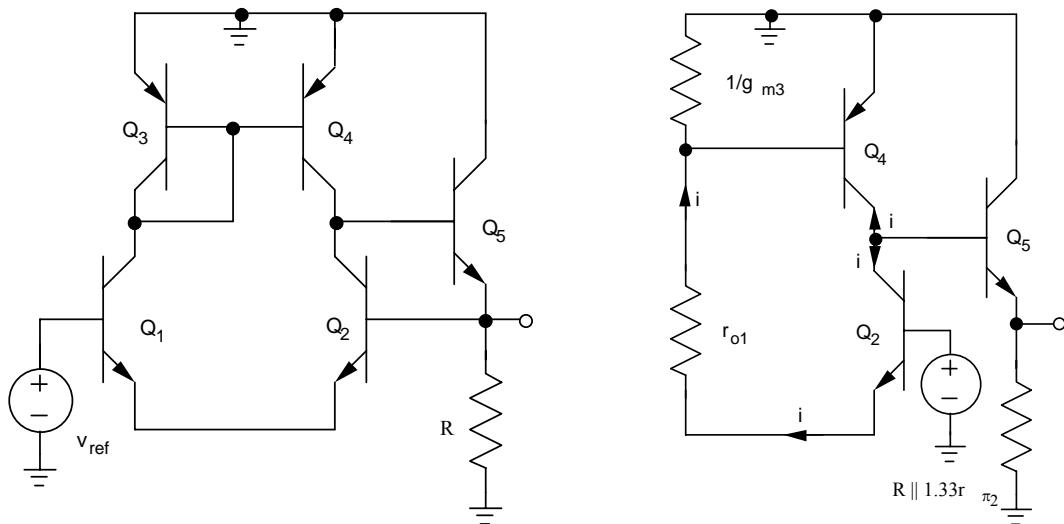
$$R_{in} = 40.9k\Omega \left(\frac{1+35.8}{1+0} \right) = 1.51M\Omega$$

With gain $A = 0$, $R_{outD} = [R_2 + (R_1 \| R_{id})] \left[\frac{r_\pi + R_o}{\beta_o + 1} \right] = 8.48k\Omega \| 134\Omega = 132\Omega$

With the output shorted, $T_{SC} = 0$. With the output open - circuited, $T_{OC} = 32.0$.

$$R_{out} = 132\Omega \left(\frac{1+0}{1+35.8} \right) = 3.59\Omega \quad | \quad R_{in} \text{ and } R_{out} \text{ agree with both Prob. 18.18 and SPICE.}$$

17.55



$$R_{inD} = 4r_{\pi 1} = 100k\Omega \quad (\text{See analysis below } **.)$$

With the input shorted, $T_{SC} = g_{m2} [r_{o2} \| r_{o4} \| (\beta_{o5} + 1)(R \| 1.33r_{\pi 2})] \Omega \left[\frac{(\beta_{o5} + 1)(R \| 1.33r_{\pi 2})}{r_{\pi 5} + (\beta_{o5} + 1)(R \| 1.33r_{\pi 2})} \right]$

$$A_{vref} = \frac{(\beta_{o5} + 1)(R \| 1.33r_{\pi 2})}{r_{\pi 5} + (\beta_{o5} + 1)(R \| 1.33r_{\pi 2})} = \frac{(101)(10k\Omega \| 33.3k\Omega)}{2.08k\Omega + (101)(10k\Omega \| 33.3k\Omega)} = 0.997$$

$$T_{SC} = 40(100\mu A) [500k\Omega \| 500k\Omega \| (101)(10k\Omega \| 33.3k\Omega)] (0.997) = 757$$

With the input open, $T_{OC} \equiv -\frac{2i}{v_i} (r_{o2} \| r_{o4}) A_{vref} \equiv -\frac{2}{r_{o1} + \frac{1}{g_{m3}}} (r_{o2} \| r_{o4}) A_{vref} \equiv -\frac{2}{r_{o1}} (r_{o2} \| r_{o4}) (0.997) \equiv -0.997$

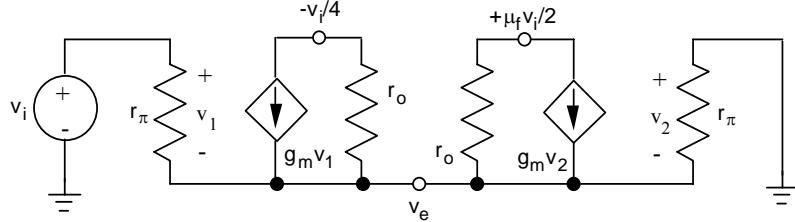
$$R_{in} = 100k\Omega \left(\frac{1+757}{1+0.997} \right) = 38.0M\Omega$$

$$R_{outD} = R \| 1.33r_{\pi 1} \| \frac{r_{\pi 5} + (r_{o2} \| r_{o4})}{\beta_{o5} + 1} = 10k\Omega \| 33.3k\Omega \| \frac{2.08k + (500k\Omega \| 500k\Omega)}{101} = 1.88k\Omega$$

With the output open, $T_{OC} = 757$. With the output shorted, $T_{SC} = 0$

$$R_{in} = 1.88k\Omega \left(\frac{1+0}{1+757} \right) = 2.48 \Omega.$$

The values of R_{in} and R_{out} agree well with simulation when the effect of imbalance due to offset voltage is considered. (Try a buffered current mirror in SPICE.)



** The input resistance to the differential pair with active load is $4r_{\pi}$ rather than the $2r_{\pi}$ that one might expect. Because of the high gain ($\mu_f/2$) to the output node, a significant current is fed back through r_{o2} . At the emitter node :

$$g_{\pi}(v_i - v_e) + g_m(v_i - v_e) + g_m(0 - v_e) + g_{\pi}(0 - v_e) + g_o\left(\frac{\mu_f}{2}v_i - v_e\right) + g_o\left(-\frac{v_i}{4} - v_e\right) = 0$$

$$\left(\frac{3}{2}g_m + g_{\pi} - \frac{g_o}{4}\right)v_i = (2g_m + 2g_{\pi} + 2g_o)v_e \quad | \quad \frac{v_e}{v_i} = \frac{\left(\frac{3}{2}g_m + g_{\pi} + \frac{g_o}{2}\right)}{(2g_m + 2g_{\pi} + 2g_o)} \cong \frac{3}{4}$$

The voltage across r_{π} of the input transistor is $\frac{v_i}{4}$, so $R_{in} \cong 4r_{\pi}$. If an input is applied to the

right side instead of the left, the sign changes on the $g_o \frac{\mu_f}{2}v_i$ term, and $R_{in} \cong \frac{4}{3}r_{\pi}$.

17.56

$$R_{inD} = 100k\Omega \parallel [1M\Omega + (10k\Omega \parallel 10k\Omega \parallel 40k\Omega)] = 91.0k\Omega \quad | \quad T_{SC} = 0$$

$$T_{OC} \cong g_m(10k\Omega \parallel 10k\Omega \parallel 40k\Omega) \frac{100k\Omega}{100k\Omega + 1M\Omega} = 0.808 \quad | \quad R_{in} = 91.0k\Omega \frac{1+0}{1+0.808} = 50.3k\Omega$$

$$R_{outD} = 10k\Omega \parallel 10k\Omega \parallel 40k\Omega \parallel 1.1M\Omega = 4.43k\Omega \quad | \quad T_{SC} = 0$$

$$T_{OC} \cong g_m(10k\Omega \parallel 10k\Omega \parallel 40k\Omega) \frac{100k\Omega}{100k\Omega + 1M\Omega} = 0.808 \quad | \quad R_{out} = 4.43k\Omega \frac{1+0}{1+0.808} = 2.45k\Omega$$

17.57

$$R_{outD} = \mu_{f4} r_{o2} \quad | \quad T_{OC} = 0 \quad | \quad T_{SC} = (g_{m3} r_{o3}) \frac{g_{m4}(r_{o2} \parallel r_{o4})}{1 + g_{m4}(r_{o2} \parallel r_{o4})} \cong \mu_{f3} \frac{\mu_{f4}}{2 + \mu_{f4}} \cong \mu_{f3}$$

$$R_{out} = \mu_{f4} r_{o2} \frac{1 + \mu_{f3}}{1 + 0} = \mu_{f4} r_{o2} (\mu_{f3} + 1)$$

$$R_{inD} = r_{o3} \quad | \quad T_{SC} = 0 \quad | \quad T_{OC} = \mu_{f3} \frac{g_{m4}(r_{o2} \parallel r_{o4})}{1 + g_{m4}(r_{o2} \parallel r_{o4})} \cong \mu_{f3} \quad | \quad R_{in} = r_{o3} \frac{1+0}{1+\mu_{f3}} = \frac{1}{g_{m3}}$$

17.58

$$\text{Using Wq. (14.28), } R_{outD} = r_o \left[1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right] = r_{o4} \left[1 + \frac{\beta_o (r_{o2} \parallel r_{\pi3})}{r_{o3} + r_{\pi4} + (r_{o2} \parallel r_{\pi3})} \right] \cong r_{o4} \frac{\beta_o r_{\pi3}}{r_{o3}} = r_{o4} \frac{\beta_o^2}{\mu_f}$$

$$T_{OC} = (g_{m3} r_{o3}) \frac{r_{o2} \parallel r_{\pi3}}{r_{o3} + r_{\pi4} + r_{o2} \parallel r_{\pi3}} \cong (g_{m3} r_{o3}) \frac{r_{\pi3}}{r_{o3}} = \beta_o$$

$$T_{SC} \cong (g_{m3} r_{o3}) \frac{(\beta_o + 1)(r_{o2} \parallel r_{\pi3})}{r_{o3} + r_{\pi4} + (\beta_o + 1)(r_{o2} \parallel r_{\pi3})} \cong \mu_f \quad | \quad R_{out} \cong r_{o4} \frac{\beta_o^2}{\mu_f} \frac{1 + \mu_f}{1 + \beta_o} \cong \beta_o r_{o4}$$

We cannot exceed the $\beta_o r_{o4}$ limit as long as the base current of Q₄ reaches ground!

$$R_{inD} = r_{o3} \parallel [r_{\pi4} + (\beta_o + 1)(r_{o2} \parallel r_{\pi3})] \cong r_{o3} \parallel \beta_o r_{\pi3} \cong r_{o3} \quad | \quad T_{SC} = 0$$

$$T_{OC} = \mu_{f3} \frac{g_{m4}(r_{o2} \parallel r_{o4})}{1 + g_{m4}(r_{o2} \parallel r_{o4})} \cong \mu_{f3} \quad | \quad R_{in} = r_{o3} \frac{1+0}{1+\mu_{f3}} \cong \frac{1}{g_{m3}}$$

17.59

$$(a) A(s) = \frac{\frac{2\pi \times 10^{10} s}{(2\pi \times 10^6)}}{(s + 2\pi \times 10^3) \left(1 + \frac{s}{2\pi \times 10^6}\right)} = \frac{10^4 s}{(s + 2\pi \times 10^3) \left(1 + \frac{s}{2\pi \times 10^6}\right)}$$

$A(s)$ represents a band-pass amplifier with two widely-spaced poles

Open-loop: $A_o = 10^4$ or 80 dB | $f_L = 1 \text{ kHz}$ | $f_H = 1 \text{ MHz}$

$$(b) A_v(s) = \frac{\frac{2\pi \times 10^{10} s}{(s + 2\pi \times 10^3)(s + 2\pi \times 10^6)}}{1 + \frac{2\pi \times 10^{10} s}{(s + 2\pi \times 10^3)(s + 2\pi \times 10^6)}(0.01)} = \frac{6.28 \times 10^{10} s}{s^2 + 1.01(2\pi \times 10^8)s + 4\pi^2 \times 10^9}$$

Using dominant-root factorization:

$$f_H = \frac{1.01(2\pi \times 10^8)}{2\pi} = 101 \text{ MHz}, \quad f_L = \frac{1}{2\pi} \left(\frac{4\pi^2 \times 10^9}{1.01(2\pi \times 10^8)} \right) = 9.90 \text{ Hz}$$

$$(c) A_v(s) = \frac{\frac{2\pi \times 10^{10} s}{(s + 2\pi \times 10^3)(s + 2\pi \times 10^6)}}{1 + \frac{2\pi \times 10^{10} s}{(s + 2\pi \times 10^3)(s + 2\pi \times 10^6)}(0.025)} = \frac{6.28 \times 10^{10} s}{s^2 + 2.51(2\pi \times 10^8)s + 4\pi^2 \times 10^9}$$

Using dominant-root factorization:

$$f_H = \frac{2.51(2\pi \times 10^8)}{2\pi} = 251 \text{ MHz}, \quad f_L = \frac{1}{2\pi} \left(\frac{4\pi^2 \times 10^9}{2.51(2\pi \times 10^8)} \right) = 3.98 \text{ Hz}$$

17.60

$$(a) A(s) = \frac{\frac{2x10^{14} \pi^2}{(2\pi x 10^3)(2\pi x 10^5)}}{1 + \frac{s}{2\pi x 10^3} \left(1 + \frac{s}{2\pi x 10^5} \right)} = \frac{5x10^5}{1 + \frac{s}{2\pi x 10^3} \left(1 + \frac{s}{2\pi x 10^5} \right)}$$

$A(s)$ represents a low - pass amplifier with two widely - spaced poles

$$Open-loop: A_o = 5x10^5 = 114 dB \quad | \quad f_L = 0 \quad | \quad f_H \approx f_1 = 1000 Hz$$

(b) A common mistake would be the following :

$$Closed-loop: f_H = 1000 Hz [1 + 5x10^5 (0.01)] = 5 MHz$$

Oops! - This exceeds $f_2 = 100 kHz$! This is a two - pole low - pass amplifier.

$$A_v(s) = \frac{\frac{2x10^{14} \pi^2}{(s + 2\pi x 10^3)(s + 2\pi x 10^5)}}{1 + \frac{2x10^{14} \pi^2}{(s + 2\pi x 10^3)(s + 2\pi x 10^5)} (0.01)} = \frac{2x10^{14} \pi^2}{s^2 + 1.01(2\pi x 10^5)s + 2x10^{12} \pi^2}$$

Using dominant - root factorization : $f_1 = 101 kHz$, $f_2 = 4.95 MHz$

So the closed - loop values are $f_H = 101 kHz$ and $f_L = 0$.

17.61

$$(a) A(s) = \frac{\frac{4\pi^2 x 10^{18} s^2}{(2\pi x 10^6)(2\pi x 10^7)}}{(s + 200\pi)(s + 2000\pi)\left(1 + \frac{s}{2\pi x 10^6}\right)\left(1 + \frac{s}{2\pi x 10^7}\right)}$$

$$A(s) = \frac{10^5 s^2}{(s + 200\pi)(s + 2000\pi)\left(1 + \frac{s}{2\pi x 10^6}\right)\left(1 + \frac{s}{2\pi x 10^7}\right)}$$

$A(s)$ represents a band-pass amplifier with four widely-spaced poles

Open-loop: $A_o = 10^5$ or 100 dB | $f_L \approx 1 \text{ kHz}$ | $f_H \approx 1 \text{ MHz}$

$$(b) A_v(s) = \frac{\frac{4\pi^2 x 10^{18} s^2}{(s + 200\pi)(s + 2000\pi)(s + 2\pi x 10^6)(s + 2\pi x 10^7)}}{1 + \frac{4\pi^2 x 10^{18} s^2}{(s + 200\pi)(s + 2000\pi)(s + 2\pi x 10^6)(s + 2\pi x 10^7)}(0.01)}$$

Using MATLAB: $D(s) = s^4 + 6.9122x10^7 s^3 + 3.9518x10^{17} s^2 + 2.7288x10^{18} s + 1.5585x10^{21}$

The closed loop amplifier has complex roots:

$$\frac{1}{2\pi}(-3.45 \pm j62.7) = (-0.637 \pm j9.98) \text{ Hz} \quad \text{and} \quad \frac{10^8}{2\pi}(-0.346 \pm j6.28) = (-0.0637 \pm j1) \times 10^8 \text{ Hz}$$

Note that the amplifier is stable since all the poles are in the left half plane. See Problem 18.67.

$$(c) A_v(s) = \frac{\frac{2\pi x 10^{10} s}{(s + 2\pi x 10^3)(s + 2\pi x 10^6)}}{1 + \frac{2\pi x 10^{10} s}{(s + 2\pi x 10^3)(s + 2\pi x 10^6)}(0.025)}$$

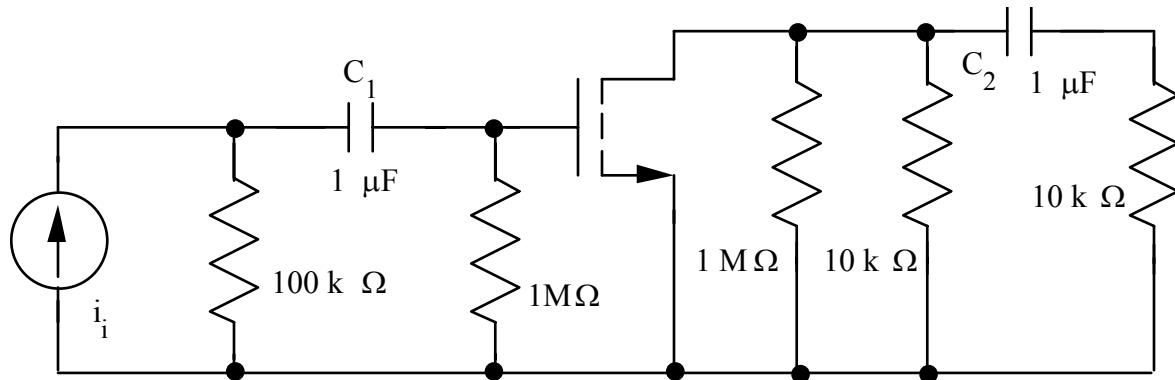
Using MATLAB: $D(s) = s^4 + 6.9122x10^7 s^3 + 9.909x10^{16} s^2 + 2.7288x10^{18} s + 1.5585x10^{21}$

The closed loop amplifier has complex roots:

$$\frac{1}{2\pi}(-13.8 \pm j124.7) = (-2.20 \pm j19.9) \text{ Hz} \quad \text{and} \quad \frac{10^8}{2\pi}(-0.346 \pm j3.13) = (-0.637 \pm j4.98) \times 10^7 \text{ Hz}$$

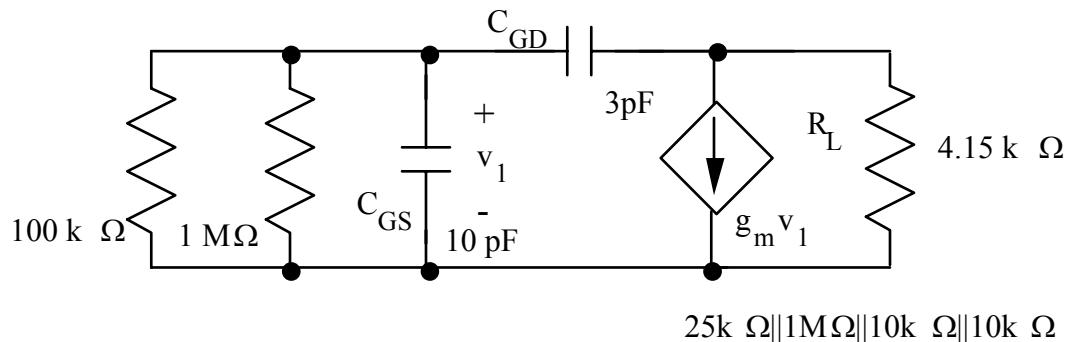
Note that the amplifier is stable since all the poles are in the left half plane.

17.62



$$\omega_1 = \frac{1}{10^{-6}(100k\Omega + 1M\Omega)} = 0.909 \frac{\text{rad}}{\text{s}} \quad | \quad \omega_2 = \frac{1}{10^{-6}(10k\Omega + 25k\Omega || 10k\Omega || 1M\Omega)} = 58.5 \frac{\text{rad}}{\text{s}}$$

Separate, widely-spaced, poles $\rightarrow f_L^A = f_2 = \frac{58.5}{2\pi} = 9.31 \text{ Hz}$



$$\omega_H^A = \frac{1}{r_{\text{ao}} C_T} = \frac{1}{(100k\Omega || 1M\Omega) \left[10pF + 3pF \left(1 + 2mS(4.15k\Omega) + \frac{4.15k\Omega}{100k\Omega || 1M\Omega} \right) \right]}$$

$$f_H^A = \frac{1}{2\pi} \frac{1}{(90.9k\Omega)(38.0pF)} = 46.1 \text{ kHz}$$

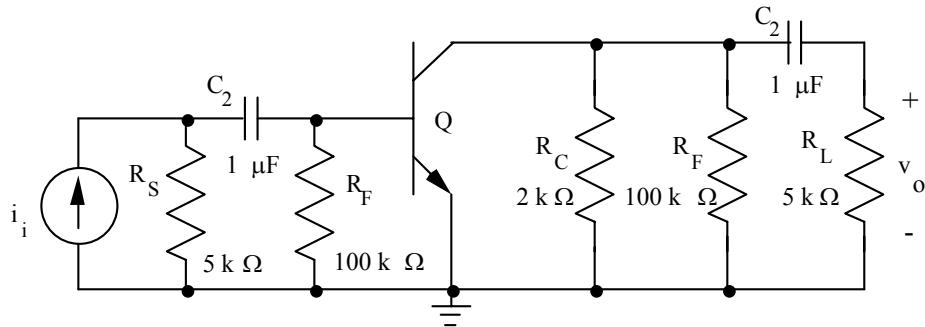
$$v_{gs} = i_s (100k\Omega || 1M\Omega) = (90.9k\Omega) i_s \quad | \quad v_o = -(2 \times 10^{-3}) v_{gs} (25k\Omega || 10k\Omega || 10k\Omega || 1M\Omega)$$

$$A = \frac{v_o}{i_s} = -(2mS)(4.15k\Omega)(90.9k\Omega) = -7.55 \times 10^5 \Omega \quad | \quad y_{12}^F = -10^{-5} S$$

$$1 + A\beta = 1 + (-7.55 \times 10^5 \Omega)(-10^{-6} S) = 1.76$$

$$f_L = \frac{9.31}{1.76} = 5.29 \text{ Hz} \quad f_H = 46.1 \text{ kHz} (1.76) = 81.0 \text{ kHz}$$

17.63



From the Exercise: $g_m = 40.3 \text{ mS}$ | $r_\pi = 3.72 \text{ k}\Omega$ | $r_o = 50.8 \text{ k}\Omega$ | $1 + A\beta = 2.19$

$$r_{o2} = \frac{50 + 1.4}{10^{-4}} = 514 \text{ k}\Omega \quad | \quad r_{o4} = \frac{50 + 11.3}{10^{-4}} = 613 \text{ k}\Omega \quad | \quad r_{\pi 5} = \frac{100(0.025)}{0.0012} = 2.08 \text{ k}\Omega$$

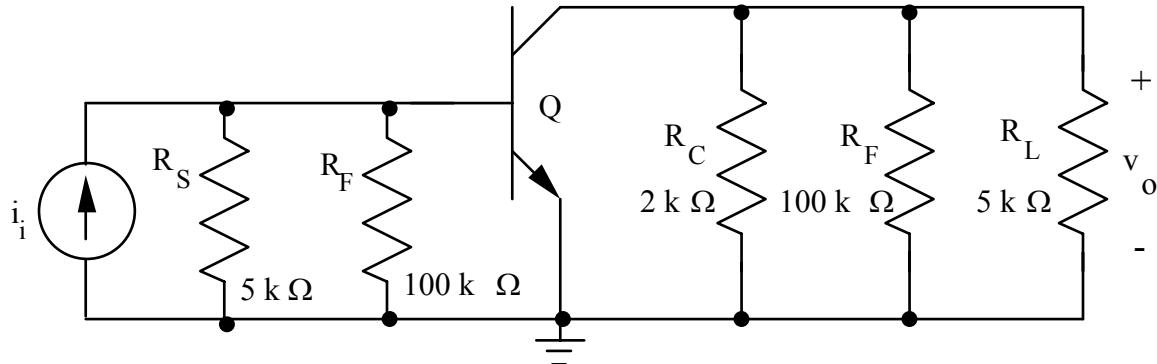
$$C_{\pi 1} = \frac{40.3 \text{ mS}}{2\pi(500 \text{ MHz})} - 0.75 \text{ pF} = 12.1 \text{ pF}$$

Using the open-circuit time constant approach with $C_1 = C_2 = 1 \mu\text{F}$:

$$R_{1O} = 5 \text{ k}\Omega + 100 \text{ k}\Omega \| r_\pi 5 \text{ k}\Omega + 100 \text{ k}\Omega \| 3.72 \text{ k}\Omega = 8.59 \text{ k}\Omega$$

$$R_{2O} = 5 \text{ k}\Omega + 50.8 \text{ k}\Omega \| 2 \text{ k}\Omega \| 100 \text{ k}\Omega = 6.89 \text{ k}\Omega$$

$$f_L = \frac{1}{2\pi} \left[\frac{1}{1\mu\text{F}(8.59 \text{ k}\Omega)} + \frac{1}{1\mu\text{F}(6.89 \text{ k}\Omega)} \right] = 41.6 \text{ Hz} \quad | \quad f_L^F = \frac{f_L}{1 + A\beta} = 19.0 \text{ Hz}$$



$$r_{\pi o} = 3.72 \text{ k}\Omega \| 100 \text{ k}\Omega \| 5 \text{ k}\Omega = 2.09 \text{ k}\Omega \quad | \quad R_L = 50.8 \text{ k}\Omega \| 2 \text{ k}\Omega \| 100 \text{ k}\Omega \| 5 \text{ k}\Omega = 1.37 \text{ k}\Omega$$

$$C_T = 12.1 \text{ pF} + 0.75 \text{ pF} \left[1 + 40.3 \text{ mS}(1.37 \text{ k}\Omega) + \frac{1.37 \text{ k}\Omega}{2.09 \text{ k}\Omega} \right] = 54.8 \text{ pF}$$

$$f_H = \frac{1}{2\pi r_{\pi o} C_T} = \frac{1}{2\pi(1.37 \text{ k}\Omega)(54.8 \text{ pF})} = 1.39 \text{ MHz} \quad | \quad f_H^F = f_H(1 + A\beta) = 3.04 \text{ MHz}$$

17.64

$$A(s) = \frac{2\pi x 10^7}{s + 2000\pi} \quad | \quad A = \frac{25k\Omega}{1k\Omega + 25k\Omega + 9.01k\Omega} \left(\frac{2\pi x 10^7}{s + 2000\pi} \right) \frac{1.96k\Omega}{1.96k\Omega + 1k\Omega} = \frac{2.97 x 10^7}{s + 2000\pi}$$

$$A_v(s) = \frac{\frac{2.97 x 10^7}{s + 2000\pi}}{1 + \frac{2.97 x 10^7}{s + 2000\pi}(0.0990)} = \frac{2.97 x 10^7}{s + 2.95 x 10^6} = \frac{10.1}{1 + \frac{s}{2.95 x 10^6}} \quad | \quad f_H = \frac{2.95 x 10^6}{2\pi} = 470 \text{ kHz}$$

17.65

$$S_{A_o}^{\omega_H^F} = \frac{A_o}{\omega_H^F} \frac{\partial \omega_H^F}{\partial A_o} \quad | \quad \omega_H^F = \omega_H^A (1 + A\beta) \quad | \quad S_{A_o}^{\omega_H^F} = \frac{A_o}{\omega_H^A (1 + A_o\beta)} \omega_H^A \beta = \frac{A_o \beta}{(1 + A_o \beta)} \cong +1$$

$$\frac{\partial \omega_H^F}{\omega_H^F} = S_{A_o}^{\omega_H^F} \frac{\partial A_o}{A_o} = \frac{10^5 (0.01)}{1 + 10^5 (0.01)} 10\% = 9.99\%$$

17.66

(a) At high frequencies with $\beta = 0.01$, $A\beta = \frac{(2x10^{14}\pi^2)(0.01)}{(s+2000\pi)(s+2\pi x 10^5)} \cong \frac{(2x10^{12}\pi^2)}{s(s+2\pi x 10^5)}$

$$|A\beta| = \frac{(2x10^{12}\pi^2)}{\omega \sqrt{\omega^2 + (2\pi x 10^5)^2}} = 1 \quad | \quad \text{Using MATLAB, } \omega = 4.42 x 10^6$$

$$\angle A\beta = -90 - \tan^{-1} \left(\frac{4.42 x 10^6}{2\pi x 10^5} \right) = 171.9^\circ \quad | \quad \Phi_M = 8.1^\circ$$

(b) At high frequencies with $\beta = 0.025$, $A\beta = \frac{(2x10^{14}\pi^2)(0.025)}{(s+2000\pi)(s+2\pi x 10^5)} \cong \frac{(5x10^{12}\pi^2)}{s(s+2\pi x 10^5)}$

$$|A\beta| = \frac{(5x10^{12}\pi^2)}{\omega \sqrt{\omega^2 + (2\pi x 10^5)^2}} = 1 \quad | \quad \text{Using MATLAB, } \omega = 7.01 x 10^6$$

$$\angle A\beta = -90 - \tan^{-1} \left(\frac{7.01 x 10^6}{2\pi x 10^5} \right) = 174.9^\circ \quad | \quad \Phi_M = 5.1^\circ$$

17.67

(a) At high frequencies with $\beta = 0.01$, $A\beta = \frac{s(2\pi x 10^{10})(0.01)}{(s+2000\pi)(s+2\pi x 10^6)} \approx \frac{2\pi x 10^8}{(s+2\pi x 10^6)}$

$$|A\beta| = \frac{2\pi x 10^8}{\sqrt{\omega^2 + (2\pi x 10^6)^2}} = 1 \quad | \quad \omega \approx 2\pi x 10^8$$

$$\angle A\beta = -\tan^{-1}\left(\frac{2\pi x 10^8}{2\pi x 10^6}\right) = -89.4^\circ \quad | \quad \Phi_M = 90.6^\circ$$

(b) At high frequencies with $\beta = 0.025$, $A\beta = \frac{s(2\pi x 10^{10})(0.025)}{(s+2000\pi)(s+2\pi x 10^6)} \approx \frac{5\pi x 10^8}{(s+2\pi x 10^6)}$

$$|A\beta| = \frac{5\pi x 10^8}{\omega \sqrt{\omega^2 + (2\pi x 10^6)^2}} = 1 \quad | \quad \omega \approx 5\pi x 10^8$$

$$\angle A\beta = -\tan^{-1}\left(\frac{5\pi x 10^8}{2\pi x 10^6}\right) = -89.8^\circ \quad | \quad \Phi_M = 90.2^\circ$$

17.68

(a) At high frequencies with $\beta = 0.01$, $A\beta = \frac{s^2(4\pi^2 x 10^{18})(0.01)}{(s+200\pi)(s+2000\pi)(s+2\pi x 10^6)(s+2\pi x 10^7)}$

$$A\beta \approx \frac{s^2(4\pi^2 x 10^{18})(0.01)}{s^2(s+2\pi x 10^6)(s+2\pi x 10^7)} \approx \frac{4\pi^2 x 10^{16}}{(s+2\pi x 10^6)(s+2\pi x 10^7)}$$

$$|A\beta| = \frac{4\pi^2 x 10^{16}}{\sqrt{\omega^2 + (2\pi x 10^6)^2} \sqrt{\omega^2 + (2\pi x 10^6)^2}} = 1 \quad | \quad \text{Using MATLAB, } \omega \approx 6.2673 \times 10^8$$

$$\angle A\beta = -\tan^{-1}\left(\frac{6.2673 \times 10^8}{2\pi x 10^6}\right) - \tan^{-1}\left(\frac{6.2673 \times 10^8}{2\pi x 10^7}\right) = -173.7^\circ \quad | \quad \Phi_M = 6.3^\circ$$

(b) At high frequencies with $\beta = 0.025$, $A\beta = \frac{s^2(4\pi^2 x 10^{18})(0.025)}{(s+200\pi)(s+2000\pi)(s+2\pi x 10^6)(s+2\pi x 10^7)}$

$$A\beta \approx \frac{s^2(4\pi^2 x 10^{18})(0.025)}{s^2(s+2\pi x 10^6)(s+2\pi x 10^7)} \approx \frac{\pi^2 x 10^{17}}{(s+2\pi x 10^6)(s+2\pi x 10^7)}$$

$$|A\beta| = \frac{\pi^2 x 10^{17}}{\sqrt{\omega^2 + (2\pi x 10^6)^2} \sqrt{\omega^2 + (2\pi x 10^6)^2}} = 1 \quad | \quad \text{Using MATLAB, } \omega \approx 9.9246 \times 10^8$$

$$\angle A\beta = -\tan^{-1}\left(\frac{9.9246 \times 10^8}{2\pi x 10^6}\right) - \tan^{-1}\left(\frac{9.9246 \times 10^8}{2\pi x 10^7}\right) = -176.0^\circ \quad | \quad \Phi_M = 4.0^\circ$$

17.69

$$(a) T(s) = \frac{4 \times 10^{19} \pi^3}{(s + 2\pi \times 10^4)(s + 2\pi \times 10^5)^2} \beta \quad | \quad \angle T(j\omega) = -\tan^{-1} \frac{f}{10^4} - 2\tan^{-1} \frac{f}{10^5} = -180^\circ$$

For $f \gg 10^4$, $-2\tan^{-1} \frac{f}{10^5} = -90^\circ \rightarrow f = 10^5 \text{ Hz}$. Using this as a starting point

for iteration, we find $f = 110 \text{ kHz}$ or $\omega = 2.2 \times 10^5 \pi$

$$(b) |A(j2.2 \times 10^5 \pi)| = \frac{4 \times 10^{19} \pi^3}{\sqrt{(2.2 \times 10^5 \pi)^2 + (2\pi \times 10^4)^2} \left[(2.2 \times 10^5 \pi)^2 + (2\pi \times 10^5)^2 \right]} = 2048$$

The amplifier will oscillate for closed-loop gains ≤ 2048 (66.2 dB).

17.70

$$T(s) = A\beta = \left(\frac{10^7}{s+50} \right) \frac{\frac{1}{sC_L}}{R_o + \frac{1}{sC_L}} = \left(\frac{10^7}{s+50} \right) \frac{1}{sC_L R_o + 1} = \left(\frac{10^7}{s+50} \right) \frac{1}{500sC_L + 1}$$

Assume that the unity-gain occurs at $\omega_i \gg 50$: $\angle T(j\omega_i) = \angle A + \angle \beta = -90^\circ - \tan^{-1}(500\omega_i C_L)$
 $-90^\circ - \tan^{-1}(500\omega_i C_L) = -180^\circ + 60^\circ \quad | \quad \tan^{-1}(500\omega_i C_L) = 30^\circ \quad | \quad 500\omega_i C_L = 0.5774$

$$|T(j\omega_i)| = 1 \quad | \quad \frac{10^7}{\omega_i \sqrt{1 + (500\omega_i C_L)^2}} = \frac{10^7}{\omega_i \sqrt{1 + [\tan(30^\circ)]^2}} = 1 \rightarrow \omega_i = 8.66 \times 10^6$$

$$C_L = \frac{\tan(30^\circ)}{500(8.66 \times 10^6)} = 133 \text{ pF}$$

17.71

$$(a) T = A\beta = \frac{4 \times 10^{13} \pi^2}{(s + 2\pi \times 10^3 \pi)(s + 2\pi \times 10^4 \pi)} \left(\frac{1}{4} \right) \quad | \quad \text{Yes, it is a second-order system and will}$$

have some phase margin, although Φ_M may be vanishingly small.

$$(b) \text{For } \omega \gg 2\pi \times 10^4, |T(j\omega)| \approx \frac{1 \times 10^{13} \pi^2}{\omega^2} \text{ and } |T(j\omega)| = 1 \text{ for } \omega = 9.935 \times 10^6 \frac{\text{rad}}{\text{s}}$$

$$\angle T(j9.935 \times 10^6) = -\tan^{-1} \frac{9.935 \times 10^6}{2000\pi} - \tan^{-1} \frac{9.935 \times 10^6}{20000\pi} = 179.6^\circ \rightarrow \Phi_M = 0.4^\circ \quad | \quad \text{A very small phase margin.}$$

17.72

$$(a) T = A\beta = \frac{2x10^{14} \pi^2}{(s + 2x10^3 \pi)(s + 2x10^5 \pi)} \left(\frac{1}{5}\right) \quad | \text{ Yes, it is a second - order system and will}$$

have some phase margin, although Φ_M may be vanishingly small.

$$(b) \text{ For } \omega \gg 2\pi \times 10^5, |T(j\omega)| \approx \frac{4x10^{13} \pi^2}{\omega^2} \text{ and } |T(j\omega)| = 1 \text{ for } \omega = 1.987 \times 10^7 \frac{\text{rad}}{\text{s}}$$

$$\angle T(j1.987 \times 10^7) = -\tan^{-1} \frac{1.987 \times 10^7}{2000\pi} - \tan^{-1} \frac{1.987 \times 10^7}{2x10^5 \pi} = 178.2^\circ \rightarrow \Phi_M = 1.83^\circ \quad | \text{ A very small phase margin.}$$

17.73

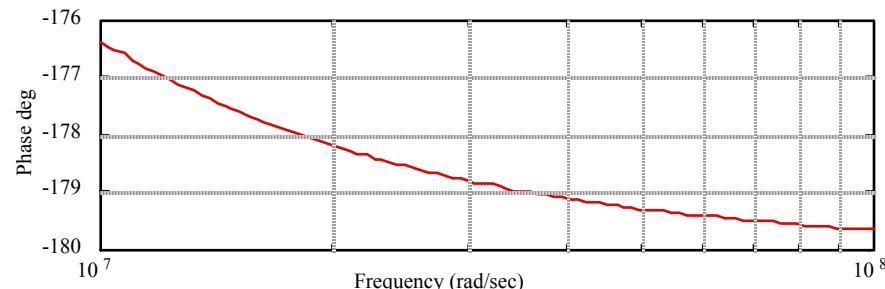
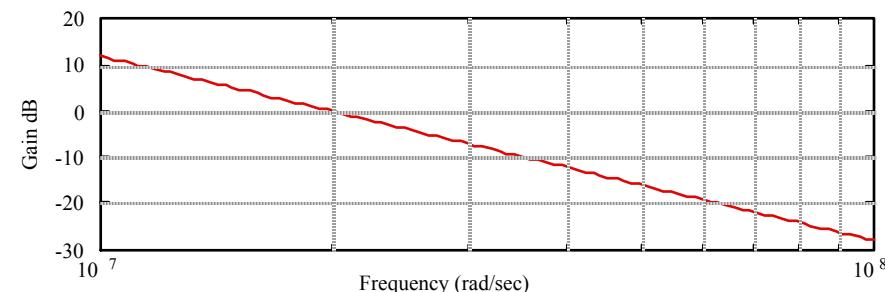
(a) The following command line will generate the complete bode plot:

`w=logspace(3,8,400); bode((2e14*pi^2/5),conv([1 2000*pi],[1 2e5*pi]),w)`

The following command line will generate the bode plot between 10^7 and 10^8 rad/s:

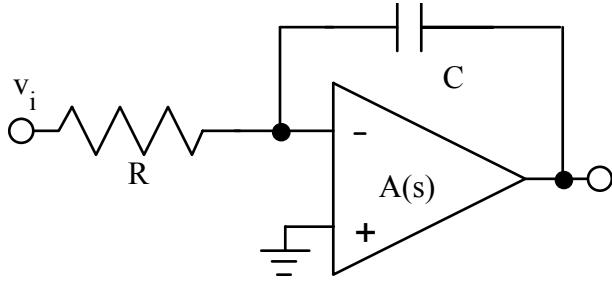
`w=logspace(7,8,100); bode((2e14*pi^2/5),conv([1 2000*pi],[1 2e5*pi]),w)`

The second plot agrees with the results calculated in the previous problem.



(b) `w=logspace(7,8,100); bode((2e14*pi^2),conv([1 2000*pi],[1 2e5*pi]),w)` yields a phase margin of only 0.75 degrees

17.74



$$\beta = \frac{R}{R + \frac{1}{sC}} = \frac{sRC}{sRC + 1} \quad | \quad T = \frac{2\pi x 10^6}{s + 20\pi} \frac{sRC}{(sRC + 1)} \quad | \quad \text{For } \omega RC \gg 1, \quad T \approx \frac{2\pi x 10^6}{s + 20\pi}$$

$$\text{and } |T| = 1 \text{ for } \omega = 2\pi x 10^6. \text{ Given } RC = 10^{-8}(10^5) = 10^{-3}, \beta = \frac{s}{s + 1000}$$

$$\angle T = 90^\circ - \tan^{-1} \frac{2\pi x 10^6}{20\pi} - \tan^{-1} \frac{2\pi x 10^6}{1000} = -90.0^\circ \quad | \quad \Phi_M = 90.0^\circ$$

17.75

$$\beta = \frac{R}{R + \frac{1}{sC}} = \frac{sRC}{sRC + 1} = \frac{s10^5(10^{-8})}{s10^5(10^{-8}) + 1} = \frac{s}{s + 1000}$$

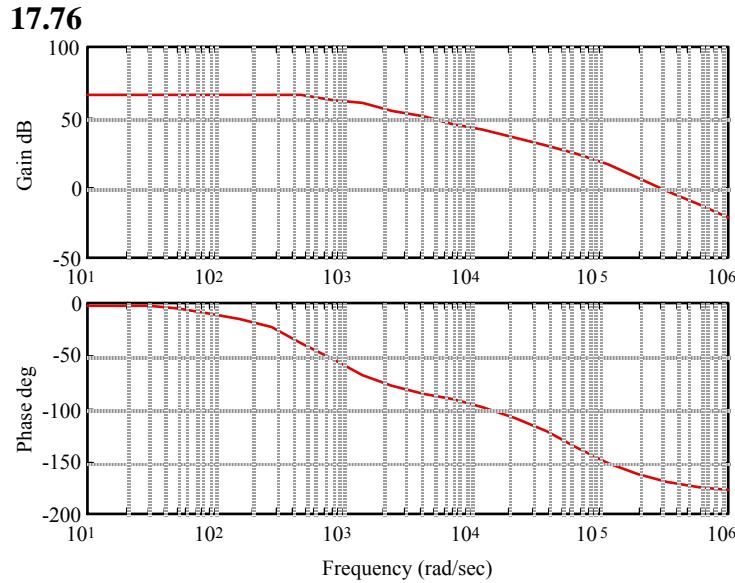
$$A(s) = \frac{10^5}{\left(1 + \frac{s}{2000\pi}\right)\left(1 + \frac{s}{200000\pi}\right)} = \frac{4\pi^2 x 10^{13}}{(s + 2000\pi)(s + 200000\pi)}$$

$$T = \frac{4\pi^2 x 10^{13}}{(s + 2000\pi)(s + 200000\pi)} \frac{s}{(s + 1000)} \quad | \quad \text{At high frequencies, } T \approx \frac{4\pi^2 x 10^{13}}{s^2}$$

and the integrator will have a positive phase margin, although Φ_M may be very small.

$$\text{For } \omega > 2\pi x 10^5, \quad |T(j\omega_1)| \approx \frac{4\pi^2 x 10^{13}}{\omega_1^2} = 1 \Rightarrow \omega_1 = 1.987 x 10^7 \frac{\text{rad}}{\text{s}} \gg 2\pi x 10^5$$

$$\angle T = 90^\circ - \tan^{-1} \frac{1.987 x 10^7}{2000\pi} - \tan^{-1} \frac{1.987 x 10^7}{200000\pi} - \tan^{-1} \frac{1.987 x 10^7}{1000} \quad | \quad \Phi_M = 1.83^\circ$$



$$(a) \beta = \frac{R_1}{R_2 \frac{1}{sC_C}} = \frac{R_1}{R_1 + \frac{R_2}{sC_C R_2 + 1}} = \frac{R_1}{R_1 + R_2} \frac{sC_C R_2 + 1}{sC_C (R_1 \| R_2) + 1}$$

$$R_1 + \frac{1}{R_2 + \frac{1}{sC_C}}$$

$$\text{For } C_C = 0, \quad T = \frac{2 \times 10^{11} \pi^2}{(s + 200\pi)(s + 20000\pi)} \frac{1}{21}$$

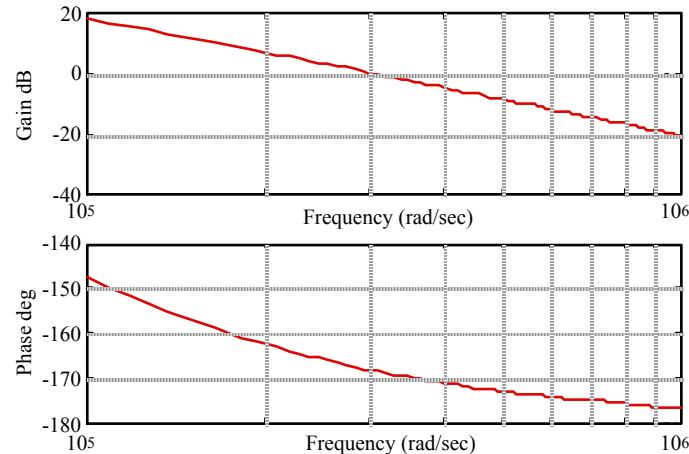
The graphs above were generated using

```
bode(2e11*pi^2/21,[1 2.02e4*pi 4e6*pi^2])
```

Blowing up the last decade:

```
w=linspace(1e5,1e6); bode(2e11*pi^2/21,[1 2.02e4*pi 4e6*pi^2],w)
```

and the phase margin is approximately 12°



Setting the zero to cancel the second pole,

$$\beta(s) = \frac{R_1}{R_1 + R_2} \frac{sC_C R_2 + 1}{sC_C(R_1\|R_2) + 1} = \frac{s + \frac{1}{C_C R_2}}{s + \frac{1}{C_C(R_1\|R_2)}}$$

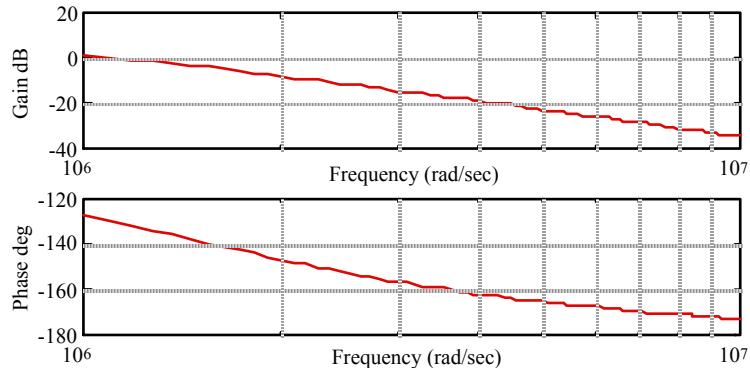
$$T = \frac{2 \times 10^{11} \pi^2}{(s + 200\pi)(s + 20000\pi)} \frac{(s + 20000\pi)}{s + 1.319 \times 10^6} = \frac{2 \times 10^{11} \pi^2}{s^2 + 1.320 \times 10^6 s + 8.288 \times 10^6}$$

Using MATLAB:

```
bode(2e11*pi^2,[1 1.320e6 8.288e8])
```

and then

```
w=linspace(1e6,1e7); bode(2e11*pi^2,[1 1.320e6 8.288e8],w)
```



The phase margin is now approximately 50°

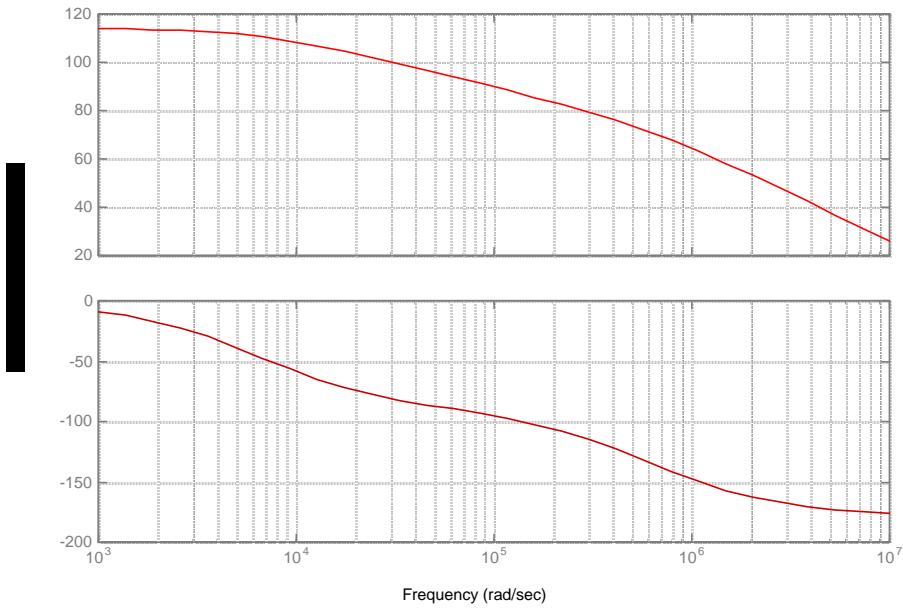
17.77

```
num=4e19*pi^3;
p=conv([1 2e5*pi],[1 2e5*pi]);
den=conv([1 2e4*pi],p);
bode(num,den)
```

Results: Frequency = 6.9×10^5 rad/s and approximately 66 dB which agree with the hand calculations in Problem 17.69.

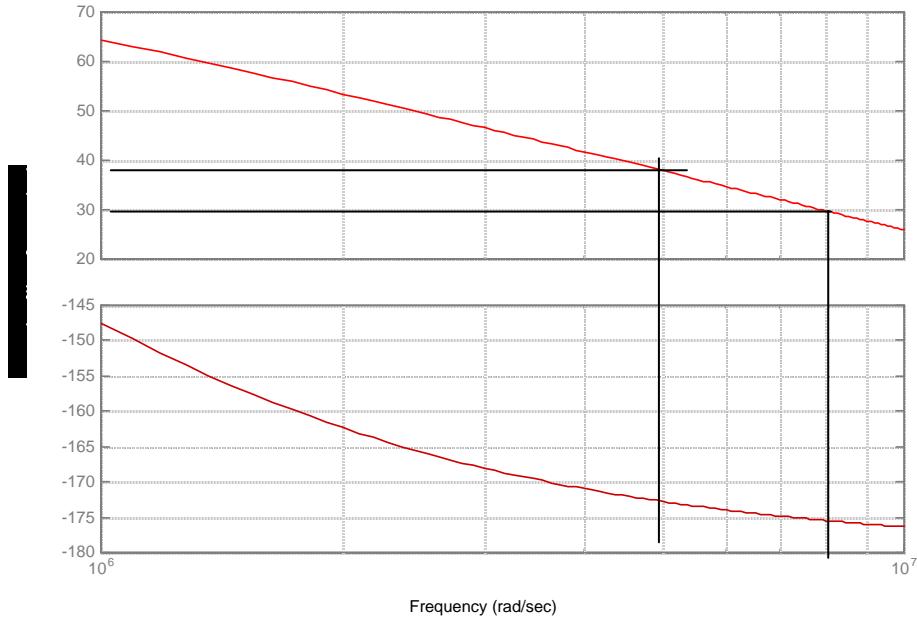
17.78

Bode Diagrams

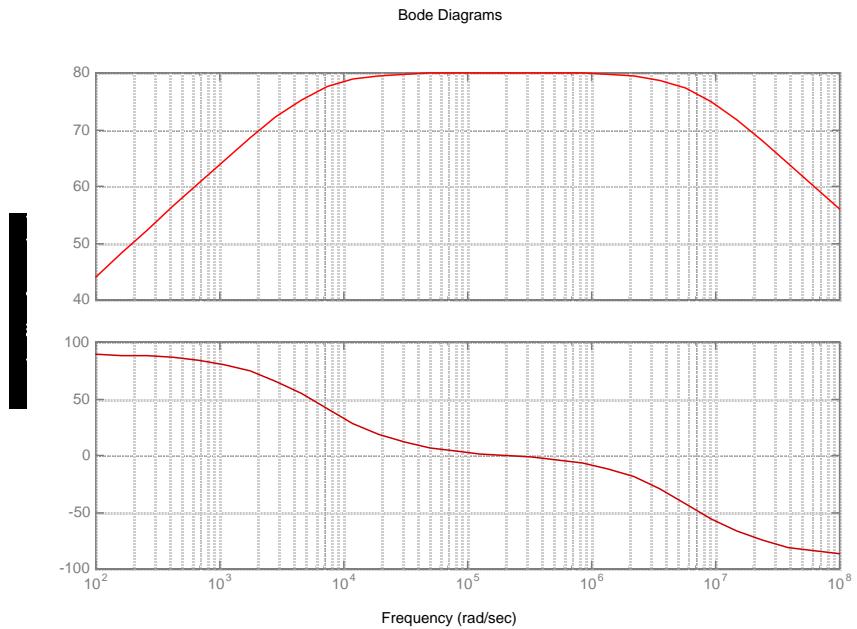


Expanded view:

Bode Diagrams

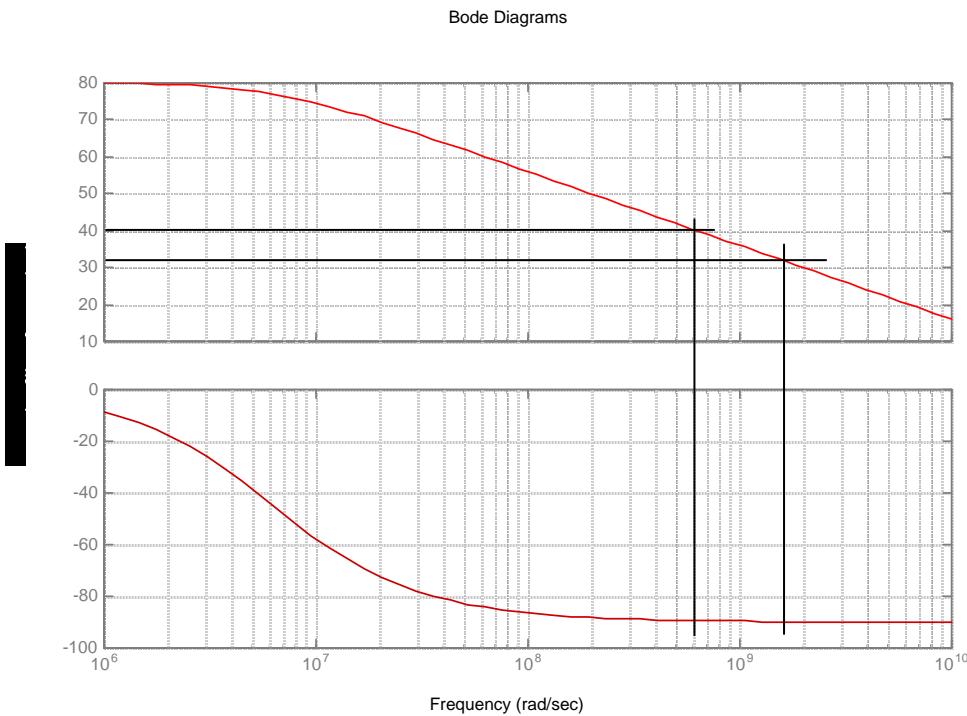


For a gain of 100 (40 dB), the phase margin is approximately 8° . For a gain of 40 (32 dB), the phase margin is approximately 5° . The gain margin is infinite in both cases since the phase shift never reaches 180° . These values agree with the calculations in Problem 17.59. (b) The amplifier will not oscillate.

17.79

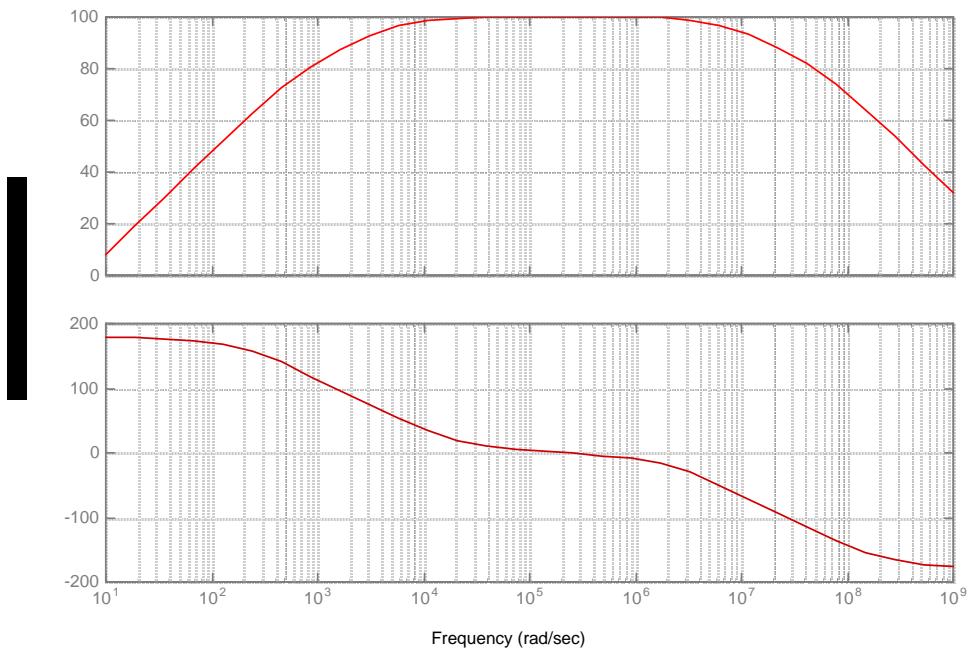
The phase shift ranges from $+90^\circ$ at low frequencies to -90° at high frequencies. The phase margin for both gains of 100 and 40 is 90° at the high frequency intersection and 270° at the low end. These values agree with the calculations in Problem 17.60. (b) The amplifier will not oscillate.

Expanded view at high frequencies:

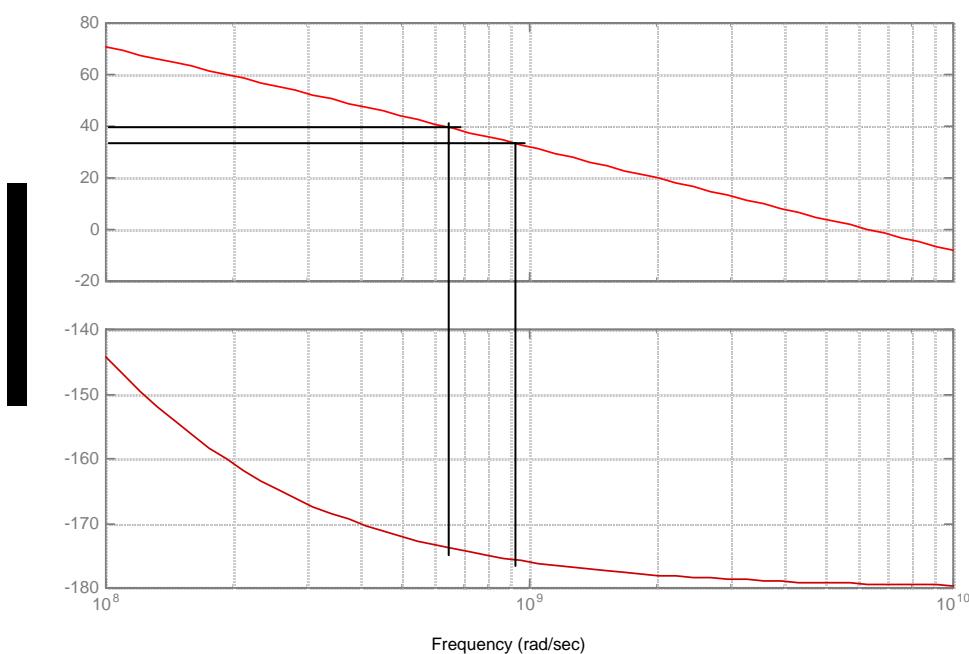


17.80

Bode Diagrams



Bode Diagrams



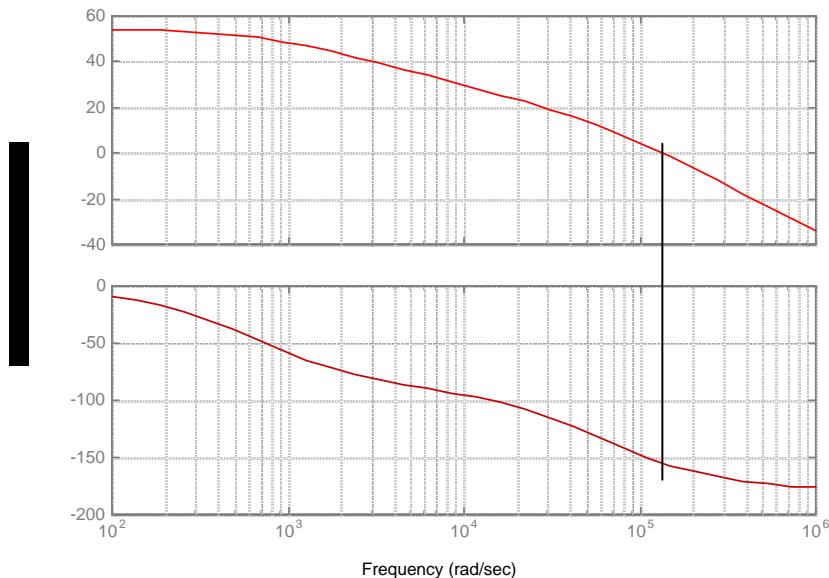
The phase margin is approximately 6° and 4° for gains of 40 dB and 32 dB respectively. The gain margin is infinite in both cases. These values agree with the calculations in Problem 17.61.
 (b) The amplifier will not oscillate.

17.81

```
num=2e11*pi^2  
den=conv([1 200*pi],[1 20000*pi]);  
bode(num/100,den)  
w=logspace(5,6,100); bode(num/100,den,w)
```

Results: Yes, the amplifier is stable with a phase margin of approximately 26°.

Bode Diagrams



17.82

$$A_v(s) = \frac{\frac{A_o \omega_o}{s + \omega_o}}{1 + \frac{A_o \omega_o}{s + \omega_o}} = \frac{\omega_T}{s + (1 + A_o)\omega_o} \cong \frac{\omega_T}{s + \omega_T} = \frac{2\pi x 10^6}{s + 2\pi x 10^6}$$

From problem 18.45: $\beta(s) = \frac{5x10^4 s}{s^2 + 7x10^4 s + 5x10^8}$

$$T(s) = A_v(s)\beta(s) = \frac{10^{11} \pi s}{(s + 2\pi x 10^6)(s^2 + 7x10^4 s + 5x10^8)}$$

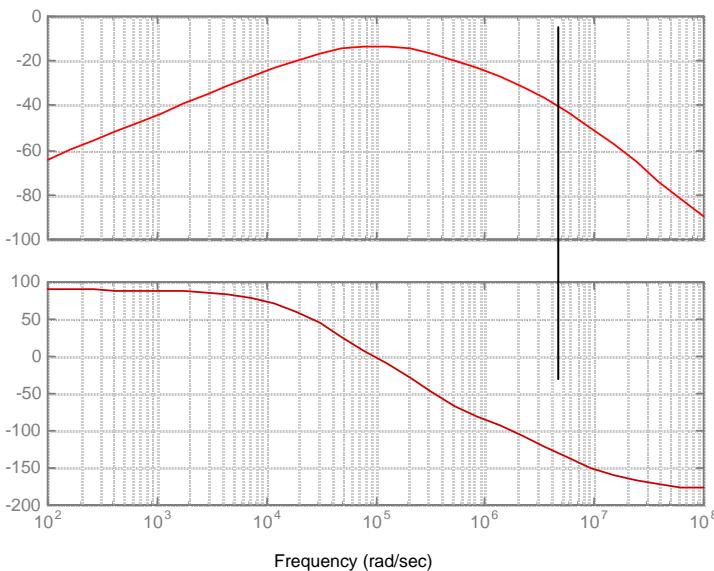
Using MATLAB:

```
num=[pi*1e11 0]
den=conv([1 3e5 1e10],[1 5e6])
bode(num,den)
```

It is also instructive to use: nyquist(num,den)

One finds that $|T(j\omega)| < 1$ for all ω , so the phase margin is undefined. The filter is stable. Note that this is a positive feedback system so the point of interest is +1. The gain of the filter is approximately -3 dB. So the filter has a gain margin of 3 dB.

Bode Diagrams



17.83

$$T(s) = K(s)\beta(s) = \left(\frac{10^7}{s + 5 \times 10^6} \right) \left(\frac{10^5 s}{s^2 + 3 \times 10^5 s + 10^{10}} \right) = \frac{10^{12} s}{(s + 5 \times 10^6)(s^2 + 3 \times 10^5 s + 10^{10})}$$

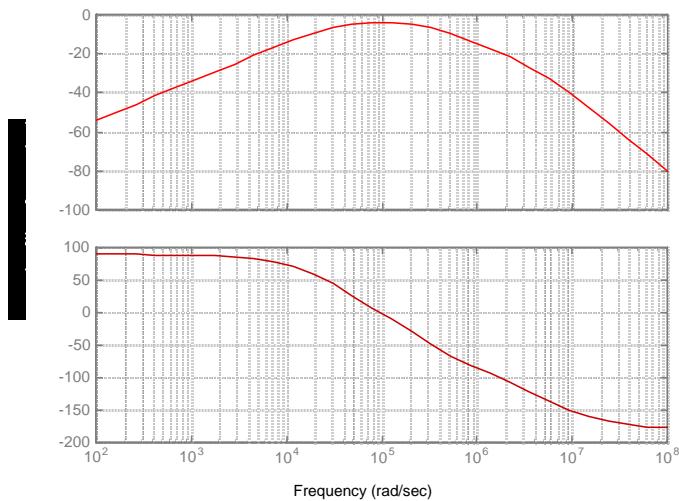
Using MATLAB:

```
num=[1e12 0]
den=conv([1 3e5 1e10],[1 5e6])
bode(num,den)
```

It is also instructive to use: nyquist(num,den)

One finds that $|T(j\omega)| < 1$ for all ω , so the phase margin is undefined. The filter is stable. Note that this is a positive feedback system so the point of interest is +1. The gain of the filter is approximately -3 dB. So the filter has a gain margin of 3 dB.

Bode Diagrams



17.84

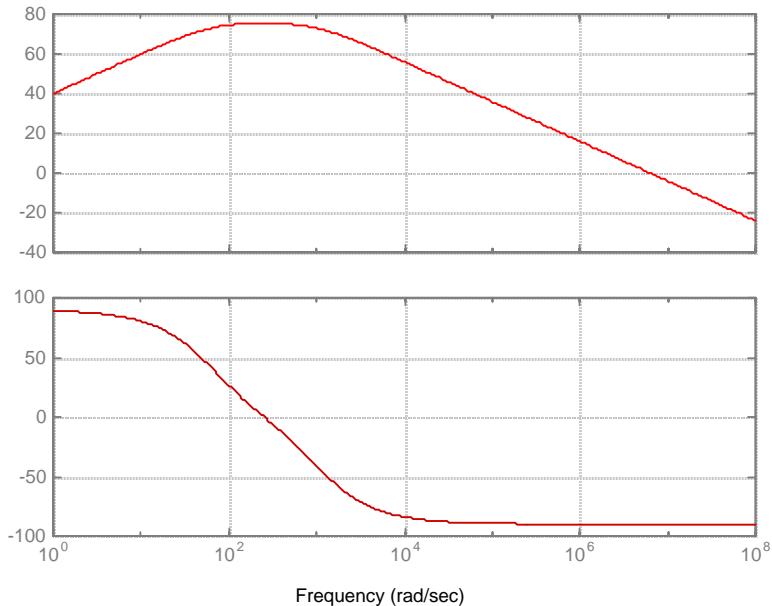
$$\beta = \frac{sRC}{sRC + 1} = \frac{s}{s + 1000} \quad | \quad T = \frac{2\pi \times 10^6 s}{(s + 20\pi)(s + 1000)}$$

Using MATLAB:

```
num=[2e6*pi 0]; den=conv([1 20*pi],[1 1000]);
w=logspace(0,8,400);
bode(num,den,w)
```

The phase margin is 90° which agrees with Problem 17.74.

Bode Diagrams



17.85

$$\beta = \frac{sRC}{sRC + 1} = \frac{s}{s + 1000} \quad | \quad A(s) = \frac{10^5}{\left(1 + \frac{s}{2000\pi}\right)\left(1 + \frac{s}{200000\pi}\right)} = \frac{4\pi^2 \times 10^{13}}{(s + 2000\pi)(s + 200000\pi)}$$

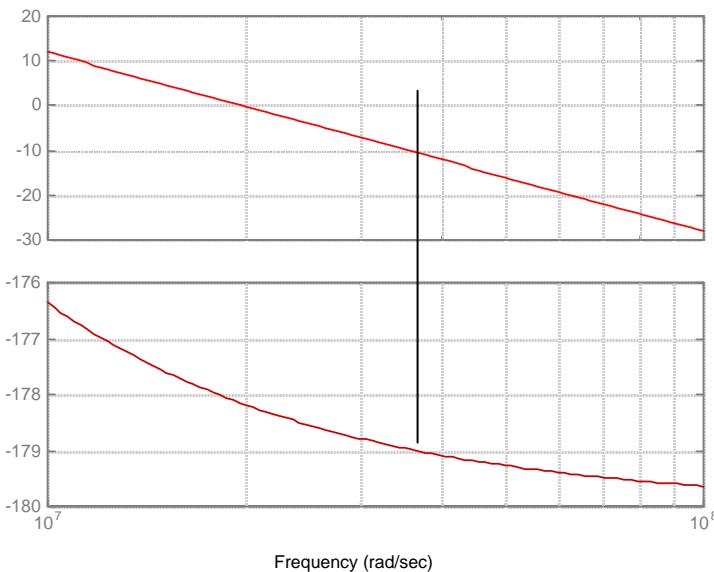
$$T = \frac{4\pi^2 \times 10^{13} s}{(s + 2000\pi)(s + 200000\pi)(s + 1000)}$$

Using MATLAB:

```
num=[4e13*pi^2 0];
den=conv([1 1000],conv([1 2000*pi],[1 200000*pi]));
w=logspace(7,8,100); bode(num,den,w)
```

The phase margin is 1.8° which agrees with Problem 17.75.

Bode Diagrams



17.86

$$\beta(s) = \frac{\frac{R_1}{sC_s R_1 + 1}}{\frac{R_1}{sC_s R_1 + 1} + R_2} = \frac{R_1}{R_1 + R_2} \frac{1}{sC_s(R_1||R_2) + 1} = \frac{1}{9.30(1.89 \times 10^{-6}s + 1)}$$

$$\beta(s) = \frac{5.69 \times 10^4}{s + 5.29 \times 10^5} \quad A_v(s) = \frac{10^7}{s + 50} \quad T(s) = A_v(s)\beta(s)$$

For $\omega \gg 50$, $|T(j\omega)| \approx \frac{5.69 \times 10^{11}}{\omega \sqrt{\omega^2 + (5.29 \times 10^5)^2}} \rightarrow |T(j\omega)| = 1$ for $\omega = 6.68 \times 10^5$

$$\Phi_M = 180 - \tan^{-1} \frac{6.68 \times 10^5}{50} - \tan^{-1} \frac{6.68 \times 10^5}{5.29 \times 10^5} = 38.4^\circ$$

17.87

$$(a) f_T = \frac{g_{m1}}{2\pi C_C} = \frac{\sqrt{2(0.001)(125 \times 10^{-6})}}{2\pi(7.5 \times 10^{-12})} = 10.6 \text{ MHz} \quad | \quad \text{Since } I_2 > I_1, \text{ the slew rate}$$

is approximately symmetrical. | $SR = \frac{I_1}{C_C} = \frac{250 \times 10^{-6}}{7.5 \times 10^{-12}} = 33.3 \times 10^6 \frac{V}{s} = 33.3 \frac{V}{\mu s}$

$$(b) f_T = \frac{g_{m1}}{2\pi C_C} = \frac{\sqrt{2(0.001)(250 \times 10^{-6})}}{2\pi(10^{-11})} = 11.3 \text{ MHz} \quad | \quad \text{Since } I_2 > I_1, \text{ the slew rate}$$

is asymmetrical. | $SR_+ = \frac{I_1}{C_C} = \frac{500 \mu A}{10 pF} = 50 \frac{V}{\mu s} \quad | \quad SR_- = \frac{250 \mu A}{10 pF} = 25 \frac{V}{\mu s}$

17.88

$$f_T = \frac{g_{m1}}{2\pi C_C} = \frac{\sqrt{2(0.001)(250 \times 10^{-6})}}{2\pi(10^{-11})} = 11.3 \text{ MHz} \quad | \quad \text{Since } I_2 > I_1, \text{ the slew rate}$$

is symmetrical. | $SR = \frac{I_1}{C_C} = \frac{500 \times 10^{-6}}{10^{-11}} = 50 \times 10^6 \frac{V}{s} = 50 \frac{V}{\mu s}$

17.89

*Problem 17.89 - CMOS Op-amp
VDD 8 0 DC 10
VSS 9 0 -10
I1 1 9 250U
I2 6 9 500U
I3 7 9 2M
V1 4 0 DC -2.23M AC 0.5
V2 2 0 AC -0.5
M1 3 2 1 1 NFET W=20U L=1U
M2 5 4 1 1 NFET W=20U L=1U
M3 3 3 8 8 PFET W=40U L=1U
M4 5 3 8 8 PFET W=40U L=1U
M5 6 5 8 8 PFET W=160U L=1U
M6 8 6 7 7 NFET W=60U L=1U
CC 5 6 7.5PF
*CC 5 10 7.5PF
*RZ 10 6 1K
.MODEL NFET NMOS KP=2.5E-5 VTO=0.70 GAMMA=0.5
+LAMBDA=0.05 TOX=20N
+CGSO=4E-9 CGDO=4E-9 CJ=2.0E-4 CJSW=5.0E-10
.MODEL PFET PMOS KP=1.0E-5 VTO=-0.70 GAMMA=0.75
+LAMBDA=0.05 TOX=20N
+CGSO=4E-9 CGDO=4E-9 CJ=2.0E-4 CJSW=5.0E-10
.OP
.TF V(7) V1
.AC DEC 100 1 20MEG
.PRINT AC VM(7) VP(7)
.PROBE
.END

Results: 8.1 MHz, -110 degrees; 8.0 MHz, -92 degrees

17.90

$$(a) f_T = \frac{g_m}{2\pi C_C} = \frac{40I_{C1}}{2\pi C_C} \quad | \quad I_{C1} = \frac{I_1}{2} \quad | \quad f_T = \frac{40(25\mu A)}{2\pi(12pF)} = 13.3 \text{ MHz}$$

$SR = \frac{I_1}{C_C} = \frac{25\mu A}{12pF} = 2.09 \frac{MV}{s} = 2.09 \frac{V}{\mu s}$ since $I_2 > I_1$. The slew rate is symmetrical.

$$(b) f_T = \frac{40(100\mu A)}{2\pi(12pF)} = 53.1 \text{ MHz} \quad | \quad SR = \frac{I_1}{C_C} = \frac{100\mu A}{12pF} = 8.33 \frac{MV}{s} = 8.33 \frac{V}{\mu s}$$

17.91

$$f_T = \frac{g_m}{2\pi C_C} = \frac{40I_{C1}}{2\pi C_C} \quad | \quad I_{C1} = \frac{I_1}{2} \quad | \quad f_T = \frac{40(250\mu A)}{2\pi(10pF)} = 159 \text{ MHz}$$

$SR = \frac{I_1}{C_C} = \frac{500\mu A}{10pF} = 50 \frac{MV}{s} = 50 \frac{V}{\mu s}$ since $I_2 > I_1$. The slew rate is symmetrical.

17.92

$$SR = \frac{I_1}{C_C} = \frac{40\mu A}{5pF} = 8 \times 10^6 \frac{V}{s} = 8 \frac{V}{\mu s}$$

*Problems 17.92 - Bipolar Op-amp

VCC 8 0 DC 10

VEE 9 0 -10

I1 1 9 40U

I2 6 9 400U

I3 7 9 500U

V1 4 0 DC 0 PWL (0 0 5U 0 5.1U 5 10U 5 10.2U -5 15U -5 15.2U 5 20U 5)

VF 2 7 DC -0.0045

Q1 3 2 1 NBJT

Q2 5 4 1 NBJT

Q3 3 10 8 PBJT

Q4 5 10 8 PBJT

Q11 0 3 10 PBJT

Q5 6 5 8 PBJT

Q6 8 6 7 NBJT

CC 5 6 5PF

.MODEL NBJT NPN BF=100 IS=1FA VAF=80 RB=250 TF=0.65NS CJC=2PF

.MODEL PBJT PNP BF=100 IS=1FA VAF=80 RB=250 TF=0.65NS CJC=2PF

.OP

.TRAN .05U 20U

.PROBE V(4) V(5) V(6) V(7)

.END

Results: -8V/ μ s, +6V/ μ s

17.93

$$SR = \frac{I_1}{C_C} = \frac{100\mu A}{8pF} = 12.5 \times 10^6 \frac{V}{s} = 12.5 \frac{V}{\mu s}$$

17.94

$$f_T = \frac{g_m}{2\pi C_C} = \frac{40I_{C1}}{2\pi C_C} \quad | \quad I_{C1} = \frac{I_1}{2} \quad | \quad f_T = \frac{40(50\mu A)}{2\pi(15 pF)} = 21.2 \text{ MHz}$$

*Problem 17.94 - Bipolar Op-amp

VCC 8 0 DC 10

VEE 9 0 -10

I1 1 9 100U

I2 6 9 500U

I3 7 9 500U

V1 4 0 DC 2.10M AC 0.5

V2 2 0 DC 0 AC -0.5

Q1 3 2 1 NBJT

Q2 5 4 1 NBJT

Q3 3 10 8 PBJT

Q4 5 10 8 PBJT

Q11 0 3 10 PBJT

Q5 6 5 8 PBJT

Q6 8 6 7 NBJT

CC 5 6 15PF

.MODEL NBJT NPN BF=100 IS=1FA VAF=80 RB=250 TF=0.65NS CJC=2PF

.MODEL PBJT PNP BF=100 IS=1FA VAF=80 RB=250 TF=0.65NS CJC=2PF

.OP

.TF V(7) V1

.AC DEC 100 1 20MEG

.PRINT AC VM(7) VP(7)

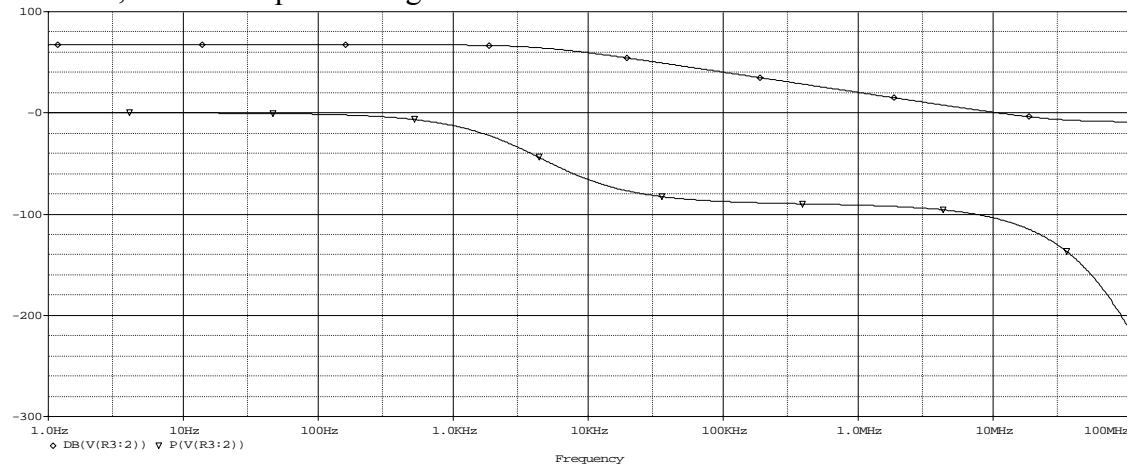
.PROBE

.END

Spice Results: (a) 16.2MHz (b) 16.3 MHz - 15 pF does not represent the effective value of C_C .

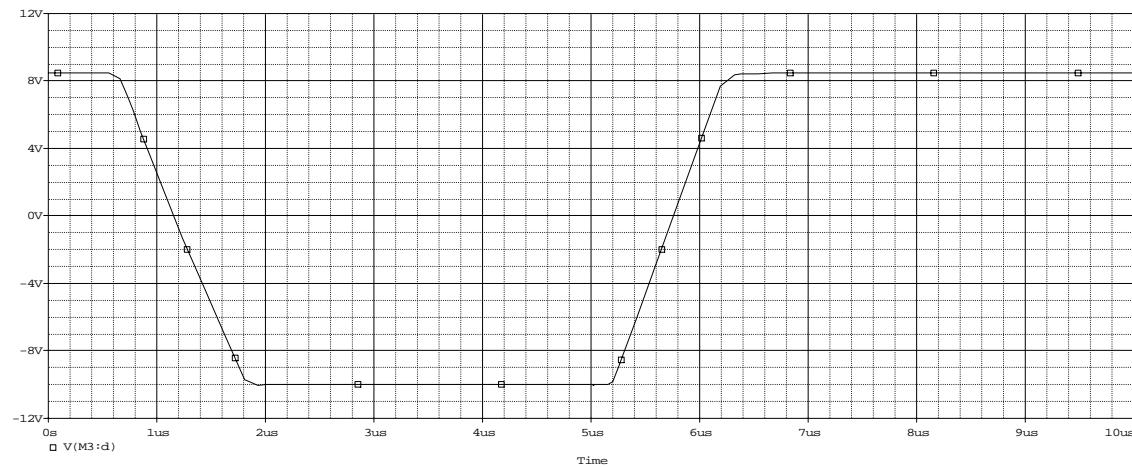
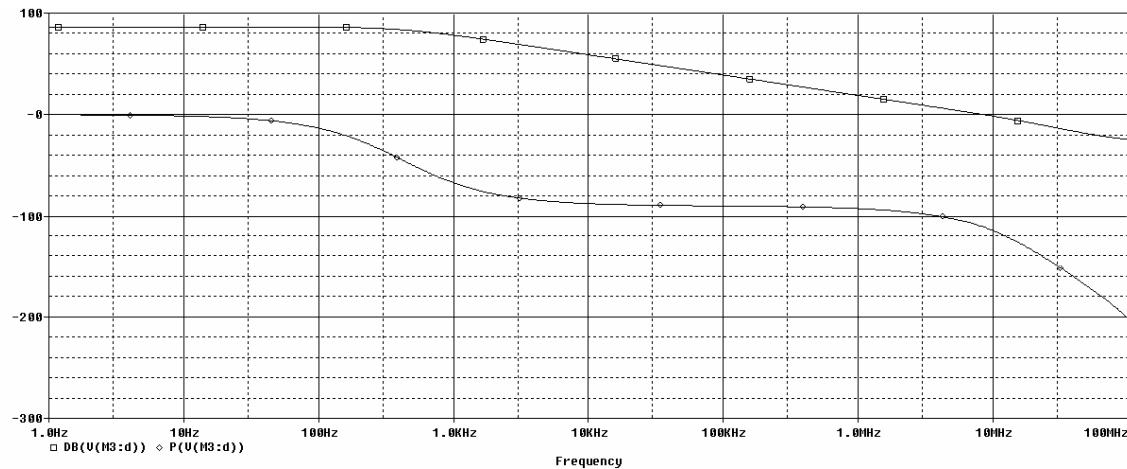
17.95

(a) The SPICE results agree with those given in Ex. 11.10: $A_o = 67.2 \text{ dB}$, $f_H = 4.5 \text{ kHz}$, $f_T = 10.5 \text{ MHz}$, and with a phase margin of 74°



(b) Note, λ should be $0.02V^{-1}$ for the MOSFETs.

(b) The SPICE results give $A_o = 86.5 \text{ dB}$, $f_T = 8.5 \text{ MHz}$ and with a phase margin of 68.4° . $SR_+ = 17.6 \text{ V}/\mu\text{sec}$, and $SR_- = -15.6 \text{ V}/\mu\text{sec}$.



17.96

$$A_{v1} = \frac{V_{o1}}{V_{o2}} = -\frac{1}{sRC} \quad V_{o2} = \left(1 + \frac{2R}{2R}\right)V_+ = 2V_+$$

$(V_+ - V_{o1})\frac{G}{2} + sCV_+ + (V_+ - V_{o2})G_F = 0$ Combining these yields

$$A_{v2} = \frac{V_{o2}}{V_{o1}} = \frac{G}{sC + \left(\frac{G}{2} - G_F\right)} \text{ and } T(s) = A_{v1}A_{v2} = \frac{1}{sRC \left(sRC + \frac{1}{2} - \frac{R}{R_F} \right)}$$

$$\angle T(j\omega_o) = 0 \rightarrow R_F = 2R \text{ and } |T(j\omega_o)| = 1 \rightarrow \omega_o = \frac{1}{RC}$$

17.97

Define V_1 as the output of the inverting amplifier and V_2 as the output of the right-hand non-inverting amplifier.

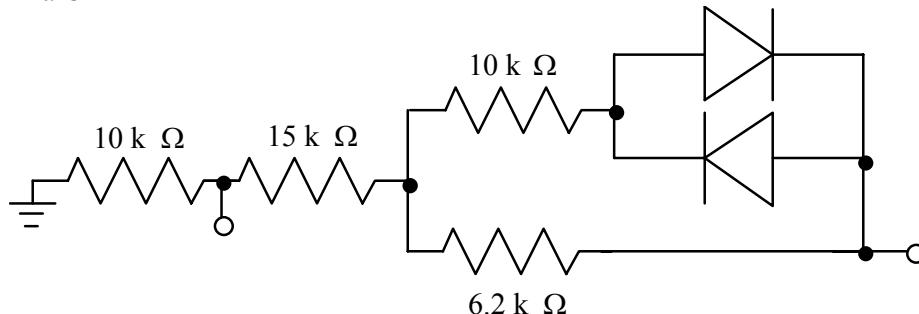
$$V_1 = -V_2 \frac{Z_2}{Z_1} = -V_2 \frac{R}{R + \frac{1}{sC}} = -V_2 \frac{sCR}{SCR + 1} \quad | \quad V_2 = V_1 \left(\frac{R}{R + \frac{1}{sC}} \right) \left(1 + \frac{R_2}{R_1} \right) \left(\frac{R}{R + \frac{1}{sC}} \right) \left(1 + \frac{R_2}{R_1} \right)$$

$$V_2 \left[1 + \left(\frac{sCR}{SCR + 1} \right)^3 \left(1 + \frac{R_2}{R_1} \right)^2 \right] = 0 \quad | \quad \left(\frac{j\omega CR}{j\omega CR + 1} \right)^3 \left(1 + \frac{R_2}{R_1} \right)^2 = -1$$

$$3[90^\circ - \tan^{-1}(\omega CR)] = 180^\circ \quad | \quad \tan^{-1}(\omega CR) = 30^\circ \quad | \quad \omega CR = \tan(30^\circ) = 0.5774$$

$$\left(1 + \frac{R_2}{R_1} \right)^2 \left(\frac{\omega CR}{\sqrt{1 + (\omega CR)^2}} \right)^3 = \left(1 + \frac{R_2}{R_1} \right)^2 \left[\frac{\tan(30^\circ)}{\sqrt{1 + \tan^2(30^\circ)}} \right]^3 = 1 \rightarrow \frac{R_2}{R_1} = \sqrt{8} - 1 = 1.83$$

17.98



$$f_o = \frac{1}{2\pi(5k\Omega)(500pF)} = 63.7 \text{ kHz} \quad | \quad |v_o| = \left(2 - \frac{15k\Omega}{10k\Omega} \left(1 + \frac{10k\Omega}{6.2k\Omega} \right) - \frac{10k\Omega}{10k\Omega} \right) \frac{3(0.7V)}{10k\Omega} = 6.85 \text{ V}$$

17.99

*Problem 17.99 - Wien-Bridge Oscillator

C1 1 0 500PF IC=1

RA 1 0 5K

C2 1 2 500PF

RB 2 3 5K

E1 3 0 1 6 1E6

R1 6 0 10K

R2 5 6 15K

R3 3 5 6.2K

R4 4 5 10K

D1 3 4 DMOD

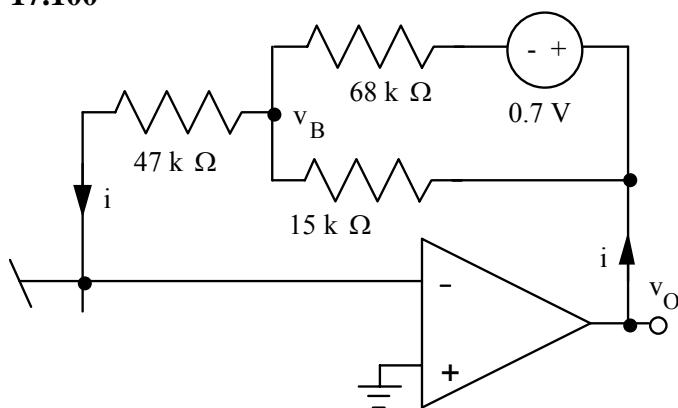
D2 4 3 DMOD

.MODEL DMOD D

.TRAN 10U 10M UIC

.PROBE V(1) V(2) V(3) V(4) V(5) V(6)

.END

Results: $f = 60.0 \text{ kHz}$, amplitude = 6.8 V**17.100**

$$\text{Using Eq. (17.135), } f_o = \frac{1}{2\pi\sqrt{3}(5000)(10^{-9})} = 18.4 \text{ kHz}$$

Using Eq. (17.136), the total feedback resistance should be $R_f = 12R = 60k\Omega$.The current in R_f is $I = \frac{V_o}{R_f} = \frac{V_o}{12R} = \frac{V_o}{60k\Omega}$. The voltage at V_B is

$$V_B = I(47k\Omega) = \frac{47k\Omega}{60k\Omega}V_o \quad | \quad \text{In the diode network, } I = \frac{V_o}{60k\Omega} = \frac{V_o - V_B}{15k\Omega} + \frac{V_o - 0.7 - V_B}{68k\Omega}$$

$$\frac{13}{15}V_o + \frac{13}{68}V_o - \frac{V_o}{60k\Omega} = \frac{0.7}{68k\Omega} \rightarrow V_o = 10.7 \text{ V}$$

17.101

*Problem 17.101 - Phase Shift Oscillator

C1 1 6 1000PF IC=1

RA 1 0 5K

C2 1 2 1000PF

RB 2 0 5K

C3 2 3 1000PF

E1 3 0 0 6 1E6

R2 6 5 47K

R3 5 3 15K

R4 5 4 68K

D1 3 4 DMOD

D2 4 3 DMOD

.MODEL DMOD D

.TRAN 10U 20M UIC

.PROBE V(1) V(2) V(3) V(4) V(5) V(6)

.END

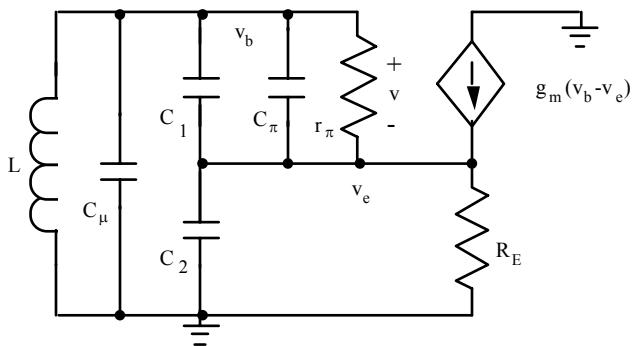
Results: f = 17.5 kHz, amplitude = 11.5 V

17.102

Note that the presence of r_π makes the analysis more complex than the FET case. C_4 is a coupling capacitor, and its impedance is neglected in the analysis. $C_5 = C_1 + C_\pi$. However, the effect of r_π can usually be neglected in the f_o calculation as shown below.

$$\begin{bmatrix} s(C_5 + C_\mu) + g_\pi + \frac{1}{sL} & -(sC_5 + g_\pi) \\ -(sC_5 + g_m + g_\pi) & s(C_2 + C_5) + g_m + g_\pi + G_E \end{bmatrix} \begin{bmatrix} V_b \\ V_e \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$\Delta(s) = s^2 [C_5 C_2 + C_\mu (C_2 + C_5)] + s [C_2 g_\pi + C_\mu (g_m + g_\pi + G_E) + C_5 G_E] + \frac{g_m + g_\pi + G_E}{sL} + g_\pi G_E + \frac{(C_2 + C_5)}{L}$$



$$\Delta(j\omega_o) = 0 \quad | \quad \omega_o^2 = \frac{1}{C_{TC}} \left[\frac{1}{L} + \frac{1}{r_\pi R_E (C_2 + C_5)} \right] = \frac{1}{C_{TC}} \left[\frac{1}{L} + \frac{g_m}{\beta_o R_E (C_2 + C_5)} \right] \quad | \quad C_{TC} = C_\mu + \frac{C_2 C_5}{C_2 + C_5}$$

$$\omega_o [C_2 g_\pi + C_\mu (g_m + g_\pi + G_E) + C_5 G_E] = \frac{g_m + g_\pi + G_E}{\omega_o L}$$

$$\omega_o^2 L \left[C_\mu + \frac{C_2}{\beta_o + 1 + \frac{r_\pi}{R_E}} + \frac{C_5}{1 + g_m R_E + \frac{R_E}{r_\pi}} \right] = 1 \quad | \quad \omega_o^2 L \left[C_\mu + \frac{C_2}{\beta_o + 1 + \frac{\beta_o}{g_m R_E}} + \frac{C_5}{1 + g_m R_E + \frac{g_m R_E}{\beta_o}} \right] = 1$$

$$(a) C_{TC} = \frac{100 pF (20 pF)}{100 pF + 20 pF} = 16.7 pF \quad | \quad \omega_o^2 = \frac{1}{16.7 pF} \left[\frac{1}{5 \mu H} + \frac{10 mS}{100(1k\Omega)(100 pF + 20 pF)} \right]$$

$$\omega_o^2 = \frac{1}{16.7 pF} [2 \times 10^5 + 833] \rightarrow f_o = 17.5 \text{ MHz}$$

Note that the correction term is negligible: $\omega_o \approx \frac{1}{LC_{TC}}$

$$(b) C_{TC} = \frac{1}{\frac{1}{C_2} + \frac{1}{C_5} + \frac{1}{C_3}}$$

$$C_{TC}^{\min} = \frac{1}{\frac{1}{100pF} + \frac{1}{20pF} + \frac{1}{5pF}} = 3.85pF \quad | \quad f_o \cong \frac{1}{2\pi\sqrt{LC_{TC}}} = \frac{1}{2\pi\sqrt{(5\mu H)(3.85pF)}} = 36.3 \text{ MHz}$$

$$C_{TC}^{\max} = \frac{1}{\frac{1}{100pF} + \frac{1}{20pF} + \frac{1}{50pF}} = 12.5pF \quad | \quad f_o \cong \frac{1}{2\pi\sqrt{(5\mu H)(12.5pF)}} = 20.1 \text{ MHz}$$

$$(c) \omega_o^2 L \left[\frac{C_2}{\beta_o + 1 + \frac{\beta_o}{g_m R_E}} + \frac{C_5}{1 + g_m R_E + \frac{g_m R_E}{\beta_o}} \right] \cong \frac{1}{C_{TC}} \left[\frac{C_2}{\beta_o + 1 + \frac{\beta_o}{g_m R_E}} + \frac{C_5}{1 + g_m R_E + \frac{g_m R_E}{\beta_o}} \right] = 1$$

$$\frac{1}{16.7pF} \left[\frac{100pF}{101 + \frac{100}{g_m(1k\Omega)}} + \frac{20pF}{1 + g_m(1k\Omega) + \frac{g_m(1k\Omega)}{100}} \right] = 1 \quad | \quad \text{MATLAB yields } g_m = 0.211 \text{ mS}$$

$$I_C = (0.211mS)(0.025V) = 5.28 \mu A$$

17.103

Assuming the effect of r_π is negligible:

$$(a) f_o \cong \frac{1}{2\pi} \sqrt{\frac{1}{C_{EQ}L}} \quad | \quad C_{EQ} = \frac{1}{\frac{1}{C_4} + \frac{1}{\frac{1}{C_\mu} + \frac{1}{\frac{1}{C_1 + C_\pi} + \frac{1}{C_2}}}} \quad | \quad C_\pi = \frac{40(5mA)}{10^9 \pi} - 3pF = 60.7pF$$

$$C_{EQ} = \frac{1}{\frac{1}{0.01uF} + \frac{1}{3pF + \frac{1}{\frac{1}{(20+60.7)pF} + \frac{1}{100pF}}}} = 47.4pF \quad | \quad f_o \cong \frac{1}{2\pi} \sqrt{\frac{1}{47.4pF(20\mu H)}} = 5.17 \text{ MHz}$$

$$(b) C_\pi = \frac{40(10mA)}{10^9 \pi} - 3pF = 124pF \quad | \quad C_{EQ} = \frac{1}{\frac{1}{0.01uF} + \frac{1}{3pF + \frac{1}{\frac{1}{20pF + 124pF} + \frac{1}{100pF}}}} = 61.6pF$$

$$f_o \cong \frac{1}{2\pi} \sqrt{\frac{1}{61.6pF(20\mu H)}} = 4.53 \text{ MHz}$$

17.104

$$C_{TC} = \frac{1}{\omega_o^2 L} = \frac{1}{(4 \times 10^7 \pi)^2 (3 \mu H)} = 21.1 \text{ pF} \quad | \quad C_{TC} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} \quad | \quad g_m R \geq \frac{C_1}{C_2} \rightarrow \frac{2I_D R}{V_{GS} - V_{TN}} \geq \frac{C_1}{C_2}$$

$$I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 = \frac{1.25 \text{ mA}}{2} (V_{GS} + 4)^2 \quad | \quad -4 \leq V_{GS} \quad \text{Suppose we pick } V_{GS} = -2 \text{ V to provide}$$

$$\text{good value of } g_m : V_{GS} = -2 \text{ V} \rightarrow I_D = 0.625 \text{ mA} (-2 + 4)^2 = 2.50 \text{ mA} \quad | \quad R = \frac{2V}{2.5 \text{ mA}} = 800 \Omega \rightarrow 820 \Omega$$

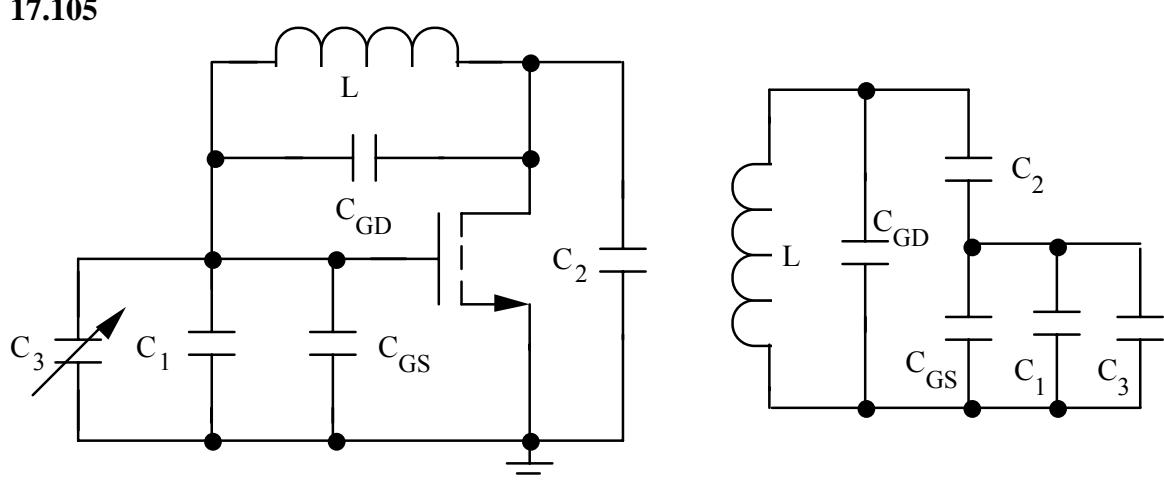
$$\frac{C_1}{C_2} \leq \frac{2I_D R}{V_{GS} - V_{TN}} = \frac{2(2.5 \text{ mA})(820 \Omega)}{-2 - (-4)} = 2.05 \quad | \quad C_1 \leq 2.05 C_2 \quad | \quad \text{Select } C_1 \approx C_2 \approx 42 \text{ pF} \quad | \quad \text{Choosing}$$

$$C_1 = 47 \text{ pF} \text{ from Appendix C, } C_2 = \frac{1}{\frac{1}{21.1 \text{ pF}} - \frac{1}{47 \text{ pF}}} = 38.3 \text{ pF} \text{ which is close to 39 pF.}$$

$$\text{If 47 pF and 39 pF are used: } f_o = \frac{1}{2\pi\sqrt{(21.3 \text{ pF})(3 \mu H)}} = 19.9 \text{ MHz}$$

In order to obtain an exact frequency of oscillation, a 33-pF capacitor in parallel with a small variable capacitor could be used. Note that including the FET capacitances would modify the design values.

17.105



$$C_{TC} = C_{GD} + \frac{1}{\frac{1}{C_2} + \frac{1}{C_1 + C_3 + C_{GS}}} = 4 \text{ pF} + \frac{1}{\frac{1}{50 \text{ pF}} + \frac{1}{50 \text{ pF} + 0 + 10 \text{ pF}}} = 31.27 \text{ pF}$$

$$f_o = \frac{1}{2\pi\sqrt{LC_{TC}}} = \frac{1}{2\pi\sqrt{(10^{-5} \text{ H})(31.27 \times 10^{-12} \text{ F})}} = 9.00 \text{ MHz}$$

$$g_m r_o \geq \frac{C_1 + C_3 + C_{GS}}{C_2} = \frac{50 \text{ pF} + 0 + 10 \text{ pF}}{50 \text{ pF}} = 1.20 \text{ which is easily met.}$$

17.106

$$(a) C_{TC} = C_{GD} + \frac{1}{\frac{1}{C_2} + \frac{1}{C_1 + C_3 + C_{GS}}} \quad | \quad C_{TC}^{\max} = 4 \text{ pF} + \frac{1}{\frac{1}{50 \text{ pF}} + \frac{1}{50 \text{ pF} + 5 \text{ pF} + 10 \text{ pF}}} = 32.3 \text{ pF}$$

$$f_o = \frac{1}{2\pi\sqrt{LC_{TC}}} = \frac{1}{2\pi\sqrt{(10\mu\text{H})(32.3 \text{ pF})}} = 8.87 \text{ MHz}$$

$$C_{TC}^{\min} = 4 \text{ pF} + \frac{1}{\frac{1}{50 \text{ pF}} + \frac{1}{50 \text{ pF} + 50 \text{ pF} + 10 \text{ pF}}} = 38.4 \text{ pF} \quad | \quad f_o = \frac{1}{2\pi\sqrt{(10\mu\text{H})(38.4 \text{ pF})}} = 8.12 \text{ MHz}$$

$$(b) g_m r_o \geq \frac{C_1 + C_3 + C_{GS}}{C_2} \quad | \quad g_m r_o \geq \frac{50 \text{ pF} + 5 \text{ pF} + 10 \text{ pF}}{50 \text{ pF}} = 1.30 \text{ and}$$

$$g_m r_o \geq \frac{50 \text{ pF} + 50 \text{ pF} + 10 \text{ pF}}{50 \text{ pF}} = 2.20 \quad | \quad \therefore g_m r_o \geq 2.20 \text{ which is easily met.}$$

17.107

$$(a) C_D = \frac{C_{jo}}{\sqrt{1 + \frac{V_{TUNE}}{\phi_j}}} \quad | \quad C_D = \frac{20 \text{ pF}}{\sqrt{1 + \frac{2V}{0.8V}}} = 10.7 \text{ pF} \quad | \quad C_{TC} = \frac{1}{\frac{1}{75 \text{ pF} + 10.7 \text{ pF}} + \frac{1}{75 \text{ pF}}} = 40.0 \text{ pF}$$

$$C_D = \frac{20 \text{ pF}}{\sqrt{1 + \frac{20V}{0.8V}}} = 3.92 \text{ pF} \quad | \quad C_{TC} = \frac{1}{\frac{1}{75 \text{ pF} + 3.92 \text{ pF}} + \frac{1}{75 \text{ pF}}} = 38.5 \text{ pF}$$

$$f_o^{\min} = \frac{1}{2\pi\sqrt{(10\mu\text{H})(40.0 \text{ pF})}} = 7.96 \text{ MHz} \quad | \quad f_o^{\max} = \frac{1}{2\pi\sqrt{(10\mu\text{H})(38.5 \text{ pF})}} = 8.11 \text{ MHz}$$

$$(b) \text{ In this circuit, } R = r_o : \mu_f = g_m r_o \geq \frac{C_1 + C_D}{C_2} \quad | \quad \mu_f \geq \frac{78.9 \text{ pF}}{75 \text{ pF}} = 1.05$$

17.108

$$C_{TC} = \frac{1}{\frac{1}{470\text{ pF}} + \frac{1}{220\text{ pF}}} = 150\text{ pF} \quad | \quad f_o = \frac{1}{2\pi\sqrt{(10\mu\text{H})(150\text{ pF})}} = 4.11\text{ MHz}$$

The required $g_m R \geq \frac{C_2}{C_1} = \frac{220\text{ pF}}{470\text{ pF}} = 0.468$ is met :

$$I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 = \frac{1.25\text{ mA}}{2} (V_{GS} + 4)^2 \quad \text{and} \quad V_{GS} = -820I_D \rightarrow V_{GS} = -2.016V, I_D = 2.46\text{ mA}$$

$$g_m R = \frac{2I_D R}{V_{GS} - V_{TN}} \cong \frac{2(2.46\text{ mA})(820\Omega)}{-2.02 - (-4)} = 1.02$$

This analysis is borne out by the SPICE simulation below.

VDD 3 0 DC 10

R 1 0 820

C1 1 0 470PF IC=2

C2 2 1 220PF IC=0

*C1 1 0 220PF IC=2

*C2 2 1 470PF IC=0

L 2 0 10UH

M1 3 2 1 NFET

.MODEL NFET NMOS VTO=-4 KP=1.25MA

.OP

.TRAN 10N 30U UIC

.PROBE

.END

(b) For this case, the required $g_m R \geq \frac{C_2}{C_1} = \frac{470\text{ pF}}{220\text{ pF}} = 2.14$ is not met,

and the circuit fails to oscillate.

SPICE simulation confirms that the circuit does not oscillate.

17.109

$$C_{TC} = 3pF + \frac{1}{\frac{1}{50pF+10pF} + \frac{1}{50pF}} = 30.3pF \quad | \quad f_o = \frac{1}{2\pi\sqrt{(10\mu H)(30.3pF)}} = 9.15 \text{ MHz}$$

*Problem 17.109 NMOS Colpitts Oscillator

VDD 3 0 DC 12

LRFC 3 2 20MH

C1 1 0 50PF

C2 2 0 50PF

L 2 1 10UH

M1 2 1 0 0 NFET

CGS 1 0 10PF

CGD 1 2 4PF

.MODEL NFET NMOS VTO=1 KP=10MA LAMBDA=0.02

.OP

.TRAN 50N 40U UIC

.PROBE

.END

Results: $f = 7.5 \text{ MHz}$, amplitude = 80 V peak-peak. There is little to set the amplitude in this circuit, and the frequency of oscillation is significantly in error. Also, μ_f of the transistor greatly exceeds the gain required for oscillation and the waveform at the drain is highly nonlinear. The voltage at the gate is filtered by the LC network and is more sinusoidal in character. A diode from ground to gate could be employed to help limit the amplitude of the oscillation.

17.110

$$f_o = \frac{1}{2\pi\sqrt{(10\mu H + 10\mu H)(20pF)}} = 7.96 \text{ MHz}$$

17.111

$$f_o = \frac{1}{2\pi\sqrt{LC_{TC}}} \quad | \quad C_{TC} = \frac{1}{\frac{1}{C} + \frac{1}{C_D}} \quad | \quad C = 220\text{pF} \quad | \quad C_D = \frac{20\text{pF}}{\sqrt{1 + \frac{V_{TUNE}}{0.8V}}} \quad | \quad L = L_1 + L_2 = 20\mu\text{H}$$

$$(a) \quad C_D = \frac{20\text{pF}}{\sqrt{1 + \frac{2V}{0.8V}}} = 10.7\text{pF} \quad | \quad C_{TC} = \frac{1}{\frac{1}{220\text{pF}} + \frac{1}{10.7\text{pF}}} = 10.2\text{pF}$$

$$f_o = \frac{1}{2\pi\sqrt{20\mu\text{H}(10.2\text{pF})}} = 11.1 \text{ MHz}$$

$$C_D = \frac{20\text{pF}}{\sqrt{1 + \frac{20V}{0.8V}}} = 3.92\text{pF} \quad | \quad C_{TC} = \frac{1}{\frac{1}{220\text{pF}} + \frac{1}{3.92\text{pF}}} = 3.85\text{pF}$$

$$f_o = \frac{1}{2\pi\sqrt{20\mu\text{H}(3.85\text{pF})}} = 18.1 \text{ MHz} \quad (b) \quad \mu_f \geq \frac{L_1}{L_2} = 1.00$$

17.112

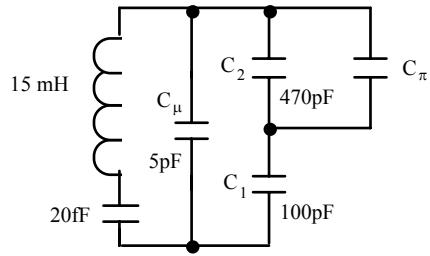
$$\omega_s = \frac{1}{\sqrt{LC_s}} \quad | \quad L = \frac{RQ}{\omega_s}$$

$$(a) \quad L = \frac{40(25000)}{2 \times 10^7 \pi} = 15.915 \text{ mH} \quad | \quad C_s = \frac{1}{\omega_s^2 L} = \frac{1}{(2 \times 10^7 \pi)^2 15.915 \text{ mH}} = 15.916 \text{ fF}$$

$$(b) \quad C_p = \frac{1}{\frac{1}{15.915 \text{ fF}} + \frac{1}{10 \text{ pF}}} = 15.890 \text{ fF} \quad | \quad f_p = \frac{1}{2\pi\sqrt{15.915 \text{ mH}(15.890 \text{ fF})}} = 10.008 \text{ MHz}$$

$$(c) \quad C_p = \frac{1}{\frac{1}{15.915 \text{ fF}} + \frac{1}{32 \text{ pF}}} = 15.907 \text{ fF} \quad | \quad f_p = \frac{1}{2\pi\sqrt{15.915 \text{ mH}(15.907 \text{ fF})}} = 10.003 \text{ MHz}$$

17.113



$$(a) C_{TC} = \frac{1}{\frac{1}{20fF} + \frac{1}{470pF} + \frac{1}{100pF}} = 19.995 fF \quad | \quad f_p = \frac{1}{2\pi\sqrt{15mH(19.995 fF)}} = 9.190 MHz$$

$$(b) I_C = 100 \frac{5 - 0.7}{100k\Omega + 101(1k\Omega)} = 2.14mA \quad | \quad C_\pi = \frac{40(2.14mA)}{2\pi(2.5 \times 10^8 Hz)} - 5pF = 49.5pF$$

$$C_{TC} = \frac{1}{\frac{1}{20fF} + \frac{1}{5pF + \frac{1}{100pF} + \frac{1}{470pF + 49.5pF}}} = 19.996 fF$$

$$f_p = \frac{1}{2\pi\sqrt{15mH(19.996 fF)}} = 9.190 MHz$$

17.114

$$C_{TC}^{\max} = \frac{1}{\frac{1}{20fF} + \frac{1}{1pF} + \frac{1}{100pF} + \frac{1}{470pF}} = 19.60 fF \quad | \quad f_p = \frac{1}{2\pi\sqrt{15mH(19.60 fF)}} = 9.28 MHz$$

$$C_{TC}^{\max} = \frac{1}{\frac{1}{20fF} + \frac{1}{35pF} + \frac{1}{100pF} + \frac{1}{470pF}} = 19.98 fF \quad | \quad f_p = \frac{1}{2\pi\sqrt{15mH(19.98 fF)}} = 9.19 MHz$$

17.115

*Problem 17.115 BJT Colpitts Crystal Oscillator
VCC 1 0 DC 5
VEE 4 0 DC -5
Q1 1 2 3 NBJT
RE 3 4 1K
RB 2 0 100K
C1 3 0 100PF
C2 2 3 470PF
LC 2 6 15M
CC 6 5 20FF IC=5
RC 5 0 50
.MODEL NBJT NPN BF=100 VA=50 TF=1N CJC=5PF
.OP
.TRAN 2N 20U UIC
.PROBE
.END

In the period of time used in the simulation results, node 6 at the interior of the crystal oscillates vigorously, but the oscillation is not coupled well to the other nodes.

Microelectronic Circuit Design

Fourth Edition - Part I

Solutions to Exercises

CHAPTER 1

Page 11

$$V_{LSB} = \frac{5.12V}{2^{10} \text{ bits}} = \frac{5.12V}{1024 \text{ bits}} = 5.00 \text{ mV} \quad V_{MSB} = \frac{5.12V}{2} = 2.560V$$

$$1100010001_2 = 2^9 + 2^8 + 2^4 + 2^0 = 785_{10} \quad V_o = 785(5.00 \text{ mV}) = 3.925 \text{ V}$$

$$\text{or } V_o = (2^{-1} + 2^{-2} + 2^{-6} + 2^{-10}) 5.12V = 3.925 \text{ V}$$

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$$V_{LSB} = \frac{5.0V}{2^8 \text{ bits}} = \frac{5.00V}{256 \text{ bits}} = 19.53 \text{ mV} \quad N = \frac{1.2V}{5.00V} 256 \text{ bits} = 61.44 \text{ bits}$$

$$61 = 32 + 16 + 8 + 4 + 1 = 2^5 + 2^4 + 2^3 + 2^2 + 2^0 = 00111101_2$$

Page 12

The dc component is $V_A = 4V$.

The signal consists of the remaining portion of v_A : $v_a = (5 \sin 2000\pi t + 3 \cos 1000 \pi t)$ Volts.

Page 23

$$v_o = -5 \cos(2000\pi t + 25^\circ) = -[-5 \sin(2000\pi t + 25^\circ - 90^\circ)] = 5 \sin(2000\pi t - 65^\circ)$$

$$V_o = 5\angle -65^\circ \quad V_i = 0.001\angle 0^\circ \quad A_v = \frac{5\angle -65^\circ}{0.001\angle 0^\circ} = 5000\angle -65^\circ$$

Page 25

$$A_v = -\frac{R_2}{R_l} \quad | \quad -5 = -\frac{R_2}{10k\Omega} \rightarrow R_2 = 50 \text{ k}\Omega$$

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$$v_s = [0.5\sin(2000\pi t) + \sin(4000\pi t) + 1.5\sin(6000\pi t)]$$

The three spectral component frequencies are $f_1 = 1000 \text{ Hz}$ $f_2 = 2000 \text{ Hz}$ $f_3 = 3000 \text{ Hz}$

(a) The gain of the band - pass filter is zero at both f_1 and f_3 . At f_2 , $V_o = 10(1V) = 10V$, and $v_o = 10.0\sin(4000\pi t)$ volts.

(b) The gain of the low - pass filter is zero at both f_2 and f_3 . At f_2 , $V_o = 6(0.5V) = 3V$, and $v_o = 3.00\sin(2000\pi t)$ volts.

Page 27

$$39k\Omega(1 - 0.1) \leq R \leq 39k\Omega(1 + 0.1) \quad \text{or} \quad 35.1 \text{ k}\Omega \leq R \leq 42.9 \text{ k}\Omega$$

$$3.6k\Omega(1 - 0.01) \leq R \leq 3.6k\Omega(1 + 0.01) \quad \text{or} \quad 3.56 \text{ k}\Omega \leq R \leq 3.64 \text{ k}\Omega$$

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$$P = \frac{V_I^2}{R_1 + R_2} \quad P^{nom} = \frac{15^2}{54k\Omega} = 4.17 \text{ mW}$$

$$P^{\max} = \frac{(1.1 \times 15)^2}{0.95 \times 54k\Omega} = 5.31 \text{ mW} \quad P^{\min} = \frac{(0.9 \times 15)^2}{1.05 \times 54k\Omega} = 3.21 \text{ mW}$$

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$$R = 10k\Omega \left[1 + \frac{10^{-3}}{^\circ C} (-55 - 25)^\circ C \right] = 9.20 \text{ k}\Omega \quad R = 10k\Omega \left[1 + \frac{10^{-3}}{^\circ C} (85 - 25)^\circ C \right] = 10.6 \text{ k}\Omega$$

CHAPTER 2

Page 47

$$n_i = \sqrt{(2.31 \times 10^{30} K^{-3} cm^{-6})(300K)^3 \exp\left[\frac{-0.66eV}{(8.62 \times 10^{-5} eV/K)(300K)}\right]} = 2.27 \times 10^{13} / cm^3$$

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$$n_i = \sqrt{(1.08 \times 10^{31} K^{-3} cm^{-6})(50K)^3 \exp\left[\frac{-1.12eV}{(8.62 \times 10^{-5} eV/K)(50K)}\right]} = 4.34 \times 10^{-39} / cm^3$$

$$n_i = \sqrt{(1.08 \times 10^{31} K^{-3} cm^{-6})(325K)^3 \exp\left[\frac{-1.12eV}{(8.62 \times 10^{-5} eV/K)(325K)}\right]} = 4.01 \times 10^{10} / cm^3$$

$$L^3 = \frac{cm^3}{4.34 \times 10^{-39}} \left(10^{-2} \frac{m}{cm}\right)^3 \rightarrow L = 6.13 \times 10^{10} m$$

Page 49

$$v_p = \mu_p E = 500 \frac{cm^2}{V-s} \left(10 \frac{V}{cm}\right) = 5.00 \times 10^3 \frac{cm}{s} \quad v_n = -\mu_n E = -1350 \frac{cm^2}{V-s} \left(1000 \frac{V}{cm}\right) = -1.35 \times 10^6 \frac{cm}{s}$$

$$E = \frac{V}{L} = \frac{1}{2 \times 10^{-4}} \frac{V}{cm} = 5.00 \times 10^3 \frac{V}{cm}$$

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(a) From Fig. 2.5: The drift velocity for Ge saturates at $6 \times 10^6 cm/sec$.

At low fields the slope is constant. Choose $E = 100 V/cm$

$$\mu_n = \frac{v_n}{E} = \frac{4.3 \times 10^5 cm/s}{100 V/cm} = 4300 \frac{cm^2}{s} \quad \mu_p = \frac{v_p}{E} = \frac{2.1 \times 10^5 cm/s}{100 V/cm} = 2100 \frac{cm^2}{s}$$

(b) The velocity peaks at $2 \times 10^7 cm/sec$

$$\mu_n = \frac{v_n}{E} = \frac{8.5 \times 10^5 cm/s}{100 V/cm} = 8500 \frac{cm^2}{s}$$

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$$n_i^2 = 1.08 \times 10^{31} (400)^3 \exp\left[\frac{-1.12}{8.62 \times 10^{-5} (400)}\right] = 5.40 \times 10^{24} / cm^6 \quad | \quad n_i = 2.32 \times 10^{12} / cm^3$$

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60 \times 10^{-19} [(2.32 \times 10^{12})(1350) + (2.32 \times 10^{12})(500)]} = 1450 \Omega - cm$$

$$n_i^2 = 1.08 \times 10^{31} (50)^3 \exp\left[\frac{-1.12}{8.62 \times 10^{-5} (50)}\right] = 1.88 \times 10^{-77} / cm^6 \quad | \quad n_i = 4.34 \times 10^{-39} / cm^3$$

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60 \times 10^{-19} [(4.34 \times 10^{-39})(6500) + (4.34 \times 10^{-39})(2000)]} = 1.69 \times 10^{53} \Omega - cm$$

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$$n_i^2 = 1.08 \times 10^{31} (400)^3 \exp\left[\frac{-1.12}{8.62 \times 10^{-5} (400)}\right] = 5.40 \times 10^{24} / cm^6$$

$$p = N_A - N_D = 10^{16} - 2 \times 10^{15} = 8 \times 10^{15} \frac{\text{holes}}{cm^3} \quad n = \frac{n_i^2}{p} = \frac{5.40 \times 10^{24}}{8 \times 10^{15}} = 6.75 \times 10^8 \frac{\text{electrons}}{cm^3}$$

Antimony (Sb) is a Column - V element, so it is a donor impurity. $n = N_D = 2 \times 10^{16} \frac{\text{electrons}}{cm^3}$

$$p = \frac{n_i^2}{n} = \frac{10^{20}}{2 \times 10^{16}} = 5.00 \times 10^3 \frac{\text{holes}}{cm^3} \quad n > p \rightarrow \text{n-type silicon}$$

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Reading from the graph for $N_T = 10^{16}/cm^3$, $1230 \text{ cm}^2/\text{V-s}$ and $405 \text{ cm}^2/\text{V-s}$.

Reading from the graph for $N_T = 10^{17}/cm^3$, $800 \text{ cm}^2/\text{V-s}$ and $230 \text{ cm}^2/\text{V-s}$.

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$$\sigma = 1000 = 1.60 \times 10^{-19} \mu_n n \rightarrow u_n n = 6.25 \times 10^{21} / cm^3 = (6.25 \times 10^{19})(100) \quad | \quad \rho = \frac{1}{\sigma} = 0.001 \Omega - cm$$

$$(a) N_D = 2 \times 10^{16} / cm^3 \quad | \quad N_A = 0 / cm^3 \quad | \quad N_T = 2 \times 10^{16} / cm^3 \quad |$$

$$\mu_n = 92 + \frac{1270}{1 + \left(\frac{2 \times 10^{16}}{1.3 \times 10^{17}} \right)^{0.91}} = 1170 \text{ cm}^2 / V - s \quad | \quad \mu_p = 48 + \frac{447}{1 + \left(\frac{2 \times 10^{16}}{6.3 \times 10^{16}} \right)^{0.76}} = 363 \text{ cm}^2 / V - s$$

$$(b) N_T = N_D + N_A = 2 \times 10^{16} / cm^3 + 3 \times 10^{16} / cm^3 = 5 \times 10^{16} / cm^3$$

$$\mu_n = 92 + \frac{1270}{1 + \left(\frac{5 \times 10^{16}}{1.3 \times 10^{17}} \right)^{0.91}} = 990 \text{ cm}^2 / V - s \quad | \quad \mu_p = 48 + \frac{447}{1 + \left(\frac{5 \times 10^{16}}{6.3 \times 10^{16}} \right)^{0.76}} = 291 \text{ cm}^2 / V - s$$

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Boron (B) is a Column - III element, so it is an acceptor impurity.

$$p = N_A - N_D = 4 \times 10^{18} \frac{\text{holes}}{cm^3} \quad | \quad n = \frac{n_i^2}{p} = \frac{10^{20}}{4 \times 10^{18}} = 25 \frac{\text{electrons}}{cm^3} \quad | \quad \text{p-type material}$$

$$N_T = \frac{4 \times 10^{18}}{cm^3} \text{ and mobilities from Fig. 2.8: } \mu_n = 150 \text{ cm}^2 / V - s \quad | \quad \mu_p = 70 \text{ cm}^2 / V - s$$

$$\rho \cong \frac{1}{q \mu_p p} = \frac{1}{1.60 \times 10^{-19} (4 \times 10^{18}) (70)} = 0.022 \Omega - cm$$

Indium (In) is a Column - III element, so it is an acceptor impurity.

$$p = N_A - N_D = 7 \times 10^{19} \frac{\text{holes}}{cm^3} \quad | \quad n = \frac{n_i^2}{p} = \frac{10^{20}}{7 \times 10^{19}} = 1.43 \frac{\text{electrons}}{cm^3} \quad | \quad \text{p-type material}$$

$$N_T = \frac{7 \times 10^{19}}{cm^3} \text{ and mobilities from Fig. 2.8: } \mu_n = 100 \text{ cm}^2 / V - s \quad | \quad \mu_p = 50 \text{ cm}^2 / V - s$$

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60 \times 10^{-19} (7 \times 10^{19}) (50)} = 1.79 \text{ m}\Omega - cm$$

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$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23}(50)}{1.602 \times 10^{-19}} = 4.31 \text{ mV} \quad | \quad V_T = \frac{1.38 \times 10^{-23}(300)}{1.602 \times 10^{-19}} = 25.8 \text{ mV}$$

$$V_T = \frac{1.38 \times 10^{-23}(400)}{1.602 \times 10^{-19}} = 34.5 \text{ mV}$$

$$D_n = \frac{kT}{q} \mu_n = 25.8 \text{ mV} \left(1362 \frac{\text{cm}^2}{V - s} \right) = 35.1 \frac{\text{cm}^2}{s} \quad | \quad D_p = \frac{kT}{q} \mu_p = 25.8 \text{ mV} \left(495 \frac{\text{cm}^2}{V - s} \right) = 12.8 \frac{\text{cm}^2}{s}$$

$$j_n = qD_n \frac{dn}{dx} = 1.60 \times 10^{-19} C \left(20 \frac{\text{cm}^2}{s} \right) \left(\frac{10^{16}}{\text{cm}^3 - \mu\text{m}} \right) \left(\frac{10^4 \mu\text{m}}{\text{cm}} \right) = 320 \frac{A}{\text{cm}^2}$$

$$j_p = -qD_p \frac{dp}{dx} = -1.60 \times 10^{-19} C \left(4 \frac{\text{cm}^2}{s} \right) \left(\frac{10^{16}}{\text{cm}^3 - \mu\text{m}} \right) \left(\frac{10^4 \mu\text{m}}{\text{cm}} \right) = -64 \frac{A}{\text{cm}^2}$$

CHAPTER 3

Page 79

$$\phi_j = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.025V \ln\left(\frac{2x10^{18}(10^{20})}{10^{20}}\right) = 1.05 \text{ V}$$

$$w_{do} = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j} = \sqrt{\frac{2(11.7)(8.85x10^{-14})}{1.60x10^{-19}} \left(\frac{1}{2x10^{18}} + \frac{1}{10^{20}} \right) (1.05)} = 2.63x10^{-6} \text{ cm} = 0.0263 \text{ } \mu\text{m}$$

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$$E_{\max} = \frac{1}{\epsilon_s} \int_{-x_p}^0 -qN_A dx = \frac{qN_A x_p}{\epsilon_s} \quad E_{\max} = -\frac{1}{\epsilon_s} \int_0^{x_n} qN_D dx = \frac{qN_D x_n}{\epsilon_s} \quad \text{For the values in Ex.3.2 :}$$

$$E_{\max} = \frac{1.6x10^{-19} C(10^{17} / \text{cm}^3)(1.13x10^{-5} \text{ cm})}{11.7(8.854x10^{-14} F / \text{cm})} = 175 \frac{kV}{\text{cm}}$$

$$E_{\max} = \frac{2(1.05V)}{2.63x10^{-6} \text{ cm}} = 798 \frac{kV}{\text{cm}}$$

$$x_p = 0.0263 \mu\text{m} \left(1 + \frac{2x10^{18}}{10^{20}} \right)^{-1} = 0.0258 \mu\text{m} \quad x_n = 0.0263 \mu\text{m} \left(1 + \frac{10^{20}}{2x10^{18}} \right)^{-1} = 5.16x10^{-4} \mu\text{m}$$

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$$n \frac{kT}{q} = 1 \frac{1.381x10^{-23}(300)}{1.602x10^{-19}} = 0.0259 \quad | \quad T = \frac{300}{1.03} = 291 K$$

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$$i_D = 40x10^{-15} A \left[\exp\left(\frac{0.55}{0.025}\right) - 1 \right] = 143 \mu\text{A} \quad i_D = 40x10^{-15} A \left[\exp\left(\frac{0.70}{0.025}\right) - 1 \right] = 57.9 mA$$

$$V_D = (0.025V) \ln\left(1 + \frac{6x10^{-3} A}{40x10^{-15} A}\right) = 0.643 V$$

$$i_D = 5x10^{-15} A \left[\exp\left(\frac{-0.04}{0.025}\right) - 1 \right] = -3.99 fA \quad | \quad i_D = 5x10^{-15} A \left[\exp\left(\frac{-2.0}{0.025}\right) - 1 \right] = -5.00 fA$$

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$$(a) V_{BE} = V_T \ln\left(1 + \frac{I_D}{I_S}\right) = 0.025V \ln\left(1 + \frac{40x10^{-6}A}{2x10^{-15}A}\right) = 0.593 \text{ V}$$

$$V_{BE} = V_T \ln\left(1 + \frac{I_D}{I_S}\right) = 0.025V \ln\left(1 + \frac{400x10^{-6}A}{2x10^{-15}A}\right) = 0.651 \text{ V} \quad \Delta V_{BE} = 57.6 \text{ mV}$$

$$(b) V_{BE} = V_T \ln\left(1 + \frac{I_D}{I_S}\right) = 0.0258V \ln\left(1 + \frac{40x10^{-6}A}{2x10^{-15}A}\right) = 0.612 \text{ V}$$

$$V_{BE} = V_T \ln\left(1 + \frac{I_D}{I_S}\right) = 0.0258V \ln\left(1 + \frac{400x10^{-6}A}{2x10^{-15}A}\right) = 0.671 \text{ V} \quad \Delta V_{BE} = 59.4 \text{ mV}$$

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$$\ln\left(\frac{i_D}{I_S}\right) = \ln(i_D) - \ln(I_S) \quad | \quad \text{Assume } i_D \text{ is constant, and } E_G = E_{GO}$$

$$\frac{dv_D}{dT} = \frac{k}{q} \ln\left(\frac{i_D}{I_S}\right) - \frac{kT}{q} \frac{1}{I_S} \frac{dI_S}{dT} = \frac{v_d}{T} - V_T \frac{1}{I_S} \frac{dI_S}{dT} \quad | \quad I_S = Kn_i^2 = KBT^3 \exp\left(-\frac{E_{GO}}{kT}\right)$$

$$\frac{dI_S}{dT} = 3KBT^2 \exp\left(-\frac{E_{GO}}{kT}\right) + KBT^3 \exp\left(-\frac{E_{GO}}{kT}\right) \left(\frac{E_{GO}}{kT^2} \right)$$

$$\frac{1}{I_S} \frac{dI_S}{dT} = \frac{3}{T} + \frac{E_{GO}}{kT^2} = \frac{3}{T} + \frac{qV_{GO}}{kT^2} = \frac{3}{T} + \frac{V_{GO}}{V_T T} \quad | \quad \frac{dv_D}{dT} = \frac{v_d}{T} - V_T \frac{1}{I_S} \frac{dI_S}{dT} = \frac{v_d - V_{GO} - 3V_T}{T}$$

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$$w_d = 0.113 \mu m \sqrt{1 + \frac{10V}{0.979V}} = 0.378 \mu m \quad | \quad E_{max} = \frac{2(V + \phi_j)}{w_d} = \frac{2(10.979V)}{0.378 \times 10^{-4} cm} = 581 \frac{kV}{cm}$$

$$I_S = 10 fA \sqrt{1 + \frac{10V}{0.8V}} = 36.7 fA$$

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$$C_{jo} = \frac{11.7(8.854 \times 10^{-14} F/cm)}{0.113 \times 10^{-4} cm} = 91.7 \frac{nF}{cm^2} \quad | \quad C_j(0V) = 91.7 \frac{nF}{cm^2} (10^{-2} cm)(1.25 \times 10^{-2} cm) = 11.5 pF$$

$$C_j(5V) = \frac{11.5 pF}{\sqrt{1 + \frac{5V}{0.979V}}} = 4.64 pF$$

$$C_D = \frac{10^{-5} A}{0.025V} 10^{-8} s = 4.00 pF \quad | \quad C_D = \frac{8 \times 10^{-4} A}{0.025V} 10^{-8} s = 320 pF \quad | \quad C_D = \frac{5 \times 10^{-2} A}{0.025V} 10^{-8} s = 0.02 \mu F$$

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Two points on the load line : $V_D = 0, I_D = \frac{5V}{5k\Omega} = 1 \text{ mA}$; $I_D = 0, V_D = 5V$

The intersection of the two curves occurs at the Q-pt : $(0.88 \text{ mA}, 0.6 \text{ V})$

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$$10 = 10^4 I_D + V_D \quad | \quad V_D = V_T \ln\left(1 + \frac{I_D}{I_S}\right) \quad | \quad 10 = 10^4 I_D + 0.025 \ln\left(1 + \frac{I_D}{I_S}\right)$$

Page 101

fzero(@(id) (10-10000*id-0.025*log(1+id/1e-13), 5e-4)

ans = 9.4258e-004

Page 102

fzero(@(id) (10-10000*(1e-14)*(exp(40*vd)-1)-vd), 0.5)

ans = 0.6316

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From the answer, the diodes are on, on, off.

$$I_1 = I_{D1} + I_{D2} \quad \frac{10V - V_B}{2.5k\Omega} = \frac{V_B - 0.6V - (-20V)}{10k\Omega} + \frac{V_B - 0.6V - (-10V)}{10k\Omega} = 0 \rightarrow V_B = 1.87 \text{ V}$$

$$I_{D1} = \frac{1.87 - 0.6 - (-20V)}{10k\Omega} = 2.13 \text{ mA} \quad | \quad I_{D2} = \frac{1.87 - 0.6 - (-10V)}{10k\Omega} = 1.13 \text{ mA} \quad | \quad V_{D3} = -(1.87 - 0.6) = -1.27 \text{ V}$$

$I_{D1} > 0, I_{D2} > 0, V_{D3} < 0$. These results are consistent with the assumptions.

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$$R_{\min} = \frac{5k\Omega}{\frac{20}{5} - 1} = 1.67 \text{ k}\Omega \quad | \quad V_O = 20V \frac{1k\Omega}{5k\Omega + 1k\Omega} = 3.33 \text{ V} \text{ (V}_Z \text{ is off)} \quad | \quad V_O = 5 \text{ V} \text{ (V}_Z \text{ is conducting)}$$

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$$\frac{V_L - 20V}{1k\Omega} + \frac{V_L - 5V}{0.1k\Omega} + \frac{V_L}{5k\Omega} = 0 \rightarrow V_L = 6.25 \text{ V} \quad | \quad I_Z = \frac{6.25V - 5V}{0.1k\Omega} = 12.5mA$$

$$P_Z = 5V(12.5mA) + 100\Omega(12.5mA)^2 = 78.1 \text{ mW}$$

$$\text{Line Regulation} = \frac{0.1k\Omega}{0.1k\Omega + 5k\Omega} = 19.6 \frac{mV}{V} \quad \text{Load Regulation} = 0.1k\Omega \parallel 5k\Omega = 98.0 \text{ }\Omega$$

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$$V_{dc} = V_p - V_{on} = 6.3\sqrt{2} - 1 = 7.91 \text{ V} \quad I_{dc} = \frac{7.91V}{0.5\Omega} = 15.8 \text{ A} \quad V_r = \frac{I_{dc}}{C} T = \frac{15.8A}{0.5F} \frac{1}{60}s = 0.527 \text{ V}$$

$$\Delta T = \frac{1}{\omega} \sqrt{2 \frac{V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{2 \left(\frac{0.527V}{8.91V} \right)} = 0.912 \text{ ms} \quad \theta_c = 120\pi(0.912ms) \frac{180^\circ}{\pi} = 19.7^\circ$$

$$V_{dc} = V_p - V_{on} = 10\sqrt{2} - 1 = 13.1 \text{ V} \quad I_{dc} = \frac{13.1V}{2\Omega} = 6.57 \text{ A} \quad C = \frac{I_{dc}}{V_r} T = \frac{6.57A}{0.1F} \frac{1}{60}s = 1.10 \text{ F}$$

$$\Delta T = \frac{1}{\omega} \sqrt{2 \frac{V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{2 \left(\frac{0.1V}{14.1V} \right)} = 0.316 \text{ ms} \quad \theta_c = 120\pi(0.316ms) \frac{180^\circ}{\pi} = 6.82^\circ$$

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$$\text{At } 300\text{K: } V_D = \frac{kT}{q} \ln \left(1 + \frac{I_D}{I_S} \right) = \frac{1.38 \times 10^{-23} J / K (300K)}{1.60 \times 10^{-19} C} \ln \left(1 + \frac{48.6A}{10^{-15} A} \right) = 0.994 \text{ V}$$

$$\text{At } 50^\circ\text{C: } V_D = \frac{kT}{q} \ln \left(1 + \frac{I_D}{I_S} \right) = \frac{1.38 \times 10^{-23} J / K (273K + 50K)}{1.60 \times 10^{-19} C} \ln \left(1 + \frac{48.6A}{10^{-15} A} \right) = 1.07 \text{ V}$$

$$\text{Note: For } V_T = 0.025V, \quad V_D = \frac{kT}{q} \ln \left(1 + \frac{I_D}{I_S} \right) = 0.025V \ln \left(1 + \frac{48.6A}{10^{-15} A} \right) = 0.961 \text{ V}$$

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$$V_{rms} = \frac{V_{dc} + V_{on}}{\sqrt{2}} = \frac{15+1}{\sqrt{2}} = 11.3 \text{ V} \quad | \quad C = \frac{I_{dc}}{V_r} T = \frac{2A}{0.01(15V)} \frac{1}{60}s = 0.222F = 222,000 \mu\text{F}$$

$$I_{SC} = \omega C V_p = 2\pi(60\text{Hz})(0.222F)(16V) = 1340 \text{ A}$$

$$\Delta T = \frac{1}{\omega} \sqrt{2 \frac{V_r}{V_p}} = \frac{1}{2\pi(60)} \sqrt{2 \left(\frac{(0.01)(15)}{16} \right)} = 0.363 \text{ ms} \quad | \quad I_p = I_{dc} \frac{2T}{\Delta T} = 2A \frac{2s}{60(0.363ms)} = 184 \text{ A}$$

CHAPTER 4

Page 153

$$K_n = \mu_n \frac{\varepsilon_{ox}}{T_{ox}} = 500 \frac{cm^2}{V-s} \frac{3.9(8.854 \times 10^{14} F/cm)}{25 \times 10^{-7} cm} = 69.1 \times 10^{-6} \frac{C}{V^2 - s} = 69.1 \frac{\mu A}{V^2}$$

$$K_n = K_n \frac{W}{L} = 50 \frac{\mu A}{V^2} \left(\frac{20 \mu m}{1 \mu m} \right) = 1000 \frac{\mu A}{V^2} \quad K_n = 50 \frac{\mu A}{V^2} \left(\frac{60 \mu m}{3 \mu m} \right) = 1000 \frac{\mu A}{V^2}$$

$$K_n = 50 \frac{\mu A}{V^2} \left(\frac{10 \mu m}{0.25 \mu m} \right) = 2000 \frac{\mu A}{V^2}$$

For $V_{GS} = 0V$ and $1V$, $V_{GS} < V_{TN}$ and the transistor is off. Therefore $I_D = 0$.

$V_{GS} - V_{TN} = 2 - 1.5 = 0.5V$ and $V_{DS} = 0.1 V \rightarrow$ Triode region operation

$$I_D = K_n \frac{W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = 25 \frac{\mu A}{V^2} \left(\frac{10 \mu m}{1 \mu m} \right) \left(2 - 1.5 - \frac{0.1}{2} \right) 0.1 V^2 = 11.3 \mu A$$

$V_{GS} - V_{TN} = 3 - 1.5 = 1.5V$ and $V_{DS} = 0.1 V \rightarrow$ Triode region operation

$$I_D = K_n \frac{W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = 25 \frac{\mu A}{V^2} \left(\frac{10 \mu m}{1 \mu m} \right) \left(3 - 1.5 - \frac{0.1}{2} \right) 0.1 V^2 = 36.3 \mu A$$

$$K_n = 25 \frac{\mu A}{V^2} \left(\frac{100 \mu m}{1 \mu m} \right) = 250 \frac{\mu A}{V^2}$$

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$$R_{on} = \frac{1}{K_n \frac{W}{L} (V_{GS} - V_{TN})} = \frac{1}{250 \frac{\mu A}{V^2} (2-1)} = 4.00 k\Omega \quad | \quad R_{on} = \frac{1}{250 \frac{\mu A}{V^2} (4-1)} = 1.00 k\Omega$$

$$V_{GS} = V_{TN} + \frac{1}{K_n R_{on}} = 1V + \frac{1}{250 \frac{\mu A}{V^2} (2000 \Omega)} = 3.00 V$$

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$V_{GS} - V_{TN} = 5 - 1 = 4 \text{ V}$ and $V_{DS} = 10 \text{ V} \rightarrow$ Saturation region operation

$$I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 = \frac{1}{2} \frac{mA}{V^2} (5 - 1)^2 V^2 = 8.00 \text{ mA}$$

$$K_n = K_n \frac{W}{L} \rightarrow \frac{W}{L} = \frac{1mA}{40\mu A} = \frac{25}{1} \quad W = 25L = 8.75 \text{ } \mu m$$

Assuming saturation region operation,

$$I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 = \frac{1}{2} \frac{mA}{V^2} (2.5 - 1)^2 V^2 = 1.13 \text{ mA}$$

$$g_m = K_n (V_{GS} - V_{TN}) = 1 \frac{mA}{V^2} (2.5 - 1) V = 1.50 \text{ mS}$$

$$\text{Checking: } g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2(1.125mA)}{(2.5 - 1)V} = 1.50 \text{ mS}$$

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$V_{GS} - V_{TN} = 5 - 1 = 4 \text{ V}$ and $V_{DS} = 10 \text{ V} \rightarrow$ Saturation region operation

$$I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS}) = \frac{1}{2} \frac{mA}{V^2} (5 - 1)^2 V^2 [1 + 0.02(10)] = 9.60 \text{ mA}$$

$$I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS}) = \frac{1}{2} \frac{mA}{V^2} (5 - 1)^2 V^2 [1 + 0(10)] = 8.00 \text{ mA}$$

$V_{GS} - V_{TN} = 4 - 1 = 3 \text{ V}$ and $V_{DS} = 5 \text{ V} \rightarrow$ Saturation region operation

$$I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS}) = \frac{25}{2} \frac{\mu A}{V^2} (4 - 1)^2 V^2 [1 + 0.01(5)] = 118 \text{ } \mu A$$

$$I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS}) = \frac{25}{2} \frac{\mu A}{V^2} (5 - 1)^2 V^2 [1 + 0.01(10)] = 220 \text{ } \mu A$$

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Assuming pinchoff region operation, $I_D = \frac{K_n}{2} (0 - V_{TN})^2 = \frac{50}{2} \frac{\mu A}{V^2} (+2V)^2 = 100 \text{ } \mu A$

$$V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = 2V + \sqrt{\frac{2(100 \text{ } \mu A)}{50 \mu A / V^2}} = 4.00 \text{ V}$$

Assuming pinchoff region operation, $I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 = \frac{50}{2} \frac{\mu A}{V^2} [1 - (-2V)]^2 = 225 \text{ } \mu A$

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$$V_{TN} = V_{TO} + \gamma \left(\sqrt{V_{SB} + 0.6V} - \sqrt{0.6V} \right) = 1 + 0.75 \left(\sqrt{0 + 0.6} - \sqrt{0.6} \right) = 1 \text{ V}$$

$$V_{TN} = 1 + 0.75 \left(\sqrt{1.5 + 0.6} - \sqrt{0.6} \right) = 1.51 \text{ V} \quad | \quad V_{TN} = 1 + 0.75 \left(\sqrt{3 + 0.6} - \sqrt{0.6} \right) = 1.84 \text{ V}$$

(a) V_{GS} is less than the threshold voltage, so the transistor is cut off and $I_D = 0$.

(b) $V_{GS} - V_{TN} = 2 - 1 = 1 \text{ V}$ and $V_{DS} = 0.5 \text{ V} \rightarrow$ Triode region operation

$$I_D = K_n \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = 1 \frac{mA}{V^2} \left(2 - 1 - \frac{0.5}{2} \right) 0.5V^2 = 375 \mu A$$

(c) $V_{GS} - V_{TN} = 2 - 1 = 1 \text{ V}$ and $V_{DS} = 2 \text{ V} \rightarrow$ Saturation region operation

$$I_D = \frac{K_n}{2} \left(V_{GS} - V_{TN} \right)^2 \left(1 + \lambda V_{DS} \right) = 0.5 \frac{mA}{V^2} \left(2 - 1 \right)^2 V^2 \left[1 + 0.02(2) \right] = 520 \mu A$$

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(a) V_{GS} is greater than the threshold voltage, so the transistor is cut off and $I_D = 0$.

(b) $|V_{GS} - V_{TN}| = |-2 + 1| = 1 \text{ V}$ and $|V_{DS}| = 0.5 \text{ V} \rightarrow$ Triode region operation

$$I_D = K_n \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} = 0.4 \frac{mA}{V^2} \left(-2 + 1 - \frac{-0.5}{2} \right) (-0.5)V^2 = 150 \mu A$$

(c) $|V_{GS} - V_{TN}| = |-2 + 1| = 1 \text{ V}$ and $|V_{DS}| = 2 \text{ V} \rightarrow$ Saturation region operation

$$I_D = \frac{K_n}{2} \left(V_{GS} - V_{TN} \right)^2 \left(1 + \lambda V_{DS} \right) = \frac{0.4}{2} \frac{mA}{V^2} \left(-2 + 1 \right)^2 V^2 \left[1 + 0.02(2) \right] = 208 \mu A$$

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$$C_{GC} = \left(200 \frac{\mu F}{m^2} \right) (5 \times 10^{-6} m) (0.5 \times 10^{-6} m) = 0.500 fF$$

$$\text{Triode region : } C_{GD} = C_{GS} = \frac{C_{GC}}{2} + C_{GSO}W = 0.25 fF + \left(300 \frac{pF}{m} \right) (5 \times 10^{-6} m) = 1.75 fF$$

$$\text{Saturation region : } C_{GS} = \frac{2}{3} C_{GC} + C_{GSO}W = 0.333 fF + \left(300 \frac{pF}{m} \right) (5 \times 10^{-6} m) = 1.83 fF$$

$$C_{GD} = C_{GSO}W = \left(300 \frac{pF}{m} \right) (5 \times 10^{-6} m) = 1.50 fF$$

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$$KP = K_n = 150U \quad | \quad LAMBDA = \lambda = 0.0133 \quad | \quad VTO = V_{TN} = 1 \quad | \quad PHI = 2\phi_F = 0.6$$

$$W = W = 1.5U \quad | \quad L = L = 0.25U$$

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$$\text{Circuits/cm}^2 \propto \alpha^2 = \left(\frac{1 \mu m}{0.25 \mu m} \right)^2 = 16$$

$$\text{Power - Delay Product} \propto \frac{1}{\alpha^3} = \frac{1}{4^3} = \frac{1}{64} \rightarrow 64 \text{ times improvement}$$

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$$i_D^* = \mu_n \frac{\epsilon_{ox}}{T_{ox}/\alpha} \frac{W/\alpha}{L/\alpha} \left(v_{GS} - V_{TN} - \frac{v_{DS}}{2} \right) v_{DS} = \alpha i_D \quad | \quad P^* = V_{DD} i_D^* = V_{DD} (\alpha i_D) = \alpha P$$

$$\frac{P^*}{A^*} = \frac{\alpha P}{(W/\alpha)(L/\alpha)} = \alpha^3 \frac{P}{A}$$

$$(a) f_T = \frac{1}{2\pi} \frac{500cm^2/V - s}{(10^{-4}cm)^2} (1V) = 7.96 \text{ GHz} \quad | \quad (b) f_T = \frac{1}{2\pi} \frac{500cm^2/V - s}{(0.25 \times 10^{-4}cm)^2} (1V) = 127 \text{ GHz}$$

$$\frac{V}{L} \geq 10^5 \frac{V}{cm} \rightarrow L = \left(10^5 \frac{V}{cm} \right) (10^{-4} cm) = 10 V \quad | \quad L = \left(10^5 \frac{V}{cm} \right) (0.25 \times 10^{-4} cm) = 1 V$$

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- (a) From the graph for $V_{GS} = 0.25 V$, $I_D \approx 10^{-18} A$ |
 (b) From the graph for $V_{GS} = V_{TN} - 0.5 V$, $I_D \approx 3 \times 10^{-15} A$
 (c) $I = (10^9 \text{ transistors}) (3 \times 10^{-15} \text{ A/transistor}) = 3 \mu\text{A}$
-

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$$\text{Active area} = 10\Lambda(12\Lambda) = 120\Lambda^2 = 120(0.125\mu\text{m})^2 = 1.88 \mu\text{m}^2$$

$$L = 2\Lambda = 0.250 \mu\text{m} \quad | \quad W = 10\Lambda = 1.25 \mu\text{m}$$

$$\text{Gate area} = 2\Lambda(10\Lambda) = 20\Lambda^2 = 20(0.125\mu\text{m})^2 = 0.313 \mu\text{m}^2$$

$$\text{Transistor area} = (10\Lambda + 2\Lambda + 2\Lambda)(12\Lambda + 2\Lambda + 2\Lambda) = 224\Lambda^2 = 224(0.125\mu\text{m})^2 = 3.50 \mu\text{m}^2$$

$$N = \frac{(10^4 \mu\text{m})^2}{3.50 \mu\text{m}^2} = 28.6 \times 10^6 \text{ transistors}$$

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Assume saturation region operation and $\lambda = 0$. Then I_D is independent of V_{DS} , and $I_D = 50 \mu\text{A}$.

$$V_{DS} = V_{DD} - I_D R_D = 10 - 50k\Omega(50\mu\text{A}) = 7.50 V. \quad V_{DS} \geq V_{GS} - V_{TN}, \text{ so our assumption was correct.}$$

$$\text{Q-Point} = (50.0 \mu\text{A}, 7.50 V)$$

$$V_{EQ} = \frac{270k\Omega}{270k\Omega + 750k\Omega} 10V = 2.647 V \quad | \quad R_{EQ} = 270k\Omega \parallel 750k\Omega \quad | \quad \text{Assume saturation region.}$$

$$I_D = \frac{25 \times 10^{-6}}{2} \frac{A}{V^2} (2.647 - 1)^2 V^2 = 33.9 \mu\text{A} \quad | \quad V_{DS} = V_{DD} - I_D R_D = 10 - 100k\Omega(33.9\mu\text{A}) = 6.61 V.$$

$$V_{DS} \geq V_{GS} - V_{TN}, \text{ so our assumption was correct.} \quad \text{Q-Point} = (33.9 \mu\text{A}, 6.61 V)$$

$$V_{GS} \text{ does not change: } V_{GS} = 3.00 V \quad | \quad I_D = \frac{30 \times 10^{-6}}{2} \frac{A}{V^2} (3 - 1)^2 V^2 = 60.0 \mu\text{A}$$

$$V_{DS} = V_{DD} - I_D R_D = 10 - 100k\Omega(60.0\mu\text{A}) = 4.00 V. \quad V_{DS} \geq V_{GS} - V_{TN}, \text{ so our assumption was correct.}$$

$$\text{Q-Point} = (60.0 \mu\text{A}, 4.00 V)$$

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$$V_{GS} \text{ does not change: } V_{GS} = 3.00 \text{ V} \quad | \quad I_D = \frac{25 \times 10^{-6}}{2} \frac{A}{V^2} (3 - 1.5)^2 V^2 = 28.1 \mu A$$

$$V_{DS} = V_{DD} - I_D R_D = 10 - 100k\Omega (28.1 \mu A) = 7.19 \text{ V}. \quad V_{DS} \geq V_{GS} - V_{TN}, \text{ so our assumption was correct.}$$

$$\text{Q-Point} = (28.1 \mu A, 7.19 \text{ V})$$

$$V_{DS} = 10 - \frac{25 \times 10^{-6} (10^5)}{2} (3 - 1)^2 (1 + 0.01 V_{DS}) \rightarrow V_{DS} = 10 - 5(1 + 0.01 V_{DS})$$

$$V_{DS} = \frac{10 - 5}{1.05} V = 4.76 \text{ V} \quad I_D = \frac{25 \times 10^{-6}}{2} (3 - 1)^2 [1 + 0.01(4.76)] = 52.4 \mu A$$

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$$\text{For } I_D = 0, V_{DS} = 10 \text{ V}. \quad \text{For } V_{DS} = 0, I_D = \frac{10V}{66.7k\Omega} = 150 \mu A.$$

The load line intersects the $V_{GS} = 3 - V$ curve at $I_D = 50 \mu A, V_{DS} = 6.7 \text{ V}$.

Page 185 Upper group

$$V_{GS}^2 + V_{GS} \left(\frac{2}{K_n R_S} - 2V_{TN} \right) + V_{TN}^2 - \frac{2V_{EQ}}{K_n R_S} = 0 \quad | \quad V_{GS} = -\left(\frac{1}{K_n R_S} - V_{TN} \right) \pm \sqrt{\left(\frac{1}{K_n R_S} - V_{TN} \right)^2 - V_{TN}^2 + \frac{2V_{EQ}}{K_n R_S}}$$

$$V_{GS} = V_{TN} - \frac{1}{K_n R_S} \pm \sqrt{\left(\frac{1}{K_n R_S} \right)^2 - \frac{2V_{TN}}{K_n R_S} + V_{TN}^2 - V_{TN}^2 + \frac{2V_{EQ}}{K_n R_S}} = V_{TN} + \frac{1}{K_n R_S} \left(\sqrt{1 + 2K_n R_S (V_{EQ} - V_{TN})} - 1 \right)$$

Assume saturation region operation.

$$I_D = \frac{1}{2K_n R_S^2} \left(\sqrt{1 + 2K_n R_S (V_{EQ} - V_{TN})} - 1 \right)^2 = \frac{1}{2(30\mu A)(39k\Omega)^2} \left(\sqrt{1 + 2(30\mu A)(39k\Omega)(4-1)} - 1 \right)^2 = 36.8 \mu A$$

$$V_{DS} = 10 - 114k\Omega(36.8\mu A) = 5.81 V \quad | \quad \text{Saturation region is correct.} \quad | \quad \text{Q - Point : } (36.8 \mu A, 5.81 V)$$

$$\text{Assume saturation region operation. } I_D = \frac{1}{2(25\mu A)(39k\Omega)^2} \left(\sqrt{1 + 2(25\mu A)(39k\Omega)(4-1.5)} - 1 \right)^2 = 26.7 \mu A$$

$$V_{DS} = 10 - 114k\Omega(26.7\mu A) = 6.96 V \quad | \quad \text{Saturation region is correct.} \quad | \quad \text{Q - Point : } (26.7 \mu A, 6.96 V)$$

$$\text{Assume saturation region operation. } I_D = \frac{1}{2(25\mu A)(62k\Omega)^2} \left(\sqrt{1 + 2(25\mu A)(62k\Omega)(4-1)} - 1 \right)^2 = 36.8 \mu A$$

$$V_{DS} = 10 - 137k\Omega(25.4\mu A) = 6.52 V \quad | \quad \text{Saturation region is correct.} \quad | \quad \text{Q - Point : } (25.4 \mu A, 6.52 V)$$

Page 185 Lower group

$$V_{EQ} = \frac{R_1}{R_1 + R_2} V_{DD} = \frac{1M\Omega}{1M\Omega + 1.5M\Omega} 10V = 4 V \quad | \quad \text{Assume saturation region operation.}$$

$$I_D = \frac{1}{2K_n R_S^2} \left(\sqrt{1 + 2K_n R_S (V_{EQ} - V_{TN})} - 1 \right)^2 = \frac{1}{2(25\mu A)(1.8k\Omega)^2} \left(\sqrt{1 + 2(25\mu A)(1.8k\Omega)(4-1)} - 1 \right)^2 = 99.5 \mu A$$

$$V_{DS} = 10 - 40.8k\Omega(99.5\mu A) = 5.94 V \quad | \quad \text{Saturation region is correct.} \quad | \quad \text{Q-Point : } (99.5 \mu A, 5.94 V)$$

$$V_{EQ} = \frac{R_1}{R_1 + R_2} V_{DD} = \frac{1.5M\Omega}{1.5M\Omega + 1M\Omega} 10V = 6 V \quad | \quad \text{Assume saturation region operation.}$$

$$I_D = \frac{1}{2(25\mu A)(22k\Omega)^2} \left(\sqrt{1 + 2(25\mu A)(22k\Omega)(6-1)} - 1 \right)^2 = 99.2 \mu A$$

$$V_{DS} = 10 - 40k\Omega(99.2\mu A) = 6.03 V \quad | \quad \text{Saturation region is correct.} \quad | \quad \text{Q-Point : } (99.2 \mu A, 6.03 V)$$

$$I_{Bias} = \frac{V_{DD}}{R_1 + R_2} \rightarrow R_1 + R_2 = \frac{V_{DD}}{I_{Bias}} = \frac{10V}{2\mu A} = 5 M\Omega$$

$$V_{EQ} = \frac{R_1}{R_1 + R_2} V_{DD} \rightarrow R_1 = (R_1 + R_2) \frac{V_{EQ}}{V_{DD}} = 5M\Omega \frac{4V}{10V} = 2 M\Omega$$

$$R_2 = 5M\Omega - R_1 = 3 M\Omega \quad | \quad R_{EQ} = R_1 \| R_2 = 1.2 M\Omega$$

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$$V_{GS} = 6 - 22000I_D \quad V_{SB} = 22000I_D \quad V_{TN} = 1 + 0.75 \left(\sqrt{V_{SB} + 0.6} - \sqrt{0.6} \right) \quad I_D = \frac{25\mu A}{2} (V_{GS} - V_{TN})^2$$

Spreadsheet iteration yields $I_D = 83.2 \mu A$.

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$$\text{Equation 4.55 becomes } 6 - \left[1 + 0.75 \left(\sqrt{V_{SB} + 0.6} - \sqrt{0.6} \right) + 2.83 \right] - V_{SB} = 0.$$

$$V_{SB}^2 - 6.065V_{SB} + 7.231 = 0 \rightarrow V_{SB} = 1.63V.$$

$$R_S = \frac{1.63V}{10^{-4} A} = 16.3 k\Omega \rightarrow 16 k\Omega \quad R_D = \frac{(10 - 6 - 1.63)V}{10^{-4} A} = 23.7k\Omega \rightarrow 24 k\Omega$$

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Assume saturation region operation.

$$10 - 6 = \frac{25 \times 10^{-6} (62 \times 10^4)}{2} (V_{GS} + 1)^2 - V_{GS} \rightarrow V_{GS}^2 + 0.710 V_{GS} - 4.161 = 0 \rightarrow V_{GS} = -2.426V, +1.716V$$

$$I_D = \frac{25 \times 10^{-6}}{2} (-2.426 + 1)^2 = 25.4 \mu A \quad | \quad V_{DS} = -[10 - 137k\Omega(25.4\mu A)] = -6.52 V$$

Saturation region is correct. | Q-Point : (25.4 μA , -6.52 V)

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(a) $V_{DS} = 3 V$, $V_{GS} - V_P = -2 - (-3.5) = +1.5 V$. The transistor is pinched off.

$$I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_P}\right)^2 = 1mA \left[1 - \left(\frac{-2V}{-3.5V}\right)\right]^2 = 184 \mu A \quad | \quad \text{Pinchoff requires } V_{DS} \geq V_{GS} - V_P = +1.5 V$$

(b) $V_{DS} = 6 V$, $V_{GS} - V_P = -1 - (-3.5) = +2.5 V$. The transistor is pinched off.

$$I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_P}\right)^2 = 1mA \left[1 - \left(\frac{-1V}{-3.5V}\right)\right]^2 = 510 \mu A \quad | \quad \text{Pinchoff requires } V_{DS} \geq V_{GS} - V_P = +2.5 V$$

(c) $V_{DS} = 0.5 V$, $V_{GS} - V_P = -2 - (-3.5) = +1.5 V$. The transistor is in the triode region.

$$I_D = \frac{2I_{DSS}}{V_P^2} \left(V_{GS} - V_P - \frac{V_{DS}}{2}\right) V_{DS} = \frac{2(1mA)}{(-3.5)^2} \left(-2 + 3.5 - \frac{0.5}{2}\right) 0.5 = 51.0 \mu A$$

Pinchoff requires $V_{DS} \geq V_{GS} - V_P = +1.5 V$

(a) $V_{DS} = 0.5 V$, $V_{GS} - V_P = -2 - (-4) = +2 V$. The transistor is in the triode region.

$$I_D = \frac{2I_{DSS}}{V_P^2} \left(V_{GS} - V_P - \frac{V_{DS}}{2}\right) V_{DS} = \frac{2(0.2mA)}{(-4)^2} \left(-2 + 4 - \frac{0.5}{2}\right) 0.5 = 21.9 \mu A$$

(b) $V_{DS} = 6 V$, $V_{GS} - V_P = -1 - (-4) = +3 V$. The transistor is pinched off.

$$I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_P}\right)^2 = 0.2mA \left[1 - \left(\frac{-1V}{-4V}\right)\right]^2 = 113 \mu A$$

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(a) $V_{DS} = -3 \text{ V}$, $V_{GS} - V_P = 3 - 4 = -1 \text{ V}$. The transistor is pinched off.

$$I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_P}\right)^2 = 2.5mA \left[1 - \frac{3V}{4V}\right]^2 = 156 \mu A \quad | \quad \text{Pinchoff requires } V_{DS} \leq V_{GS} - V_P = -1 \text{ V}$$

(b) $V_{DS} = -6 \text{ V}$, $V_{GS} - V_P = 1 - (4) = -3 \text{ V}$. The transistor is pinched off.

$$I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_P}\right)^2 = 2.5mA \left[1 - \frac{1V}{4V}\right]^2 = 1.41 mA \quad | \quad \text{Pinchoff requires } V_{DS} \leq V_{GS} - V_P = -3 \text{ V}$$

(c) $V_{DS} = -0.5 \text{ V}$, $V_{GS} - V_P = 2 - (4) = -2 \text{ V}$. The transistor is in the triode region.

$$I_D = \frac{2I_{DSS}}{V_P^2} \left(V_{GS} - V_P - \frac{V_{DS}}{2}\right) V_{DS} = \frac{2(2.5mA)}{4^2} \left(2 - 4 - \frac{-0.5}{2}\right) (-0.5) = 273 \mu A$$

Pinchoff requires $V_{DS} \leq V_{GS} - V_P = -2 \text{ V}$

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$$\text{BETA} = \frac{I_{DSS}}{V_P^2} = \frac{2.5mA}{(-2)^2} = 0.625 mA \quad | \quad \text{VTO} = V_P = -2 \text{ V} \quad | \quad \text{LAMBDA} = \lambda = 0.025 \text{ V}^{-1}$$

$$\text{BETA} = \frac{I_{DSS}}{V_P^2} = \frac{5mA}{2^2} = 1.25 mA \quad | \quad \text{VTO} = V_P = 2 \text{ V} \quad | \quad \text{LAMBDA} = \lambda = 0.02 \text{ V}^{-1}$$

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$$VTO = V_p = -5 \text{ V} \quad | \quad \text{BETA} = \frac{I_{DSS}}{V_p^2} = \frac{5mA}{(-5)^2} = 0.2 \text{ mA} \quad | \quad \text{LAMBDA} = \lambda = 0.02 \text{ V}^{-1}$$

$$V_{GS} = V_G - V_S = -I_G R_G - I_S R_S = 0 - I_D R_S = -I_D R_S$$

$$V_{GS} = -\frac{K_n}{2} (V_{GS} - V_{TN})^2 R_S = -\frac{K_n}{2} V_{TN}^2 R_S \left(\frac{V_{GS}}{V_{TN}} - 1 \right)^2 = -I_{DSS} R_S \left(1 - \frac{V_{GS}}{V_p} \right)^2 \quad \text{for } I_{DSS} = \frac{K_n}{2} V_{TN}^2 \text{ and } V_p = V_{TN}$$

$$V_{GS} = -\frac{0.4mA}{2} (-5)^2 (1k\Omega) \left(1 - \frac{V_{GS}}{-5} \right)^2 = 5 \left(1 + \frac{V_{GS}}{5} \right)^2 \rightarrow V_{GS}^2 - 15V_{GS} + 25 = 0 \text{ and the rest is identical.}$$

$$\text{Assuming pinchoff, } I_D = 1.91 \text{ mA and } V_{DS} = 9 - 1.91mA(2k\Omega + 1k\Omega) = 3.27 \text{ V.}$$

$$V_{GS} - V_p = 3.09 \text{ V}, V_{DS} > V_{GS} - V_p, \text{ and pinchoff is correct.}$$

$$\text{Assuming pinchoff, } V_{GS} = -I_{DSS} R_S \left(1 - \frac{V_{GS}}{V_p} \right)^2 = -(5 \times 10^{-3})(2 \times 10^3) \left(1 + \frac{V_{GS}}{5} \right)^2 \rightarrow V_{GS}^2 + 12.5V_{GS} + 25 = 0$$

$$V_{GS} = -2.5 \text{ V} \quad | \quad I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_p} \right)^2 = 5mA \left(1 - \frac{-2.5}{-5} \right)^2 = 1.25 \text{ mA}$$

$$V_{DS} = 12 - 1.25mA(2k\Omega + 2k\Omega) = 7.00 \text{ V.}$$

$$V_{GS} - V_p = -2.5 - (-5) = +2.5 \text{ V}, V_{DS} > V_{GS} - V_p, \text{ and pinchoff is correct. Q-Point : (1.25 mA, 7.00 V)}$$

$$(a) V_G = -I_G R_G = -10nA(680k\Omega) = -6.80 \text{ mV.}$$

$$V_{GS} = V_G - V_S = -I_G R_G - I_{DSS} R_S \left(1 - \frac{V_{GS}}{V_p} \right)^2 = -0.00680 - (5 \times 10^{-3})(10^3) \left(1 + \frac{V_{GS}}{5} \right)^2 \rightarrow V_{GS}^2 - 15V_{GS} + 25 = 0$$

The value of V_G is insignificant with respect to the constant term of 25. So the answers are the same to 3 significant digits.

$$(b) V_G = -I_G R_G = -1\mu A(680k\Omega) = 0.680 \text{ V and now cannot be neglected.}$$

$$V_{GS} = V_G - V_S = -I_G R_G - I_{DSS} R_S \left(1 - \frac{V_{GS}}{V_p} \right)^2 = -0.680 - (5 \times 10^{-3})(10^3) \left(1 + \frac{V_{GS}}{5} \right)^2 \rightarrow V_{GS}^2 - 15V_{GS} + 28.4 = 0$$

$$V_{GS} = -2.226 \text{ V} \quad | \quad I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_p} \right)^2 = 5mA \left(1 - \frac{-2.226}{-5} \right)^2 = 1.54 \text{ mA}$$

$$V_{DS} = 12 - 1.54mA(2k\Omega + 1k\Omega) = 7.38 \text{ V} \quad | \quad \text{Q-Point : (1.54 mA, 7.38 V)}$$

CHAPTER 5

Page 223

$$(a) \beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.970}{1-0.970} = 32.3 \quad | \quad \beta_F = \frac{0.993}{1-0.993} = 142 \quad | \quad \beta_F = \frac{0.250}{1-.250} = 0.333$$

$$(b) \alpha_F = \frac{\beta_F}{\beta_F + 1} = \frac{40}{41} = 0.976 \quad | \quad \alpha_F = \frac{200}{201} = 0.995 \quad | \quad \alpha_F = \frac{3}{4} = 0.750$$

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$$i_C = 10^{-15} A \left[\exp\left(\frac{0.700}{0.025}\right) - \exp\left(\frac{-9.30}{0.025}\right) \right] - \frac{10^{-15} A}{0.5} \left[\exp\left(\frac{-9.30}{0.025}\right) - 1 \right] = 1.45 \text{ mA}$$

$$i_E = 10^{-15} A \left[\exp\left(\frac{0.700}{0.025}\right) - \exp\left(\frac{-9.30}{0.025}\right) \right] + \frac{10^{-15} A}{100} \left[\exp\left(\frac{0.700}{0.025}\right) - 1 \right] = 1.46 \text{ mA}$$

$$i_B = \frac{10^{-15} A}{100} \left[\exp\left(\frac{0.700}{0.025}\right) - 1 \right] + \frac{10^{-15} A}{0.5} \left[\exp\left(\frac{-9.30}{0.025}\right) - 1 \right] = 14.5 \text{ } \mu\text{A}$$

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$$i_C = 10^{-16} A \left[\exp\left(\frac{0.750}{0.025}\right) - \exp\left(\frac{0.700}{0.025}\right) \right] - \frac{10^{-16} A}{0.4} \left[\exp\left(\frac{0.700}{0.025}\right) - 1 \right] = 563 \text{ } \mu\text{A}$$

$$i_E = 10^{-16} A \left[\exp\left(\frac{0.750}{0.025}\right) - \exp\left(\frac{0.700}{0.025}\right) \right] + \frac{10^{-16} A}{75} \left[\exp\left(\frac{0.750}{0.025}\right) - 1 \right] = 938 \text{ } \mu\text{A}$$

$$i_B = \frac{10^{-16} A}{75} \left[\exp\left(\frac{0.750}{0.025}\right) - 1 \right] + \frac{10^{-16} A}{0.4} \left[\exp\left(\frac{0.700}{0.025}\right) - 1 \right] = 376 \text{ } \mu\text{A}$$

$$i_T = 10^{-15} A \left[\exp\left(\frac{0.750}{0.025}\right) - \exp\left(\frac{-2}{0.025}\right) \right] = 10.7 \text{ mA}$$

$$i_T = 10^{-16} A \left[\exp\left(\frac{0.750}{0.025}\right) - \exp\left(\frac{-4.25}{0.025}\right) \right] = 1.07 \text{ mA}$$

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$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S} + 1\right) = 0.025V \ln\left(\frac{10^{-4}A}{10^{-16}A} + 1\right) = 0.691 \text{ V}$$

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S} + 1\right) = 0.025V \ln\left(\frac{10^{-3}A}{10^{-16}A} + 1\right) = 0.748 \text{ V}$$

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*n*p*n*: $V_{BE} > 0$, $V_{BC} < 0 \rightarrow$ Forward - Active Region | *p*n*p*: $V_{EB} > 0$, $V_{CB} > 0 \rightarrow$ Saturation Region

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$$\beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.95}{0.05} = 19 \quad \beta_R = \frac{\alpha_R}{1-\alpha_R} = \frac{0.25}{0.75} = \frac{1}{3}$$

$$V_{BE} = 0, V_{BC} \ll 0: I_C = I_S \left(1 + \frac{1}{\beta_R}\right) = 10^{-16} A \left(1 + \frac{1}{0.333}\right) = 0.400 fA$$

$$I_E = I_S = 0.100 fA \quad I_B = -\frac{I_S}{\beta_R} = -\frac{10^{-16} A}{0.333} = -0.300 fA$$

$$V_{BE} \ll 0, V_{BC} \ll 0: I_C = \frac{I_S}{\beta_R} = 3 \times 10^{-16} A = 0.300 fA$$

$$I_E = \frac{I_S}{\beta_F} = \frac{10^{-16} A}{19.0} = 5.26 aA \quad I_B = -\frac{I_S}{\beta_F} - \frac{I_S}{\beta_R} = -\frac{10^{-16} A}{19.0} - \frac{10^{-16} A}{1/3} = -0.305 fA$$

Page 235

(a) The currents do not depend upon V_{CC} as long as the collector - base junction is reverse biased by more than 0.1 V. (Later when Early voltage V_A is discussed, one should revisit this problem.)

$$(b) I_E = 100 \mu A \quad | \quad I_B = \frac{I_E}{\beta_F + 1} = \frac{100 \mu A}{51} = 1.96 \mu A \quad | \quad I_C = \beta_F I_B = 50 I_B = 98.0 \mu A$$

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S} + 1\right) = 0.025V \ln\left(\frac{98.0 \mu A}{10^{-16} A} + 1\right) = 0.690 \text{ V}$$

Page 236

(a) The currents do not depend upon V_{CC} as long as the collector - base junction is reverse biased by more than 0.1 V. (Later when Early voltage V_A is discussed, one should revisit this problem.)

(b) Forward - active region : $I_B = 100 \mu A$ | $I_E = (\beta_F + 1)I_B = 5.10 mA$ | $I_C = \beta_F I_B = 5.00 mA$

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S} + 1\right) = 0.025V \ln\left(\frac{5.00mA}{10^{-16}A} + 1\right) = 0.789 V \quad | \quad \text{Checking: } V_{BC} = -5 + 0.789 = -4.21$$

Forward - active region with $V_{CB} \geq 0$ requires $V_{CC} \geq V_{BE}$ or $V_{CC} \geq 0.764 V$

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(a) Resistor R is changed.

$$I_E = \frac{-0.7V - (-9V)}{5.6k\Omega} = 1.48 mA \quad | \quad I_B = \frac{I_E}{\beta_F + 1} = \frac{I_E}{51} = 29.1 \mu A \quad | \quad I_C = \beta_F I_B = 50I_B = 1.45 mA$$

$$V_{CE} = V_C - V_E = (9 - 4300I_C) - (-0.7) = 3.47 V \quad | \quad Q\text{-Point: } (1.45 mA, 3.47 V)$$

$$(b) I_E = \frac{\beta_F + 1}{\beta_F} I_C = \frac{51}{50} 100 \mu A = 102 \mu A \quad | \quad R = \frac{-0.7V - (-9V)}{102 \mu A} = \frac{8.3V}{102 \mu A} = 81.4 k\Omega$$

The nearest 5% value is 82 $k\Omega$.

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$$I_E = \frac{-0.7V - (-9V)}{5.6k\Omega} = 1.48 mA \quad | \quad I_B = \frac{I_E}{\beta_F + 1} = \frac{I_E}{50} = 29.1 \mu A \quad | \quad I_C = \beta_F I_B = 50I_B = 1.45 mA$$

$$I_E = \frac{\beta_F + 1}{\beta_F} I_C = \frac{51}{50} I_C = 1.02 I_C \quad V_{BE} = V_T \ln\left(\frac{I_C}{I_S} + 1\right) = 0.025 \ln(2 \times 10^{15} I_C + 1)$$

$$V_{BE} + 8200 \left[1.02 \left(5 \times 10^{-16} \right) \exp\left(\frac{V_{BE}}{0.025}\right) - 1 \right] = 9 \rightarrow V_{BE} = 0.7079 V \text{ using a calculator solver}$$

$$\text{or spreadsheet. } I_C = 5 \times 10^{-16} \exp\left(\frac{0.7079}{0.025}\right) = 992 \mu A \quad | \quad V_{CE} = 9 - 4300I_C - (-0.708) = 5.44 V$$

$$I_{SD} = \frac{I_{SBJT}}{\alpha_F} = \frac{2 \times 10^{-14} A}{0.95} = 21.0 fA$$

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Resistor R is changed :

$$-I_C = \frac{-0.7V - (-9V)}{5.6k\Omega} = 1.48 \text{ mA} \quad | \quad I_B = \frac{-I_C}{\beta_R + 1} = \frac{-I_C}{2} = 0.741 \text{ mA} \quad | \quad -I_E = \beta_R I_B = (1)I_B = 0.741 \text{ mA}$$

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$$V_{CESAT} = (0.025V) \ln \left[\left(\frac{1}{0.5} \right) \frac{1 + \frac{1mA}{2(40\mu A)}}{1 - \frac{1mA}{50(40\mu A)}} \right] = 99.7 \text{ mV}$$

$$V_{BESAT} = (0.025V) \ln \left[\frac{0.1mA + (1-0.5)1mA}{10^{-15}A \left(\frac{1}{50} + 1 - 0.5 \right)} \right] = 0.694 \text{ mV}$$

$$V_{BCSAT} = (0.025V) \ln \left[\frac{0.1mA - \frac{1mA}{50}}{10^{-15}A \left(\frac{1}{0.5} \right) \left(\frac{1}{50} + 1 - 0.5 \right)} \right] = 0.627 \text{ mV} \quad | \quad V_{CESAT} = V_{BESAT} - V_{BCSAT} = 67.7 \text{ mV}$$

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$$(a) D_n = \frac{kT}{q} \mu_n = 0.025V (500 \text{ cm}^2 / V - s) = 12.5 \text{ cm}^2 / s$$

$$(b) I_s = \frac{qAD_n n_i^2}{N_{AB}W} = \frac{1.6 \times 10^{-19} C (50 \mu m^2) (10^{-4} \text{ cm} / \mu m) (12.5 \text{ cm}^2 / s) (10^{20} / \text{cm}^6)}{(10^{18} / \text{cm}^3) (1 \mu m)} = 10^{-18} A = 1 \text{ aA}$$

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$$V_T = \frac{(1.38 \times 10^{-23} J/K)(373K)}{1.60 \times 10^{-19} C} = 32.2 \text{ mV} \quad | \quad C_D = \frac{I_C}{V_T} \tau_F = \frac{10A}{0.0322V} (4 \times 10^{-9} s) = 1.24 \text{ } \mu F$$

$$f_\beta = \frac{f_T}{\beta_F} = \frac{300 \text{ MHz}}{125} = 2.40 \text{ MHz}$$

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$$I_C = 10^{-15} A \exp\left(\frac{0.7}{0.025}\right) \left(1 + \frac{10}{50}\right) = 1.74 \text{ mA} \quad | \quad \beta_F = 75 \left(1 + \frac{10}{50}\right) = 90.0 \quad | \quad I_B = \frac{1.74 \text{ mA}}{90.0} = 19.3 \text{ } \mu\text{A}$$

$$I_C = 10^{-15} A \exp\left(\frac{0.7}{0.025}\right) = 1.45 \text{ mA} \quad | \quad \beta_F = 75 \quad | \quad I_B = \frac{1.45 \text{ mA}}{75} = 19.3 \text{ } \mu\text{A}$$

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$$g_m = \frac{40}{V} (10^{-4} A) = 4.00 \text{ mS} \quad | \quad g_m = \frac{40}{V} (10^{-3} A) = 40.0 \text{ mS}$$

$$C_D = 4.00 \text{ mS} (25 \text{ ps}) = 0.100 \text{ pF} \quad | \quad C_D = 40.0 \text{ mS} (25 \text{ ps}) = 1.00 \text{ pF}$$

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$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23} (300)}{1.60 \times 10^{-19}} = 25.9 \text{ mV} \quad | \quad \text{IS} = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{350 \mu\text{A}}{\exp\left(\frac{0.68}{0.0259}\right)} = 1.39 \text{ fA}$$

$$\text{BF} = 80 \quad | \quad \text{VAF} = 70 \text{ V}$$

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$$V_{EQ} = \frac{18k\Omega}{18k\Omega + 36k\Omega} 12V = 4.00 \text{ V} \quad | \quad R_{EQ} = 18k\Omega \parallel 36k\Omega = 12 \text{ k}\Omega$$

$$I_B = \frac{4.00 - 0.7}{12 + (75+1)16} \frac{V}{k\Omega} = 2.687 \text{ } \mu\text{A} \quad | \quad I_C = 75I_B = 202 \text{ } \mu\text{A} \quad | \quad I_E = 76I_B = 204 \text{ } \mu\text{A}$$

$$V_{CE} = 12 - 22000I_C - 16000I_E = 4.29 \text{ V} \quad | \quad Q\text{-point: } (202 \text{ } \mu\text{A}, 4.29 \text{ V})$$

$$V_{EQ} = \frac{180k\Omega}{180k\Omega + 360k\Omega} 12V = 4.00 \text{ V} \quad | \quad R_{EQ} = 180k\Omega \parallel 360k\Omega = 120 \text{ k}\Omega$$

$$I_B = \frac{4.00 - 0.7}{120 + (75+1)16} \frac{V}{k\Omega} = 2.470 \text{ } \mu\text{A} \quad | \quad I_C = 75I_B = 185 \text{ } \mu\text{A} \quad | \quad I_E = 76I_B = 188 \text{ } \mu\text{A}$$

$$V_{CE} = 12 - 22000I_C - 16000I_E = 4.29 \text{ V} \quad | \quad Q\text{-point: } (185 \text{ } \mu\text{A}, 4.93 \text{ V})$$

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$$I_2 = \frac{I_C}{5} = \frac{50I_B}{5} = 10I_B$$

$$V_{EQ} = \frac{18k\Omega}{18k\Omega + 36k\Omega} 12V = 4.00 \text{ V} \quad | \quad R_{EQ} = 18k\Omega \parallel 36k\Omega = 12 \text{ k}\Omega$$

$$I_B = \frac{4.00 - 0.7}{12 + (500 + 1)16} \frac{V}{k\Omega} = 0.4111 \mu A \quad | \quad I_C = 500I_B = 205.6 \mu A \quad | \quad I_E = 76I_B = 206.0 \mu A$$

$$V_{CE} = 12 - 22000I_C - 16000I_E = 4.18 \text{ V} \quad | \quad \text{Q-point : } (206 \mu A, 4.18 \text{ V})$$

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The voltages all remain the same, and the currents are reduced by a factor of 10. Hence all the resistors are just scaled up by a factor of 10.

$$120 \text{ k}\Omega \rightarrow 1.2 \text{ M}\Omega \quad 82 \text{ k}\Omega \rightarrow 820 \text{ k}\Omega \quad 6.8 \text{ k}\Omega \rightarrow 68 \text{ k}\Omega$$

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$$V_{CE} = 0.7 \text{ V at the edge of saturation.} \quad 12V - \left(R_C + \frac{76}{75} 16k\Omega \right) (205\mu A) \geq 0.7V \rightarrow R_C \leq 38.9 \text{ k}\Omega$$

$$V_{BESAT} = 4 - 12k\Omega(24\mu A) - 16k\Omega(184\mu A) = 0.768 \text{ V}$$

$$V_{CESAT} = 12 - 56k\Omega(160\mu A) - 16k\Omega(184\mu A) = 0.096 \text{ V}$$

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$$I_B = \frac{9 - 0.7}{36 + (50 + 1)1} \frac{V}{k\Omega} = 95.4 \mu A \quad | \quad I_C = 50I_B = 4.77 \text{ mA} \quad | \quad I_E = 51I_B = 4.87 \text{ mA}$$

$$V_{CE} = 9 - 1000(I_C + I_B) = 4.13 \text{ V} \quad | \quad \text{Q-point : } (4.77 \text{ mA}, 4.13 \text{ V})$$

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VBE (V)	IC (A)	V'BE (V)
0.70000	2.0155E-04	0.67156
0.67156	2.0328E-04	0.67178
0.67178	2.0327E-04	0.67178
0.67178	2.0327E-04	0.67178

Microelectronic Circuit Design

Fourth Edition - Part II

Solutions to Exercises

CHAPTER 6

Page 292

$$NM_L = 0.8V - 0.4V = 0.4 \text{ V} \quad | \quad NM_H = 3.6V - 2.0V = 1.6 \text{ V}$$

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$$V_{10\%} = V_L + 0.1 (\Delta V) = -2.6V + 0.1 [-0.6 - (-2.6)] = -2.4 \text{ V}$$

$$\text{Checking: } V_{10\%} = V_H - 0.9 (\Delta V) = -0.6V - 0.9 [-0.6 - (-2.6)] = -2.4 \text{ V}$$

$$V_{90\%} = V_H - 0.1 (\Delta V) = -0.6V - 0.1 [-0.6 - (-2.6)] = -0.8 \text{ V}$$

$$\text{Checking: } V_{90\%} = V_L + 0.9 (\Delta V) = -2.6V + 0.9 [-0.6 - (-2.6)] = -0.8 \text{ V}$$

$$V_{50\%} = \frac{V_H + V_L}{2} = \frac{-0.6 - 2.6}{2} = -1.6 \text{ V} \quad | \quad t_r = t_4 - t_3 = 3 \text{ ns} \quad | \quad t_f = t_2 - t_1 = 5 \text{ ns}$$

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$$\text{At } P = 1 \text{ mW: } PDP = 1 \text{ mW}(1 \text{ ns}) = 1 \text{ pJ}$$

$$\text{At } P = 3 \text{ mW: } PDP = 3 \text{ mW}(1 \text{ ns}) = 3 \text{ pJ}$$

$$\text{At } P = 20 \text{ mW: } PDP = 20 \text{ mW}(2 \text{ ns}) = 40 \text{ pJ}$$

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$$Z = (A + B)(B + C) = AB + AC + BB + BC = AB + BB + AC + BB + BC$$

$$Z = AB + B + AC + B + BC = B(A + 1) + AC + B(C + 1) = B + AC + B$$

$$Z = B + B + AC = B + AC$$

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$$I_{DD} = \frac{P}{V_{DD}} = \frac{0.4mW}{2.5V} = 160 \mu A \quad | \quad R = \frac{V_{DD} - V_L}{I_{DD}} = \frac{2.5V - 0.2V}{160\mu A} = 14.4 k\Omega$$

$$1.6 \times 10^{-4} A = 10^{-4} \frac{A}{V^2} \left(\frac{W}{L} \right)_S \left(2.5 - 0.6 - \frac{0.2}{2} \right) 0.2 V^2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{4.44}{1}$$

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$$I_{DD} = \frac{V_{DD} - V_L}{R} = \frac{3.3V - 0.1V}{102k\Omega} = 31.4 \mu A$$

$$31.4 \times 10^{-6} A = 6 \times 10^{-5} \frac{A}{V^2} \left(\frac{W}{L} \right)_S \left(3.3 - 0.75 - \frac{0.1}{2} \right) 0.1 V^2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{2.09}{1}$$

Page 303

$$0.15V = \frac{R_{on}}{R_{on} + 28.8k\Omega} 2.5V \rightarrow R_{on} = 1.84 k\Omega$$

$$\left(\frac{W}{L} \right)_S = \frac{1}{10^{-4} \left(2.5 - 0.60 - \frac{0.15}{2} \right) (1.84k\Omega)} \rightarrow \left(\frac{W}{L} \right)_S = \frac{2.98}{1}$$

$$R_{on} = \frac{1}{6 \times 10^{-5} \left(\frac{1.03}{1} \right) \left(3.3 - 0.75 - \frac{0.2}{2} \right)} = 6.61 k\Omega \quad | \quad V_L = \frac{6.61k\Omega}{6.61k\Omega + 102k\Omega} 3.3V = 0.201 V$$

$$\left[\frac{1}{K_n R} \right] = \frac{V^2}{A} \frac{1}{\Omega} = \frac{V^2}{V} = V$$

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$$K_n R = \left(6 \times 10^{-5} \right) \left(\frac{1.03}{1} \right) \left(1.02 \times 10^5 \right) = \frac{6.30}{V}$$

$$NM_H = 3.3 - 0.75 + \frac{1}{2(6.30)} - 1.63 \sqrt{\frac{3.3}{6.30}} = 1.45 V \quad NM_L = 0.75 + \frac{1}{6.30} - \sqrt{\frac{2(3.3)}{3(6.30)}} = 0.318 V$$

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Using MATLAB :

```
fzero(@(vh) ((vh - 1.9 - 0.5 * sqrt(0.6))^2 - 0.25(vh + 0.6)), 1) | ans = 1.5535
```

```
fzero(@(vh) ((vh - 1.9 - 0.5 * sqrt(0.6))^2 - 0.25(vh + 0.6)), 4) | ans = 3.2710
```

$$V_H = 5 - \left[0.75 + 0.5 \left(\sqrt{V_H + 0.6} - \sqrt{0.6} \right) \right] \rightarrow V_H = 3.61 \text{ V}$$

```
fzero(@(vh) (5 - 0.75 - 0.5 * (sqrt(vh + 0.6) - sqrt(0.6)) - vh), 1) | ans = 3.6112
```

$$(a) \quad 80x10^{-6} A = 100x10^{-6} \frac{A}{V^2} \left(\frac{W}{L} \right)_S \left(1.55 - 0.60 - \frac{0.15}{2} \right) 0.15 V^2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{6.10}{1}$$

$$V_{TNL} = 0.6 + 0.5 \left(\sqrt{1.15 + 0.6} - \sqrt{0.6} \right) = 0.646 \text{ V}$$

$$80x10^{-6} A = \frac{100x10^{-6}}{2} \frac{A}{V^2} \left(\frac{W}{L} \right)_L \left(2.5 - 0.15 - 0.646 \right)^2 V^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{0.551}{1} = \frac{1}{1.82}$$

$$(b) \quad 80x10^{-6} A = 100x10^{-6} \frac{A}{V^2} \left(\frac{W}{L} \right)_S \left(1.55 - 0.60 - \frac{0.1}{2} \right) 0.1 V^2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{8.89}{1}$$

$$V_{TNL} = 0.6 + 0.5 \left(\sqrt{1.1 + 0.6} - \sqrt{0.6} \right) = 0.631 \text{ V}$$

$$80x10^{-6} A = \frac{100x10^{-6}}{2} \frac{A}{V^2} \left(\frac{W}{L} \right)_L \left(2.5 - 0.1 - 0.631 \right)^2 V^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{0.511}{1} = \frac{1}{1.96}$$

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The high logic level is unchanged : $V_H = 2.11$

$$60x10^{-6} A = 50x10^{-6} \frac{A}{V^2} \left(\frac{W}{L} \right)_S \left(2.11 - 0.75 - \frac{0.1}{2} \right) 0.1 V^2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{9.16}{1}$$

$$V_{TNL} = 0.75 + 0.5 \left(\sqrt{1.1 + 0.6} - \sqrt{0.6} \right) = 0.781 \text{ V}$$

$$60x10^{-6} A = \frac{50x10^{-6}}{2} \frac{A}{V^2} \left(\frac{W}{L} \right)_L \left(3.3 - 0.1 - 0.781 \right)^2 V^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{0.410}{1} = \frac{1}{2.44}$$

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Using MATLAB :

```
fzero(@(vh) ((vh - 1.9 - 0.5 * sqrt(0.6))^2 - 0.25(vh + 0.6)), 1) | ans = 1.5535
```

$$\gamma = 0 \rightarrow V_{TN} = 0.6V \quad | \quad V_H = 2.5 - 0.6 = 1.9V \quad | \quad I_{DD} = 0 \text{ for } v_o = V_H$$

$$100x10^{-6} \left(\frac{10}{1} \right) \left(1.9 - 0.6 - \frac{V_L}{2} \right) V_L = \frac{100x10^{-6}}{2} \left(\frac{2}{1} \right) \left(2.5 - V_L - 0.6 \right)^2$$

$$6V_L^2 - 116.8V_L + 3.61 = 0 \rightarrow V_L = 0.235V \quad | \quad I_{DD} = 100x10^{-6} \left(\frac{10}{1} \right) \left(1.9 - 0.6 - \frac{0.235}{2} \right) 0.235 = 278 \mu A$$

$$\text{Checking: } I_{DD} = \frac{100x10^{-6}}{2} \left(\frac{2}{1} \right) \left(2.5 - 0.235 - 0.6 \right)^2 = 277 \mu A$$

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$$V_{TNL} = -1.5 + 0.5 \left(\sqrt{0.2 + 0.6} - \sqrt{0.6} \right) = -1.44V$$

$$60.6x10^{-6} = 100x10^{-6} \left(\frac{W}{L} \right)_S \left(3.3 - 0.6 - \frac{0.2}{2} \right) 0.2 \rightarrow \left(\frac{W}{L} \right)_S = \frac{1.17}{1}$$

$$60.6x10^{-6} = \frac{100x10^{-6}}{2} \left(\frac{W}{L} \right)_L \left(0 - 1.44 \right)^2 \rightarrow \left(\frac{W}{L} \right)_L = \frac{0.585}{1} = \frac{1}{1.71}$$

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$$I_{DS} = 100x10^{-6} \left(\frac{2.22}{1} \right) \left(2.5 - 0.6 - \frac{0.2}{2} \right) 0.2 = 79.9 \mu A \text{ which checks.}$$

Page 321The PMOS transistor is still saturated so $I_{DL} = 144 \mu A$, and $V_H = 2.5V$.

$$144x10^{-6} = 100x10^{-6} \left(\frac{5}{1} \right) \left(2.5 - 0.6 - \frac{V_L}{2} \right) V_L \rightarrow V_L = 0.158V$$

Page 326Place a third transistor with $\frac{W}{L} = \frac{2.22}{1}$ in parallel with transistors A and B.The W/L ratio of the load transistor remains unchanged: $\left(\frac{W}{L} \right)_L = \frac{1.81}{1}$

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Place a third transistor in series with transistors A and B.

The new W/L ratios of transistors A, B and C are $\left(\frac{W}{L}\right)_{ABC} = 3 \frac{2.22}{1} = \frac{6.66}{1}$.

The W/L ratio of the load transistor remains unchanged: $\left(\frac{W}{L}\right)_L = \frac{1.81}{1}$

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M_{L1} is saturated for all three voltages. $I_{DD} = \frac{40 \times 10^{-6}}{2} \left(\frac{1.11}{1} \right)_L \left[-2.5 - (-0.6) \right]^2 = 80.1 \mu A$

The voltages can be estimated using the on - resistance method.

For the 11000 case, $R_{onA} = \frac{132mV - 64.4mV}{80.1\mu A} = 844 \Omega$ $R_{onB} = \frac{64.4mV}{80.1\mu A} = 804 \Omega$

For the 00101 case, $R_{onE} = \frac{64.4mV}{80.1\mu A} = 804 \Omega$.

For the 01110 case, $R_{onC} = \frac{203mV - 132mV}{80.1\mu A} = 886 \Omega$ $R_{onD} = \frac{132mV - 64.4mV}{80.1\mu A} = 844 \Omega$

The voltage across a given conducting device is $I_D R_{on}$. Small variations in R_{on} are ignored.

ABCDE	Y (mV)	2 (mV)	3 (mV)	I_{DD} (uA)	ABCDE	Y (mV)	2 (mV)	3 (mV)	I_{DD} (uA)
00000	2.5 V	0	0	0	10000	2.5 V	2.5 V	0	0
00001	2.5 V	0	0	0	10001	2.5 V	2.5 V	0	0
00010	2.5 V	0	0	0	10010	2.5 V	2.5 V	2.5 V	0
00011	2.5 V	0	0	0	10011	200	130	64	80.1
00100	2.5 V	0	2.5 V	0	10100	2.5 V	2.5 V	2.5 V	0
00101	130	0	64	80.1	10101	130	130	64	80.1
00110	2.5 V	2.5 V	2.5 V	0	10110	2.5 V	2.5 V	2.5 V	0
00111	130	64	64	80.1	10111	100	83	64	80.1
01000	2.5 V	0	0	0	11000	130	64	0	80.1
01001	2.5 V	0	0	0	11001	130	64	0	80.1
01010	2.5 V	0	0	0	11010	130	64	64	80.1
01011	2.5 V	0	0	0	11011	110	43	22	80.1
01100	2.5 V	0	2.5 V	0	11100	130	64	64	80.1
01101	130	0	64	80.1	11101	66	32	32	80.1
01110	200	64	130	80.1	11110	110	64	87	80.1
01111	114	21	43	80.1	11111	65	32	32	80.1

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$$P_{av} = \frac{2.5V(80\mu A)}{2} = 0.100 \text{ mW}$$

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$$P_D = 10^{-12} F(2.5V)^2 (32 \times 10^6 \text{ Hz}) = 2 \times 10^{-4} W = 200 \mu W \text{ or } 0.200 \text{ mW}$$

$$P_D = 10^{-12} F(2.5V)^2 (3.2 \times 10^9 \text{ Hz}) = 2 \times 10^{-4} W = 0.02 \text{ W or } 20 \text{ mW}$$

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The inverter in Fig. 6.38(a) was designed for a power dissipation of 0.2 mW.

To reduce the power by a factor of two, we must reduce the W/L ratios by a factor of 2.

$$\left(\frac{W}{L}\right)_L = \frac{1}{2} \left(\frac{1}{1.68}\right) = \frac{1}{3.36} \quad | \quad \left(\frac{W}{L}\right)_S = \frac{1}{2} \left(\frac{4.71}{1}\right) = \frac{2.36}{1}$$

To increase the power by a factor of $\frac{4 \text{ mW}}{0.2 \text{ mW}}$, we must increase the W/L ratios by a factor of 20.

$$\left(\frac{W}{L}\right)_L = 20 \left(\frac{1.81}{1}\right) = \frac{36.2}{1} \quad | \quad \left(\frac{W}{L}\right)_S = 20 \left(\frac{2.22}{1}\right) = \frac{44.4}{1}$$

To reduce the power by a factor of three, we must reduce the W/L ratios by a factor of 3.

$$\left(\frac{W}{L}\right)_L = \frac{1}{3} \left(\frac{1.81}{1}\right) = \frac{0.603}{1} = \frac{1}{1.66} \quad | \quad \left(\frac{W}{L}\right)_A = \frac{1}{3} \left(\frac{3.33}{1}\right) = \frac{1.11}{1} \quad | \quad \left(\frac{W}{L}\right)_{BCD} = \frac{1}{3} \left(\frac{6.66}{1}\right) = \frac{2.22}{1}$$

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$$t_r = 2.2RC = 2.2(28.8 \times 10^3 \Omega)(2 \times 10^{-13} F) = 12.7 \text{ ns}$$

$$\tau_{PLH} = 0.69RC = 0.69(28.8 \times 10^3 \Omega)(2 \times 10^{-13} F) = 3.97 \text{ ns}$$

--

$$v_o(t) = V_F - (V_F - V_I) \exp\left(-\frac{t}{RC}\right) \quad | \quad v_o(\tau_{PHL}) = V_H - 0.5\left(\frac{V_H + V_L}{2}\right) = 2.5 - 1.15 = 1.35 \text{ V}$$

$$1.35 = 0.2 - (0.2 - 2.5) \exp\left(-\frac{\tau_{PHL}}{RC}\right) \rightarrow \tau_{PLH} = -RC \ln 0.5 = 0.69RC$$

$$v_o(t_1) = V_H - 0.1(V_H + V_L) = 2.5 + 0.23 = 2.27 \text{ V}$$

$$2.27 = 0.2 - (0.2 - 2.5) \exp\left(-\frac{t_1}{RC}\right) \rightarrow t_1 = -RC \ln 0.9$$

$$v_o(t_2) = V_L + 0.1(V_H + V_L) = 0.2 + 0.23 = 0.43 \text{ V}$$

$$0.43 = 0.2 - (0.2 - 2.5) \exp\left(-\frac{t_2}{RC}\right) \rightarrow t_2 = -RC \ln 0.1$$

$$t_f = t_2 - t_1 = -RC \ln 0.1 + RC \ln 0.9 = RC \ln 9 = 2.2RC$$

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$$t_f = 3.7(2.37 \times 10^3 \Omega)(2.5 \times 10^{-13} F) = 2.19 \text{ ns} \quad | \quad \tau_{PHL} = 1.2(2.37 \times 10^3 \Omega)(2.5 \times 10^{-13} F) = 0.711 \text{ ns}$$

$$t_r = 2.2(28.8 \times 10^3 \Omega)(2.5 \times 10^{-13} F) = 15.8 \text{ ns} \quad | \quad \tau_{PLH} = 0.69(28.8 \times 10^3 \Omega)(2.5 \times 10^{-13} F) = 4.97 \text{ ns}$$

$$\tau_p = \frac{0.711 \text{ ns} + 4.97 \text{ ns}}{2} = 2.84 \text{ ns}$$

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$$T = 2N\tau_{p0} = 2(401)(10^{-9} \text{ s}) = 802 \text{ ns} \quad | \quad f = \frac{1}{T} = \frac{1}{802 \text{ ns}} = 1.25 \text{ MHz}$$

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For our Psuedo NMOS inverter with $V_L = 0.2 V$,

$$\tau_{PHL} = 1.2 R_{onS} C = 1.2 \frac{C''_{ox} WL}{\mu_n C''_{ox} \frac{W}{L} (V_{GS} - V_{TN})} = 1.2 \frac{L^2}{\mu_n (V_{GS} - V_{TN})}$$

$$\tau_{PHL} = 1.2 \frac{(250 \times 10^{-9} m)^2 (100 cm/m)^2}{(500 cm^2/V - s)(3.3 - 0.825)V} = 0.606 ps$$

$$\tau_{PLH} = 1.2 R_{onL} C = 1.2 \frac{L^2}{0.4 \mu_p (V_{GS} - V_{TN})} = 1.2 \frac{(250 \times 10^{-9} m)^2 (100 cm/m)^2}{(125 cm^2/V - s)(3.1 - 0.825)V} = 2.63 ps$$

$$\tau_P = \frac{0.606 ps + 2.63 ps}{2} = 1.62 ps$$

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The PMOS transistor is saturated for $v_O = V_L$. $I_{DD} = \frac{40 \times 10^{-6}}{2} \left(\frac{23.7}{1} \right) \left[-2.5 - (-0.6) \right]^2 = 1.71 mA$

$$P_{av} = \frac{2.5V(1.71mA)}{2} = 2.14 mW \quad | \quad P_D = 5 \times 10^{-12} F (2.5V - 0.2V)^2 \left(\frac{1}{2 \times 10^{-9} s} \right) = 13.2 mW$$

We must increase the power by a factor of $\left(\frac{20 pF}{5 pF} \right) \left(\frac{2 ns}{1 ns} \right) = 8$,

so the W/L ratios must also be increased by a factor of 8.

$$\left(\frac{W}{L} \right)_L = 8 \left(\frac{23.7}{1} \right) = \frac{190}{1} \quad | \quad \left(\frac{W}{L} \right)_S = 8 \left(\frac{47.4}{1} \right) = \frac{379}{1} \quad | \quad P_D = 20 \times 10^{-12} F (2.5V - 0.2V)^2 \left(\frac{1}{10^{-9} s} \right) = 106 mW$$

CHAPTER 7

Page 370

$$(a) K_p = 40 \times 10^{-6} \left(\frac{20}{1} \right) = 800 \frac{\mu A}{V^2} \quad | \quad K_n = 100 \times 10^{-6} \left(\frac{20}{1} \right) = 2000 \frac{\mu A}{V^2} = 2.00 \frac{mA}{V^2}$$

$$(b) V_{TN} = 0.6 + 0.5 \left(\sqrt{2.5 + 0.6} - \sqrt{0.6} \right) = 1.09 V$$

$$(c) V_{TP} = -0.6 - 0.75 \left(\sqrt{2.5 + 0.7} - \sqrt{0.7} \right) = -1.31 V$$

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$$(a) \text{ For } v_I = 1 V, V_{GSN} - V_{TN} = 1 - 0.6 = 0.4V \text{ and } V_{GSP} - V_{TP} = -1.5 + 0.6 = -0.9V$$

M_N is saturated for $v_O \geq 0.4 V$. M_P is in the triode region for $v_O \geq 1.6 V$. $\therefore 1.6 V \leq v_O \leq 2.5 V$

$$(b) M_P \text{ is saturated for } v_O \leq 1.6 V. \therefore 0.4 V \leq v_O \leq 1.6 V$$

$$(c) M_N \text{ is in the triode region for } v_O \leq 0.4 V. M_P \text{ is saturated for } v_O \leq 1.6 V. \therefore 0 \leq v_O \leq 0.4 V$$

$$\left(\frac{W}{L} \right)_P = \frac{K_n}{K_p} \left(\frac{W}{L} \right)_N = 2.5 \left(\frac{10}{1} \right) = \frac{25}{1}$$

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Both transistors are saturated since $|V_{GS}| = |V_{DS}|$.

$$\frac{K_n}{2} (V_{GSN} - V_{TN})^2 = \frac{K_p}{2} (V_{GSP} - V_{TP})^2 \quad K_n = K_p \quad |V_{TN}| = |V_{TP}|$$

$$V_{GSN} = -V_{GSP} \rightarrow v_I = V_{DD} - v_I \rightarrow v_I = \frac{V_{DD}}{2}$$

$$\frac{10K_p}{2} (V_{GSN} - V_{TN})^2 = \frac{K_p}{2} (V_{GSP} - V_{TP})^2 \rightarrow \sqrt{10} (V_{GSN} - V_{TN}) = -V_{GSP} + V_{TP}$$

$$\sqrt{10} (v_I - 0.6) = 4 - v_I - 0.6 \rightarrow v_I = 1.273 V$$

$$\frac{K_p}{2} (V_{GSN} - V_{TN})^2 = \frac{10K_p}{2} (V_{GSP} - V_{TP})^2 \rightarrow (V_{GSN} - V_{TN}) = \sqrt{10} (-V_{GSP} + V_{TP})$$

$$v_I - 0.6 = \sqrt{10} (4 - v_I - 0.6) \rightarrow v_I = 2.37 V$$

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$$K_R = \frac{K_n \left(\frac{W}{L} \right)_N}{K_p \left(\frac{W}{L} \right)_P} = \frac{K_n}{K_p} = 2.5$$

$$V_{IH} = \frac{2K_R(V_{DD} - V_{TN} + V_{TP})}{(K_R - 1)\sqrt{1 + 3K_R}} - \frac{(V_{DD} - K_R V_{TN} + V_{TP})}{K_R - 1}$$

$$V_{IH} = \frac{2(2.5)(2.5 - 0.6 - 0.6)}{(2.5 - 1)\sqrt{1 + 3(2.5)}} - \frac{(2.5 - 2.5(0.6) - 0.6)}{2.5 - 1} = 1.22V$$

$$V_{OL} = \frac{(K_R + 1)V_{IH} - V_{DD} - K_R V_{TN} - V_{TP}}{2K_R} = \frac{(2.5 + 1)1.22 - 2.5 - 2.5(0.6) + 0.6}{2(2.5)} = 0.174V$$

$$V_{IL} = \frac{2\sqrt{K_R}(V_{DD} - V_{TN} + V_{TP})}{(K_R - 1)\sqrt{K_R + 3}} - \frac{(V_{DD} - K_R V_{TN} + V_{TP})}{K_R - 1}$$

$$V_{IL} = \frac{2\sqrt{2.5}(2.5 - 0.6 - 0.6)}{(2.5 - 1)\sqrt{2.5 + 3}} - \frac{(2.5 - 2.5(0.6) - 0.6)}{2.5 - 1} = 0.902V$$

$$V_{OH} = \frac{(K_R + 1)V_{IL} + V_{DD} - K_R V_{TN} - V_{TP}}{2} = \frac{(2.5 + 1)0.902 + 2.5 - 2.5(0.6) + 0.6}{2} = 2.38V$$

$$NM_H = V_{OH} - V_{IH} = 2.38 - 1.22 = 1.16 \text{ V} \quad | \quad NM_L = V_{IL} - V_{OL} = 0.902 - 0.174 = 0.728 \text{ V}$$

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$$\text{Symmetrical Inverter : } \tau_P = 1.2R_{on}C = 1.2 \frac{10^{-12}F}{2(10^{-4})(2.5 - 0.6)} \Omega = 3.16 \text{ ns}$$

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$$\text{Symmetrical Inverter : } R_{on} = \frac{\tau_P}{1.2C} = \frac{10^{-9}s}{1.2(5 \times 10^{-12}F)} = 167\Omega$$

$$\left(\frac{W}{L} \right)_N = \frac{1}{R_{on} K_n (V_{GS} - V_{TN})} = \frac{1}{167(10^{-4})(2.5 - 0.6)} = \frac{31.5}{1} \quad | \quad \left(\frac{W}{L} \right)_P = 2.5 \left(\frac{W}{L} \right)_N = \frac{78.8}{1}$$

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The inverters need to be increased in size by a factor of $\frac{280\text{ps}}{250\text{ps}} = 1.12$.

$$\left(\frac{W}{L}\right)_N = 1.12 \left(\frac{3.77}{1}\right) = \frac{4.22}{1} \quad | \quad \left(\frac{W}{L}\right)_P = 1.12 \left(\frac{9.43}{1}\right) = \frac{10.6}{1}$$

$$\left(\frac{W}{L}\right)_N = \left(\frac{3.77}{1}\right) \left(\frac{3.3 - 0.75}{3.3 - 0.5}\right) = \frac{3.43}{1} \quad | \quad \left(\frac{W}{L}\right)_P = \left(\frac{9.43}{1}\right) \left(\frac{3.3 - 0.75}{3.3 - 0.5}\right) = \frac{8.59}{1}$$

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$$\tau_{PHL} = 2.4R_{on}C = \frac{2.4C}{K_n(V_{GS} - V_{TN})} = \frac{2.4C}{K_n(2.5 - 0.6)} = 1.26 \frac{C}{K_n}$$

$$\tau_{PLH} = 2.4R_{onp}C = \frac{2.4C}{K_p(V_{GS} - V_{TN})} = \frac{2.4C}{K_p(2.5 - 0.6)} = 1.26 \frac{C}{K_p}$$

$$\tau_{PHL} = 2.4R_{on}C = \frac{2.4C}{K_n(V_{GS} - V_{TN})} = \frac{2.4C}{K_n(3.3 - 0.75)} = 0.94 \frac{C}{K_n}$$

$$\tau_{PLH} = 2.4R_{onp}C = \frac{2.4C}{K_p(V_{GS} - V_{TN})} = \frac{2.4C}{K_p(3.3 - 0.75)} = 0.94 \frac{C}{K_p}$$

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The inverter in Fig. 7.12 is a symmetrical design, so the maximum current occurs

for $v_O = v_I = \frac{V_{DD}}{2}$. Both transistors are saturated: $i_{DN} = \frac{10^{-4}}{2} \left(\frac{2}{1}\right) (1.25 - 0.6)^2 = 42.3 \mu A$

Checking: $i_{DP} = \frac{4 \times 10^{-5}}{2} \left(\frac{5}{1}\right) (1.25 - 0.6)^2 = 42.3 \mu A$

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$$(a) PDP \cong \frac{CV_{DD}^2}{5} = \frac{10^{-13}F(2.5V)^2}{5} = 0.13 pJ = 130 fJ$$

$$(b) PDP \cong \frac{CV_{DD}^2}{5} = \frac{10^{-13}F(3.3V)^2}{5} = 0.22 pJ = 220 fJ$$

$$(c) PDP \cong \frac{CV_{DD}^2}{5} = \frac{10^{-13}F(1.8V)^2}{5} = 0.065 pJ = 65 fJ$$

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Remove the NMOS and PMOS transistors connected to input E, and ground the source of the NMOS transistor connected to input D. There are now 4 NMOS transistors in series, and

$$\left(\frac{W}{L}\right)_N = 4\left(\frac{2}{1}\right) = \frac{8}{1} \quad | \quad \left(\frac{W}{L}\right)_P = \frac{5}{1}$$

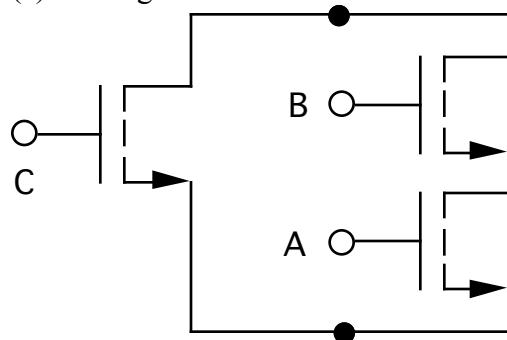
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There are two NMOS transistors in series in the AB and CD NMOS paths, and three PMOS transistors in the ACE and BDE PMOS paths. Therefore:

$$\left(\frac{W}{L}\right)_{N-ABCD} = 2\left(\frac{2}{1}\right) = \frac{4}{1} \quad | \quad \left(\frac{W}{L}\right)_{N-E} = \frac{2}{1} \quad | \quad \left(\frac{W}{L}\right)_P = 3\left(\frac{5}{1}\right) = \frac{15}{1}$$

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(a) The logic network for $F = AB + C$ is



$$P = CV_{DD}^2 f = (50 \times 10^{-12} F)(5V)^2 (10^7 Hz) = 12.5 mW$$

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$$\beta = \left(\frac{50 \text{ pF}}{50 \text{ fF}} \right)^{\frac{1}{2}} = 31.6 \quad \tau_p = 31.6 \tau_o + 31.6 \tau_o = 63.2 \tau_o$$

$$z = e^{\ln z} \quad | \quad z^{\frac{1}{\ln z}} = \left(e^{\ln z} \right)^{\frac{1}{\ln z}} = e$$

$$\beta = \left(\frac{50 \text{ pF}}{50 \text{ fF}} \right)^{\frac{1}{7}} = 2.683$$

$$1, 2.68, 2.683^2 = 7.20, 2.683^3 = 19.3, 2.683^4 = 51.8, 2.683^5 = 139, 2.683^6 = 373$$

$$A_6 = (1 + 3.16 + 10 + 31.6 + 100 + 316) A_o = 462 A_o$$

$$A_7 = (1 + 2.68 + 7.20 + 19.3 + 51.8 + 139 + 373) A_o = 594 A_o$$

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From the figure, 10/1 devices give a maximum R_{on} of 4 k Ω . The W/L ratios must be 4 times larger in order to reduce the maximum R_{on} to 1 k Ω . $\therefore \left(\frac{W}{L} \right) = 4 \left(\frac{10}{1} \right) = \frac{40}{1}$

CHAPTER 8

Page 419

$$(a) NS = \frac{2^8 \cdot 2^{20}}{2^7 \cdot 2^{10}} = 2^{11} = 2048 \text{ segments} \quad | \quad (b) NS = \frac{2^{30}}{2^9 \cdot 2^{10}} = 2^{11} = 2048 \text{ segments}$$

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$$(a) N = 2^8 \cdot 2^{20} = 2^{28} = 268,435,456$$

$$(b) I_{DD} = \frac{0.05W}{3.3V} = 15.2 \text{ mA} \quad | \quad \text{Current/cell} = \frac{15.2 \text{ mA}}{2^{28} \text{ cells}} = 56.4 \text{ pA}$$

Reverse the direction of the substrate arrows, and connect the substrates of the PMOS transistors to V_{DD}.

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M_{A1}: At t = 0⁺, V_{GS} - V_{TN} = 4 V and V_{DS} = 2.5V, so transistor M_{A1} is operating in the triode region.

$$i_1 = 60 \times 10^{-6} \left(\frac{1}{1} \right) \left(5 - 1 - \frac{2.5}{2} \right) 2.5 = 413 \mu A$$

M_{A2}: At t = 0⁺, V_{GS} = V_{DS}, so transistor M_{A2} is operating in the saturation region.

$$V_{TN2} = 1 + 0.6 \left(\sqrt{2.5 + 0.6} - \sqrt{0.6} \right) = 1.592V \quad i_2 = \frac{60 \times 10^{-6}}{2} \left(\frac{1}{1} \right) \left(5 - 2.5 - 1.592 \right)^2 = 24.8 \mu A$$

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M_{A1}: At t = 0⁺, V_{GS} = V_{DS}, so transistor M_{A1} is operating in the saturation region.

$$i_1 = \frac{60 \times 10^{-6}}{2} \left(\frac{1}{1} \right) \left(5 - 1 \right)^2 = 480 \mu A$$

M_{A2}: At t = 0⁺, V_{GS} = V_{DS}, so transistor M_{A2} is operating in the saturation region.

$$i_1 = \frac{60 \times 10^{-6}}{2} \left(\frac{1}{1} \right) \left(5 - 1 \right)^2 = 480 \mu A$$

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(a) At $t = 0^+$, $V_{GS} - V_{TN} = 3 - 0.7 = 2.3$ V and $V_{DS} = 1.9$ V, so transistor M_A is operating in the triode region. $i_l = 60 \times 10^{-6} \left(\frac{1}{1} \right) \left(3 - 0 - 0.7 - \frac{1.9}{2} \right) 1.9 = 154 \mu A$

(b) From Table 6.10: $t_f = 3.7 R_{on} C = 3.7 \frac{50 \times 10^{-15} F}{60 \times 10^{-6} (3 - 0.7)} = 1.34$ ns

$$V_C = V_{BL} - V_{TN} \quad | \quad V_C = 3 - \left[0.7 + 0.5 \left(\sqrt{V_C + 0.6} - \sqrt{0.6} \right) \right] \rightarrow V_C = 1.89$$
 V $| \quad V_C = 3 - 0.7 = 2.3$ V

$$n = \frac{CV}{q} = \frac{25 \times 10^{-15} F (1.89 V)}{1.60 \times 10^{-19} C} = 2.95 \times 10^5 \text{ electrons}$$

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(a) $\Delta V = \frac{V_C - V_{BL}}{\frac{C_{BL}}{C_C} + 1} = \frac{1.9 - 0.95}{\frac{49C_C}{C_C} + 1} V = 19.0$ mV $| \quad \Delta V = \frac{V_C - V_{BL}}{\frac{C_{BL}}{C_C} + 1} = \frac{0 - 0.95}{\frac{49C_C}{C_C} + 1} V = -19.0$ mV

(b) $\tau = R_{on} \frac{C_C}{\frac{C_C}{C_{BL}} + 1} = 5k\Omega \frac{25fF}{\frac{1}{49} + 1} = 0.123$ ns or $\tau \approx R_{on} C_C = 5k\Omega (25fF) = 0.125$ ns

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At $t = 0^+$, $V_{GS} - V_{TN} = (3 - 0) - 0.7 = 2.3$ V and $V_{DS} = 1.5$ V, so transistor M_{A2} is operating in the triode region. $i_D = 60 \times 10^{-6} \left(\frac{2}{1} \right) \left(3 - 0.7 - \frac{1.5}{2} \right) 1.5 = 279 \mu A$

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In setting the drain currents equal, we see that the change in W/L cancels out, and the voltages remain the same.

$$\therefore i_D = \frac{1}{2} \left(60 \times 10^{-6} \right) \left(\frac{5}{1} \right) (1.33 - 0.7)^2 = 59.5 \mu A \quad | \quad P_D = 2(59.5 \mu A)(3V) = 0.357 mW$$

As a check, the current should scale with W/L: $i_D = \frac{5}{2}(23.5 \mu A) = 58.8 \mu A$

Equating drain currents: $\frac{1}{2} \left(25 \times 10^{-6} \right) \left(\frac{2}{1} \right) (2.5 - V_o - 0.6)^2 = \frac{1}{2} \left(60 \times 10^{-6} \right) \left(\frac{2}{1} \right) (V_o - 0.6)^2$

$$1.4V_o^2 + 0.92V_o - 2.746 = 0 \rightarrow V_o = 1.11V$$

$$i_D = \frac{1}{2} \left(25 \times 10^{-6} \right) \left(\frac{2}{1} \right) (2.5 - 1.11 - 0.6)^2 = 15.6 \mu A \quad | \quad P_D = 2(15.6 \mu A)(2.5V) = 78.0 \mu W$$

Checking: $\frac{1}{2} \left(60 \times 10^{-6} \right) \left(\frac{2}{1} \right) (1.11 - 0.6)^2 = 15.6 \mu A$

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$$R_{on} = \frac{1}{60 \times 10^{-6} (3 - 1.3 - 1)} = 23.8 k\Omega \quad | \quad \tau = 23.8 k\Omega (25 fF) = 0.595 ns$$

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For all possible input combinations there will be two inverters and 3 output lines in the low state.

$$P_D = 5(0.2 mW) = 1.0 mW$$

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$$\left(\frac{W}{L} \right)_L = \frac{2}{2.22} \left(\frac{1.81}{1} \right) = \frac{1.63}{1}$$

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For a 0 - V input, all transistors will be on and the input nodes will all discharge to 0 V.

For the 3 - V input, the nodes will all charge to 3 V as long as $V_{TN} \leq 2\text{ V}$.

$$V_{TN} = 0.7 + 0.5(\sqrt{3+0.6} - \sqrt{0.6}) = 1.26\text{ V}. \text{ Thus the nodes will all be a } 3\text{ V}.$$

$$2 \geq 0.7 + \gamma(\sqrt{3+0.6} - \sqrt{0.6}) \rightarrow \gamma \leq 1.158$$

The output will drop below $V_{DD}/2$. For the PMOS device, $|V_{GS} - V_{TP}| = 3 - 1.9 - 0.7 = 0.4V$.

The PMOS transistor will be saturated. For the NMOS device, $|V_{GS} - V_{TP}| = 1.9 - 0.7 = 1.2V$.

Assume linear region operation.

$$\frac{40 \times 10^{-6}}{2} \left(\frac{5}{1} \right) (-1.1 + 0.7)^2 = 100 \times 10^{-6} \left(\frac{2}{1} \right) \left(1.9 - 0.7 - \frac{V_o}{2} \right) V_o$$

$$V_o^2 - 2.4V_o + 0.16 = 0 \rightarrow V_o = 68.6\text{ mV}$$

CHAPTER 9

Page 462

$$\frac{i_{C2}}{i_{C1}} = \exp\left(\frac{0.2V}{0.025V}\right) = 2.98 \times 10^3 \quad | \quad \frac{i_{C2}}{i_{C1}} = \exp\left(\frac{0.3V}{0.025V}\right) = 1.63 \times 10^5 \quad | \quad \frac{i_{C2}}{i_{C1}} = \exp\left(\frac{0.4V}{0.025V}\right) = 8.89 \times 10^6$$

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The current must be reduced by 5 while the voltages remain the same.

$$I_{EE} = \frac{300\mu A}{5} = 60 \mu A \quad | \quad R_C = 5(2k\Omega) = 10 k\Omega$$

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$$I_B = \frac{I_E}{\beta_F + 1} \quad | \quad I_{B3} = \frac{92.9\mu A}{21} = 4.42 \mu A \quad | \quad I_{B4} = \frac{107\mu A}{21} = 5.10 \mu A$$

$$I_{B3}R_C = 4.42\mu A(2k\Omega) = 8.84 mV << 0.7 V \quad | \quad I_{B4}R_C = 5.10\mu A(2k\Omega) = 10.2 mV << 0.7 V$$

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$$V_H = 0 - 0.7 = -0.7 V \quad | \quad V_L = 0 - 0.2mA(2k\Omega) - 0.7V = -1.1 V$$

$$V_{REF} = \frac{-0.7V + (-1.10V)}{2} = -0.9 V \quad | \quad \Delta V = -0.7V - (1.1V) - 0.4 V$$

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$$NM_H = NM_L = \frac{0.4V}{2} - 0.025V \left[1 + \ln\left(\frac{0.4}{0.025} - 1\right) \right] = 0.107 V$$

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$$P = 3.3V(0.3mA + 0.2mA) = 1.65 \text{ mW} \quad | \quad P = 3.3V(0.357mA + 0.2mA) = 1.84 \text{ mW}$$

$$NM_H = NM_L = \frac{0.6V}{2} - 0.025V \left[1 + \ln \left(\frac{0.6}{0.025} - 1 \right) \right] = 0.20 \text{ V}$$

From the graph, the VTC slope is -1 for $V_{IL} = -1.08 \text{ V}$, $V_{OH} = -0.71 \text{ V}$ and

$$V_{IH} = -0.91 \text{ V}, V_{OL} = -1.28 \text{ V}. \quad NM_H = -0.71 - (-0.91) = 0.20 \text{ V}. \quad NM_L = -1.08 - (-1.28) = 0.20 \text{ V}$$

The voltages remain the same. Thus the currents must be reduced by a factor of 3, and the resistor values must be increased by a factor of 3.

$$R_{EE} = \frac{-1.7V - (-5.2V)}{0.20mA} = 17.5 \text{ k}\Omega \quad | \quad I_E = \frac{-1.4V - (-5.2V)}{18 \text{ k}\Omega} = 0.211 \text{ mA} \quad | \quad R_{C1} = \frac{0.4V}{0.211mA} = 1.90 \text{ k}\Omega$$

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$$\text{For all inputs low : } I_{EE} = \frac{-1 - 0.7 - (-5.2)}{11.7} \frac{V}{k\Omega} = 299 \mu A$$

$$\frac{\Delta V}{2} = V_H - V_{REF} = -0.7 - (-1) = 0.3 \text{ V} \quad | \quad \Delta V = 0.6 \text{ V} \quad | \quad R_{C2} = \frac{0.6V}{299\mu A} = 2.00 \text{ k}\Omega$$

$$\text{For an inputs high : } I_{EE} = \frac{-0.7 - 0.7 - (-5.2)}{11.7} \frac{V}{k\Omega} = 325 \mu A \quad | \quad R_{C1} = \frac{0.6V}{325\mu A} = 1.85 \text{ k}\Omega$$

$$\text{Based upon analysis above, } R_C = \frac{0.6V}{325\mu A} = 1.85 \text{ k}\Omega$$

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$$\text{For all inputs low : } I_{EE} = \frac{-1 - 0.7 - (-5.2)}{11.7} \frac{V}{k\Omega} = 299 \mu A$$

$$\frac{\Delta V}{2} = V_H - V_{REF} = -0.7 - (-1) = 0.3 \text{ V} \quad | \quad \Delta V = 0.6 \text{ V} \quad | \quad R_C = \frac{0.6V}{299\mu A} = 2.00 \text{ k}\Omega$$

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$$R_E = \frac{V_E - (-V_{EE})}{0.3mA} = \frac{0 - 0.7 - (-5.2V)}{0.3} \frac{V}{mA} = 15.0 \text{ k}\Omega$$

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$$(a) \text{ For } I_E = 0, v_O = -5.2 \text{ V. } (b) \text{ For } I_E = 0, v_O = -5.2V \frac{10k\Omega}{10k\Omega + 15k\Omega} = -2.08 \text{ V}$$

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The transistor's power dissipation is

$$P = V_{CB}I_C + V_{BE}I_E = 5V \left(2.55mA \frac{50}{51} \right) + 0.7V(2.55mA) = 14.3 \text{ mW}$$

The total power dissipation in the circuit is

$$P = V_{CC}I_C + V_{EE}I_E = 5V \left(2.55mA \frac{50}{51} \right) + 5V(2.55mA) = 25.3 \text{ mW}$$

$$\text{For } v_O = -3.7V, I_E = \frac{-3.7 - (-5)}{1300} - \frac{3.7}{5000} = 260 \mu A.$$

$$\text{At the Q-point, } I_E = \frac{-0.7 - (-5)}{1300} - \frac{0.7}{5000} = 3.17 \text{ mA}$$

The transistor's power dissipation is

$$P = V_{CB}I_C + V_{BE}I_E = 5V \left(3.17mA \frac{50}{51} \right) + 0.7V(3.17mA) = 17.8 \text{ mW}$$

$$(a) -4V = -5.2V \frac{10k\Omega}{10k\Omega + R_E} \rightarrow R_E = 3.00 k\Omega$$

$$(b) I_E = \frac{5.2V}{3k\Omega} = 1.73 \text{ mA} \quad | \quad I_E = \frac{-4 - (-5.2)}{3000} - \frac{4}{10000} = 0 \quad | \quad I_E = \frac{4 - (-5.2)}{3000} + \frac{4}{10000} = 3.47 \text{ mA}$$

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Increase the value of each resistor by a factor of 10.

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$$R_C = \frac{\Delta V}{I_{EE}} = \frac{0.6V}{0.5mA} = 1.2 \text{ k}\Omega \quad | \quad \tau_P = 0.69(1.2k\Omega)(2pF) = 1.66 \text{ ns}$$

$$P = 5.2V(0.5 + 0.1 + 0.1)mA = 3.64 \text{ mW} \quad | \quad PDP = 6.0 \text{ pJ}$$

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$$R_{C2} = R_{C1} = \frac{0 - V_L}{I_{EE}} = \frac{0.4V}{0.5mA} = 800 \Omega \quad | \quad P = I_{EE}V_{EE} = 0.5mA(2.8V) = 1.40 mW$$

$$PDP = 1.4mW(50ps) = 70 fJ$$

$$I_{EF} = \frac{I_{EE}}{2} = 250 \mu A \quad | \quad P = I_{EE}V_{EE} = 0.25mA(2.8V) = 0.70 mW$$

$$V_H = 0 \quad | \quad V_L = -0.2 V \quad | \quad V_{Bias} = 0.1 V \quad | \quad V_{BH} = -0.7 \quad | \quad V_{BL} = -0.9 V \quad | \quad V_{BiasB} = -0.8 V$$

$$V_{AH} = -1.4 \quad | \quad V_{AL} = -1.6 V \quad | \quad V_{BiasA} = -1.5 V$$

$$-V_{EE} = V_{AH} - 0.7V - 0.7V = -1.4 - 0.7 - 0.7 = -2.8 V \quad | \quad V_{EE} = 2.8 V$$

$$V_H = 0 V, \quad V_L = -0.4 V, \quad : \text{ The C-level bias is } V_{BiasC} = \frac{V_H + V_L}{2} = -0.2 V$$

Using the level shifter in Fig. 9.27,

$$V_{BH} = -0.7 \quad | \quad V_{BL} = -1.1 V \quad | \quad V_{BiasB} = -0.9 V$$

$$V_{AH} = -1.4 \quad | \quad V_{AL} = -1.8 V \quad | \quad V_{BiasA} = -1.6 V$$

$$-V_{EE} = V_{emitterA} - 0.7V = -0.7 = -2.8 V \quad | \quad V_{EE} = 2.8 V$$

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$$\text{For } v_O = V_H, \quad I_C = 0, \quad \text{and } P = 0. \quad P = V_{DD}I_{DD} = 5V(2.43mA) = 12.1 mA$$

$$\text{Increase R by a factor of 10: } R = 10(2k\Omega) = 20k\Omega.$$

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$$\Gamma = \exp\left(\frac{0.1}{0.0258}\right) = 48.2 \quad | \quad I_B \geq \frac{10A}{20} \left[\frac{1 + \frac{20}{0.1(48.2)}}{1 - \frac{11}{48.2}} \right] = 3.34 A \quad | \quad \beta_{FOR} = \frac{10A}{3.34A} = 3.00$$

$$\alpha_R = \frac{0.2}{0.2+1} = \frac{1}{6} \quad | \quad I_B \geq \frac{10A}{20} \left[\frac{1 + \frac{20}{0.2(54.6)}}{1 - \frac{6}{54.6}} \right] = 1.59 A$$

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$$\Gamma = \exp\left(\frac{0.15}{0.025}\right) = 403 \quad | \quad I_B \geq \frac{10A}{20} \left[\frac{1 + \frac{20}{0.1(403)}}{1 - \frac{11}{403}} \right] = 0.769 A$$

$$V_T = \frac{1.38 \times 10^{-23} (273 + 150)}{1.60 \times 10^{-19}} = 36.5 \text{ mV} \quad | \quad V_{CEMIN} = 36.5 \text{ mV} \ln\left(\frac{0.05 + 1}{0.05}\right) = 111 \text{ mV}$$

$$\Gamma = \exp\left(\frac{0.1}{0.025}\right) = 54.6 \quad | \quad \alpha_R = \frac{0.25}{1 + 0.25} = \frac{1}{5}$$

$$I_B \geq \frac{10mA}{40} \left[\frac{1 + \frac{40}{0.25(54.6)}}{1 - \frac{5}{54.6}} \right] = 1.08 \text{ mA} \quad | \quad \beta_{FOR} = \frac{10mA}{1.08mA} = 9.24$$

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$$1ns = 6.4ns \ln \left(\frac{1mA - I_{BR}}{\frac{2.5mA}{40.7} - I_{BR}} \right) \quad | \quad 1.169 = \frac{1mA - I_{BR}}{0.0614mA - I_{BR}} \rightarrow I_{BR} = -5.49 \text{ mA}$$

$$i_{CMAX} = \frac{V_{CC} - V_{CE}}{\beta_F} \cong \frac{5-0}{2500} = 2.5mA \quad | \quad Q_{XS} = 6.4ns \left(1mA - \frac{2.5mA}{40.7} \right) = 6.01 \text{ pC}$$

$$Q_F = i_F \tau_F = 2.5mA(0.25ns) = 0.625 \text{ pC} \quad | \quad Q_{XS} >> Q_F$$

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$$\text{For } v_I = V_L = 0.15 \text{ V:} \quad i_{IL} = -\frac{5-0.95}{4000} = -1.01 \text{ mA} \quad | \quad V_{BE2} = V_L + V_{CESAT1}$$

Using the value of V_{CESAT} in Fig. 9.32, $V_{BE2} = 0.15 + 0.04 = 0.19 \text{ V}$

$$\text{A better estimate is } V_{CESAT1} = 25mV \ln \left(\frac{2+1}{2} \right) = 10.1 \text{ mV}$$

$$V_{BE2} = 0.15 + 0.010 = 0.16 \text{ V}$$

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$$\text{For } v_I = V_H = 5 \text{ V:} \quad i_{IH} = 2 \frac{5-1.5}{4000} = 1.75 \text{ mA} \quad | \quad V_{BE2} = 0.8 \text{ V}$$

$$\text{Using Eq. (5.29), } V_{BESAT} = 0.025V \ln \frac{0.875mA + \left(1 - \frac{2}{3} \right)(2.4mA)}{10^{-15}A \left[\frac{1}{40} + \left(1 - \frac{2}{3} \right) \right]} = 0.729 \text{ V}$$

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$$5V - N(2k\Omega)\beta_R I_B \geq 1.5V \quad | \quad I_B = \frac{5-1.5}{4000} = 0.875mA$$

$$\beta_R \leq \frac{3.5V}{5(2k\Omega)(0.875mA)} = 0.4 \quad | \quad \beta_R \leq \frac{3.5V}{10(2k\Omega)(0.875mA)} = 0.2$$

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$$I_{B2} = (2+1) \frac{5-1.5}{4000} = 2.63 \text{ mA} \quad | \quad 2.43mA + N(1.01mA) \leq 28.3(2.63mA) \rightarrow N \leq 71$$

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$$v_I = V_L \text{ and } v_O = 0 : I_{B4} = \frac{5 - V_{B4}}{1600} = \frac{5 - (0 + 0.7 + 0.7)}{1600} = 2.25 \text{ mA} \quad | \quad I_L = 41I_{B4} = 92.3 \text{ mA}$$

$$5 - 1600 \frac{I_L}{41} - 0.7 - 0.7 \geq 3 \rightarrow I_L \leq 15.4 \text{ mA}$$

$$I_{B4} = \frac{5 - (3 + 0.7 + 0.7)}{1600} = 0.375 \text{ mA} \quad | \quad I_L = 41I_{B4} = 15.4 \text{ mA}$$

$$V_{CE} = 5 - 130\Omega I_C - V_O = 5V - 130\Omega(15.4 \text{ mA}) - 3.7 = -0.702 \text{ V}$$

Oops! - the transistor is not in the forward - active region. Assume saturation with $V_{CESAT} = 0.15V$.

$$I_L = I_B + I_C = \frac{5 - (0.8 + 0.7 + 3.0)}{1600} + \frac{5 - (0.15 + 0.7 + 3)}{130} = 9.16 \text{ mA}$$

Page 513

(a) BiCMOS NAND gate : Replace the CMOS NOR - gate with a two - input CMOS

NAND - gate, and connect its output to the bases of Q_3 and Q_4 .

(b) BiNMOS NAND gate : Replace the input CMOS NOR - gate with a two - input CMOS

NAND - gate, and connect M_6 and M_7 in series instead of parallel.

Microelectronic Circuit Design

Fourth Edition - Part III

Solutions to Exercises

Updated - 09/25/10

CHAPTER 10

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$$(a) A_p = |A_v| A_i = 4 \times 10^4 (2.75 \times 10^8) = 1.10 \times 10^{13}$$

$$(b) V_o = \sqrt{2P_o R_L} = \sqrt{2(20W)(16\Omega)} = 25.3 \text{ V} \quad | \quad A_v = \frac{V_o}{V_i} = \frac{25.3V}{0.005V} = 5.06 \times 10^3$$

$$I_o = \frac{V_o}{R_L} = \frac{25.3V}{16\Omega} = 1.58 \text{ A} \quad | \quad I_i = \frac{V_i}{R_s + R_{in}} = \frac{0.005V}{10k\Omega + 20k\Omega} = 0.167\mu\text{A} \quad | \quad A_i = \frac{I_o}{I_i} = \frac{1.58A}{0.167\mu\text{A}} = 9.48 \times 10^6$$

$$A_p = \frac{P_o}{P_s} = \frac{25.3V(1.58A)}{0.005V(0.167\mu\text{A})} = 4.79 \times 10^{10} \quad | \quad \text{Checking: } A_p = (5.06 \times 10^3)(9.48 \times 10^6) = 4.80 \times 10^{10}$$

$$A_{v dB} = 20 \log(5060) = 74.1 \text{ dB} \quad | \quad A_{i dB} = 20 \log(9.48 \times 10^6) = 140 \text{ dB} \quad | \quad A_{P dB} = 10 \log(4.80 \times 10^{10}) = 107 \text{ dB}$$

$$A_{v dB} = 20 \log(4 \times 10^4) = 92.0 \text{ dB} \quad | \quad A_{i dB} = 20 \log(2.75 \times 10^8) = 169 \text{ dB} \quad | \quad A_{P dB} = 10 \log(1.10 \times 10^{13}) = 130 \text{ dB}$$

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$$G_{in} = g_{11} = \frac{1}{20k\Omega + 76(50k\Omega)} = 0.262 \text{ } \mu\text{S} \quad | \quad A = g_{21} = 0.262\mu\text{S}(76)(50k\Omega) = 0.995$$

$$R_{out} = g_{22} = \left[\frac{1}{50k\Omega} + \frac{1}{20k\Omega} + \frac{75}{20k\Omega} \right]^{-1} = 262 \text{ } \Omega \quad | \quad g_{12} = -\frac{g_{22}}{(20k\Omega)} = -\frac{262\Omega}{(20k\Omega)} = -0.0131$$

$$R_{in} = \frac{1}{g_{11}} = 3.82 \text{ } M\Omega \quad | \quad A = g_{21} = 0.995 \quad | \quad R_{out} = \frac{1}{g_{22}} = 262 \text{ } \Omega$$

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(a) The constant slope region spanning a maximum input range is between $-0.5 \text{ V} \leq v_{ID} \leq 1.5 \text{ V}$,

and the bias voltage V_{ID} should be centered in this range: $V_{ID} = \frac{1.5 + (-0.5)}{2}V = +0.5 \text{ V}$.

$$v_{ID} = V_{ID} + v_{id} \quad | \quad -0.5\text{V} \leq 0.5V + v_{id} \rightarrow v_{id} \geq -1 \text{ V} \quad \text{and} \quad 0.5V + v_{id} \leq 1.5 \rightarrow v_{id} \leq +1 \text{ V}$$

$$\therefore -1 \text{ V} \leq v_{id} \leq +1 \text{ V} \quad \text{or} \quad |v_{id}| \leq 1 \text{ V} \quad \text{and} \quad |v_o| \leq 10 \text{ V}$$

(b) For $V_{ID} = -1 \text{ V}$, the slope of the voltage transfer characteristics is zero, so $A = 0$.

$$v_o = 10(v_{ID} - 0.5V) = 10(-0.5 + 0.25 + 0.75\sin 1000\pi t) = (-2.5 + 7.5\sin 1000\pi t) \text{ V} \quad | \quad V_o = -2.5 \text{ V}$$

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$$v_{id} = \frac{10V}{100} = 0.100V = 100 \text{ mV} \quad | \quad v_{id} = \frac{10V}{10^4} = 0.001 \text{ V} = 1.00 \text{ mV}$$

$$v_{id} = \frac{10V}{10^6} = 1.00 \times 10^{-5}V = 10.0 \text{ } \mu\text{V}$$

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$$A_v = -\frac{360k\Omega}{68k\Omega} = -5.29 \quad | \quad v_o = -5.29(0.5V) = -2.65 \text{ V}$$

$$i_i = \frac{0.5V}{68k\Omega} = 7.35 \text{ } \mu\text{A} \quad | \quad i_o = -i_2 = -i_i = -7.35 \text{ } \mu\text{A}$$

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$$I_I = \frac{2V}{4.7k\Omega} = 426 \text{ } \mu\text{A} \quad | \quad I_2 = I_I = 426 \text{ } \mu\text{A} \quad | \quad I_O = -I_2 = -426 \text{ } \mu\text{A}$$

$$A_v = -\frac{24k\Omega}{4.7k\Omega} = -5.11 \quad | \quad V_o = -5.11(2V) = -10.2 \text{ V}$$

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$$A_{tr} = -R_2 = -\frac{5V}{25\mu\text{A}} = -0.2 \text{ M}\Omega \quad | \quad R_2 = 200 \text{ k}\Omega$$

$$v_o = -R_2 i_i = -2 \times 10^5 (5 \times 10^{-5} \sin 2000\pi t) = -10 \sin 2000\pi t \text{ V}$$

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$$A_v = 1 + \frac{36k\Omega}{2k\Omega} = +19.0 \quad | \quad v_o = 19.0(-0.2V) = -3.80 V \quad | \quad i_o = \frac{-3.80V}{36k\Omega + 2k\Omega} = -100 \mu A$$

$$A_v = 1 + \frac{39k\Omega}{1k\Omega} = +40.0 \quad | \quad A_{v dB} = 20 \log(40.0) = 32.0 \text{ dB} \quad | \quad R_{in} = 100k\Omega \parallel \infty = 100k\Omega$$

$$v_o = 40.0(0.25V) = 10.0 V \quad | \quad i_o = \frac{10.0V}{39k\Omega + 1k\Omega} = 0.250 mA$$

$$A_v = 10^{\frac{54}{20}} = 501 \quad 1 + \frac{R_2}{R_l} = 501 \quad \frac{R_2}{R_l} = 500 \quad i_o = \frac{v_o}{R_2 + R_l} \quad \frac{10}{R_2 + R_l} \leq 0.1 mA$$

$R_1 + R_2 \geq 100k\Omega$ $501R_l \geq 100k\Omega \rightarrow R_l \geq 200 \Omega$ There are many possibilities.
 $(R_l = 200 \Omega, R_2 = 100 k\Omega)$, but $(R_l = 220 \Omega, R_2 = 110 k\Omega)$ is a better solution since resistor tolerances could cause i_o to exceed 0.1 mA in the first case.

Page 563

$$\text{Inverting Amplifier: } A_v = -\frac{30k\Omega}{1.5k\Omega} = -20.0 \quad | \quad R_{in} = R_l = 1.5 \text{ k}\Omega$$

$$v_o = -20.0(0.15V) = -3.00 V \quad | \quad i_o = \frac{v_o}{R_2} = \frac{-3.00V}{30k\Omega} = -100 \mu A$$

$$\text{Non-Inverting Amplifier: } A_v = 1 + \frac{30k\Omega}{1.5k\Omega} = +21.0 \quad | \quad R_{in} = \frac{v_i}{i_i} = \frac{0.15V}{0A} = \infty$$

$$v_o = 21.0(0.15V) = 3.15 V \quad | \quad i_o = \frac{v_o}{R_2 + R_l} = \frac{3.15V}{30k\Omega + 1.5k\Omega} = 100 \mu A$$

Add resistor R_3 in parallel with the op amp input as in the schematic on page 560 with $R_3 = 2 k\Omega$.

Page 564

$$V_{o1} = 2V \left(-\frac{3k\Omega}{1k\Omega} \right) = -6V \quad | \quad V_{o2} = 4V \left(-\frac{3k\Omega}{2k\Omega} \right) = -6V \quad | \quad v_o = (-6 \sin 1000\pi t - 6 \sin 2000\pi t) V$$

$$\text{The summing junction is a virtual ground: } R_{in1} = \frac{v_1}{i_1} = R_l = 1 k\Omega \quad | \quad R_{in2} = \frac{v_2}{i_2} = R_2 = 2 k\Omega$$

$$I_{o1} = \frac{V_{o1}}{R_3} = \frac{-6V}{3k\Omega} = -2mA \quad | \quad I_{o2} = \frac{V_{o2}}{R_3} = \frac{-6V}{3k\Omega} = -2mA \quad | \quad i_o = (-2 \sin 1000\pi t - 2 \sin 2000\pi t) mA$$

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$$\text{Since } i_+ = 0, I_2 = \frac{3V}{10k\Omega + 100k\Omega} = 27.3 \mu A$$

$$A_v = -\frac{100k\Omega}{10k\Omega} = -10.0 \quad | \quad V_o = -10(3V - 5V) = +20.0 V \quad | \quad I_o = \frac{V_o - V_-}{100k\Omega} = \frac{V_o - V_+}{100k\Omega}$$

$$V_+ = V_2 \frac{R_4}{R_3 + R_4} = 5 \frac{100k\Omega}{10k\Omega + 100k\Omega} = 4.545V$$

$$I_o = \frac{20.0 - 4.545}{100k\Omega} = +155 \mu A \quad | \quad I_2 = \frac{5V}{10k\Omega + 100k\Omega} = 45.5 \mu A$$

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$$A_v = -\frac{36k\Omega}{2k\Omega} = -18.0 \quad | \quad V_o = -18(8V - 8.25V) = 4.50 V \quad | \quad I_o = \frac{V_o - V_-}{36k\Omega} = \frac{V_o - V_+}{36k\Omega}$$

$$V_+ = V_2 \frac{R_2}{R_1 + R_2} = 8.25 \frac{36k\Omega}{2k\Omega + 36k\Omega} = 7.816 V \quad | \quad I_o = \frac{4.50 - 7.816}{36k\Omega} = -92.1 \mu A$$

Page 570

$$A_v(s) = -\frac{2\pi s \cdot 10^6}{s + 5000\pi} = \frac{-400}{1 + \frac{s}{5000\pi}} \rightarrow A_{mid} = -400 \quad | \quad f_H = \frac{5000\pi}{2\pi} = 2.50 kHz$$

$$BW = f_H - f_L = 2.50 kHz - 0 = 2.50 kHz \quad | \quad GBW = (400)(2.50 kHz) = 1.00 MHz$$

Page 572

$$f_H = \frac{1}{2\pi} \frac{1}{(1k\Omega \parallel 100k\Omega)(200pF)} = 804 kHz$$

Page 573

$$A_v(s) = \frac{250}{1 + \frac{250\pi}{s}} \quad | \quad A_o = 250 \quad | \quad f_L = \frac{250\pi}{2\pi} = 125 Hz \quad | \quad f_H = \infty \quad | \quad BW = \infty - 125 = \infty$$

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$$f_L = \frac{1}{2\pi} \frac{1}{(1k\Omega \parallel 100k\Omega)(0.1\mu F)} = 15.8 Hz$$

Page 577

$$A_v(j1) = 50 \frac{-1+4}{-1+2+j2} = \frac{150}{1+j2} \quad | \quad |A_v(j1)| = \frac{150}{\sqrt{(1)^2 + (2)^2}} = 67.08$$

$$A_{\text{v dB}} = 20 \log(67.08) = 36.5 \text{ dB} \quad | \quad \angle A_v(j1) = \angle(50) + \angle(3) - \tan^{-1}\left[\frac{2}{1}\right] = 0 + 0 - 63.4^\circ = -63.4^\circ$$

$$A_v(j5) = 50 \frac{-25+4}{-25+2+j10} = \frac{1050}{23-j10} \quad | \quad |A_v(j5)| = \frac{1050}{\sqrt{(-23)^2 + (10)^2}} = 41.87$$

$$A_{\text{v dB}} = 20 \log(41.87) = 32.4 \text{ dB} \quad | \quad \angle A_v(j5) = \angle(1050) + -\tan^{-1}\left[\frac{10}{-23}\right] = 0 - (-23.5^\circ) = +23.5^\circ$$

$$A_v(j\omega) = \frac{20}{1+j\frac{0.1\omega}{1-\omega^2}} \quad | \quad |A_v(j0.95)| = \frac{20}{\sqrt{1^2 + \frac{(0.1)^2(0.95^2)}{(1-0.95^2)^2}}} = 14.3$$

$$\angle A_v(j0.95) = \angle 20 - \tan^{-1}\left[\frac{0.1(0.95)}{1-0.95^2}\right] = 0 - (44.3^\circ) = -44.3^\circ$$

$$|A_v(j1)| = \frac{20}{\sqrt{1^2 + \frac{(0.1)^2(1^2)}{(1-1^2)^2}}} = 0 \quad | \quad \angle A_v(j1) = \angle 20 - \tan^{-1}\left[\frac{0.1(1)}{1-1^2}\right] = 0 - (90^\circ) = -90.0^\circ$$

$$|A_v(j1.1)| = \frac{20}{\sqrt{1^2 + \frac{(0.1)^2(1.1^2)}{(1-1.1^2)^2}}} = 17.7 \quad | \quad \angle A_v(j1.1) = \angle 20 - \tan^{-1}\left[\frac{0.1(1.1)}{1-1.1^2}\right] = 0 - (-27.6^\circ) = +27.6^\circ$$

$$(i) \quad A_v(s) = \frac{-400}{\left(1+\frac{100}{s}\right)\left(1+\frac{s}{50000}\right)} \quad | \quad A_o = 400 \text{ or } 52 \text{ dB}$$

$$f_L = \frac{100}{2\pi} = 15.9 \text{ Hz} \quad | \quad f_H = \frac{50000}{2\pi} = 7.96 \text{ kHz} \quad | \quad BW = 7960 - 15.9 = 7.94 \text{ kHz}$$

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$$A_v(s) = -\frac{2 \times 10^7 s}{(s + 100)(s + 50000)} = \frac{-400}{\left(1 + \frac{100}{s}\right)\left(1 + \frac{s}{50000}\right)}$$

$$\angle A_v(j\omega) = -180 + 90^\circ - \tan^{-1}\left(\frac{\omega}{100}\right) - \tan^{-1}\left(\frac{\omega}{50000}\right) = -90^\circ - \tan^{-1}\left(\frac{100}{100}\right) - \tan^{-1}\left(\frac{100}{50000}\right)$$

$$\angle A_v(j0) = -90 - 0 - 0 = -90^\circ$$

$$\angle A_v(j100) = -90^\circ - \tan^{-1}\left(\frac{100}{100}\right) - \tan^{-1}\left(\frac{100}{50000}\right) = -90 - 45 - 0.57 = -136^\circ$$

$$\angle A_v(j50000) = -90^\circ - \tan^{-1}\left(\frac{50000}{100}\right) - \tan^{-1}\left(\frac{50000}{50000}\right) = -90 - 89.9 - 45 = -225^\circ$$

$$\angle A_v(j\infty) = -90 - 90 - 90 = -270^\circ$$

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$$A_v = -\frac{R_2}{R_1} = -10^{\frac{26}{20}} = -20.0 \quad | \quad R_i = R_m = 10 \text{ k}\Omega$$

$$R_2 = 20R_1 = 200 \text{ k}\Omega \quad | \quad C = \frac{1}{2\pi(3\text{kHz})(200\text{k}\Omega)} = 265 \text{ pF}$$

Closest values: $R_i = 10 \text{ k}\Omega \quad | \quad R_2 = 200 \text{ k}\Omega \quad | \quad C = 270 \text{ pF}$

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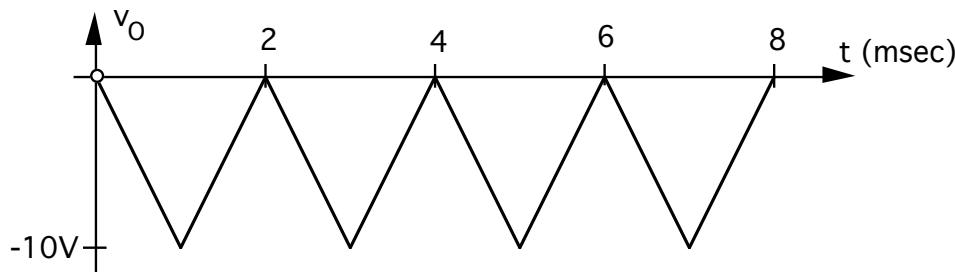
$$A_v = -\frac{R_2}{R_1} = -10^{\frac{20}{20}} = -10.0 \quad | \quad R_i = R_m = 18 \text{ k}\Omega$$

$$R_2 = 10R_1 = 180 \text{ k}\Omega \quad | \quad C = \frac{1}{\omega_L R_1} = \frac{1}{2\pi(5\text{kHz})(18\text{k}\Omega)} = 1.77 \text{ nF} = 1770 \text{ pF}$$

Closest values: $R_i = 10 \text{ k}\Omega \quad | \quad R_2 = 180 \text{ k}\Omega \quad | \quad C = 1800 \text{ pF}$

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$$R_m = R_i = 10 \text{ k}\Omega \quad | \quad \Delta V = -\frac{I}{C} \Delta T \quad | \quad C = \frac{(10V/2)}{10k\Omega} \left(\frac{1}{10V} \right) (1ms) = 0.05 \mu F$$



Page 567

$$v_o = -RC \frac{dv_I}{dt} = -(20k\Omega)(0.02\mu F)(2.50V)(2000\pi)(\cos 2000\pi t) = -6.28 \cos 2000\pi t \text{ V}$$

CHAPTER 11

Page 605

$$A_v^{ideal} = \frac{1}{\beta} = 100 \quad | \quad T = A\beta = \frac{10^5}{100} = 1000 \quad | \quad A_v = A_v^{ideal} \frac{T}{1+T} = 100 \frac{1000}{1001} = 99.90$$

$$v_o = A_v v_i = 99.9(0.1V) = 9.99 V \quad | \quad v_{id} = \frac{v_o}{A} = \frac{9.99V}{10^5} = 99.9 \mu V$$

$$A_v^{ideal} = -\frac{R_2}{R_1} \quad | \quad \frac{1}{\beta} = 1 + \frac{R_2}{R_1} \rightarrow \frac{R_2}{R_1} = 99 \quad | \quad A_v^{ideal} = -99 \quad | \quad T = A\beta = \frac{10^5}{100} = 1000$$

$$A_v = A_v^{ideal} \frac{T}{1+T} = -99 \frac{1000}{1001} = -98.90$$

$$v_o = A_v v_i = -98.9(0.1V) = -9.89 V \quad | \quad v_{id} = \frac{v_o}{A} = \frac{-9.89V}{10^5} = -98.9 \mu V$$

Values taken from OP - 27 specification sheet

(www.jaegerblalock.com or www.analog.com)

Values taken from OP - 27 specification sheet

(www.jaegerblalock.com or www.analog.com)

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$$A_v^{ideal} = \frac{1}{\beta} = 1 + \frac{R_2}{R_1} = 1 + \frac{39k\Omega}{1k\Omega} = +40.0 \quad | \quad T = A\beta = \frac{10^4}{40} = 250 \quad | \quad A_v = A_v^{ideal} \frac{T}{1+T} = 40 \frac{250}{251} = 39.8$$

$$FGE = \frac{1}{1+T} = 0.00398 \text{ or } 0.398 \% \quad | \quad FGE \cong \frac{1}{T} = 0.40 \%$$

$$A_v^{ideal} = -\frac{R_2}{R_1} = -\frac{39k\Omega}{1k\Omega} = -39.0 \quad | \quad \beta = \frac{1}{1 + \frac{R_2}{R_1}} = \frac{1}{40} \quad | \quad T = A\beta = \frac{10^4}{40} = 250 \quad |$$

$$A_v = A_v^{ideal} \frac{T}{1+T} = -39 \frac{250}{251} = -38.8 \quad | \quad FGE = \frac{1}{1+T} = 0.00398 \text{ or } 0.398 \% \quad | \quad FGE \cong \frac{1}{T} = 0.40 \%$$

Page 608Values taken from OP - 77 specification sheet (www.jaegerblalock.com or www.analog.com)**Page 609**

$$1 + T = \frac{R_o}{R_{out}} \rightarrow T = \frac{50\Omega}{0.1\Omega} - 1 = 499 \quad | \quad A = T \left(\frac{1}{\beta} \right) = 499(40) = 2.00 \times 10^4$$

$$A_v = A_v^{ideal} \frac{T}{1+T} \quad | \quad A_v^{ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{39k\Omega}{1k\Omega} = +40.0$$

$$T = A\beta = 10^4 \frac{1k\Omega}{0.05k\Omega + 39k\Omega + 1k\Omega} = 249.7 \quad | \quad A_v = A_v^{ideal} \frac{T}{1+T} = 40 \frac{249.7}{250.7} = 39.8$$

$$A_v^{\max} = 1 + \frac{39k\Omega(1.05)}{1k\Omega(0.95)} = 44.1 \quad | \quad GE = 44.2 - 40.0 = 4.20 \quad | \quad FGE = \frac{4.20}{40} = 10.5 \%$$

$$A_v^{\min} = 1 + \frac{39k\Omega(0.95)}{1k\Omega(1.05)} = 36.3 \quad | \quad GE = 36.3 - 40.0 = -3.70 \quad FGE = \frac{-3.70}{40} = -9.3 \%$$

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$$1 + T = \frac{R_o}{R_{out}} \rightarrow T = \frac{200\Omega}{0.1\Omega} - 1 = 1999 \quad | \quad A = T \left(\frac{1}{\beta} \right) = 1999(100) = 2.00 \times 10^5 \text{ or } 106 \text{ dB}$$

Page 612Values taken from op - amp specification sheets (www.jaegerblalock.com or www.analog.com)**Page 613**

$$R_{in} = R_{id}(1 + T) \quad | \quad T = A\beta = 10^4 \left(\frac{10k\Omega}{10k\Omega + 1M\Omega + 390k\Omega} \right) = \frac{10^4}{40.39} = 248 \quad | \quad R_{in} = 1M\Omega [1 + 248] = 249 M\Omega$$

$$i_- = -\frac{v_i}{R_{in}} = -\frac{1V}{249 M\Omega} = -4.02 nA \quad | \quad i_1 = \frac{\beta v_o}{R_1} \quad | \quad v_o = A_v^{Ideal} \frac{T}{1+T} v_i = 40 \frac{248}{249} v_i = 39.8 v_i$$

$$i_1 = \frac{\beta v_o}{R_1} = \frac{39.8}{40.4} \left(\frac{1V}{10k\Omega} \right) = 98.5 \mu A \quad | \quad \text{Yes, } |i_1| >> |i_-|$$

$$\text{If we assume } 1M\Omega >> 10k\Omega, \quad T = A\beta = 10^4 \left(\frac{10k\Omega}{10k\Omega + 390k\Omega} \right) = \frac{10^4}{40} = 250 \quad | \quad R_{in} = 1M\Omega [1 + 250] = 251 M\Omega$$

$$i_- = -\frac{v_i}{R_{in}} = -\frac{1V}{251 M\Omega} = -3.98 nA \quad | \quad i_1 = \frac{\beta v_o}{R_1} \quad | \quad v_o = A_v^{Ideal} \frac{T}{1+T} v_i = 40 \frac{250}{251} v_i = 39.8 v_i$$

$$i_1 = \frac{\beta v_o}{R_1} = \frac{39.8}{40} \left(\frac{1V}{10k\Omega} \right) = 99.5 \mu A \quad | \quad \text{Yes, } |i_1| >> |i_-|$$

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$$R_{in} \cong R_1 + R_{id} \left| \left| \frac{R_2}{1+A} = 1k\Omega + 1M\Omega \right| \right| \frac{100k\Omega}{1+10^5} = 1001 \Omega \quad | \quad R_{in}^{ideal} = R_1 = 1000 \Omega \quad | \quad 1 \Omega \text{ or } 0.1 \%$$

Page 622

$$A_v^{Ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{91k\Omega}{10k\Omega} = 10.1$$

$$R_{in}^D = R_{id} + R_l \parallel (R_2 + R_o) = 25k\Omega + 10k\Omega \parallel (91k\Omega + 1k\Omega) = 34.0 k\Omega$$

$$R_{out}^D = R_o \parallel [R_2 + R_l] \parallel R_{id} = 1k\Omega \parallel [91k\Omega + 10k\Omega] \parallel 25k\Omega = 990 \Omega$$

$$T = A_o \frac{R_l \parallel R_{id}}{R_o + R_2 + R_l \parallel R_{id}} = 10^4 \frac{10k\Omega \parallel 25k\Omega}{1k\Omega + 91k\Omega + 10k\Omega \parallel 25k\Omega} = 720$$

$$A_v = A_v^{Ideal} \frac{T}{1+T} = 10.1 \frac{720}{1+720} = 10.1$$

$$R_{in} = R_{in}^D (1+T) = 34.0k\Omega (1+720) = 24.5 M\Omega$$

$$R_{out} = \frac{R_{out}^D}{1+T} = \frac{990\Omega}{1+720} = 1.37 \Omega$$

$$A_v^{Ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{91k\Omega}{10k\Omega} = 10.1$$

$$R_{in}^D = R_I + R_{id} + R_l \parallel (R_2 + R_o) \parallel R_L = 2k\Omega + 25k\Omega + 10k\Omega \parallel (91k\Omega + 1k\Omega) \parallel 5k\Omega = 36.0 k\Omega$$

$$R_{out}^D = R_L \parallel R_o \parallel [R_2 + R_l] \parallel (R_{id} + R_I) = 5k\Omega \parallel 1k\Omega \parallel [91k\Omega + 10k\Omega] \parallel (25k\Omega + 2k\Omega) = 826 \Omega$$

$$v_{th} = \left(A_o \frac{R_L}{R_o + R_L} v_{id} \right) \frac{R_l}{R_L \parallel R_o + R_2 + R_l} = 10^4 \frac{5k\Omega}{1k\Omega + 5k\Omega} v_{id} \frac{10k\Omega}{1k\Omega \parallel 5k\Omega + 91k\Omega + 10k\Omega} = 818 v_{id}$$

$$R_{th} = R_l \parallel (R_2 + R_L) \parallel R_o = 10k\Omega \parallel (91k\Omega + 1k\Omega) \parallel 5k\Omega = 9.02 k\Omega$$

$$T = - \left(\frac{v_{th}}{v_{id}} \right) \frac{R_{id}}{R_{th} + R_{id} + R_I} = -818 \frac{25k\Omega}{9.02k\Omega + 25k\Omega + 2k\Omega} = -568$$

$$A_v = A_v^{Ideal} \frac{T}{1+T} = 10.1 \frac{568}{1+568} = 10.1$$

$$R_{in} = R_{in}^D (1+T) = 36.0k\Omega (1+568) = 20.5 M\Omega$$

$$R_{out} = \frac{R_{out}^D}{1+T} = \frac{826\Omega}{1+568} = 1.45 \Omega$$

Continued on next page.

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$$A_v^{ideal} = 1 + \frac{R_2}{R_l} = 1 + \frac{91k\Omega}{10k\Omega} = 10.1$$

$$R_{in}^D = R_{id} = 25k\Omega \quad | \quad R_{out}^D = R_o = 1 k\Omega$$

$$T = A_o \frac{R_l}{R_l + R_2} = 10^4 \frac{10k\Omega}{10k\Omega + 91k\Omega} = 990$$

$$A_v = A_v^{ideal} \frac{T}{1+T} = 10.1 \frac{990}{1+990} = 10.1$$

$$R_{in} = R_{in}^D(1+T) = 25.0k\Omega(1+990) = 24.8 M\Omega$$

$$R_{out} = \frac{R_{out}^D}{1+T} = \frac{1k\Omega}{1+990} = 1.01 \Omega$$

$$A_v^{ideal} = 1 + \frac{R_2}{R_l} = 1 + \frac{91k\Omega}{10k\Omega} = 10.1$$

$$R_{in}^D = R_I + R_{id} + R_l \parallel (R_2 + R_o) = 5k\Omega + 25k\Omega + 10k\Omega \parallel (91k\Omega + 1k\Omega) = 39.0 k\Omega$$

$$R_{out}^D = R_o \parallel [R_2 + R_l \parallel (R_{id} + R_I)] = 1k\Omega \parallel [91k\Omega + 10k\Omega \parallel (25k\Omega + 5k\Omega)] = 990 \Omega$$

$$v_{th} = A_o v_{id} \frac{R_l}{R_o + R_2 + R_l} = 10^4 v_{id} \frac{10k\Omega}{1k\Omega + 91k\Omega + 10k\Omega} = 980 v_{id}$$

$$R_{th} = R_l \parallel (R_2 + R_o) = 10k\Omega \parallel (91k\Omega + 1k\Omega) = 9.02 k\Omega$$

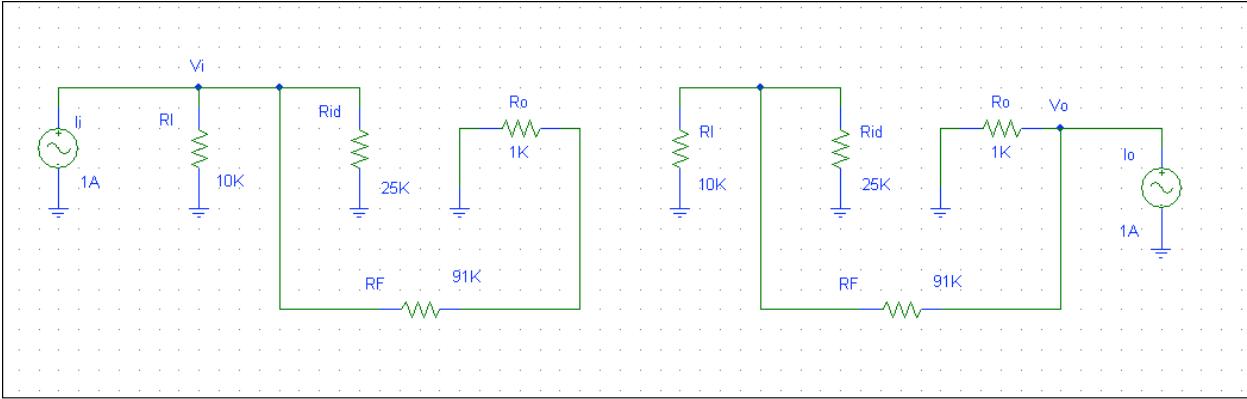
$$T = \frac{v_{th}}{v_{id}} \frac{R_{id}}{R_{th} + R_{id} + R_I} = 980 \frac{25k\Omega}{9.02k\Omega + 25k\Omega + 5k\Omega} = 628$$

$$A_v = A_v^{ideal} \frac{T}{1+T} = 10.1 \frac{628}{1+628} = 10.1$$

$$R_{in} = R_{in}^D(1+T) = 39.0k\Omega(1+628) = 24.5 M\Omega$$

$$R_{out} = \frac{R_{out}^D}{1+T} = \frac{990\Omega}{1+628} = 1.57 \Omega$$

Page 626



$$R_{in}^D = \frac{V_i}{I_i} = R_I \| R_{id} \| (R_F + R_o) \quad | \quad R_{out}^D = \frac{V_o}{I_o} = R_o \| (R_F + R_{id}) \| R_I$$

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$$A_{tr}^{Ideal} = -R_F = -91k\Omega$$

$$R_{in}^D = R_I \| (R_F + R_o) = 10k\Omega \| (91k\Omega + 1k\Omega) = 9.02 k\Omega$$

$$R_{out}^D = R_o \| (R_F + R_I) = 1k\Omega \| (91k\Omega + 10k\Omega) = 990 \Omega$$

$$T = A_o \frac{R_I}{R_o + R_F + R_I} = 10^4 \frac{10k\Omega}{1k\Omega + 91k\Omega + 10k\Omega} = 980$$

$$A_{tr} = A_{tr}^{Ideal} \frac{T}{1+T} = -91k\Omega \frac{980}{1+980} = -90.9 k\Omega$$

$$R_{in} = \frac{R_{in}^D}{1+T} = \frac{9.02k\Omega}{1+980} = 9.19 \Omega \quad R_{out} = \frac{R_{out}^D}{1+T} = \frac{990\Omega}{1+980} = 1.01 \Omega$$

$$A_{tr}^{Ideal} = -R_F = -91k\Omega$$

$$R_{in}^D = R_{id} \| (R_F + R_o) = 25k\Omega \| (91k\Omega + 1k\Omega) = 19.7 k\Omega$$

$$R_{out}^D = R_o \| (R_F + R_{id}) = 1k\Omega \| (91k\Omega + 25k\Omega) = 991 \Omega$$

$$T = A_o \frac{R_{id}}{R_o + R_F + R_{id}} = 10^4 \frac{25k\Omega}{1k\Omega + 91k\Omega + 25k\Omega} = 2137$$

$$A_{tr} = A_{tr}^{Ideal} \frac{T}{1+T} = -91k\Omega \frac{2137}{1+2137} = -91.0 k\Omega$$

$$R_{in} = \frac{R_{in}^D}{1+T} = \frac{19.7k\Omega}{1+2137} = 9.21 \Omega \quad R_{out} = \frac{R_{out}^D}{1+T} = \frac{991\Omega}{1+2137} = 0.464 \Omega$$

Page 633

$$A_{ic}^{ideal} = -\frac{1}{R} = -\frac{1}{10k\Omega} = -10^{-4} S$$

$$R_{in}^D = R_{id} + R \parallel R_o = 25k\Omega + 10k\Omega \parallel 1k\Omega = 25.9 k\Omega$$

$$R_{out}^D = R_o + R \parallel R_{id} = 1k\Omega + 10k\Omega \parallel 25k\Omega = 8.14 k\Omega$$

$$T = -\left(\frac{v_{th}}{v_{id}}\right) \frac{R_{id}}{R_{th} + R_{id}} = 9090 \frac{25k\Omega}{0.909k\Omega + 25k\Omega} = 8770$$

$$A_{ic} = -\frac{1}{R} \left(\frac{T}{1+T} \right) = -\frac{1}{10k\Omega} \left(\frac{8770}{1+8770} \right) = -0.100 mS$$

$$R_{in} = R_{in}^D (1+T) = 25.9k\Omega (1+8770) = 227 M\Omega$$

$$R_{out} = R_{out}^D (1+T) = 8.14k\Omega (1+8770) = 71.4 M\Omega$$

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$$A_i^{ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{27k\Omega}{3k\Omega} = +10$$

$$R_{in}^D = R_{id} \parallel (R_2 + R_1 \parallel R_o) = 25k\Omega \parallel (27k\Omega + 3k\Omega \parallel 1k\Omega) = 13.2 k\Omega$$

$$R_{out}^D = R_o + R_1 \parallel (R_2 + R_{id}) = 1k\Omega + 3k\Omega \parallel (27k\Omega + 25k\Omega) = 3.84 k\Omega$$

$$T = A_o \frac{\left[R_1 \parallel (R_2 + R_{id}) \right]}{R_1 \parallel (R_2 + R_{id}) + R_o} \left(\frac{R_{id}}{R_2 + R_{id}} \right)$$

$$T = 10^4 \frac{3k\Omega \parallel (27k\Omega + 25k\Omega)}{1k\Omega + 3k\Omega \parallel (27k\Omega + 25k\Omega)} \left(\frac{25k\Omega}{27k\Omega + 25k\Omega} \right) = 3555$$

$$A_i = +10 \left(\frac{T}{1+T} \right) = +10 \left(\frac{3555}{1+3555} \right) = +10.0$$

$$R_{in} = \frac{R_{in}^D}{(1+T)} = \frac{13.2k\Omega}{1+3555} = 3.71 \Omega$$

$$R_{out} = R_{out}^D (1+T) = 3.84k\Omega (1+3555) = 13.7 M\Omega$$

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$$R'_{id} = R_i \parallel R_{id} = 10k\Omega \parallel 25k\Omega = 7.14 k\Omega$$

$$A_i^{ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{270k\Omega}{30k\Omega} = +10$$

$$R_{in}^D = R'_{id} \parallel (R_2 + R_1 \parallel R_o) = 7.14k\Omega \parallel (270k\Omega + 30k\Omega \parallel 1k\Omega) = 6.96 k\Omega$$

$$R_{out}^D = R_o + R_1 \parallel (R_2 + R'_{id}) = 1k\Omega + 30k\Omega \parallel (270k\Omega + 7.14k\Omega) = 28.1 k\Omega$$

$$T = A_o \frac{\left[R_1 \parallel (R_2 + R'_{id}) \right]}{R_1 \parallel (R_2 + R'_{id}) + R_o} \left(\frac{R'_{id}}{R_2 + R'_{id}} \right)$$

$$T = 10^4 \frac{30k\Omega \parallel (270k\Omega + 7.14k\Omega)}{30k\Omega \parallel (270k\Omega + 7.14k\Omega) + 1k\Omega} \left(\frac{7.14 k\Omega}{270k\Omega + 7.14k\Omega} \right) = 248.5$$

$$A_i = +10 \left(\frac{T}{1+T} \right) = +10 \left(\frac{248.5}{1+248.5} \right) = +9.96$$

$$R_{in} = \frac{R_{in}^D}{(1+T)} = \frac{6.96k\Omega}{1+248.5} = 27.9 \Omega$$

$$R_{out} = R_{out}^D (1+T) = 28.1k\Omega (1+248.5) = 7.01 M\Omega$$

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Values taken from op - amp specification sheets (www.jaegerblalock.com or www.analog.com)

$$|V_O| \leq 50(0.002V) \rightarrow -0.100 V \leq V_O \leq +0.100 V$$

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Values taken from op - amp specification sheets (via www.jaegerblalock.com or www.analog.com)

$$R = 39k\Omega \parallel 1k\Omega = 975 \Omega$$

$R = 1 k\Omega$ is the closest 5% value, or one could use $39 k\Omega$ and $1 k\Omega$ resistors in parallel.

$$v_o(t) = V_{OS} + \frac{V_{OS}}{RC}t + \frac{I_{B2}}{C}t \quad | \quad 1.5mV + \frac{1.5mV}{10k\Omega(100pF)}t + \frac{100nA}{100pF}t = 15V \rightarrow t = 6.00 ms$$

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Values taken from op - amp specification sheets (via www.jaegerblalock.com or www.analog.com)

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Values taken from op - amp specification sheets (via www.jaegerblalock.com or www.analog.com)

$$R_{EQ} = R_L \left| (R_2 + R_1) \geq \frac{20V}{5mA} = 4k\Omega \quad R_1 + R_2 \geq \left(\frac{1}{4k\Omega} - \frac{1}{5k\Omega} \right)^{-1} = 20k\Omega \right.$$

Including 5% tolerances, $R_1 + R_2 \geq 21k\Omega \quad A_v = 10 \rightarrow R_2 = 9R_1$

A few possibilities : 27 k Ω and 3 k Ω , 270 k Ω and 30 k Ω , 180 k Ω and 20 k Ω , etc.

Page 653

$$v_o = A \left(v_{id} + \frac{v_{ic}}{CMRR} \right)$$

$$v_o^{\min} = A \left(v_{id} + \frac{v_{ic}}{CMRR} \right) = 2500 \left(0.002 - \frac{5.000}{10^4} \right) = 3.750 \text{ V}$$

$$v_o^{\max} = A \left(v_{id} + \frac{v_{ic}}{CMRR} \right) = 2500 \left(0.002 + \frac{5.000}{10^4} \right) = 6.250 \text{ V} \quad | \quad 3.750 \text{ V} \leq v_o \leq 6.250 \text{ V}$$

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$$A_v = \frac{A \left(1 + \frac{1}{2CMRR} \right)}{1 + A \left(1 - \frac{1}{2CMRR} \right)} = \frac{10^4 \left(1 + \frac{1}{2 \times 10^4} \right)}{1 + 10^4 \left(1 - \frac{1}{2 \times 10^4} \right)} = 1.000 \quad A_v = \frac{10^3 \left(1 + \frac{1}{2 \times 10^3} \right)}{1 + 10^3 \left(1 - \frac{1}{2 \times 10^3} \right)} = 1.000$$

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$$GE = FGE (A_v) \leq 5 \times 10^{-5} (1) = 5 \times 10^{-5} \quad \text{Worst case occurs for negative CMRR : } GE \cong \frac{1}{A} + \frac{1}{CMRR}$$

If both terms make equal contributions : $A = CMRR = \frac{1}{2.5 \times 10^{-5}} = 4 \times 10^4$ or 92 dB

For other cases : $CMRR = \left(5 \times 10^{-5} - \frac{1}{A} \right)^{-1}$ or $A = \left(5 \times 10^{-5} - \frac{1}{CMRR} \right)^{-1}$

$$A = 100 \text{ dB} \quad CMRR = \left(5 \times 10^{-5} - \frac{1}{10^5} \right)^{-1} = 2.5 \times 10^4 \text{ or } 88 \text{ dB}$$

$$CMRR = 100 \text{ dB} \quad A = \left(5 \times 10^{-5} - \frac{1}{10^5} \right)^{-1} = 2.5 \times 10^4 \text{ or } 88 \text{ dB}$$

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Values taken from op - amp specification sheets (via www.jaegerblalock.com or www.analog.com)

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$$A_o = 10^{\frac{100}{20}} = 10^5 \quad | \quad \omega_B = \frac{\omega_T}{A_o} = \frac{2\pi(5 \times 10^6)}{10^5} = \frac{10^7 \pi}{10^5} = 100\pi \quad | \quad f_B = \frac{100\pi}{2\pi} = 50 \text{ Hz}$$

$$A(s) = \frac{\omega_T}{s + \omega_B} = \frac{10^7 \pi}{s + 100\pi}$$

$$A_v(s) = \frac{\omega_T}{s + \frac{\omega_T}{A_o}} = \frac{2\pi x 10^6}{s + \frac{2\pi x 10^6}{2 \times 10^5}} = \frac{2\pi x 10^6}{s + 10\pi}$$

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$$A_o = 10^{\frac{90}{20}} = 31600 \quad | \quad f_B = \frac{f_T}{A_o} = \frac{5 \times 10^6}{31600} = 158 \text{ Hz} \quad | \quad f_H \cong \beta f_T = 0.01(5 \text{ MHz}) = 50 \text{ kHz}$$

$$A(s) = \frac{\omega_T}{s + \omega_B} = \frac{2\pi(5 \times 10^6)}{s + 2\pi(158)} = \frac{10^7 \pi}{s + 316\pi} \quad | \quad A_v(s) = \frac{2\pi(5 \times 10^6)}{s + 2\pi(5 \times 10^4)} = \frac{10^7 \pi}{s + 10^5 \pi}$$

$$A\beta = \frac{\omega_T}{s + \omega_B} \beta \quad | \quad \text{For } \omega_H \gg \omega_B : A\beta \cong \frac{\beta \omega_T}{j\omega_H} = \frac{1}{j} = -j1 \quad \text{since } \omega_H = \beta \omega_T$$

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$$A_o = 10^{\frac{90}{20}} = 31600 \quad | \quad f_B = \frac{f_T}{A_o} = \frac{5 \times 10^6}{31600} = 158 \text{ Hz} \quad | \quad f_H \cong \beta f_T = \frac{5 \text{ MHz}}{1 + 10^{\frac{50}{20}}} = 15.8 \text{ kHz}$$

$$A(s) = \frac{2\pi(5 \times 10^6)}{s + 2\pi(158)} = \frac{10^7 \pi}{s + 316\pi} \quad | \quad A_v(s) = \frac{2\pi(5 \times 10^6)}{s + 2\pi(15.8 \times 10^3)} = \frac{10^7 \pi}{s + 3.16 \times 10^4 \pi}$$

$$f_H \cong \beta f_T = \frac{1}{2}(10 \text{ MHz}) = 5 \text{ MHz} \quad | \quad f_H \cong \beta f_T = \frac{1}{2}(10 \text{ MHz}) = 5 \text{ MHz}$$

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$$A_o = 10^{\frac{100}{20}} = 10^5 \quad | \quad f_B = \frac{f_T}{A_o} = \frac{10 \times 10^6}{10^5} = 100 \text{ Hz} \quad | \quad f_H \cong \beta f_T = \frac{10 \text{ MHz}}{10^{\frac{60}{20}}} = \frac{10 \text{ MHz}}{1000} = 10 \text{ kHz}$$

$$A(s) = \frac{\omega_T}{s + \omega_B} = \frac{2\pi(10^7)}{s + 2\pi(100)} = \frac{2\pi x 10^7}{s + 200\pi} \quad | \quad A_v(s) = \frac{2\pi(10^7)}{s + 2\pi(10^4)} = \frac{2 \times 10^7 \pi}{s + 2 \times 10^4 \pi}$$

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$$V_M \leq \frac{SR}{\omega} = \frac{5 \times 10^5 V/s}{2\pi(20 kHz)} = 3.98 V \quad | \quad f_M = \frac{SR}{2\pi V_{FS}} = \frac{5 \times 10^5 V/s}{2\pi(10V)} = 7.96 kHz$$

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Values taken from op-amp specification sheets (via www.jaegerblalock.com or www.analog.com)

$$A_o = 1.8 \times 10^6 \quad | \quad f_T = 8 MHz \quad | \quad \omega_B = \frac{\omega_T}{A_o} = \frac{2\pi(8 MHz)}{1.8 \times 10^6} = 8.89\pi \quad | \quad RC = \frac{1}{\omega_B} = \frac{1}{8.89\pi} s$$

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$$0.01 = \exp\left(-\frac{\pi\xi}{\sqrt{1-\xi^2}}\right) \quad | \quad \text{Let } \kappa = \left(\frac{\ln 100}{\pi}\right)^2 \quad | \quad \xi = \sqrt{\frac{\kappa}{1+\kappa}} = 0.826$$

$$\phi_M = \tan^{-1} \frac{2\xi}{\left(\sqrt{4\xi^4 + 1} - 2\xi^2\right)^{0.5}} = 70.9^\circ$$

$$\cos(45^\circ) = \sqrt{4\xi^4 + 1} - 2\xi^2 \rightarrow \xi = 0.420 \quad | \quad \text{Overshoot} = 100\% \exp\left(-\frac{\pi\xi}{\sqrt{1-\xi^2}}\right) = 23.4 \%$$

$$\text{Settling within the 10\% error bars requires } \omega_n t \geq 13. \quad \therefore \omega_n \geq \frac{13}{10^{-5} s} = 1.3 \times 10^6 rad/s$$

$$\omega_n = \sqrt{\omega_B \omega_2 (1 + A_o \beta)} \cong \sqrt{\omega_B \omega_2 A_o \beta} = \sqrt{\beta \omega_T \omega_2} \quad | \quad f_2 = \frac{f_n^2}{\beta f_T} \geq \frac{(1.3 \times 10^6 / 2\pi)^2}{0.1(10^6)} = 428 kHz$$

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$$\angle T(j\omega_1) = -180^\circ \rightarrow 3 \tan^{-1} \frac{\omega_1}{1} = 180 \rightarrow \omega_1 = \sqrt{3}$$

$$|T(j\omega_{180})| = \frac{5}{\left(\sqrt{\omega_1^2 + 1}\right)^3} = \frac{5}{\left(\sqrt{3+1}\right)^3} = \frac{5}{8} \quad | \quad \text{GM} = \frac{8}{5} = 1.60 \text{ or } 4.08 dB$$

Page 682

From the upper graph, the final value of the first step is 5 mV, and the peak of the response is

$$\text{approximately } 4mV + 2mV \left(\frac{9.5mm}{11mm} \right) = 5.7 \text{ mV. Overshoot} = 100\% \frac{5.7mV - 5mV}{5mV} = 14 \%$$

$$0.14 = \exp \left(-\frac{\pi \zeta}{\sqrt{1-\zeta^2}} \right) \quad | \quad \text{Let } \kappa = \left(\frac{-\ln 0.14}{\pi} \right)^2 = 0.3917 \quad | \quad \zeta = \sqrt{\frac{\kappa}{1+\kappa}} = 0.5305$$

$$\phi_M = \tan^{-1} \frac{2\zeta}{\left(\sqrt{4\zeta^4 + 1} - 2\zeta^2 \right)^{0.5}} = 54.2^\circ$$

From the lower graph, the final value of the first step is 5 mV, and the peak of the response is

$$\text{approximately } 5mV + 5mV \left(\frac{10mm}{12mm} \right) = 9.2 \text{ mV. Overshoot} = 100\% \frac{9.2mV - 5mV}{5mV} = 84 \%$$

$$0.84 = \exp \left(-\frac{\pi \zeta}{\sqrt{1-\zeta^2}} \right) \quad | \quad \text{Let } \kappa = \left(\frac{-\ln 0.84}{\pi} \right)^2 = 0.3080 \quad | \quad \zeta = \sqrt{\frac{\kappa}{1+\kappa}} = 0.05541$$

$$\phi_M = \tan^{-1} \frac{2\zeta}{\left(\sqrt{4\zeta^4 + 1} - 2\zeta^2 \right)^{0.5}} = 6.34^\circ$$

The μ A741 curves will be distorted by slew rate limiting.

CHAPTER 12

Page 700

$$A_{vA} = A_{vB} = A_{vC} = -\frac{R_2}{R_1} = -\frac{68k\Omega}{2.7k\Omega} = -25.2 \quad | \quad R_{inA} = R_{inB} = R_{inC} = R_1 = 2.7 \text{ k}\Omega$$

The op-amps are ideal: $R_{outA} = R_{outB} = R_{outC} = 0$

$$A_v = A_{vA} A_{vB} A_{vC} = (-25.2)^3 = -16,000 \quad | \quad R_{in} = R_{inA} = 2.7 \text{ k}\Omega \quad | \quad R_{out} = R_{outC} = 0$$

$$A_v = (-25.2)^3 \left(\frac{2.7k\Omega}{R_{out} + 2.7k\Omega} \right)^2 \geq 0.99 (25.2)^3 \quad | \quad \left(\frac{2.7k\Omega}{R_{out} + 2.7k\Omega} \right)^2 \geq 0.99$$

$$\frac{2.7k\Omega}{R_{out} + 2.7k\Omega} \geq 0.9950 \rightarrow R_{out} \geq 13.6 \text{ }\Omega$$

Page 705

$$A_v(0) = 50(25) = 1250 \quad | \quad |A_v(\omega_H)| = \frac{1250}{\sqrt{2}} = 884$$

$$\left[1 + \frac{\omega_H^2}{(10000\pi)^2} \right] \left[1 + \frac{\omega_H^2}{(20000\pi)^2} \right] = 2 \rightarrow (\omega_H^2)^2 + 4.935 \times 10^9 \omega_H^2 - 3.896 \times 10^{18} = 0$$

$$\omega_H^2 = 6.925 \times 10^8 \rightarrow \omega_H = 26.3 \times 10^3 \rightarrow f_H = \frac{26.3 \times 10^3}{2\pi} = 4190 \text{ Hz}$$

$$A_v(0) = -100(66.7)(50) = -3.33 \times 10^5 \quad | \quad |A_v(\omega_H)| = \frac{-3.34 \times 10^5}{\sqrt{2}} = -2.36 \times 10^5$$

$$\left[1 + \frac{\omega_H^2}{(10000\pi)^2} \right] \left[1 + \frac{\omega_H^2}{(15000\pi)^2} \right] \left[1 + \frac{\omega_H^2}{(20000\pi)^2} \right] = 2$$

$$\omega_H^6 + 7.156 \times 10^9 \omega_H^4 + 1.486 \times 10^{10} \omega_H^2 - 8.562 \times 10^{27} = 0$$

$$\text{Using MATLAB, } \omega_H = 21.7 \times 10^3 \rightarrow f_H = \frac{21.7 \times 10^3}{2\pi} = 3450 \text{ Hz}$$

$$A_v(0) = (-30)^3 = -2.70 \times 10^4 \quad | \quad f_H = (33.3 \text{ kHz}) \sqrt{2^{\frac{1}{3}} - 1} = 17.0 \text{ kHz}$$

Page 711

$$A_{v1} = 1 + \frac{130k\Omega}{22k\Omega} = 6.909 \quad | \quad v_{o1} = 0.001(6.909) = 6.91 \text{ mV} \quad | \quad v_{o2} = 0.001V(6.909)^2 = 47.7 \text{ mV}$$

$$v_{o3} = 0.001(6.909)^3 = 330 \text{ mV} \quad | \quad v_{o4} = 0.001V(6.909)^4 = 2.28 \text{ V}$$

$$v_{o5} = 0.001V(6.909)^5 = 15.7 \text{ V} > 15 \text{ V}. \quad \therefore v_{o5} = V_O^{\max} = 15 \text{ V}$$

$$v_{o6} = 15V(6.909) = 104 \text{ V} > 15 \text{ V}. \quad \therefore v_{o6} = V_O^{\max} = 15 \text{ V}$$

Page 714

$$V_A = V_1 + IR_2 \quad | \quad V_B = V_2 - IR_2 \quad | \quad I = \frac{V_A - V_B}{2R_1} = \frac{5.001V - 4.999V}{2k\Omega} = 1.00 \mu A$$

$$V_A = V_1 + IR_2 = 5.001V + 1.00\mu A(49k\Omega) = 5.05 \text{ V}$$

$$V_B = V_2 - IR_2 = 4.999V - 1.00\mu A(49k\Omega) = 4.95 \text{ V}$$

$$V_O = \left(-\frac{R_4}{R_3}\right)(V_A - V_B) = \left(-\frac{10k\Omega}{10k\Omega}\right)(5.05 - 4.95) = -0.100 \text{ V}$$

Page 717

$$A_{LP}(s) = \frac{\omega_o^2}{s^2 + s \frac{\omega_o}{Q} + \omega_o^2} \quad | \quad A_{LP}(0) = \frac{\omega_o^2}{\omega_o^2} = 1 \text{ or } 0 \text{ dB}$$

$$\text{For } Q = \frac{1}{\sqrt{2}}: A_{LP}(j\omega) = \frac{\omega_o^2}{-\omega^2 + j\omega\sqrt{2}\omega_o + \omega_o^2} \quad | \quad |A_{LP}(j\omega_H)|^2 = \frac{\omega_o^4}{(\omega_o^2 - \omega_H^2)^2 + 2\omega_o^2\omega_H^2} = \left(\frac{1}{\sqrt{2}}\right)^2$$

$$2\omega_o^4 = \omega_o^4 + \omega_H^4 \rightarrow \omega_H = \omega_o$$

To increase the cutoff frequency from 5 kHz to 10 kHz while maintaining the resistances

the same, we must decrease the capacitances by a factor of $\frac{10\text{kHz}}{5\text{kHz}} = 2$

$$\therefore C_1 = \frac{0.02\mu F}{2} = 0.01 \mu F \quad | \quad C_2 = \frac{0.01\mu F}{2} = 0.005 \mu F$$

$$A_{LP}(j\omega) = \frac{\omega_o^2}{-\omega^2 + j\omega\frac{\omega_o}{Q} + \omega_o^2} \quad | \quad A_{LP}(j\omega_o) = \frac{\omega_o^2}{-\omega_o^2 + j\frac{\omega_o^2}{Q} + \omega_o^2} = -jQ \quad | \quad |A_{LP}(j\omega_o)| = Q$$

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To decrease the cutoff frequency from 5 kHz to 2 kHz, we must increase the

$$\text{resistances by a factor of } \frac{5\text{kHz}}{2\text{kHz}} = 2.50 \rightarrow R_1 = R_2 = 2.50(2.26k\Omega) = 5.65 k\Omega$$

$$Q = \sqrt{\frac{2C}{C} \frac{\sqrt{R^2}}{2R}} = \frac{\sqrt{2}}{2} = \frac{1}{\sqrt{2}} \quad | \quad Q \text{ is unchanged.}$$

$$\frac{1}{\sqrt{2}} = \sqrt{\frac{C}{C} \frac{\sqrt{R_1 R_2}}{R_1 + R_2}} \rightarrow R_1^2 + 2R_1 R_2 + R_2^2 = 2R_1 R_2 \rightarrow R_1^2 = -R_2^2 \quad \text{-- can't be done!}$$

$$Q = \frac{\sqrt{R_1 R_2}}{R_1 + R_2} \quad \frac{dQ}{dR_2} = \frac{1}{(R_1 + R_2)^2} \left[\frac{R_1(R_1 + R_2)}{2\sqrt{R_1 R_2}} - \sqrt{R_1 R_2} \right] = 0 \rightarrow R_2 = R_1 \rightarrow Q_{\max} = \frac{1}{2}$$

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$$|A_{HP}(j\omega_o)| = K \left| \frac{-\omega_o^2}{-\omega_o^2 + j(3-K)\omega_o^2 + \omega_o^2} \right| = \frac{K}{3-K} \quad | \quad A_{HP}(j\omega_o) = \frac{K}{3-K} \angle 90^\circ$$

$$f_o = \frac{1}{2\pi\sqrt{10k\Omega(20k\Omega)(0.0047\mu F)(0.001\mu F)}} = 5.19 \text{ kHz}$$

$$Q = \left[\sqrt{\frac{10k\Omega}{20k\Omega}} \frac{4.7nF + 1.0nF}{\sqrt{4.7nF(1.0nF)}} + (1-2) \sqrt{\frac{20k\Omega(1.0nF)}{10k\Omega(4.7nF)}} \right]^{-1} = 0.829$$

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$$S_K^Q = \frac{K}{Q} \frac{dQ}{dK} \quad | \quad Q = \frac{1}{3-K} \quad | \quad \frac{dQ}{dK} = \frac{-1}{(3-K)^2} (-1) = Q^2 \quad | \quad S_K^Q = \frac{K}{Q} \frac{dQ}{dK} = KQ$$

$$Q = \frac{1}{3-K} \rightarrow KQ = 3Q - 1 \quad S_K^Q = 3Q - 1 = \frac{3}{\sqrt{2}} - 1 = 1.12$$

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$$R_{th} = 2k\Omega \parallel 2k\Omega = 1k\Omega \quad | \quad f_o = \frac{1}{2\pi\sqrt{1k\Omega(82k\Omega)(0.02\mu F)(0.02\mu F)}} = 879 \text{ Hz} \quad | \quad Q = \frac{1}{2} \sqrt{\frac{82k\Omega}{1k\Omega}} = 4.53$$

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The lower gain results in a larger gain error and center frequency shift.

$$|A_{BP}(j\omega_o)| = KQ = \frac{R_2}{R_1} \quad | \quad 10 = \frac{294k\Omega}{R_1} \rightarrow R_1 = 29.4 \text{ k}\Omega$$

$$R = \frac{1}{\omega_o C} = \frac{1}{2\pi(2000)(2000 \text{ pF})} = 39.8 \text{ k}\Omega \quad | \quad R_2 = QR = 10(39.8 \text{ k}\Omega) = 398 \text{ k}\Omega$$

$$R_1 = \frac{R_2}{|A_{BP}(j\omega_o)|} = \frac{398 \text{ k}\Omega}{20} = 19.9 \text{ k}\Omega \quad | \quad R_3 \text{ can remain the same.}$$

The nearest 1% values are $R = 40.2 \text{ k}\Omega$, $R_2 = 402 \text{ k}\Omega$, $R_1 = 20.0 \text{ k}\Omega$, $R_3 = 49.9 \text{ k}\Omega$

$$f_o = \frac{1}{2\pi RC} = \frac{1}{2\pi(40.2 \text{ k}\Omega)(2nF)} = 1.98 \text{ kHz} \quad | \quad BW = \frac{1}{2\pi R_2 C} = \frac{1}{2\pi(402 \text{ k}\Omega)(2nF)} = 198 \text{ Hz}$$

$$A_{BP}(j\omega_o) = -\frac{R_2}{R_1} = -\frac{402 \text{ k}\Omega}{20.0 \text{ k}\Omega} = -20.1$$

Blindly using the equations at the top of page 580 yields

$$f_o^{\min} = \frac{1}{2\pi RC} = \frac{1}{2\pi(1.01)(29.4 \text{ k}\Omega)(1.02)(2.7nF)} = 1946 \text{ Hz}$$

$$f_o^{\max} = \frac{1}{2\pi RC} = \frac{1}{2\pi(0.99)(29.4 \text{ k}\Omega)(0.98)(2.7nF)} = 2067 \text{ Hz}$$

$$BW^{\min} = \frac{1}{2\pi R_2 C} = \frac{1}{2\pi(1.01)(294 \text{ k}\Omega)(1.02)(2.7nF)} = 195 \text{ Hz}$$

$$BW^{\max} = \frac{1}{2\pi R_2 C} = \frac{1}{2\pi(0.99)(294 \text{ k}\Omega)(0.98)(2.7nF)} = 207 \text{ Hz}$$

$$A_{BP}^{\min} = -\frac{R_2}{R_1} = -\frac{294 \text{ k}\Omega(1.01)}{14.7 \text{ k}\Omega(0.99)} = -20.4 \quad | \quad A_{BP}^{\max} = -\frac{R_2}{R_1} = -\frac{294 \text{ k}\Omega(0.99)}{14.7 \text{ k}\Omega(1.01)} = -19.6$$

The W/C results are similar if R and C are not the same for example where $\omega_o = \frac{1}{\sqrt{R_A R_B C_A C_B}}$.

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$$S_{C_1}^Q = \frac{C_1}{Q} \frac{dQ}{dC_1} = \frac{C_1}{Q} \left[\frac{1}{2\sqrt{C_1 C_2}} \frac{\sqrt{R_1 R_2}}{R_1 + R_2} \right] = \frac{C_1}{Q} \frac{Q}{2C_1} = 0.5$$

$$S_{R_2}^Q = \frac{R_2}{Q} \frac{dQ}{dR_2} \quad | \quad R_1 = R_2 \rightarrow Q = \frac{1}{2} \sqrt{\frac{C_1}{C_2}} \rightarrow S_{R_2}^Q = 0$$

$$S_R^{\omega_o} = \frac{R}{\omega_o} \frac{d\omega_o}{dR} = \frac{R}{\omega_o} \left(\frac{-1}{R^2 C} \right) = -\frac{\omega_o}{\omega_o} = -1 \quad | \quad S_C^{\omega_o} = \frac{C}{\omega_o} \frac{d\omega_o}{dR} = \frac{C}{\omega_o} \left(\frac{-1}{RC^2} \right) = -\frac{\omega_o}{\omega_o} = -1$$

$$S_K^Q = \frac{K}{Q} \frac{dQ}{dK} = \frac{K}{Q} \frac{(-1)(-1)}{(3-K)^2} = \frac{K}{Q} Q^2 = KQ = \frac{K}{3-K}$$

$$S_{R_1}^{\omega_o} = \frac{R_1}{\omega_o} \frac{d\omega_o}{dR_1} = \frac{R_1}{\omega_o} \left(-\frac{\omega_o}{2R_{th}} \right) \frac{dR_{th}}{dR_1} = -\frac{R_1}{2R_{th}} \left(\frac{R_{th}^2}{R_1^2} \right) = -\frac{1}{2} \frac{R_3}{R_1 + R_3}$$

$$S_{R_2}^{\omega_o} = \frac{R_2}{\omega_o} \frac{d\omega_o}{dR_2} = \frac{R_2}{\omega_o} \left(-\frac{\omega_o}{2R_2} \right) = -\frac{1}{2}$$

$$S_{R_3}^{\omega_o} = \frac{R_3}{\omega_o} \frac{d\omega_o}{dR_3} = \frac{R_3}{\omega_o} \left(-\frac{\omega_o}{2R_{th}} \right) \frac{dR_{th}}{dR_3} = -\frac{R_3}{2R_{th}} \left(\frac{R_{th}^2}{R_3^2} \right) = -\frac{1}{2} \frac{R_1}{R_1 + R_3}$$

$$S_C^{\omega_o} = \frac{C}{\omega_o} \frac{d\omega_o}{dC} = \frac{C}{\omega_o} \left(-\frac{\omega_o}{C} \right) = -1$$

$$S_{R_1}^Q = \frac{R_1}{Q} \frac{dQ}{dR_1} = \frac{R_1}{Q} \left(-\frac{Q}{2R_{th}} \right) \frac{dR_{th}}{dR_1} = -\frac{R_1}{2R_{th}} \left(\frac{R_{th}^2}{R_1^2} \right) = -\frac{1}{2} \frac{R_3}{R_1 + R_3}$$

$$S_{R_2}^Q = \frac{R_2}{Q} \frac{dQ}{dR_2} = \frac{R_2}{Q} \left(\frac{Q}{2R_2} \right) = +\frac{1}{2}$$

$$S_{R_3}^Q = \frac{R_3}{Q} \frac{dQ}{dR_3} = \frac{R_3}{Q} \left(-\frac{Q}{2R_{th}} \right) \frac{dR_{th}}{dR_3} = -\frac{R_3}{2R_{th}} \left(\frac{R_{th}^2}{R_3^2} \right) = -\frac{1}{2} \frac{R_1}{R_1 + R_3}$$

$$S_C^Q = \frac{C}{Q} \frac{dQ}{dC} = \frac{C}{Q} (0) = 0 \quad | \quad S_C^{BW} = \frac{C}{BW} \frac{dBW}{dC} = \frac{C}{BW} \left(-\frac{BW}{C} \right) = -1$$

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$$(a) R_1 = R_2 = 5(2.26k\Omega) = 11.3 k\Omega \quad | \quad C_1 = \frac{0.02\mu F}{5} = 0.004 \mu F \quad | \quad C_2 = \frac{0.01\mu F}{5} = 0.002 \mu F$$

$$f_o = \frac{1}{2\pi\sqrt{(11.3k\Omega)(11.3k\Omega)(0.004\mu F)(0.002\mu F)}} = 4980 \text{ Hz}$$

$$Q = \sqrt{\frac{11.3k\Omega}{11.3k\Omega}} \frac{\sqrt{(0.004\mu F)(0.002\mu F)}}{0.004\mu F + 0.002\mu F} = \frac{\sqrt{2}}{3} = 0.471$$

$$(b) R_1 = R_2 = 0.885(2.26k\Omega) = 2.00 k\Omega \quad | \quad C_1 = \frac{0.02\mu F}{0.885} = 0.0226 \mu F \quad | \quad C_2 = \frac{0.01\mu F}{0.885} = 0.0113 \mu F$$

$$f_o = \frac{1}{2\pi\sqrt{(2.00k\Omega)(2.00k\Omega)(0.0226\mu F)(0.0113\mu F)}} = 4980 \text{ Hz}$$

$$Q = \sqrt{\frac{2.00k\Omega}{2.00k\Omega}} \frac{\sqrt{(0.0226\mu F)(0.0113\mu F)}}{0.0226\mu F + 0.0113\mu F} = \frac{\sqrt{2}}{3} = 0.471$$

$$f_o = \frac{1}{2\pi\sqrt{(2k\Omega)(2k\Omega)(82k\Omega)(0.02\mu F)(0.02\mu F)}} = 879 \text{ Hz} \quad | \quad Q = \sqrt{\frac{82k\Omega}{1k\Omega}} \frac{\sqrt{(0.02\mu F)(0.02\mu F)}}{0.02\mu F + 0.02\mu F} = 4.53$$

The values of the resistors are unchanged. $C_1 = C_2 = \frac{0.02\mu F}{4} = 0.005 \mu F$

$$f_o = \frac{1}{2\pi\sqrt{(1k\Omega)(82k\Omega)(0.005\mu F)(0.005\mu F)}} = 3520 \text{ Hz} \quad | \quad Q = \sqrt{\frac{82k\Omega}{1k\Omega}} \frac{\sqrt{(0.005\mu F)(0.005\mu F)}}{0.005\mu F + 0.005\mu F} = 4.53$$

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$$\Delta v_o = -\frac{C_1}{C_2} V_I = -\frac{2pF}{0.5pF} 0.1V = -0.4 V$$

$$v_o(T) = 0 + \Delta v_o = -0.4 V \quad | \quad v_o(5T) = 0 + 5\Delta v_o = -2.0 V \quad | \quad v_o(9T) = 0 + 9\Delta v_o = -3.6 V$$

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$$f_o = \frac{1}{2\pi} f_C \sqrt{\frac{C_3 C_4}{C_1 C_2}} = \frac{200kHz}{2\pi} \sqrt{\frac{4pF(0.25pF)}{3pF(3pF)}} = 10.6 kHz$$

$$Q = \sqrt{\frac{C_3}{C_4} \frac{\sqrt{C_1 C_2}}{C_1 + C_2}} = \sqrt{\frac{4pF}{0.25pF} \frac{\sqrt{3pF(3pF)}}{3pF + 3pF}} = 2 \quad | \quad \text{BW} = \frac{f_o}{Q} = \frac{10.6 kHz}{2} = 5.30 kHz$$

$$A_{BP}(j\omega_o) = -\frac{R_2}{2R_1} = -\frac{C_3}{2C_4} = -\frac{4pF}{0.5pF} = -8.00$$

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$$0.01100001_2 = \left(2^{-2} + 2^{-3} + 2^{-8}\right)_{10} = 0.37980625_{10} \quad | \quad 0.10001000_2 = \left(2^{-1} + 2^{-5}\right)_{10} = 0.53125_{10}$$

$$V_O = \frac{5.12V}{2^{12}} \left(2^{11} + 2^9 + 2^7 + 2^5 + 2^3 + 2^1\right) = 3.41250 \text{ V}$$

$$V_{LSB} = \frac{5.12V}{2^{12}} = 1.25 \text{ mV} \quad | \quad V_{MSB} = \frac{5.12V}{2} = 2.56 \text{ V}$$

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$$V_{OS} = V_O(000) = 0.100 \text{ V}_{FS} \quad | \quad V_{LSB} = \frac{0.8V_{FS} - 0.1V_{FS}}{7} = 0.1 \text{ V}_{FS}$$

$$2R = 1 \text{ k}\Omega \quad | \quad 4R = 2 \text{ k}\Omega \quad | \quad 8R = 4 \text{ k}\Omega \quad | \quad 16R = 8 \text{ k}\Omega \quad | \quad 32R = 16 \text{ k}\Omega \quad | \quad 64R = 32 \text{ k}\Omega$$

$$128R = 64 \text{ k}\Omega \quad | \quad 256R = 128 \text{ k}\Omega \quad | \quad R = 500 \text{ }\Omega$$

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$$R_{Total} = R + 2R + 2R + (n-1)(2R + R) = (3n+2)R \quad | \quad R_{Total} = (3x8+2)(1k\Omega) = 26 \text{ k}\Omega$$

$$R = 1 \text{ k}\Omega \quad | \quad 2R = 2 \text{ k}\Omega \quad | \quad 4R = 4 \text{ k}\Omega \quad | \quad 8R = 8 \text{ k}\Omega \quad | \quad 16R = 16 \text{ k}\Omega \quad | \quad 32R = 32 \text{ k}\Omega$$

$$64R = 64 \text{ k}\Omega \quad | \quad 128R = 128 \text{ k}\Omega \quad | \quad 256R = 256 \text{ k}\Omega \quad | \quad R_{Total} = 511 \text{ k}\Omega$$

$$\text{In general: } R_{Total} = R(2^0 + 2^1 + \dots + 2^{n-1} + 2^n) = (2^{n+1} - 1)R \quad | \quad R_{Total} = (2^{8+1} - 1)1k\Omega = 511 \text{ k}\Omega$$

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The general case requires 2^n resistors, and the number of switches is

$$(2^1 + 2^2 + \dots + 2^n) = 2(2^0 + 2^1 + \dots + 2^{n-1}) = 2(2^n - 1) = 2^{n+1} - 2$$

$$2^{10} = 1024 \text{ resistors} \quad | \quad 2^{10+1} - 2 = 2046 \text{ switches.}$$

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$$(a) \text{ In general: } C_{Total} = R(2^0 + 2^1 + \dots + 2^n) = (2^{n+1} - 1)C \quad | \quad C_{Total} = (2^{8+1} - 1)1pF = 511 pF$$

$$(b) \text{ In general: } R_{Total} = 2C + 2C + (n-1)(2C + C) = 2R + n(3R) \quad | \quad R_{Total} = 2R + 8(3k\Omega) = 26 \text{ k}\Omega$$

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$$V_{LSB} = \frac{5V}{2^8} = 19.53 \text{ mV} \quad | \quad 1.2V \frac{2^8 LSB}{5V} = 61.44 \text{ LSB} \quad | \quad \text{The closest code is } 61_{10} = 00111101_2$$

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$$2^n \geq 10^6 \quad | \quad n \geq \frac{6 \log 10}{\log 2} = 19.93 \rightarrow n \geq 20 \text{ bits}$$

The minimum width is 0 corresponding to the missing code 110.

The maximum code width is 2.5 LSB corresponding to output code 101.

$$DNL = 2.5 - 1 = 1.5 \text{ LSB}$$

At code 110, the ADC transfer characteristic is 1 LSB off of the fitted line.

$$\therefore INL = 1 \text{ LSB}$$

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$$T_T^{\max} = \frac{2^n}{f_C} = \frac{2^{12}}{2 \times 10^6} = 2.048 \text{ ms} \quad | \quad N_{\max} = \frac{1}{T_T^{\max}} = \frac{1}{2.048 \text{ ms}} = 488 \frac{\text{conversions}}{\text{second}}$$

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$$T_T = \frac{n}{f_C} = \frac{12}{2 \times 10^6} = 6.00 \mu\text{s} \quad | \quad N_{\max} = \frac{1}{T_T} = \frac{1}{6 \mu\text{s}} = 167,000 \frac{\text{conversions}}{\text{second}}$$

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$$V_{FS} = \frac{1}{RC} \int_0^T V_R(t) dt = \frac{V_R T}{RC} \quad | \quad RC = \frac{V_R}{V_{FS}} T = \frac{V_R}{V_{FS}} \frac{2^n}{f_C} = \frac{2.00V}{5.12V} \left(\frac{2^8}{1 \text{ MHz}} \right) = 0.100 \text{ ms}$$

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$$T_T^{\max} = \frac{2^{n+1}}{f_C} = \frac{2^{17}}{10^6 \text{ Hz}} = 0.131 \text{ s} \quad | \quad N_{\max} = \frac{1}{T_T^{\max}} = \frac{1}{0.131 \text{ s}} = 7.63 \frac{\text{conversions}}{\text{second}}$$

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In general, 2^n resistors and $(2^n - 1)$ comparators :

$$2^{10} = 1024 \text{ resistors and } (2^{10} - 1) = 1023 \text{ comparators}$$

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$$f_o = \frac{1}{2\pi(10k\Omega)(1nF)} = 15.9 \text{ kHz} \quad | \quad |V_o| = \frac{3(0.6V)}{\left(2 - \frac{10k\Omega}{10k\Omega}\right)\left(1 + \frac{24k\Omega}{12k\Omega}\right) - \frac{24k\Omega}{10k\Omega}} = 3.00 \text{ V}$$

SPICE Results : 15.90 kHz, 3.33 V

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For $v_I > 0$, the diode will conduct and pull the output up to $v_O = v_I = 1.0 \text{ V}$.

$$v_1 = v_O + v_D = 1.0 + 0.6 = 1.6 \text{ V}$$

For a negative input, there is no path for current through R, so $v_O = 0 \text{ V}$. The op-amp sees a -1V input so the output will limit at the negative power supply: $v_O = -10 \text{ V}$.

(Note that the output voltage will actually be determined by the reverse saturation current of the diode: $v_O = -I_S R \approx 0$.)

The diode has a 10-V reverse bias across it, so $V_Z > 10 \text{ V}$.

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$v_S = +2 \text{ V}$: Diode D₂ conducts, and D₁ is off. The negative input is a virtual ground.

$v_1 = -v_{D2} = -0.6 \text{ V}$. The current in R is 0, so $v_O = 0 \text{ V}$.

$v_I = -2 \text{ V}$: Diode D₁ conducts, and D₂ is off. The negative input is a virtual ground.

$$v_O = -\frac{R_2}{R_1}v_I = -\frac{68k\Omega}{22k\Omega}(-2V) = +6.18 \text{ V} \quad | \quad v_1 = v_O + v_{D1} = 6.78 \text{ V}$$

The maximum output voltage is $v_O^{\max} = 15V - 0.6V = 14.4 \text{ V}$.

$$A_v = -\frac{68k\Omega}{22k\Omega} = -3.09 \quad | \quad v_I = \frac{14.4V}{-3.09} = -4.66 \text{ V}$$

When $v_O = 15 \text{ V}$, $v_{D2} = -15 \text{ V}$, so $V_Z = 15 \text{ V}$.

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$$v_O = \frac{20k\Omega}{20k\Omega} \left(\frac{10.2k\Omega}{3.24k\Omega} \right) \frac{2V}{\pi} = 2.00 \text{ V}$$

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$$V_{I-} = -\frac{R_1}{R_1 + R_2} V_{EE} = -\frac{1k\Omega}{1k\Omega + 9.1k\Omega} 10V = -0.990 \text{ V}$$

$$V_{I+} = +\frac{R_1}{R_1 + R_2} V_{CC} = \frac{1k\Omega}{1k\Omega + 9.1k\Omega} 10V = +0.990 \text{ V}$$

$$V_n = 0.990V - (-0.990V) = 1.98 \text{ V}$$

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$$T = 2RC \ln \frac{1+\beta}{1-\beta} \quad | \quad \beta = \frac{R_1}{R_1 + R_2} = \frac{6.8k\Omega}{6.8k\Omega + 6.8k\Omega} = \frac{1}{2}$$

$$T = 2(10k\Omega)(0.001\mu F) \ln \left(\frac{1+0.5}{1-0.5} \right) = 21.97\mu s \quad | \quad f = \frac{1}{T} = 45.5 \text{ kHz}$$

$$\beta = \frac{R_1}{R_1 + R_2} = \frac{22k\Omega}{22k\Omega + 18k\Omega} = 0.550 \quad | \quad T = (11k\Omega)(0.002\mu F) \ln \left[\frac{1 + \frac{0.7}{5}}{1 - 0.550} \right] = 20.4 \text{ } \mu s$$

$$T_r = (11k\Omega)(0.002\mu F) \ln \left[\frac{1 + 0.55 \left(\frac{5V}{5V} \right)}{1 - \frac{0.7}{5}} \right] = 13.0 \text{ } \mu s \quad | \quad T_{\min} = 20.4 \mu s + 13.0 \mu s = 33.4 \text{ } \mu s$$

CHAPTER 13

Page 789

$$(a) \text{At the Q-point: } \beta_F = \frac{I_C}{I_B} = \frac{1.5mA}{15\mu A} = 100 \quad (b) I_S = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{1.5mA}{\exp\left(\frac{0.700V}{0.025V}\right)} = 1.04 fA$$

$$(c) R_{in} = \frac{v_{be}}{i_b} = \frac{8mV}{5\mu A} = 1.6 k\Omega \quad (d) \text{Yes. With the given applied signal, the smallest value of } v_{CE} \text{ is } v_{CE}^{\min} = 5V - 0.5mA(3.3k\Omega) = 3.35 V \text{ which exceeds } v_{BE} = 0.708 V. \quad (e) A_{vdb} = 20 \log| -206 | = 46.3 dB$$

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(a) No: $v_{DS}^{\min} \cong 2.7V$ with $v_{GS} - V_{TN} = 4 - 1 = 3V$, so the transistor has entered the triode region.

(b) Choose two points on the i-v characteristics. For example,

$$1.56mA = \frac{K_n}{2}(3.5 - V_{TN})^2 \quad \text{and} \quad 1.0mA = \frac{K_n}{2}(3.0 - V_{TN})^2.$$

Solving for K_n and V_{TN} yields $500 \frac{\mu A}{V^2}$ and 1 V respectively.

$$(c) A_{vdb} = 20 \log| -4.13 | = 12.3 dB$$

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$$V_{EQ} = \frac{10k\Omega}{10k\Omega + 30k\Omega} 12V = 3.00 V \quad | \quad R_{EQ} = 10k\Omega \parallel 30k\Omega = 7.5 k\Omega$$

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_4} = 100 \frac{3.0V - 0.7V}{7.5k\Omega + (101)(1.5k\Omega)} = 1.45 mA$$

$$V_{CE} = 12 - 4300I_C - 1500I_E = 12 - 4300(1.45mA) - 1500\left(\frac{101}{100}\right)(1.45mA) = 3.57 V$$

$$V_B = V_{EQ} - I_B R_{EQ} = 3.00 - \frac{1.45mA}{100}(7.5k\Omega) = 2.89 V$$

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$$v_C(t) = V_C + v_C = (5.8 - 1.1 \sin 2000\pi t) V \quad | \quad v_E(t) = V_E + 0 = 1.45mA \left(\frac{101}{100} \right) (1.5k\Omega) = 2.20 V$$

$$|i_c| = \frac{1.1V}{4.3k\Omega} = 0.256mA \quad | \quad \angle i_c = 180^\circ \quad | \quad i_c(t) = -0.26 \sin 2000\pi t mA \quad | \quad v_B(t) = V_B + v_b(t)$$

$$V_B = V_{EQ} - I_B R_{EQ} = 3.00 - \frac{1.45mA}{100} (7.5k\Omega) = 2.89 V \quad | \quad v_B(t) = (2.89 + 0.005 \sin 2000\pi t) V$$

$$X_C = \frac{1}{\omega C} = \frac{1}{2000\pi(500\mu F)} = 0.318 \Omega \quad | \quad X_C \ll R_{in}$$

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$$R_B = 20k\Omega \parallel 62k\Omega = 15.1 k\Omega \quad | \quad R_L = 8.2k\Omega \parallel 100k\Omega = 7.58 k\Omega$$

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$$r_d = \frac{V_T}{I_D + I_S} \quad | \quad r_d = \frac{0.025V}{1fA} = 25.0 T\Omega \quad | \quad r_d = \frac{0.025V}{50\mu A} = 500 \Omega$$

$$r_d = \frac{0.025V}{2mA} = 12.5 \Omega \quad | \quad r_d = \frac{0.025V}{3A} = 8.33 m\Omega$$

$$r_d = \frac{0.025V}{1.5mA} = 16.7 \Omega \quad | \quad \frac{kT}{q} = \left(8.62 \times 10^{-5} \frac{V}{K} \right) (373K) = 0.0322 V \quad | \quad r_d = \frac{0.0322V}{1.5mA} = 21.4 \Omega$$

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$$g_m = 40I_C = 40(50\mu A) = 2.00 \text{ mS} \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{75}{2 \text{ mS}} = 37.5 \text{ k}\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{60V + 5V}{50\mu A} = 1.30 \text{ M}\Omega \quad | \quad \mu_f = g_m r_o = 2 \text{ mS}(1.30 \text{ M}\Omega) = 2600$$

$$g_m = 40I_C = 40(250\mu A) = 10.0 \text{ mS} \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{50}{10 \text{ mS}} = 5.00 \text{ k}\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{75V + 15V}{250\mu A} = 360 \text{ k}\Omega \quad | \quad \mu_f = g_m r_o = 10 \text{ mS}(360 \text{ k}\Omega) = 3600$$

The slope of the output characteristics is zero, so $V_A = \infty$ and $r_o = \infty$.

$$\beta_{FO} = \frac{\beta_F}{1 + \frac{V_{CE}}{V_A}} = \beta_F = \frac{I_C}{I_B} = \frac{1.5mA}{15\mu A} = 100 \quad | \quad g_m = \frac{\Delta i_C}{\Delta v_{BE}} = \frac{0.5mA}{8mV} = 62.5 \text{ mS}$$

$$\beta_o = \frac{\Delta i_C}{\Delta i_B} = \frac{500\mu A}{5\mu A} = 100 \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{100}{62.5 \text{ mS}} = 1.60 \text{ k}\Omega \quad | \quad r_\pi = \frac{\Delta v_{BE}}{\Delta i_B} = \frac{8mV}{0.5mA/100} = 1.60 \text{ k}\Omega$$

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$A_{vt} = -g_m R_L = -9.80mS(18k\Omega) = -176$ | Ten percent of the input signal is being lost by voltage division between source resistance R_i and the amplifier input resistance.

Assume the Q-point remains constant.

$$(a) R_{iB} = r_\pi = \frac{125}{9.80mS} = 12.8 k\Omega \quad | \quad A_v = -9.80mS(18k\Omega) \left(\frac{104k\Omega \| 12.8k\Omega}{1k\Omega + 104k\Omega \| 12.8k\Omega} \right) = -162$$

$$(b) R_L^{\max} = 1.1(18k\Omega) = 19.8 k\Omega \quad | \quad R_L^{\min} = 0.9(18k\Omega) = 16.2 k\Omega$$

$$A_v^{\min} = -9.80mS(16.2k\Omega) \left(\frac{104k\Omega \| 10.2k\Omega}{1k\Omega + 104k\Omega \| 10.2k\Omega} \right) = -143$$

$$A_v^{\max} = A_v^{\min} \left(\frac{19.8k\Omega}{16.2k\Omega} \right) = -143 \left(\frac{19.8k\Omega}{16.2k\Omega} \right) = -175$$

$$\text{Checking: } A_v^{\min} = A_v^{\text{nom}} \left(\frac{16.2k\Omega}{18k\Omega} \right) = -159(0.9) = -143 \quad | \quad A_v^{\max} = A_v^{\text{nom}} \left(\frac{19.8k\Omega}{18k\Omega} \right) = -159(1.1) = -175$$

$$(c) V_{CE} = 12V - 22k\Omega I_C - 13k\Omega I_E = 12V - 0.275mA \left(22k\Omega + \frac{101}{100} 13k\Omega \right) = 2.34 V$$

$$g_m = 40(0.275mA) = 11.0 mS \quad | \quad R_{iB} = r_\pi = \frac{100}{11.0mS} = 9.09 k\Omega$$

$$A_v = -11.0mS(18k\Omega) \left(\frac{104k\Omega \| 9.09k\Omega}{1k\Omega + 104k\Omega \| 9.09k\Omega} \right) = -177$$

$$A_v^{CE} \cong -10V_{CC} = -10(20) = -200 \quad | \quad g_m = 40I_C = 40(100\mu A) = 4.00 mS \quad | \quad R_{iB} = r_\pi = \frac{\beta_o}{g_m} = \frac{100}{4mS} = 25 k\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{50V + 10V}{100\mu A} = 600 k\Omega \quad | \quad \mu_f = g_m r_o = 4mS(600k\Omega) = 2400$$

$$A_v = -g_m(R_C \| r_o) \frac{R_B \| R_{iB}}{R_i + R_B \| R_{iB}} = -4.00mS(100k\Omega \| 600k\Omega) \left(\frac{150k\Omega \| 25k\Omega}{5k\Omega + 150k\Omega \| 25k\Omega} \right) = -278$$

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$$V_{EQ} = \frac{160k\Omega}{160k\Omega + 300k\Omega} 12V = 4.17 \text{ V} \quad | \quad R_{EQ} = 160k\Omega \parallel 300k\Omega = 104 \text{ k}\Omega$$

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} = 100 \frac{4.17V - 0.7V}{104k\Omega + (101)(13k\Omega)} = 0.245 \text{ mA}$$

$$V_{CE} = 12 - 22000I_C - 13000I_E = 12 - 22000(0.245 \text{ mA}) - 13000\left(\frac{101}{100}\right)(0.245 \text{ mA}) = 3.39 \text{ V}$$

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CB}}{V_A}\right) \quad | \quad V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23}(300)}{1.6 \times 10^{-19}} = .025875 \text{ V}$$

$$I_S = \frac{0.245 \text{ mA}}{\exp\left(\frac{0.7}{0.025875}\right) \left(1 + \frac{3.39 - 0.7}{75}\right)} = 422 \text{ fA}$$

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$$(a) g_m = \sqrt{2K_n I_D (1 + \lambda V_{DS})} = \sqrt{2(1 \text{ mA}/V^2)(0.25 \text{ mA})[1 + 0.02(5)]} = 0.742 \text{ mS}$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{50V + 5V}{250 \mu A} = 220 \text{ k}\Omega \quad | \quad \mu_f = g_m r_o = 0.742 \text{ mS}(220 \text{ k}\Omega) = 163$$

$$g_m = \sqrt{2K_n I_D (1 + \lambda V_{DS})} = \sqrt{2(1 \text{ mA}/V^2)(5 \text{ mA})[1 + 0.02(10)]} = 3.46 \text{ mS}$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{50V + 10V}{5 \text{ mA}} = 12 \text{ k}\Omega \quad | \quad \mu_f = g_m r_o = 3.46 \text{ mS}(12 \text{ k}\Omega) = 41.5$$

(b) The slope of the output characteristics is zero, so $\lambda = 0$ and $r_o = \infty$.

$$\text{For the positive change in } v_{gs}, g_m = \frac{\Delta i_D}{\Delta v_{GS}} \cong \frac{3.3 \text{ k}\Omega}{0.5V} = 1.3 \text{ mS}$$

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$$|v_{gs}| \leq 0.2(V_{GS} - V_{TN}) = 0.2 \sqrt{\frac{2I_D}{K_n}} = 0.2 \sqrt{\frac{2(25 \text{ mA})}{2.0 \text{ mA}/V^2}} = 1.00 \text{ V} \quad | \quad |v_{be}| \leq 0.005 \text{ V}$$

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$$\eta = \frac{\gamma}{2\sqrt{V_{SB} + 2\phi_F}} = \frac{0.75}{2\sqrt{0 + 0.6}} = 0.48 \quad | \quad \eta = \frac{0.75}{2\sqrt{3 + 0.6}} = 0.20$$

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$$g_m = 2 \frac{\sqrt{I_{DSS} I_D (1 + \lambda V_{DS})}}{|V_P|} = 2 \frac{\sqrt{5mA(2mA)[1+0.02(5)]}}{|-2|} = 3.32 \text{ mS}$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{50V + 5V}{2mA} = 27.5 \text{ k}\Omega \quad | \quad \mu_f = g_m r_o = 3.32 \text{ mS} (27.5 \text{ k}\Omega) = 91.3$$

$$V_{GS} = V_P \left(1 - \sqrt{\frac{I_D}{I_{DSS}}} \right) = -2V \left(1 - \sqrt{\frac{2mA}{5mA}} \right) = -0.735 \text{ V}$$

$$|v_{gs}| \leq 0.2(V_{GS} - V_P) = 0.2(-0.735 + 2) = 0.253 \text{ V}$$

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$$V_{EQ} = \frac{1.5M\Omega}{1.5M\Omega + 2.2M\Omega} 12V = 4.87 \text{ V} \quad | \quad R_{EQ} = 1.5M\Omega \| 2.2M\Omega = 892 \text{ k}\Omega$$

Neglect λ in hand calculations of the Q-point.

$$4.87 = V_{GS} + 12000I_D \quad | \quad 4.87 = V_{GS} + 12000 \left(\frac{5 \times 10^{-4}}{2} \right) (V_{GS} - 1)^2$$

$$3V_{GS}^2 - 5V_{GS} - 1.87 = 0 \rightarrow V_{GS} = 1.981 \text{ V} \quad | \quad I_D = 241 \mu A$$

$$V_{DS} = 12 - 22000I_D - 12000I_D = 3.81 \text{ V} \quad | \quad \text{Q-point: } (241 \mu A, 3.81 \text{ V})$$

The small-signal model appears in Fig. 13.27(c).

$$V_{GS} - V_{TN} \cong \sqrt{\frac{2(241\mu A)}{2 \times 10^{-3}}} = 0.491 \text{ V} \quad | \quad A_v^{CS} \cong -\frac{12V}{0.491V} = -24.4 \quad | \quad M = \frac{K_{n2}}{K_{nl}} = \frac{2 \times 10^{-3}}{5 \times 10^{-4}} = 4$$

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$$r_\pi = \frac{\beta_o V_T}{I_C} = \frac{100(0.025V)}{0.725mA} = 3.45 \text{ k}\Omega \quad | \quad R_{in}^{CE} = R_B \| r_\pi = 104k\Omega \| 3.45k\Omega = 3.34 \text{ k}\Omega$$

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$$R_{in}^{CS} = 680k\Omega \| 1.0M\Omega = 405 \text{ k}\Omega \quad | \quad V_{EQnew} = \frac{680k\Omega}{680k\Omega + 1M\Omega} V_{DD} = 0.405V_{DD}$$

$$V_{EQold} = \frac{1.5M\Omega}{1.5Mk\Omega + 2.2M\Omega} V_{DD} = 0.405V_{DD} \quad | \quad \text{No change. The gate voltages are the same.}$$

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From Ex. 13.6, $\mu_f = 230$ and $A_v = -20.3$. $|A_v| \ll \mu_f$

$$V_{GS} = V_P \left(1 - \sqrt{\frac{I_D}{I_{DSS}}} \right) = -1V \left(1 - \sqrt{\frac{0.25mA}{1mA}} \right) = -0.500 V$$

$$|v_{gs}| \leq 0.2(V_{GS} - V_P) = 0.2(-0.5 + 1) = 0.100 V \quad | \quad |v_o| \leq 20.3(0.1) = 2.03 V$$

SPICE Results :

$$\lambda = 0 : Q\text{-point} = (250 \mu A, 4.75 V) \quad | \quad \lambda = 0.02 V^{-1} : Q\text{-point} = (257 \mu A, 4.54 V)$$

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$$I_C = 245 \mu A \quad | \quad V_{CE} = 3.39 V \quad | \quad I_E = 245 \mu A \left(\frac{66}{65} \right) = 249 \mu A$$

$$P_D = I_C V_{CE} + I_B V_{BE} = 245 \mu A (3.39V) + \frac{245 \mu A}{65} (0.7V) = 0.833 mW$$

$$P_S = V_{CC}(I_C + I_2) \quad | \quad I_2 = \frac{V_{CC} - V_B}{R_2} = \frac{V_{CC} - (V_{BE} + I_E R_E)}{R_2} = \frac{12 - 0.7 - 0.249mA(13k\Omega)}{300k\Omega} = 26.9 \mu A$$

$$P_S = 12V(245 \mu A + 26.9 \mu A) = 3.26 mW$$

$$P_D = I_D V_{DS} = 241 \mu A (3.81V) = 0.918 mW \quad | \quad P_S = V_{DD}(I_D + I_2)$$

$$I_2 = \frac{V_{DD}}{R_1 + R_2} = \frac{12V}{1.5M\Omega + 2.2M\Omega} = 3.24 \mu A \quad | \quad P_S = 12V(241 \mu A + 3.24 \mu A) = 2.93 mW$$

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$$(a) V_M \leq \min[I_C R_C, (V_{CE} - V_{BE})] = \min[245 \mu A (22k\Omega), (3.39 - 0.7)V] = 2.69 V$$

V_M is limited by the value of V_{CE} .

$$(b) V_M \leq \min[I_D R_D, (V_{DS} - V_{DSSAT})] = \min[241 \mu A (22k\Omega), (3.81 - 0.982)V] = 2.83 V$$

Limited by the value of V_{DS} .

CHAPTER 14

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$$V_{EQ} = \frac{160k\Omega}{160k\Omega + 300k\Omega} 12V = 4.17 \text{ V} \quad | \quad R_{EQ} = 160k\Omega \parallel 300k\Omega = 104 \text{ k}\Omega$$

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} = 100 \frac{4.17V - 0.7V}{104k\Omega + (101)(13k\Omega)} = 0.245 \text{ mA}$$

$$V_{CE} = 12 - 22000I_C - 13000I_E = 12 - 22000(0.245 \text{ mA}) - 13000 \left(\frac{101}{100} \right) (0.245 \text{ mA}) = 3.39 \text{ V}$$

$$g_m = 40I_C = 40(0.245 \text{ mA}) = 9.80 \text{ mS} \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{100}{9.80 \text{ mS}} = 10.2 \text{ k}\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{53.4V}{0.245mA} = 218 \text{ k}\Omega \quad | \quad \mu_f = g_m r_o = 2140$$

$$V_{EQ} = \frac{1.5M\Omega}{1.5M\Omega + 2.2M\Omega} 12V = 4.87 \text{ V} \quad | \quad R_{EQ} = 1.5M\Omega \parallel 2.2M\Omega = 892 \text{ k}\Omega$$

Neglect λ in hand calculations of the Q-point.

$$4.87 = V_{GS} + 12000I_D \quad | \quad 4.87 = V_{GS} + 12000 \left(\frac{5 \times 10^{-4}}{2} \right) (V_{GS} - 1)^2$$

$$3V_{GS}^2 - 5V_{GS} - 1.87 = 0 \rightarrow V_{GS} = 1.981 \text{ V} \quad | \quad I_D = 241 \text{ }\mu\text{A}$$

$$V_{DS} = 12 - 22000I_D - 12000I_D = 3.81 \text{ V} \quad | \quad \text{Q-point: } (241 \text{ }\mu\text{A}, 3.81 \text{ V})$$

$$g_m = \sqrt{2K_n I_D} = \sqrt{2(5 \times 10^{-4})(2.41 \times 10^{-4})} = 0.491 \text{ mS} \quad | \quad r_o = \frac{\lambda^{-1} + V_{CE}}{I_C} = \frac{53.8V}{0.241mA} = 223 \text{ k}\Omega$$

$$\mu_f = g_m r_o = 110$$

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$$R_B = 160k\Omega \parallel 300k\Omega = 104 \text{ k}\Omega \quad | \quad R_E = 3.00 \text{ k}\Omega \quad | \quad R_L = 22k\Omega \parallel 100k\Omega = 18.0 \text{ k}\Omega$$

$$R_G = 1.5M\Omega \parallel 2.2M\Omega = 892 \text{ k}\Omega \quad | \quad R_S = 2.00 \text{ k}\Omega \quad | \quad R_L = 22k\Omega \parallel 100k\Omega = 18.0 \text{ k}\Omega$$

$$R_B = 160k\Omega \parallel 300k\Omega = 104 \text{ k}\Omega \quad | \quad R_L = 13k\Omega \parallel 100k\Omega = 11.5 \text{ k}\Omega$$

$$R_G = 1.5M\Omega \parallel 2.2M\Omega = 892 \text{ k}\Omega \quad | \quad R_L = 12k\Omega \parallel 100k\Omega = 10.7 \text{ k}\Omega$$

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$$R_I = 2 \text{ k}\Omega \quad | \quad R_6 = 13 \text{ k}\Omega \quad | \quad R_L = 22\text{k}\Omega \parallel 100\text{k}\Omega = 18.0 \text{ k}\Omega$$

$$R_I = 2 \text{ k}\Omega \quad | \quad R_6 = 12 \text{ k}\Omega \quad | \quad R_L = 22\text{k}\Omega \parallel 100\text{k}\Omega = 18.0 \text{ k}\Omega$$

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$$(a) I_C \cong \frac{V_{EQ} - V_{BE}}{R_E + R_4} \quad \text{or} \quad I_C \propto \frac{1}{R_E + R_4} \quad | \quad I_C = 0.245mA \frac{13k\Omega}{R_E + R_4}$$

$$\text{For large } g_m R_E, \quad A_{vt}^{CE} = -\frac{g_m R_L}{1 + g_m R_E} \cong -\frac{R_L}{R_E} = -\frac{R_C \| R_3}{R_E}$$

$$\text{For } A_{vt}^{CE \max} \text{ make } R_C \text{ and } R_3 \text{ large and } R_E \text{ small.} \quad R_L = 1.1(22k\Omega) \| 1.1(100k\Omega) = 19.8 k\Omega$$

$$R_E = 0.9(3k\Omega) = 2.7 k\Omega \quad | \quad I_C = 0.245mA \frac{13k\Omega}{12.7k\Omega} = 0.251 mA \quad | \quad g_m = 40(0.251 mA) = 10.0 mS$$

$$r_\pi = \frac{\beta_o}{g_m} = \frac{100}{10.0mS} = 10.0 k\Omega \quad | \quad R_{iB} = 10.0k\Omega + 101(2.7k\Omega) = 283 k\Omega$$

$$A_v^{CE \max} = -\frac{10.0mS(19.8k\Omega)}{1 + 10.0mS(2.7k\Omega)} \left(\frac{104k\Omega \| 283k\Omega}{1k\Omega + 104k\Omega \| 283k\Omega} \right) = -6.98$$

$$\text{For } A_{vt}^{CE \min} \text{ make } R_C \text{ and } R_3 \text{ small and } R_E \text{ large.} \quad R_L = 0.9(22k\Omega) \| 0.9(100k\Omega) = 16.2 k\Omega$$

$$R_E = 1.1(3k\Omega) = 3.3 k\Omega \quad | \quad I_C = 0.245mA \frac{13k\Omega}{13.3k\Omega} = 0.239 mA \quad | \quad g_m = 40(0.239 mA) = 9.56 mS$$

$$r_\pi = \frac{\beta_o}{g_m} = \frac{100}{9.56mS} = 10.5 k\Omega \quad | \quad R_{iB} = 10.5k\Omega + 101(3.3k\Omega) = 344 k\Omega$$

$$A_v^{CE \ min} = -\frac{9.56mS(16.2k\Omega)}{1 + 9.56mS(3.3k\Omega)} \left(\frac{104k\Omega \| 344k\Omega}{1k\Omega + 104k\Omega \| 344k\Omega} \right) = -4.70$$

(b) Assume the collector current does not change.

$$r_\pi = \frac{\beta_o}{g_m} = \frac{125}{9.8mS} = 12.8 k\Omega \quad | \quad R_{iB} = 12.8k\Omega + 126(3.0k\Omega) = 391 k\Omega$$

$$A_v^{CE} = -\frac{9.80mS(18k\Omega)}{1 + 9.80mS(3k\Omega)} \left(\frac{104k\Omega \| 391k\Omega}{1k\Omega + 104k\Omega \| 391k\Omega} \right) = -5.73 \quad \text{The gain is essentially unchanged.}$$

$$(c) V_{CE} = V_{CC} - I_C R_C - I_E(R_E + R_4) = 12V - 0.275mA \left(22k\Omega + \frac{101}{100} 13k\Omega \right) = 2.34 V$$

2.34 V > 0.7 V Therefore the transistor is still in the active region.

$$g_m = 40(0.275mA) = 11.0 mS \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{100}{11mS} = 9.09 k\Omega \quad | \quad R_{iB} = 9.09k\Omega + 101(3.0k\Omega) = 312 k\Omega$$

$$A_v^{CE} = -\frac{11.0mS(18k\Omega)}{1 + 11.0mS(3k\Omega)} \left(\frac{104k\Omega \| 312k\Omega}{1k\Omega + 104k\Omega \| 312k\Omega} \right) = -5.75 \quad \text{The gain is essentially unchanged.}$$

Continued on the next page

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$$R_{iC} = 320k\Omega \left[1 + \frac{100(2k\Omega)}{(1k\Omega||104k\Omega) + 10.2k\Omega + 2k\Omega} \right] = 5.17 M\Omega \quad | \quad \mu_f R_E = 3140(2k\Omega) = 6.28 M\Omega$$

$$R_{iC} < \mu_f R_E \quad | \quad R_{out} = 5.17 M\Omega || 22k\Omega = 21.9 k\Omega \quad | \quad R_{out} << \mu_f R_E$$

$$\lim_{R_E \rightarrow \infty} R_{iC} = \lim_{R_E \rightarrow \infty} r_o \left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E} \right) = r_o \left(1 + \frac{\beta_o R_E}{R_E} \right) = (\beta_o + 1)r_o$$

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$$R_{iB} = 10.2k\Omega + 101(1k\Omega) = 111 k\Omega$$

$$A_v = -\frac{9.80mS(18k\Omega)}{1 + 9.80mS(1k\Omega)} \left(\frac{104k\Omega||111k\Omega}{1k\Omega + 104k\Omega||111k\Omega} \right) = -16.0 \quad | \quad R_4 = 13k\Omega - 1k\Omega = 12 k\Omega.$$

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CB}}{V_A} \right) \quad | \quad V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23}(300)}{1.60 \times 10^{-19}} = .025875 V$$

$$I_S = \frac{0.245mA}{\exp\left(\frac{0.7}{0.025875}\right) \left(1 + \frac{3.39 - 0.7}{100} \right)} = 425 fA$$

$$A_v^{CE} \cong -10V_{CC} = -10(20) = -200 \quad | \quad g_m = 40I_C = 40(100\mu A) = 4.00 mS \quad | \quad R_{iB} = r_\pi = \frac{\beta_o}{g_m} = \frac{100}{4mS} = 25 k\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{50V + 10V}{100\mu A} = 600 k\Omega \quad | \quad \mu_f = g_m r_o = 4mS(600k\Omega) = 2400$$

$$A_v^{CE} = -g_m(R_C||r_o) \frac{R_B||R_{iB}}{R_i + R_B||R_{iB}} = -4.00mS(100k\Omega||600k\Omega) \left(\frac{150k\Omega||25k\Omega}{5k\Omega + 150k\Omega||25k\Omega} \right) = -278$$

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$$V_{EQ} = \frac{1.5 M\Omega}{1.5 M\Omega + 2.2 M\Omega} 12V = 4.87 V \quad | \quad R_{EQ} = 1.5 M\Omega \parallel 2.2 M\Omega = 892 k\Omega$$

Neglect λ in hand calculations of the Q-point.

$$4.87 = V_{GS} + 12000I_D \quad | \quad 4.87 = V_{GS} + 12000 \left(\frac{5 \times 10^{-4}}{2} \right) (V_{GS} - 1)^2$$

$$3V_{GS}^2 - 5V_{GS} - 1.87 = 0 \rightarrow V_{GS} = 1.981 V \quad | \quad I_D = 241 \mu A$$

$$V_{DS} = 12 - 22000I_D - 12000I_D = 3.81 V \quad | \quad \text{Q-point: } (241 \mu A, 3.81 V)$$

$$A_{vdb}^{CS} = 20 \log |-4.50| = -13.1 dB$$

$$R_{iB} = 10.2 k\Omega + 101(1k\Omega) = 111 k\Omega$$

$$A_v^{CE} = -\frac{9.80mS(18k\Omega)}{1 + 9.80mS(1k\Omega)} \left(\frac{104k\Omega \parallel 111k\Omega}{1k\Omega + 104k\Omega \parallel 111k\Omega} \right) = -16.0 \quad | \quad R_4 = 13k\Omega - 1k\Omega = 12 k\Omega$$

$$A_v^{CS} = -\frac{0.503mS(18k\Omega)}{1 + 0.503mS(1k\Omega)} \left(\frac{892k\Omega}{1k\Omega + 892k\Omega} \right) = -6.02 \quad | \quad R_4 = 12k\Omega - 1k\Omega = 11 k\Omega$$

$$(iii) \quad R_{iB} = 10.2 k\Omega + 101(13k\Omega) = 1.32 M\Omega$$

$$A_v^{CE} = -\frac{9.80mS(18k\Omega)}{1 + 9.80mS(13k\Omega)} \left(\frac{104k\Omega \parallel 1.32 M\Omega}{1k\Omega + 104k\Omega \parallel 1.32 M\Omega} \right) = -1.36 \quad | \quad A_v^{CE} \cong -\frac{R_L}{R_E + R_4} = -\frac{18k\Omega}{13k\Omega} = -1.38$$

$$A_v^{CS} = -\frac{0.503mS(18k\Omega)}{1 + 0.503mS(12k\Omega)} \left(\frac{892k\Omega}{1k\Omega + 892k\Omega} \right) = -1.29 \quad | \quad A_v^{CS} \cong -\frac{R_L}{R_S + R_4} = -\frac{18k\Omega}{12k\Omega} = -1.50$$

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$$V_T = \left(\frac{1.381 \times 10^{-23}}{1.602 \times 10^{-19}} \frac{V}{K} \right) (273K + 27K) = 25.861 mV \quad | \quad I_S = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{245 \mu A}{\exp\left(\frac{0.700V}{0.025861V}\right)} = 0.430 fA$$

$$g_m R_L = -9.80mS(18k\Omega) = -176 \quad | \quad A_v^{CE} \cong -\frac{18k\Omega}{3k\Omega} = -6.00 \quad | \quad 5.72 < 6.00$$

$$g_m R_L = -0.503mS(18k\Omega) = -9.05 \quad | \quad A_v^{CS} \cong -\frac{18k\Omega}{2k\Omega} = -9.00 \quad | \quad 4.50 < 9.00$$

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$$R_B = 160k\Omega \parallel 300k\Omega = 104k\Omega \quad | \quad R_{iB} \equiv r_\pi(1 + g_m R_L) = \frac{2.5V}{0.25mA} [1 + 10mS(11.5k\Omega)] = 1.16 M\Omega$$

$$v_i \leq 0.005V(1 + g_m R_L) \frac{R_I + R_B \parallel R_{iB}}{R_B \parallel R_{iB}} = 0.005V[1 + 10mS(11.5k\Omega)] \frac{2k\Omega + 95.4k\Omega}{95.4k\Omega} = 0.592 V$$

$$v_i \leq 0.2(V_{GS} - V_{TN})(1 + g_m R_L) \frac{R_I + R_G}{R_G} = 0.2(1V)[1 + 0.5mS(10.7k\Omega)] \frac{2k\Omega + 892k\Omega}{892k\Omega} = 1.27 V$$

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$$A_{vt} = \frac{2k\Omega + 892k\Omega}{892k\Omega} 0.971 = 0.973 \quad | \quad \frac{(0.491ms)R_L}{1 + (0.491ms)R_L} = 0.973 \rightarrow R_L = 73.4k\Omega$$

$R_6 \parallel 100k\Omega = 73.4k\Omega \rightarrow R_6 = 276 k\Omega$ | Note, however, that the 12 kΩ resistor can't simply be replaced with a 276 kΩ resistor because of Q-point problems.

$$R_{iB} = 10.2k\Omega + 101(13k\Omega) = 1.32M\Omega \quad | \quad R_{in}^{CC} = 104k\Omega \parallel 1.32M\Omega = 96.4k\Omega$$

$$A_v^{CE} = -\frac{9.80mS(13k\Omega)}{1 + 9.80mS(13k\Omega)} \left(\frac{96.4k\Omega}{2k\Omega + 96.4k\Omega} \right) = +0.972$$

$$A_v^{CS} = -\frac{0.491mS(12k\Omega)}{1 + 0.491mS(12k\Omega)} \left(\frac{892k\Omega}{2k\Omega + 892k\Omega} \right) = +0.853$$

$$\text{BJT: } g_m R_L = 9.80mS(11.5k\Omega) = 113 \quad | \quad \text{FET: } g_m R_L = 0.491mS(10.7k\Omega) = 5.25$$

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$$\text{BJT: } v_i \leq 0.005V(1 + g_m R_I) \frac{R_I + R_6}{R_6} = 0.005V[1 + 9.8mS(2k\Omega)] \left(\frac{2k\Omega + 13k\Omega}{13k\Omega} \right) = 119 \text{ mV}$$

$$\text{Neglecting } R_6, \quad v_i \leq 0.005V(1 + g_m R_I) = 0.005V[1 + 9.8mS(2k\Omega)] = 103 \text{ mV}$$

$$\text{FET: } v_i \leq 0.2(V_{GS} - V_{TN})(1 + g_m R_I) \frac{R_I + R_6}{R_6} = 0.2(0.982)[1 + 0.491mS(2k\Omega)] \frac{2k\Omega + 12k\Omega}{12k\Omega} = 454 \text{ mV}$$

$$\text{Neglecting } R_6, \quad v_i \leq 0.2(V_{GS} - V_{TN})(1 + g_m R_I) = 0.2(0.982)[1 + 0.491mS(2k\Omega)] = 389 \text{ mV}$$

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$$R_{iC} = r_o \left[1 + \frac{\beta_o R_{th}}{R_{th} + r_\pi} \right] = 219k\Omega \left[1 + \frac{100(1.73k\Omega)}{1.73k\Omega + 10.2k\Omega} \right] = 3.40 M\Omega$$

Or more approximately, $R_{iC} = r_o [1 + g_m R_{th}] = 219k\Omega [1 + 9.8mS(1.73k\Omega)] = 3.93 M\Omega$

$$R_{iD} = r_o [1 + g_m R_{th}] = 223k\Omega [1 + 0.491(1.71k\Omega)] = 410 k\Omega$$

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$$A_v^{CB} = g_m R_L \frac{\frac{R_6}{g_m}}{R_6 + \frac{1}{R_I + \frac{R_6}{g_m}}} = g_m R_L \frac{\frac{R_6}{g_m}}{g_m R_I + \frac{R_6}{R_6 + \frac{1}{g_m}}} = g_m R_L \frac{\frac{R_6}{R_6(1 + g_m R_I) + R_I}}{R_6(1 + g_m R_I) + R_I}$$

$$A_v^{CB} = g_m R_L \frac{R_6}{R_6 + R_I} \frac{1}{1 + \frac{g_m R_I R_6}{R_6 + R_I}} = \frac{g_m R_L}{1 + g_m R_{th}} \left(\frac{R_6}{R_6 + R_I} \right)$$

The voltage gains are proportional to the load resistance

$$A_v^{CE} = +8.48 \left(\frac{22k\Omega}{18k\Omega} \right) = +10.4 \quad | \quad A_v^{CG} = +4.12 \left(\frac{22k\Omega}{18k\Omega} \right) = +5.02$$

$$\text{CB: } A_v^{CB} \leq g_m R_L = 176 \quad | \quad A_v^{CB} \cong \frac{R_L}{R_{th} \| R_6} = \frac{R_L}{R_I \| R_6} = \frac{18k\Omega}{1.73k\Omega} = 10.4 \quad | \quad 8.48 < 10.4 << 176$$

$$\text{CG: } A_v^{CG} \leq g_m R_L = 8.84 \quad | \quad A_v^{CG} \cong \frac{R_L}{R_{th} \| R_6} = \frac{R_L}{R_I \| R_6} = \frac{18k\Omega}{1.71k\Omega} = 10.5 \quad | \quad 4.11 < 8.84 < 10.5$$

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$$A_v^{CS} = \frac{1}{1 + \eta} \sqrt{\frac{(W/L)_1}{(W/L)_2}} \quad | \quad 10^{\frac{26}{20}} = \frac{1}{1 + 0.2} \sqrt{\frac{(W/L)_1}{4}} = \frac{2290}{1}$$

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$\eta = 0$ | $I_{D2} = I_{D1}$ | Both transistors are in the active region since $V_{DS} = V_{GS}$.

$$\text{Neglecting } \lambda: \frac{10^{-4}}{2} \left(\frac{2}{1} \right) (5 - V_o - 1)^2 = \frac{10^{-4}}{2} \left(\frac{8}{1} \right) (V_o - 1)^2 \rightarrow V_o = 2.00 \text{ V}$$

$$\text{Keeping } \lambda: \frac{10^{-4}}{2} \left(\frac{2}{1} \right) (5 - V_o - 1)^2 [1 + 0.02(5 - V_o)] = \frac{10^{-4}}{2} \left(\frac{8}{1} \right) (V_o - 1)^2 (1 + 0.02V_o) \rightarrow$$

$$V_o = 2.0064 \text{ V}, I_D = 421.39 \mu\text{A} \rightarrow \text{Q-point: } (2.01 \text{ V}, 421 \mu\text{A})$$

$I_{D2} = I_{D1}$ | Both transistors are in the active region since $V_{DS} = V_{GS}$.

$$K_n = 10^{-4} \left(\frac{20}{1} \right) = 2 \times 10^{-3} \frac{A}{V^2} \quad | \quad K_p = 4 \times 10^{-5} \left(\frac{50}{1} \right) = 2 \times 10^{-3} \frac{A}{V^2} \quad | \quad \text{The transistors are symmetrical.}$$

$$\therefore V_o = \frac{V_{DD}}{2} = \frac{3.3V}{2} = 1.65 \text{ V} \quad | \quad I_D = \frac{10^{-4}}{2} \left(\frac{20}{1} \right) (1.65 - 0.7)^2 [1 + 0.02(1.65)] = 932 \mu\text{A}$$

$$\text{Q-point: } (1.65 \text{ V}, 932 \mu\text{A})$$

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Since we need high gain, the emitter should be bypassed, and $R_{in}^{CE} = R_B \| r_\pi = 250k\Omega$.

$$\text{If we choose } R_B \cong r_\pi, I_C = \frac{\beta_o}{40r_\pi} \cong \frac{100}{40(500k\Omega)} = 5 \mu\text{A}$$

$$R_{in}^{CG} \cong \frac{1}{g_m} \quad | \quad I_C \cong \frac{1}{40(2k\Omega)} = 12.5 \mu\text{A}$$

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Common – Emitter :

$$C_1 \gg \frac{1}{2\pi(250\text{Hz})(1k\Omega + 77.9k\Omega)} = 8.07nF \quad | \quad \text{Choose } C_1 = 82 \text{ nF} = 0.082 \mu\text{F}$$

$$C_2 \gg \frac{1}{2\pi(250\text{Hz})(21.9k\Omega + 82k\Omega)} = 6.13nF \quad | \quad \text{Choose } C_2 = 68 \text{ nF} = 0.068 \mu\text{F}$$

$$C_3 \gg \frac{1}{2\pi(250\text{Hz})\left[10k\Omega \left(3k\Omega + \frac{1}{9.80mS}\right)\right]} = 0.269\mu\text{F} \quad | \quad \text{Choose } C_3 = 2.7 \mu\text{F}$$

Common – Source :

$$C_1 \gg \frac{1}{2\pi(250\text{Hz})(1k\Omega + 892k\Omega)} = 713pF \quad | \quad \text{Choose } C_1 = 8200 \text{ pF}$$

$$C_2 \gg \frac{1}{2\pi(250\text{Hz})(21.5k\Omega + 82k\Omega)} = 6.15nF \quad | \quad \text{Choose } C_2 = 68 \text{ nF} = 0.068 \mu\text{F}$$

$$C_3 \gg \frac{1}{2\pi(250\text{Hz})\left[10k\Omega \left(2k\Omega + \frac{1}{0.491mS}\right)\right]} = 0.221\mu\text{F} \quad | \quad \text{Choose } C_3 = 2.2 \mu\text{F}$$

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Common – Collector :

$$C_1 \gg \frac{1}{2\pi(250\text{Hz})(1k\Omega + 95.5k\Omega)} = 6.60nF \quad | \quad \text{Choose } C_1 = 68 \text{ nF} = 0.068 \mu\text{F}$$

$$C_2 \gg \frac{1}{2\pi(250\text{Hz})(120\Omega + 82k\Omega)} = 7.75nF \quad | \quad \text{Choose } C_2 = 82 \text{ nF} = 0.082 \mu\text{F}$$

Common – Drain :

$$C_1 \gg \frac{1}{2\pi(250\text{Hz})(1k\Omega + 892k\Omega)} = 713pF \quad | \quad \text{Choose } C_1 = 8200 \text{ pF}$$

$$C_2 \gg \frac{1}{2\pi(250\text{Hz})(1.74k\Omega + 82k\Omega)} = 7.60nF \quad | \quad \text{Choose } C_2 = 82 \text{ nF} = 0.082 \mu\text{F}$$

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Common – Base :

$$C_1 \gg \frac{1}{2\pi(250\text{Hz})(1k\Omega + 0.1k\Omega)} = 0.579 \mu F \quad | \quad \text{Choose } C_1 = 6.8 \mu F$$

$$C_2 \gg \frac{1}{2\pi(250\text{Hz})(21.9k\Omega + 82k\Omega)} = 6.13nF \quad | \quad \text{Choose } C_2 = 0.068 \mu F$$

$$C_3 \gg \frac{1}{2\pi(250\text{Hz})\left(160k\Omega \parallel 300k\Omega \parallel \left[10.2k\Omega + 101(13k\Omega \parallel 1k\Omega)\right]\right)} = 12.2nF \quad | \quad \text{Choose } C_3 = 0.12 \mu F$$

Common – Gate :

$$C_1 \gg \frac{1}{2\pi(250\text{Hz})(1k\Omega + 1.74k\Omega)} = 0.232 \mu F \quad | \quad \text{Choose } C_1 = 2.2 \mu F$$

$$C_2 \gg \frac{1}{2\pi(250\text{Hz})(20.9k\Omega + 82k\Omega)} = 6.19nF \quad | \quad \text{Choose } C_2 = 0.068 \mu F$$

$$C_3 \gg \frac{1}{2\pi(250\text{Hz})(1.5M\Omega \parallel 2.2M\Omega)} = 714 pF \quad | \quad \text{Choose } C_3 = 8200 pF$$

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(a) Common – Source :

$$C_3 = \frac{1}{2\pi(1000\text{Hz})\left[10k\Omega \parallel \left(2k\Omega + \frac{1}{0.491mS}\right)\right]} = 55.3nF \quad | \quad \text{Choose } C_3 = 0.056 \mu F$$

(b) Common – Collector :

$$C_2 \gg \frac{1}{2\pi(2000\text{Hz})(120\Omega + 100k\Omega)} = 795 pF \quad | \quad \text{Choose } C_2 = 820 pF$$

(c) Common – Gate :

$$C_1 \gg \frac{1}{2\pi(1000\text{Hz})(2k\Omega + 1.74k\Omega)} = 42.6nF \quad | \quad \text{Choose } C_1 = 0.042 \mu F$$

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$$20V = V_{GS} + 3600I_D \quad | \quad 20 = V_{GS} + 3600 \frac{0.020}{2} (V_{GS} - 1.5)^2 \rightarrow V_{GS} = 2.203 \text{ V} \quad | \quad I_D = 4.94 \text{ mA}$$

$$V_{DS} = 5 - (-V_{GS}) = 7.20 \text{ V} \quad | \quad \text{Q-point: } (4.94 \text{ mA}, 7.20 \text{ V}) \quad | \quad R_{in} = R_G = 22 \text{ M}\Omega$$

$$A_v^{CD} = \frac{g_m R_L}{1 + g_m R_L} \quad | \quad g_m = \frac{2(4.94 \text{ mA})}{(2.20 - 1.50)V} = 14.2 \text{ mS} \quad | \quad R_L = 3600\Omega \parallel 3000\Omega = 1630 \text{ }\Omega \quad | \quad A_v^{CD} = 0.959$$

$$R_{out}^{CD} = 3.6k\Omega \left\| \frac{1}{g_m} \right\| = 3.6k\Omega \left\| \frac{1}{0.0142} \right\| = 69.1 \text{ }\Omega \quad | \quad v_{gs} \leq 0.2(2.20 - 1.50) [1 + 0.0142(1630)] = 3.38 \text{ V}$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{\frac{1}{0.015} + 5 + 2.21}{0.005} = 14.8 \text{ k}\Omega \quad | \quad R_L = 3600\Omega \parallel 3000\Omega \parallel 14.8k\Omega = 1470 \text{ }\Omega \quad | \quad A_v^{CD} = 0.954$$

$$\frac{W}{L} = \frac{K_n}{K'_n} = \frac{2 \times 10^{-2}}{5 \times 10^{-5}} = \frac{400}{1}$$

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$$A = \frac{g_m R_S}{1 + g_m R_S} \quad | \quad g_m = \frac{2(4.94 \text{ mA})}{(2.20 - 1.50)V} = 14.2 \text{ mS} \quad | \quad R_S = 3600 \text{ }\Omega \quad | \quad A_v^{CD} = 0.981 \quad | \quad R_{in} = R_G = 22 \text{ M}\Omega$$

$$R_{out}^{CD} = 3.6k\Omega \left\| \frac{1}{g_m} \right\| = 3.6k\Omega \left\| \frac{1}{0.0142} \right\| = 69.1 \text{ }\Omega \quad | \quad A_v^{CD} = A \frac{3000\Omega}{69.1\Omega + 3000\Omega} = 0.959$$

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Reverse the direction of the arrow on the emitter of the transistor as well as the values of V_{EE} and V_{CC} .

$$R_{in}^{CG} = R_E \left| \frac{1}{g_m} \right| = 13k\Omega \left| \frac{1}{40(331\mu A)} \right| = 75.1 \Omega \quad | \quad A_v^{CB} = \frac{75.1\Omega}{75\Omega + 75.1\Omega} (13.2mS)(7.58k\Omega) = 50.1$$

For $v_{CB} \geq 0$, we require $v_C \geq 0$. $V_C = 5 - I_C R_C = 2.29 V \quad \therefore |v_c| \leq 2.29 V$

$$v_o \leq 5mV(g_m R_L) = 5mV(13.2mS)(7580\Omega) = 0.500 V$$

$$R_E = 75\Omega [1 + 40(7.5 - 0.7)] = 20.5 k\Omega \text{ (a standard 1% value)} \quad | \quad I_C \cong \frac{6.8V}{20.5k\Omega} = 332 \mu A$$

$$50 = 40(332\mu A)R_L \frac{75}{75 + 75} \rightarrow R_L = 7.53k\Omega \rightarrow R_C = 8.14 k\Omega \rightarrow 8.06 k\Omega \text{ (a standard 1% value)}$$

$$V_{EC} = 0.7 + 7.5 - I_C R_C = 5.52 V$$

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$$5\% \text{ tolerances } I_C^{\max} \cong \frac{V_{EE}^{\max} - 0.7V}{R_E^{\min}} = \frac{5(1.05) - 0.7V}{13k\Omega(0.95)} = 368\mu A$$

$$V_C^{\min} = V_{CC}^{\min} - I_C^{\max} R_C^{\max} = 5V(0.95) - 368\mu A(8.2k\Omega)(1.05) = 1.58 V \quad | \quad 1.58 \geq 0, \text{ so active region is ok.}$$

$$10\% \text{ tolerances } I_C^{\max} \cong \frac{V_{EE}^{\max} - 0.7V}{R_E^{\min}} = \frac{5(1.1) - 0.7V}{13k\Omega(0.9)} = 410\mu A$$

$$V_C^{\min} = V_{CC}^{\min} - I_C^{\max} R_C^{\max} = 5V(0.90) - 410\mu A(8.2k\Omega)(1.1) = 0.802 V \quad | \quad 0.802 \geq 0, \text{ so active region is ok.}$$

$$v_{th} = v_i \frac{R_{in}^{CB}}{75\Omega + R_{in}^{CB}} g_m R_C = v_i \frac{75}{75\Omega + 75} (13.2mS)(8200\Omega) = 54.1v_i \quad | \quad R_{th} = R_{out}^{CB} = 8.2 k\Omega$$

$$A_v^{CG} = \frac{v_o}{v_i} = \frac{v_{th}}{v_i} \frac{100k\Omega}{R_{th} + 100k\Omega} = 54.1 \frac{100k\Omega}{8.2k\Omega + 100k\Omega} = 50.0$$

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$$r_o \cong r_o = \frac{1}{\lambda I_D} = \frac{1}{0.015(2 \times 10^{-4})} = 333 \text{ k}\Omega$$

$$\text{or more exactly } V_{DS} = 25 - 10^5 I_D - 9.1 \times 10^3 I_D = 25 - 1.09 \times 10^5 (0.2 \text{ mA}) = 3.18 \text{ V}$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{\frac{1}{0.015} + 3.18}{2 \times 10^{-4}} = 349 \text{ k}\Omega \quad | \quad R_L = 100 \text{ k}\Omega \parallel 100 \text{ k}\Omega \parallel 349 \text{ k}\Omega = 43.7 \text{ k}\Omega$$

$$A_v^{CS} = -(g_m R_L) \frac{R_{in}}{R_I + R_{in}} = -\frac{2(0.2 \text{ mA})}{0.2V} (43.7 \text{ k}\Omega) \left(\frac{75 \Omega}{75 \Omega + 75 \Omega} \right) = -43.7$$

$$I_D = \frac{0.01}{2} (0.25)^2 = 0.3125 \text{ mA} \quad | \quad V_{GS} - V_{TN} = 0.25 \text{ V} \quad | \quad V_{GS} = 0.25 - 2 = -1.75 \text{ V}$$

$$R_S = \frac{-V_{GS}}{I_D} = \frac{1.75V}{0.3125mA} = 5.60 \text{ k}\Omega \rightarrow 5.6 \text{ k}\Omega \quad | \quad R_L = 2 \frac{A_v}{g_m} = \frac{50(0.25V)}{0.3125mA} = 40 \text{ k}\Omega \quad | \quad R_D \parallel 100 \text{ k}\Omega = 40 \text{ k}\Omega$$

$$R_D = 66.7 \text{ k}\Omega \rightarrow 68 \text{ k}\Omega \quad | \quad C_1 \text{ remains unchanged.}$$

$$C_2 \gg \frac{1}{10^6 \pi (68 \text{ k}\Omega + 100 \text{ k}\Omega)} = 1.90 \text{ pF} \rightarrow \text{Choose } C_2 = 20 \text{ pF}$$

$$C_3 \gg \frac{1}{10^6 \pi (5.6 \text{ k}\Omega \parallel \frac{1}{2.5 \text{ mS}})} = 0.853 \text{ nF} \rightarrow \text{Choose } C_3 = 8200 \text{ pF}$$

$$v_{th} = v_i \frac{R_{in}^{CG}}{75 \Omega + R_{in}^{CG}} g_m R_D = v_i \frac{75 \Omega}{75 \Omega + 75 \Omega} (2 \text{ mS}) (100 \text{ k}\Omega) = 100 v_i \quad | \quad R_{th} = R_{out}^{CG} = 100 \text{ k}\Omega$$

$$A_v^{CG} = \frac{v_o}{v_i} = \frac{v_{th}}{v_i} \frac{100 \text{ k}\Omega}{R_{th} + 100 \text{ k}\Omega} = 100 \frac{100 \text{ k}\Omega}{100 \text{ k}\Omega + 100 \text{ k}\Omega} = 50.0$$

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$$M_1: I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2 \quad | \quad V_{GS} = -R_{S1} I_D \quad | \quad I_D = \frac{0.01}{2} (-200I_D + 2)^2 \rightarrow I_D = 5.00 \text{ mA}$$

$$V_{DS} = 15 - 5\text{mA}(820\Omega) = 10.9 \text{ V}$$

$$g_m = \sqrt{2K_n I_D} = \sqrt{2(0.01)(0.005)} = 10.0 \text{ mS} \quad | \quad r_o = \frac{1 + \lambda V_{DS}}{\lambda I_D} = \frac{1 + 0.02(10.9)}{0.02(5\text{mA})} = 12.2 \text{ k}\Omega$$

$$Q_2: V_{EQ} = \frac{22k\Omega}{22k\Omega + 78k\Omega} (15V) = 3.30 \text{ V} \quad | \quad R_{EQ} = 22k\Omega \| 78k\Omega = 17.2 \text{ k}\Omega$$

$$I_C = 150 \frac{3.30 - 0.7}{17.2k\Omega + 151(1.6k\Omega)} = 1.52 \text{ mA} \quad | \quad V_{CE} = 15 - 1.52\text{mA} \left(4.7k\Omega + \frac{151}{150} 1.6k\Omega \right) = 5.41 \text{ V}$$

$$g_m = 40(1.52\text{mA}) = 60.8 \text{ mS} \quad | \quad r_\pi = \frac{150}{60.8\text{mS}} = 2.47 \text{ k}\Omega \quad | \quad r_o = \frac{80 + 5.41}{1.52\text{mA}} = 56.2 \text{ k}\Omega$$

$$Q_3: V_{EQ} = \frac{120k\Omega}{120k\Omega + 91k\Omega} (15V) = 8.53 \text{ V} \quad | \quad R_{EQ} = 120k\Omega \| 91k\Omega = 51.8 \text{ k}\Omega$$

$$I_C = 80 \frac{8.53 - 0.7}{51.8k\Omega + 81(3.3k\Omega)} = 1.96 \text{ mA} \quad | \quad V_{CE} = 15 - 1.96\text{mA} \left(\frac{81}{80} 3.3k\Omega \right) = 8.45 \text{ V}$$

$$g_m = 40(1.96\text{mA}) = 78.4 \text{ mS} \quad | \quad r_\pi = \frac{80}{78.4\text{mS}} = 1.02 \text{ k}\Omega \quad | \quad r_o = \frac{60 + 8.45}{1.96\text{mA}} = 34.9 \text{ k}\Omega$$

A typical op-amp gain is at least 10,000 which exceeds the amplification factor of a single transistor.

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$$R_{L1} = 478\Omega \| 12.2k\Omega = 460 \text{ }\Omega \quad | \quad R_{L2} = 3.53k\Omega \| 54.2k\Omega = 3.31 \text{ k}\Omega \quad | \quad R_{L3} = 232\Omega \| 34.4k\Omega = 230 \text{ }\Omega$$

$$A_v = -10\text{mS}(460\Omega)(-62.8\text{mS})(3.31\text{k}\Omega) \left[\frac{79.6\text{mS}(230\Omega)}{1 + 79.6\text{mS}(230\Omega)} \right] \left(\frac{1\text{M}\Omega}{10\text{k}\Omega + 1\text{M}\Omega} \right) = 898$$

$$20 \log(898) = 59.1 \text{ dB}$$

$$A_v \cong \left(-\frac{V_{DD}}{V_{GS} - V_{TN}} \right) (-10V_{CC})(1) = -\frac{15}{1} (-10)(15)(1) = 2250$$

$$A_v = -10\text{mS}(2.39\text{k}\Omega)(-62.8\text{mS})(19.8\text{k}\Omega)(0.95)(0.99) = 28000$$

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$$R_{out} = 3300 \left| \left(\frac{1}{0.0796S} + \frac{3990}{90.1} \right) \right| = 55.9 \Omega$$

Note that the answers are obtained directly from SPICE.

$$A_{vl} = -g_m R_{L1} = -\sqrt{2(0.01)(0.001)} (3k\Omega \| 17.2k\Omega \| 2.39k\Omega) = 5.52$$

$$A_v = -5.52(-222)(3.31k\Omega)(0.95)(0.99) = 1150$$

CHAPTER 15

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$$I_C = \alpha_F I_E = \frac{60}{61} \left[\frac{15 - 0.7}{2(75k\Omega)} \right] = 93.8 \mu A \quad | \quad V_{CE} = 15 - 93.8\mu A (75k\Omega) - (-0.7V) = 8.67 V$$

$$I_C = \alpha_F I_E = \frac{60}{61} \left[\frac{15 - V_{BE}}{2(75k\Omega)} \right] \quad \text{and} \quad V_{BE} = 0.025V \ln \left(\frac{I_C}{0.5 \times 10^{-15} A} \right) \rightarrow I_C = 94.7 \mu A, V_{BE} = 0.649 V$$

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$$v_{id} = v_1 - v_2 = 1.01 - 0.990 = 0.020 V \quad | \quad v_{ic} = \frac{v_1 + v_2}{2} = \frac{1.01 + 0.99}{2} = 1.00 V$$

$$v_{id} = v_1 - v_2 = 4.995 - 5.005 = -0.010 V \quad | \quad v_{ic} = \frac{v_1 + v_2}{2} = \frac{4.995 + 5.005}{2} = 5.00 V$$

$$v_{od} = A_{dd}v_{id} + A_{cd}v_{ic} \quad | \quad v_{oc} = A_{dc}v_{id} + A_{cc}v_{ic}$$

$$\begin{bmatrix} 2.20 \\ 0 \end{bmatrix} = \begin{bmatrix} A_{dd} & A_{cd} \end{bmatrix} \begin{bmatrix} 0.02 & 1.00 \\ -0.01 & 5.00 \end{bmatrix} \rightarrow \begin{bmatrix} A_{dd} & A_{cd} \end{bmatrix} = \begin{bmatrix} 100 & 0.20 \end{bmatrix}$$

$$\begin{bmatrix} 1.002 \\ 5.001 \end{bmatrix} = \begin{bmatrix} A_{dc} & A_{cc} \end{bmatrix} \begin{bmatrix} 0.02 & 1.00 \\ -0.01 & 5.00 \end{bmatrix} \rightarrow \begin{bmatrix} A_{dc} & A_{cc} \end{bmatrix} = \begin{bmatrix} 0.100 & 1.00 \end{bmatrix}$$

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$$\text{Differential output : } A_{dm} = A_{dd} = -20V_{CC} = -300 \quad | \quad A_{cm} = 0 \quad | \quad CMRR = \infty$$

$$\text{Single - ended output : } A_{dm} = \frac{A_{dd}}{2} = +10V_{CC} = 150 \quad | \quad CMRR = 20V_{EE} = 300 \quad | \quad A_{cm} = -\frac{150}{300} = -0.5$$

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$$V_{IC} = 15V \left[\frac{1 - \frac{100}{101} \left(\frac{R_C}{2R_C} \right) \frac{15 - 0.7}{15}}{1 + \frac{100}{101} \left(\frac{R_C}{2R_C} \right)} \right] = 5.30 V$$

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$$I_{DC} = I_{SS} - \frac{V_o}{R_{SS}} = 100\mu A - \frac{15V}{750k\Omega} = 80 \mu A$$

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$$I_D = \frac{I_{SS}}{2} = 100 \mu A \quad | \quad V_{DS} = 12 - I_D R_D + V_{GS} = 12 - 100\mu A (62k\Omega) + V_{GS} = 5.8V + V_{GS}$$

$$V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = V_{TN} + 0.2V \quad | \quad V_{TN} = 1 + 0.75(\sqrt{V_{SB} + 0.6} - \sqrt{0.6}) \quad | \quad V_{SB} = -V_{GS} - (-12V)$$

$$V_{SB} = 11.8 - V_{TN} \quad | \quad V_{TN} = 1 + 0.75(\sqrt{12.4 - V_{TN}} - \sqrt{0.6}) \rightarrow V_{TN} = 2.75V \quad | \quad V_{DS} = 8.75 V$$

Q-point: $(100 \mu A, 8.75 V)$

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$$R_{od} = 2r_o \cong 2 \frac{V_A}{I_C} = 2 \frac{60V}{37.5\mu A} = 3.20 M\Omega \quad | \quad R_{oc} \cong 2\mu_f R_{EE} = 2(40)(60)(1M\Omega) = 4.80 G\Omega$$

$$i_{dm} = g_m v_{dm} = 40(37.5\mu A)v_{dm} = 1.5 \times 10^{-3}v_{dm} \quad | \quad i_{cm} \cong \frac{v_{cm}}{2R_{EE}} = \frac{v_{cm}}{2M\Omega} = 5.00 \times 10^{-7}v_{cm}$$

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$$I_{C1} = I_{C2} = \frac{100}{101} \left(\frac{150\mu A}{2} \right) = 74.3 \mu A \quad | \quad I_{C3} = \frac{15V}{20k\Omega} = 750 \mu A \quad | \quad V_{CE3} = 15 - 0 = 15.0 V$$

$$V_{CE1} = 15 - 74.3\mu A (10k\Omega) - (-0.7) = 15.0 V \quad | \quad V_{CE2} = 15 - (74.3\mu A - 7.5\mu A)(10k\Omega) - (-0.7) = 15.0 V$$

$$V_{EB3} = (74.3\mu A - 7.5\mu A)(10k\Omega) = 0.668 V \quad | \quad I_{S3} = \frac{750\mu A}{\exp\left(\frac{0.668V}{0.025}\right)} = 1.87 \times 10^{-15} A$$

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$$A_{dm}^{\max} = 560 (15) = 8400 \quad | \quad I_{C1} \leq 50(1\mu A) = 50 \mu A \quad | \quad A_{dm} = \frac{8400}{1 + \frac{28}{100} \left(\frac{500\mu A}{50\mu A} \right)} = 2210$$

$$I_{C1} \leq 50(1\mu A) = 50 \mu A \quad | \quad A_{dm} = \frac{8400}{1 + \frac{28}{100} \left(\frac{5mA}{50\mu A} \right)} = 290$$

$$R_{in} = 2r_\pi = 2 \frac{50}{40(50\mu A)} = 50 k\Omega \quad | \quad R_{out} \cong \frac{15V}{0.5mA} = 30 k\Omega$$

$$R_{in} = 2r_\pi = 2 \frac{50}{40(50\mu A)} = 50 k\Omega \quad | \quad R_{out} \cong \frac{15V}{5mA} = 3.0 k\Omega$$

$$A_{dm}^{\max} = 560 (1.5) = 840$$

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$$CMRR \cong g_{m2}R_i = 40 \left(50\mu A \right) \left(750k\Omega \right) = 1500 \quad | \quad CMRR_{dB} = 20 \log(1500) = 63.5 \text{ dB}$$

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$$A_{dm} = \frac{g_{m2}}{2} \left(\frac{R_C r_{\pi 3}}{R_C + r_{\pi 3}} \right) (g_{m3} r_{o3}) = \frac{40}{2} \left(\frac{I_{C2} R_C r_{\pi 3}}{R_C + r_{\pi 3}} \right) (40 I_{C3} r_{o3}) \cong 800 \left(\frac{0.7 r_{\pi 3}}{R_C + r_{\pi 3}} \right) (V_{A3}) = \frac{560 V_{A3}}{1 + \frac{R_C}{r_{\pi 3}}}$$

$$A_{dm} = \frac{560 V_{A3}}{1 + \frac{40 I_{C3} R_C}{\beta_{o3}}} = \frac{560 V_{A3}}{1 + \frac{40 I_{C2} R_C}{\beta_{o3}} \left(\frac{I_{C3}}{I_{C2}} \right)} = \frac{560 V_{A3}}{1 + \frac{40(0.7)}{\beta_{o3}} \left(\frac{I_{C3}}{I_{C2}} \right)} = \frac{560 V_{A3}}{1 + \frac{28}{\beta_{o3}} \left(\frac{I_{C3}}{I_{C2}} \right)}$$

$$A_{dm}^{\max} = 560 \left(75 \right) = 42000 \quad | \quad I_{C1} \leq 50 \left(1\mu A \right) = 50 \text{ } \mu A$$

$$A_{dm} = \frac{42000}{1 + \frac{28}{100} \left(\frac{500\mu A}{50\mu A} \right)} = 11000 \quad | \quad A_{dm} = \frac{42000}{1 + \frac{28}{100} \left(\frac{5mA}{50\mu A} \right)} = 1450$$

$$R_{in} = 2r_{\pi} = 2 \frac{50}{40(50\mu A)} = 50 \text{ } k\Omega \quad | \quad R_{out} \cong r_{o3} = \frac{75V + 15V}{0.5mA} = 180 \text{ } k\Omega$$

$$R_{in} = 2r_{\pi} = 2 \frac{50}{40(50\mu A)} = 50 \text{ } k\Omega \quad | \quad R_{out} \cong \frac{90V}{5mA} = 18.0 \text{ } k\Omega$$

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$$A_{vt1} = -3.50 \quad | \quad A_{vt2} = -22mS(150k\Omega \parallel 162k\Omega \parallel 203k\Omega) = -1238$$

$$A_{vt3} = \frac{0.198S(2k\Omega \parallel 18k\Omega)}{1 + 0.198S(2k\Omega \parallel 18k\Omega)} = 0.9971 \quad | \quad A_{dm} = -3.50(-1238)(0.9971) = 4320$$

$$R_{in} = 2r_\pi = 2 \frac{100}{40(49.5\mu A)} = 101 k\Omega \quad | \quad R_{out} \cong \frac{1}{g_{m4}} + \frac{r_{o3} \parallel R_2}{\beta_{o4} + 1} = \frac{1}{40(4.95mA)} + \frac{162k\Omega \parallel 150k\Omega}{101} = 776 \Omega$$

$$P \cong (I_1 + I_2 + I_3)(V_{CC} + V_{EE}) = (100 + 500 + 5000)\mu A(30V) = 168 mW$$

$$I_C = 50\mu A \left(\frac{150}{151} \right) = 49.7 \mu A \quad | \quad I_{C3} = 500\mu A + \frac{5mA}{151} = 533 \mu A \quad | \quad R_C = \frac{0.7V}{\left(49.7 - \frac{533}{150} \right) \mu A} = 15.2 k\Omega$$

$$r_{\pi3} = \frac{150}{40(533\mu A)} = 7.04 k\Omega \quad | \quad A_{vt2} = -20(49.7\mu A)(15.2k\Omega \parallel 7.04k\Omega) = -4.68$$

$$I_{C4} = \frac{150}{151} 5mA = 4.97 mA \quad | \quad r_{\pi4} = \frac{150}{40(4.97mA)} = 755 \Omega \quad | \quad r_{o3} = \frac{75 + 14.3}{533\mu A} = 168 k\Omega$$

$$A_{vt2} = -40(533\mu A) [168k\Omega \parallel 755 + 151(2k\Omega)] = -2304$$

$$g_{m4} = 40(4.97mA) = 0.199 S \quad | \quad A_{vt3} = \frac{0.199S(2k\Omega)}{1 + 0.199S(2k\Omega)} = 0.998$$

$$A_{dm} = -4.78(-2304)(0.998) = 11000$$

$$R_{id} = 2r_{\pi1} = 2 \frac{150}{40(49.7\mu A)} = 151 k\Omega \quad | \quad R_{out} \cong \frac{1}{g_{m4}} + \frac{r_{o3} \parallel R_2}{\beta_{o4} + 1} = \frac{1}{40(4.95mA)} + \frac{168k\Omega}{151} = 1.12 k\Omega$$

CMRR is set by the input stage and doesn't change since the bias current is the same.

$$r_{o3} = \frac{50 + 14.3}{550\mu A} = 117 k\Omega \quad | \quad A_{vt2} = -22mS(117k\Omega \parallel 203k\Omega) = -1630 \quad | \quad A_{dm} = -3.50(-1630)(0.998) = 5700$$

$$2 \frac{100}{40(49.5\mu A)} = 101 k\Omega \quad | \quad R_{out} \cong \frac{1}{g_{m4}} + \frac{r_{o3} \parallel R_2}{\beta_{o4} + 1} = \frac{1}{40(4.95mA)} + \frac{117k\Omega}{101} = 1.16 k\Omega$$

CMRR and input resistance are set by the input stage and don't change.

$$A_v = \frac{T}{1+T} = \frac{6920}{6921} = 0.99986 \quad | \quad T_{OC} = T \quad | \quad T_{SC} = 0 \quad | \quad R_{out} = \frac{R_o}{1+T} = \frac{1.62k\Omega}{1+6920} = 0.234 \Omega$$

$$R_{in} \cong R_{id}(1 + T_{SC}) = 101k\Omega(6921) = R_{id}(1 + T) = 699 M\Omega \quad (\text{Assuming } T_{OC} \ll 1)$$

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$$V_{GS3} = 1 + \sqrt{\frac{2(500\mu A)}{2.5mA}} = 1.63 V \quad | \quad R_D = \frac{1.63V}{100\mu A} = 16.3 k\Omega$$

$$A_{vt1} = -\frac{1}{2} \sqrt{2(0.005)(100\mu A)(16.3k\Omega)} = -8.16 \quad | \quad A_{vt2} = -g_m r_{o3} = -\sqrt{2(0.0025)(0.0005)} \left(\frac{1}{0.01(0.5mA)} \right) = -316$$

$$g_{m4} = \sqrt{2(0.005mA)(0.005mA)} = 7.07 mS \quad | \quad A_{vt3} = \frac{7.07mS(2k\Omega)}{1 + 7.07mS(2k\Omega)} = 0.934$$

$$A_{dm} = -8.16(-316)(0.934) = 2410 \quad | \quad R_{id} = \infty \quad | \quad R_o = \frac{1}{g_{m4}} = \frac{1}{7.07mS} = 141 \Omega$$

$$CMRR = g_m R_l = 1.00mS(375k\Omega) = 375 \text{ or } 51.5 dB$$

$$P \cong (I_1 + I_2 + I_3)(V_{DD} + V_{SS}) = (5.7mA)(24V) = 137 mW$$

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$$A_{dd1} = -\sqrt{\frac{K'_n}{K'_P}} \sqrt{\frac{(W/L)_2}{(W/L)_{L2}}} \quad | \quad 10 = \sqrt{2.5} \sqrt{\frac{(W/L)_2}{4}} \rightarrow (W/L)_2 = \frac{160}{1}$$

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$$V_{GS1} + V_{SG2} = 0.5mA(4.4k\Omega) = 2.2 V \quad | \quad \text{Since the device parameters are the same,}$$

$$V_{GS1} = V_{SG2} = 1.1 V \quad | \quad I_D = \frac{0.025}{2} (1.1 - 1)^2 = 125 \mu A$$

$$\text{Since the device parameters are the same, } V_{BE1} = V_{EB2} = \frac{0.5mA(2.4k\Omega)}{2} = 0.6 V$$

$$I_C = (10^{-14} A) \exp\left(\frac{0.6}{0.025}\right) = 265 \mu A$$

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$$A_{v1} = \frac{v_d}{v_g} = -g_m n^2 R_L = -(50mA/V^2)(2V - 1V)(10)^2(8\Omega) = -40.0$$

$$A_{vo} = A_{v1} \frac{1}{n} = -\frac{40.0}{10} = -4.00 \quad | \quad |v_g| \leq 0.2(2 - 1)V = 0.200 V \quad | \quad |v_d| \leq 0.2V(40) = 8.00 V$$

$$|v_o| \leq \frac{8V}{10} = 0.800 V$$

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$$R_B \rightarrow 0 \quad | \quad R_{out} = 432k\Omega \left[1 + \frac{150(18.4k\Omega)}{18.8k\Omega + 18.4k\Omega} \right] = 32.5 M\Omega$$

$$V_{EQ} = -15V \frac{270k\Omega}{110k\Omega + 270k\Omega} = -10.66 V \quad | \quad R_{EQ} = 110k\Omega \parallel 270k\Omega = 78.2 k\Omega$$

$$I_C = 150 \frac{-10.66 - 0.7 - (-15)}{78.2k\Omega + 151(18k\Omega)} = 195 \mu A \quad | \quad V_B = V_{EQ} - I_B R_{EQ} = -10.66 - \frac{195 \mu A}{150} (78.2 k\Omega) = -10.8 V$$

$$P_{R_1} = \frac{(-10.8 + 15)^2}{110k\Omega} = 0.160 mW \quad | \quad P_{R_2} = \frac{(-10.8)^2}{270k\Omega} = 0.432 mW$$

$$P_{R_E} = \frac{(-10.8 - 0.7 + 15)^2}{18k\Omega} = 1.33 mW \quad | \quad r_o = \frac{(75 + 11.5)V}{195\mu A} = 446 k\Omega \quad | \quad r_\pi = \frac{150}{40(195\mu A)} = 19.3 k\Omega$$

$$R_{out} = 446k\Omega \left[1 + \frac{150(18k\Omega)}{78.2k\Omega + 19.3k\Omega + 18k\Omega} \right] = 10.9 M\Omega$$

$$R_i + R_2 \cong \frac{15V}{20\mu A} = 750k\Omega \quad | \quad \text{Using a spreadsheet with } I_o = 200 \mu A \text{ yields } V_{BB} = 9V.$$

$$R_i = 750k\Omega \left(\frac{9V}{15V} \right) = 450 k\Omega \quad | \quad R_i = 300 k\Omega \quad | \quad R_E = \frac{150}{151} \left[\frac{9 - 0.7 - 1.33\mu A(180k\Omega)}{200\mu A} \right] = 40.0 k\Omega$$

$$R_{out} = \left(\frac{75 + 15 - 8.3}{2 \times 10^{-4}} \right) \left[1 + \frac{150(40.0k\Omega)}{180k\Omega + 18.75k\Omega + 40.0k\Omega} \right] = 10.7 M\Omega$$

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$$V_{DS} \geq V_{GS} - V_{TN} = 1 + \sqrt{\frac{2(0.2mA)}{2.49mA/V^2}} = 1.40 V \quad | \quad V_D = V_S + 1.40 = -15 + 0.2mA(18.2k\Omega) + 1.40 = -9.96 V$$

$$\frac{W}{L} = \frac{K_n}{K'_n} = \frac{2.49mA/V^2}{25\mu A/V^2} = \frac{99.6}{1}$$

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$$P_{R_s} = (0.2mA)^2 18.2k\Omega = 0.728 \text{ mW} \quad | \quad I_{BIAS} = \frac{15V}{499k\Omega + 249k\Omega} = 20.1 \mu A$$

$$P_{R_4} = (20.1\mu A)^2 499k\Omega = 0.202 \text{ mW} \quad | \quad P_{R_3} = (20.1\mu A)^2 249k\Omega = 0.101 \text{ mW}$$

$$V_{GG} = -15V \frac{510k\Omega}{510k\Omega + 240k\Omega} = -10.2 \text{ V} \quad | \quad -10.2 - V_{GS} - 18000I_D = -15 \text{ V}$$

$$4.8 - V_{GS} - 18000 \frac{2.49mA}{2} (V_{GS} - 1)^2 = 0 \quad | \quad V_{GS} = 1.390 \text{ V} \quad | \quad I_D = 189 \mu A$$

$$R_{out} \cong \mu_f R_S \cong \frac{1}{0.01} \sqrt{\frac{2(2.49 \times 10^{-3})}{189 \times 10^{-6}}} [1 + 0.01(11.6)] (18k\Omega) = 10.3 M\Omega$$

CHAPTER 16

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$$R_{avg} = 10k\Omega(1 + 0.2) = 12 \text{ k}\Omega \quad | \quad 12k\Omega(1 - 0.01) \leq R \leq 12k\Omega(1 + 0.01) \quad | \quad 11.88 \text{ k}\Omega \leq R \leq 12.12 \text{ k}\Omega$$

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$$V_{DS1} = V_{TN} + \sqrt{\frac{2I_{REF}}{K_n(1 + \lambda V_{DS1})}} \quad | \quad V_{DS1} = 1 + \sqrt{\frac{2(150\mu A)}{250\mu A/V^2[1 + 0.0133V_{DS1}]}} \rightarrow V_{DS1} = 2.08 \text{ V}$$

$$I_O = 150\mu A \frac{1 + 0.0133(10)}{1 + 0.0133(2.08)} = 165 \text{ } \mu A$$

$$V_{DS} \geq V_{GS} - V_{TN} \quad | \quad V_D - (-10V) \geq \sqrt{\frac{2I_D}{K_n}} \quad | \quad V_D \geq -10V + \sqrt{\frac{2(150\mu A)}{250\mu A/V^2}} = -8.91 \text{ V}$$

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$$MR = \frac{25/1}{3/1} = 8.33 \quad | \quad V_{DS1} = 1V + \sqrt{\frac{2(50\mu A)}{3(25\mu A/V^2)}} = 2.16 \text{ V} \quad | \quad MR = 8.33 \frac{1 + 0.02(15)}{1 + 0.02(2.16)} = 10.4$$

$$MR = \frac{2/1}{5/1} = 0.400 \quad | \quad V_{DS1} = 1V + \sqrt{\frac{2(50\mu A)}{5(25\mu A/V^2)}} = 1.89 \text{ V} \quad | \quad MR = 8.33 \frac{1 + 0.02(10)}{1 + 0.02(1.89)} = 0.463$$

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$$I_{REF} = I_S \exp\left(\frac{V_{BE1}}{V_T}\right) \left(1 + \frac{V_{BE1}}{V_{A1}} + \frac{2}{\beta_{FO}}\right) \quad | \quad 100\mu A = (0.1fA) \exp(40V_{BE1}) \left(1 + \frac{V_{BE1}}{50V} + \frac{2}{100}\right) \rightarrow V_{BE1} = 0.690$$

$$V_{CE} \geq V_{BE} \rightarrow V_C \geq -V_{EE} + 0.690 \text{ V}$$

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$$(a) MR = \frac{0.5A}{A} = 0.5 \quad | \quad MR = \frac{5A}{2A} = 2.50$$

$$(b) MR = \frac{0.5}{1 + \frac{1.5}{75}} = 0.490 \quad | \quad MR = \frac{2.50}{1 + \frac{3.5}{75}} = 2.39$$

$$(c) MR = 0.5 \frac{1 + \frac{15}{60}}{1 + \frac{0.7}{60} + \frac{1.5}{75}} = 0.606 \quad | \quad MR = 2.5 \frac{1 + \frac{15}{60}}{1 + \frac{0.7}{60} + \frac{3.5}{75}} = 2.95$$

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$$I_{O_2} = 100\mu A \left(\frac{10/1}{5/1} \right) = 200 \mu A \quad | \quad I_{O_3} = 100\mu A \left(\frac{20/1}{5/1} \right) = 400 \mu A$$

$$I_{O_4} = 100\mu A \left(\frac{40/1}{5/1} \right) = 800 \mu A \quad | \quad I_{O_5} = 100\mu A \left(\frac{2.5/1}{5/1} \right) = 50 \mu A$$

$$I_{O_2} = 200\mu A \frac{1 + 0.02(10)}{1 + 0.02(2)} = 231 \mu A \quad | \quad I_{O_3} = 400\mu A \frac{1 + 0.02(5)}{1 + 0.02(2)} = 423 \mu A$$

$$I_{O_4} = 800\mu A \frac{1 + 0.02(12)}{1 + 0.02(2)} = 954 \mu A \quad | \quad I_{O_5} = 50\mu A \frac{1 + 0.02(8)}{1 + 0.02(2)} = 55.8 \mu A$$

$$I_{O_2} = 10\mu A \frac{1}{1 + \frac{17}{50}} = 7.46 \mu A \quad | \quad I_{O_3} = 5(7.46\mu A) = 37.3 \mu A \quad | \quad I_{O_4} = 10(7.46\mu A) = 74.6 \mu A$$

$$I_{O_2} = 10\mu A \frac{1 + \frac{10}{50}}{1 + \frac{0.7}{50} + \frac{17}{50}} = 8.86 \mu A \quad | \quad I_{O_3} = 50\mu A \frac{1 + \frac{10}{50}}{1 + \frac{0.7}{50} + \frac{17}{50}} = 44.3 \mu A$$

$$I_{O_4} = 100\mu A \frac{1 + \frac{10}{50}}{1 + \frac{0.7}{50} + \frac{17}{50}} = 88.6 \mu A$$

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$$MR = \frac{10}{1 + \frac{11}{50(51)}} = 9.957 \quad | \quad FE = \frac{10 - 9.957}{10} = 4.3 \times 10^{-3} \quad | \quad V_{CE2} = V_{BE1} + V_{BE3} = 1.4 V$$

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MOS

$$I_{O_2} = 200\mu A \frac{1 + 0.02(10)}{1 + 0.02(2)} = 231 \mu A \quad | \quad R_{out2} = \frac{50V + 10V}{231\mu A} = 260 k\Omega$$

$$I_{O_3} = 400\mu A \frac{1 + 0.02(5)}{1 + 0.02(2)} = 423 \mu A \quad | \quad R_{out3} = \frac{50V + 5V}{423\mu A} = 130 k\Omega$$

BJT

$$I_{O_2} = 10\mu A \frac{1 + \frac{10}{50}}{1 + \frac{0.7}{50} + \frac{17}{100}} = 10.1 \mu A \quad | \quad R_{out2} = \frac{50V + 10V}{10.1\mu A} = 5.94 M\Omega$$

$$I_{O_3} = 50\mu A \frac{1 + \frac{10}{50}}{1 + \frac{0.7}{50} + \frac{17}{100}} = 50.7 \mu A \quad | \quad R_{out3} = \frac{50V + 10V}{50.7\mu A} = 1.19 M\Omega$$

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$$I_{C1} = 100\mu A \frac{1 + \frac{0.7V}{50V}}{1 + \frac{0.7V}{50V} + \frac{6}{50V}} = 89.4\mu A \quad | \quad I_{C2} = 500\mu A \frac{1 + \frac{10V}{50V}}{1 + \frac{0.7V}{50V} + \frac{6}{50V}} = 529\mu A$$

$$R_{in} \cong \frac{1}{g_{m1}} = \frac{1}{40(89.4\mu A)} = 280 \Omega \quad | \quad \beta = \frac{529\mu A}{89.4\mu A} = 5.92 \quad | \quad R_{out} = \frac{50V + 10V}{529\mu A} = 113 k\Omega$$

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$$V_{DS1} = V_{GS1} = 0.75V + \sqrt{\frac{2(100\mu A)}{1mA/V^2}} = 1.20 V \quad | \quad I_{D2} = 100\mu A \frac{1 + \frac{10V}{50V}}{1 + \frac{1.2}{50V}} = 117 \mu A$$

$$R_{in} \cong \frac{1}{g_{m1}} = \frac{1}{\sqrt{2(10^{-3})(10^{-4})}} = 2.24 k\Omega \quad | \quad \beta = \frac{117\mu A}{100\mu A} = 1.17 \quad | \quad R_{out} = \frac{50V + 10V}{117\mu A} = 513 k\Omega$$

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$$R = \frac{V_T}{I_O} \ln\left(\frac{I_{REF}}{I_O} \frac{A_{E2}}{A_{E1}}\right) = \frac{0.025V}{25\mu A} \ln\left(\frac{100\mu A}{25\mu A} 5\right) = 3000 \Omega$$

$$K = 1 + \ln\left(\frac{100\mu A}{25\mu A} 5\right) = 4.00 \quad | \quad R_{out} = 4\left(\frac{75V}{25\mu A}\right) = 12.0 M\Omega$$

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$$I_O = \frac{V_T}{R} \ln\left(\frac{I_{REF}}{I_O} \frac{A_{E2}}{A_{E1}}\right) \quad | \quad I_O = \frac{0.025V}{100\Omega} \ln\left(\frac{1000\mu A}{I_O}\right) \rightarrow I_O = 300.54 \mu A$$

$$K = 1 + \ln\left(\frac{100\mu A}{300.54\mu A} 10\right) = 2.202 \quad | \quad R_{out} = 2.202\left(\frac{75V}{300.54\mu A}\right) = 550 k\Omega$$

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$$I_O = \frac{1}{R} \sqrt{\frac{2I_{REF}}{K_{n1}}} \left(1 - \sqrt{\frac{I_O}{I_{REF}} \frac{(W/L)_1}{(W/L)_2}} \right) \quad | \quad I_O = \frac{1}{2k\Omega} \sqrt{\frac{2(200\mu A)}{25\mu A/V^2}} \left(1 - \sqrt{\frac{I_O}{200\mu A} \frac{1}{10}} \right)$$

$$I_O = 2.00mA \left(1 - \sqrt{\frac{I_O}{2.00mA}} \right) \rightarrow I_O = 764 \mu A$$

$$R_{out} = \frac{50V + 10V}{764\mu A} \left(1 + 2000 \sqrt{2(2.5 \times 10^{-4})(7.64 \times 10^{-4})} \right) = 176 k\Omega$$

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$$R_{out} \cong \frac{\beta_o r_o}{2} = \frac{150}{2} \left(\frac{50V + 15V}{50\mu A} \right) = 97.5 M\Omega \quad | \quad R_{out} = r_o = \frac{50V + 15V}{50\mu A} = 1.30 M\Omega$$

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$$V_{DS2} = V_{GS2} = 0.8V + \sqrt{\frac{2(5 \times 10^{-5})}{2.5 \times 10^{-4}}} = 1.43 V \quad | \quad V_{DS4} = 15 - 1.43 = 13.6 V$$

$$R_{out} \cong \mu_{f4} r_{o2} = \sqrt{2(2.5 \times 10^{-4})(5 \times 10^{-5})[1 + 0.015(13.6)]} \left(\frac{\frac{1}{0.015} V + 13.6V}{50\mu A} \right) \left(\frac{\frac{1}{0.015} V + 1.43V}{50\mu A} \right) = 379 M\Omega$$

$$R_{out} = r_o = \frac{66.7V + 15V}{50\mu A} = 1.63 M\Omega$$

$$R_{out} \cong \frac{\beta_o r_o}{2} = \frac{100}{2} \left(\frac{67V + 14.3V}{50\mu A} \right) = 81.3 M\Omega \quad | \quad R_{out} = r_o = \frac{67V + 15V}{50\mu A} = 1.64 M\Omega$$

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$$I_O = 25.014 \mu A + \frac{10V - 20V}{1.66G\Omega} = 25.008 \mu A$$

$$V_{DS4} \geq V_{GS4} - V_{TN} = 0.2 \text{ V} \quad | \quad V_{D4} \geq V_{S4} + 0.2V \quad | \quad V_{D4} \geq 0.95 + 0.2 = 1.15 \text{ V}$$

$$I_O = 50 \mu A \pm 0.1\% \quad | \quad \Delta I_O \leq 50 \text{ nA} \quad | \quad R_{out} \geq \frac{20V}{50nA} = 400 M\Omega \quad | \quad \text{Choose } R_{out} = 1 G\Omega.$$

$$r_o \cong \frac{50V}{50\mu A} = 1 M\Omega \rightarrow \mu_f = 1000 \quad | \quad \mu_f \cong \frac{1}{\lambda} \sqrt{\frac{2K_n}{I_D}} \quad | \quad K_n = \left[\frac{0.01}{V} (1000) \right]^2 \frac{50\mu A}{2} = 2.5 \frac{mA}{V^2}$$

$$(W/L)_2 = (W/L)_4 = \frac{2.5 \times 10^{-3}}{5 \times 10^{-5}} = \frac{50}{1} \quad | \quad (W/L)_3 = (W/L)_1 = \frac{1}{2} \left(\frac{50}{1} \right) = \frac{25}{1}$$

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$$I_{REF} = \frac{5V - 0.7V}{43k\Omega} = 100 \mu A \quad | \quad I_{REF} = \frac{7.5V - 0.7V}{43k\Omega} = 158 \mu A$$

$$\text{Since the transistors have the same parameters, } V_{GS1} = \frac{V_{DD} - (-V_{SS})}{3}$$

$$I_{D2} = I_{D1} = \frac{4 \times 10^{-4}}{2} (1.667 - 1)^2 = 89.0 \mu A \quad | \quad I_{D2} = I_{D1} = \frac{4 \times 10^{-4}}{2} (2.5 - 1)^2 = 450 \mu A$$

$$I_O \cong \frac{0.025V}{6.8k\Omega} \ln \frac{5 - 1.4}{10^{-16}(39k\Omega)} = 101 \mu A \quad | \quad I_O \cong \frac{0.025V}{6.8k\Omega} \ln \frac{7.5 - 1.4}{10^{-16}(39k\Omega)} = 103 \mu A$$

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$$I_O = \frac{V_T}{R} \ln \left(\frac{I_{C1}}{I_{C2}} \frac{A_{E2}}{A_{E1}} \right) \quad | \quad I_O = \frac{0.025V}{1000\Omega} \ln [10(10)] = 115 \mu A$$

$$V_{CC} + V_{EE} \geq V_{BE1} + V_{BE4} \cong 1.4 \text{ V}$$

Page 1076

$$R = \sqrt{\frac{2}{5(25 \times 10^{-6})(10^{-4})}} \left(1 - \sqrt{\frac{5}{50}} \right) = 8.65 k\Omega$$

Page 1077

$$R = \frac{V_T}{I_O} \ln\left(\frac{I_{C1}}{I_{C2}} \frac{A_{E2}}{A_{E1}}\right) = \frac{0.025875V}{45\mu A} \ln\left(\frac{25}{5}\right) = 925 \Omega$$

$$A_{E1} = A \quad | \quad A_{E2} = 25 A_{E1} = 25 A \quad | \quad A_{E3} = A \quad | \quad A_{E4} = 5.58 A_{E3} = 5.58 A$$

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$$V_{PTAT} = V_T \ln\left(\frac{A_{E2}}{A_{E1}}\right) = (27.57mV) \ln(20) = 82.59 mV \quad | \quad R_l = \frac{V_{PTAT}}{I_E} = \frac{82.59mV}{25\mu A} = 3.30 k\Omega$$

$$V_{BE1} = V_T \ln\left(\frac{I_{C1}}{I_{S1}}\right) = (27.57mV) \ln\left(\frac{25\mu A}{0.5fA}\right) = 0.6792 V$$

$$\frac{R_2}{R_l} = \frac{V_{GO} + 3V_T - V_{BE1}}{2V_{PTAT}} = \frac{1.12 + 3(0.02757) - 0.6792}{2(0.08259)} = 3.169 \quad | \quad R_2 = 3.169 R_l = 10.5 k\Omega$$

$$V_{BG} = V_{BE1} + 2 \frac{R_2}{R_l} V_{PTAT} = 0.6792 + 2(3.169)(0.08259) = 1.203 V$$

The other resistors remain the same.

Page 1084

$$I_{D3} = I_{D4} = I_{D1} = I_{D2} = \frac{250\mu A}{2} = 125 \mu A \quad | \quad V_{GS1} = 0.75V + \sqrt{\frac{2(125\mu A)}{250\mu A/V^2}} = 1.75 V$$

$$V_{GS3} = -0.75V - \sqrt{\frac{2(125\mu A)}{200\mu A/V^2}} = -1.87 V$$

$$V_{DS1} = V_{D1} - V_{S1} = (5 - 1.87) - (-1.75) = 4.88 V \quad | \quad V_{SD3} = V_{SG3} = 1.87 V$$

$$M_1 \text{ and } M_2 : (125 \mu A, 4.88 V) \quad | \quad M_3 \text{ and } M_4 : (125 \mu A, 1.87 V)$$

$$G_m = g_{m1} = \sqrt{2(2.5 \times 10^{-4})(1.25 \times 10^{-4})} = 250 \mu S$$

$$R_o = r_{o2} \parallel r_{o4} = \frac{75.2V + 4.88V}{125\mu A} \parallel \frac{75.2V + 1.87V}{125\mu A} = 314 k\Omega \quad | \quad A_v = G_m R_o = 78.5$$

Page 1085

$$CMRR \cong \mu_{f3} g_{m2} R_{SS} = \left(\frac{1}{\lambda} \sqrt{\frac{2K_{n3}}{I_{D3}}} \right) \left(\sqrt{2K_{n2} I_{D2}} \right) R_{SS} = \left(\frac{1}{\lambda} \sqrt{\frac{2K_{n3}}{I_{D3}}} \right) \left(\sqrt{2K_{n2} I_{D2}} \right) R_{SS}$$

$$K_{n3} = K_{n2} \quad | \quad I_{D2} = I_{D3} \quad | \quad CMRR = \frac{1}{0.0167} 2(0.005) 10^7 = 5.99 \times 10^6 \quad \text{or} \quad 136 dB$$

Page 1089

For the buffered current mirror, $V_{EC4} = V_{EB3} + V_{EB11} + \frac{2V_A}{\beta_{FO4}(\beta_{FO11} + 1)}$

$$I_{C11} \cong \frac{2I_{C4}}{\beta_{FO4}} = \frac{2I_{C4}}{50} = \frac{I_{C4}}{25} \quad | \quad \Delta V_{EB} = 0.025 \ln\left(\frac{I_{C4}}{I_{C4}/25}\right) = 80.5 \text{ mV}$$

$$V_{EC4} = 0.7 + (0.7 - 0.081) + \frac{2(60)}{50(51)} = 1.37 \text{ V} \quad | \quad \Delta V_{EC} = \frac{2(60V)}{50(51)} = 47.1 \text{ mV} \quad | \quad V_{os} = \frac{47 \text{ mV}}{100} = 0.47 \text{ mV}$$

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$$A_{v1} \cong \left(\beta_{o5} \frac{I_{C2}}{I_{C5}} \right) = \frac{150}{3} = 50$$

For the whole amplifier: $A_{dm} \cong A_{v1} A_{v2} A_{v3} \quad | \quad A_{v2} \cong \mu_{f5} \cong 40(75) = 3000 \quad | \quad A_{v3} \cong 1$

$A_{dm} \cong 50(3000)(1) = 150000 \quad | \quad$ Note that this assumes $R_L = \infty$.

Page 1091

$$CMRR = \left[\frac{2}{\beta_{o3}} \left(\frac{1}{\beta_{o2} \mu_{f2}} - \frac{1}{2g_{m2} R_{EE}} \right) \right]^{-1} = \left[\frac{2}{100} \left(\frac{1}{100(40)(75)} - \frac{1}{2(40)(10^{-4})(10^7)} \right) \right]^{-1} = 5.45 \times 10^6 \rightarrow 135 \text{ dB}$$

Page 1096

$$A_{dm} \cong A_{v1} A_{v2} A_{v3} \quad | \quad A_{v1} \cong \frac{I_{C2}}{I_{C5}} \beta_{o5} = \frac{I_{REF}}{2} \frac{\beta_{o5}}{5I_{REF}} = \frac{50}{10} = 5 \quad | \quad A_{v2} \cong \frac{\mu_{f5}}{2} \cong \frac{40(60 + 14.7)}{2} \cong 1500 \quad | \quad A_{v3} \cong 1$$

$A_{dm} \cong 5(1500)(1) = 7500$ assuming the input resistance of the emitter followers is much greater than r_{o5} and $V_{A8} = V_{A5}$. Checking: $r_{o5} \cong \frac{60V + 14.7V}{500\mu A} = 149 \text{ k}\Omega \quad | \quad R_{iB6} \cong \beta_{o6} R_L = 300 \text{ M}\Omega$

$$I_{C5} = 10I_{C4} = 10I_{C3} \rightarrow A_{E5} = 10A \quad | \quad R_{id} = 2r_{\pi1} = 2 \frac{150}{40(50\mu A)} = 150 \text{ k}\Omega$$

Page 1098

$$I_{REF} = \frac{22 + 22 - 1.4}{39k\Omega} = 1.09 \text{ mA} \quad | \quad I_1 = \frac{0.025V}{5k\Omega} \ln\left(\frac{1.09mA}{I_1}\right) \rightarrow I_1 = 20.0 \text{ } \mu\text{A}$$

$$I_2 = 0.75(1.09mA) \frac{1 + \frac{23.4V}{60V}}{1 + \frac{0.7V}{60V} + \frac{2}{50}} = 1.08 \text{ mA} \quad | \quad I_2 = 0.25(1.09mA) \frac{1 + \frac{21.3V}{60V}}{1 + \frac{0.7V}{60V} + \frac{2}{50}} = 351 \text{ } \mu\text{A}$$

$$R_o = r_{o21} \left[1 + \ln \frac{I_{C20}}{I_{C21}} \frac{A_{E20}}{A_{E21}} \right] = \frac{60V + 13.5V}{18.4\mu\text{A}} \left[1 + \ln \left(\frac{733\mu\text{A}}{18.4\mu\text{A}} \right) \right] = 18.7 \text{ M}\Omega$$

Page 1102

$$V_{CE6} = V_{CE5} + \frac{2V_{A6}}{\beta_{FO6}} = 0.7 + \frac{2(60V)}{100} = 1.90 \text{ V}$$

Page 1105

$$R_{th} = R_{out4} \parallel R_{out6} = 2r_{o4} \parallel 1.3r_{o6} = 2 \left(\frac{60 + 13}{7.25\mu\text{A}} \right) \parallel 1.3 \left(\frac{60 + 1.3}{7.16\mu\text{A}} \right) = 20.1 \text{ M}\Omega \parallel 11.1 \text{ M}\Omega = 7.15 \text{ M}\Omega$$

Page 1107

$$A_{vl} = -1.46 \times 10^{-4} (6.54 \text{ M}\Omega \parallel R_{in1}) = -1.46 \times 10^{-4} (6.54 \text{ M}\Omega \parallel 20.7 \text{ k}\Omega) = -3.01$$

Page 1109

$$R_{eq2} = r_{\pi15} + (\beta_{o15} + 1)R_L = \frac{50(0.025)}{2mA} + 51(2k\Omega) = 103 \text{ k}\Omega$$

$$R_{eq1} = r_{d14} + (r_{d13} + R_3) \parallel R_{eq2} = \frac{0.025V}{0.216mA} + \left[\frac{0.025V}{0.216mA} + 344k\Omega \right] \parallel 103k\Omega = 79.4 \text{ k}\Omega$$

$$R_{in12} = \frac{50(0.025V)}{0.216mA} + 51(79.4k\Omega) = 4.06 \text{ M}\Omega$$

$$R_{eq3} = (r_{d13} + R_3) \left(r_{d14} + \frac{r_{\pi12} + y_{22}^{-1}}{\beta_{o12} + 1} \right) = \left(\frac{0.025V}{0.216mA} + 344k\Omega \right) \left(\frac{0.025V}{0.216mA} + \frac{5.79k\Omega + 89.1k\Omega}{51} \right) = 1.97 \text{ k}\Omega$$

$$r_{\pi16} = 50 \frac{0.025}{2mA} = 625 \text{ }\Omega \quad | \quad R_{out} = \frac{625 + 1970}{51} + 27 = 78 \text{ }\Omega$$

$$I_{SC+} \cong \frac{0.7V}{27\Omega} = 25.9 \text{ mA} \quad | \quad I_{SC-} \cong -\frac{0.7V}{22\Omega} = -31.8 \text{ mA}$$

Page 1112

$$v_o = \left(\frac{R}{I_{EE} R_1 R_3} \right) v_1 v_2 = K_M v_1 v_2 \quad | \quad K_M = \frac{|v_o|}{|v_1 v_2|} = \frac{5}{5^2} = 0.2 \quad | \quad K_M = \frac{|v_o|}{|v_1 v_2|} = \frac{1}{1^2} = 1$$

CHAPTER 17

Page 1131

$$f_L \cong \frac{1}{2\pi} \sqrt{10^2 + 1000^2 - 2(50)^2 - 2(0)^2} = 159 \text{ Hz} \quad | \quad f_L \cong \frac{1}{2\pi} \sqrt{100^2 + 1000^2 - 2(500)^2 - 2(0)^2} = 114 \text{ Hz}$$

Page 1132

$$\left| \frac{200s}{(s+1000)} \right| \geq 0.9 \left| \frac{200s(s+100)}{(s+10)(s+1000)} \right| \quad | \quad 1 \geq 0.9 \frac{\sqrt{\omega^2 + 100^2}}{\sqrt{\omega^2 + 10^2}} \rightarrow 0.81 \leq \frac{\omega^2 + 10^2}{\omega^2 + 100^2} \rightarrow \omega \geq 205 \text{ rad/s}$$

Page 1133

$$f_H \cong \frac{10^6}{2\pi} = 159 \text{ kHz}$$

Page 1134

$$f_H \cong \frac{1}{2\pi} \frac{1}{\sqrt{\left(\frac{1}{10^5}\right)^2 + \left(\frac{1}{5 \times 10^5}\right)^2 - 2\left(\frac{1}{2 \times 10^5}\right)^2 - 2\left(\frac{1}{\infty}\right)^2}} = 21.7 \text{ kHz}$$

Page 1139

The value of C_3 does not change A_{mid} , ω_{p1} , ω_{p2} , ω_{z1} , or ω_{z2} .

$$\omega_{p3} = -\frac{1}{2\mu F \left(1.3k\Omega \parallel \frac{1}{1.23mS} \right)} = -1000 \text{ rad/s} \quad | \quad \omega_{z3} = -\frac{1}{2\mu F (1.3k\Omega)} = -385 \text{ rad/s}$$

$$f_L = \frac{1}{2\pi} \sqrt{41.0^2 + 95.9^2 + 1000^2 - 2(0^2 + 0^2 + 385^2)} = 135 \text{ Hz}$$

$$A_{\text{mid}} = 10^{\frac{13.5}{20}} = 4.732 \quad | \quad 4.3k\Omega \parallel 100k\Omega \parallel r_o = \frac{4.732}{1.23mS} \rightarrow r_o = 57.5 \text{ k}\Omega$$

Note that the SPICE value of g_m probably differs from 1.23 mS as well.

$$\omega_{p3} = -\frac{1}{10\mu F \left(1.3k\Omega \parallel \frac{1}{1.23mS} \parallel 57.5k\Omega \right)} = -202 \text{ rad/s}$$

$$f_L = \frac{1}{2\pi} \sqrt{41.0^2 + 95.9^2 + 202^2 - 2(0^2 + 0^2 + 76.9^2)} = 31.8 \text{ Hz}$$

Page 1142

$$r_\pi = \frac{140(0.025V)}{175\mu A} = 20.0 \text{ k}\Omega \quad | \quad R_{1S}C_1 = (1k\Omega + 75k\Omega \parallel 20.0k\Omega)2\mu F = 33.6 \text{ ms} \quad | \quad R_{th} = 75k\Omega \parallel 1k\Omega = 987 \text{ }\Omega$$

$$R_{2S}C_2 = (43k\Omega + 100k\Omega)0.1\mu F = 14.3 \text{ ms} \quad | \quad R_{3S}C_3 = \left(13k\Omega \parallel \frac{20.0k\Omega + 987\Omega}{141}\right)10\mu F = 1.47 \text{ ms}$$

$$f_L \cong \frac{1}{2\pi} \left(\frac{1}{33.6ms} + \frac{1}{1.47ms} + \frac{1}{14.3ms} \right) = 124 \text{ Hz}$$

Page 1144

$$A_v = -\frac{R_{in}}{R_I + R_{in}} \left(\frac{\beta_o}{r_\pi} R_L \right) \cong -\left(\frac{1260}{2260} \right) \left(\frac{100}{1.51k\Omega} \right) (4.3k\Omega \parallel 100k\Omega) = -157$$

$$A_v = -\frac{R_{in}}{R_I + R_{in}} \left(\frac{\beta_o}{r_\pi} R_L \right) \cong -\left(\frac{1260}{2260} \right) \left(\frac{100}{1.51k\Omega} \right) (4.3k\Omega \parallel 100k\Omega \parallel 46.8k\Omega) = -140$$

r_o is responsible for most of the discrepancy. r_π and β_o will also be differ from our hand calculations. Note that 45% of the gain is lost because of the amplifier's low input resistance.

$$g_m = \frac{2(1.5mA)}{0.5V} = 6.00 \text{ mS} \quad | \quad R_{1S}C_1 = (1k\Omega + 243k\Omega)0.1\mu F = 24.4 \text{ ms}$$

$$R_{2S}C_2 = (4.3k\Omega + 100k\Omega)0.1\mu F = 10.4 \text{ ms} \quad | \quad R_{3S}C_3 = \left(1.3k\Omega \parallel \frac{1}{6.00mS}\right)10\mu F = 1.48 \text{ ms}$$

$$f_L \cong \frac{1}{2\pi} \left(\frac{1}{24.4ms} + \frac{1}{1.48ms} + \frac{1}{10.4ms} \right) = 129 \text{ Hz}$$

Page 1146

$$g_m = 40(0.1mA) = 4.00 \text{ mS} \quad | \quad R_{1S}C_1 = \left(100\Omega + 43k\Omega \parallel \frac{1}{4.00mS}\right)4.7\mu F = 1.64 \text{ ms}$$

$$R_{2S}C_2 = (22k\Omega + 75k\Omega)1\mu F = 97.0 \text{ ms} \quad | \quad f_L \cong \frac{1}{2\pi} \left(\frac{1}{1.64ms} + \frac{1}{97.0ms} \right) = 98.7 \text{ Hz}$$

Page 1147

$$g_m = \frac{2(1.5mA)}{0.5V} = 6.00 \text{ mS} \quad | \quad R_{1S}C_1 = \left(100\Omega + 1.3k\Omega \parallel \frac{1}{6.00mS}\right)1\mu F = 0.248 \text{ ms}$$

$$R_{2S}C_2 = (4.3k\Omega + 75k\Omega)0.1\mu F = 7.93 \text{ ms} \quad | \quad f_L \cong \frac{1}{2\pi} \left(\frac{1}{0.248ms} + \frac{1}{7.93ms} \right) = 662 \text{ Hz}$$

Page 1148

$$g_m = 40(1mA) = 40.0 \text{ mS} \quad | \quad r_\pi = \frac{100}{.04S} = 2.50 \text{ k}\Omega$$

$$R_{1S}C_1 = \left(1k\Omega + 100k\Omega \parallel [2.5k\Omega + 101(3k\Omega \parallel 47k\Omega)] \right) 0.1\mu F = 7.52 \text{ ms}$$

$$R_{2S}C_2 = \left(\frac{2.5k\Omega + (100k\Omega \parallel 1k\Omega)}{101} \right) 100\mu F = 4.70 \text{ s} \quad | \quad f_L \cong \frac{1}{2\pi} \left(\frac{1}{7.52ms} + \frac{1}{4.7s} \right) = 21.2 \text{ Hz}$$

$$A_{mid} \cong \frac{(\beta_o + 1)R_L}{R_{th} + r_\pi + (\beta_o + 1)R_L} \left(\frac{R_I}{R_I + R_B} \right) = \frac{101(3k\Omega \parallel 47k\Omega)}{990\Omega + 2.5k\Omega + 101(3k\Omega \parallel 47k\Omega)} \left(\frac{100k\Omega}{1k\Omega + 100k\Omega} \right) = +0.978$$

$$R_{1S}C_1 = (1k\Omega + 243k\Omega)0.1\mu F = 24.4 \text{ ms} \quad | \quad R_{2S}C_2 = \left(24k\Omega + 1.3k\Omega \parallel \frac{1}{1mS} \right) 47\mu F = 1.15 \text{ s}$$

$$f_L \cong \frac{1}{2\pi} \left(\frac{1}{24.4ms} + \frac{1}{1.15s} \right) = 6.66 \text{ Hz}$$

$$A_{mid} = + \left(\frac{R_G}{R_I + R_G} \right) \frac{g_m R_L}{1 + g_m R_L} = + \left(\frac{243k\Omega}{244k\Omega} \right) \left[\frac{1mS(1.3k\Omega \parallel 24k\Omega)}{1 + 1mS(1.3k\Omega \parallel 24k\Omega)} \right] = +0.550$$

Page 1152

$$C_\pi = \frac{g_m}{\omega_T} - C_\mu \quad C_\mu = \frac{C_{\mu o}}{\sqrt{1 + \frac{V_{CB}}{\varphi_{jc}}}}$$

$$(100 \mu A, 8 V): \quad C_\mu = \frac{2 pF}{\sqrt{1 + \frac{7.3V}{0.6V}}} = 0.551 pF \quad | \quad C_\pi = \frac{40(10^{-4})}{2\pi(500 MHz)} - 0.551 \times 10^{-12} = 0.722 pF$$

$$(2 mA, 5 V): \quad C_\mu = \frac{2 pF}{\sqrt{1 + \frac{4.3V}{0.6V}}} = 0.700 pF \quad | \quad C_\pi = \frac{40(2 \times 10^{-3})}{2\pi(500 MHz)} - 0.700 \times 10^{-12} = 24.8 pF$$

$$(50 mA, 8 V): \quad C_\mu = \frac{2 pF}{\sqrt{1 + \frac{7.3V}{0.6V}}} = 0.551 pF \quad | \quad C_\pi = \frac{40(5 \times 10^{-2})}{2\pi(500 MHz)} - 0.551 \times 10^{-12} = 636 pF$$

Page 1155

$$C_{GS} = C_{GD} = \frac{1}{2} C_{ISS} = 0.5 \text{ pF}$$

$$C_{GS} + C_{GD} = \frac{g_m}{\omega_T} \quad | \quad 5C_{GD} + C_{GD} = \frac{\sqrt{2(0.01)(0.01)}}{2\pi(200 \text{ MHz})} = 11.3 \text{ pF} \quad | \quad C_{GD} = 1.88 \text{ pF} \quad | \quad C_{GS} = 9.38 \text{ pF}$$

$$C_\mu = \frac{C_{uo}}{\sqrt{1 + \frac{V_{CB}}{\varphi_{jc}}}} = \frac{2 \text{ pF}}{\sqrt{1 + \frac{7.3V}{0.6V}}} = 0.551 \text{ pF} \quad | \quad C_\pi = \frac{g_m}{\omega_T} - C_\mu = \frac{40(20\mu A)}{2\pi(500 \text{ MHz})} - 0.551 \text{ pF} = -0.296 \text{ pF}$$

Page 1158

$$\begin{aligned} A_v &= -\frac{R_{in}}{R_I + R_{in}} \left(\frac{\beta_o}{r_x + r_\pi} R_L \right) \quad | \quad R_{in} = 7.5k\Omega \parallel (1.51k\Omega + 250\Omega) = 1.43k\Omega \\ &\equiv -\left(\frac{1430}{2430} \right) \left(\frac{100}{1.76k\Omega} \right) (4.3k\Omega \parallel 100k\Omega) = -139 \\ A_v &= -\frac{R_{in}}{R_I + R_{in}} \left(\frac{\beta_o}{r_\pi} R_L \right) \equiv -\left(\frac{1260}{2260} \right) \left(\frac{100}{1.51k\Omega} \right) (4.3k\Omega \parallel 100k\Omega) = -157 \end{aligned}$$

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The term $C_L \frac{R_L}{r_{\pi o}}$ is added to the value of C_T .

$$C_L \frac{R_L}{r_{\pi o}} = 3 \text{ pF} \left(\frac{4120}{656} \right) = 18.8 \text{ pF} \quad | \quad f_{P1} = \frac{1}{2\pi(656\Omega)(156 + 18.8)\text{pF}} = 1.39 \text{ MHz}$$

$$f_{P2} = \frac{g_m}{2\pi(C_\pi + C_L)} = \frac{0.064S}{2\pi(19.9 + 3)\text{pF}} = 445 \text{ MHz}$$

$$C_\pi = \frac{0.064}{2\pi(500 \text{ MHz})} - 10^{-12} = 19.4 \text{ pF}$$

$$C_T = 19.4 + 1 \left[1 + 0.064(4120) + \frac{4120}{656} \right] = 290 \text{ pF} \quad | \quad f_{P1} = \frac{1}{2\pi(656\Omega)290 \text{ pF}} = 837 \text{ kHz}$$

$$f_{P2} = \frac{g_m}{2\pi C_\pi} = \frac{0.064S}{2\pi(19.4 \text{ pF})} = 525 \text{ MHz} \quad | \quad f_z = \frac{g_m}{2\pi C_\mu} = \frac{0.064S}{2\pi(1 \text{ pF})} = 10.2 \text{ GHz}$$

$A_{mid} = -135$ is not affected by the value of f_T .

Page 1167

$$C_T = 10 + 2 \left[1 + 1.23mS(4.12k\Omega) + \frac{4120}{996} \right] = 30.4 \text{ pF} \quad | \quad f_{P1} = \frac{1}{2\pi(996\Omega)30.4 \text{ pF}} = 5.26 \text{ MHz}$$

$$f_{P2} = \frac{g_m}{2\pi C_{GS}} = \frac{1.23mS}{2\pi(10 \text{ pF})} = 19.6 \text{ MHz} \quad | \quad f_Z = \frac{g_m}{2\pi C_{GD}} = \frac{1.23mS}{2\pi(2 \text{ pF})} = 97.9 \text{ MHz}$$

$$f_T = \frac{g_m}{2\pi(C_{GS} + C_D)} = \frac{1.23mS}{2\pi(12 \text{ pF})} = 16.3 \text{ MHz}$$

Page 1174

$$1 + g_m R_E = 1 + 0.064(100) = 7.40 \quad | \quad R_{iB} = 250 + 1560 + 101(100) = 11.9 \text{ k}\Omega$$

$$r_{\pi 0} = 11.9 \text{ k}\Omega \parallel (882 + 250) = 1030 \text{ }\Omega \quad | \quad A_i = \frac{10 \text{ k}\Omega \parallel 30 \text{ k}\Omega \parallel 11.9 \text{ k}\Omega}{1 \text{ k}\Omega + 10 \text{ k}\Omega \parallel 30 \text{ k}\Omega \parallel 11.9 \text{ k}\Omega} = 0.821$$

$$A_{mid} = -0.821 \left(\frac{264}{7.4} \right) = -29.3 \quad | \quad f_H = \frac{1}{2\pi(1.03 \text{ k}\Omega) \left[\frac{19.9 \text{ pF}}{7.4} + 0.5 \text{ pF} \left(1 + \frac{264}{7.4} + \frac{4120}{1030} \right) \right]} = 6.70 \text{ MHz}$$

$$GBW = 29.3(6.70 \text{ MHz}) = 196 \text{ MHz}$$

Page 1176

$$A_{mid} \cong \frac{g'_m R_L}{1 + g'_m R_E} \quad | \quad g'_m = \frac{\beta_o}{r_x + r_\pi} = \frac{100}{250 + \frac{100}{40(0.1mA)}} = 3.96 \text{ mS} \quad | \quad A_{mid} \cong \frac{3.96mS(17.0k\Omega)}{1 + 3.96mS(100\Omega)} = +48.2$$

$$f_H \cong \frac{1}{2\pi(17.0k\Omega)(0.5 \text{ pF})} = 18.7 \text{ MHz} \quad | \quad GBW = 903 \text{ MHz}$$

$$R_{iS} = R_4 \left\| \frac{1}{g_m} \right\| = 1.3k\Omega \left\| \frac{1}{3mS} \right\| = 265 \text{ }\Omega$$

$$A_{mid} = 0.726(g_m R_L) = 0.726(3mS)(4.12k\Omega) = 8.98 \quad | \quad f_H \cong \frac{1}{2\pi(4.12k\Omega)(4 \text{ pF})} = 9.66 \text{ MHz}$$

$$GBW = 86.7 \text{ MHz} \quad | \quad f_T \cong \frac{3mS}{2\pi(11 \text{ pF})} = 43.4 \text{ MHz}$$

Page 1179

$$R_L = 1.3k\Omega \parallel 24k\Omega = 1.23k\Omega \quad | \quad A_{mid} = 0.998 \frac{3mS(1.23k\Omega)}{1 + 3mS(1.23k\Omega)} = 0.785$$

$$f_H \cong \frac{1}{2\pi} \frac{1}{(1k\Omega \parallel 430k\Omega) \left(1pF + \frac{10pF}{1 + 3.69} \right)} = 50.9 \text{ MHz}$$

Page 1182

$$f_z = \frac{1}{2\pi(25M\Omega)1pF} = 6.37 \text{ kHz} \quad | \quad f_p = \frac{1}{2\pi(50.25k\Omega)0.5pF} = 6.33 \text{ MHz}$$

Page 1184

Differential Pair : $A_{dm} = -g_m R_C = -40(99.0\mu A)(50k\Omega) = -198$

$$C_\pi = \frac{40(99.0\mu A)}{2\pi(500 \text{ MHz})} - 0.5pF = 0.761pF \quad | \quad r_\pi = \frac{100}{40(99.0\mu A)} = 25.3k\Omega$$

$$f_H = \frac{1}{2\pi(250\Omega) \left[0.761pF + 0.5pF \left(1 + 198 + \frac{50k\Omega}{250\Omega} \right) \right]} = 3.18 \text{ MHz}$$

$$\text{CC - CB Cascade : } A_v = \frac{g_{m1} \left(\frac{1}{g_{m2}} \right)}{1 + g_{m1} \left(\frac{1}{g_{m2}} \right)} (g_m R_C) = +\frac{198}{2} = +99.0$$

$$f_H \cong \frac{1}{2\pi(50k\Omega)(0.5pF)} = 6.37 \text{ MHz}$$

Page 1185

$$g_m = 40(1.6mA) = 64.0 \text{ mS} \quad | \quad r_\pi = \frac{100}{64mS} = 1.56k\Omega \quad | \quad C_\pi = \frac{64.0mS}{2\pi(500 \text{ MHz})} - 0.5pF = 19.9pF$$

$$A_{mid} = \frac{r_\pi}{R_i + r_x + r_\pi} (-g_m R_L) = \frac{1.56k\Omega}{882\Omega + 250\Omega + 1.56k\Omega} (-64.0mS)(4.12k\Omega) = -153$$

$$f_{P1} \cong \frac{1}{2\pi r_{\pi 0} (C_\pi + 2C_\mu)} = \frac{1}{2\pi (656\Omega)(19.9 + 1)pF} = 11.6 \text{ MHz}$$

$$f_{P2} \cong \frac{1}{2\pi R_L (C_\mu + C_L)} = \frac{1}{2\pi (4120\Omega)(0.5 + 5)pF} = 7.02 \text{ MHz}$$

Page 1186

$$f_{P1} \cong \frac{1}{4\pi C_{GGD} r_{o2}} = \frac{0.02(100\mu A)}{4\pi(1\text{pF})} = 159 \text{ kHz} \quad | \quad f_{P1} \cong \frac{1}{4\pi C_{GGD} r_{o2}} = \frac{0.02(25\mu A)}{4\pi(1\text{pF})} = 39.8 \text{ kHz}$$

Page 1193

$$X_C = \frac{1}{2\pi(530\text{Hz})39\text{pF}} = 7.69 \text{ M}\Omega \gg 2.39 \text{ k}\Omega$$

$$X_C = \frac{1}{2\pi(530\text{Hz})1\text{pF}} = 300 \text{ M}\Omega \quad | \quad 51.8\text{k}\Omega \parallel 19.8\text{k}\Omega = 14.3 \text{ k}\Omega \quad | \quad 300 \text{ M}\Omega \gg 14.3 \text{ k}\Omega$$

$$X_1 = \frac{1}{2\pi(667\text{kHz})0.01\mu F} = 23.9 \text{ }\Omega \ll 1.01 \text{ M}\Omega \quad | \quad X_2 = \frac{1}{2\pi(667\text{kHz})47\mu F} = 5.08 \text{ m}\Omega \ll 66.7 \text{ }\Omega$$

$$X_3 = \frac{1}{2\pi(667\text{kHz})1\mu F} = 239 \text{ m}\Omega \ll 2.69 \text{ k}\Omega$$

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$$Z_C = \frac{1}{2\pi j(5\text{MHz})0.01\mu F} = -j3.18 \text{ }\Omega$$

Page 1199

$$(i) f_o = \frac{1}{2\pi\sqrt{(10\mu H)(100\text{pF} + 20\text{pF})}} = 4.59 \text{ MHz} \quad | \quad r_o = \frac{50V + 15V - 1.6V}{3.2mA} = 19.8 \text{ k}\Omega$$

$$Q = \frac{100\text{k}\Omega \parallel 100\text{k}\Omega \parallel r_o}{2\pi(4.59 \text{ MHz})(10\mu H)} = 49.2 \quad | \quad BW = \frac{4.59 \text{ MHz}}{49.2} = 93.3 \text{ kHz}$$

$$A_{mid} = -g_m(100\text{k}\Omega \parallel 100\text{k}\Omega \parallel r_o) = -\sqrt{2(0.005)(0.0032)}(100\text{k}\Omega \parallel 100\text{k}\Omega \parallel 19.8\text{k}\Omega) = -80.2$$

$$f_o \text{ is unchanged} \quad | \quad r_o = \frac{50V + 10V - 1.6V}{3.2mA} = 18.3 \text{ k}\Omega \quad | \quad Q = \frac{100\text{k}\Omega \parallel 100\text{k}\Omega \parallel r_o}{2\pi(4.59 \text{ MHz})(10\mu H)} = 46.4$$

Page 1203

$$R_{EQ} = g_m \frac{L_S}{C_{GS}} = \frac{g_m}{C_{GS} + C_{GD}} L_S \left(1 + \frac{C_{GD}}{C_{GS}} \right) = \omega_T L_S \left(1 + \frac{C_{GD}}{C_{GS}} \right)$$

$$R_{EQ} \cong \omega_T L_S \quad \text{for } C_{GS} \gg C_{GD}$$

Page 1204

$$L_s \cong \frac{R_{EQ}}{\omega_T} = \frac{L^2 R_{EQ}}{\mu_n (V_{GS} - V_{TN})} = \frac{(5 \times 10^{-5} \text{ cm})^2 75 \Omega}{(400 \text{ cm}^2/V - s)(0.25V)} = 1.88 \times 10^{-9} \text{ H}$$

Page 1207

$$A_{CG} = \frac{1}{A} \frac{A}{\pi} = \frac{1}{\pi} \quad | \quad 20 \log \left(\frac{1}{\pi} \right) = -9.94 \text{ dB}$$

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$$A_{CG} = \frac{1}{A} \frac{2A}{\pi} = \frac{2}{\pi} \quad | \quad 20 \log \left(\frac{2}{\pi} \right) = -3.92 \text{ dB}$$

Page 1210

From Fig. 17.81(a), the amplitude of the output signal is approximately 70 mV, so the conversion gain is approximately:

$$A_{CG} = \frac{1}{100 \text{ mV}} (0.7) \left(\frac{200 \text{ mV}}{\pi} \right) = \frac{1.4}{\pi} \quad | \quad 20 \log \left(\frac{1.4}{\pi} \right) = -7.02 \text{ dB}$$

From Fig. 17.81(b), the spectral components at 46 and 54 kHz have amplitudes of approximately 45 mV, so the conversion gain is:

$$A_{CG} = \frac{45 \text{ mV}}{100 \text{ mV}} = 0.45 \quad | \quad 20 \log(0.45) = -6.93 \text{ dB} \quad | \quad \text{Note: } \frac{1.4}{\pi} = 0.446$$

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$$f_C - f_m = 20 - 0.01 = 19.99 \text{ MHz} \quad | \quad f_C + f_m = 20 + 0.01 = 20.01 \text{ MHz}$$

$$3f_C - f_m = 60 - 0.01 = 59.99 \text{ MHz} \quad | \quad 3f_C + f_m = 60 + 0.01 = 60.01 \text{ MHz}$$

$$5f_C - f_m = 100 - 0.01 = 99.99 \text{ MHz} \quad | \quad 5f_C + f_m = 100 + 0.01 = 100.01 \text{ MHz}$$

$$A_{f_C + f_m} = A_{f_C - f_m} = 3 \text{ V}$$

$$A_{3f_C + f_m} = A_{3f_C - f_m} = \frac{A_{f_C - f_m}}{3} = 1 \text{ V}$$

$$A_{5f_C + f_m} = A_{5f_C - f_m} = \frac{A_{f_C - f_m}}{5} = 0.6 \text{ V}$$

CHAPTER 18

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$$I_{C4} = I_{C3} = I_{C2} = I_{C1} = \frac{I_1}{2} = 1 \text{ mA} \quad | \quad V_{CE2} = 0.7 \text{ V} \quad | \quad V_{EC3} = 0.7 \text{ V} \quad | \quad V_O = 0 \text{ V}$$

$$V_{EC4} = 5V - V_O = 5 - 0 = 5.0 \text{ V} \quad | \quad V_{EC1} = 5 - V_{C1} - V_{E1} = 5 - 0.7 - (-0.7) = 5.0 \text{ V}$$

$$(1 \text{ mA}, 5.0 \text{ V}), (1 \text{ mA}, 0.7 \text{ V}), (1 \text{ mA}, 0.7 \text{ V}), (1 \text{ mA}, 5.0 \text{ V})$$

Page 1234

With the output shorted, current cannot make it around the loop, so $T_{SC} = 0$.

$T_{OC} = 0$ is zero only if r_{o1} is neglected since the voltage across r_π must be zero for $i_b = 0$.

If we include r_{o1} , and start at the base of Q₂ assuming $r_{o1} \gg \frac{1}{g_{m3}}$ and a current mirror gain of 1:

$$v_{c4} \cong \frac{v_{el}}{r_{o1}} (1) [r_{o4} \| R_{iB2} \| R_L \| r_{o4} (1 + g_{m2} r_{o1})] = \left(v_{b2} \frac{g_{m2} r_{o1}}{1 + g_{m2} r_{o1}} \right) \left(\frac{1}{r_{o1}} \right) [r_{o4} \| R_{iB2} \| R_L]$$

$$T \cong \frac{r_{o4} \| R_{iB2} \| R_L}{r_{o1}} = \frac{55k\Omega \| 5.1k\Omega \| 10k\Omega}{55k\Omega} = 0.0579$$

$$\text{Evaluating Eq. 18.7 without } R_L, T_{OC} = g_{m2} (r_{o1} \| r_{o1} \| R_{iB2}) = 0.04 (55k\Omega \| 55k\Omega \| 5.1k\Omega) = 172$$

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$$T_{new} = \left[g_{m1} (R_3 \| r_{\pi2}) \right] \left[-g_{m2} \left(R_2 + R_1 \| R_{iE1} \right) \| R_5 \| R_L \right] \left(\frac{R_1 \| R_{iE1}}{R_1 \| R_{iE1} + R_2} \right)$$

$$T_{new} = T_{old} \frac{R_3 \| r_{\pi2}}{R_3 \| R_{iB2}} (1 + g_{m2} R_4) = -2.01 \frac{1k\Omega \| 2.5k\Omega}{970\Omega} [1 + 0.04S(300\Omega)] = -19.2$$

$$A_v = 10 \frac{19.2}{1 + 19.2} = 9.50 \quad | \quad \text{Now } R_{iC2} = r_{o2} = \infty \quad | \quad R_{in}^D \cong 31.7 \text{ k}\Omega \quad | \quad R_{out}^D \cong 1.74 \text{ k}\Omega$$

$$\text{Scaling using the previous result : } T_{SC} = -19.2 \left(\frac{1.86}{2.01} \right) = 17.8 \quad | \quad R_{in} = 31.7k\Omega \frac{1 + 17.8}{1 + 0} = 596k\Omega$$

$$R_{out} = 1.74k\Omega \frac{1 + 0}{1 + 19.2} = 86.1 \text{ }\Omega \quad | \quad \text{Removing } R_L : R'_{out} = \left[\frac{1}{86.1} - \frac{1}{10^4} \right]^{-1} = 86.8 \text{ }\Omega$$

Page 1241

$$R_x^D = R_x^D \frac{1+T_{SC}}{1+T_{OC}} \quad | \quad R_x^D = R_3 \| R_{iD1} \| R_{iG3} = R_3 \| 2r_{o1} \| R_{iG3} = 3k\Omega \| \infty \| \infty = 3k\Omega$$

$$T_{SC} = 0 \quad | \quad T_{OC} = T = 61.1 \quad | \quad R_x = 3k\Omega \left(\frac{1+0}{1+61.1} \right) = 48.3 \Omega$$

$$I_{D2} = I_{D1} = \frac{I_1}{2} = 0.500 \text{ mA} \quad | \quad I_{D4} = I_2 = 2.00 \text{ mA} \quad | \quad I_{D3} = \frac{1.63V - (-5V)}{13k\Omega} = 0.510 \text{ mA}$$

$$V_{DS1} = 3.5 + V_{GS1} \quad | \quad V_{GS1} = 1 + \sqrt{\frac{2(0.5mA)}{10mA}} = 1.32 \text{ V} \quad | \quad V_{DS1} = 3.5 + 1.32 = 4.82 \text{ V}$$

$$V_{DS2} = 5 + 1.32 = 6.32 \text{ V} \quad | \quad V_{DS3} = 5 - 1.63 = 3.37 \text{ V} \quad | \quad V_{DS4} = 5 - V_O = 5.00 \text{ V}$$

$$(0.5 \text{ mA}, 4.82 \text{ V}), (0.5 \text{ mA}, 6.32 \text{ V}), (0.51 \text{ mA}, 3.37 \text{ V}), (2 \text{ mA}, 5.0 \text{ V})$$

Page 1245

$$R_i \text{ appears in parallel with } r_\pi : r'_\pi = r_\pi \| R_i = 4.69k\Omega \| 10k\Omega = 3.19 \text{ k}\Omega$$

$$T = -g_m \left(R_C \| (R_F + r'_\pi) \| r_o \right) \left(\frac{r'_\pi}{r'_\pi + R_F} \right) = -0.032S \left(5k\Omega \| (50k\Omega + 3.19k\Omega) \| 62.4k\Omega \right) \left(\frac{3.19k\Omega}{3.19k\Omega + 50k\Omega} \right) = -8.17$$

$$A_{tr} = A_{tr}^{Ideal} \frac{T}{1+T} = -50k\Omega \frac{8.17}{1+8.17} = -44.5 \text{ k}\Omega$$

$$R_{in}^D = r'_\pi \| (R_F + R_C \| r_o) = 3.19k\Omega \| (50k\Omega + 5k\Omega \| 62.4k\Omega) = 3.01 \text{ k}\Omega \quad | \quad T_{SC} = 0 \quad | \quad |T_{OC}| = |T|$$

$$R_{in} = 3.01k\Omega \frac{1+0}{1+8.17} = 328 \text{ }\Omega$$

$$R_{out}^D = R_C \| r_o \| (R_F + r'_\pi) = 5k\Omega \| 62.4k\Omega \| (50k\Omega + 3.19k\Omega) = 4.26 \text{ k}\Omega \quad | \quad T_{SC} = 0 \quad | \quad |T_{OC}| = |T|$$

$$R_{out} = 4.26k\Omega \frac{1+0}{1+8.17} = 463 \text{ }\Omega$$

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$$A_v = -\left(\frac{R_F}{R_i + R_{in}}\right)\left(\frac{R_L}{R_{out} + R_L}\right) = -\left(\frac{45.1k\Omega}{2k\Omega + 340\Omega}\right)\left(\frac{10k\Omega}{336\Omega + 10k\Omega}\right) = -18.6$$

$$A_v = -\left(\frac{R_F}{R_i + R_{in}}\right)\left(\frac{R_L}{R_{out} + R_L}\right) = -\left(\frac{45.1k\Omega}{10k\Omega + 340\Omega}\right)\left(\frac{2k\Omega}{336\Omega + 2k\Omega}\right) = -3.73$$

$$T = \frac{-A_{tr}}{R_F + A_{tr}} = \frac{48.5k\Omega}{50k\Omega - 48.5k\Omega} = 32.3 \quad | \quad g_{m3} = \frac{1}{R_{out}} \left(\frac{1}{1+T} \right) = \frac{1}{12\Omega} \left(\frac{1}{1+32.3} \right) = 2.50 \text{ mS}$$

$$R_{in} = \left(R_F + \frac{1}{g_{m3}} \right) \left(\frac{1}{1+T} \right) = \left(50k\Omega + \frac{1}{2.5mS} \right) \left(\frac{1}{1+32.3} \right) = 1.51 \text{ k}\Omega$$

Page 1250

$$T \text{ is the same : } |T| = 306. \quad | \quad A_v^{Ideal} = 1 \quad | \quad A_v = A_{tr}^{Ideal} \frac{T}{1+T} = 1 \left(\frac{306}{1+306} \right) = 0.997$$

$$R_{out}^D = R_F \left\| \frac{1}{g_{m5}} \right\| = 10k\Omega \left\| \frac{1}{3.16mS} \right\| = 307 \text{ }\Omega \quad | \quad T_{SC} = 0 \quad | \quad |T_{OC}| = |T|$$

$$R_{out} = 307\Omega \frac{1+0}{1+306} = 1.00 \text{ }\Omega$$

Page 1251

$$T \text{ is the same : } |T| = 306. \quad | \quad A_v^{Ideal} = 1 \quad | \quad A_v = A_{tr}^{Ideal} \frac{T}{1+T} = 1 \left(\frac{306}{1+306} \right) = 0.997$$

$$R_{in}^D = r_{o1} \left(1 + g_{m1} \frac{2}{g_{m2}} \right) \left\| \frac{1}{g_{m3}} \right\| = 600k\Omega \left\| \frac{1}{2.00mS} \right\| = 500 \text{ }\Omega \quad | \quad |T_{OC}| = 306$$

Note : The impedance looking in the source of a transistor with a high resistance load of r_o is $2/g_m$ rather than $1/g_m$.

$$T_{SC} = -\frac{g_{m2}}{2} \left(2r_{o2} \| r_{o4} \right) \frac{g_{m5} R_F}{1+g_{m5} R_F} = -\frac{3.16mS}{2} \left(400k\Omega \| 200k\Omega \right) \frac{3.16mS(10k\Omega)}{1+3.16mS(10k\Omega)} = -204$$

$$R_{out} = 500\Omega \frac{1+204}{1+306} = 334 \text{ }\Omega$$

Page 1254

$$T \text{ is the same : } |T| = 152. \quad | \quad A_v^{ideal} = -\frac{R_2}{R_I} = -1 \quad | \quad A_v = A_{tr}^{ideal} \frac{T}{1+T} = -1 \left(\frac{152}{1+152} \right) = -0.993$$

$$R_{out}^D = (R_2 + R_I) \| R_i \| \frac{1}{g_m} = 40k\Omega \| 10k\Omega \| \frac{1}{3.16mS} = 304 \Omega \quad | \quad T_{SC} = 0 \quad | \quad |T_{OC}| = |T| = 152$$

$$R_{out} = 304\Omega \frac{1+0}{1+152} = 1.99 \Omega$$

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$$\text{There are approximately 15 cycles in } 0.8 \mu\text{sec} : f \cong \frac{15\text{cycles}}{0.8\mu\text{s}} = 18.8 \text{ MHz}$$

Page 1256

$$f_T = \frac{1}{2\pi} \frac{g_m}{C_{GS} + C_{GD}} \quad | \quad g_m = \sqrt{2K_n I_D} \quad | \quad f_{T2} = f_{T1} = \frac{1}{2\pi} \frac{\sqrt{2(0.01)(0.0005)}}{5pf + 1pF} = 83.9 \text{ MHz}$$

$$f_{T3} = \frac{1}{2\pi} \frac{\sqrt{2(0.004)(0.0005)}}{5pf + 1pF} = 53.1 \text{ MHz} \quad | \quad f_{T4} = \frac{1}{2\pi} \frac{\sqrt{2(0.01)(0.002)}}{5pf + 1pF} = 168 \text{ MHz}$$

Page 1265

$$G_m = g_{m2} = \sqrt{2(10^{-3})(5 \times 10^{-5})} = 0.316 mS \quad | \quad R_o = r_{o4} \| r_{o2} \cong \frac{1}{2\lambda I_D} = \frac{1}{2(0.02)5 \times 10^{-5}} = 500 \text{ k}\Omega$$

$$f_T = \frac{1}{2\pi} \left(\frac{G_m}{C_C} \right) = \frac{1}{2\pi} \left(\frac{0.316mS}{20\text{pF}} \right) = 2.51 \text{ MHz}$$

$$f_B = \frac{1}{2\pi} \left[\frac{1}{R_o C_C (1 + A_{v2})} \right] = \frac{1}{2\pi} \left[\frac{1}{R_o C_C (1 + \mu_{f2})} \right] \cong \frac{1}{2\pi} \left[\frac{1}{500k\Omega (20\text{pF}) \left[1 + \frac{1}{0.02} \sqrt{\frac{2(0.001)}{5 \times 10^{-4}}} \right]} \right] = 158 \text{ Hz}$$

Page 1266

$$f_z \cong \frac{1}{2\pi} \frac{g_{m5}}{C_C} = \frac{1}{2\pi} \frac{\sqrt{2(0.001)5 \times 10^{-4}}}{20 \times 10^{-12}} = 7.96 \text{ MHz} \quad | \quad R = \frac{1}{g_{m5}} = \frac{1}{\sqrt{2(0.001)5 \times 10^{-4}}} = 1.00 \text{ k}\Omega$$

$$G_m = g_{m2} = 40(5 \times 10^{-5}) = 2.00 \text{ mS} \quad | \quad R_o = r_{\pi 5} \cong \frac{100V}{40(5.5 \times 10^{-4} A)} = 4.54 \text{ k}\Omega$$

$$f_T = \frac{1}{2\pi} \left(\frac{G_m}{C_C} \right) = \frac{1}{2\pi} \left(\frac{2.00 \text{ mS}}{30 \text{ pF}} \right) = 10.6 \text{ MHz} \quad | \quad f_Z = \frac{1}{2\pi} \left(\frac{g_{m5}}{C_C} \right) = \frac{1}{2\pi} \left[\frac{40(5 \times 10^{-4})}{3 \times 10^{-11}} \right] = 106 \text{ MHz}$$

$$f_B = \frac{1}{2\pi} \left[\frac{1}{r_{\pi 5} C_C (1 + \mu_{f2})} \right] \cong \frac{1}{2\pi} \left[\frac{1}{4.54 \text{ k}\Omega (30 \text{ pF}) [1 + 40(50)]} \right] = 584 \text{ Hz}$$

Page 1269

$$SR = \frac{100 \mu A}{20 \text{ pF}} = 5.00 \times 10^6 \frac{V}{s} = 5.00 \frac{V}{\mu s}$$

$$SR = \frac{100 \mu A}{20 \text{ pF}} = 5.00 \times 10^6 \frac{V}{s} = 5.00 \frac{V}{\mu s}$$

Page 1273

$$G_m = g_{m2} = 40(2.5 \times 10^{-4}) = 10.0 \text{ mS} \quad | \quad f_T = \frac{1}{2\pi} \left(\frac{G_m / 2}{C_C + C_{\mu 3}} \right) = \frac{1}{4\pi} \left(\frac{10.0 \text{ mS}}{50.8 \text{ pF}} \right) = 15.7 \text{ MHz}$$

$$\phi_M = 90 - \tan^{-1} \left(\frac{15.7 \text{ MHz}}{49.2 \text{ MHz}} \right) + \tan^{-1} \left(\frac{15.7 \text{ MHz}}{82.1 \text{ MHz}} \right) + \tan^{-1} \left(\frac{15.7 \text{ MHz}}{192 \text{ MHz}} \right) + \tan^{-1} \left(\frac{15.7 \text{ MHz}}{206 \text{ MHz}} \right) = 69.5^\circ$$

Page 1277

$$SR \cong \frac{I_1}{C_C + C_{GD5}} = \frac{1 \text{ mA}}{65 \text{ pF}} = 15.4 \times 10^6 \frac{V}{s} = 15.4 \frac{V}{\mu s}$$

$$30^\circ = \tan^{-1} \left(\frac{f_T}{49.2 \text{ MHz}} \right) + \tan^{-1} \left(\frac{f_T}{82.1 \text{ MHz}} \right) + \tan^{-1} \left(\frac{f_T}{100 \text{ MHz}} \right) \rightarrow f_T = 16.6 \text{ MHz}$$

$$C_C = 65 \text{ pF} \left(\frac{8.5 \text{ MHz}}{16.6 \text{ MHz}} \right) - 2 \text{ pF} = 31.3 \text{ pF}$$

Page 1283

When the circuit is drawn symmetrically, capacitor $2C_{GD}$ is replaced with 2 capacitors of value $4C_{GD}$ in series. The circuit can then be cut vertically down the middle to form a differential mode half-circuit. The total capacitance at the drain end of inductor L is $C+C_{GS}+4C_{GD}$.

Page 1285

$$f_P = \frac{1}{2\pi \sqrt{31.8mH \left[\frac{31.8fF(7pF)}{7.0318pF} \right]}} = 5.016 \text{ MHz} \quad | \quad f_P = \frac{1}{2\pi \sqrt{31.8mH \left[\frac{31.8fF(25pF)}{25.0318pF} \right]}} = 5.008 \text{ MHz}$$

MICROELECTRONIC CIRCUIT DESIGN

Fourth Edition

Richard C. Jaeger and Travis N. Blalock

Answers to Selected Problems – Updated 2/27/11

Chapter 1

- 1.4** 1.52 years, 5.06 years
1.5 1.95 years, 6.46 years
1.8 402 MW, 1.83 MA
1.10 2.50 mV, 5.12 V, 5.885 V
1.12 19.53 mV/bit, 10011000_2
1.14 14 bits, 20 bits
1.16 0.003 A , $0.003 \cos(1000t) \text{ A}$
1.19 $v_{DS} = [5 + 2 \sin(2500t) + 4 \sin(1000t)] \text{ V}$
1.20 15.7 V, 2.32 V, 75.4 μA , 206 μA
1.22 150 μA , 150 μA , 12.3 V
1.24 39.8Ω , $0.0251 v_s$
1.27 $56 \text{ k}\Omega$, $1.60 \times 10^{-3} v_s$
1.29 $1.50 \text{ M}\Omega$, $7.50 \times 10^8 i_i$
1.36 $50/\underline{-12^\circ}, 10/\underline{-45^\circ}$
1.38 $-82.4 \sin 750\pi t \text{ mV}$, $11.0 \sin 750\pi t \mu\text{A}$
1.40 $1 + R_2/R_1$
1.42 -1.875 V, -2.500 V
1.43 Band-pass amplifier
1.45 $50.0 \sin(2000\pi t) + 30.0 \cos(8000\pi t) \text{ V}$
1.48 0 V
1.47 $[4653 \Omega, 4747 \Omega], [4465 \Omega, 4935 \Omega], [4230 \Omega, 5170 \Omega]$
1.55 $6200 \Omega, 4.96 \Omega/\text{ }^\circ\text{C}$

1.61 3.29, 0.995, -6.16; 3.295, 0.9952, -6.155

Chapter 2

- 2.3** 500 mA
- 2.4** 160Ω , 319Ω
- 2.6** For Ge : $2.63 \times 10^{-4} / cm^3$, $2.27 \times 10^{13} / cm^3$, $8.04 \times 10^{15} / cm^3$,
- 2.9** 305.2 K
- 2.10** $-1.75 \times 10^6 cm/s$, $+6.25 \times 10^5 cm/s$, $2.80 \times 10^4 A/cm^2$, $1.00 \times 10^{-10} A/cm^2$
- 2.11** $1.60 \times 10^6 A/cm^2$, $1.60 \times 10^{-10} A/cm^2$
- 2.13** 4 MA/cm²
- 2.16** $1.60 \times 10^7 A/cm^2$, 4.00 A
- 2.17** 316.6 K
- 2.22** Donor, acceptor
- 2.23** 200 V/cm
- 2.25** 1.25×10^4 atoms
- 2.27** p-type, $6 \times 10^{18}/cm^3$, $16.7/cm^3$, $5.28 \times 10^9/cm^3$, $8.80 \times 10^{-10}/cm^3$
- 2.29** $3 \times 10^{17}/cm^3$, $333/cm^3$
- 2.30** $4 \times 10^{16}/cm^3$, $2.50 \times 10^5/cm^3$
- 2.34** $40/cm^3$, $2.5 \times 10^{18}/cm^3$, $170 cm^2/s$, $80 cm^2/s$, p-type, 31.2 mΩ-cm
- 2.36** $10^{16}/cm^3$, $10^4/cm^3$, $800 cm^2/s$, $220 cm^2/s$, n-type, 2.84 Ω-cm
- 2.38** $1.16 \times 10^{20}/cm^3$
- 2.40** $1.24 \times 10^{19}/cm^3$
- 2.41** Yes—add equal amounts of donor and acceptor impurities. Then $n = n_i = p$, but the mobilities are reduced. See Prob. 2.44.
- 2.43** $6.27 \times 10^{21}/cm^3$, $6.22 \times 10^{21}/cm^3$
- 2.46** $2.00/\Omega\text{-cm}$, $2.50 \times 10^{19}/cm^3$
- 2.48** 75K: 6.64 mV, 150K: 12.9 mV, 300K: 25.8 mV, 400K: 34.5 mV
- 2.49** -28.0 kA/cm²
- 2.50** $1.20 \times 10^5 \exp(-5000 x/cm) A/cm^2$, 12.0 mA
- 2.54** 1.108 μm
- 2.57** 8 atoms, $1.60 \times 10^{-22} cm^3$, $5.00 \times 10^{22} atoms/cm^3$, $3.73 \times 10^{-23} g$, $1.66 \times 10^{-24} g/proton$

Chapter 3

- 3.1** 0.0373 μm , 0.0339 μm , $3.39 \times 10^{-3} \mu\text{m}$, 0.979 V, $5.24 \times 10^5 \text{ V/cm}$
- 3.4** $10^{18}/\text{cm}^3$, $10^2/\text{cm}^3$, $10^{18}/\text{cm}^3$, $10^2/\text{cm}^3$, 0.921 V, 0.0488 μm
- 3.6** 6.80 V, 1.22 μm
- 3.10** 640 kA/cm^2
- 3.13** $1.00 \times 10^{21}/\text{cm}^4$
- 3.17** 290 K
- 3.20** 312 K
- 3.21** 1.39, 3.17 pA
- 3.22** 0.791 V; 0.721 V; 0 A; 9.39 aA, -10.0 aA
- 3.25** 1.34 V; 1.38 V
- 3.28** 0.518 V; 0.633 V
- 3.29** 335.80 K, 296.35 K
- 3.33** 0.757 V; 0.717 V
- 3.35** -1.96 mV/K
- 3.39** 0.633 V, 0.949 μm , 3.89 μm , 12.0 μm
- 3.40** 374 V
- 3.42** 4 V, 0 Ω
- 3.44** 10.5 nF/cm^2 ; 232 pF
- 3.46** 800 fF, 20 fC; 20 pF, 0.5 pC
- 3.50** 9.87 MHz; 15.5 MHz
- 3.51** 0.495 V, 0.668 V
- 3.53** 0.708 V, 0.718 V; 0.808 V
- 3.58** (a) Load line: (450 μA , 0.500 V); SPICE: (443 μA , 0.575 V)
(b) Load line: (-667 μA , -4 V);
(c) Load line: (0 μA , -3 V);
- 3.61** (0.600 mA, -4 V), (0.950 mA, 0.5 V), (-2.00 mA, -4 V)
- 3.68** Load line: (50 μA , 0.5 V); Mathematical model: (49.9 μA , 0.501 V); Ideal diode model: (100 μA , 0 V); CVD model: (40.0 μA , 0.6 V)
- 3.72** (a) 0.625 mA, -5 V; 0.625 mA, +3 V; 0 A, 7 V; 0 A, -5 V

- 3.74** (c) (270 μ A, 0 V), (409 μ A, 0 V); (c) (0 A -3.92 V), (230 μ A, 0 V)
- 3.76** (b) (0.990 mA, 0 V) (0 mA, -1.73 V) (1.09 mA, 0)
(c) (0 A, -0.667 V) (0 A, -1.33 V) (1.21 mA, 0 V)
- 3.79** (1.50 mA, 0 V) (0 A, -5.00 V) (1.00 mA, 0)
- 3.82** (I_Z , V_Z) = (887 μ A, 4.00 V)
- 3.84** 12.6 mW
- 3.86** 1.25 W, 3.50 W
- 3.91** 17.6 V
- 3.95** -7.91 V, 1.05 F, 17.8 V, 3530 A, 840 A ($\Delta T = 0.628$ ms)
- 3.97** (b) -7.91V, 904 μ F, 17.8 V, 3540 A, 839 A
- 3.99** 6.06 F, 8.6 V, 3.04 V, 962 A, 9280 A
- 3.104** -24.5 V, 1.63 F, 50.1 V, 15600 A, 2200 A
- 3.107** 3.03 F, 8.6 V, 3.04 V, 962 A, 3770 A
- 3.112** 2380 μ F, 2800 V, 1980 V, 126 A, 2510 A
- 3.119** 5 mA, 4.4 mA, 3.6 mA, 5.59 ns
- 3.123** (0.969 A, 0.777 V); 0.753 W; 1 A, 0.864 V
- 3.125** 1.11 μ m, 0.875 μ m; far infrared, near infrared

Chapter 4

- 4.3** $10.5 \times 10^{-9} \text{ F/cm}^2$
- 4.4** $43.2 \mu\text{A/V}^2$, $86.4 \mu\text{A/V}^2$, $173 \mu\text{A/V}^2$, $346 \mu\text{A/V}^2$
- 4.8** (a) 4.00 mA/V^2 (b) 4.00 mA/V^2 , 8.00 mA/V^2
- 4.11** $+840 \mu\text{A}$; $-880 \mu\text{A}$
- 4.15** 23.0Ω ; 50.0Ω
- 4.18** $125 \mu\text{A/V}^2$; 1.5 V ; enhancement mode; $1.25/1$
- 4.20** 0 A , 0 A , 1.88 mA , 7.50 mA , 3.75 mA/V^2
- 4.22** 1.56 mA , saturation region; $460 \mu\text{A}$, triode region; 0 A , cutoff
- 4.23** saturation; cutoff; saturation; triode; triode; triode
- 4.27** 6.50 mS , 13.0 mS
- 4.30** 2.48 mA ; 2.25 mA
- 4.34** 9.03 mA , 18.1 mA , 10.8 mA
- 4.37** 1.13 mA ; 1.29 mA
- 4.39** Triode region
- 4.40** $99.5 \mu\text{A}$; $199 \mu\text{A}$; $99.5 \mu\text{A}$; $99.5 \mu\text{A}$
- 4.44** $202 \mu\text{A}$; $184 \mu\text{A}$
- 4.46** 5.17 V
- 4.51** $40.0 \mu\text{A}$; $72.0 \mu\text{A}$; $4.41 \mu\text{A}$; $32.8 \mu\text{A}$
- 4.53** $5810/1$; $2330/1$
- 4.56** 235Ω ; 235Ω
- 4.57** 0.629 A/V^2
- 4.58** $400 \mu\text{A}$
- 4.61** The transistor must be a depletion-mode device and the symbol is not correct.
- 4.65** (a) $6.09 \times 10^{-8} \text{ F/cm}^2$; 1.73 fF
- 4.67** 17.3 pF/cm
- 4.69** 20.7 nF
- 4.71** (a) 1.35 fF , 0.20 fF , 0.20 fF
- 4.74** 50U , 0.5U , 2.5U , 1V , 0
- 4.77** 10U , 0.5U , 25U , 1V , 0

- 4.79** $432 \mu\text{A}/\text{V}^2$, 1.94 mA ; $864 \mu\text{A}/\text{V}^2$, 0.972 mA
- 4.82** 6.37 GHz , 2.55 Ghz ; 637 GHz , 255 GHz
- 4.85** $22\lambda \times 12\lambda$; 15.2%
- 4.88** $12\lambda \times 12\lambda$; 15.2%
- 4.89** $(350 \mu\text{A}, 1.7 \text{ V})$; triode region
- 4.92** $(390 \mu\text{A}, 4.1 \text{ V})$; saturation region
- 4.95** $(572 \mu\text{A}, 7.94 \text{ V})$; $(688 \mu\text{A}, 7.52 \text{ V})$
- 4.97** $(50.3 \mu\text{A}, 8.43 \text{ V})$; $(54.1 \mu\text{A}, 8.16 \text{ V})$
- 4.102** (a) $(116 \mu\text{A}, 4.15 \text{ V})$
- 4.105** $510 \text{ k}\Omega$, $470 \text{ k}\Omega$, $12 \text{ k}\Omega$, $12 \text{ k}\Omega$, $5/1$
- 4.107** $(124 \mu\text{A}, 2.36 \text{ V})$
- 4.109** $620 \text{ k}\Omega$, $910 \text{ k}\Omega$, $2.4 \text{ k}\Omega$, $2.7 \text{ k}\Omega$
- 4.111** $(109 \mu\text{A}, 1.08 \text{ V})$; $(33.5 \mu\text{A}, 0.933 \text{ V})$
- 4.113** $(42.6 \mu\text{A}, 0.957 \text{ V})$; $(42.6 \mu\text{A}, 0.935 \text{ V})$
- 4.115** $8.8043 \times 10^{-5} \text{ A}$; $8.3233 \times 10^{-5} \text{ A}$
- 4.118** $(73.1 \mu\text{A}, 9.37 \text{ V})$
- 4.119** $(69.7 \mu\text{A}, 9.49 \text{ V})$; $(73.1 \mu\text{A}, 8.49 \text{ V})$
- 4.122** $(8.17 \mu\text{A}, 7.06 \text{ V})$, $(6.74 \mu\text{A}, 7.57 \text{ V})$; $(8.36 \mu\text{A}, 6.99 \text{ V})$, $(6.89 \mu\text{A}, 7.52 \text{ V})$
- 4.124** $(91.5 \mu\text{A}, 8.70 \text{ V})$, $(70.7 \mu\text{A}, 9.23 \text{ V})$; $(97.8 \mu\text{A}, 8.48 \text{ V})$, $(81.9 \mu\text{A}, 9.05 \text{ V})$
- 4.125** 2.25 mA ; 16.0 mA ; 1.61 mA
- 4.127** $(322 \mu\text{A}, 3.18 \text{ V})$,
- 4.129** 18.1 mA ; 45.2 mA ; 13.0 mA
- 4.131** $1/3.84$
- 4.132** $(153 \mu\text{A}, -3.53 \text{ V})$; $(195 \mu\text{A}, -0.347 \text{ V})$
- 4.134** 4.04 V , 10.8 mA ; 43.2 mA ; 24.5 mA ; 98.0 mA
- 4.135** 14.4 mA ; 27.1 mA ; 10.4 mA
- 4.137** $(1.13 \text{ mA}, 1.75 \text{ V})$
- 4.138** $(63.5 \mu\text{A}, -5.48 \text{ V})$, $R \leq 130 \text{ k}\Omega$
- 4.140** $(55.3 \mu\text{A}, -7.09 \text{ V})$, $R \leq 164 \text{ k}\Omega$
- 4.143** $22.3 \text{ k}\Omega \rightarrow (127 \mu\text{A}, -5.50 \text{ V})$

4.146 $35.2 \mu\text{A}$, $R \leq 318 \text{ k}\Omega$

4.148 One possible design: $220 \text{ k}\Omega$, $200 \text{ k}\Omega$, $5.1 \text{ k}\Omega$, $4.7 \text{ k}\Omega$

4.149 $(281 \mu\text{A}, -12.2 \text{ V})$

4.151 $(32.1 \mu\text{A}, -1.41 \text{ V})$

4.153 $(36.1 \mu\text{A}, 80.6 \text{ mV})$; $(32.4 \mu\text{A}, -1.32 \text{ V})$; $(28.8 \mu\text{A}, -2.49 \text{ V})$

4.155 $(431 \mu\text{A}, 6.47 \text{ V})$

4.156 $2.5 \text{ k}\Omega$, $10 \text{ k}\Omega$

4.157 $I_D = 1.38 \text{ mA}$, $I_G = 0.62 \text{ mA}$, $V_S = -0.7 \text{ V}$

4.159 $(76.4 \mu\text{A}, 7.69 \text{ V})$, $(76.4 \mu\text{A}, 6.55 \text{ V})$, 5.18 V

4.160 (a) $(69.5 \mu\text{A}, 3.52 \text{ V})$

4.162 $(69.5 \mu\text{A}, 5.05 \text{ V})$; $(456 \mu\text{A}, 6.20 \text{ V})$,

4.167 10.0 V ; 10.0 mA , 501 mA ; 13.8 V

4.169 15.0 V ; 15.0 mA , 1.00 A ; 12.2 V

Chapter 5

- 5.4** 0.167, 0.667, 3.00, 0.909, 49.0, 0.995, 0.999, 5000
- 5.5** 0.2 fA; 0.101 fA, -0.115 V
- 5.6** 0.374 μ A, -149.6 μ A, +150 μ A, 0.626 V
- 5.9** 0.404 fA
- 5.11** 1.45 mA; -1.45 mA
- 5.14** -25 μ A, -100 μ A, +75 μ A, 65.7, 1/3, 0, 0.599 V
- 5.17** 1.77 μ A, -33.2 μ A, +35 μ A, 0.623 V
- 5.20** (a) 723 μ A
- 5.24** 0.990, 0.333, 2.02 fA, 6.00 fA
- 5.26** 83.3, 87.5, 100
- 5.33** 39.6 mV/dec, 49.5 mV/dec, 59.4 mV/dec, 69.3 mV/dec
- 5.34** 5 V, 60 V, 5 V
- 5.35** 2.31 mA; 388 μ A; 0
- 5.36** 60.7 V
- 5.40** Cutoff
- 5.42** saturation, forward-active region, reverse-active region, cutoff
- 5.46** 25.0 aA, 1.33 aA, 26.3 aA
- 5.47** $I_C = 81.4 \text{ pA}$, $I_E = 81.4 \text{ pA}$, $I_B = 4.28 \text{ pA}$, forward-active region; although I_C , I_E , I_B are all very small, the Transport model still yields $I_C \cong \beta_F I_B$
- 5.48** 79.0, 6.83 fA
- 5.49** 83.3, 1.73 fA
- 5.50** 55.3 μ A, 0.683 μ A, 54.6 μ A
- 5.51** 6.67 MHz; 500 MHz
- 5.53** 1.5, 31.1 aA
- 5.55** -19.9 μ A, 26.5 μ A, -46.4 μ A
- 5.58** 17.3 mV, 0.251 mV
- 5.60** 1.81 A, 10.1 A
- 5.62** 0.768 V, 0.680 V, 27.5 mV
- 5.65** 24.2 μ A
- 5.66** 4.0 fF; 0.4 pF; 40 pF

- 5.68** 750 MHz, 3.75 MHz
- 5.71** 0.149 μm
- 5.72** 71.7, 43.1 V
- 5.74** 74.1, 40.0 V
- 5.75** 100 μA , 4.52 μA , 95.5 μA , 0.651 V, 0.724
- 5.77** 26.3 μA
- 5.78** (c) 33.1 mS
- 5.79** 0.388 pF at 1 mA
- 5.81** (b) 38% reduction
- 5.83** (80.9 μA , 3.80 V) ; (405 μA , 3.80 V); (16.2 μA , 3.80 V) ; (81.9 μA , 3.72 V);
- 5.88** (38.8 μA , 5.24 V)
- 5.90** 36 k Ω , 75 k Ω , 3.9 k Ω , 3 k Ω ; (0.975 mA, 5.24 V)
- 5.93** 12 k Ω , 20 k Ω , 2.4 k Ω , 1.2 k Ω ; (0.870 mA, 1.85 V)
- 5.95** (7.5 mA, 4.3 V)
- 5.97** (5.0 mA, 1.3 V)
- 5.99** 30 k Ω , 620 k Ω ; 24.2 μA , 0.770 V
- 5.101** 5.28 V
- 5.103** 3.21 Ω
- 5.104** 10 V, 100 mA, 98.5 mA, 10.7 V
- 5.105** 10 V, 109 mA, 109 mA, 14.3 V

Chapter 6

- 6.1** 10 $\mu\text{W}/\text{gate}$, 8 $\mu\text{A}/\text{gate}$
- 6.3** 2.5 V, 0 V, 0 W, 62.5 μW ; 3.3 V, 0 V, 0 V, 109 μW
- 6.5** $V_{OL} = 0 \text{ V}$, $V_{OH} = 2.5 \text{ V}$, $V_{REF} = 0.8 \text{ V}$; $Z = A$
- 6.7** 3 V, 0 V, 2 V, 1 V, -3
- 6.9** 2 V, 0 V, 2 V, 5 V, 3 V, 2 V
- 6.11** 3.3 V, 0 V, 3.0 V, 0.25 V, 1.8 V, 1.5 V, 1.2 V, 1.25 V
- 6.13** -0.80 V, -1.35 V
- 6.15** 1 ns
- 6.17** 0.152 $\mu\text{W}/\text{gate}$, 22.7 aJ
- 6.19** 2.5 $\mu\text{W}/\text{gate}$, 1.39 $\mu\text{A}/\text{gate}$, 2.5 fJ
- 6.20** 2.20 RC ; 2.20 RC
- 6.22** -0.78 V, -1.36 V; 9.5 ns, 9.5 ns; 4 ns, 4 ns; 4 ns
- 6.25** $Z = 01010101$
- 6.27** $Z = 000100011$
- 6.30** 2 ; 1
- 6.32** 84.5 A
- 6.33** 0.583 pF
- 6.37** 3 $\mu\text{W}/\text{gate}$, 1.67 $\mu\text{A}/\text{gate}$
- 6.38** 72 k Ω , 1/1.04
- 6.39** (b) 2.5 V, 5.48 mV, 15.6 μW
- 6.43** (a) 0.450 V, 1.57 V
- 6.46** (a) 0.521 V, 1.81 V
- 6.49** NM_L: 0.242 V, 0.134 V, 0.351 V; NM_H: 0.941 V, 0.508 V, 1.25 V
- 6.51** 34.1 k Ω ; 1.82/1; 1.49 V, 0.266 V
- 6.53** 81.8 k Ω , 1/1.15
- 6.54** 250 Ω ; 625 Ω ; a resistive channel exists connecting the source and drain; 20/1
- 6.55** 1.44 V
- 6.57** 2.17 V
- 6.58** 1.55 V, 0.20 V, 0.140 mW, 0.260 mW

- 6.62** 2.5 V, 0.206 V, 0.434 mW
- 6.65** 1.40/1, 6.67/1
- 6.67** (b) 2.43/1, 1/3.97
- 6.69** 0.106 V
- 6.71** 1.55 V, 0.20 V, 0.150 mW
- 6.74** -2.40 at $v_O = 0.883$ V
- 6.75** -2.44 at $v_O = 1.08$ V
- 6.77** 3.79 V
- 6.79** 3.3 V, 0.296 V, 1.25 mW
- 6.82** 1.75/1, 1/8.79
- 6.84** 1.014
- 6.85** 1.46/1, 1.72/1
- 6.86** 2.5 V, 0.2 V, 0.16 mW
- 6.89** -5.98 at $v_O = 1.24$ V
- 6.90** 1.80/1, 0.610 V, 0.475 V
- 6.91** (a) 0.165 V, 80 μ A (b) 0.860 V, 0.445 V
- 6.93** (a) 0.224 V, 88.8 μ A (b) 0.700 V, 0.449 V
- 6.95** 1.65/1, 1/2.32, 0.300 V, 0.426 V
- 6.97** 0.103 V, 84.5 μ A
- 6.98** 0.196 V
- 6.102** 2.22/1, 1.81/1
- 6.103** 2.22/1, 1.11/1, 0.0643 V
- 6.104** 6.66/1, 1.11/1, 0.203 V, 6.43/1, 6.74/1, 7.09/1
- 6.107** $Y = \overline{(A+B)(C+D)E}$, 6.66/1, 1.11/1
- 6.111** $Y = \overline{ACE + ACDF + BF + BDE}$, 3.33/1, 26.6/1, 17.8/1
- 6.115** 1/1.80, 3.33/1
- 6.117** $Y = \overline{(C+E)[A(B+D)+G]+F}$; 3.62/1, 13.3/1, 4.44/1, 6.67/1
- 6.120** 3.45/1, 6.43/1, 7.09/1, 6.74/1
- 6.122** 1.11/1, 7.09/1, 6.43/1, 6.74/1
- 6.124** 64.9 mV

6.126 (a) 5.43/1, 9.99/1, 6.66./1, 20.0/1

6.128 (a) 7.24/1, 26.6/1, 13.3/1

6.132 $I_D^* = 2I_D$ | $P_D^* = 2P_D$

6.133 80 mW, 139 mW

6.134 1 ns

6.137 60.2 ns, a potentially stable state exists with no oscillation

6.139 31.7 ns, 4.39 ns, 5.86 ns

6.141 5.50 k Ω , 11.6/1

6.144 68.4 ns, 3.55 ns, 9.18 ns

6.146 47.1 ns, 6.14 ns, 5.39 ns

6.148 2.11/1, 16.7/1, 12.8 ns, 0.923 ns

6.149 2.68/1, 3.29/1, 884 μ W

6.150 (a) 1/1.68 (d) 1/5.89 (f) 1/1.60

6.152 -1.90 V, -0.156 V

6.153 1/3.30, 1.75/1

6.154 2.30 V, 1.07 V

6.156 $Y = \overline{A + B}$

Chapter 7

- 7.1** $173 \mu\text{A/V}^2$; $69.1 \mu\text{A/V}^2$
- 7.3** 250 pA ; 450 pA ; 450 pA
- 7.6** $2.5 \text{ V}, 0 \text{ V}$
- 7.8** cutoff, triode, triode, cutoff, saturation, saturation
- 7.11** 1.25 V ; $42.3 \mu\text{A}$; 1.104 V ; $25.4 \mu\text{A}$
- 7.12** 0.90 V ; $16.0 \mu\text{A}$; 0.810 V ; $96.2 \mu\text{A}$
- 7.14** 1.104 V
- 7.15** (b) 2.5 V , 92.8 mV
- 7.17** 1.16 V , 0.728 V
- 7.18** 0.810 V
- 7.22** 0.9836 V , 2.77 mA
- 7.23** $6.10/1$, $1/5.37$
- 7.24** (a) 1.89 ns , 1.89 ns , 0.630 ns
- 7.27** 9.47 ns , 3.97 ns , 2.21 ns
- 7.31** $2.11/1$, $5.26/1$
- 7.33** $63.2/1$, $158/1$
- 7.35** $6.00/1$, $15.0/1$
- 7.38** $2.76/1$
- 7.41** 1.7 ns , 2.3 ns , 1.1 ns , 0.9 ns , $\langle C \rangle = 138 \text{ fF}$
- 7.43** $0.200 \mu\text{W/gate}$; 55.6 A
- 7.44** $1.0 \mu\text{W/gate}$; 18.4 fF ; 32.0 fF ; 61.7 fF
- 7.46** 5.00 W ; 8.71 W
- 7.49** $90.3 \mu\text{A}$; $25.0 \mu\text{A}$
- 7.52** 436 fJ ; 425 MHz ; $926 \mu\text{W}$
- 7.55** $\alpha\Delta T$, $\alpha^2 P$, $\alpha^3 PDP$
- 7.58** SPICE: 22.3 ns , 24.2 ns , 16.3 ns , 18.3 ns ; Propagation delay formulas: 7.6 ns , 6.9 ns
- 7.59** $2/1$, $20/1$; $6/1$, $60/1$
- 7.61** $1/3.75$
- 7.63** $1.25/1$

- 7.70** 3.95 ns, 3.95 ns, 11.8 ns
- 7.71** 4.67/1; 7.5/1
- 7.72** 5 transistors; The CMOS design requires 47% less area.
- 7.74** $Y = \overline{(A+B)(C+D)E} = \overline{ACE + ADE + BDE + BCE}$; 12/1, 20/1, 10/1; 2.4/1; 30/1
- 7.76** $Y = \overline{(A+B)}\overline{(C+D)}\overline{(E+F)} = \overline{AB + CD + EF}$; 4/1, 15/1; 6/1; 10/1
- 7.78** 2/1, 4/1, 6/1, 20/1
- 7.81** (a) Path through NMOS A-D-E (d) Paths through PMOS A-C and B-E
- 7.83** 24/1, 20/1, 40/1
- 7.84** 6/1, 4/1, 10/1
- 7.91** 5.37 ns, 1.26 ns
- 7.93** 1.26 ns, 0.737 ns, 4.74 ns, 4.16 ns
- 7.95** 4.74 ns, 2.37 ns
- 7.103** $V_{DD} \rightarrow \frac{2}{3}V_{DD} \rightarrow \frac{1}{2}V_{DD}; R \geq \frac{2V_{IH}}{V_{DD} - V_{IH}} = \frac{2V_{IH}}{NM_H}, C_1 \geq 83.1C_2$
- 7.109** 8; 2.90; 23.2 A_o
- 7.112** $A_o \frac{\beta^N - 1}{\beta - 1}$
- 7.113** 263 Ω; 658 Ω
- 7.116** 240/1, 96.2/1
- 7.117** 1.41 V, 2.50 V
- 7.119** Latchup does not occur.
- 7.122** +0.25; +0.31
- 7.124** 211,000/1; 0.0106 cm²

Chapter 8

- 8.1** 268,435,456 bits, 1,073,741,824 bits; 2048 blocks
- 8.2** 3.73 pA/cell , 233 fA/cell
- 8.5** 3 V, 0.667 μ V
- 8.9** 1.55 V, 0 V, 3.59 V
- 8.11** “1” level is discharged by junction leakage current
- 8.13** 1.47 V, 1.43 V
- 8.14** -19.8 mV; 2.48 V
- 8.16** 0 V, 1.90; Junction leakage will destroy the “1” level
- 8.18** 5.00 V, 1.60 V; -1.84 V
- 8.22** 135 μ A, 346 mW
- 8.24** 0.266 V
- 8.25** 0.945 V (The sense amplifier provides a gain of 10.5.)
- 8.31** 0 V, 1.43 V, 3.00 V
- 8.32** 0.8 V, 1.2 V; 0.95 V, 0.95 V
- 8.34** 53,296
- 8.37** $V_{DD} \rightarrow \frac{2}{3}V_{DD} \rightarrow \frac{1}{2}V_{DD}; R \geq \frac{2V_{IH}}{V_{DD} - V_{IH}} = \frac{2V_{IH}}{NM_H}; C_1 \geq 2.88C_2$
- 8.41** $W_1 = 01000110_2, W_3 = 00101011_2$
- 8.45** 1.16/1

Chapter 9

- 9.1** 0 V, -0.700 V
- 9.2** (a) -1.38 V, -1.12
- 9.3** -1.50 V, 0 V
- 9.6** 0 V, -0.40 V; 3.39 k Ω ; Saturation, cutoff; Cutoff, saturation
- 9.8** -0.70 V, -1.30 V, -1.00 V, 0.60 V
- 9.11** -0.70 V, -1.50 V, -1.10 V, 2.67 k Ω ; 0.289 V; -0.10 V, +0.30 V
- 9.13** -1.70 V, -2.30 V, 0.60 V, Yes
- 9.15** 11
- 9.16** 11.1 k Ω , 12.0 k Ω , 70.2 k Ω , 252 k Ω
- 9.18** -1.10 V, -1.50 V, -1.30 V, 0.400 V, 0.107 V, 1.10 mW
- 9.19** 0.383 V
- 9.21** -0.70 V, -1.50 V, -1.10 V, 11.3 k Ω , 2.67 k Ω , 2.38 k Ω ; 0.289 V
- 9.23** 0.413 V
- 9.25** 50.0 μ A, -2.30 V
- 9.26** Standard values: 11 k Ω , 150 k Ω , 136 k Ω
- 9.30** +0.300 V, -0.535 V, 334 Ω
- 9.33** 5.15 mA
- 9.36** 0.135 mA
- 9.38** 10.7 mA
- 9.40** 400 Ω , 75.0 mA
- 9.42** (c) 0 V, -0.7 V, 3.93 mA (d) -3.7 V, 0.982 mA (e) 2920 Ω
- 9.45** $Y = A + \bar{B}$
- 9.47** -0.850 V; 3.59 pJ
- 9.49** 359 ns
- 9.50** 0 V, -0.600 V, 5.67 mW, 505 Ω , 600 Ω ; $Y = A + B + C$, 5 vs. 6
- 9.53** 5.00 k Ω , 5.40 k Ω , 31.6 k Ω , 113 k Ω
- 9.54** 1 k Ω , 1 k Ω , 1.30 mW
- 9.56** 2.23 k Ω , 4.84 k Ω , 60.1 k Ω
- 9.59** 1.446 mA, 1.476 mA, 29.66 μ A; 1.446 mA, 1.476 mA, 29.52 μ A

- 9.61** -0.9 V, -1.1 V, -1.8 V, -2.0 V, -2.7 V, -2.9 V, -4.2 V
- 9.64** $Y = AB + \overline{AC}$
- 9.68** 0, -0.8. 0, -0.8, 3.8 V
- 9.69** 2.98 pA, 70.5 fA
- 9.71** 160; 0.976; 0.976; 0.773 V
- 9.72** 0.691 V, 0.710 V
- 9.76** 63.3 μ A, 265 μ A
- 9.78** 40.2 mV, 0.617 mV
- 9.80** 20.6 mW, 4.22 mW
- 9.82** 68.2 mV
- 9.83** 2.5 V, 0.15 V, 0.66 V, 0.80 V
- 9.85** 44.8 k Ω , 22.4 k Ω
- 9.88** 5 V, 0.15 V, 0, -1.06 mA; 31; -1.06 mA vs. -1.01 mA, 0 mA vs. 0.2 mA
- 9.95** 8
- 9.97** $R_B \geq 5 \text{ k}\Omega$
- 9.99** 7
- 9.100** 234 mA, 34.9 mA
- 9.104** (I_B, I_C): (a) (135 μ A, -169 μ A); (515 μ A, 0); (169 μ A, 506 μ A); (0, 0) (b) all 0 except $I_{B1} = I_{E1} = 203 \mu\text{A}$
- 9.107** 180
- 9.108** 22
- 9.111** 1.85 V, 0.15 V; 62.5 μ A, -650 μ A; 13
- 9.113** $Y = \overline{ABC}$; 1.9 V; 0.15 V; 0, -408 μ A
- 9.115** 1.5 V, 0.25 V; 0, -1.00 mA; 16
- 9.116** 0.7 V, 191 μ A, 59 μ A, 1.18 mA
- 9.117** -1.13 mA, 0, 4.50 mA, 0, 0, 1.80 mA; 0, 0, 0, 0, 1.23 mA, 0
- 9.119** $Y = A + B + C$; 0 V, -0.8 V; -0.40 V
- 9.121** 1.05 mA, 26.9 μ A
- 9.122** 2 fJ; 10 fJ
- 9.124** 1.67 ns; 0.5 mW
- 9.126** 2.8 ns; 140 mW

Chapter 10

10.2 (a) 41.6 dB, 35.6 dB, 94.0 dB, 100 dB, -0.915 dB

10.4 29.35

10.5 Using MATLAB:

```
t = linspace(0,.004);
vs = sin(1000*pi*t)+0.333*sin(3000*pi*t)+0.200*sin(5000*pi*t);
vo= 2*sin(1000*pi*t+pi/6)+sin(3000*pi*t+pi/6)+sin(5000*pi*t+pi/6); plot(t,vs,t,vo)par
500 Hz: 1 0°, 1500 Hz: 0.333 0°, 2500 Hz: 0.200 0°; 2 30°, 1 30°, 1 30° 2 30°, 3 30°, 5
30° yes
```

10.7 29.0 dB, 105 dB, 67.0 dB

10.9 19.0 dB, 87.0 dB, 53.0 dB; $V_o = 8.94$ V, recommend ± 10 -V or ± 12 -V supplies

10.11 3.61×10^{-8} S, -7.93×10^{-3} , 1.00, 79.3 Ω

10.13 0.333 mS, -0.333, -1600, 1.78 M Ω

10.15 1.00 mS, -1.00, 3001, 30.0 k Ω

10.16 53.7 dB, 150 dB, 102 dB; 11.7 mV; 31.3 mW

10.17 45.3 mV, 1.00 W

10.21 -5440

10.23 0, ∞ , 80 mW, ∞

10.24 182

10.29 -10 (20 dB), 0.1 V; 0, 0 V

10.31 $v_o = [8 - 4 \sin(1000t)]$ volts; there are only two components; dc: 8 V, 159 Hz: -4 V

10.33 24.1 dB, 2nd and 3rd, 22.4%

10.35 [2.4588](#) 0.0038 [5.3105](#) 0.0066 [1.3341](#) 0.0026 [0.4427](#) 0.0028 [0.0883](#)
0.0012 [0.1863](#) 0.0023

10.37 59.7 dB, 119 dB, 88.9 dB; 5.66 mV

10.41 $R_{id} \geq 4.95$ M Ω

10.43 50 μ V, 140 dB

10.44 (a) -46.8, 4.7 k Ω , 0, 33.4 dB

10.47 (d) $(-1.10 + 0.75 \sin 2500\pi t)$ V

10.49 (a) $v_o = (4.00 - 20V_i \sin 2000\pi t)$ V (b) 0.3 V

10.53 30.1 k Ω , 604 k Ω $A_v = -20.1$, $R_{in} = 30.1$ k Ω

10.56 -70.0, 10 k Ω , 0

10.59 $2 \text{ M}\Omega$

10.60 $83.9, \infty, 0, 38.5 \text{ dB}$

10.63 (d) $(5.28 - 2.88 \sin 3250\pi t) \text{ V}$

10.67 $2 \text{ k}\Omega, 86.6 \text{ k}\Omega, A_v = 44.3$

10.69 $(-0.47 \sin 3770t - 0.94 \sin 10000t) \text{ V}, 0 \text{ V}$

10.70 $-0.3750 \sin 4000\pi t \text{ V}; -0.6875 \sin 4000\pi t \text{ V}; 0 \text{ to } -0.9375 \text{ V} \text{ in } -62.5\text{-mV steps}$

10.71 $455/1, 50/1$

10.72 $-10, 110 \text{ k}\Omega, 10 \text{ k}\Omega, (-30 + 15\cos 8300\pi t) \text{ V}, (-30 + 30\cos 8300\pi t) \text{ V}$

10.73 $3.2 \text{ V}, 3.1 \text{ V}, 2.82 \text{ V}, 2.82 \text{ V}, -1.00 \text{ V}; 3.82 \mu\text{A}; 3.80 \mu\text{A}, 2.80 \mu\text{A}$

10.76 $60 \text{ dB}, 10 \text{ kHz}, 10 \text{ Hz}, 9.99 \text{ kHz}, \text{band-pass amplifier}$

10.77 $80 \text{ dB}, \infty, 100 \text{ Hz}, \infty, \text{high-pass amplifier}$

10.81 $60 \text{ dB}, 100 \text{ kHz}, 28.3 \text{ Hz}, 100 \text{ kHz}$

10.83 Using MATLAB: $n=[1e4 \ 0]; d=[1 \ 200*pi]; bode(n,d)$

10.86 Using MATLAB: $n=[-20 \ 0 \ -2e13]; d=[1 \ 1e4 \ 1e12]; bode(n,d)$

10.89 $0.030 \sin(2\pi t + 89.4^\circ) \text{ V}, 1.34 \sin(100\pi t + 63.4^\circ) \text{ V}, 3.00 \sin(10^4\pi t + 1.15^\circ) \text{ V}$

10.92 $0.956 \sin(3.18 \times 10^5 \pi t + 101^\circ) \text{ V}, 5.00 \sin(10^5 \pi t + 180^\circ) \text{ V}, 5.00 \sin(4 \times 10^5 \pi t - 179^\circ) \text{ V}$

$$\mathbf{10.94} \quad A_v(s) = \frac{2x10^8\pi}{s + 10^7\pi} \quad | \quad A_v(s) = -\frac{2x10^8\pi}{s + 10^7\pi}$$

10.96 $66 \text{ dB}, 12.8 \text{ kHz}, -60 \text{ dB/decade}$

10.97 $3.16 \sin(1000\pi t + 10^\circ) + 1.05 \sin(3000\pi t + 30^\circ) + 0.632 \sin(5000\pi t + 50^\circ) \text{ V}$

Using MATLAB:

```
t = linspace(0,004);
A=10^(10/20);
vs = sin(1000*pi*t)+0.333*sin(3000*pi*t)+0.200*sin(5000*pi*t);
vo = A*sin(1000*pi*t+pi/18)+3.33*sin(3000*pi*t+3*pi/18)+2.00*sin(5000*pi*t+5*pi/18);
plot(t, A*vs, t, vo)
```

10.98 $-4.44 \text{ dB}, 26.5 \text{ kHz}$

10.100 $10 \text{ k}\Omega, 0.015 \mu\text{F}$

10.103 $80 \text{ dB}, 100 \text{ Hz}$

10.105 $-1.05 \text{ dB}, 181 \text{ Hz}$

10.107 (b) $-20.7, 105 \text{ kHz}$

10.108 $10.5 \text{ k}\Omega, 105 \text{ k}\Omega, 0.015 \mu\text{F}$

10.113 $T(s) = -sRC$

10.116 $-6.00, 20.0 \text{ k}\Omega, 0; +9.00, 91.0 \text{ k}\Omega, 0; 0, 160 \text{ k}\Omega, 0$

10.117 $1 \text{ A}, 2.83 \text{ V}, > 10 \text{ W} (\text{choose } 15 \text{ W})$

10.118 $0.484 \text{ A}; 0.730 \text{ V}; 0.730 \text{ V}; \geq 7.03 \text{ W} (\text{choose } 10 \text{ W}), 7.27 \text{ W}$

Chapter 11

- 11.1** (c) 4, 5.00, 4.00, 20 %
- 11.3** 120 dB
- 11.4** $1/(1+A\beta)$; 9.99×10^3 percent
- 11.5** (a) 13.49, 9.11×10^{-3} , 0.0675%
- 11.7** 120 dB
- 11.9** (a) -9.997, 2.76×10^{-3} , 0.0276%
- 11.13** 103 dB
- 11.16** 100 μ A, 100 μ A, -48.0 pA, +48.0 pA
- 11.17** (a) 13.5, 296 M Ω , 135 m Ω
- 11.19** (a) -17.4, 2.70 k Ω , 36.8 m Ω
- 11.22** If the gain specification is met with a non-inverting amplifier, the input and output specifications cannot be met.
- 11.24** 145V_s, 3.56 Ω
- 11.25** ≤ 0.75 %
- 11.27** (b) shunt-series feedback (d) series-shunt feedback
- 11.29** (a) Series-shunt (a) and series-series (c) feedback
- 11.32** 122 dB, 31.5 S
- 11.33** 9.96, 6.55 M Ω , 3.19 Ω
- 11.35** 9130, 3.00, 3.00, 369 M Ω , 0.398 Ω
- 11.37** (c) $-T/(1+T)$
- 11.39** -9.998 k Ω , 1.200 Ω , 0.1500 Ω
- 11.41** -35.99 k Ω , 4.418 Ω , 0.2799 Ω
- 11.44** -99.91 μ S, 50.04 M Ω , 17.79 M Ω
- 11.49** $10000s/(s + 5000)$, $10000/(2s + 1)$
- 11.54** 1.100, 1.899 Ω , 24.65 M Ω
- 11.56** 10.96, 35.12 Ω , 3.461 M Ω
- 11.57** 680.4, 0.334
- 11.59** 330, 0.0260
- 11.61** 6.25 %, 16.7 %

11.62 0.00372 %, 0.0183 %

11.63 0 V, -26 mV, 90.9 k Ω

11.65 +7500, -0.667 mV

11.68 The nearest 5% values are 1 M Ω and 10 k Ω

11.70 -6.2 V, 0 V; 10 V, -1.19 V

11.72 -5.00 V, 0 V; -10.0 V, 0.182 V

11.74 10 V, 0 V; 15 V, 0.125 V

11.77 110 Ω and 22 k Ω represent the smallest acceptable resistor pair.

11.79 39.2 Ω

11.81 0 V, 3 V; 0.105 V; 0 V; 49.0 dB

11.83 (d) $[-0.313 \sin 120\pi t - 4.91 \sin 5000\pi t]$ V

11.85 (b) 124 dB

11.86 60 dB

11.87 20.0 k Ω , 56.0 k Ω

11.89 20 Hz

11.91 50 Hz; 5 MHz; 2.5 MHz

11.93 200; 199

11.95 80 dB, 1 kHz, 1 MHz; 101 MHz, 9.90 Hz; 251 MHz, 3.98 Hz

11.97 100 dB, 1 kHz, 1 MHz; 8.4 Hz, 119 MHz; 5.3 Hz, 188 MHz

11.99 (a) $R_o(s + \omega_B)/(s + \omega_B(1 + A_o\beta))$

11.102 (a) $R_{id}[s + \omega_B(1 + A_o\beta)]/(s + \omega_B)$

11.105 $A_v(s) = -\frac{3.285 \times 10^{12}}{s^2 + 1.284 \times 10^7 s + 1.675 \times 10^{11}}$; (2 poles: 2.08 kHz and 2.04 MHz)

11.107 $A_v(s) = -\frac{6.283 \times 10^{10}}{s^2 + 3.142 \times 10^7 s + 6.283 \times 10^5}$; (2 poles: 3.18 mHz and 5.00 MHz)

11.109 6.91, 7.53, 6.35; 145 kHz, 157 kHz, 133 kHz

11.111 2.51 V/ μ s; 2.51 V/ \square s

11.113 10 V/ μ s

11.117 $10^{10} \Omega$, 7.96 pF, 4×10^6 , R_o not specified

- 11.119** $90.6^\circ; 90.2^\circ$
- 11.120** $8.1^\circ; 5.1^\circ$
- 11.122** 110 kHz; $A \leq 2048$; larger
- 11.123** Yes, but almost no phase margin; 0.4°
- 11.125** 75° versus 90° ; 65° versus 90°
- 11.128** 5 MHz, 90.0° ; 2.5 MHz, 90.0°
- 11.130** $A_v(s) = -\frac{5.712 \times 10^6 s}{s^2 + 5.741 \times 10^5 s + 1.763 \times 10^{10}}$; 143°
- 11.132** Yes, but almost no phase margin; 1.83°
- 11.134** 90.0°
- 11.136** 12° ; Yes, 50°
- 11.141** Yes, 24.4° , 50 %
- 11.143** 1.8°
- 11.144** 38.4° , 31 %
- 11.147** 133 pF
- 11.149** 90.4°
- 11.152** (a) 72.2°
- 11.153** (a) 11.9 MHz, 5.73° , 85.4%
- 11.155** (a) 70.2, 23.4%
- 11.157** (a) 18.8 MHz

Chapter 12

12.1 A and B taken together, B and C taken together

12.3 -8000, 2 k Ω , 0

12.5 48.0, 968 M Ω , 46.5 m Ω

12.7 78.1 dB, 2.00 k Ω , 0.105 Ω

12.8 (c) 2.00 mV, -40.0 mV, 4.00 μ V, 0.800 V, 80.0 μ V, 0 V, -12.0 V, 0.190 V, 0V (ground node)

12.11 -1080, 3.9 k Ω , 0

12.12 8.62 k Ω , 8.62 k Ω

12.16 2744, 2434, 3094, 1 M Ω , 1.02 M Ω , 980 k Ω , 0

12.17 -1320, 75 k Ω , 0; 5.00 mV, 5.00 mV, 55.0 mV, 0 V, -1.10 V, -1.10 V, -6.60 V, 0V (ground node)

12.19 50.0, 298 kHz; 48.0, 349 kHz; -42.0, 368 kHz

12.21 14.0, 286 kHz, 68.8 dB, 146 kHz

12.23 -2380, 613 M Ω , 98.0 m Ω , 29.6 kHz; 0 V, 10.0 mV, 49.0 mV, 389 μ V, -3.89 V, -3.06 V, -15.0 V, +15.0 V, -15.0 V, 0 V

12.25 3

12.27 20 k Ω , 62 k Ω , 394 kHz

12.30 103 dB, 98.5 dB, 65 kHz, 38 kHz

12.33 (a) In a simulation of 5000 cases, 33.5% of the amplifiers failed to meet one of the specifications. (b) 1.5% tolerance.

12.36 -12, (-6.00 + 1.20 sin 4000 π t) V

12.38 4.500 V, 4.99 V, 5.01 V, 5.500 V, 2.7473 V, 2.7473 V, 0.991 V, -75.4 μ A, -375 μ A, +175 μ A, 0.002, -50.0, 88 dB

12.40 (b) 0.005 μ F, 0.0025 μ F, 1.13 k Ω

$$\frac{V_o}{V_s} = \frac{K}{s^2 R_1 R_2 C_1 C_2 + s [R_1 C_1 (1-K) + C_2 (R_1 + R_2)] + 1} \quad | \quad S_K^o = \frac{K}{3-K}$$

12.46 -1

12.48 270 pF, 270 pF, 23.2 k Ω

12.49 (a) 51.2 kHz, 7.07, 7.24 kHz

12.52 (a) 1 rad/s, 4.65, 0.215 rad/s; $A_{BP}(s) = \left(\frac{-6s}{s^2 + \frac{s}{3} + 1} \right)^2$

12.54 5.48 kHz, 4.09, 1.34 kHz

12.56 10 kΩ, 100 kΩ, 20 kΩ, 0.0133 μF

12.58 $T = +K \frac{\frac{s}{R_2 C_2}}{s^2 + s \left[\frac{1}{R_2 C_2} + \frac{1}{(R_1 \| R_2) C_1} \right] + \frac{1}{R_1 R_2 C_1 C_2}}$

12.64 -5.5 V, -5.5, 10 %; -5.0 V, -5.0, 0

12.66 12.6 kHz, 1.58, 7.97 kHz

12.69 (a) -1-125 V (b) -1.688 V

12.70 10.6 mV, 5 %

12.73 455/1, 50/1

12.74 0.31 LSB, 0.16 LSB

12.76 1.43%, 2.5%, 5%, 10%

12.77 11 resistors, 1024:1

12.79 (a) 1.0742 kΩ, 0.188 LSB, 0.094 LSB

12.81 (a) $(2^{n+1}-1)C$

12.84 (b) 2.02 inches

12.85 $3.415469 \text{ V} \leq V_x \leq 3.415781 \text{ V}$

12.86 1.90735 μV, 11010000101000111101₂, 0111111100111011101₂

12.89 0001011111₂, 95 μs

12.91 800 kHz, 125 ns

12.93 $v_o(t) = 2.5 \times 10^5 \left(1 - \exp \frac{-t}{5 \times 10^4 RC} \right)$ for $t \geq 0$ | $RC \geq 0.0447 \text{ s}$

12.94 19.1 ns

12.97 1/RC, 2R

12.98 0.5774/RC, 1.83

12.100 60 kHz, 6.8 V

12.102 17.5 kHz, 11.5 V

12.106 0.759 V

12.107 2.4 Hz

12.112 $V_O = -V_1 V_2 / 10^4 I_S$

12.113 3.11 V, 2.83 V, 0.28 V

12.115 0.445 V, -0.445 V, 0.89 V

12.117 9.86 kHz

12.118 $V_O = 0$ is a stable state, so the circuit does not oscillate. $f = 0$.

12.120 0, 0.298 V, 69.0 mV

12.122 13 k Ω , 30 k Ω , 51 k Ω , 150 pF

Chapter 13

- 13.1** $(0.700 + 0.005 \sin 2000\pi t)$ V, $-1.03 \sin 2000\pi t$ V, $(5.00 - 1.03 \sin 2000\pi t)$ V, 2.82 mA
- 13.3** (a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a coupling capacitor that couples the ac component of the signal at the collector to the output v_O . C_3 is a bypass capacitor. (b) The signal voltage at the top of resistor R_4 will be zero.
- 13.5** (a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a bypass capacitor. C_3 is a coupling capacitor that couples the ac component of the signal at the drain to output v_O . (b) The signal voltage at the source of M_1 will be $v_s = 0$.
- 13.7** (a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a bypass capacitor. C_3 is a coupling capacitor that couples the ac component of the signal at the collector to output v_O . (b) The signal voltage at the emitter terminal will be $v_e = 0$.
- 13.9** (a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a coupling capacitor that couples the ac component of the signal at the drain to output v_O .
- 13.13** (a) C_1 is a coupling capacitor that couples the ac component of v_I into the amplifier. C_2 is a bypass capacitor. C_3 is a coupling capacitor that couples the ac component of the signal at the drain to the output v_O . (b) The signal voltage at the top of R_4 will be zero.
- 13.16** (1.46 mA, 5.36 V)
- 13.18** (19.2 μ A, 6.37 V)
- 13.20** (62.2 μ A, 43.65 V)
- 13.24** (91.3 μ A, 6.05 V)
- 13.28** (245 μ A, 3.73 V)
- 13.32** (423 μ A, -6.76 V)
- 13.34** (1.25 mA, 8.63 V)
- 13.46** Thévenin equivalent source resistance, gate-bias voltage divider, gate-bias voltage divider, source-bias resistor—sets source current, drain-bias resistor—sets drain-source voltage, load resistor
- 13.51** 118Ω , $3.13 \text{ T}\Omega$, ≤ -28.5 mV
- 13.52** (c) 8.65Ω
- 13.53** Errors: +10.7%, -9.37%; +23.0%, -17.5%

- 13.54** (c) $1.25 \mu\text{A}$
- 13.55** $(213 \mu\text{A}, \geq 0.7 \text{ V}), 8.52 \text{ mS}, 469 \text{ k}\Omega$
- 13.60** (b) +16.7%, -13.6%
- 13.61** 90, 120; 95, 75
- 13.66** $[-76.7, -75.8]$
- 13.68** -40.0
- 13.72** -90
- 13.74** Yes, using $I_C R_C = (V_{CC} + V_{EE})/2$
- 13.76** 3
- 13.77** 20 mA; 24.7 V
- 13.78** 0.500 V
- 13.79** No, there will be significant distortion
- 13.80** -263
- 13.85** 32/1, 0.500 V
- 13.86** 0.800 A
- 13.87** 10%, 20%
- 13.90** $(78 \mu\text{A}, 9 \text{ V})$
- 13.91** Virtually any desired Q-point
- 13.92** $400 = 133,000i_P + v_{PK}; (1.4 \text{ mA}, 215 \text{ V}); 1.6 \text{ mS}, 55.6 \text{ k}\Omega, 89.0, -62.7$
- 13.93** FET
- 13.94** BJT
- 13.95** $37.5 \mu\text{A}, 2400$
- 13.96** 2000, 200, 8.00 mS, 0.800 mS
- 13.99** 23.5 dB
- 13.101** $(142 \mu\text{A}, 7.5 \text{ V})$
- 13.102** 0.300 V
- 13.103** 1.0 V, 56 V
- 13.105** 3
- 13.107** -11.0
- 13.110** -7.28

- 13.115** $29.4 \text{ k}\Omega, 93.4 \text{ k}\Omega$
- 13.118** $833 \text{ k}\Omega, 1.46 \text{ M}\Omega$
- 13.120** $243 \text{ k}\Omega, 40.1 \text{ k}\Omega$
- 13.122** $6.8 \text{ M}\Omega, 45.8 \text{ k}\Omega$, independent of K_n
- 13.124** $1 \text{ M}\Omega, 3.53 \text{ k}\Omega$
- 13.125** $-281v_i, 3.74 \text{ k}\Omega$
- 13.127** $-23.6v_i, 508 \text{ k}\Omega$
- 13.129** $38.9 \text{ dB}, 6.29 \text{ k}\Omega, 9.57 \Omega$
- 13.131** $36.4 \text{ dB}, 62.9 \text{ k}\Omega, 95.7 \text{ k}\Omega$
- 13.135** $138 \mu\text{W}, 182 \mu\text{W}, 1.28 \text{ mW}, 0.780 \text{ mW}, 0.820 \text{ mW}, 3.19 \text{ mW}$
- 13.139** $0.552 \text{ mW}, 0.684 \text{ mW}, 0.225 \text{ mW}, 18.7 \mu\text{W}, 50.4 \mu\text{W}, 1.53 \text{ mW}$
- 13.142** $V_{CC}/15$
- 13.143** $3.38 \text{ V}, 13.6 \text{ V}$
- 13.144** $(V_{CC})^2/8R_L, (V_{CC})^2/2R_L, 25\%$
- 13.145** 0.992 V
- 13.147** 2.24 V
- 13.148** 1.65 V
- 13.149** 2.93 V
- 13.153** $833 \mu\text{A}$
- 13.154** $-4.60, 1 \text{ M}\Omega, 6.82 \text{ k}\Omega$

Chapter 14

- 14.1** (a) C-C or emitter-follower (c) C-E (e) not useful, signal is being injected into the drain (h) C-B (k) C-G (o) C-D or source-follower
- 14.14** -32.6, 9.58 k Ω , 596 k Ω , -27.1; -17.2, 11.6 k Ω , 1060 k Ω , -17.1
- 14.15** -3.77, 2 M Ω , 26.5 k Ω , -3770; -8.03, 2 M Ω , 10.0 k Ω , -10000
- 14.16** (a) -6.91 (e) -240
- 14.17** 3.3 k Ω , 33 k Ω
- 14.20** -178, - $\tilde{\square}$ 58, 21.4 k Ω , 39 k Ω , 5.13 mV
- 14.21** ~ 121, - $\tilde{\square}$ 62, 2.84 k Ω , 7.58 k Ω , 6.76 mV, -120
- 14.22** -12.3, -9.62, 368 k Ω , 82 k Ω , 141 mV, -7.50
- 14.24** -2.74, -762, 10 M Ω , 1.80 k Ω , 0.800 V
- 14.25** -3790, -5.44, 1.30 k Ω , 68.5 k Ω , 5.96 mV
- 14.27** 0.747, 29.8 k Ω , 104 Ω , 29.7
- 14.28** 0.896, 2 M Ω , 125 Ω , 16,000
- 14.29** 0.987, 44.8 k Ω , 15.2 Ω , 1.54 V
- 14.30** 0.960, 1 M Ω , 507 Ω , 6.19 V
- 14.31** 0.992, 12.6 M Ω , 1.32 k Ω , 0.601 V
- 14.32** ~ $\square\square\square$, 7.94 M Ω , 247 Ω , ∞
- 14.33** $v_i \leq (0.005 + 0.2V_{R_E}) V$
- 14.35** 0.9992, 30.1 V
- 14.37** 190, 980 Ω , 2.52 M Ω , 0.990; 62.1, 980 Ω , 7.57 M Ω , 0.969
- 14.38** 39.4, 1.20 k Ω , ∞ , 0.600; 7.94, 1.43 k Ω , ∞ , 0.714
- 14.41** 40.7, 185 Ω , 39.0 k Ω , 18.5 mV
- 14.42** 4.11, 1.32 k Ω , 20 k Ω , 354 mV
- 14.43** 5.01, 3.02 k Ω , 24 k Ω , 352 mV
- 14.46** 32.1 Ω , 260 Ω
- 14.47** 633 Ω , 353 Ω
- 14.49** $(\beta_o + 1)r_o = 244 M\Omega$

14.51 Low R_{in} , high gain: Either a common-base amplifier operating at a current of 71.4 μA or a common-emitter amplifier operating at a current of approximately 7.14 mA can meet the specifications with $V_{CC} \approx 14$ V.

14.53 Large R_{in} , moderate gain: Common-source amplifier.

14.55 Common-drain amplifier.

14.56 Low R_{in} , high gain: Common-emitter amplifier with 5- Ω input "swamping" resistor.

14.57 Cannot be achieved with what we know at this stage in the text.

14.59 1.66 Ω

14.62

v_i	1 kHz	2 kHz	3 kHz	THD
5 mV	621 mV	26.4 mV (4.2%)	0.71 mV (0.11%)	4.2%
10 mV	1.23 V	0.104 V (8.5%)	5.5 mV (0.45%)	8.5%
15 mV	1.81 V	0.228 V (12.6%)	18.2 mV (1.0%)	12.7%

14.64 (b) $479v_i$, $384\text{ k}\Omega$

14.65 v_i , $297\text{ }\Omega$

14.68 g_m , 0; $400\text{ }\mu S$, 0

$$\mathbf{14.70} \quad -g_m \left(1 + \frac{1}{\mu_f} \right) \mid -g_o \mid \mu_f + 1 ; -502\text{ }\mu S, -2.00\text{ }\mu S$$

$$\mathbf{14.71} \quad -\frac{g_m}{1 + g_m R_E} \mid -\frac{g_o}{(1 + g_m R_E)} \left(\frac{R_E}{R_E + r_\pi} \right) \mid \frac{G_m}{G_r} = \mu_f \left(1 + \frac{r_\pi}{R_E} \right) \gg 1$$

14.74 -0.984, 0.993, 0.766 V

14.76 SPICE: (116 μA , 7.53 V), -150, 19.6 $\text{k}\Omega$, 37.0 $\text{k}\Omega$

14.78 SPICE: (115 μA , 6.30 V), -20.5, 368 $\text{k}\Omega$, 65.1 $\text{k}\Omega$

14.80 SPICE: (66.7 μA , 4.47 V), -16.8, 1.10 $\text{M}\Omega$, 81.0 $\text{k}\Omega$

14.83 SPICE: (5.59 mA, -5.93 V), -3.27, 10.0 $\text{M}\Omega$, 1.52 $\text{k}\Omega$

14.85 SPICE: (6.20 mA, 12.0 V), 0.953, 2.00 $\text{M}\Omega$, 388 Ω

14.86 SPICE: (175 μA , 4.29 V), -4.49, 500 $\text{k}\Omega$, 17.0 $\text{k}\Omega$

14.87 (430 μA , 1.97 V), (430 μA , 3.03 V), -2.89, 257 $\text{k}\Omega$, 3.22 $\text{k}\Omega$, (Note $A_{tr} = 743\text{ k}\Omega$)

14.88 (4.50 mA, 2.50 V), (4.50 mA, 2.50 V), -83.5, 6.63 $\text{k}\Omega$, 10.3 $\text{k}\Omega$,

14.89 0.485, 182 $\text{k}\Omega$, 435 Ω

14.92 1.80 μF , 0.068 μF , 120 μF ; 2.7 μF

- 14.94** 0.20 μF , 270 $\square\text{F}$; 100 μF , 0.15 μF
- 14.96** 1.5 μF , 0.027 μF
- 14.98** 8200 pF, 820 pF
- 14.102** 33.3 mA
- 14.103** $R_1 = 120 \text{ k}\Omega$, $R_2 = 110 \text{ k}\Omega$
- 14.106** $45.1 \leq A_v \leq 55.3$ - Only slightly beyond the limits in the Monte Carlo results.
- 14.108** The second MOSFET
- 14.111** The supply voltage is not sufficient - transistor will be saturated.
- 14.113** 4.08, 1.00 $\text{M}\Omega$, 64.3 Ω
- 14.116** 2.17, 1.00 $\text{M}\Omega$, 64.3 Ω
- 14.121** 468, 73.6 $\text{k}\Omega$, 18.8 $\text{k}\Omega$
- 14.122** 0.670, 107 $\text{k}\Omega$, 20.0 $\text{k}\Omega$
- 14.124** 7920, 10.0 $\text{k}\Omega$, 18.8 $\text{k}\Omega$
- 14.125** 140, 94.7 Ω , 113 Ω
- 14.127** 19.2 Hz; 18.0 Hz
- 14.129** 1.56 Hz; 1.22 Hz
- 14.131** 6.40 Hz; 5.72 Hz
- 14.133** 0.497 Hz, 0.427 Hz
- 14.134** 1.70 kHz; 1.68 kHz

Chapter 15

- 15.1** (26.2 μ A, 7.08 V); -346, 191 k Ω , 660 k Ω ; -0.604, 49.2 dB, 27.3 M Ω
- 15.2** (5.25 μ A, 1.68 V); -21.0, -0.636, 24.4 dB, 572 k Ω , 4.72 M Ω , 200 k Ω , 50.0 k Ω
- 15.4** (85.6 μ A, 10.1 V); -342, -0.494, 50.8 dB, 58.4 k Ω , 10.1 M Ω , 200 k Ω , 50.0 k Ω
- 15.7** $R_{EE} = 1.1 \text{ M}\Omega$, $R_C = 1.0 \text{ M}\Omega$
- 15.8** (a) (198 μ A, 3.39 V); differential output: -372, 0, ∞ (b) single-ended output: -186, -0.0862, 66.7 dB; 25.2 k Ω , 27.3 M Ω , 94.0 k Ω , 13.5 k Ω
- 15.9** 2.478 V, 6.258 V, -2.78 V, 4.64 V
- 15.11** $V_O = 5.99 \text{ V}$, $v_o = 0$; $V_O = 5.99 \text{ V}$; $v_o = 1.80 \text{ V}$; 33.3 mV
- 15.15** (37.4 μ A, 5.22 V); Differential output: -300, 0, ∞ ; single-ended output: -150, -0.661, 47.2 dB; 200 k Ω , 22.7 M Ω
- 15.16** -5.850 V, -3.450 V, -2.40 V
- 15.18** (4.94 μ A, 1.77 V); differential output: -77.2, 0, ∞ ; single-ended output: -38.6, -0.0385, 60.0 dB; 810 k Ω , 405 M Ω , [-1.07 V, 1.60 V]
- 15.21** -283, -0.00494, 95.2 dB
- 15.22** -273.6, -0.004429, 94.9 dB
- 15.24** (107 μ A, 10.1 V); differential output: -18.2, 0, ∞ ; single-ended output: -9.10, -0.487, 25.4 dB; ∞ , ∞
- 15.27** 2.4 k Ω , 5.6 k Ω
- 15.31** (150 μ A, 5.62 V); differential output: -26.0, 0, ∞ ; single-ended output: -13.0, -0.232, 35.0 dB; ∞ , ∞
- 15.34** (20.0 μ A, 9.05 V); differential output: -38.0, 0, ∞ ; single-ended output: -19.0, -0.120, 44.0 dB; ∞ , ∞
- 15.35** 312 μ A, 27 k Ω
- 15.38** -20.26, -0.7812, 22.3 dB, ∞ , ∞
- 15.40** -3.80 V, -2.64 V, 48.3 mV
- 15.44** -79.9, -0.494, 751 k Ω
- 15.45** (99.0 μ A, 8.80 V), -30.4, -0.167, 550 k Ω
- 15.47** (49.5 μ A, 3.29 V), (49.5 μ A, 8.70 V); -149, -0.0625, 101 k Ω
- 15.48** (100 μ A, 1.20 V), (100 μ A, 3.18 V); -13.4, 0, ∞
- 15.51** (24.8 μ A, 15.0 V), (625 μ A, 15.0 V); 896, 202 k Ω ; 20.0 k Ω ; 153 M Ω ; v_2
- 15.52** [-13.6 V, 14.3 V]

- 15.57** (24.8 μA , 14.3 V), (4.95 μA , 14.3 V), (495 μA , 15.0 V); 5010, 202 $\text{k}\Omega$; 19.4 $\text{k}\Omega$; 150 $\text{M}\Omega$; v_2
- 15.58** (98.8 μA , 17.1 V), (360 μA , 17.1 V); 620, 40.5 $\text{k}\Omega$; 48.8 $\text{k}\Omega$; 37.5 $\text{M}\Omega$; v_2
- 15.59** [-16.6 V, 16.4 V]
- 15.63** (98.8 μA , 15.3 V), (300 μA , 15.3 V); 27700, 40.5 $\text{k}\Omega$; 2.59 $\text{M}\Omega$
- 15.67** (250 μA , 18.6 V), (500 μA , 18.0 V); 4490, ∞ ; 170 $\text{k}\Omega$
- 15.69** 5770
- 15.71** (250 μA , 7.42 V), (6.10 μA , 4.30 V), (494 μA , 5.00 V); 4230, ∞ ; 97.5 $\text{k}\Omega$
- 15.75** (49.5 μA , 18.0 V), (360 μA , 17.3 V), (990 μA , 18.0 V); 12700, 101 $\text{k}\Omega$; 1.88 $\text{k}\Omega$; 69.2 $\text{M}\Omega$; v_2
- 15.77** (300 μA , 5.10 V), (500 μA , 2.89 V), (2.00 mA, 5.00 V); 528, ∞ , 341 Ω
- 15.79** (300 μA , 5.55 V), (500 μA , 2.89 V), (2.00 mA, 5.00 V), 2930, ∞ , 341 Ω
- 15.81** (250 μA , 10.9 V), (2.00 mA, 9.84 V), (5.00 mA, 12.0 V); 868, ∞ ; 127 Ω
- 15.82** (99.0 μA , 4.96 V), (99.0 μA , 5.00 V), (500 μA , 3.41V), (2.00 mA, 5.00 V); 11400, 50.5 $\text{k}\Omega$, 224 Ω
- 15.84** (49.5 μA , 11.0 V), (98.0 μA , 10.3 V), (735 μA , 16.0 V); 2680, 101 $\text{k}\Omega$, 3.05 $\text{k}\Omega$ [for an ideal current source, 10.3 V]; 1.44 mV
- 15.86** No, R_{id} must be reduced or R_{out} must be increased.
- 15.88** (24.8 μA , 17.3 V), (24.8 μA , 17.3 V), (9.62 μA , 15.9 V), (490 μA , 16.6 V), (49.0 μA , 17.3 V), (4.95 mA, 18.0 V); 88.5 dB, 202 $\text{k}\Omega$, 22.0 Ω
- 15.90** 250 $\mu\text{A/V}^2$; 280; 868
- 15.92** 196; 896
- 15.94** 0.9996, 239 $\text{M}\Omega$, 21.2 Ω
- 15.96** 9.992, 67.6 $\text{M}\Omega$, 1.48 Ω
- 15.98** 36.8 μA
- 15.101** 391 μA
- 15.104** 22.8 μA
- 15.106** 5 mA, 0 mA, 10 mA, 12.5 percent
- 15.107** 66.7 percent
- 15.110** 46.7 mA, 13.5 V
- 15.112** 23.5 μA

- 15.113** 6.98 mA, 0 mA
- 15.114** 25.0 mΩ
- 15.116** (a) 18.7 μA, 61.5 MΩ
- 15.118** (a) 134 μA, 8.19 MΩ
- 15.120** Two of many: 75 kΩ, 6.2 kΩ, 150 Ω; 68 kΩ, 12 kΩ, 1 kΩ
- 15.122** 59.4 μA, 15.7 MΩ
- 15.123** 0, ∞
- 15.125** 88.6 μA, 18.6 MΩ
- 15.127** 17.0 μA, 131 MΩ
- 15.130** 390 kΩ, 210 kΩ, 33 kΩ
- 15.132** 157.4 μA, 16.61 MΩ, 31.89 μA, 112.2 MΩ
- 15.133** 44.1 μA, 22.1 MΩ, 10.1 μA, 209 MΩ
- 15.136** 400 μA, 2.89×10^{11} Ω
- 15.137** (4.64 μA, 7.13 V), (9.38 μA, 9.02 V); 40.9 dB, 96.5 dB
- 15.140** $\beta_o \mu_{f1}/2$, For typical numbers: $20(100)(70) = 140,000$ or 103 dB
- 15.141** 3σ limits: $I_O = 199 \mu A \pm 32.5 \mu A$, $R_{OUT} = 11.8 M\Omega \pm 2.6 M\Omega$
3σ limits: $I_O = 201 \mu A \pm 34.7 \mu A$, $R_{OUT} = 21.7 M\Omega \pm 3.6 M\Omega$

Chapter 16

16.1 [4.28 k Ω , 4.50 k Ω]

16.2 2.50 mV; 5.02 mV; 1%

16.4 7.7%, 0.813 μ A, 0.855 μ A, ($I_{OS} = -42.0$ nA)

16.7 25.0 mV; 1.2%; 0.4%

16.8 (a) 94.8 μ A, 186 μ A, 386 μ A, 1.16 M Ω , 580 k Ω , 290 k Ω

16.11 87.5 μ A, 175 μ A, 350 μ A; 0.0834 LSB, 0.126 LSB, 0.411 LSB

16.12 316 μ A, 332 k Ω , 662 μ A, 166 k Ω

16.16 (a) 693 μ A, 93.8 k Ω , 1.11 mA, 56.8 k Ω

16.18 422 k Ω , 112 μ A; 498 k Ω , 112 μ A

16.21 202 μ A, 327 μ A

16.22 472 μ A, 759 μ A; 479 μ A, 759 μ A; 430 μ A, 692 μ A

16.24 63.8 k Ω , 11.8 μ A, 123 μ A

16.26 10

16.28 15 k Ω , 2/3

16.30 138 μ A, 514 M Ω

16.32 4.90 k Ω

16.34 172 k Ω , 15.0 k Ω , 0.445

16.36 21.8 μ A, 18.4 M Ω ; 43.7 μ A, 9.17 M Ω

16.38 29.8 μ A, 92.9 M Ω ; 87.9 μ A, 31.5 M Ω ; 2770; 1.40 V

16.42 17.0 μ A, 80/1; 89.9 M Ω

16.44 2/g_{m2}

16.46 5.49/1

16.49 11.7 M Ω , 0, 6.687, 90.4 M Ω

16.51 1.33 M Ω , 1, 126, 84.4 M Ω

16.52 20.0 μ A, 953 M Ω ; 19.1 kV; 2.21 V

16.54 21.0 μ A, 4.40 nA

16.57 (b) 50 μ A, 240 M Ω ; 12.0 kV; 3.05 V

16.60 16.9 μ A, 163 M Ω , 2750 V; $2V_{BE} = 1.40$ V

16.62 2.86 k Ω

16.64 (a) $102 \text{ G}\Omega$

16.66 (a) $51.0 \text{ G}\Omega$

16.68 (a) $64.0 \mu\text{A}$, $3.10 \text{ M}\Omega$

16.70 $5.71 \text{ k}\Omega$

16.72 $317 \mu\text{A}$; $295 \mu\text{A}$; $66.5 \mu\text{A}$

16.74 $\cong \beta_o r_{o4}/2$

16.76 $14.5 \text{ k}\Omega$, $226 \text{ k}\Omega$

16.78 $11.5 \text{ k}\Omega$, $313 \text{ k}\Omega$

16.80 $I_{C1} = 137 \mu\text{A}$, $I_{C1} = 44.8 \mu\text{A}$, $S_{V_{CC}}^{I_{C1}} = 4.40 \times 10^{-2}$, $S_{V_{CC}}^{I_{C2}} = 1.54 \times 10^{-2}$

16.82 $n > 1/3$

16.84 6.24 mA

16.86 (b) $I_{D1} = 8.19 \mu\text{A}$ $I_{D2} = 7.24 \mu\text{A}$ $S_{V_{DD}}^{I_{D1}} = 7.75 \times 10^{-2}$ $S_{V_{DD}}^{I_{D2}} = 6.31 \times 10^{-2}$

The currents differ considerably from the hand calculations. The currents are quite sensitive to the value of λ . The hand calculations used $\lambda = 0$. If the simulations are run with $\lambda = 0$, then the results are identical to the hand calculations.

16.88 $14.4 \mu\text{A}$, $36.0 \mu\text{A}$, $6.56 \mu\text{A}$, $72.0 \mu\text{A}$, $9.48 \mu\text{A}$

16.90 $I_{C2} = 16.9 \mu\text{A}$ $I_{C1} = 31.5 \mu\text{A}$ - Similar to hand calculations.

$$S_{V_{CC}}^{I_{C1}} = 9.36 \times 10^{-3} \quad S_{V_{CC}}^{I_{C2}} = 2.64 \times 10^{-3}$$

16.92 (a) $388 \mu\text{A}$, $259 \mu\text{A}$

16.94 $110 \mu\text{A}$

16.96 4.90 V , 327.4 K

16.98 1.20 V , 304.9 K

16.100 5.07 V , $+44.0 \mu\text{V/K}$

16.102 $-472 \mu\text{V/K}$, $-199 \mu\text{V/K}$

16.104 $2.248 \text{ k}\Omega$, $10.28 \text{ k}\Omega$, $80 \text{ k}\Omega$, $23.9 \text{ k}\Omega$, $126 \text{ k}\Omega$

16.105 79.1 , 6.28×10^{-5} , 122 dB

16.107 47.2 , 6.97×10^{-5} , 117 dB

16.109 1200 , 4×10^{-3} , 110 dB , $\pm 2.9 \text{ V}$

16.113 $(100 \mu\text{A}, 8.70 \text{ V})$, $(100 \mu\text{A}, 7.45 \text{ V})$, $(100 \mu\text{A}, -2.50 \text{ V})$, $(100 \mu\text{A}, -1.25 \text{ V})$, 324 , 152

16.115 $(125 \mu\text{A}, 1.54 \text{ V})$, $(125 \mu\text{A}, -2.79 \text{ V})$, $(125 \mu\text{A}, 2.50 \text{ V})$, $(125 \mu\text{A}, 1.25 \text{ V})$; 19600

- 16.118** 171 μA
- 16.119** (b) 100 μA
- 16.120** (250 μA , 5.00 V), (250 μA , 5.00 V), (250 μA , -1.75 V), (250 μA , -1.75 V), (500 μA , -3.21 V), (135 μA , 5.00 V), (135 μA , -5.00 V), (250 μA , 2.16 V), (500 μA , 3.25 V), (500 μA , 3.21 V), (500 μA , 3.58 V); 4130; 2065
- 16.122** 12,600
- 16.124** (250 μA , 7.50 V), (250 μA , 7.50 V), (250 μA , -1.75 V), (250 μA , -1.75 V), (1000 μA , -5.13 V), (330 μA , 7.50 V), (330 μA , -7.50 V), (1000 μA , 4.75 V), (250 μA , 2.16 V), (500 μA , 5.75 V), (1000 μA , 5.13 V), 3160
- 16.126** (b) 42.9/1 (c) 23000
- 16.130** 7.78, 574 Ω , 3.03×10^5 , 60.0 $\text{k}\Omega$
- 16.132** $\pm 1.4 \text{ V}$, $\pm 2.4 \text{ V}$
- 16.133** (a) 9.72 μA , 138 μA , 46.0 μA
- 16.134** 271 $\text{k}\Omega$, 255 Ω
- 16.136** $V_{EE} \geq 2.8 \text{ V}$, $V_{CC} \geq 1.4 \text{ V}$; 3.8 V, 2.4 V
- 16.138** 2.84 $\text{M}\Omega$, 356 $\text{k}\Omega$, 6.11×10^5
- 16.141** 100 μA , 15.7 V), (100 μA , 15.7 V), ((50 μA , -12.9 V), (50 μA , -0.700 V), (50 μA , -0.700 V), (50 μA , -12.9 V), (50 μA , 1.40 V), (50 μA , 1.40 V), (2.00 μA , 29.3 V), (100 μA , 0.700 V), (100 μA , 13.6 V); 1.00 mS, 752 $\text{k}\Omega$
- 16.142** (50 μA , 15.7 V), (50 μA , 15.7 V), (50 μA , 12.9 V), (50 μA , 12.9 V), (50 μA , 1.40 V), (50 μA , 1.40 V), (1.00 μA , 29.3 V), (100 μA , 1.40 V), (1 μA , 0.700 V), (1 μA , 13.6 V); 1.00 mS, 864 $\text{k}\Omega$
- 16.143** (50 μA , 2.50 V), (25 μA , 3.20 V)
- 16.144** (a) 125 μA , 75 μA , 62.5 μA , 37.5 μA ,
- 16.146** $(500 - 195 \sin 5000\pi t) \mu\text{A}$, $(500 + 195 \sin 5000\pi t) \mu\text{A}$; 0.488 mS

Chapter 17

17.1 $A_{mid} = 50$, $F_L(s) = \frac{s^2}{(s+4)(s+30)}$, yes, $A_v(s) \approx 50 \frac{s}{(s+30)}$, 4.77 Hz, 4.82 Hz

17.4 200, $\frac{1}{\left(\frac{s}{10^4} + 1\right)\left(\frac{s}{10^5} + 1\right)}$, yes, 1.59 kHz, 1.58 kHz

17.7 200, $\frac{s^2}{(s+1)(s+2)}$, $\frac{1}{\left(1 + \frac{s}{500}\right)\left(1 + \frac{s}{1000}\right)}$, 0.356 Hz, 142 Hz; 0.380 Hz, 133 Hz

17.9 (b) -14.3 (23.1 dB), 11.3 Hz

17.10 (b) -15.6, 8.15 Hz

17.11 1.52 μ F; 1.50 μ F, 49.4 Hz

17.13 0.213 μ F; 0.22 μ F; 1940 Hz

17.14

$$A_v(s) = A_{mid} \frac{s^2}{(s+\omega_1)(s+\omega_2)} \quad | \quad \omega_1 = \frac{1}{C_1 \left(R_S + R_E \right) \left| \frac{1}{g_m} \right|} \quad | \quad \omega_2 = \frac{1}{C_2 (R_C + R_3)} \quad | \quad 2 \text{ zeros at } \omega = 0$$

35.5 dB, 13.2 Hz; -5.0 V, 7.9 V

17.16 123 Hz; 91 Hz; (145 μ A, 3.57 V)

17.18 -131, 49.9 Hz, 12.0 V

17.19 45.5 Hz

17.21 7.23 dB, 19.8 Hz

17.23 0.739, 11.9 Hz, 10.0 V

17.24 0.15 μ F

17.25 1.8 μ F

17.27 Cannot reach 2 Hz; $f_L = 13.1$ Hz for $C_1 = \infty$, limited by C_3

17.29 0.15 μ F

17.30 308 ps

17.33 (a) 22.5 GHz

17.34 -96.7; -110

17.35 0.978; 0.979

- 17.37** (a) -5100, -98.0, -5000, -100, 2% error (b) -350, -42.9, -300, -50, 18% error
- 17.39** Real roots: -100, -20, -15, -5
- 17.41** (3.31 mA, 2.71 V); -89.6, 1.45 MHz; 130 MHz
- 17.43** -14.3, 540 kHz
- 17.45** (0.834 mA, 2.41 V); -8.27, 3.29 MHz; 27.2 MHz
- 17.49** 61.0 pF, 303 MHz
- 17.52** $1/10^5 RC$; $1/10^6 RC$; $-1/sRC$
- 17.54** 39.2 dB, 5.51 MHz
- 17.56** -114, 1.11 MHz; 127 MHz, 531 MHz
- 17.59** 680Ω , -18.0, 92.7 MHz
- 17.60** -29.3, 7.41 MHz, 227 MHz
- 17.62** 300Ω , $1 \text{ k}\Omega$
- 17.63** -1300; -92.3; -100, -1200
- 17.64** 9.55, 64.4 MHz
- 17.66** 59.7, 1.72 MHz
- 17.69** 2.30, 14.1 MHz
- 17.70** 3.17, 14.1 MHz, 15.4 Hz
- 17.71** 0.960, 114 MHz
- 17.74** -1.56 dB, 73.3 MHz
- 17.75** $C_{GD} + C_{GS}/(1 + g_m R_L)$ for $\omega \ll \omega_T$
- 17.77** Using a factor of 2 margin: 8 GHz, 19.9 ps
- 17.81** 672 mA - not a realistic design. A different FET is needed.
- 17.83** 393 kHz; 640 kHz
- 17.87** 294 kHz
- 17.89** 48.2 kHz
- 17.90** 52.9 kHz
- 17.92** (a) 568 kHz
- 17.94** (a) 2.01 MHz
- 17.96** 53.4 dB, 833 Hz, 526 kHz
- 17.97** 1.52 MHz; 323 μH , 3.65 MHz
- 17.99** -45° ; -118° ; -105°

- 17.101** 22.5 MHz, -41.1, 2.91
- 17.102** 20.1 pF; 12.6; $n = 2.81$; 21.8 pF
- 17.103** 15.2 MHz; 27.5 MHz
- 17.104** 13.4 MHz, 7.98, $112/-90^\circ$; 4.74 MHz, 5.21, $46.1/-90^\circ$
- 17.105** 10.1 MHz, 3.96, -35.3; 10.94 MHz, 16.8, -75.1
- 17.108** 65 pF; $240, -4.41 \times 10^4$, 25.1 kHz
- 17.110** 62.3 pF; 152 kHz, 40
- 17.112** (b) 497Ω , 108 pF
- 17.113** 100 Ω , 104 fF; 52.2 Ω , 144 fF
- 17.117** (a) 100 MHz, 1900 MHz
- 17.119** 58.9 dB
- 17.121** -19.5 dB; -23.9 dB
- 17.123** 0.6 A
- 17.125** -13.5 dB; -17.9 dB
- 17.127** 0.2 A
- 17.129** 1, 0.5, 0.5
- 17.131** 0.567 V
- 17.133** $0.2I_1R_C$

Chapter 18

18.1 (b) 200, 4.975, 0.498%

18.3 1/40, 790.6, -38.95

18.5 104 dB

18.7 1/(1+T); 0.0498 %

18.9 (a) Series-shunt feedback (b) Shunt-series feedback

18.13 857Ω , 33.3, 57.1, 506 Ω

18.15 245Ω , 0, 0.952, 126 Ω

18.17 8.33×10^5 , 16.7 S

18.19 12.9, 8.88 M Ω , 1.52 Ω

18.21 31.1 Ω , 2.01, 17.9, 195 Ω

18.23 10.1, 252 k Ω , 358 Ω

18.25 2.66 Ω ; (32.2 Ω , 0, 11.1)

18.27 141 Ω ; (13.0 k Ω , 0, 91.2)

18.29 0.9987, 110.4 M Ω , 2.845 Ω vs. 0.999, 108 M Ω , 2.70 Ω

18.31 -39.0 k Ω , 8.31 Ω , 0.295 Ω

18.33 33.2 Ω , 45.6 Ω , -38.9 k Ω

18.35 29.7 k Ω , 1.48 k Ω , -672 k Ω

18.37 0.133 mS, 60.4 M Ω , 26.8 M Ω

18.39

SPICE Results : $A_{tc} = 9.92 \times 10^{-5}$ S $R_{in} = 144.1 M\Omega$ $R_{out} = 11.91 M\Omega$

Hand Calculations $A_{tc} = 9.92 \times 10^{-5}$ S $R_{in} = 148 M\Omega$ $R_{out} = 11.1 M\Omega$

18.41 0.467 mS, 95.0 M Ω

18.42 8.48, 15.1 Ω , 3.51 M Ω

18.43 400 Ω , 12.5 M Ω , 0.992

18.45 29.8 M Ω , 799 M Ω , 1.08 G Ω

18.47 2.97, 14.5 Ω , 24.3 M Ω ; 2.99, 14.6 Ω , 18.1 M Ω

18.49 30.39 G Ω ; 33.3 G Ω

18.51 47.32 M Ω ; 37.5 M Ω

18.53 $T_v = 105$, $T_i = 18.1$, $T = 15.2$, $R_2/R_1 = 5.55$

18.55 $T_v = 988$, $T_i = 109$, $T = 98.0$, $R_2/R_1 = 8.99$

18.57 110 kHz, 2048, ≤ 2048

18.59 219 pF

18.61 76.6°

18.63 107°

18.67 9.38 MHz, 41.7 V/ μ S

18.69 (b) 95.5 MHz, 30 V/ μ S

18.71 ± 8.57 V/ μ S

18.73 71.5 MHz, 11.4 kHz, 236 MHz, 326 MHz, 300 MHz; 84.4 dB; < 0 ; 16.8 pF

18.75 $12 \text{ k}\Omega$; 9.05 MHz, 101 MHz, 74.8 MHz, 320 MHz; 2.60 MHz, 44.6 pF

18.77 (a) 81.9°

18.79 6.32 pF; 315 MHz, 91.5 MHz; 89.4°

18.81 17.5 MHz; [20.1 MHz, 36.3 MHz]; 0.211 mS, 5.28 μ A

18.82 5.17 MHz, 4.53 MHz

18.84 9.00 MHz, 1.20

18.86 7.96 MHz, 8.11 MHz, 1.05

18.88 7.5 MHz, 80 V_{p-p}

18.89 7.96 MHz

18.90 11.1 MHz, 18.1 MHz, 1.00

18.91 $L_{EQ} = L_1 + L_2$ | $R_{EQ} = -\omega^2 g_m L_1 L_2$

18.92 $\omega_o^2 = \frac{1}{L(C + C_{GS} + 4C_{GD})}$ | $\mu_f \geq 1 + \frac{r_o}{R_p}$

18.94 5.13 pF; 1 GHz can't be achieved.

18.95 6.33 pF; 2.81 mA; 3.08 mA; 1.32 V

18.97 15.915 mH, 15.915 fF; 10.008 MHz, 10.003 MHz

18.99 9.28 MHz; 9.19 MHz

Congratulations! you have just conquered most of electrical engineering! except for Ch 18, now where did that go?