

INSTRUCTOR'S SOLUTIONS MANUAL TO ACCOMPANY

MICROELECTRONIC CIRCUITS
ANALYSIS AND DESIGN

SECOND EDITION

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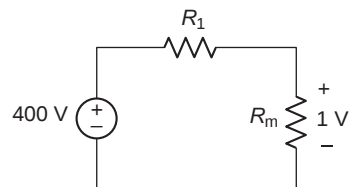
Chapter 1

1.1

$$R_m = \frac{1 \text{ V}}{I_m} = \frac{1 \text{ V}}{100 \mu\text{A}} = 10 \text{ k}\Omega$$

$$\frac{10 \text{ k} \times 400}{R_1 + 10 \text{ k}} = 1 \text{ V}, \quad R_1 = 10 \text{ k} (400 - 1) = 3990 \text{ k}\Omega$$

Take $R_1 \approx 4 \text{ M}\Omega \pm 1\%$.

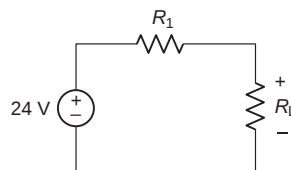


1.2

$$R_L = \frac{6 \text{ V}}{5 \text{ A}} = 1.2 \Omega$$

$$\frac{1.2 \times 24}{R_1 + 1.2} = 6 \text{ V}, \quad R_1 = \frac{1.2 \times 24}{6} - 1.2 = 3.6 \Omega$$

Take $R_1 = 3.6 \Omega \pm 5\%$.



1.3

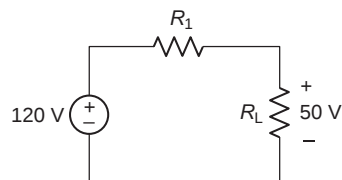
$$\frac{V^2}{R_L} = \frac{50^2}{R_L} = 60 \text{ W}$$

$$R_L = \frac{50^2}{60} = 41.667 \Omega$$

$$\frac{R_L \times 120}{R_1 + R_L} = 50 \text{ V}$$

$$\frac{41.667 \times 120}{50} = R_1 + 41.667, \quad R_1 = 58.334 \Omega$$

Take $R \approx 62 \Omega \pm 5\%$.

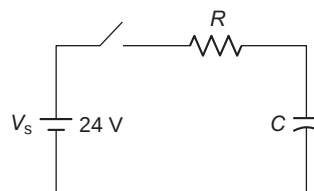


1.4

$$I_o = 1 \text{ mA}$$

$$i(t) = \frac{V_s}{R} e^{-t/\tau}$$

$$\frac{V_s}{R} = \frac{24}{R} = 1 \text{ mA}, \quad R = 24 \text{ k}\Omega \pm 5\%$$



1.5

$$|A_v| = \frac{V_O}{V_I} = \frac{400}{5} = 80, \quad Q = 60^\circ$$

1.6

For NMOS

$$\begin{aligned}
 i_D &= K_p (V_{GS} - V_t)^2 \\
 \left. \frac{\partial i_D}{\partial V_{GS}} \right|_{Q \text{ point}} &= g_m = 2K_p (V_{GSQ} - V_t) \\
 &= 2 \times 20 \text{ mA/V}^2 \times (3 - 1.5) \text{ V} \\
 &= 60 \text{ mS}
 \end{aligned}$$

1.7

$$\begin{aligned}
 i_D &= I_{ss} \left(1 - \frac{V_{GS}}{V_p} \right)^2 \\
 g_m &= \left. \frac{\partial i_D}{\partial V_{GS}} \right|_{Q \text{ point}} = \frac{2 I_{DSS}}{|V_p|} \left(1 - \frac{V_{GS}}{V_p} \right) \\
 &= \frac{40 \text{ mA}}{3 \text{ V}} \left(1 - \frac{1.5}{3} \right) = 6.67 \text{ mS}
 \end{aligned}$$

1.8

$$\begin{aligned}
 i_B &= 2 (1 + \sin 2000\pi t) \text{ mA} \\
 \beta_F &= 100, \quad I_B = 2 \text{ mA} \\
 i_b &= 2 \sin (2000\pi t) \text{ mA} \\
 \beta_F &= \frac{I_C}{I_B} = 100, \quad I_C = \beta_F I_B = 100 \times 2 = 200 \text{ mA} \\
 i_C &= \beta_F i_b = 100 \times 2 \sin 2000\pi t \\
 &= 200 \sin (2000\pi t) \text{ mA}
 \end{aligned}$$

1.9

$$\begin{aligned}
 \text{(a)} \quad v_{CE} &= V_{CE} + v_{ce} = 6 - 0.1 \sin (2000\pi t) \text{ V} \\
 v_{BE} &= V_{BE} + v_{be} = 700 + 1 \sin (2000\pi t) \text{ mV} \\
 \text{(b)} \quad \text{Small-signal voltage gain } A_v &= \frac{v_{ce}}{v_{be}} = \frac{-100}{1} = -100
 \end{aligned}$$

1.10

$$\begin{aligned}
 V_{DS} &= 6 \text{ V}, \quad v_{ds} = -50 \sin (1000\pi t) \text{ mV} \\
 V_{GS} &= 3 \text{ V}, \quad v_{gs} = 2 \sin (1000\pi t) \text{ mV} \\
 \text{(a)} \quad v_{DS} &= V_{DS} + v_{ds} = 6000 - 50 \sin (1000\pi t) \text{ mV} \\
 v_{GS} &= V_{GS} + v_{gs} = 3000 + 2 \sin (1000\pi t) \text{ mV} \\
 \text{(b)} \quad A_v &= \frac{v_{ds}}{v_{gs}} = \frac{-50 \sin (1000\pi t)}{2 \sin (1000\pi t)} = -25
 \end{aligned}$$

Chapter 2

2.1

(a)
$$A_v = \frac{v_{o(\text{peak})}}{v_{i(\text{peak})}} = \frac{6.5}{50 \times 10^{-3}} = 1.30 \times 10^3 = 130 \text{ or } 42.28 \text{ dB}$$

$$i_o = \frac{v_o}{R_L} = \frac{6.5 \sin 1000 \pi t}{5000} = 1.3 \sin (1000 \pi t) \text{ mA}$$

$$A_i = \frac{i_{o(\text{peak})}}{i_{L(\text{peak})}} = \frac{1.3 \times 10^{-3}}{1 \times 10^{-6}} = 1300 \text{ or } 62.28 \text{ dB}$$

$$A_p = A_v \cdot A_i = 130 \times 1300 = 169 \times 10^3 \text{ or } 52.28 \text{ dB } (10 \log P_o/P_i)$$

$$R_i = \frac{v_{i(\text{peak})}}{i_{i(\text{peak})}} = \frac{50 \times 10^{-3}}{1 \times 10^{-6}} = 50 \text{ k}\Omega$$

(b)
$$P_{dc} = V_{CC} I_{CC} + V_{EE} I_{EE} = 15 (15 + 15) \text{ mW} = 450 \text{ mW}$$

$$P_L = \frac{v_{o(\text{peak})}}{\sqrt{2}} \cdot \frac{i_{o(\text{peak})}}{\sqrt{2}} = \frac{6.5 \times 1.3 \times 10^{-3}}{2} = 4.225 \text{ mW}$$

$$P_i = \frac{v_{i(\text{peak})}}{\sqrt{2}} \cdot \frac{i_{i(\text{peak})}}{\sqrt{2}} = \frac{50 \times 10^{-3} \times 1 \times 10^{-6}}{2} = 25 \text{ nW}$$

$$\eta = \frac{P_L}{P_{dc} + P_i} = \frac{4.225 \times 10^{-3}}{450 \times 10^{-3} + 25 \times 10^{-9}} \approx 0.938\%$$

(c)
$$A_v v_{i(\text{max})} = V_{o(\text{max})} = V_{CC}$$

$$v_{i(\text{max})} = \frac{15}{130} = 115.4 \text{ mV}$$

2.2

$$V_o = 5.3 \text{ V at } V_I = 21 \text{ mV, } V_o = 5.8 \text{ V at } V_I = 27 \text{ mV}$$

$$\Delta V_o = 5.8 - 5.3 = 0.5 \text{ V, } \Delta V_I = 27 - 21 = 6 \text{ mV}$$

(a)
$$A_v = \frac{\Delta V_o}{\Delta V_I} = \frac{0.5}{6 \times 10^{-3}} = 83.3 \text{ or } 38.4 \text{ dB}$$

(b)
$$A_{dc} = \frac{V_o}{V_I} = \frac{5.5}{24 \times 10^{-3}} = 229 \text{ or } 47.2 \text{ dB}$$

(c)
$$\frac{V_o - V_{(\text{min})}}{A_v} \leq V_F - 24 \text{ mV} \leq \frac{V_{o(\text{max})} - V_o}{A_v}$$

$$\frac{-5.5 + 2}{83.3} \leq V_I - 24 \text{ mV} \leq \frac{11 - 5.5}{83.3}$$

$$-42 \text{ mV} \leq V_1 - 24 \text{ mV} \leq 66 \text{ mV}$$

$$-18 \text{ mV} \leq V_1 \leq 90 \text{ mV}$$

2.3

(a)

$$i_o = \frac{v_o}{R_L} = \frac{2 \text{ V}}{10 \text{ k}\Omega} = 0.2 \text{ mA}$$

$$i_i = \frac{v_i}{R_i} = \frac{1 \text{ mV}}{100 \text{ k}\Omega} = 10 \text{ nA}$$

$$A_i = \frac{i_o}{i_i} = \frac{0.2 \times 10^{-3}}{10 \times 10^{-9}} = 2 \times 10^4 \text{ or } 86 \text{ dB}$$

$$A_v = \frac{v_o}{v_i} = \frac{2}{1 \times 10^{-3}} = 2 \times 10^3$$

$$A_p = A_v A_i = 2 \times 10^3 \times 2 \times 10^4 = 4 \times 10^7 \text{ or } 152 \text{ dB}$$

(b)

$$v_i = i_i R_i = 1 \times 10^{-3} \times 100 = 10^{-1} \text{ V}$$

$$v_o = i_o R_L = 100 \times 10^{-3} \times 10^3 = 100 \text{ V}$$

$$A_v = \frac{v_o}{v_i} = \frac{100}{0.1} = 1000 \text{ or } 60 \text{ dB}$$

$$A_i = \frac{i_o}{i_i} = \frac{100 \times 10^{-3}}{10^{-3}} = 100 \text{ or } 40 \text{ dB}$$

$$A_p = A_v A_i = 1000 \times 100 = 10^5 \text{ or } 50 \text{ dB}$$

2.4

(a) From Eq. (2.21)

$$A_v = \frac{A_{vo}}{(1 + R_s/R_i)(1 + R_o/R_L)}$$

$$= \frac{150}{(1 + 200/1800)(1 + 50/4700)} = 133.6$$

From Eq. (2.22)

$$A_i = \frac{A_{vo} R_i}{R_L + R_o} = \frac{150 \times 1800}{4700 + 50} = 56.84$$

From Eq. (12.23)

$$A_p = A_v A_i = 133.6 \times 56.84 = 7593.82$$

(b) Problem 2.4 Amplifier

```

VS      1  0  AC      100MV
RS      1  2      200
RI      2  0      1.8K
E1      3  0      2  0    150
R0      3  4      50
RL      4  0      4.7K
. TF    V(4)  VS
. End

```

2.5

For maximum power transfer

$$R_o = R_L = 50 \, \Omega$$

$$P_L = v_o i_o$$

$$= (A_v v_i) (A_i i_i)$$

$$= \frac{A_{v_o} \cdot v_i}{(1 + R_s/R_i)(1 + R_o/R_L)} \cdot \frac{A_{v_o} R_i}{R_L + R_o} i_i$$

$$= \frac{A_{v_o}^2 R_i R_L v_i}{(R_i + R_s)(R_L + R_o)} \cdot \frac{A_{v_o} \cdot v_i}{(R_L + R_o)}$$

$$= \frac{A_{v_o}^2 R_i R_L}{(R_L + R_o)^2 (R_i + R_s)} \cdot v_i^2$$

$$= \frac{A_{v_o}^2 R_i R_L}{(R_L + R_o)^2 (R_i + R_s)} \cdot \frac{R_i^2 v_s^2}{(R_i + R_o)^2}$$

$$= \frac{A_{v_o}^2 R_L R_i^3 v_s^2}{(R_L + R_o)^2 (R_i + R_s)^3}$$

$$\therefore P_{L(\max)} = \frac{150^2 \times 50 \times 1800^3 (100 \times 10^{-3})^2}{100^2 (1800 + 200)^3}$$

$$= 820 \text{ mW}$$

2.6

$$\frac{\Delta v_o}{v_o} = \frac{R_o}{R_L + R_o}$$

$$\frac{\Delta v_o}{v_o} = 0.15 = \frac{R_o}{1.5 \text{ k} + R_o}$$

$$R_o = \frac{1.5 \times 10^3 \times 0.15}{0.85} = 264.7 \, \Omega$$

2.7

$$\begin{aligned} \text{(a)} \quad v_o &= A_{v_o} v_i \frac{R_L}{R_L + R_o} = A_{v_o} \frac{R_L}{R_L + R_o} \cdot \frac{R_i \cdot V_s}{R_i + R_s} \\ &= \frac{200 \times 22 \times 10^5 \times 50 \times 10^{-3}}{(22 + 20)(10^5 + 1500)} = 5.16 \text{ V} \end{aligned}$$

(b) From Problem 2.5

$$\begin{aligned} P_L &= \frac{A_{v_o}^2 R_L R_i^3 V_s^2}{(R_L + R_o)^2 (R_i + R_s)^3} \\ &= \frac{200^2 \times 22 \times 10^{15} \times (50 \times 10^{-3})^2}{(22 + 20)^2 \cdot (10^5 + 1500)^3} \\ &= 1.19 \text{ W} \end{aligned}$$

$$(c) A_v = \frac{v_o}{v_s} = \frac{5.16}{50 \times 10^{-3}} = 103.2$$

$$(d) A_i = \frac{i_o}{i_s}, i_o = \frac{5.16}{22 + 20} = 122.86 \text{ mA}$$

$$i_s = \frac{v_s}{R_s + R_i} = \frac{50 \times 10^{-3}}{1500 + 10^5} = 4.93 \times 10^{-7} \text{ A}$$

$$A_i = \frac{122.86 \times 10^{-3}}{4.93 \times 10^{-7}} = 249 \times 10^3$$

$$(e) A_p = A_v A_i = 103.2 \times 249 \times 10^3 = 25.7 \times 10^6$$

2.8

$$i_s \leq 1 \text{ } \mu\text{A} = \frac{v_s}{R_s + R_i} = \frac{10 \times 10^{-3}}{2.5 \text{ k} + R_i}$$

$$R_i \geq 7500 \text{ } \Omega$$

From Eq. (2.25)

$$\frac{\Delta v_o}{v_o} = \frac{R_o}{R_L + R_o}, R_L \text{ ranging from } 2 \text{ k}\Omega \text{ to } 10 \text{ k}\Omega$$

$$\text{For } \frac{\Delta v_o}{v_o} \leq 0.5\%$$

$$\frac{5}{1000} = \frac{R_o}{R_L + R_o}, R_o \leq 10 \text{ } \Omega$$

$$A_v = \frac{5 \text{ V}}{10 \text{ mV}} = 500 \text{ or } 53.98 \text{ dB}$$

From Eq. (2.21)

$$500 = \frac{A_{vo}}{(1 + R_s/R_i)(1 + R_o/R_L)} = \frac{A_{vo}}{(1 + 2.5 \text{ k}/7.5 \text{ k})(1 + 10/2000)}$$

$$\therefore A_{vo} = 669.8$$

2.9

From Eq. (2.21)

$$A_v = \frac{A_{vo}}{(1 + R_s/R_i)(1 + R_o/R_L)}$$

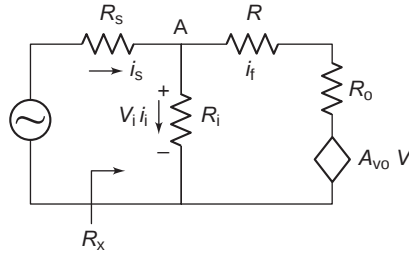
Variation in A_v will be contributed by A_{vo} , R_s , and R_L . Assume equal contribution by each. Hence the value of R_o that will keep the variation in gain within 0.5% for variation in R_L from 5 k Ω to 20 k Ω can be found from

$$\frac{5 \text{ k}}{5 \text{ k} + R_o} = \frac{20 \text{ k}}{20 \text{ k} + R_o} \times 0.995$$

$$R_o = \frac{20 \text{ k} (1 - 0.995)}{4 \times 0.995 - 1} \geq 33.5 \text{ } \Omega$$

2.10

(a) By Kirchoff's current law at node A



$$i_s = i_i + i_f = \frac{v_i}{R_i} + \frac{v_i - A_{vo} v_i}{R + R_o}$$

$$= v_i \left[\frac{1}{R_i} + \frac{1 - A_{vo}}{R + R_o} \right]$$

$$R_x = \frac{v_i}{i_s} = \frac{1}{1/R_i + (1 - A_{vo})/(R + R_o)}$$

(b) For $R_i = 50 \text{ k}$, $R_o = 75 \text{ } \Omega$, $A_{vo} = 2$, $R = 10 \text{ k}$

$$R_x = \frac{1}{1/50 \text{ k} + (1 - 2)/(10 \text{ k} + 75)}$$

$$= -12.62 \text{ k}\Omega$$

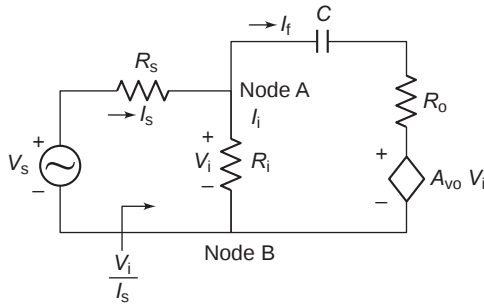
$$i_s = \frac{V_s}{R_s + R_x} = \frac{20 \text{ mV}}{1.5 \text{ k}\Omega - 12.62 \text{ k}\Omega} = -1.8 \text{ } \mu\text{A}$$

(c) For $i_s = 2.5 \text{ } \mu\text{A}$, $R_s + R_x = \frac{V_s}{i_s}$

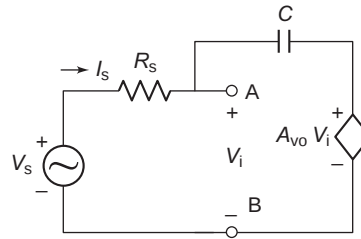
$$= \frac{20 \text{ mV}}{-2.5 \text{ } \mu\text{A}} = -8 \text{ k}\Omega$$

$$\therefore R_x = -8 \text{ k} - 1.5 \text{ k} = -9.5 \text{ k}\Omega$$

2.11



(a) Voltage amplifier



(b) Ideal voltage amplifier

Since the response of feedback capacitor C is frequency dependent, all voltages and currents will be phasor quantities and will have both magnitude and phase angle. Use rms values for voltages and currents.

(a) KCL at node A and currents and voltages in s-domain

$$\begin{aligned} I_s(s) &= I_i(s) + I_f(s) \\ &= \frac{V_i(s)}{R_i} + \frac{V_i(s) - V_i(s)A_{vo}}{R_o + 1/sC} = V_i(s) \left[\frac{1}{R_i} + \frac{1 + A_{vo}}{R_o + 1/sC} \right] \end{aligned}$$

which gives input impedance Z_i as

$$Z_x(s) = \frac{V_i(s)}{I_s(s)} = \frac{1}{1/R_i + (1 - A_{vo})/(R_o + 1/sC)}$$

(b) For $R_i = \infty$ and $R_o = 0$, $Z_x(s)$ reduces to

$$Z_x(s) = \frac{V_i(s)}{I_s(s)} = \frac{1}{sC(1 - A_{vo})} = \frac{1}{sC_x}$$

where $C_x = C(1 - A_{vo})$

For $A_{vo} = -100$, $C = 0.01 \mu\text{F}$

$$C_x = C(1 + 100) = 101 \times 0.01 = 1.01 \mu\text{F}$$

$$\begin{aligned} Z_s(j\omega) &= R_s + Z_{Cx}(j\omega) = 1.5 \text{ k}\Omega - \frac{j}{(2\pi \times 100 \times 1.01 \mu\text{F})} \\ &= 1.5 \text{ k} - j 1576 = 2.176 \angle -46.4^\circ \text{ k}\Omega \end{aligned}$$

Input current drawn from the source

$$I_s = \frac{V_s}{Z_s} = \frac{20 \text{ mV}}{\sqrt{2}} (2.176 \angle -46.4^\circ \text{ k}\Omega) = 6.5 \angle 46.4^\circ \mu\text{A}$$

2.12

From Problem 2.10

$$\begin{aligned} R_x &= \frac{1}{1/R_i + (1 - A_{vo})/(R + R_o)}, \quad R_x = -5 \text{ k}\Omega \\ -5000 &= \frac{1}{1/50 \text{ k} + (1 - A_{vo})/(10 \text{ k} + 75)} \\ -5000 &= \frac{1}{20 \times 10^{-6} + 99.255 \times 10^{-6}(1 - A_{vo})} \\ A_{vo} &= 3.216 \end{aligned}$$

2.13

$$A_{is} = 200, \quad R_i = 150 \Omega, \quad R_o = 2.5 \text{ k}\Omega$$

$$R_L = 100 \Omega, \quad i_s = 4 \text{ mA}, \quad R_s = 47 \text{ k}\Omega$$

(a) From Eq. (2.28)

$$\begin{aligned} A_i &= \frac{A_{is}}{(1 + R_i/R_s)(1 + R_L/R_o)} = \frac{200}{(1 + 150/47 \text{ k})(1 + 100/2500)} \\ &= 191.7 \end{aligned}$$

$$A_v = A_i \frac{R_L}{R_s} = 191.7 \times \frac{100}{47k} = 0.4078$$

$$A_p = A_v A_i = 191.7 \times 0.407 = 78.17$$

(b) Problem 2.13a Amplifier

```

VS      1  0      AC  1MV
RS      1  2      47K
RI      3  0      150
F1      0  4      VX  200
VX      2  3      0V
VY      4  5      DC  0V
R0      4  0      2.5K
RL      4  0      100
. TF    V(s)    VS
. END

```

Problem 2.13b Amplifier

```

IS      0  1      AC  1MA
RS      1  0      47K
RI      2  0      150
F1      0  3      VX  200
VX      1  2      DC  0V
VY      3  5      DC  0V
R0      3  0      2.5K
RL      5  0      100
. TF    I(VY)   IS
. END

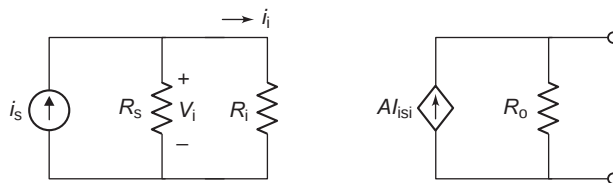
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2.14

From Eqs. (2.26) and (2.27)

$$\begin{aligned}
 i_o &= \frac{A_{is} R_o}{R_o + R_L} \cdot \frac{R_s}{R_s + R_i} \cdot i_s \\
 &= \frac{10 \times 22 \times 10^3}{22 \times 10^3 + 150} \times \frac{100 \times 10^3}{10^5 + 50} \times 50 \times 10^{-3} \\
 &= 4.96 \text{ A}
 \end{aligned}$$

2.15



(a) Output resistance = $\frac{\text{open-circuit voltage}}{\text{short-circuit current}}$

$$= \frac{12}{100 \times 10^{-3}} = 120 \Omega$$

$$A_{is} i_i = \text{short circuit current} = 100 \times 10^{-3} \text{ A}$$

$$i_i = i_s \frac{R_s}{R_i + R_s} = \frac{5 \times 10^{-6} \times 100 \text{ k}}{50 + 100 \text{ k}} \approx 5 \times 10^{-6} \text{ A}$$

$$A_{is} = \frac{100 \times 10^{-3}}{5 \times 10^{-6}} = 20 \times 10^3$$

$$\begin{aligned} A_v &= \frac{v_o}{v_s} = A_{is} i_L \frac{R_o}{R_o + R_L} \cdot \frac{R_L}{i_s R_s} \\ &= 100 \times 10^{-3} \times \frac{120}{120 + 2700} \times \frac{2700}{5 \times 10^{-6} \times 10^5} \\ &= 22.98 \end{aligned}$$

(b) $A_i = \frac{20 \times 10^3}{(1 + 50/100 \text{ k})(1 + 2.7 \text{ k}/120)} = 850.6$

(c) $A_p = A_v A_i = 22.98 \times 850.6$
 $= 19,547$

2.16

Following Example 2.5 we have

$$0.99 \frac{R_o}{R_o + 20} = \frac{R_o}{R_o + 500}$$

$$R_o (1 - 0.99) = 500 \times 0.99 - 20$$

$$R_o = 47.5 \text{ k}\Omega$$

For R_i

$$0.99 \times \frac{100 \text{ k}}{100 \text{ k} \times R_i} = \frac{10 \text{ k}}{10 \text{ k} + R_i}$$

$$R_i = 111.23 \Omega$$

$$A_{is} = \frac{20 \times 10^{-3}}{100 \times 10^{-6}} = 200 \text{ A/A}$$

2.17

Assume A_i varies equally due to contribution from A_{is} , R_s , and R_o .

$$\frac{R_o}{R_o + R_L} = 0.995, \quad \frac{R_o}{R_o + 100} = 0.995$$

$$R_o = \frac{100 \times 0.995}{1 - 0.995} \geq 19.9 \text{ k}\Omega$$

Similarly

$$\frac{R_s}{R_s + R_i} = 0.995, \quad \frac{100 \text{ k}}{100 \text{ k} + R_i} = 0.995$$

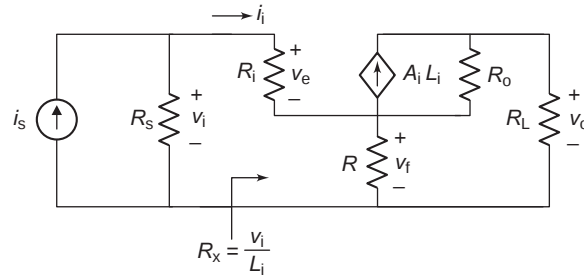
$$R_i \leq 503 \Omega$$

$$A_i = \frac{A_{is}}{(1 + R_i/R_s)(R_L/R_o)}$$

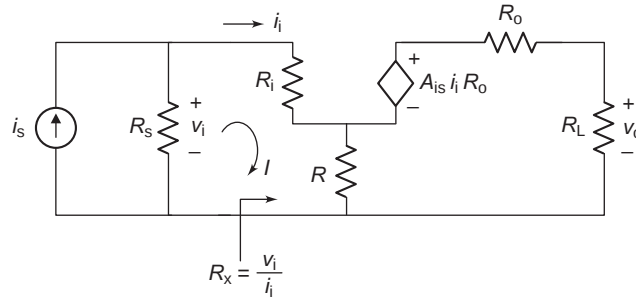
$$50 = \frac{A_{is}}{(1 + 503/100 \text{ k})(1 + 100/19.9 \text{ k})} \approx A_{is}$$

$$\therefore A_{is} \approx 50$$

2.18



- (a) R allows a voltage that is proportional to lead current i_o to be fed back to the input side.
Converting current source to voltage source



Applying KVL to loop II

$$\begin{aligned} A_{is} R_o i_i &= R_o i_o = R(i_i - i_o) + R_L i_o \\ &= (R_o + R_L + R) i_o - R i_i \\ i_o &= \frac{A_{is} R_o + R}{R_o + R_L + R} i_i \end{aligned} \quad (1)$$

Applying KVL to loop I

$$\begin{aligned} v_i &= R_i i_i + R(i_i - i_o) \\ &= (R_i + R) i_i - R i_o \end{aligned} \quad (2)$$

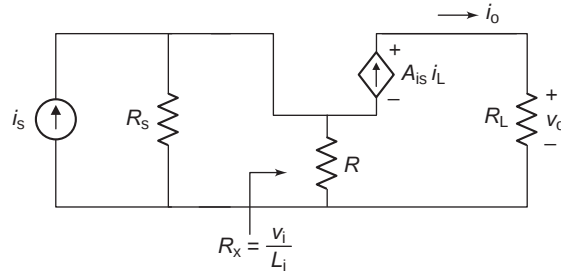
Substituting i_o from Eq. (1) into Eq. (2) and simplifying

$$v_i = (R_i + R) i_i - R \cdot \frac{A_{is} R_o + R}{R_o + R_L + R} i_i$$

$$\frac{v_i}{i_i} = R_i + R - R \frac{A_{is} R_o + R}{R_o + R_L + R}$$

$$R_x = \frac{v_i}{i_i} = R_i + R - R \frac{(A_{is} + R/R_o)}{1 + (R_L + R)/R_o}$$

(b) Assume ideal current amplifier with $R_i = 0$ and $R_o = \infty$, we have the reduced figure as



$$R_x = R - R A_{is} = R(1 - A_{is})$$

For $A_{is} > 1$, R_x is negative, and if $A_{is} = 2$

$$R_x = -R$$

For $R_x = -10 \text{ k}\Omega$ we need $R = 10 \text{ k}\Omega$.

Thus an ideal current amplifier with $A_{is} = 2$ and $R = 10 \text{ k}\Omega$ will simulate a negative resistance.

2.19

(a) Using the result of Problem 2.18 for $A_{is} = 2$ and substituting R by impedances $Z(s)$

$$\begin{aligned} Z_x &= \frac{V_i(s)}{I_i(s)} = -Z(s) = -\left[R + \frac{-R(R + 1/sC)}{-R + R + 1/sC} \right] \\ &= -[R - sCR^2 - R] = sCR^2 \end{aligned}$$

$Z_x = sL_e$ where the effective inductance L_e is given by CR^2 . Thus, the circuit simulates an inductance.

(b) To simulate $L_e = 10 \text{ mH}$, let $C = 0.01 \text{ }\mu\text{F}$,

$$10 \times 100^{-3} = 0.01 \times 10^{-6} \times R^2$$

$$R^2 = 10^6, \quad R = 1 \text{ k}\Omega$$

(c) Problem 2.19 Inductance Simulation

IS	0	4	AC	1MA
V1	4	1	DC	0V
F1	1	0	V1	2
R1	1	2	1K	
R2	2	3	1K	
C1	3	0	0.01UF	
V2	2	5	DC	0V
R3	5	0	1K	
F2	5	0	V2	2
. AC LIN	10		1K	10K

```
. PRINT AC VM(1)VP(1)
. END
```

2.20

(a) $L_e = 50$ mH, choosing $C = 0.1$ μ F

$$R = \sqrt{\frac{L_e}{C}} = \sqrt{\frac{50 \times 10^{-3}}{0.1 \times 10^{-6}}} = 707.1 \, \Omega$$

(b) Problem 2.20 Inductance Simulation

```
IS 0 4 AC 1MA
V1 4 1 DC 0V
F1 1 0 V1 2
R1 1 2 707.1
R2 2 3 707.1
C1 3 0 0.01UF
V2 2 5 DC 0V
R3 5 0 707.1
F2 5 0 V2 2
. AC LIN10 1K 10K
. PRINT AC VM(1)VP(1)
. END
```

2.21

$$R = \sqrt{\frac{L_e}{C}} = \sqrt{\frac{50 \times 10^{-3}}{0.1 \times 10^{-12}}} = 12.25 \, \text{k}\Omega$$

2.22

(a)

$$v_o = -G_{m1} v_i(s) \cdot \frac{1}{sC}$$

$$i_i(s) = -G_{m2} v_o(s) = G_{m1} G_{m2} \frac{v_i(s)}{sC}$$

$$Z_i = \frac{v_i(s)}{i_i(s)} = \frac{sC}{G_{m1} G_{m2}}$$

$$Z_i(j\omega) = j\omega \frac{C}{G_{m1} G_{m2}}$$

(b) Problem 2.22 Amplifier

```
VS 1 0 AC 1V
RS 1 2 100
G1 0 2 3 0 3M
G2 3 0 2 0 3M
C1 3 0 0.1UF
R1 3 0 100M
. TRAN15US1.5 MS
. PROBE
. END
```